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investigation of
the column strength
of USS "T-I" STEEL
round bars

FOR THE UNITED STATES STEEL CORPORATION

by Yuzuru Fujita and George C. Driscoll, Jr.
Errata

The following errors in this report have been discovered since its publication:

(1) In Appendix 1, Sample Calculations, Calculation at Load 19 for Middle Point of C-10, on the first line, "E" should precede the words "Measured Strains".

(2) In the Legend in Figure 4, "C-12" should read "C-3".

(3) In Figure 4, the scales on both axes are incorrect. Each index mark on the ordinate-axis should equal 0.10 unit and each index mark on the abscissa-axis should equal 0.20 unit.
LEHIGH UNIVERSITY COLUMN TESTING MACHINE
INVESTIGATION OF THE COLUMN STRENGTH
OF USS "T-1" STEEL ROUND BARS
FOR THE UNITED STATES STEEL CORPORATION

by

Yuzuru Fujita and George C. Driscoll, Jr.

(This Report or any Part Thereof is not for Publication)

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

April 1956

Fritz Laboratory Report No. 200-56.166.1
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INVESTIGATION OF THE COLUMN STRENGTH
OF USS "T-1" STEEL ROUND BARS
FOR THE UNITED STATES STEEL CORPORATION

Introduction - A program of testing was sponsored by the United States Steel Corporation at the Fritz Engineering Laboratory, Lehigh University, to obtain information upon which design formulas could be based for use with USS "T-1" Constructional Alloy Steel round bars used as compression members.

The need for such information arose from the possibility of using this steel in round bars for the vertical members of television transmission towers.

The planning and execution of the program followed the same procedure used in previous investigations for the determination of column curves for wide flange shapes of structural carbon steel. Compressive stress-strain curves for the material were obtained from compression tests of very short lengths of the bars and the equation for a column curve for "T-1" steel round bars was determined. Tests of several "T-1" steel round bar columns of different lengths were made to verify the ultimate loads predicted by the column curve.

The report describes the tests in detail and presents the column curves which were obtained and verified in the program.
Axially Loaded Columns - For the purpose of designing compression members, expressions are derived relating the ultimate strength of the member to the mechanical properties of the material in the member and to the size, shape, end conditions, and loading.

The Euler buckling equation gives the critical stress for an axially loaded column in the elastic range of stress: terms are defined at the end of the report.

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

The tangent modulus buckling equation introduced by Engesser, defines the critical stress for an axially loaded column in which the material yields prior to buckling:

\[ \sigma_{cr} = \frac{\pi^2 E_t}{(KL/r)^2} \]  

These two equations are identical, with the exception that the Engesser equation includes the more general tangent modulus of elasticity which makes the equation applicable for both elastic and plastic buckling.

To use these equations in plotting a column curve, values of the tangent modulus of elasticity corresponding to various levels of stress must be determined. These are best obtained from a compression test of a short piece of the material (L ≤ 4D). The slope of the stress-strain curve from such a test, at any stress ordinate, is the tangent modulus for that stress. Tangent modulus may be plotted versus stress in a non-dimensional curve to facilitate plotting of the column curve (Fig. 6).

Having the relationship between stress and tangent modulus, equation (2) may be plotted with \( \sigma_{cr} \) versus KL/r, giving the theoretical column curve (Fig. 2). Typical calculations are presented in Appendix 1.
Eccentrically Loaded Columns - Methods for obtaining the ultimate strength of members subjected to combined bending and axial load are given in References 2 and 3. The procedure is involved and will not be discussed in detail here, these references being recommended to the reader for further study of the subject.

The fundamental theory upon which the procedure is based, is the modified plastic theory for determining the reduction in moment of a bending member subjected to compressive load.

The information needed to calculate the theoretical ultimate load consists of the yield strength and modulus of elasticity of the material, shape, and dimensions of the cross section, length, end conditions, and manner and location of application of load.

Having this data and following the procedures in the references, ultimate loads and column curves for eccentrically loaded columns may be readily calculated. Sample calculations using the expressions developed are shown in Appendix 2.
DESCRIPTION OF TEST SPECIMENS*

The test specimens for the testing program were various lengths of solid round bars of USS "T-1" steel, a quenched and tempered constructional alloy steel developed by the United States Steel Corporation. In the heat-treated condition, this steel is furnished to a minimum yield strength of 90,000 psi, (0.2 per cent offset or 0.005 inches per inch extension under load) and a minimum tensile strength of 105,000 psi. Because of the very high strength of USS "T-1" steel, and because of the limited capacity of the testing machine at Lehigh University (800,000-pound-capacity), the maximum size bar that could be tested was 2-3/4 inches in diameter. The test specimens for the testing program were supplied to the Fritz Engineering Laboratory, Lehigh University by the United States Steel Corporation.

For the USS "T-1" steel specimens, three 24-foot-long, 2 3/4-inch-diameter, hot-rolled, open-hearth steel bars were obtained from United States Steel Corporation's Duquesne Works Heat No. 25C212 which had the following composition, ladle analyses in per cent:

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount</th>
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<tbody>
<tr>
<td>Carbon</td>
<td>0.13</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.90</td>
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<tr>
<td>Phosphorus</td>
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<tr>
<td>Sulfur</td>
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<td>Silicon</td>
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<td>Nickel</td>
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<td>Vanadium</td>
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<tr>
<td>Boron</td>
<td>0.0020</td>
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</tbody>
</table>

* This information was supplied by the United States Steel Corporation.
The bars were austenitized by heating at 1600°F for 2-1/2 hours, and water quenched to ambient temperature. The bars were then tempered by heating at 1150°F for 3 hours and 20 minutes, and air cooled. The bars were cold-straightened in a Medart straightener and subsequently stress relieved by heating at 1100°F for 3 hours, and air cooling. They were then saw-cut into 12 bars of various lengths and the ends were machined parallel to each other and perpendicular to the longitudinal axis of the bars. These lengths of bars were identified as the test specimens listed in Table I. The maximum amount of out-of-straightness of each bar was located and measured. These measurements are also given in Table I. Because of the excessive amount of out-of-straightness, specimen C-8 was restraightened and again stress relieved at 1100°F.

Prior to cutting the 24-foot-long bars into the various lengths for the compression test specimens, a standard tensile test was performed on an ASTM standard, 0.505-inch-diameter by 2-inch-gage length, tension test specimen that was machined from a sample of the steel obtained at the mid-radius from one of the ends of the long bars. The following mechanical properties were determined from this test:

- **Yield strength, 0.2 per cent offset, psi**: 126,000
- **Tensile strength, psi**: 133,600
- **Elongation in 2 inches, per cent**: 22.0
- **Reduction of area, per cent**: 67.5

The stress-strain diagram obtained from this test is shown by a solid line (without circles) in Fig. 1.

A pair of end plates, adaptable to the Fritz Engineering Laboratory loading fixtures, were supplied for each of the two test specimens that were to be tested as eccentrically loaded columns. These end plates were
of a manganese-molybdenum steel obtained from plate produced at Homestead Works from Homestead Heat No. 70P270 which had the following composition, ladle analyses in per cent:

<table>
<thead>
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<td>Boron</td>
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The manganese-molybdenum steel plates were austenitized by heating at 1560 F for 2-1/2 hours, and then water quenching to ambient temperature. The plates were tempered by heating at 1000 F for one hour followed by water quenching. The heat-treated plates had a minimum hardness of 321 Brinell.

The face of each end plate that was to bear on the test specimen was then machined to have a 2 11/16-inch-diameter by 3/16-inch-deep recess at the center of the square face. Each end of the USS "T-1" steel specimens C-13 and C-14 was turned down to 2 5/8-inch diameter for a length of 3/8 inch from the end of the specimen. Two end plates were then positioned, clamped and welded to the ends of specimens C-13 and C-14 using E12015 electrodes to form 5/16-inch fillet welds around the circumferences of the 2 3/4-inch-diameter specimens. The two end surfaces of the end plates of the two specimens were then machined parallel to each other and perpendicular to the longitudinal axis of the specimens.

The two test specimens of structural carbon steel (ASTM A-7 minimum yield point, 33,000 psi, and tensile strength range of, 60,000—72,000 psi)
that are included in the testing program were obtained from a suitable length of 2 3/4-inch-diameter, hot-rolled, open-hearth ASTM A-7 steel bar which was made from Duquesne Works Heat No. 28051, having the following composition, ladle analyses in per cent:

<table>
<thead>
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<th>Element</th>
<th>Per Cent</th>
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<tbody>
<tr>
<td>Carbon</td>
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<tr>
<td>Manganese</td>
<td>0.51</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.016</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.023</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The length of structural carbon steel bar was cold-straightened in a Medart straightener and then stress relieved by heating at 1100 F for 3 hours followed by air-cooling. The bar was then saw-cut into two bars of different lengths and the ends of the two bars were machined parallel to each other and perpendicular to the longitudinal axis of the bars. The bars were identified and the maximum amount of out-of-straightness was located and measured. These measurements are given in Table I.

Again, prior to cutting the structural carbon steel bar into the lengths for the compression test specimens, and as was done for the USS "T-1" steel, a standard tension test was performed on an ASTM standard tension test specimen obtained from the structural carbon steel bar. The following mechanical properties were determined from this test.

- Yield strength, 0.2 per cent offset, psi: 34,840
- Tensile strength, psi: 64,460
- Elongation in 2 inches, per cent: 37.0
- Reduction of area, per cent: 61.7

The stress-strain diagram obtained from this test is shown by a solid line (without circles) in Fig. 1.
DESCRIPTION OF EXPERIMENTAL WORK

Cross section compression tests were conducted on short lengths of USS "T-1" steel bars to obtain the stress-strain curves necessary for the calculation of the theoretical column curves.

The column curves calculated from these cross section tests were then checked by tests of a number of axially loaded columns, as shown in Table 2.

Numerous tests on structural carbon steel columns have demonstrated that there is good agreement between the results obtained from column tests and the theoretical column curve obtained from the cross section test. To verify the applicability of the test methods used in this testing program, a cross section test and a concentrically loaded column test were conducted on two bars of structural carbon steel having the same diameter as the USS "T-1" steel bars. By comparing the agreement between the results of the column tests with the theoretical column curve for USS "T-1" steel, and the agreement of the result of the column test with the theoretical column curve for the structural carbon steel, it was possible to establish the applicability of the test methods.

Tests were also conducted on two eccentrically loaded columns to check the applicability of the method for calculating the strength of eccentrically loaded columns given in References 2 and 3.

1. Cross Section Tests - Cross section tests, required in the determination of tangent modulus of elasticity, were carried out on three USS "T-1" steel specimens, C-1, C-2, C-9-2, and on C-3, a structural carbon steel specimen (Table 2). The specimens were 2-3/4 in. rounds of
ll-in. lengths, machined flat at each end. The complete setup for testing including gages and end fixtures, is shown in Fig. 13.

Two types of gages were applied for the measurement of strains. Four SR-4 gages (type A-11) were applied longitudinally to each cross section test specimen at mid-length. Also, a mechanical compression gage having a 5-in. gage length was attached over the mid-length of the specimen.

All specimens were tested in the flat-ended condition in an 800,000-lb. screw-type testing machine. A uniform distribution of applied stress in the test specimen was obtained by the use of a spherical bearing block at the upper end, and a set of tapered discs at the lower end of the test specimen.

The SR-4 gages were used as a guide during alignment of the test specimen, and the mechanical gage was used to measure the average strain in the test specimen during testing. The mechanical gage indicated the average shortening over a 5-in. gage length along the longitudinal axis of the specimen. The two types of measurement showed good agreement.

The specimens were aligned at loads not exceeding one-third of the assumed proportional limit, and the precision of the alignment was within three per cent in strain.

Load was applied to the specimens and readings of load and strain were taken. The application of the load was made in increments as determined from a running plot of load versus strain during the test. Beyond the proportional limit, the readings were taken after the load and strain had stabilized, usually requiring about fifteen minutes after each increment of load was applied.
2. **Concentric Column Tests** - The column curve, obtained as explained previously, was correlated with the results of tests on ten columns. The column specimens were 2-3/4 in. rounds of various lengths, machined flat at each end, and tested in the flat-ended condition. For theoretical purposes, pin-ended columns would have been desirable, but because end fixtures of sufficient load capacity were not available, the columns were tested in the flat-ended condition. For full fixity of the ends, the effective length of the column is one-half that of a pin-ended column, \( K = 0.50 \), but because the ends were not fully fixed, and because there was a possibility of less than complete rigidity of the testing machine structure, it was assumed, for test prediction purposes, that the value of \( K \) would be between 0.50 and 0.55. The actual effective length of each column was measured between the inflection points located by strain measurement from SR-4 gages applied at appropriate distances along the length of each column.

The SR-4 gages, A-11 type, were mounted as shown in Fig. 11, i.e., at 3 in. from each end of the column, at the center, and at distances 0.45L and 0.65L spaced equi-distant about the center.

The columns were tested in the same 800,000-lb. screw-type testing machine that was used for testing the cross section specimens. A pair of adjustable tapered discs at both the top and bottom ends of the columns were used in aligning the columns and during the axial loading of the columns in the flat-ended condition. Structural frames were used at the upper and lower ends of the specimen to maintain its position while adjustments of wedges were being made during alignment, see Fig. 14 and 15. Two perpendicular components of the lateral deflection were measured at the mid-length and at 1/4-in. from each end of the specimen during each loading test.
A vector addition of the components of the deflection was made, so that a running plot was available during each loading test of the magnitude and direction of the lateral deflection of the column at mid-length, with respect to the ends of the specimen.

The alignment was checked by both a spirit level and the SR-4 gage readings. The initial vertical adjustment of the column was made with the level, and the strains at the ends and at mid-length of the column, due to a small load, were measured. When the strain readings indicated that the load was eccentric, the load was removed and adjustments of the tapered discs were made. This procedure was repeated until the difference of the strain readings was less than plus or minus five per cent. As before, the loads applied during alignment did not exceed one-third of the assumed proportional limit.

When satisfactory alignment was achieved, the loading test was conducted, during which the load, lateral deflection, and shortening of the column, were read after each increment of load was applied, until buckling of the column occurred.

3. Eccentric Column Tests - The theoretical column curve for the eccentrically-loaded condition was not verified through its complete range, but was checked at two selected points, to indicate the applicability of the theory.

Two identical specimens were tested as eccentrically loaded columns. The specimens were 2-3/4 in. rounds welded to end plates adapted to a column testing frame. See Fig. 12, 16, and 17. Groups of SR-4 gages applied longitudinally to the columns, were used to check alignment and to read the strains in the column under load. The eccentric loading of the columns
was accomplished by superimposing concentric loads and applied moments. The concentric loads were applied through knife edges by the 800,000-lb. testing machine, and the end moments by 50-kip-capacity hydraulic jacks attached to the testing frame. These jacks were connected by a lever arm to the fixture at each end of the column. This placed the point of eccentric load application at a distance of 29 inches from the axis of the column. Two 12-kip-capacity hydraulic jacks were used at the sides of the knife edges to maintain the ends in their correct position during loading.

The alignment of each eccentrically loaded column was the same as has been described for the concentrically loaded column tests.

During testing, strains were measured at the ends and at the mid-length of the columns and the deflection of the mid-length relative to the ends was determined. Level bars at each loading head were used to measure the inclination of the loading heads during load testing.

A discussion of the experimental procedure for superimposing axial loads and moments is given in Appendix 3.

4. Supplementary Tests. As will be discussed later, the results of the cross section and column tests (see Fig. 1) showed a difference in the yield strengths of specimens C-1 and C-2, and the results of the column tests of specimens C-4 and C-6 showed a difference in the ultimate load for the two columns (see Fig. 2). This indicated that the specimens were probably obtained from bars differing somewhat in strength.

The specimens, as received, were not identified as to their relative location in the original rolled bars. It is seen that the column curves, Fig. 2, would have been substantiated if it could have been shown that C-1 and C-4 were from the same bar, and that C-2 and C-6 were from a
similar but different bar, since C-4 fell near the C-1 curve, and C-6 near the C-2 curve. It was therefore decided to make supplementary cross section and concentric column tests on specimens cut from a single bar. For these tests, the following specimens were cut from specimen C-9 which was a spare specimen: C-9-2 (for the cross section test), C-9-1, and C-9-3 (identical specimens for the column tests).

These supplementary tests were in good agreement with the corresponding column curve (see Fig. 2).
RESULTS

Table 2 summarizes the descriptions of all column and cross section tests and presents the principal results of each test.

In Fig. 1 are shown all the stress-strain diagrams obtained from cross section tests together with the representative tension stress-strain curve furnished by the United States Steel Corporation for the USS "T-I" steel and for the structural carbon steel.

The theoretical column curves for these specimens of USS "T-I" steel and of structural carbon steel are given in Fig. 2. On these curves are plotted the results obtained from the column tests.

These same curves and results are plotted in non-dimensional form in Fig. 4, and a practical column formula suggested by Bleich (Ref. 1) is plotted for comparison.

Typical curves obtained from individual tests are shown in Fig. 5 to 10.

The compression stress-strain curve for specimen C-9-2 is plotted in Fig. 5. From this curve the yield strength and the different values of the tangent modulus of elasticity corresponding to different values of the stress for the material were obtained. In Fig. 6, the values of the tangent modulus of elasticity for specimen C-9-2 are plotted against stress in a non-dimensional form. This auxiliary curve and similarly obtained auxiliary curves for specimens C-1 and C-2 were used to obtain values for the calculation of the column curves in Fig. 2 and 4. Samples of these and other calculations are given in Appendix 1.

Curves of load versus lateral deflection and load versus column shortening, obtained during testing of columns C-9-1 and C-9-3, are shown.
in Fig. 7 and 8. These curves facilitate the determination of the actual ultimate load carried by the column.

Fig. 9 is the load versus lateral deflection curve for the eccentrically loaded column C-13, and also serves to aid in determination of the ultimate load of that specimen.

A plot of the curvature along column C-10 for several loads is given in Fig. 10. Fitted curves through the data indicate the approximate locations of the inflection points which define the effective length of the column.
DISCUSSION

All the cross section tests of USS "T-1" steel gave stress-strain curves of the same general appearance (Fig. 1). The maximum variation in yield strength of the specimens tested was about ten per cent. The average compressive yield strength was 127,300 psi. The average value of Young's modulus of elasticity for the specimens was 30,330,000 psi, with an extreme variation of about 1.2 per cent.

The greatest effect of variation of properties on the theoretical column curve occurs in the region where KL/r is less than about 55 (Fig. 2). In this range, differences in yield strength and proportional limit are directly reflected in differences in the critical stress for the column.

Comparison of the ultimate strengths of the concentrically loaded columns with the theoretical curve in Fig. 2 indicates that the experimental results were slightly below those predicted by the theoretical curve in all cases except the two long columns, C-10, C-11. The percentage error between the predicted values and the experimental results was less than three per cent, with the exception of specimens C-7, C-8, and C-11. For these specimens, the errors were 11, 13.5, and 9 per cent, respectively. These latter columns had KL/r values in the steep portion of the theoretical column curve where a one per cent error in the prediction of the effective length of the column could result in a four per cent error in the prediction of ultimate load.

For the eccentrically loaded columns C-13 and C-14, the plastic theory predicted the ultimate loads within three per cent (Fig. 3). The secant formula applied to these two columns gave a very good indication of the beginning of non-proportionality of the load deflection curve, but was conservative as a prediction of ultimate load (Fig. 9).
The non-dimensional plot of the concentric column curve (Fig. 4) shows that although the cross sections C-1, C-2, and C-9-2, had different yield strength values, the specimens had the same type of column characteristics. A column formula suggested by Bleich(1) approximated the tangent modulus column curves very well. This column formula is as follows:

\[
\sigma_{cr} = \sigma_y - \frac{(\sigma_y - \sigma_p)}{\pi^2 E} \cdot \sigma_p \left(\frac{KL}{P}\right)^2 \quad (\frac{KL}{P} < \frac{\pi}{2} \frac{E}{\sigma_p})
\]

\[
\tau_{cr} = \frac{\pi E}{(\frac{KL}{P})^2} \quad (\frac{KL}{P} > \frac{\pi}{2} \frac{E}{\sigma_p})
\]

where \( \sigma_p \) = proportional limit stress

Measurement of the effective pin-ended length of columns loaded in the flat-ended condition was one unique part of this series of tests. This was accomplished by computing the curvature at several positions along the length of each column from strain measurements for various loads on the column, and locating the points of zero curvature graphically. The resulting effective lengths ranged from 0.51L to 0.55L with an average of 0.526L as compared with 0.50L, the theoretical value for a fixed-ended column.

As is shown in Fig. 2, the column curve obtained from structural carbon steel cross section C-3 gave an excellent prediction of the ultimate load of the structural carbon steel column, C-12.
SUMMARY AND CONCLUSIONS

The results of the tests indicate that the tangent modulus formula applied to the results of a cross section test predicts with reasonable accuracy the ultimate load of a concentrically loaded column. Though the predictions tend to be slightly on the high side, this variation is reasonable in the light of usual experimental error, accidental eccentricities, and unavoidable out-of-straightness in members of this size.

Since the column test results are in good agreement with the column curve obtained from the cross section test, the latter is a reasonable basis for design formulas for USS "T-1" steel round bars in the stress relieved condition.

The plastic theory applied to the problem of eccentrically loaded columns predicts their maximum strength with good accuracy.

The secant formula predicts the proportional limit of the load-deflection curve of an eccentrically loaded column with small error, but is conservative in predicting the ultimate load of the column. This is because the secant formula does not take advantage of the reserve of strength beyond the elastic limit.
ACKNOWLEDGMENTS

The authors wish to express their sincere appreciation to Lynn S. Beedle and Robert L. Ketter for the technical assistance given by them, based on their wide experience in column research.

Grateful acknowledgment is extended also to the several Research Assistants associated with the project; in particular, Tadahiko Kawai, Satoro Niumoto, and Lambert Tall, and the Fritz Laboratory shop personnel under the supervision of Kenneth R. Harpel, Foreman.

Typical moment-curvature curves for round bars subjected to bending and axial loads (Fig. 18) were prepared by Paul C. Paris, under the direction of Mr. Ketter, for use in calculating the ultimate loads of the eccentrically loaded columns.

This project was sponsored by the Research and Technology Department of the United States Steel Corporation, being part of a program designed and directed by H. Malcolm Priest and John A. Gilligan of the United States Steel Corporation, with whom a very pleasant association was enjoyed.

All tests were conducted in the Fritz Engineering Laboratory of which William J. Eney is Director.
REFERENCES

1. Bleich, Frederick

BUCKLING STRENGTH OF METAL STRUCTURES


PLASTIC DEFORMATION OF WIDE-FLANGE BEAM-COLUMNS


3. Ketter, Robert L.

STABILITY OF BEAM COLUMNS ABOVE THE ELASTIC LIMIT

NOMENCLATURE

a  lever arm of hydraulic jack used for eccentric loading

c  distance from neutral axis to extreme fiber of bending member

d  length of loading head used in eccentric column tests

D  diameter

e  end eccentricity of axial load application

E  Young's modulus of elasticity

\( E_t \)  tangent modulus of elasticity

F  eccentric load on test column

I  moment of inertia

K  coefficient, ratio of effective to actual length of column

L  length of column

P  axial load on column

\( P_e \)  Euler buckling load

\( P_y \)  axial load corresponding to yield stress level

\( P_m \)  axial load, measured on loading platform

r  radius of hydration of section

\( \sigma_p \)  proportional limit

\( \sigma_{cr} \)  maximum stress in column

\( \sigma_y \)  yield stress level or yield strength

\( \theta \)  inclination of loading head, eccentric column

\( \phi \)  curvature

\( \varepsilon \)  strain
1. Column Curve C-9-2

(a) From \( \frac{E_t}{E} - \frac{\sigma}{\sigma_y} \) curve,

at \( P = 748.3 \text{ kips} \), \( \frac{\sigma}{\sigma_y} = 0.978 \) and thus \( \frac{E_t}{E} = 0.118 \),
i.e., \( E_t = 3.64 \times 10^3 \text{ kips/in}^2 \)

Now, \( \sigma_{cr} = \frac{\pi^2 E_t}{(K_T)^2} \)

\[
(K_T)^2 = \frac{\pi^2 E_t}{\sigma_{cr}} = \frac{\pi^2 \cdot 3.64 \times 10^3}{748.3} = 287.5
\]
i.e., \( K_T = 17.0 \)

for \( \sigma_{cr} = \frac{748.3}{5.99} = 124.8 \text{ kips/in}^2 \)

whereby one point in the \( K_T \) versus \( \sigma_{cr} \) curve is obtained.

(b) Also, from the elastic portion of the stress-strain curve,

at \( P \leq 548 \text{k}, E = 30,500 \text{ kips/in}^2 \), by measurement.

For \( K_T = 60 \),

\[
\sigma_{cr} = \frac{\pi^2 30,500}{3600} = 83.6 \text{ kips/in}^2
\]

2. Calculation of Curvature From Measured Strains

The position of the SR-4 gages is shown in Fig. 11.

The equations to be used for calculation of curvature are as follows:
Explanation of Curvature Calculations for "Flat Ended" Concentrically Loaded Column

\[ \bar{\varepsilon} = \left( \varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4 \right) \div 4 \] Ave. Strain

\[ \varepsilon_1' = \varepsilon_1 - \bar{\varepsilon}, \quad \varepsilon_2' = \varepsilon_2 - \bar{\varepsilon}, \quad \varepsilon_3' = \varepsilon_3 - \bar{\varepsilon}, \quad \varepsilon_4' = \varepsilon_4 - \bar{\varepsilon}, \quad \varepsilon_0' = \varepsilon_0 - \bar{\varepsilon} \]

Since

\[ \varepsilon_1' = \varepsilon_0' \cos \theta, \quad \varepsilon_3' = \varepsilon_0' \cos \theta, \]

\[ \varepsilon_4' = \varepsilon_0' \sin \theta, \quad \varepsilon_4' = \varepsilon_0' \sin \theta, \]

\[ \varepsilon_0' = \sqrt{\varepsilon_1'^2 + \varepsilon_4'^2} = \sqrt{\varepsilon_3'^2 + \varepsilon_4'^2} \]

\[ \text{THE REQUIRED CURVATURE } \phi, \]

\[ \phi = \frac{2 \varepsilon_0'}{D} = \frac{\sqrt{\varepsilon_1'^2 + \varepsilon_4'^2} + \sqrt{\varepsilon_3'^2 + \varepsilon_4'^2}}{D} \]
Calculation at Load 19 for Middle Point of C-10

\[ \varepsilon_{13} = 10.70 \times 10^{-4} \]  

Measured Strains

\[ \varepsilon_{14} = 20.36 \]

\[ \varepsilon_{15} = 24.91 \]

\[ \varepsilon_{16} = 18.53 \]

Average strain:

\[ \overline{\varepsilon} = \frac{10.70 + 20.36 + 24.91 + 18.53}{4} = 18.63 \times 10^{-4} \]

\[ \varepsilon_1' = \varepsilon_{13} - \overline{\varepsilon} = -7.93 \times 10^{-4} \]

\[ \varepsilon_2' = \varepsilon_{14} - \overline{\varepsilon} = 1.73 \]

\[ \varepsilon_3' = \varepsilon_{15} - \overline{\varepsilon} = 6.28 \]

\[ \varepsilon_4' = \varepsilon_{16} - \overline{\varepsilon} = -0.10 \]

\[ \phi = \frac{\sqrt{\varepsilon_1'^2 + \varepsilon_2'^2 + \sqrt{\varepsilon_3'^2 + \varepsilon_4'^2}}}{\text{Diameter}} \]

\[ = \frac{\sqrt{(7.93)^2 + (0.10)^2} + \sqrt{(6.28)^2 + (0.10)^2}}{2.77} \]

\[ \phi = 5.22 \times 10^{-4} \]

A plot of all these values is shown in Fig. 10. The inflection points are located where the curvature is zero. The effective length is the distance between the inflection points.

3. Calculations for Eccentric Column

(a) Calculation of \( \frac{P}{F_y} \) vs. \( \frac{e_2}{r^2} \) curve

(b) Calculation of column curve

This calculation uses the method of reference 3 as adapted in Appendix 2.
Data for Calculation: 

\[ L = 26-1/4 \text{ in.} \]

\[ \text{Area} = 6.02 \text{ in}^2 \]

\[ L/r = 38.0 \]

assume: \( \sigma_y = 120 \text{ ksi} \)

\[ E = 30,000 \text{ ksi} \]

(a) Calculation of \( \frac{P}{P_y} \) vs. \( \frac{Ec}{r^2} \) curve

For the case \( P = 0.4 \ P_y \):

\[
\Delta M \cdot \phi_y = \frac{P}{P_e} = \frac{P}{P_y} \cdot \frac{\sigma_y}{E} \cdot (\frac{L}{P})^2
\]

\[
= 0.4 \cdot \frac{120}{192^2 \cdot 30,000} \cdot (38)^2
\]

\[
= 0.234 = \text{slope of } \frac{M}{M_y} \text{ vs. } \frac{\phi}{\phi_y} \text{ curve}
\]

(see Fig. 18)

from the graphs, \( \frac{M}{M_y} = 1.195 \)

\( \frac{\phi}{\phi_y} = 1.700 \)

Fig. a: \( \frac{M}{M_y} \) vs. \( \frac{\phi}{\phi_y} \) curve.

now \( \frac{P}{P_y} \cdot \frac{Ec}{r^2} = \frac{M}{M_y} - \frac{P}{P_e} \cdot \frac{\phi}{\phi_y} \)

\[
= 1.195 - 0.234 \times 1.700 = 0.797
\]

since \( \frac{P}{P_y} = 0.4 \),

then \( \frac{Ec}{r^2} = \frac{0.797}{0.400} = 1.99 \)

and hence the following curve can be drawn:

Fig. b
This gives a $\frac{P}{F_y}$ vs. $\frac{Ec}{r^2}$ curve for a particular slenderness ratio $\frac{L}{r}$.

(b) Calculation of column curve.

The column curve may be drawn as $\sigma_{cr}$ vs. $\frac{L}{r}$ as for the concentric case, there being a curve for each eccentricity; for example, from the $\frac{P}{F_y}$ vs. $\frac{Ec}{r^2}$ curve above,

$$P = 0.33 P_y \text{ for } \frac{Ec}{r^2} = 3.0, \frac{L}{r} = 38.$$  

i.e., $\sigma_{cr} = 0.33 \sigma_y$

$$= 39.6 \text{ ksi for } \frac{L}{r} = 38,$$

which gives an ordinate on the column curve, $\sigma_{cr}$ vs. $\frac{L}{r}$.

Calculation of Ultimate Load for C-13

The given data are: $e = 0.98 \text{ in.}$

$$c = 1.375 \text{ in.}$$  

$$r = 0.6875 \text{ in.}$$

and hence, $\frac{Ec}{r^2} = 2.85$

assume $\sigma_y = 120 \text{ ksi}$

then $P_y = A \sigma_y = 6.02 \times 120 = 722k$

then, from the curve, $\frac{P}{F_y} = 0.338$, for $\frac{Ec}{r^2} = 2.85$

i.e., $P = 0.338 \times 722$

$$= 244k$$

$(P = 259k \text{ for } \sigma_y = 127 \text{ ksi})$
Estimate of Maximum Load for C-13 from the Secant Formula

\[ \sigma_{\text{ult}} = \frac{\sigma_y}{1 + \frac{e c}{r^2} \sec \frac{L}{2r}} \sqrt{\sigma_{\text{ult}} \frac{E}{E}} \]

\( \sigma_{\text{ult}} \) can be deduced by a method of successive approximations, e.g.,

\[
\begin{align*}
\sigma_y &= 127 \text{ ksi} & L &= 26.25 \text{ in.} \\
\frac{e c}{r^2} &= 2.85 & \frac{L}{2r} &= 18.95 \\
E &= 30,000 \text{ ksi} \\
\end{align*}
\]

eventually, get \( \sigma_{\text{ult}} = 28.6 \text{ ksi} \)

then

ult. load = \( \sigma_{\text{ult}} \times \text{area} = 28.6 \times 6.02 = 172 \text{ kips} \)
APPENDIX 2

MAXIMUM LOAD OF ECCENTRICALLY LOADED COLUMN(3)

The maximum load of an eccentrically loaded column of circular cross section may be obtained from the curves of Fig. 18. The derivation involves the following assumptions:

a. the deflection curve is sinusoidal
b. the column is pin-ended
c. the cross section is circular
d. an idealized stress-strain diagram

The assumptions and derivation are outlined in the reference 3).

Following the theory given in this reference, the maximum load is computed as follows:

1. \( \frac{L}{r} \) is given from the data

2. \( \frac{P}{P_y} \) assumed, e.g., 0.2, 0.4, \ldots

3. Calculate \( \frac{P}{P_y} \) as described in the following:

\[
\frac{P}{P_e} = \frac{P}{P_y} \cdot \frac{\sigma_y}{\gamma^2 E} \cdot (\frac{L}{r})^2
\]

Also:

\[
\frac{P}{P_e} = \frac{\Delta M}{\Delta \phi} \cdot \frac{\phi_y}{M_y} = \text{tangent of } \frac{M}{M_y} \text{ vs. } \frac{\phi}{\phi_y}
\]

Now, there exists a relationship between \( \frac{M}{M_y} \) and \( \frac{\phi}{\phi_y} \) for any particular \( \frac{P}{P_y} \) (2). For the case in hand, this relationship is shown as a series of curves in Fig. 18.
Hence, from the above tangent, \( \frac{M}{M_y} \) and \( \frac{\phi}{\phi_y} \) can be determined, i.e., the coordinates of the point where the tangent has the value \( \frac{P}{P_e} \).

4. Calculate \( \frac{m_o}{M_y} \) from

\[
\frac{m_o}{M_y} = \frac{M_o}{M_y} - \frac{P}{P_e} \cdot \frac{\phi}{\phi_y}
\]

also \( \frac{m_o}{M_y} = \frac{P}{P_y} \cdot \frac{ec}{r^2} \)

Hence, for a fixed \( L/r \), the relationship between \( \frac{P}{P_y} \) and \( \frac{ec}{r^2} \) may be obtained.
Appendix 3

Eccentric Column Test Theory - The derivation of the load relationships for an eccentrically-loaded column can be made by considering axial load and end moments on a column. From the upper sketch, Fig. c, it is seen that the axial force is \( P_m + F \), where \( P_m \) is measured in the testing machine, and \( F \) is the jack load.

It will be seen that the following relationships will hold:

\[
M = Fa = P \cdot e = (P_m + F)e
\]
i.e., \( F = \frac{e}{a-e} P_m = \gamma P_m \), where \( \gamma \) is a constant.

There is further induced moment due to the inclination of the loading head, and taking \( P_m, d, \theta \), as shown, then: additional moment = \( \theta P_m d = \Delta F \cdot a \), i.e., \( \Delta F = \frac{P_m d}{a} \)

and \( F_0 = F - \Delta F = \gamma P_m - \frac{\theta P_m d}{a} \)

\[
= P_m \left( \gamma - \frac{\theta d}{a} \right)
= P_m \left( \frac{e}{a-e} - \frac{\theta d}{a} \right)
\]

which gives the relationship between \( F_0 \) and \( P_m \).

\[ P = P_m + F_0 = p - F_0 \]

Fig. c
From the above considerations, the following procedure for loading was used in order to simulate the action of an eccentrically loaded column.

1. With a given value of $P_m$ and $F_o$, the next loads were chosen and determined from the relationship derived above.

2. A load $P_m + \Delta P_m$ a little greater than $P_m$, was applied.

3. With an assumption for $\theta$, $\Delta F$ was obtained, and hence $F_o$, and then the jacks were loaded to $F_o$. This load compensated with $(P_m + \Delta P_m)$ so that $P_m \to 0$, to obtain the desired load $P_m$.

4. If the combination of loads was unsatisfactory, the procedure was repeated until the correct values of $P_m$ and $F_o$ were obtained.

A graph was then plotted of $(P_m + F_o)$ versus $\delta$, the deflection at center.
Table I
Description of Test Specimens Supplied for Testing

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type of Steel</th>
<th>Dimensions</th>
<th>Max. Out-of-Straightness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Diameter</td>
<td>Length</td>
</tr>
<tr>
<td>C-1</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>11</td>
</tr>
<tr>
<td>C-2</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>11</td>
</tr>
<tr>
<td>C-3</td>
<td>Structural Carbon</td>
<td>2-3/4</td>
<td>11</td>
</tr>
<tr>
<td>C-4</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>46-1/4</td>
</tr>
<tr>
<td>C-5</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>46-1/4</td>
</tr>
<tr>
<td>C-6</td>
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</tr>
<tr>
<td>C-7</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>60</td>
</tr>
<tr>
<td>C-8</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>60</td>
</tr>
<tr>
<td>C-9</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>92</td>
</tr>
<tr>
<td>C-10</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>92</td>
</tr>
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<td>C-11</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>92</td>
</tr>
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<td>Structural Carbon</td>
<td>2-3/4</td>
<td>92</td>
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<td>2-3/4</td>
<td>26-5/8</td>
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<tr>
<td>C-14</td>
<td>&quot;T-1&quot;</td>
<td>2-3/4</td>
<td>26-5/8</td>
</tr>
</tbody>
</table>

(1) Distance measured from end of bar.
(2) 0.050 inches after restraightening and restress relieving.
Table 2
USS "T-l" Steel Column Tests

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Loading Condition</th>
<th>Length (in.)</th>
<th>Area (in.)</th>
<th>L/r</th>
<th>K Calculated from Measured Curvature</th>
<th>L/r</th>
<th>P_{max} (kips)</th>
<th>( \frac{E}{10^3} ) kips/in²</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>---</td>
<td>11.0</td>
<td>6.06</td>
<td>*</td>
<td>---</td>
<td>---</td>
<td>731</td>
<td>121.1</td>
<td>29.9</td>
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<td>C-2</td>
<td>---</td>
<td>11.0</td>
<td>6.04</td>
<td>*</td>
<td>---</td>
<td>---</td>
<td>803</td>
<td>133.1</td>
<td>30.4</td>
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<td>6.04</td>
<td>*</td>
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<td>191</td>
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<td>C-4</td>
<td>Conc.</td>
<td>46-1/4</td>
<td>6.02</td>
<td>66.8</td>
<td>0.53</td>
<td>35.4</td>
<td>680</td>
<td>112.9</td>
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</tr>
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<td>C-5</td>
<td>Conc.</td>
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<td>6.02</td>
<td>67.0</td>
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<td>---</td>
<td>---</td>
<td>---</td>
<td>Omitted</td>
</tr>
<tr>
<td>C-6</td>
<td>Conc.</td>
<td>46-1/4</td>
<td>6.03</td>
<td>66.8</td>
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<td>744</td>
<td>123.4</td>
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<td>0.51</td>
<td>51.1</td>
<td>570</td>
<td>96.4</td>
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<td>6.02</td>
<td>99.7</td>
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<td>51.8</td>
<td>550</td>
<td>91.4</td>
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<tr>
<td>C-9-1</td>
<td>Conc.</td>
<td>39-1/2</td>
<td>6.01</td>
<td>57.1</td>
<td>0.53</td>
<td>30.3</td>
<td>728</td>
<td>121.1</td>
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<td>6.01</td>
<td>133.1</td>
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<td>368</td>
<td>61.2</td>
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<td>6.02</td>
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<td>38.0</td>
<td>1.00°</td>
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<td>765</td>
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* Cross Section Test.  ° By Definition.
STRESS-STRAIN DIAGRAMS

USS "T-1" Steel
Tension Coupon

USS "T-1" Steel
Cross Section Compression Tests

Structural Carbon Steel
Cross Section Compression Test

Typical Structural Carbon Steel
Tension Coupon

STRESS-STRAIN DIAGRAMS

Stress

\( \sigma \) (kips/in\(^2\))

Strain \( \varepsilon \) (in/in.)

Fig. 1

0.002 in/in.

125

100

75

50

25

0

C-1

C-2

C-9-2

C-3

Typical Structural Carbon Steel Tension Coupon
COLUMN CURVES FOR USS "T-1" STEEL

Theoretical Column Curve Based On Cross Section Tests, C-1, C-2, C-9-2 Of Specimens As Shown. Concentric Loading.

Theoretical Column Curve For Structural Carbon Steel, Based on C-3 Cross Section Test

Fig. 2
ECCENTRICALLY LOADED COLUMNS

Fig. 3

Portion of Predicted Curves

- Predicted by Secant Formula

- Predicted Ultimate Load

Axially loaded column

- C-13 \( \frac{\sigma_0}{r^2} = 2.85 \)

- C-14 \( \frac{\sigma_0}{r^2} = 3.57 \)
COLUMNS CURVE FOR USS "T-1" STEEL

(Non-Dimensional)

Bleich's Approximate Column Curve

Structural Carbon Steel

Fig. 4 \( \eta = \frac{1}{\pi} \sqrt{\frac{\sigma_y}{E}} \left( \frac{KL}{r} \right) \)
STRESS-STRAIN DIAGRAM FROM CROSS SECTION TEST OF USS "T-1" STEEL

Specimen C-9-2

2-3/4" Ø bar
11" length

Fig. 5

STRAIN $\varepsilon$ (in/in.) $\times 10^{-3}$
STRESS VS. TANGENT MODULUS OF ELASTICITY CURVE
FOR USS "T-1" STEEL

Calculated From Cross Section Compression Test C-9-2

\[
\frac{\sigma}{\sigma_y} vs. \frac{E_t}{E}
\]

Fig. 6
LOAD-LATERAL DEFLECTION CURVES FOR CONCENTRICALLY LOADED COLUMN OF USS "T-1" STEEL

Specimen C-9-1

Specimen C-9-3

Fig. 7
LOAD VERSUS SHORTENING CURVES
FOR
CONCENTRICALLY LOADED COLUMN
OF
USS "T-1" STEEL

Specimen C-9-1

Specimen C-9-3

2-3/4" Ø Column
Flat End Test

Fig. 8
LOAD - LATERAL DEFLECTION CURVES
FOR
ECCENTRICALLY LOADED COLUMN
OF
USS "T-1" STEEL, SPECIMEN C-13

Fig. 9

Center Line Deflection
δ_f (inches)

Load
P(kips)

Secant Formula

2-3/4" Ø Column
Pin ended test

\( \frac{ec}{r^2} = 2.85 \)

- Pin ended test
- Eccentrically loaded column
- USS "T-1" steel specimen C-13
- Secant formula
- Load vs. center line deflection graph
CURVATURE CURVES
USS "T-1" SPECIMEN C - 10

Length = 92"
Nom. Dia. = 2-3/4"
Area = 6.01 in²

Fig. 10
POSITION OF SR-4 GAGES

Fig. 11
SCHEMATIC DIAGRAM OF COLUMN LOADING FRAME

Fig. 12
Fig. 13 - Cross Section Test Setup
Fig. 14 - Measuring The Final Deformed Shape Of Concentrically Loaded Column C-7

Fig. 15 - Concentric Column Test Setup (C-9-1)
Fig. 16 - Eccentrically-Loaded Column Test Setup (C-13)

Fig. 17 - Closeup Of Eccentrically-Loaded Column Test Setup (C-13)