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EUROPEAN COLUMN STUDIES

ON TESTING METHODS FOR HEAVY COLUMNS

BY

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European Column Studies

ON TESTING METHODS FOR HEAVY COLUMNS

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This study has been carried out as part of an investigation jointly sponsored by the European Convention of Constructional Steelwork, National Science Foundation, and the Welding Research Council. Technical guidance was provided by the Task Group 11 of the Column Research Council.

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ABSTRACT

This report describes an experimental study on different column testing methods for medium and heavy columns and their effects on test results. Two methods were investigated, namely, the "old" Lehigh method and the European Convention method.

Tests were performed on seven U.S. shapes, W12x161 (A36 grade steel), as pinned-end columns having a slenderness ration of 50. The specimens were prepared from a single unstraightened rolled piece. Supplementary tests (residual stress measurement, stub column and tension coupon) were also made. The instrumentation and testing procedure used for each method are discussed.

As a result of this study the testing method required by the European Convention for Constructional Steelwork was clarified and additional measurements were suggested. Also, a new procedure for the testing of medium and heavy columns is proposed.

1. INTRODUCTION

1.1 Objective

The ultimate objective in this study of column testing is to evaluate different testing procedures used especially for medium and heavy column shapes, and to propose a new testing procedure, alignment and instrumentation for medium to heavy columns.

1.2 The Pinned-End Column

A column may be defined as a member subjected to compressive loads at the ends and whose length is considerably larger than its cross-sectional dimensions. Columns may have different end conditions, ranging from full restraint to zero restraint in rotation and warping.

Most column investigators in the past have used the pinned-end condition for column testing for a number of reasons. Under pinned-end conditions the critical stress exists at about the mid-height section thus making the section of interest remote from the boundary and, therefore, not influenced by any end effects. For the same effective slenderness ratio, the pinned-end condition requires the use of a shorter column length than the fixed-end condition.

The pinned-end column is regarded as the basic column, although it does not exist in actual structures. It is the member to which the strength of all other columns is referred. Until methods for the design of structures as a whole come into use, the design of columns will continue to be based on the strength of the simple pinned-end column.

1.3 Experiments on Columns

In testing column specimens, the experimental results form a wide scatter band instead of a well-defined relationship between strength and slenderness ratio. This is due to imperfections in the experimental conditions, such as end conditions, initial out-of-straightness, eccentricities of load, lateral loads, as well as to residual stresses and nonhomogeneity of the material. To understand column behavior, there is a need to isolate the effects of these factors.

For pinned-end conditions it is essential that friction virtually be eliminated since a small amount of end constraint will cause an appreciable increase in the column strength. Several schemes have been used to provide the required pin condition. Some of the different basic types of end fixtures used by column investigators are shown in Fig. 1.[1] The end fixtures differ from each other in that they are either "position-fixed" or "direction-fixed" at the ends.[2] The other basic differences are with respect to their maximum carrying capacity and effective column length.

Probably the best way to reduce friction is by the use of a relatively large hardened cylindrical surface bearing on a flat hardened surface. Even if an indentation should occur under heavy load, rotation will be virtually frictionless. Plastic indentation, however, is not desirable. Another interesting feature about the cylindrical fixtures is that the effective column length can be made equal to the actual length of the column by designing the fixtures so that the center of the cylinder is located on the center line at the end of the column.[3] When using a cylindrical fixture, the column acts as pinned-end about one axis (usually the weak axis) and is essentially fixed-end about the other.

A schematic diagram of the end fixtures used at Fritz Engineering Laboratory is shown in Fig. 2. The fixtures have a maximum capacity of 2.5 million pounds.(4) Description of the fixture and its performances as a "pin" is given in Ref. 3.

1.4 Testing Procedure

In column tests, as in other stability tests, the response of a column is influenced by the loading device used. The common types of loading are the gravity, deformation and pressure types. The resulting "load-deflection characteristics" of each loading system are not alike.(5)

The oldest form of testing device used for columns was the gravity type. The load-deformation characteristics for such a system are simple and can be represented by a series of straight lines parallel to the deformation axis. Later, the screw-type testing machine became a common laboratory apparatus. Such a loading device has the advantage of providing an accurately defined load-deflection characteristic, where the slope of this characteristic depends on the elastic response of the loading system. As higher capacity of loading machines became needed, the hydraulic-type testing machine was utilized. Such a loading device, however, does not have an easily defined load-deflection characteristic and depends on the properties of hydraulic system, leakage, temperature and other similar factors.

1.5 Recording of Results

In experimental investigations of column strength it is common practice to represent deflections of the column as a function of the axially applied load even though in ideal cases there will be no lateral deflections up to the critical load. The experimental column will almost always begin to deflect with the beginning of loading owing to various kinds of imperfections.

The behavior of test columns under load is determined with the assistance of measurements of lateral deflections at various levels, rotations at the ends, strains at characteristic points, and angles of twist. These measurements will be used to check theoretical predictions.

The instrumentation for measurements has changed drastically in the past few years due to progress made on measuring techniques and devices. It is now possible to obtain automatic recordings for all measurements in the form of plots. Such recordings have been found to be convenient and more precise than the manual readings used before. There is now the possibility also of recording all measurements automatically which may then be analyzed directly using the computer.

As heavy shapes are used increasingly more in today's structures, tests on heavy columns will soon become of considerable importance. This requires the use of high-capacity testing machines and end fixtures. Since repetition of such tests to allow statistical evaluation is very expensive, special care should be taken for the testing procedure, instrumentation and recording of results.

2. PREPARATION OF SPECIMENS

2.1 Specimens

A total of eight straight specimens were obtained from a single rolled shape W12x161 having a total length of 125 ft., (38 m.). No cold-straightening on the rolled piece was performed in order to avoid redistribution of the original residual stresses due to cooling. Table 1 shows the properties of the material as indicated in the mill test.

Each individual column was designated by a number (01 through 07). The ends of each column were marked such that it would be possible to identify the location of each piece on the original length.

From the eight specimens available, each having a length of 15 ft. (4.6 m.), seven were used for pinned-end column testing. The remaining one piece was used for supplementary tests.

Milling was performed perpendicular to the end portions of the columns. For columns initially not straight, the milled surfaces may not therefore be parallel to each other, but will be perpendicular to the center line at the ends. Base plates were welded at each end of the specimen using $\frac{1}{4}$ inch (6 mm) welds by matching the center of the web to the center of the plate.

The study of the behavior of a column requires supplementary tests of tensile coupon, residual stress and stub column. The description and results from the supplementary tests are discussed in the following sections.

2.2 Tension Coupon Tests

The mechanical properties of the material were obtained from tension coupon tests conducted in accordance with the ASTM Specification. A total number of three coupons were tested; two from the flange and one from the web. Figure 3 shows a schematic diagram of the dimensions and the location of the coupons with respect to the cross section. The gage length used was 8 inches (200 mm).

The static yield stress[6] was obtained after the testing machine was stopped at a strain of 0.005 in./in. (0.005 mm /mm). The results of the tensile coupon tests are summarized in Table 1.

It was noted that the tension coupons taken from the flange did not exhibit a "flat" yield plateau, whereas the web coupon had a "flat" yield plateau. Figure 4 shows the flanges and web coupon test results. Notice also the slight positive modulus in the yield region of the flange coupon while the web coupon has the "flat" yield region usually observed in A36 tensile coupon.[7]

2.3 Residual Stress Measurement

The residual stress magnitude and distribution was measured by the method of "sectioning"[8] using the gage length of 10 in. (254 mm). Figure 5 shows the residual stress pattern. The edges have compressive residual stress varying from 6 to 18 ksi with an average value of about 13 ksi; and the web has an average of 14 ksi in tension. Since the specimens were prepared from an unstraightened rolled length, it is expected that the residual stress distribution would be uniform along the length.

One noteworthy aspect of the pattern of residual stress distribution is the considerable difference in residual stresses for the two flanges. This may be due to the positioning of the specimen on the cooling bed. During cooling, the upper flanges of the specimens may have, for instance, been exposed to a different air circulation.

2.4 Stub Column Test

Two stub column tests were made on sections from the same piece from which the actual column specimen was cut. A stub column may be defined as a column long enough to retain the original magnitude of residual stress in the section and short enough to prevent any premature failure occurring before the yield load of the section is obtained.[9]

A stub column test is performed in order to obtain an average stress-strain curve for the complete cross section which takes into account the effects of residual stress. The proportional limit, the elastic modulus, and tangent modulus are the important data furnished by the curve. Using prepared charts,[10] where a simplified residual stress pattern and a homogeneous material are assumed, column strength may be predicted directly from stub column test results.

Two 1/10,000 inch dial gages and an electrical clip gage were mounted along the middle line of the flanges at opposite sides of the specimen to measure strain over the 10 inch gage length. The original magnitude of residual stress is not disturbed within this gage length. Figure 6 shows the instrumentation of the stub column.

Two methods of loading were tried to obtain the stress-strain curve. The first method dealt with making a point to point plot of the static curve. The static points from the proportional limit to the point near to the yield stress level were obtained by maintaining the applied load until no increase in strain is observed. The static points for the remaining portion of the curve were obtained by keeping the cross-head movement constant until the load is stabilized. This was obtained by closing the loading valve until the increase in deformation and the decrease in load approached zero.

In the second method the specimen was loaded continuously with only one stop made at the yield plateau to determine the static yield stress level. A loading rate of 1 kp/sq. mm per minute (1.42 ksi per minute) was used in the elastic range and the same valve setting was used throughout the test. The results from these tests are shown in Fig. 7.

The usual procedure in evaluating the stub column test results is to use a yield stress level criteria defined by the stress at 0.005 in/in. (0.005 mm/mm) strain.[9] Using this criteria, the static yield stress was found to be 27.5 ksi (19.4 kp/mm^2) and 27.6 ksi (19.5 kp/mm^2) from the two tests, both of which indicate a very close correlation to the yield stress determined by tensile coupons, 27.1 ksi (19.2 kp/mm^2).

3. COLUMN TESTING AND TEST RESULTS

3.1 Design of Tests

A total number of seven W12x161 pinned-end columns each having a slenderness ratio of 50 were tested in order to make a comparison of different testing procedures, instrumentation, alignment and some other variables. The U.S. W12x161 shape was used since it is the shape almost identical to the European shape HEM340 currently being tested at Lehigh University under the program European Column Studies.(11) The slenderness ratio of 50 was selected, it being one of the two slenderness ratios 50 and 95 used under the European column testing program.

The experimental testing procedure as well as the results obtained are discussed below.

3.2 Initial Measurements

Initial geometric imperfections in axially loaded columns affect the column strength. Thus, initial measurement of the geometric characteristics of a column is an important step in column testing. Initial measurements were made for all columns of the cross-sectional dimensions and out-of-straightness.

Cross-sectional measurements were obtained to determine the variation between the actual dimensions of the section and the nominal handbook dimensions. Measurement of the initial out-of-straightness will be used in the evaluation of the results of the tests.

Figure 8 shows all cross-sectional dimensions measured at five locations: the two ends, the quarter, the middle, and the three-quarter points. A typical example of the recorded dimensions and the calculated cross-sectional areas are given in Table 2. The percentage variation of cross-sectional areas and dimensions with respect to handbook values are given in Table 3.

The initial out-of-straightness of each specimen was measured at nine levels, each spaced at one-eighth of the column length. Measurements were taken in the two axes of symmetry of the section.

Out-of-straightness (e_x) about the minor axis is obtained from four readings - one with reference to each tip surface of the flange. The average of the four readings is taken as the out-of-straightness of the whole section.

Out-of-straightness (e_y) about the major axis is obtained from two readings of which the average of both is also plotted. All measurements taken were within an accuracy of 1/100 inch.

A typical plot of readings obtained for Col. 01 is shown in Fig. 9 for weak axis measurements, and in Fig. 10 for strong axis measurements.

3.3 Alignment

A proper alignment of the column before testing is another important step. In this study three methods of alignment are considered and in the following each method is described briefly.

The first method, developed at Fritz Laboratory and now known as the "Old Lehigh Method" requires the column to be aligned according to established criterion. The alignment is based on the four strain gages at each end of the specimen and at midheight. The alignment is considered satisfactory if the deviation of any of the four corner gage readings does not exceed five percent of their average value at maximum alignment load. The criterion is applied at each end of the three control sections.[1]

The second method, known as the ECCS* method, is based on geometric alignment. The alignment of the specimen is required to be through the center of web and not through the real center of gravity of the section, even if the section shows a dissymmetry due to unusual tolerances.[11]

The third method is the proposed method which is also based on geometric alignment. The reference point for alignment is the center of flanges and not the center of web. The reason for not using the center of web is based on the fact that the web contributes very little to minor

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*European Convention for Constructional Steelwork.

axis buckling. Further discussion on the choice of reference points can be found in Section 5.3.

Out of the seven columns, one column (Col. 01) was aligned according to the old Lehigh method and the remaining columns according to the ECCS method. Effects of methods of alignment on test results can be seen in a later section.

3.4 Testing Procedure

After a careful alignment was completed, the test was started with an initial load of 1/20 to 1/15 of the estimated ultimate load capacity of the column. This was done to preserve the alignment established at the beginning of the test. At this load all measuring devices were adjusted for initial readings. The testing was continued by loading the column progressively. In this study three column testing methods were considered and these are explained.

The Old Lehigh Method

The testing procedure practiced in Fritz Engineering Laboratory[1] for some decades gives the static curve by making a point-by-point plot of the load-deflection curve.

The load is applied in appropriate increments as estimated from the progress of the load deflection curve being plotted during the test. Readings are taken when the load and the strains have stabilized. The dial gage used for measuring the overall shortening may be used simultaneously for observing stabilization. The single criterion for stabilization can best be defined by plotting the load change and cross-head movement versus time.

The ECCS Method

In the ECCS method a continuous loading at a prescribed rate is performed. The applied load and the corresponding deflections are recorded instantly. The rate of loading is 1 kp/sq. mm [11] per minute (1.42 ksi per minute). This rate is established when the column behavior is elastic and the established valve setting is kept fixed until the end of testing. Thus, only the dynamic curve is determined.

The Proposed Method

The method proposed to be used in the future in Fritz Engineering Laboratory also determines the static curve, to make the results comparable with those obtained earlier. This method acknowledges the difficulties in determining the static load when using a hydraulic type testing machine. The dynamic loading with constant "strain rate" and continuous recording of data is used up to the ultimate load where a static reading is taken, and the dynamic loading is then resumed. The static column curve is derived from the dynamic curve using the relationship between the dynamic and static yield stresses.

3.5 Instrumentation and Test Results

The most important records needed are the applied load and the corresponding deflections, strains at characteristic points, angles of twist and the end rotations. The set-up and the instrumentation is shown in Fig. 11 and is described in detail below.

The magnitude of applied load was obtained from the dial indicator of the 5,000,000 bl. hydraulic universal testing machine.

Lateral deflections about the minor axis were measured from strip scales attached at nine levels, spaced evenly and read with a theodolite. Automatic recordings of the lateral deflections were also made using potentiometers attached at the one-fourth column length levels. A typical recording obtained using a multichannel oscillograph is shown in Fig.12. The X-Y plotter was used to make a continuous plot of the mid-height load-deflection curve. In Fig. 13 the results from all column tests are shown.

Lateral deflections about the major axis were measured with 1/1000 inch dial gages attached to the center of the flange at mid-height and at the two ends. Figure 14 shows the results for Col. 02.

The strains were measured at selected points with SR-4 electric strain gages, Type A-1. Figure 15 shows strain measurements made at the mid-height section of Col. 01.

End rotations were measured using mechanical and electrical rotation gages. The mechanical rotation gage[12] is used by mounting the level bar on a support bracket welded to the base plate and the top plate of the column (Fig. 16). Angle changes are measured by centering the level bubble by adjusting the micrometer screw. A vertical dial gage attached to the end of the level bar gives an indication of the rotation of the bar over a gage length of 20 inches (510 mm). In the electrical rotation gage, rotations are measured in the form of bending strains induced in a thin strip from which a heavy pendulum is suspended (Fig. 16). It has been shown[13] that the strain at any location of the strip is proportional to the end rotation. Figure 17 shows typical end rotations measured using both electrical and mechanical rotation gages.

The overall shortening was obtained by measuring the cross-head movement using a dial gage graduated to 1/10,000 inch. Since the dial gage was located at a remote point making it inconvenient for frequent reading, a TV camera was used to obtain the readings at the floor level (Fig. 18). Figure 19 shows a typical result of load versus overall shortening curve.

The angles of twist were determined at mid-height and at the two ends by using the differences in lateral deflections of the flanges about the weak axis. Figure 20 shows the measured angles of twist for Col. 07.

4. DISCUSSION

4.1 Test Specimen

The test specimens were prepared from a single rolled piece in order to reduce the number of variable parameters, such as material, geometry and residual stresses, to a possible minimum. For the same reason, the specimens were not allowed to be cold-straightened.

Cooling conditions, such as the type of cooling bed and position of specimen on the cooling bed, influence the final residual stress distribution, and this may be one reason for the slightly unsymmetrical distribution of residual stresses measured for the shape in this study (Fig. 5). Such an unsymmetrical distribution of residual stresses may be considered equivalent to some initial eccentricity imposed on the test specimen.

The column ends may not always be machined to have parallel surfaces, since milling is usually performed with reference to the end portions of the columns. Such deviations are difficult to measure or check, but would be expected to significantly influence the column strength. Even though the alignment is accomplished on strictly geometrical basis, the alignment may be improved by adjusting the leveling plates at the sensitive cross-head of the testing machine. For extreme cases it may be recommended to use the four strain gages at the flange tips at mid-height of the column and use the differences in readings as an indication for adusting of end plates.

4.2 Supplementary Tests

The purpose for conducting supplementary tests including residual stress measurement is to determine the basic properties of the specimen material so as to enable evaluation of theoretical predictions of column strengths.

To determine more exact values of the mechanical properties for such a heavy section, it may be advisable to conduct tensile tests on test pieces taken from a number of specified points through the thickness of the flanges and the web.[14] The discrepancy in values and the differences in the characteristic stress-strain curves shown in Fig. 4 suggest strongly that tension tests should be conducted on more specimens taken at characteristic locations.

For heavy shapes, further measurement of residual stress through the thickness may also be required if more accurate data for theoretical evaluation is desired. The measurement can be obtained by "slicing"(15) the elements after a complete "sectioning" has been performed.

The purpose for carrying out a stub column test is to determine the tangent-modulus load from the stress-strain curve of the specimen to predict the column strength. For columns of intermediate slenderness ratio, the curve after the proportional limit would then be of greater importance. To make this portion of the curve smooth, the test points should be closely spaced.

Plotting the "static curve" requires a much longer testing time (a period of 20 to 30 minutes is required for stabilization) and the resulting curve may not be smooth. Establishing a smooth curve is essential for determining the tangent modulus. If the "dynamic curve" is plotted instead, the required testing time will be very short and a smooth curve will be obtained. The problem associated with the second alternative, however, is in determining the static curve. The static curve is dependent, mainly, on the ratio of the yielded to the total area. The effect of strain rate is significant after the commencement of yielding.

4.3 Column Testing

The comparative study was designed to allow comparison of different testing procedures for heavy columns and to clarify some problems in instrumentation and recording. The study was encouraged since sufficient references, experience and data about testing of heavy columns were not presently available.

The extension of initial measurements for cross-sectional dimensions and out-of-straightness should correspond to the accuracy and coverage of other complementary tests (mechanical properties, residual stress and stub column tests). The variation in cross-sectional area and shape and the initial out-of-straightness directly affect the column strength. In general, small imperfections result in significant reductions of the ultimate load.

The alignment of a column is the most important step to be carried out before testing the column. Basically, there are two systems for aligning pinned-end columns. The first method is to align the column carefully such that the absolute maximum load which the pinned-end column can carry can be attained. The second method is simply to align geometrically with respect to some reference point on the cross-section.

The first method, as in the old Lehigh method, has problems associated with it in satisfying the criterion and are summarized as follows:

- it is time consuming (Table 4)
- it is difficult or sometimes impossible to satisfy the criteria especially for long columns with large out-of-straightness
- the maximum alignment load is not a clearly defined load, instead, it requires a certain degree of judgement for its determination, since it depends on the proportional limit and the degree of accuracy of the alignment.

The geometric alignment, on the other hand, is very simple and time saving since the end plates can easily be welded with reference to any desired reference point on the cross section. Consequently, the end plates can be positioned with reference to the centerline of the testing machine without much difficulty. Another attractive feature about geometric alignment is its conformity to practical conditions employed in steelwork construction.

It should be mentioned, however, that a new variable is introduced for sections with the center of gravity not at the center of web. Practical considerations prohibit use of the center of gravity as a reference point. The best centering would then be with respect to the flanges, since the web has little effect on buckling about the minor axis. This reference point may be located at the mid-point of the line connecting the two centers of flanges. Still another feature about the center of flanges, according to the rolled shape considered in this study, is that its position on the cross section is usually nearer to the center of gravity than the center of the web. This is indicated in Fig. 21 which shows a plot of the computed resluts obtained from the measurements made at each end for all seven columns. It has been found that there is variation of the positions of the three reference points along the length.

4.4 Testing Procedure

Loading of the column in a testing machine is always conducted under some rate of loading which causes the difference between static and dynamic curves correlated to the static and dynamic yield stresses. The experimental curve is, therefore, influenced by the rate of loading. Two types of column curves can be obtained from column testing; the dynamic and the static curve which may be defined as the dynamic curve at "zero" rate of loading. This is one basic explanation for the difference of the two methods used in this investigation. Evaluation for the old Lehigh method is based on the static measurements while the European procedure uses only the dynamic loading completely neglecting the static equilibrium.

To obtain the "static" curve there are some factors to be considered. According to the old Lehigh method, the static curve is determined when the load carried by the column shows no further decrease in magnitude while maintaining the cross-head movement fixed. This, for example, is rather easy to satisfy if a mechanical type machine is used since the cross-head can be held fixed in position. The contrary is true if a hydraulic type machine is used, since leakage of oil, change in oil temperature and other factors which always are inherent during normal working conditions make it rather difficult to maintain the cross-head movement. Maintaining the load is usually simpler when using a hydraulic type machine. Therefore, the definition for determining the static curve should take into consideration the type of machine used and the manner of loading imposed.

In general, the effect of the rate of loading is noticeable after yielding on some fibers starts and becomes more noticeable as the yielding progresses. Therefore, the preferable manner of loading depends on the state of the column. For a hydraulic type testing machine, the portion of the static curve up to the ultimate load can be found more accurately by maintaining the load. The curve obtained will always be higher or may match the "true" static curve. Figure 22 shows the possible range of error when using the "horizontal" approach which varies from 0.25 to 0.5 percent on the unconservative side. This approach, however, has the disadvantage that it cannot be applied after the ultimate load is reached (unless the load is lowered well below the static curve and then maintained), also it requires a much longer period of time for stabilization especially for loads very close to the ultimate. In general, since the stable region of the column curve is usually of prime importance in engineering design, the "horizontal" approach may thus be used effectively.

The "vertical" approach (that is by maintaining the cross-head movement) may not give as accurate a static curve as the other approach if a hydraulic type machine is used. Under normal conditions an asymptotic load (Fig. 23) would not be observed. The possible range of error depends on the condition of the testing machine. The continuous drop of the load while maintaining the cross-head movement is not only due to oil leakage, but could also be due to creep at bearing surfaces such as the cover plates and also friction at bearing surfaces. For the columns tested in this study the difference was in the order of magnitude of one percent (Fig. 24).

While the technique and precision in column testing is being improved some objective questions which may alter the whole testing procedure seem to be as yet unanswered. These questions may be summarized as:

What actually would simulate the actual manner of loading on a column of a structure? Static or dynamic loading?

If the P-Δ curve for a static loading would be required, should it be obtained from a plot of static points? Or should it be derived from the dynamic curve?

What should be the appropriate testing approach to determine a static point? Maintaining the deflection or maintaining the load?

If the dynamic curve would be sufficient, what should be the rate of loading to use?

In an attempt to find a solution to these problems, a method of testing is recommended where an "interrupted" dynamic loading is used. The dynamic curve will be plotted until the ultimate load is reached immediately after which the static load will be recorded using the "vertical" approach. After the static load is recorded the test will be resumed using the value setting established originally until the desired configuration has been attained. A sketch of the complete P-Δ curve resulting from such a test will be similar to that shown in Fig. 25.

Such a procedure will present the dynamic curve and the main information about the ultimate static load which should be sufficient for statistical evaluation and for comparison with theoretical predictions. This method was applied for the European Column testing program and has been found very successful.[19]

5. SUMMARY AND CONCLUSIONS

The purpose of this experimental study was to investigate and to compare different column testing procedures for medium and heavy pinned-end columns. The main subjects of interest were the alignment and the manner of loading.

Based on the experience and test results the following recommendations and conclusions can be stated:

1. The testing of heavy columns requires a well-developed testing procedure, more complete in instrumentation and supplementary tests, than for light-sized columns. This is to avoid very expensive replications required for statistical evaluation, and to allow more accurate correlations with theoretical analysis.

2. The measurement of cross-sectional dimensions at closer points along the length (which is possible to include individually in the computer program for predictions) and the respective initial out-of-straightnesses both about the weak and strong axes are of considerable

importance. Measuring techniques providing better accuracy were developed and are described in this paper. The measurement of initial twist which may also be required, was not considered.

3. For heavy columns, the mechanical properties of the material may not only be different for the web and flanges, but may also vary significantly through the thickness. For heavier shapes, it would be recommended, therefore, to conduct coupon tests on test pieces taken from a number of specified points throughout the thickness and to use these results for theoretical predictions. Mechanical properties of the material from a mill test, generally, may differ very much compared to coupon test results (Table 1).

4. The magnitude and distribution of residual stresses is required to make a theoretical prediction and for correlation with test results. Residual stresses may be measured using the method of sectioning and slicing or may be obtained from previous studies on heavy shapes.

5. Column strength with zero initial out-of-straightness may be predicted from stub column test results and using charts where a simplified residual stress pattern, and

homogeneous and ideal elastic-plastic material are assumed. If a more accurate column strength prediction is required using stub column test results, additional information of the residual stress distribution and mechanical properties across the section especially for medium and heavy shapes is required. But if such information is already available, column strength may be predicted directly analytically and stub column test would not be required.

6. Different stub column testing procedures were investigated and compared. To obtain the static curve the "horizontal" approach (maintaining load) would be more preferable for a hydraulic type testing machine. If the measured residual stress distribution is available, the testing procedure can be simplified using a dynamic curve and one static point after the yield plateau is reached.

7. The stub column test should be used for heavy shapes only if direct analytical prediction cannot be made to allow comparison.

8. The test results for medium and heavy columns are greatly influenced by the alignment method used. The "stress criterion" alignment used in the old Lehigh method was

introduced to reduce the effects of initial out-of-straightness, but it also increased the ultimate load. Such alignment is not only tedious and time-consuming, but does not correspond to the behavior of a compression member in an actual structure. Also from a statistical point of view, this methods depends on an uncontrolled variable - the end moments. The ECCS method requires a geometric alignment through the center of the web, a point which has little effect on buckling about the minor axis.

9. After comparing the two alternatives of alignment methods (old Lehigh method and ECCS method) the geometrical alignment is recommended, using the center of flanges as a reference point instead of the center of web. Such a method is very simple and not time-consuming. The boundary conditions are kept the same and are easily included in theoretical predictions.

10. The results from column tests using different testing methods are often not directly comparable. One of the main reasons is the mode of loading. Some testing methods use dynamic loading and the static curve is not recorded at all, whereas, some other methods are based

on the static curve and only the ultimate dynamic load is recorded. To allow comparison on column test results the mode and the rate of loading must be comparable.

11. The investigation of loading of a column in an actual structure will not give a single answer; some loadings may be considered as static loads (dead load and live load) and some as dynamic loads (wind, earthquake, etc.).

    It is therefore recommended to obtain from a column test both curves, static and dynamic. The proposed new testing procedure may be considered as a compromise between static and dynamic testing methods.

6. ACKNOWLEDGEMENTS

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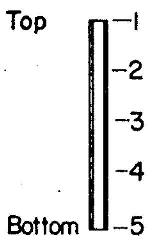
7. TABLES AND FIGURES

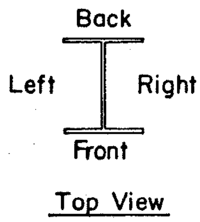
TABLE 1 MECHANICAL PROPERTIES OF SPECIMEN

No.	Location	ASTM STANDARD TENSION TEST				
		Static Load Stress, σ_y		Ultimate Tensile Stress σ_u		Percent Elongation (%)
		ksi	kp/mm^2	ksi	kp/mm^2	
1	Web	28.8	20.7	62.5	44.0	30.95
2	Flange	27.1	19.1	61.5	43.4	34.08
3	Flange	25.4	17.9	61.4	43.4	33.75

MILL TEST	Min. Max.	33.4 35.7	23.5 25.1	62.6 67.8	44.1 47.6	32 33

TABLE 2: CROSS SECTION DIMENSION





Proj. No: 351
Steel Grade: A36
Shape: W 12 x 161
Col. No: 01
Length: 13'-4½"
Recd: P.M. & N.T.
Date: 2/9/69

Section	h_ℓ	h_r	b_f	b_b	t_{fr} / $t_{f\ell}$	t_{br} / $t_{b\ell}$	w_f	w_b	c_{fr} / $c_{f\ell}$	c_{br} / $c_{b\ell}$	Area (in^2)
1	13.765	13.829	12.613	12.596	1.464 / 1.460	1.440 / 1.460	.978	.993	5.789 / 5.846	5.804 / 5.799	47.432
2	13.771	13.856	12.604	12.594	1.464 / 1.447	1.432 / 1.460	.973	.990	5.785 / 5.845	5.815 / 5.789	47.266
3	13.795	13.818	12.603	12.577	1.469 / 1.452	1.432 / 1.471	.975	.982	5.773 / 5.855	5.801 / 5.794	47.323
4	13.780	13.832	12.618	12.596	1.471 / 1.451	1.427 / 1.439	1.034	1.006	5.784 / 5.800	5.804 / 5.786	47.615
5	13.763	13.845	12.608	12.598	1.472 / 1.455	1.433 / 1.436	1.025	1.006	5.788 / 5.795	5.800 / 5.792	47.599
Average	13.775	13.836	12.609	12.592	1.461	1.443	0.997	0.995	5.806	5.798	47.450

See Fig. 8 for Notation

NOTE: Dimensions given in inches.
1 in. = 25.4 mm

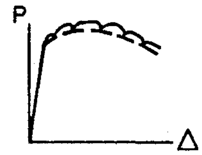
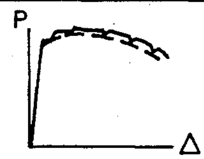
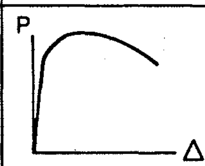
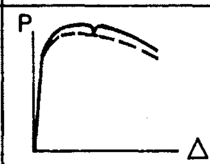
Table 3 DIMENSIONS OF TEST SPECIMENS

Col. No.		Area, A, $in.^2$	Depth of Section, d	Flange width, b	Flange Thickness, t	Web Thickness, w
01	Measured	47.45	13.806	12.600	1.450	0.996
	% Variation	+0.1	-0.5	+0.7	-1.6	+10.1
02	Measured	47.42	13.810	12.625	1.448	0.994
	% Variation	+0.1	-0.5	+0.9	-2.6	+9.8
03	Measured	46.90	13.820	12.606	1.457	0.932
	% Variation	-1.0	-0.4	+0.7	-2.0	+3.0
04	Measured	47.33	13.813	12.589	1.456	0.979
	% Variation	-0.1	-0.5	+0.6	-2.0	+8.2
05	Measured	47.36	13.815	12.617	1.455	0.977
	% Variation	0	-0.5	+0.8	-2.1	+8.0
06	Measured	47.36	13.809	12.607	1.449	0.979
	% Variation	0	-0.5	+0.7	-2.5	+8.2
07	Measured	47.75	13.811	12.600	1.472	0.981
	% Variation	-0.8	-0.5	+0.7	-0.9	+8.4
Handbook Values		47.38	13.88	12.515	1.486	0.905

NOTE: Dimensions given in inches
1 in. = 25.4 mm

Table 4 SUMMARY OF COMPARISON OF TESTING METHODS

LOADING

Method	Typical Column Curve	Loading	Testing Time	Accuracy of Static Curve	Remarks
Old L.U.		Static	4-6 hrs.	0.5 to 1.0% (for hydraulic testing machine)	- Time Consuming - Dynamic Curve not available except P_{ud}.
Alternative Old L.U.		Static	4-6 hrs.	"Horizontal" approach 0.25-0.50% "Vertical" approach 0.5 - 1.0%	- Time Consuming - Dynamic curve not available except P_{ud}. - Slightly more accurate Static Curve.
ECCS		Dynamic	15-20 min.	Static Curve not available.	Static Curve not available.
New L.U.		Semi-Dynamic	30-40 min.	0.5 - 1.0%	Only the ultimate Static Point available.

ALIGNMENT

Method		Aligning Time	Remarks
Old L.U.		4-5 hrs.	5% max. deviation from uniform stress at three levels.
ECCS		30 min.	Center of Web.
New L.U.		30 min.	Center of Flanges.

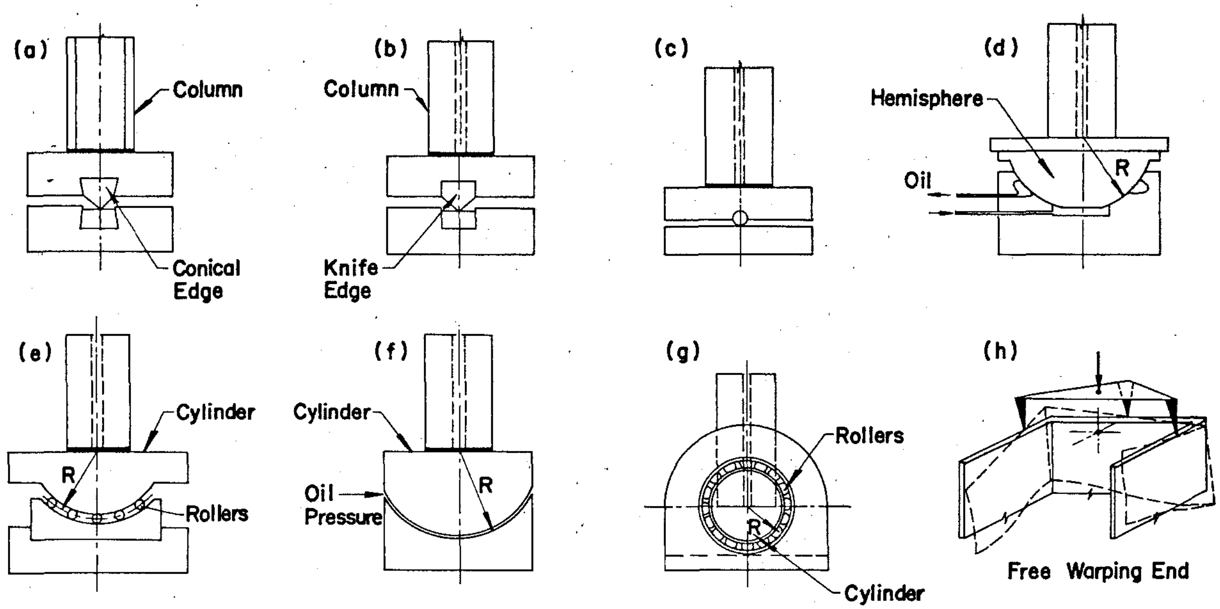


Fig. 1 Basic Types of End Fixtures

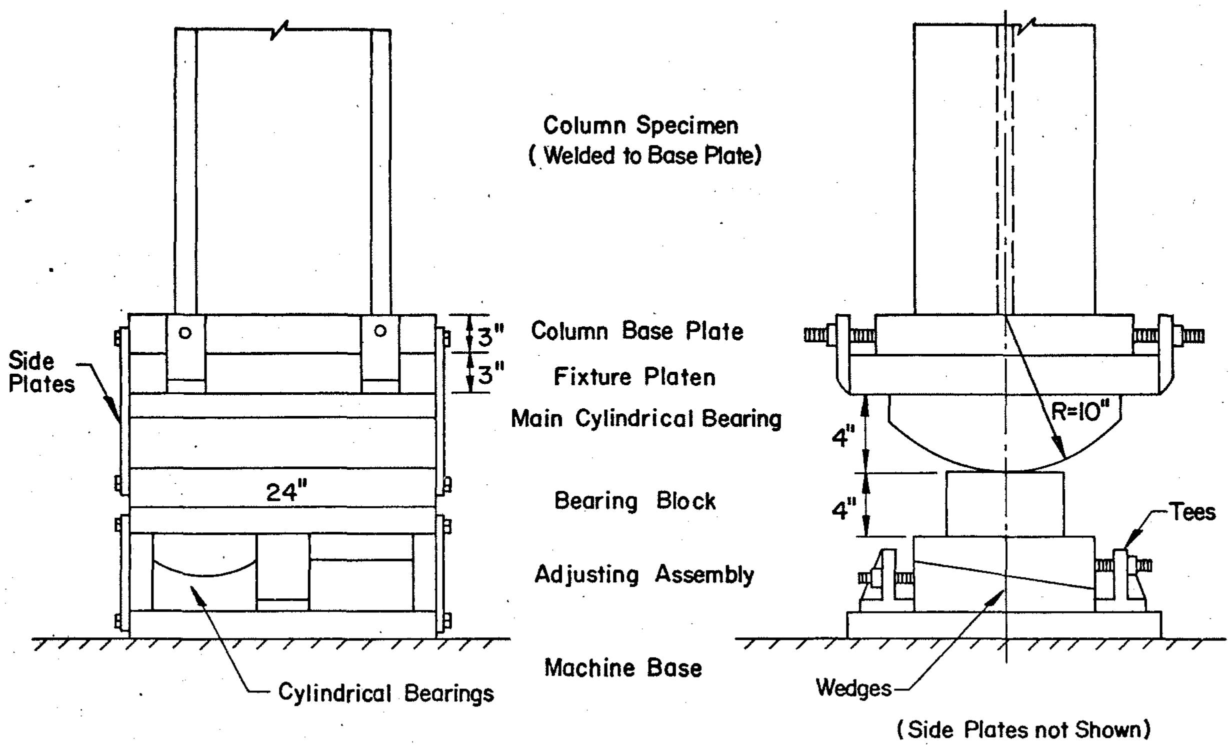


Fig. 2 Standard Column End Fixture at Fritz Engineering Laboratory

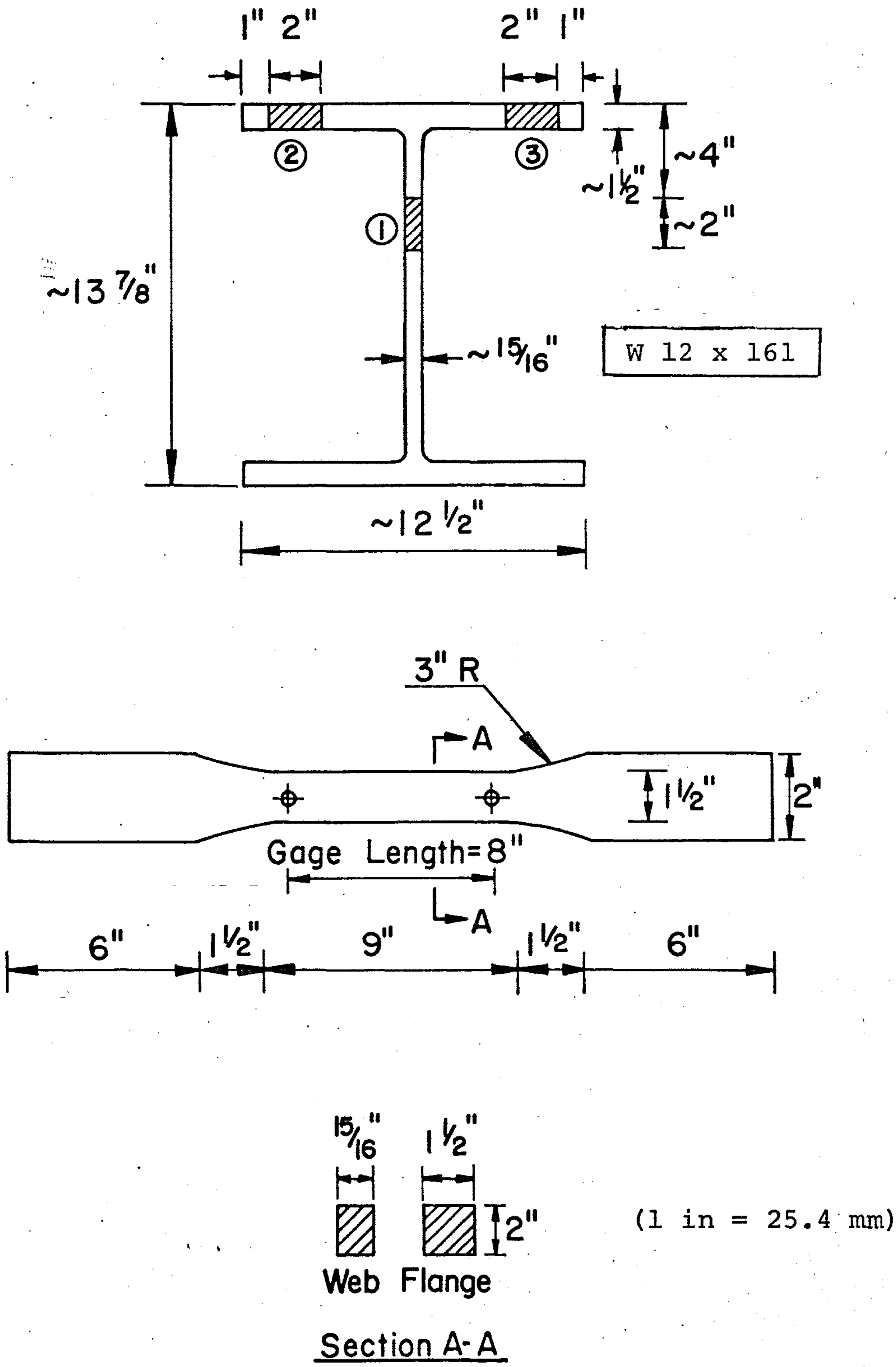


Fig. 3 Location of Coupons with Respect to the Cross Section

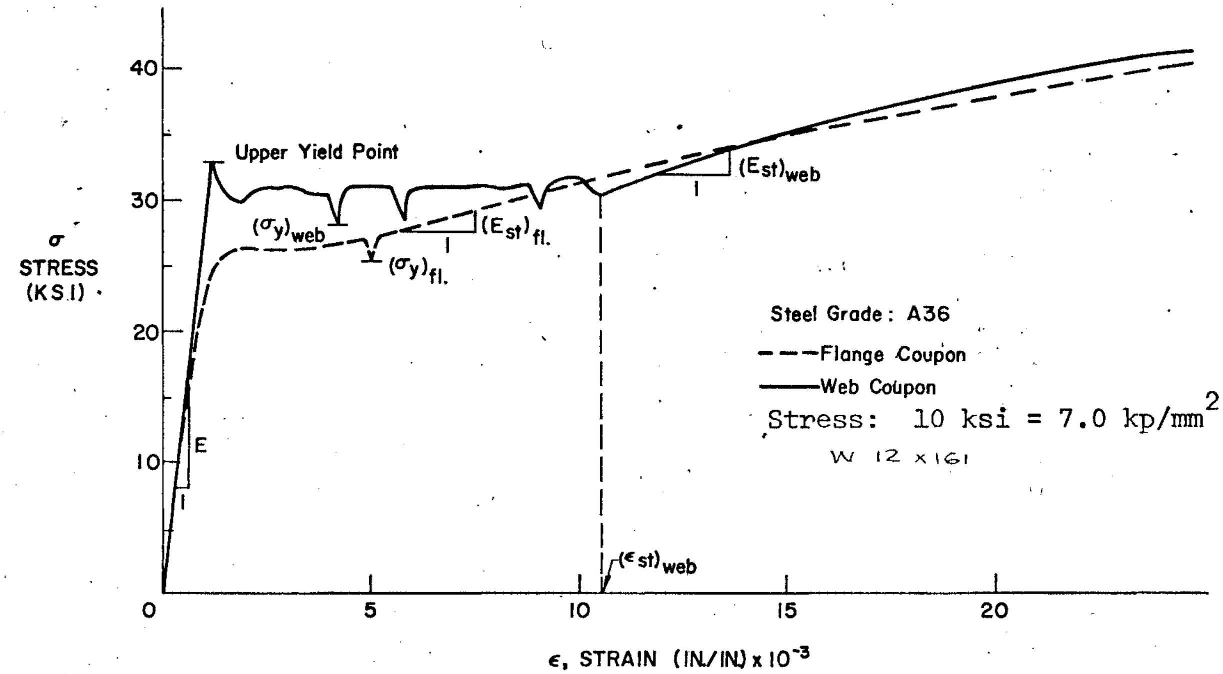
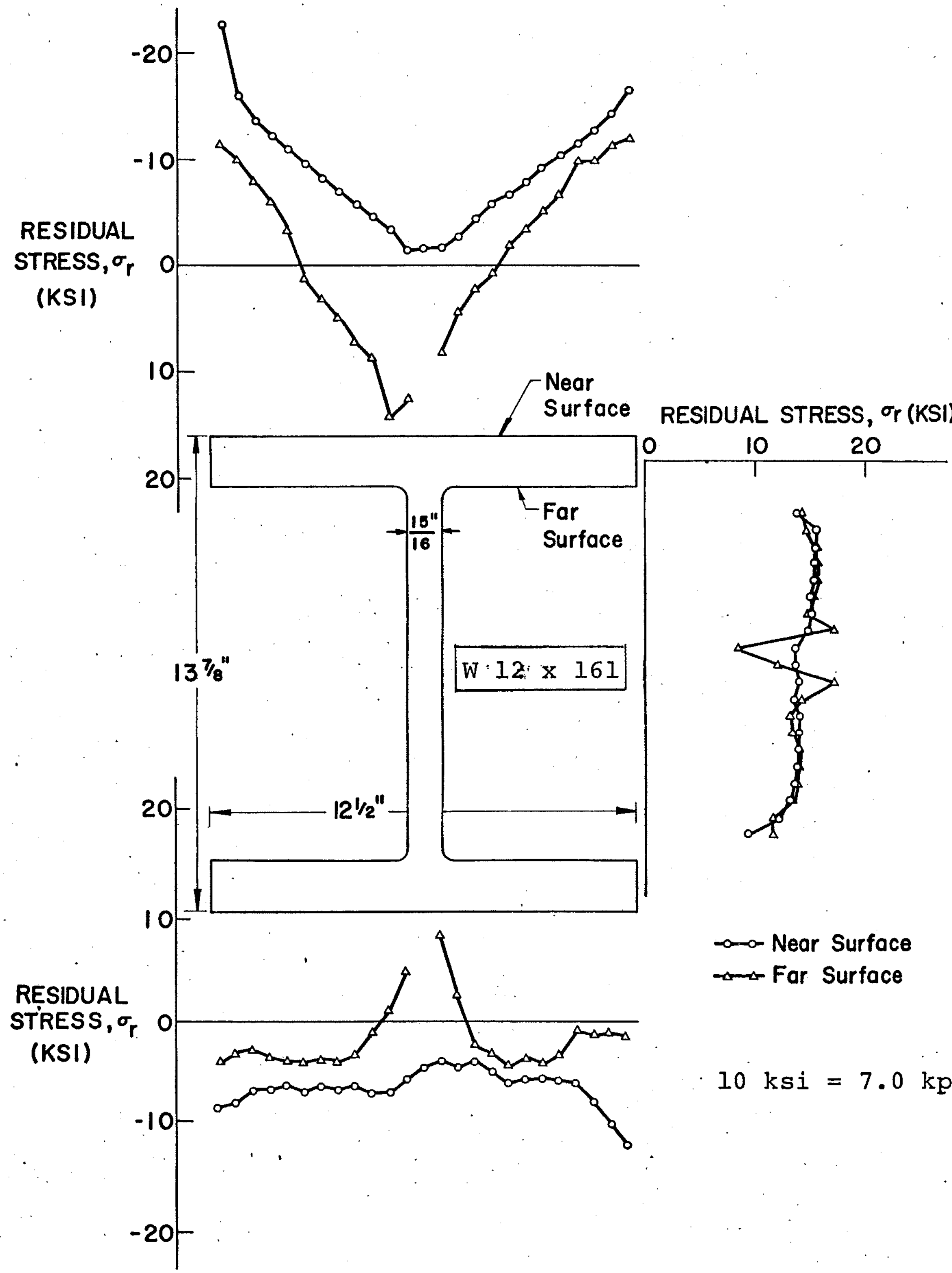
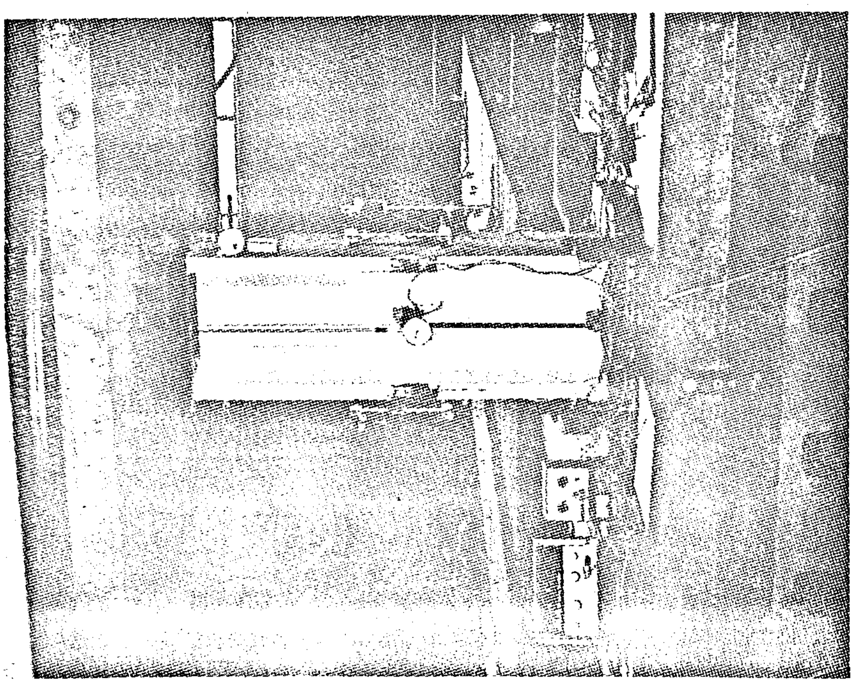


Fig. 4 Stress-Strain Curves from Tension Coupon Tests

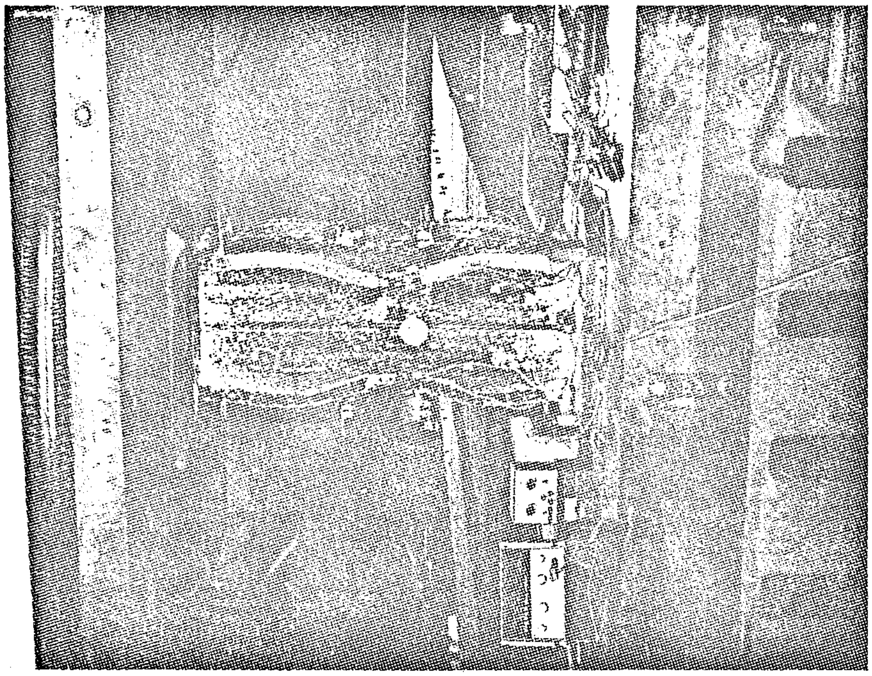


10 ksi = 7.0 kp/mm^2

Fig. 5 Residual Stresses in 12WF161

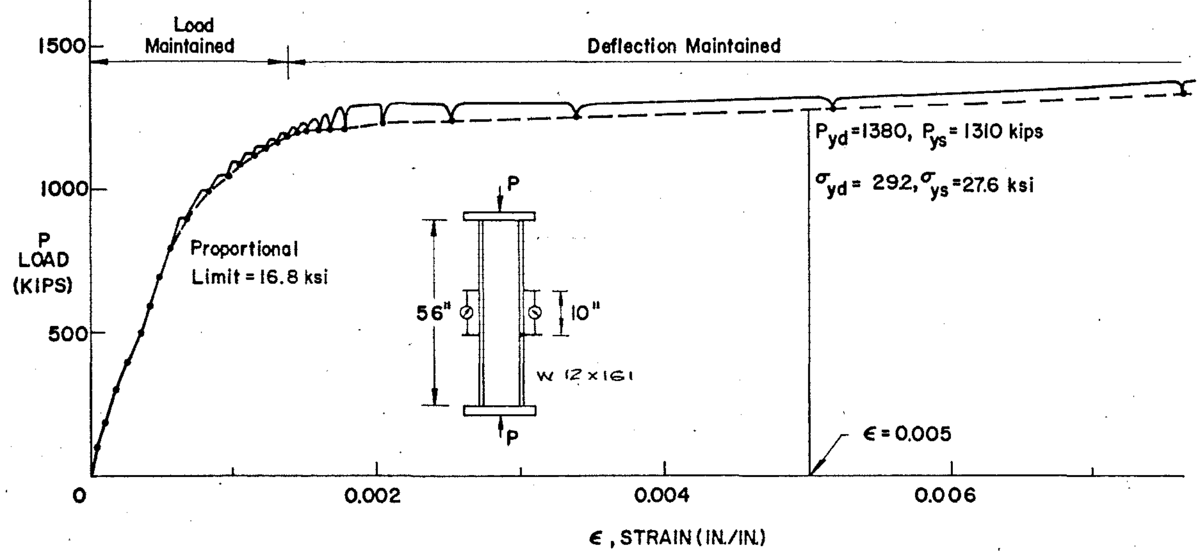


a) Instrumentation

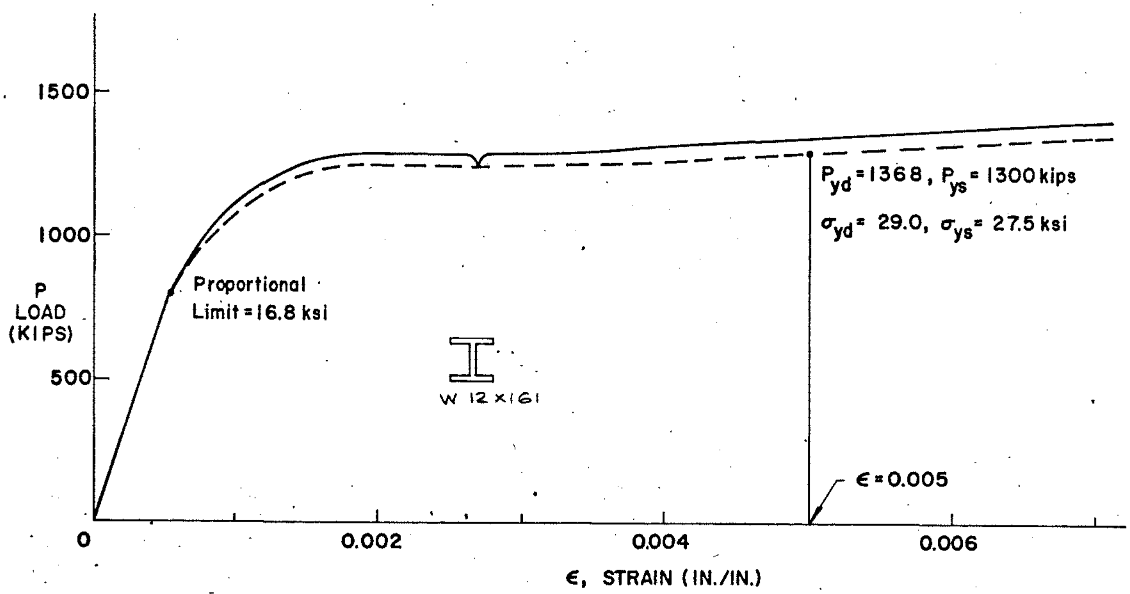


b) End of Test

Fig. 6 Test Set-Up of Stub Column



a. Point to Point Plot of Static Curve



b. Extrapolation of Static Curve from Dynamic Curve

Fig. 7 Stub Column Test Results

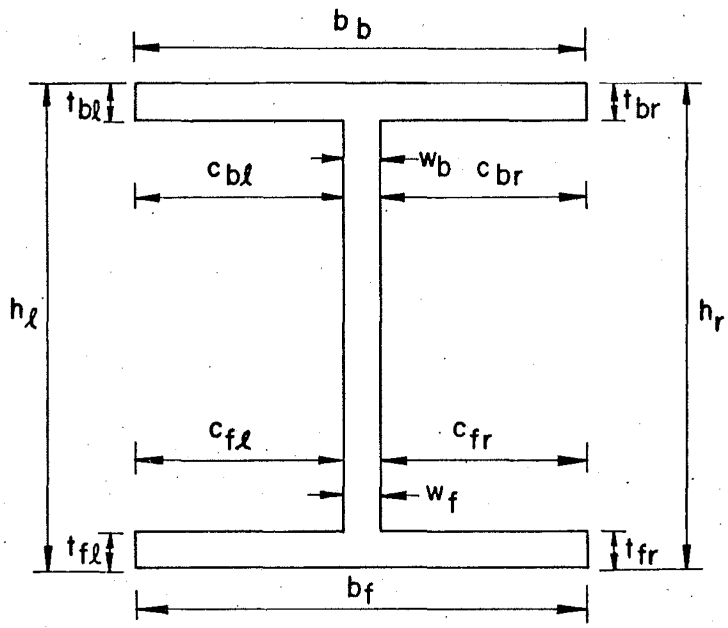
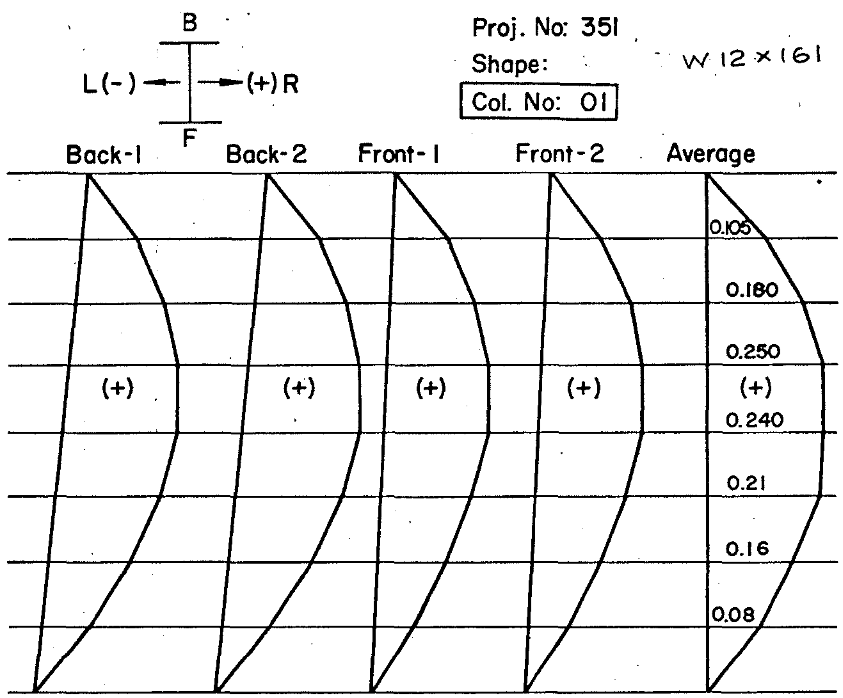


Fig. 8 Required Measurements of Cross-Sectional Dimensions

WEAK AXIS, INITIAL OUT-OF-STRAIGHTNESS

	Front	Back
Right		
Left		
1	3.50	2.320
	1.60	4.280
1'	3.40	2.42
	1.50	4.34
2	3.30	2.44
	1.40	4.35
2'	3.26	2.46
	1.34	4.38
3	3.24	2.44
	1.32	4.34
3'	3.28	2.40
	1.38	4.30
4	3.36	2.33
	1.44	4.25
4'	3.46	2.23
	1.55	4.14
5	3.54	2.12
	1.62	4.04



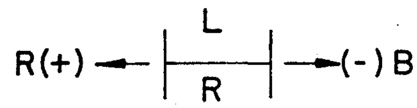
Proj. No: 351
Shape: W 12 × 161
Col. No: 01

Read and Recd: P.M. & N.T.
Date: 2/9/69

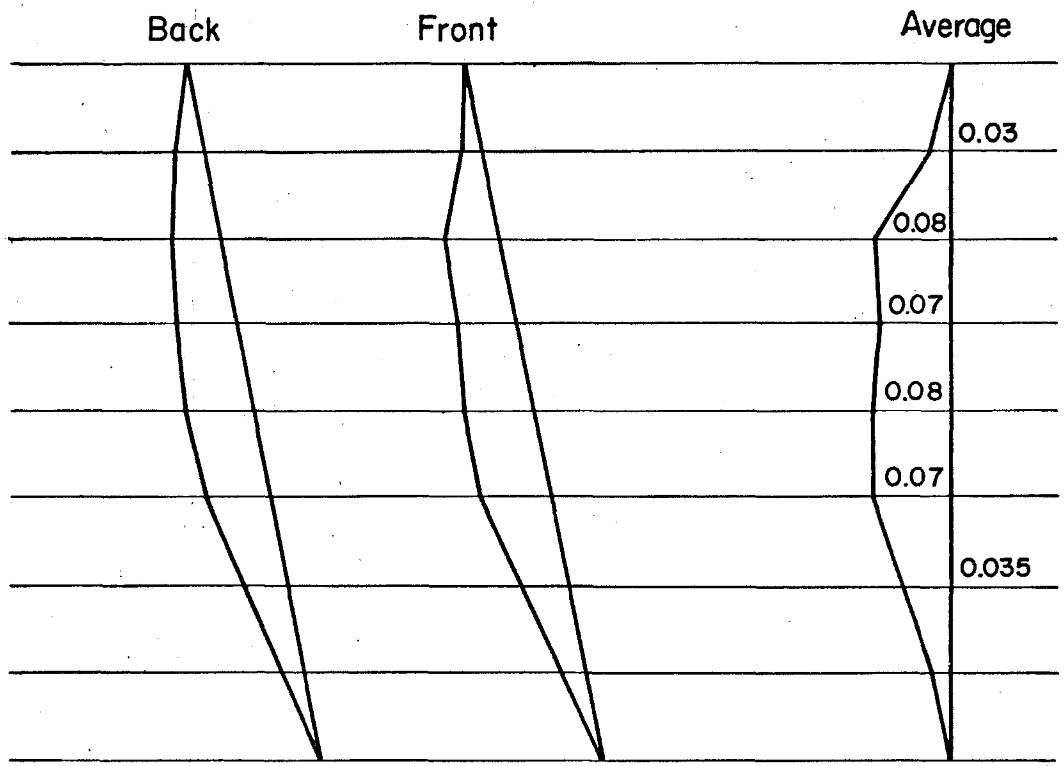
Fig. 9 Measurement of Initial Out-of-Straightness (Weak Axis) (Dimensions in inches)

STRONG AXIS, INITIAL OUT-OF-STRAIGHTNESS

Proj. No: 351
Shape: W 12 x 161
Col. No: 01

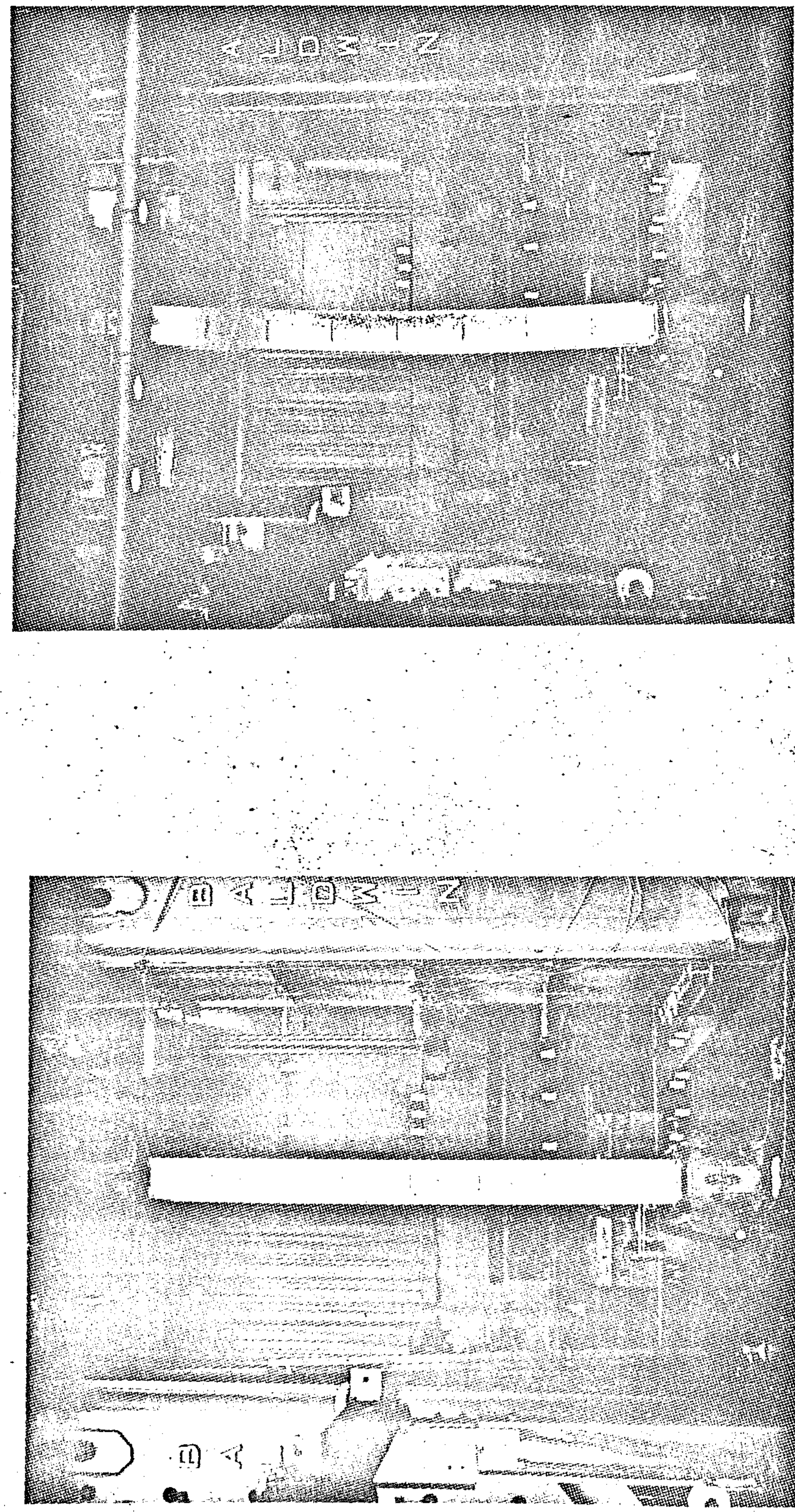


	Back	Front
1	1.0	4.0
1'	0.98	4.0
2	0.98	3.96
2'	1.00	4.00
3	1.02	4.01
3'	1.05	4.05
4	1.10	4.12
4'	1.16	4.17
5	1.19	4.20



Read and Recd: P.M. & N.T.
Date: 2/9/69

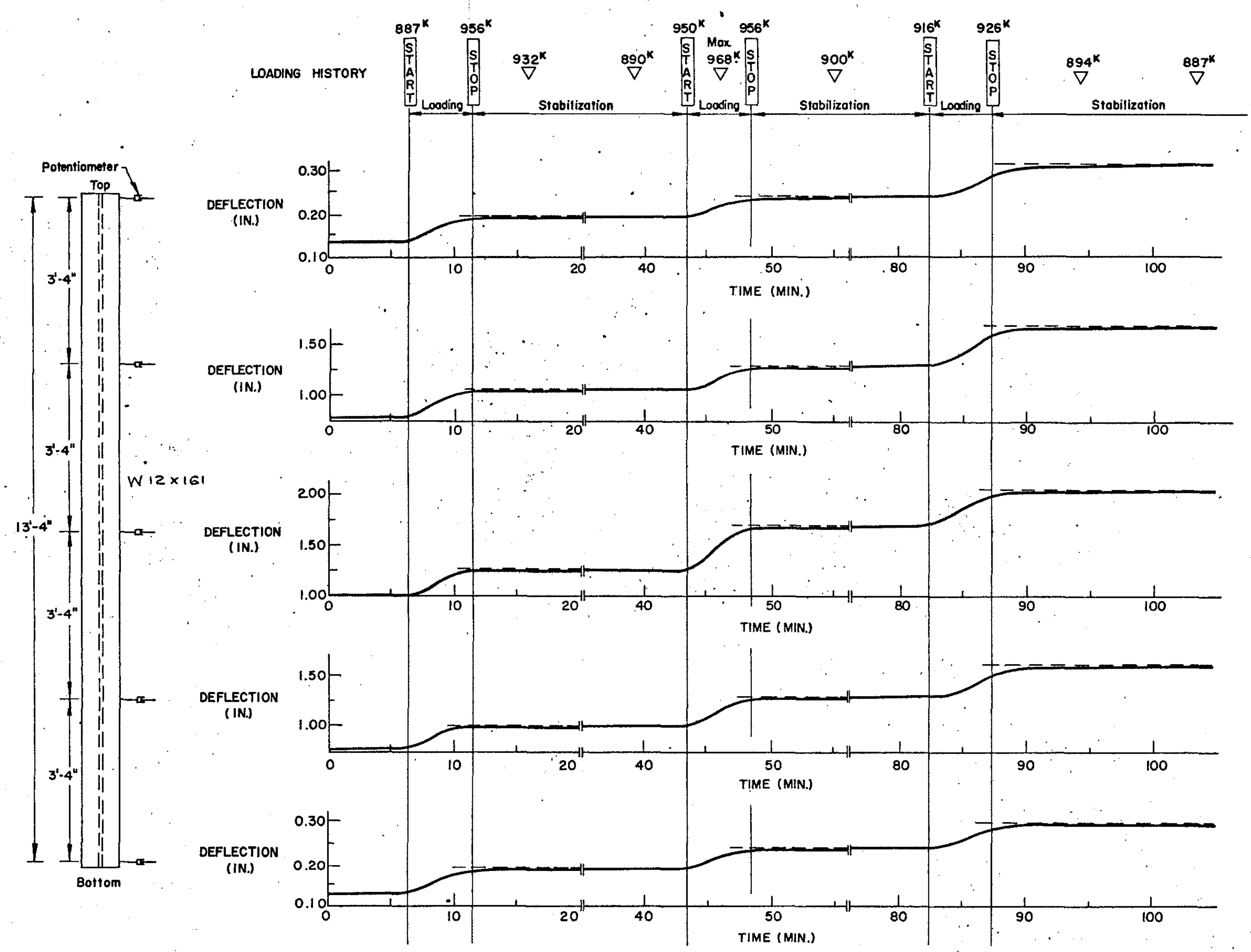
Fig. 10 Measurement of Initial Out-of-Straightness (Strong Axis) (Dimensions in inches)



a) Beginning of Test

b) End of Test

Fig. 11 Set-Up for Column Testing



1" = 25.4 mm   12" = 1' = 304.8 mm   1 kip = 1000 lb = 453.9 kp

Fig. 12   Typical Load-Deflection Time Recordings From Multichannel Oscillograph

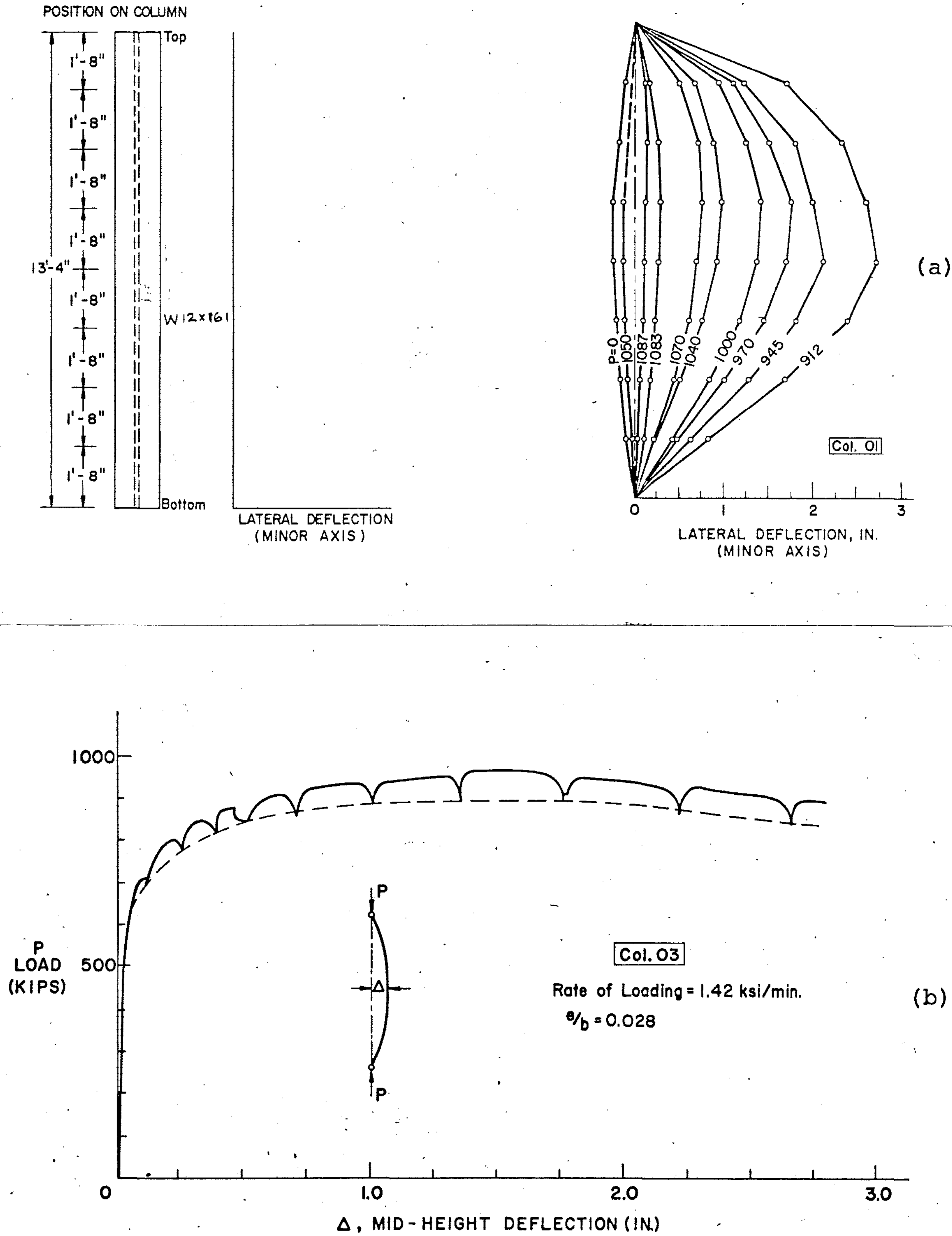


Fig. 13 Lateral Weak-Axis Deflections

a. Transit Readings

b. Recording from X-Y plotter

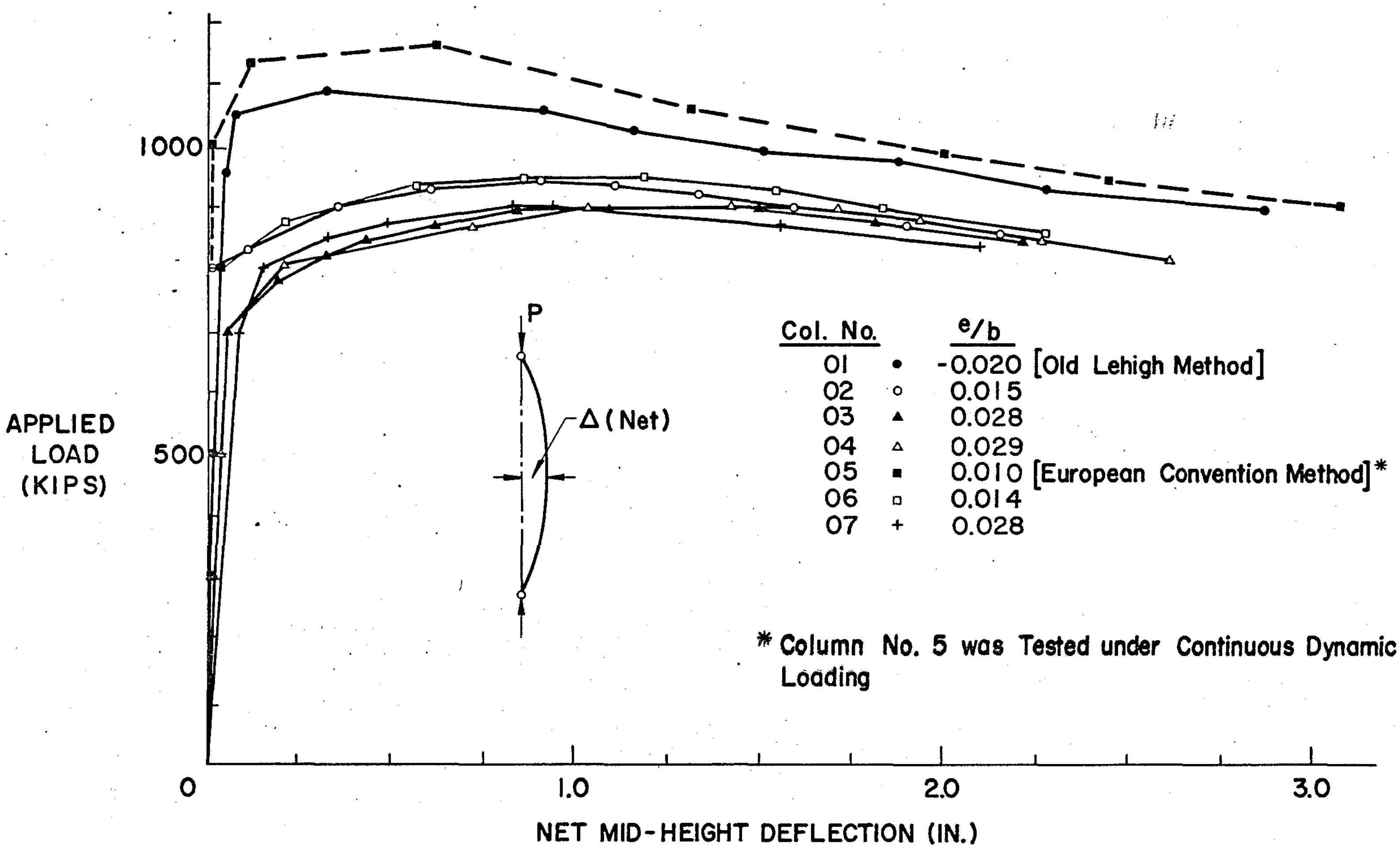


Fig. 13(c) Load Versus Net Mid-Height Deflection Curves of Columns

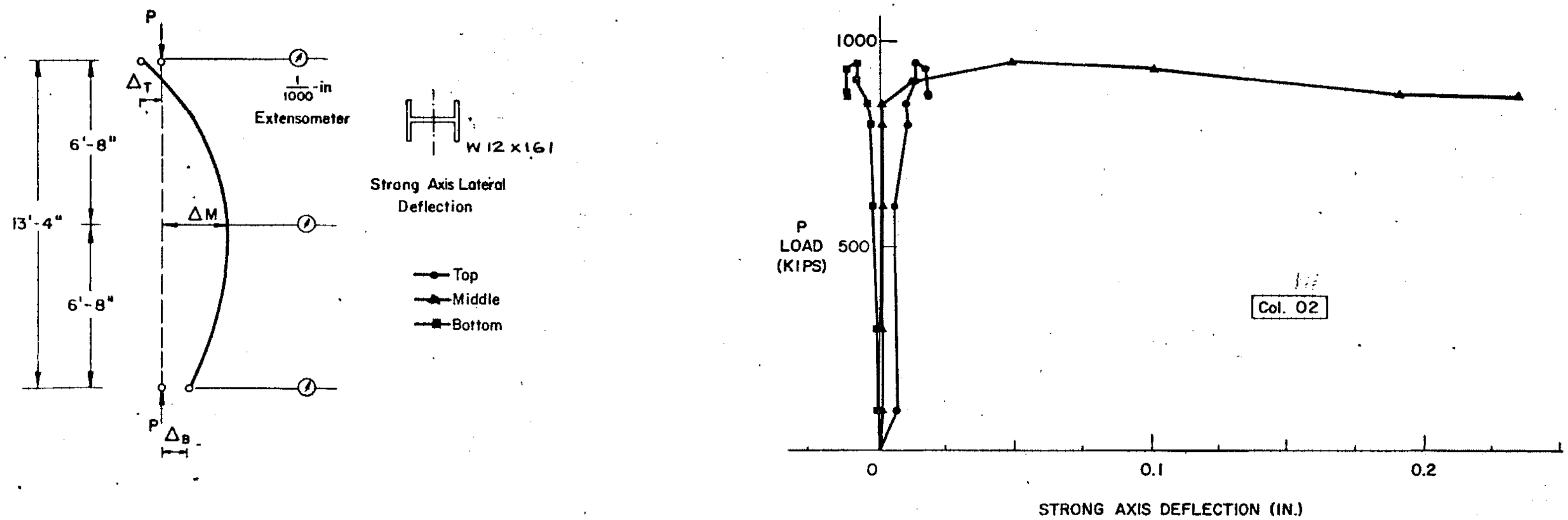


Fig. 14 Lateral Strong-Axis Deflections

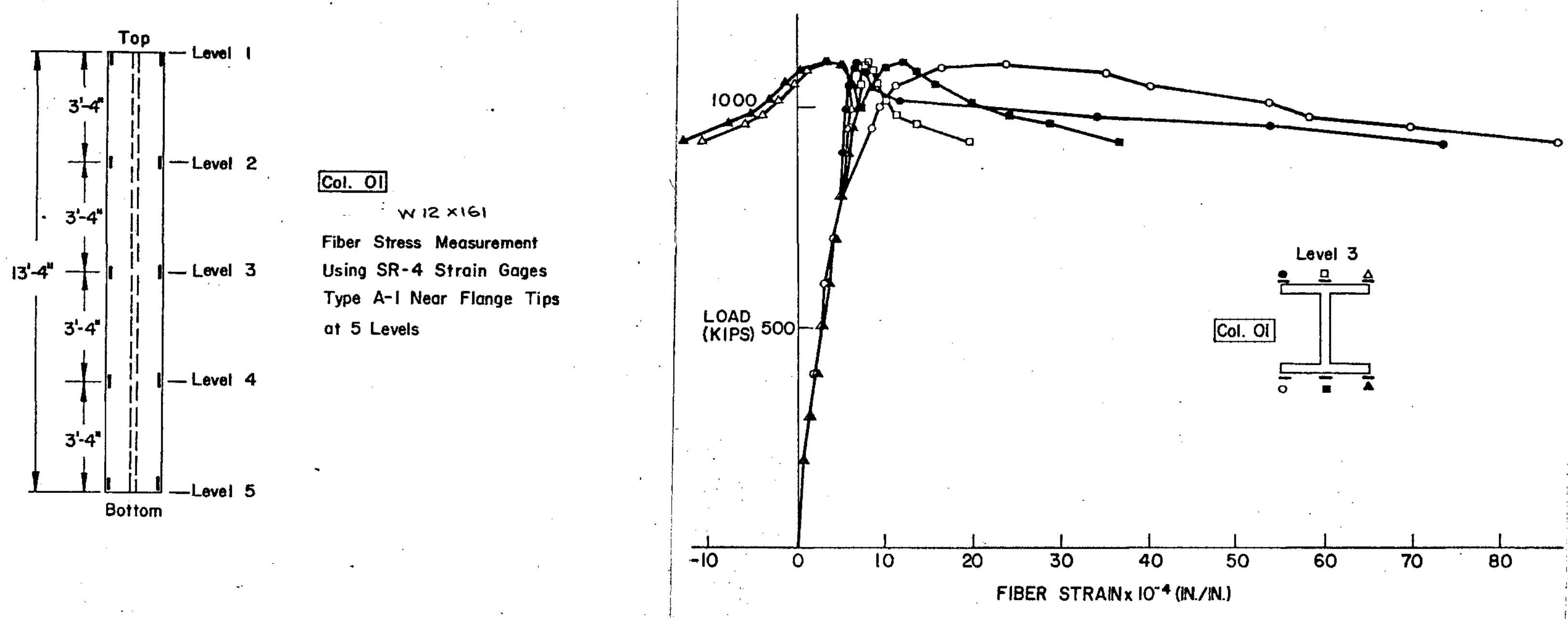
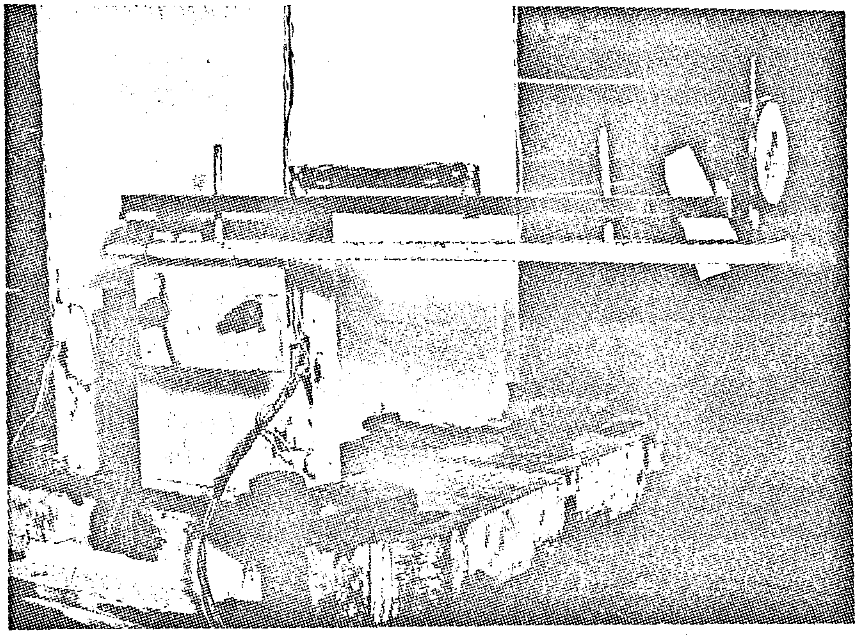
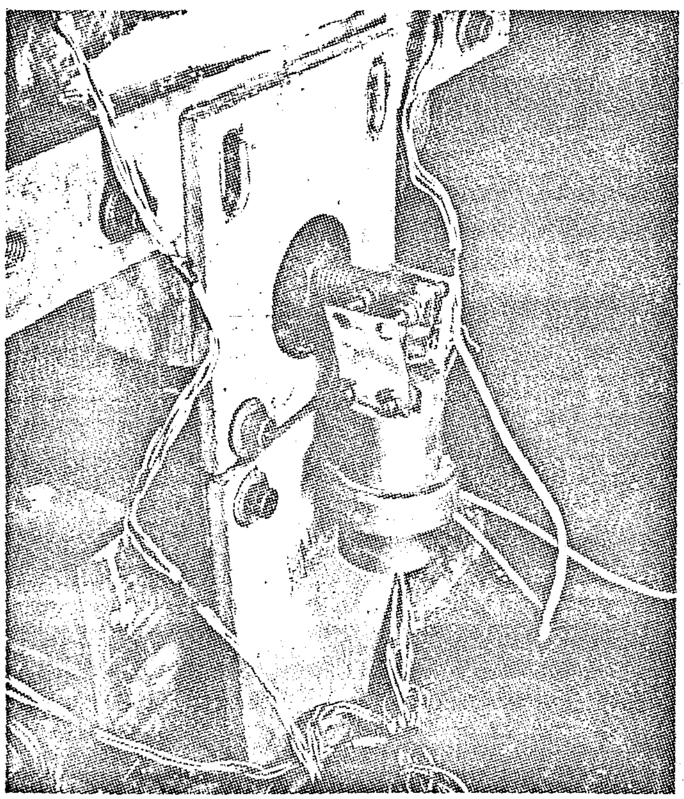


Fig. 15 Strain Measurements at Mid-Height Section Using Strain Gages



(a)



(b)

Fig. 16 Rotation Gages

(a) Mechanical
(b) Electrical

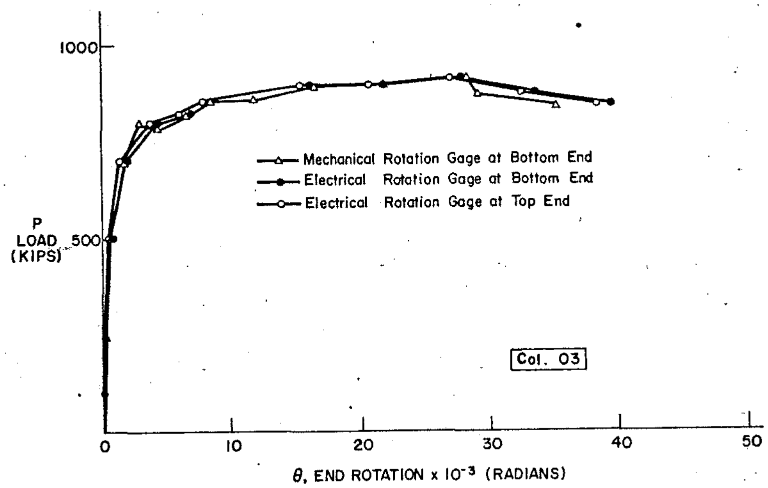


Fig. 17 End Rotations of Col. 03 Using Mechanical and Rotation Gages

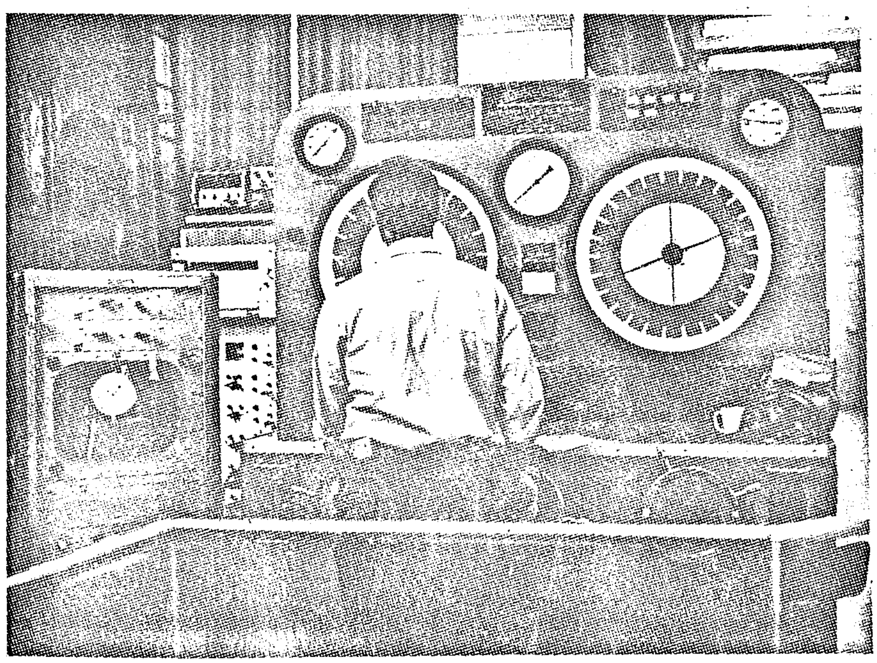


Fig. 18 Simultaneous Reading of Load Dial and 1/10,000 inch Extensometer as seen through the TV Screen

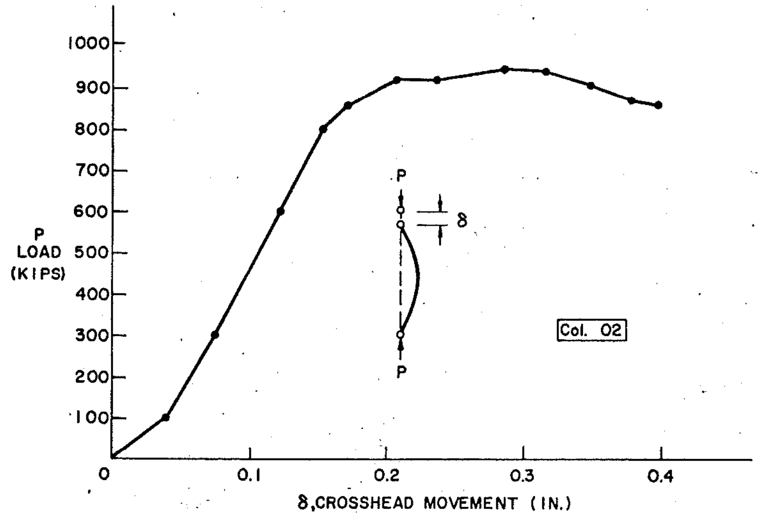


Fig. 19 Load Versus Overall Shortening Curve

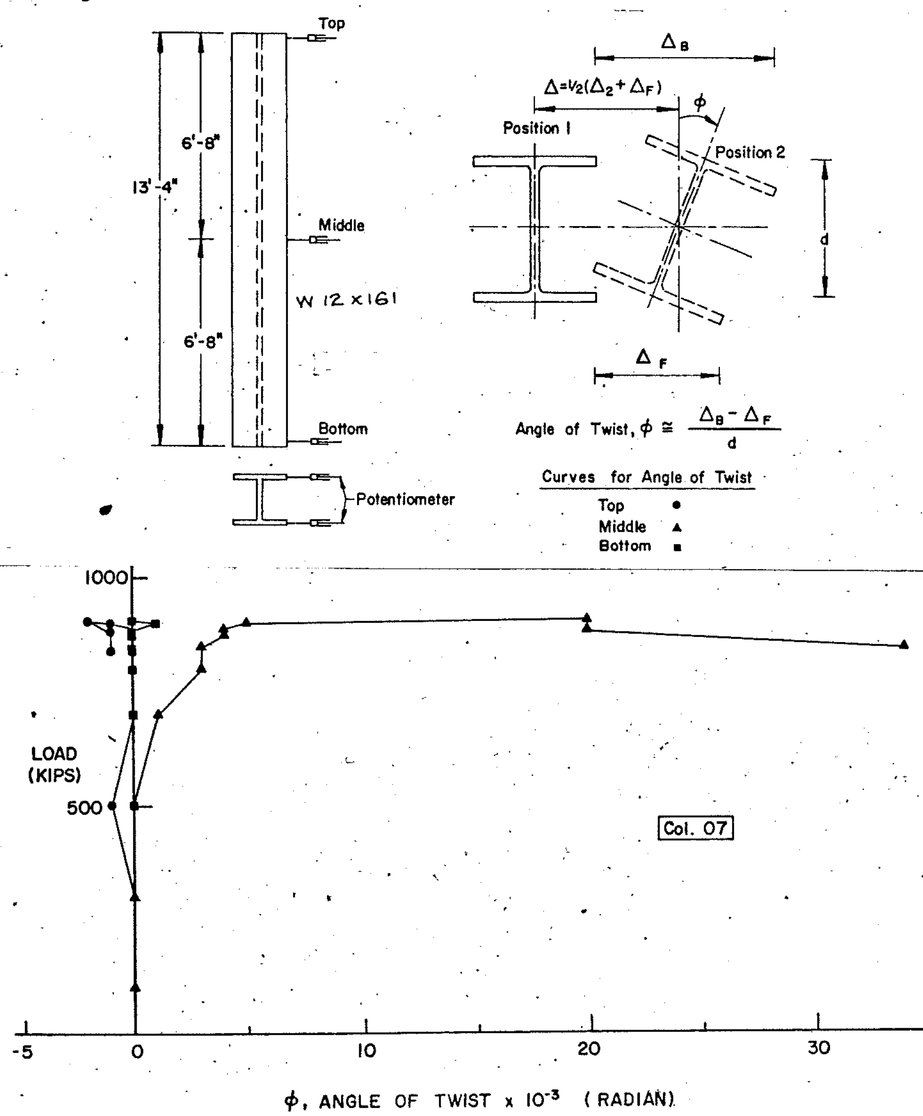


Fig. 20 Angles of Twist at Three Levels

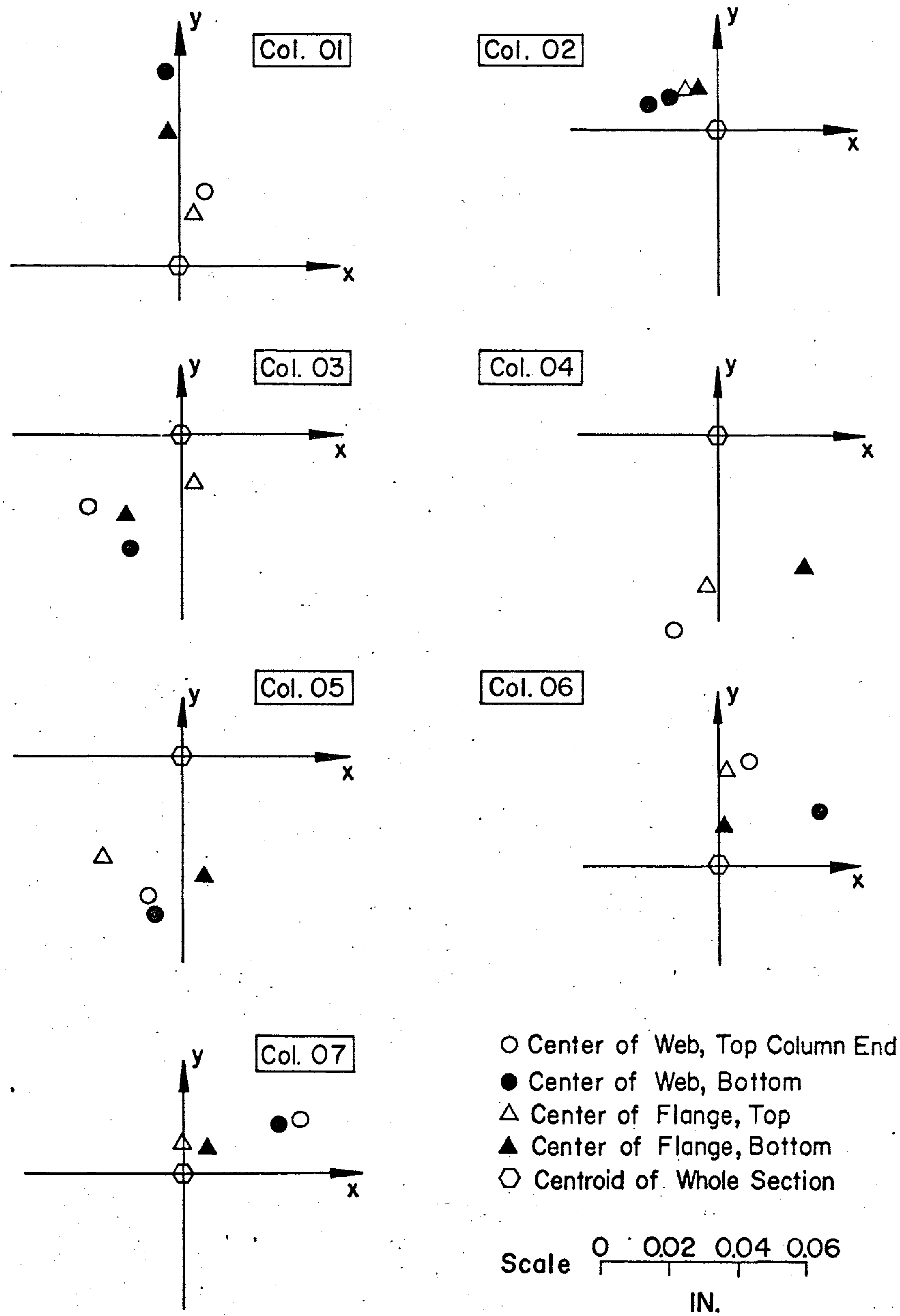


Fig. 21 Comparison of Geometric Centers of Flanges and Webs with the Centroids at Ends of Specimen

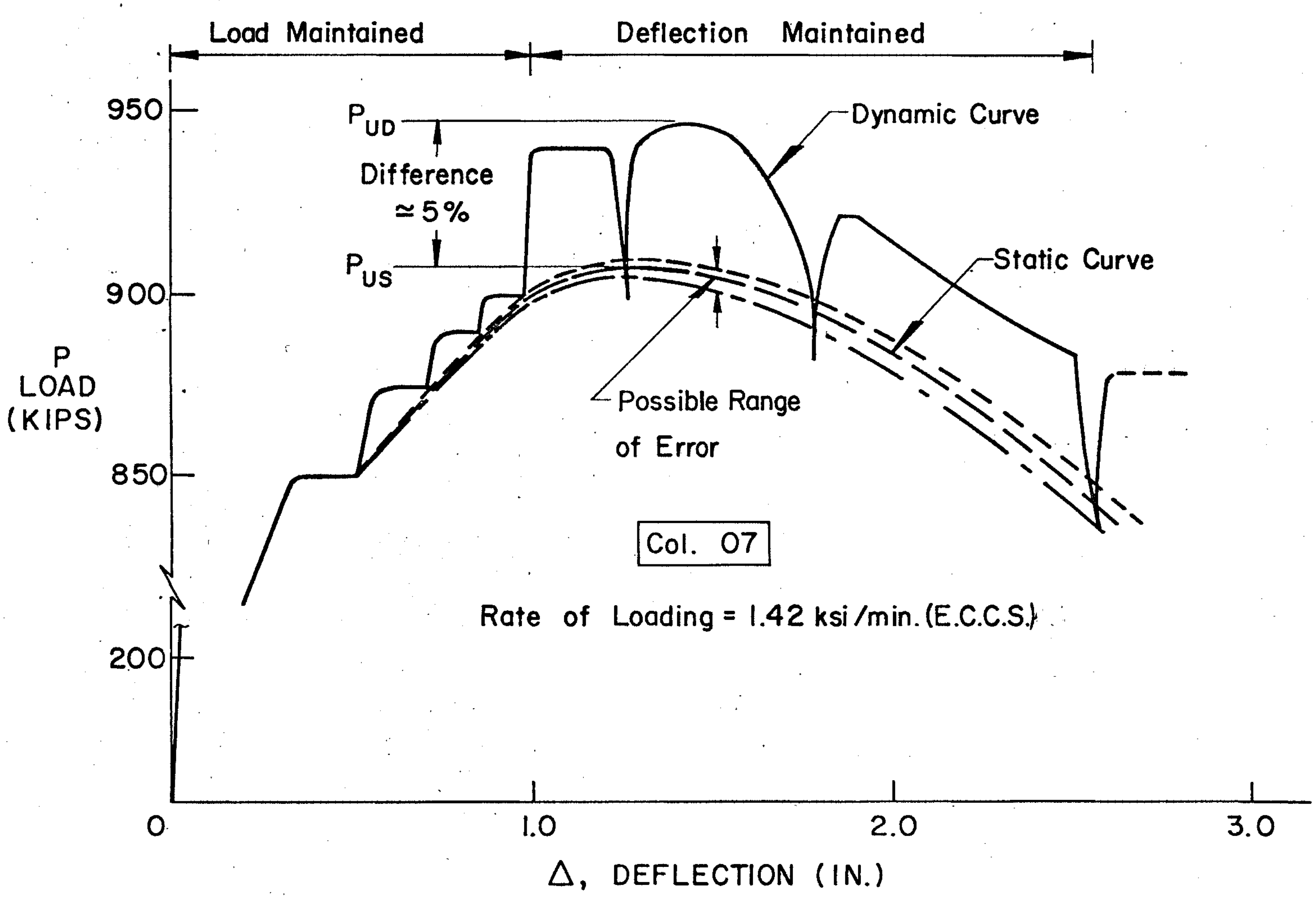


Fig. 22 "Horizontal" and "Vertical" Approaches to Determine the Static Curve

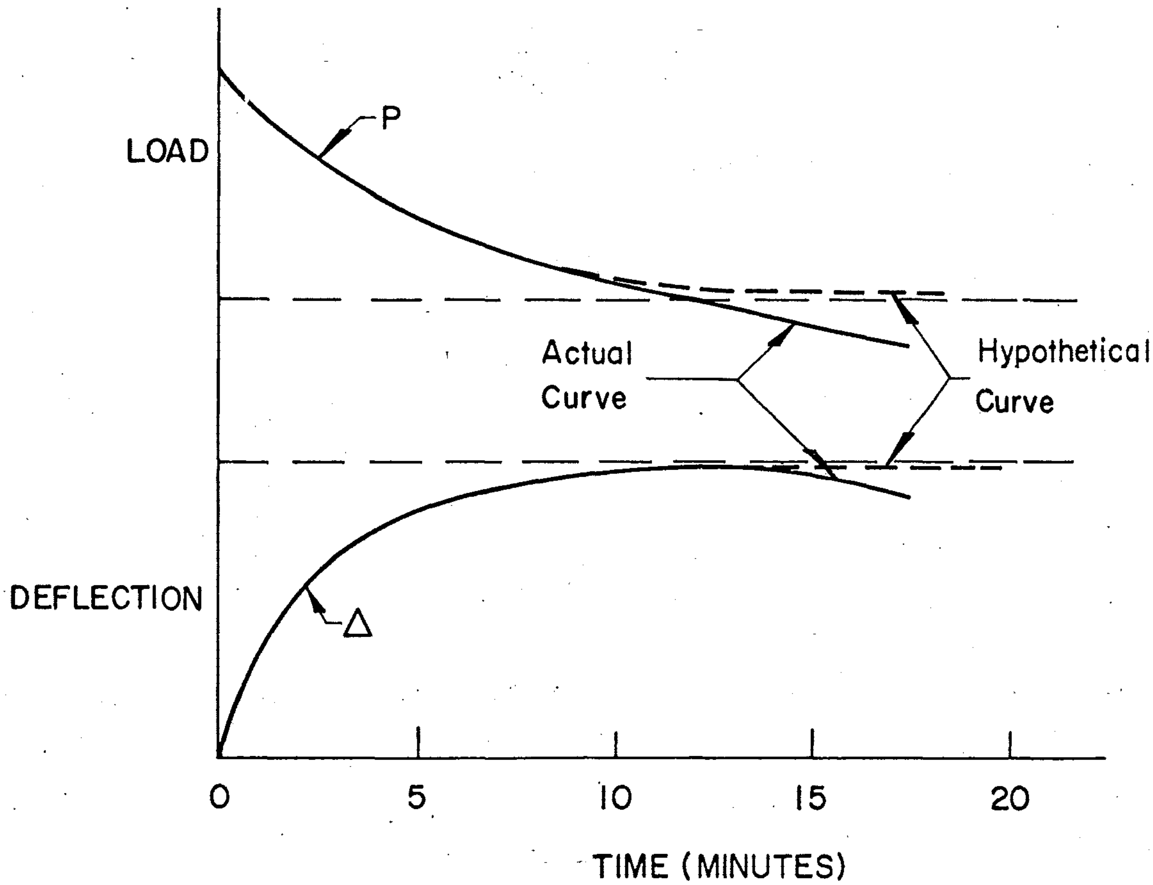


Fig. 23 Actual Load-Relaxation Curves

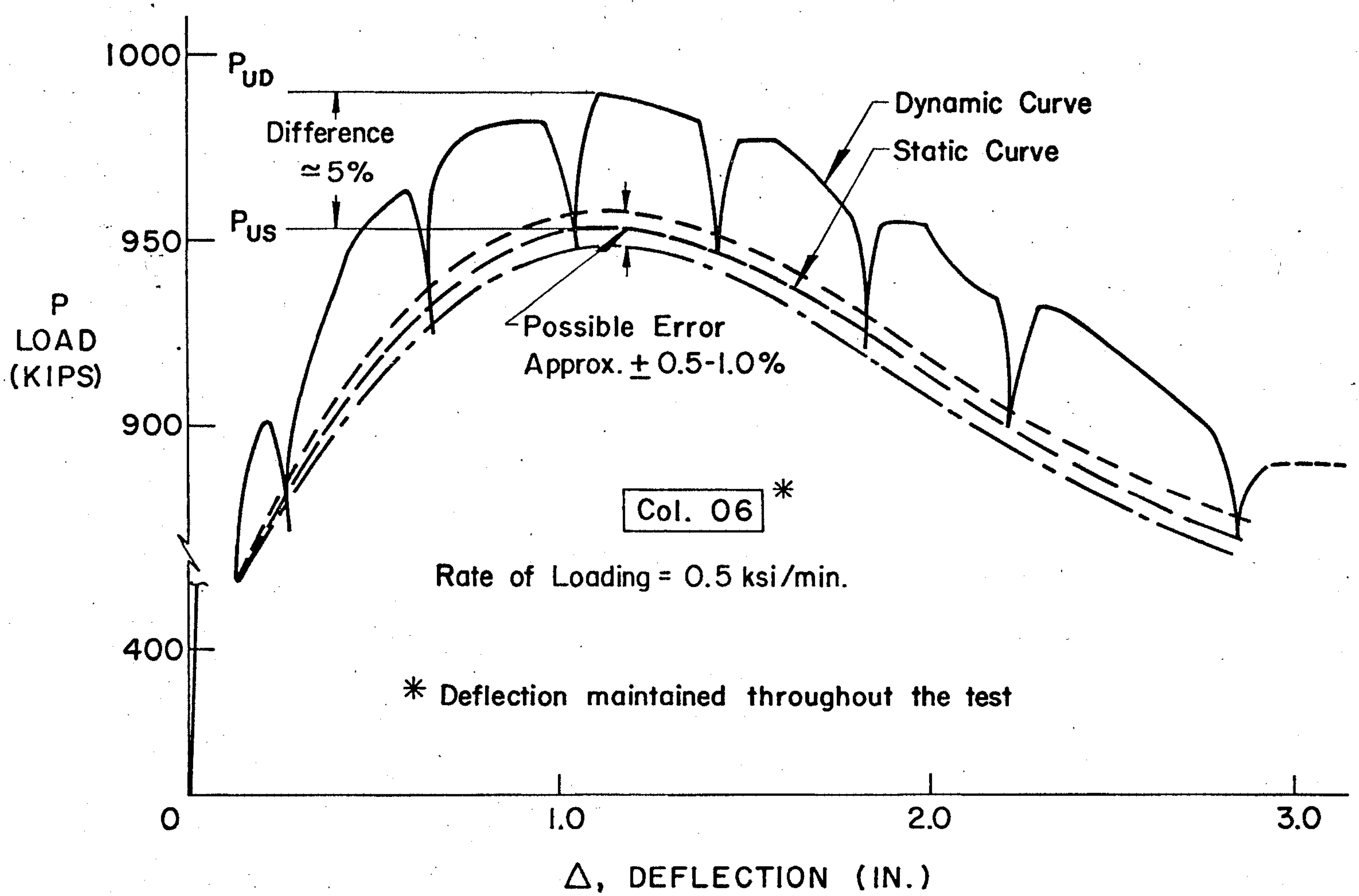


Fig. 24 Range of Error Using the "Vertical" Approach for Static Curve

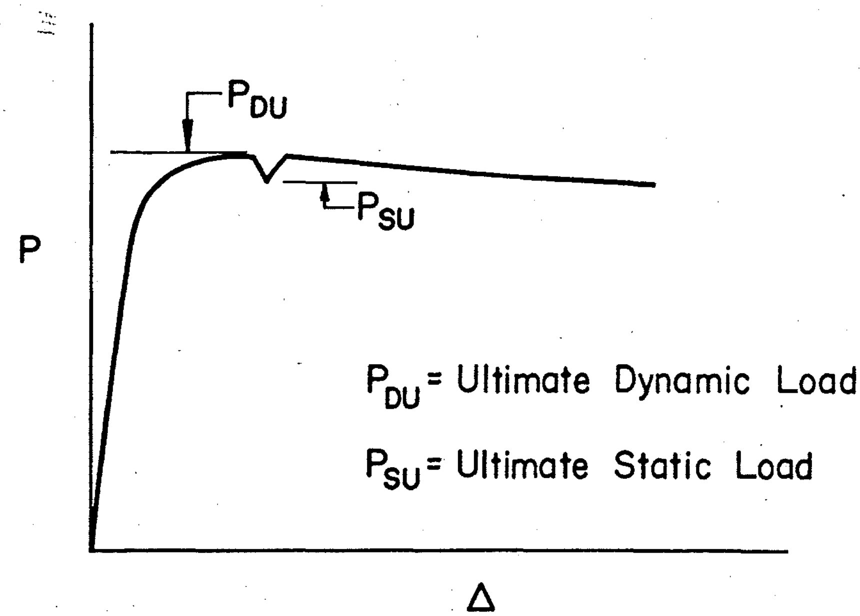


Fig. 25 Typical Load-Deflection Curve for the Proposed Method

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