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OFFICE OF RESEARCH

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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 a procedure for the testing of centrally loaded steel columns. A detailed description is presented on the preparation of specimen, initial measurements, alignment, instrumentation, and the testing procedure. Also, a procedure for data analysis and evaluation of the results is presented.

The scope of this procedure is applicable to light and heavy columns of rolled shapes as well as built-up shapes. The column specimens may have pinned or flat end conditions.

1. INTRODUCTION

A column may be defined as a member subjected to compressive loads at the ends and whose length is considerably greater than its cross-sectional dimensions. Even though an extensive analytical and experimental study on column behavior has been conducted for more than two centuries, many factors make indispensable the experimental approach.

Experimental column strengths generally form a wide scatterband when strength is plotted against slenderness ratio. The scatter is due to initial out-of-straightness, eccentricities of load, residual stresses, and nonhomogeniety of the material. To understand column behavior, there is a need to isolate the effects of these factors.

In column tests, as in other stability tests, the response of a column is influenced by the loading device used. The common types of loadings are the gravity, deformation and pressure types. The load-deflection characteristics of each loading system are different. The oldest form of testing device used for columns was the gravity type. For such a system, the load-deflection characteristics are simple and can be represented by a series of straight lines parallel to the deflection axis. Later, the screw-type testing machine came into use. 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 capacities of loading machines became needed, the hydraulic-type testing machines were developed. Hydraulic machines in their present form are a recent development, but the use of hydraulic power in testing machines goes back to

1829[1]. Such loading devices, however, do not have easily defined load-deflection characteristics and depend on the properties of the hydraulic system, leakage, temperature and other factors. For all types of testing machines the experimental results are influenced by the rate of loading used, as well as by the characteristics of the machine.

It is common practice to plot deflections of the column as a function of the axially applied load. For the perfect column there would be no lateral deflection up to the critical load, but the experimental column will begin to deflect at the beginning of loading owing to various kinds of imperfections.

Measurements of the more important deflections and deformations are used to check theoretical predictions. The instrumentation for column tests has changed markedly in the past few years due to progress made on measuring techniques and data acquisition systems, and it is now possible to obtain automatic recordings and plotting of the measurements. Such recordings are to be more convenient than manual readings.

2. THE CENTRALLY LOADED COLUMN

2.1 Application

Pinned-end conditions are frequently used in column tests, in which case the critical stress is at the mid-height section, 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 only half the column length used for the fixed end condition. When using the pinned-end condition, however, it is necessary to provide special end fixtures. This may introduce some difficulties and considerable expense when testing columns of heavy shapes.

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.

2.2 Experiments on Columns

The experimental study of column behavior is conducted by treating separately the factors that cause the wide scatter band in test results. With regard to the effect of end condition of centrally loaded columns, the choice may be reduced to the two limiting conditions of end restraint. In testing columns under the fixed-end condition, there may be a problem of determining the degree of end fixity since complete fixity cannot be attained in reality. Also, the amount of end fixity and, thus, the effective length of the column may not be a constant but a function of the applied load. This may be due partly to the fact that the rigidity of the testing machine varies with the applied load and partly to the indeterminate nature of the stress distribution at the end, particularly at the range of loads where the material starts to yield. The initial out-of-straightness may also be another factor to cause variation in the effective length. These problems are not usually as severe if pinned-end conditions are used, since the critical stress exists at about the mid-height section.

With regard to the other factors causing wide scatter of the experimental results, further discussion is given in later sections.

2.3 End Fixtures

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 strength investigators are shown in Fig. 1[(2)]. The end fixtures differ from each other in that they are either "position-fixed" or "direction-fixed" at the ends[(3)]. The other basic differences are with respect to their maximum carrying capacity and effective length. Detailed descriptions on the historical accounts and characteristic features of the basic types of end fixtures (Fig. 1) are given in Refs. 2 and 3.

Probably the best way to reduce friction, for end fixtures of high capacity, is by the use of a relatively large hardened cylindrical surface bearing on a flat hardened surface. Even if an identation should occur under heavy load, rotation will be virtually frictionless. 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[4]. When using a cylindrical fixture, the column acts pinned-end about one axis (usually the minor 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. Description of the fixture and its performances as a "pin" is given in Ref. 4.

Another type of end fixture, used in testing columns with round-end conditions at the Aluminium Research Laboratories, is shown in Fig. 1d. The fixture is spherically seated and has a capacity of 300,000 pounds[5]. The essential features of these fixtures are the supporting block in which a recess has been provided to allow oil under pressure to seep through the spherical bearing surface of the platen. Provision is made for collecting oil after passing between the spherical surfaces, and for returning it to the reservoir of the pump.

3. COLUMN TEST PROCEDURE

3.1 Preparation of Specimens

The column specimen is cut from a straight portion of the fabricated column length in order to minimize the initial out-of-straightness of the specimen. Both ends of the specimen are milled and base plates are then welded by matching the geometric center of the specimen to the center of the base plate. For columns initially not straight, the milled surfaces may not be parallel to each other, but will be perpendicular to the centerline at the ends 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. For small deviations the leveling plates at the sensitive cross-head of the testing machine may be adjusted to improve the alignment. The tolerance in deviation must not exceed the range of adjustments of the leveling plates of the particular testing machine.

3.2 Initial Measurements

The variation in cross-sectional area and shape and the initial out-of-straightness will affect the column strength. Thus, initial measurement of the geometric characteristics of a column is an important step in column testing.

Cross-sectional measurements are obtained to determine the variation between the actual dimensions of the section and the specified nominal dimensions. Measurements of cross-sectional dimensions for wide flange type shapes shown in Fig. 3 are taken at different points (the quarter points of the column length are recommended). In the final evaluation the actual cross-sectional area is used as calculated from the actual measured dimensions. A check on the calculated area may be made by weighing the column.

The initial out-of-straightness of each specimen is measured at nine levels, each spaced at one-eighth of the column length. Measurements are taken in the two principal axes.

Figure 4 shows a method of measuring initial out-of-straightness about both the minor and major axes of a column. Readings are taken from a theodolite (stationed in line with the column and near one of the ends) on a strip scale mounted to a movable carpenters frame square. The out-of-straightness 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 the final value to be used. The out-of-straightness about the major axis is obtained from two readings - one with reference to each flange surface. These values are used later in the evaluation of the test results.

3.3 Alignment

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 centrally loaded columns. The first method is to align the column carefully such that the absolute maximum load which the column can carry can be attained. The alignment is performed under load until a certain stress criterion is satisfied.

In the second method, no special attention is given to the stress condition, except for a careful geometric alignment. Geometric alignment is performed with respect to some defined reference point on the cross section. The specific reference point will be defined later. The method of geometric alignment is recommended since it is, in general, simple and time saving. The end plates can easily be centered with reference to the centerline of the testing machine[6].

The reference point on the cross section depends on the form of the shape. For wide flange type shapes the best centering point is with respect to the center of 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 the flanges[6].

3.4 Instrumentation

The most important records needed in column testing are the applied load and the corresponding lateral displacements about the minor and major axes, strains at characteristic points, end rotations, angles of twist, and over-all shortening. A typical column test set-up and the required instrumentation are shown in Fig. 5.

Lateral deflections about both axes are automatically recorded using potentiometers attached at quarter points of the column (more points may be used for longer columns). Lateral deflections about the minor axis may also be measured from strip scales attached to the column and read with a theodolite.

Strains are measured using electric resistance strain gages. For ordinary pinned-end column tests it is sufficient to mount four strain gages at each end and eight at mid-height level. For long columns, it may be necessary to mount four more strain gages each at the quarter- and three quarter points. In the fixed-end test condition more strain gages are mounted below and above the quarter- and three-quarter levels. This is to determine the actual effective-length of the column by locating the inflection points using the measurements taken from the strain gages.

End rotations are measured using either mechanical or electrical rotation gages. Mechanical rotation gages[7] are used by mounting the level bars on support brackets fastened to the base plate and the top plate of the column (Fig. 6). 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. 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. 6). It has been shown[8] that the strain at any location of the strip is proportional to the end rotation.

The angles of twist are determined at mid-height and at the two ends by measuring at each level the differences in lateral deflections. For better accuracy, measurements may be taken at points located at a further distance from the column such as the ends of two rods attached transversely on the adjacent sides of the column.

The overall shortening is determined by measuring the movement of the sensitive crosshead using a dial gage or potentiometer.

Hot-rolled steel column specimens with original mill scale are whitewashed with hydrated lime. During testing, the whitewash cracking pattern caused by the flaking of the mill scale gives an indication of the progression of yielding.

3.5 Testing Procedure

After the alignment is completed, the test is started with an initial load of 1/20 to 1/15 of the estimated ultimate load capacity of the column. This is done to preserve the alignment established at the beginning of the test. At this load all measuring devices are adjusted for initial readings.

The load is applied at a rate of 1 kip per square inch per minute and the corresponding deflections are recorded instantly. This rate is established when the column is still elastic. The dynamic curve is plotted until the ultimate load is reached immediately after which the "static" load is recorded. After the static load is recorded the test is resumed using the valve setting established originally (using the same "strain rate") until the desired configuration has been attained. A sketch of the complete load-deflection curve resulting from such a test will be similar to that shown in Fig. 7.

The "static" point is obtained by maintaining the cross-head movement until the applied load is stabilized. The criterion for load stabilization is dependent on the type of testing machine being used.

Basically, there are two types of testing machines: the mechanical and the hydraulic type. For a mechanical testing machine the criterion can easily be satisfied since the cross-head can be fixed in position. For the hydraulic type, however, it is rather difficult to maintain the position of the crosshead since factors such as leakage of oil and change in oil temperature are always inherent during normal working conditions. In such cases, the criterion is a simulation of that used for a mechanical testing machine; that is, for no movement of the cross-head as controlled by the loading valve, the load is allowed to stabilize until there is no further decrease in load.

The criterion is best checked by plotting the load change (or the crosshead movement) versus the time of stabilization. Under normal conditions an asymptotic load (Fig. 8) may not be observed, nevertheless, a fair estimate of the asymptotic load can be made without much loss in accuracy. This load is known as the "static" load since it is determined at "zero" rate of loading. Usually, a time interval of 10 to 15 minutes is satisfactory[6].

4. TEST RESULTS

4.1 Presentation of the Data

The behavior of test columns under load is determined with the assistance of measurements of lateral deflections at various levels along the two principal directions, rotations at the ends, strains at characteristic points, angles of twist, and the column shortening. These measurements are used to check theoretical predictions. The results of the test are best presented in diagrammatic form. Such plots are shown in Figs. 9 through 14.

In Fig. 9 a typical plot of the deformed shape of the column is shown where the deflection components are measured along the minor and the major axes. These data are used to determine the reduction in column strength due to initial out-of-straightness.

Figure 10(a) shows the mid-height load-deflection curve of the column along the minor axis, and Fig. 10(b) along the major axis. The load-deflection curves give the most significant data of the column test.

A plot of the strains at mid-height of the column measured with the strain gages is shown in Fig. 11. This plot may be compared with the stub column test result to detect any unusual behavior of the column.

End rotations of the column as measured by both mechanical and electrical rotation gages are shown in Fig. 12. The results may be checked by comparing with the lateral measurements along the length of the column (Fig. 10).

The angles of twist at mid-height and at the two ends are shown in Fig. 13. The values are determined by using the differences in lateral deflections of the flanges about the weak axis.

Figure 14 shows a typical plot of the load and the corresponding overall shortening of the column.

The progression of yielding of the cross section is detected from the cracking of the whitewash. The subsequent development of the whitewash cracks may be recorded in order to indicate the yielding pattern during loading. Whenever local buckling or any other phenomena occurs during the test it should be recorded.

4.2 Evaluation of Test Results

Evaluation of the test results may be performed by comparing the experimental load-deflection behavior and the theoretical prediction. A preliminary theoretical prediction can be made based on simplified assumptions of material properties, residual stresses and measured initial out-of-straightness. The prediction may be improved if the actual residual stresses and the variation in material properties are used in the analysis.

5. ACKNOWLEDGMENTS

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Thanks are due to Mrs. Sharon Balogh for the preparation of the drawings and to Ms. Shirley Matlock for her care in typing the manuscript.

6. FIGURES

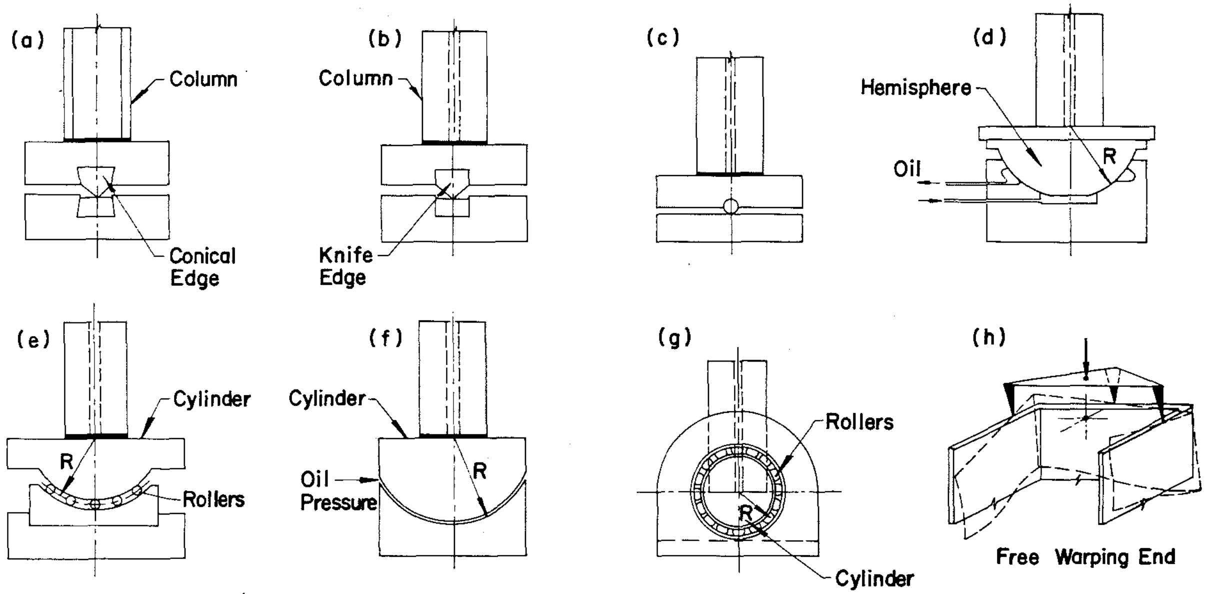


Fig. 1 Basic Types of End Fixtures

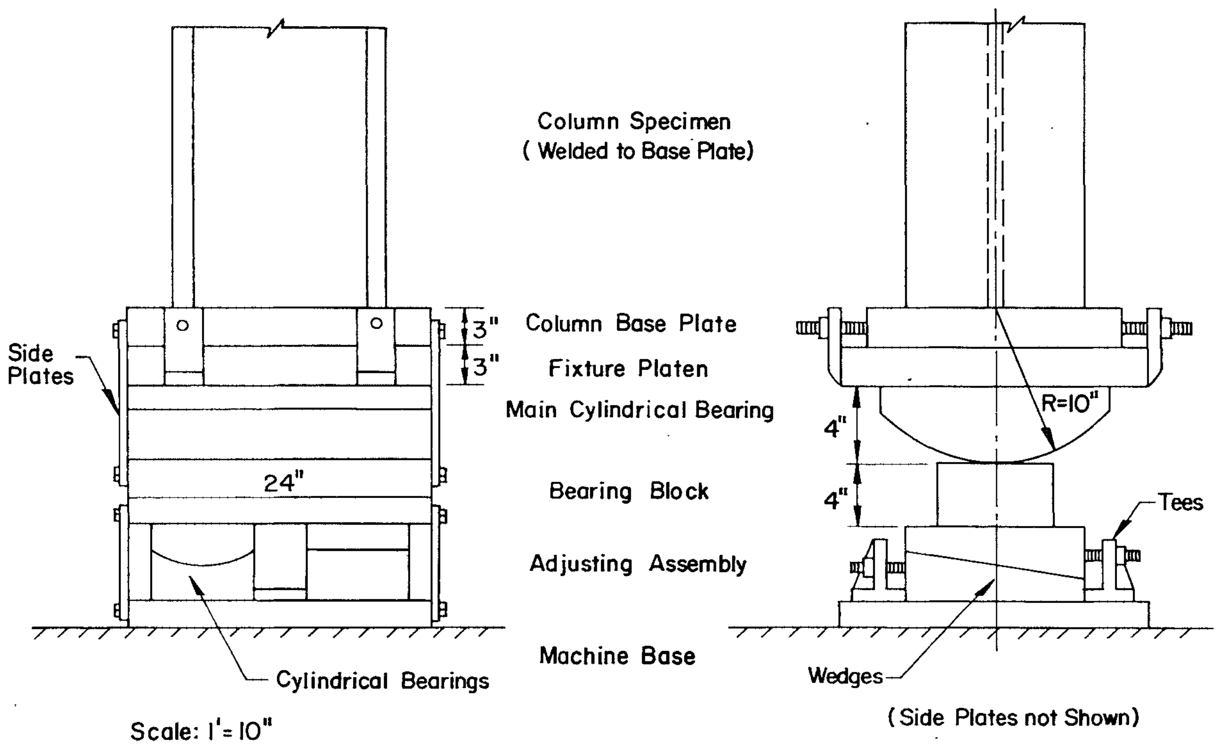


Fig. 2 Standard Column End Fixture at Fritz Engineering Laboratory (Capacity=2.5 Million Pounds)

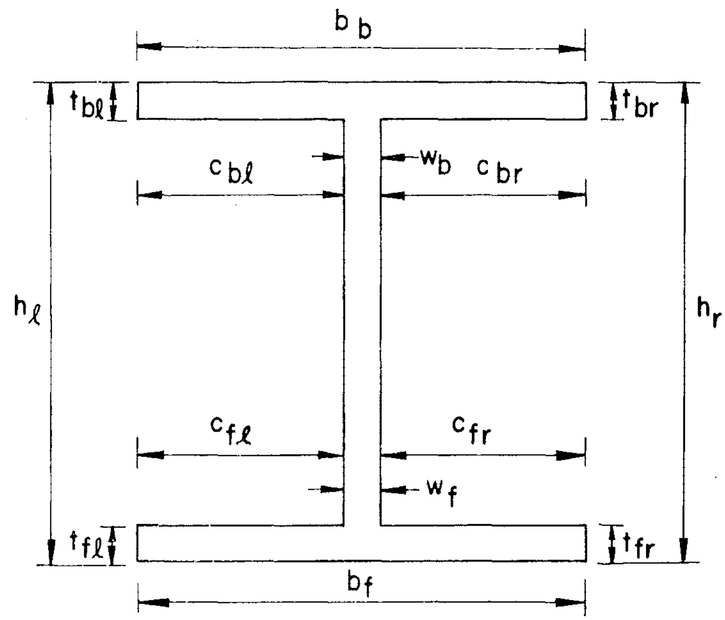


Fig. 3 Required Measurements of Cross-Sectional Dimensions to Determine Actual Shape and Area

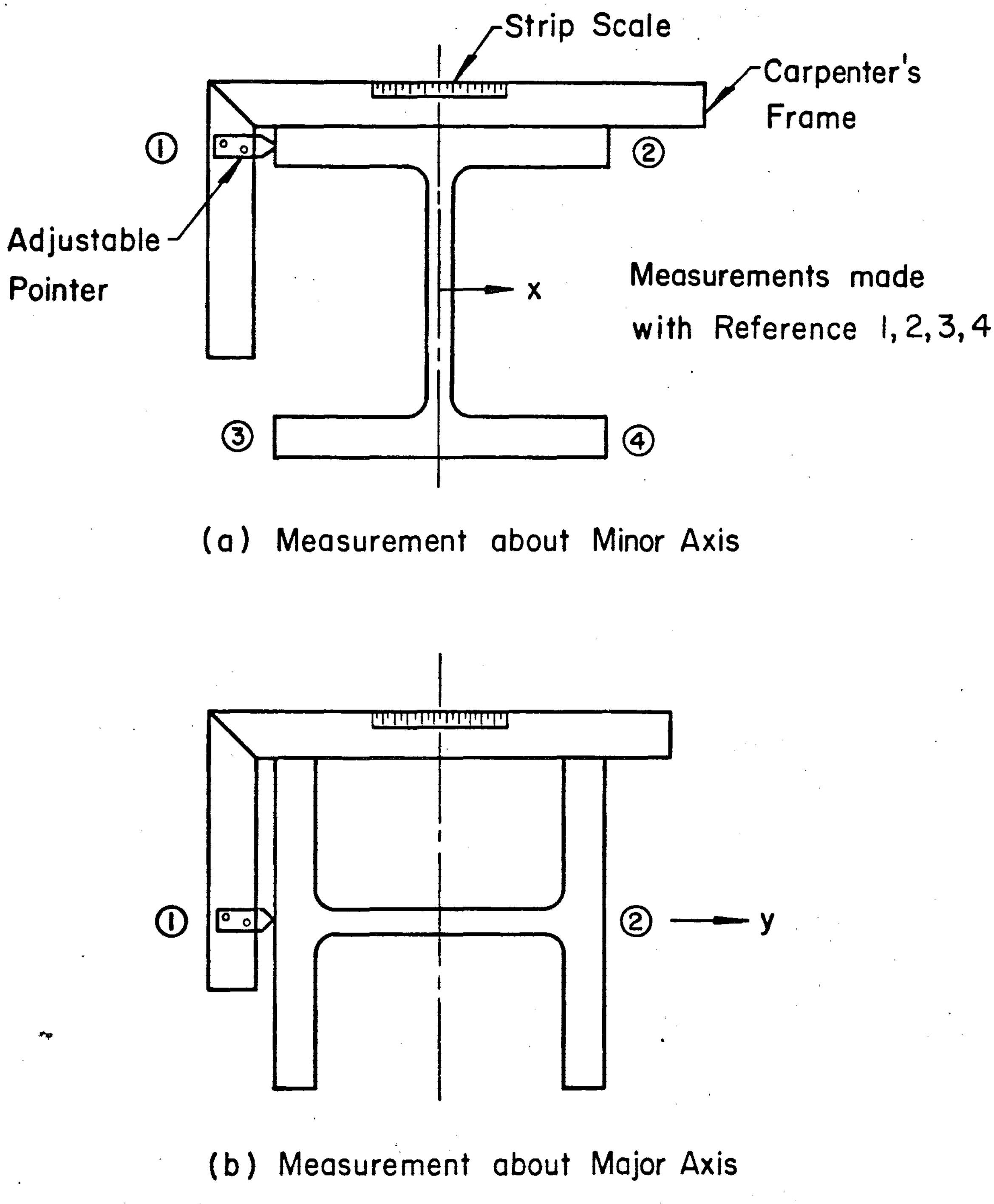
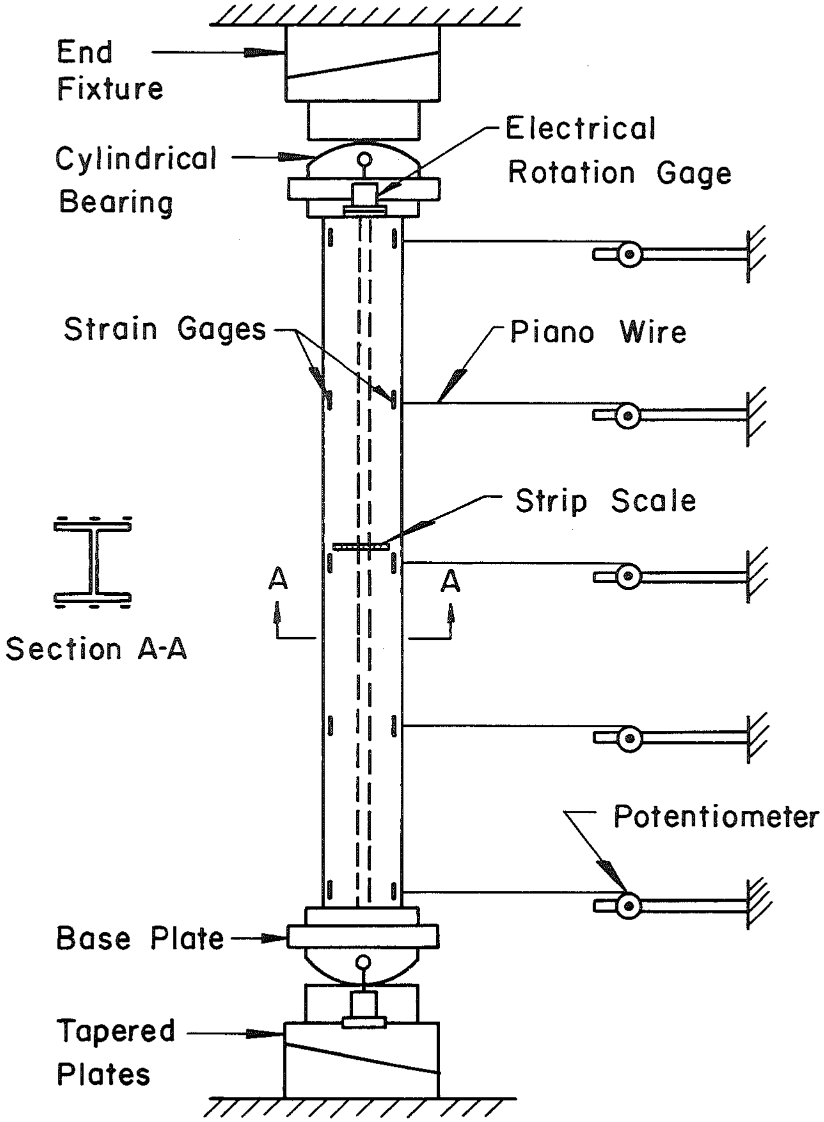


Fig. 4 A Method for Measuring Initial Out-of-Straightness of Columns



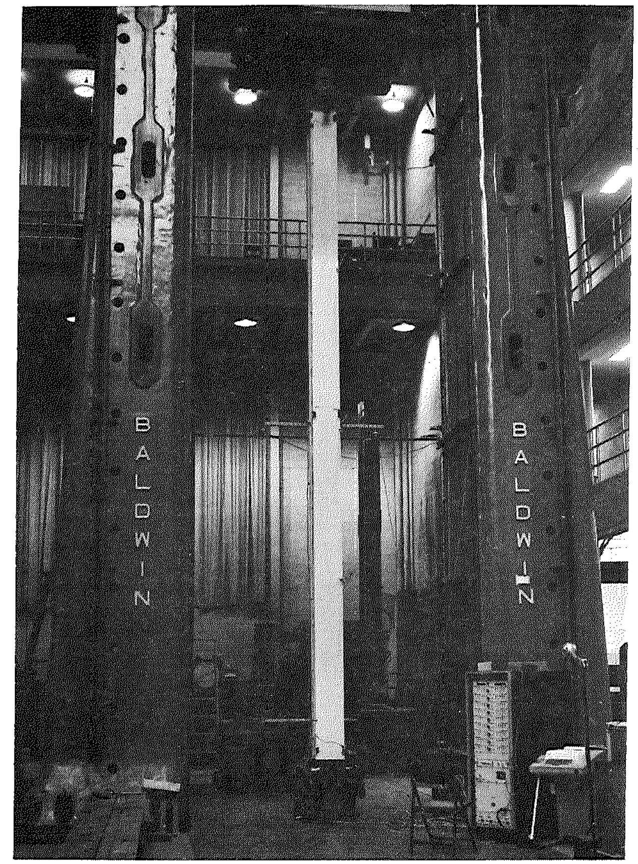
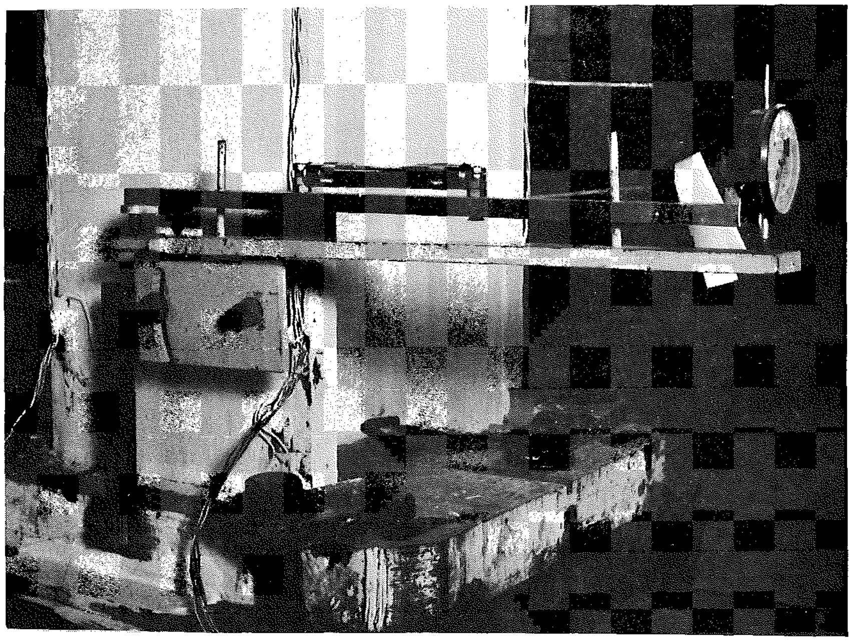
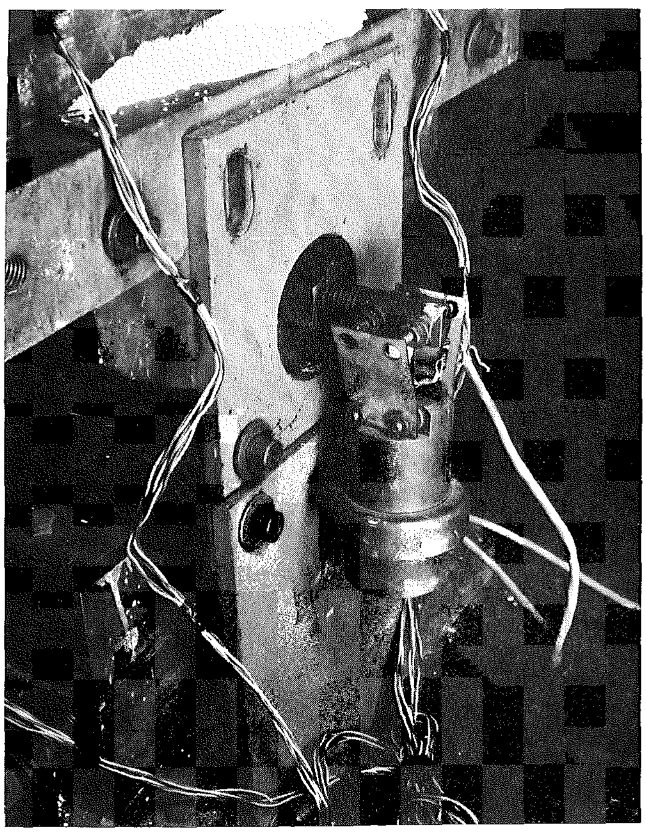


Fig. 5 Set-up for Column Testing



(a)



(b)

Fig. 6 Rotation Gages
(a) Mechanical, (b) Electrical

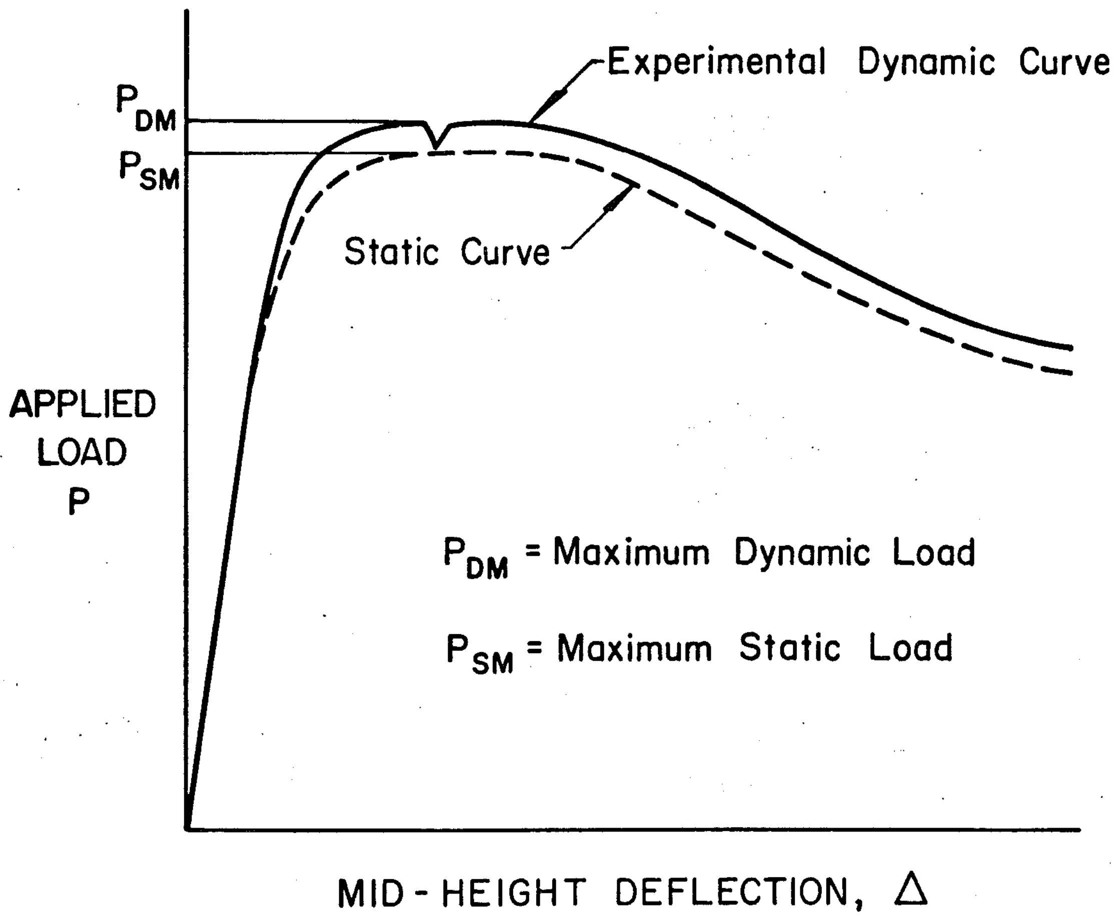


Fig. 7 Typical Load-Deflection Curve of Column

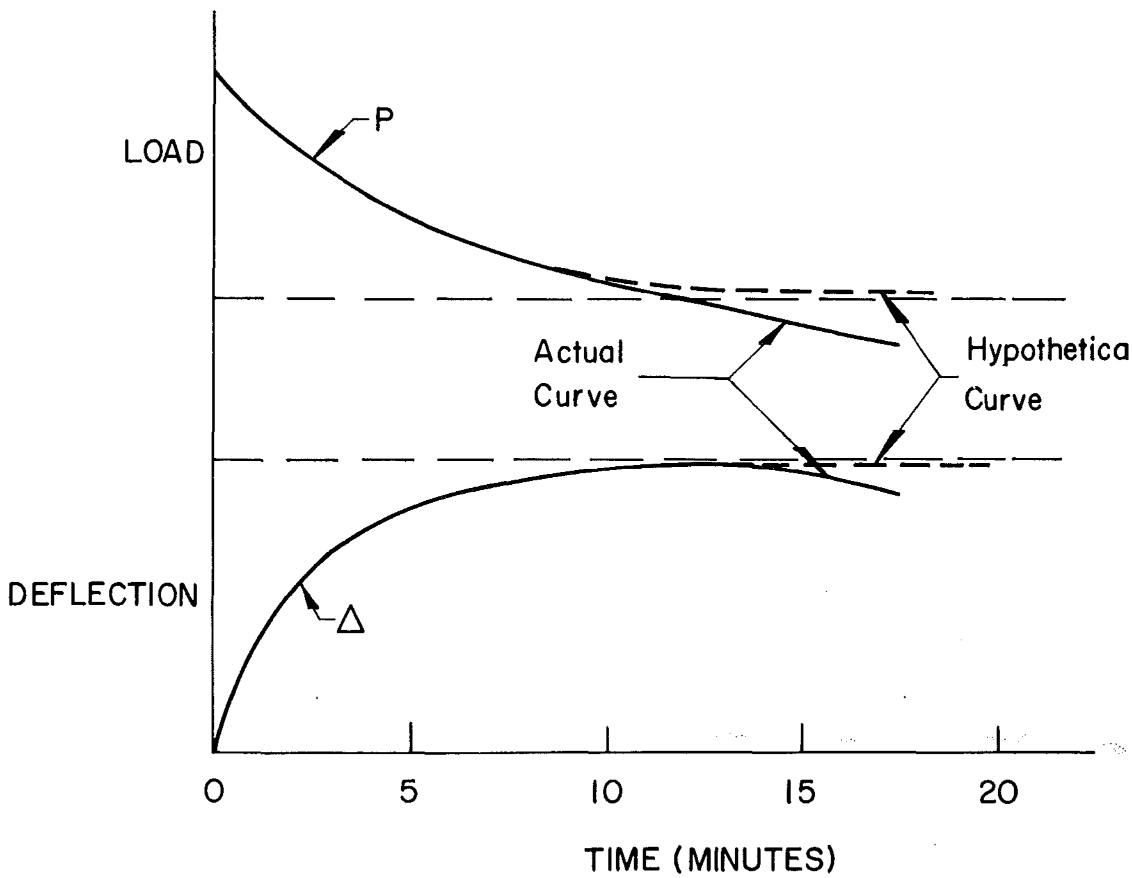


Fig. 8 Actual Load-Relaxation Curves

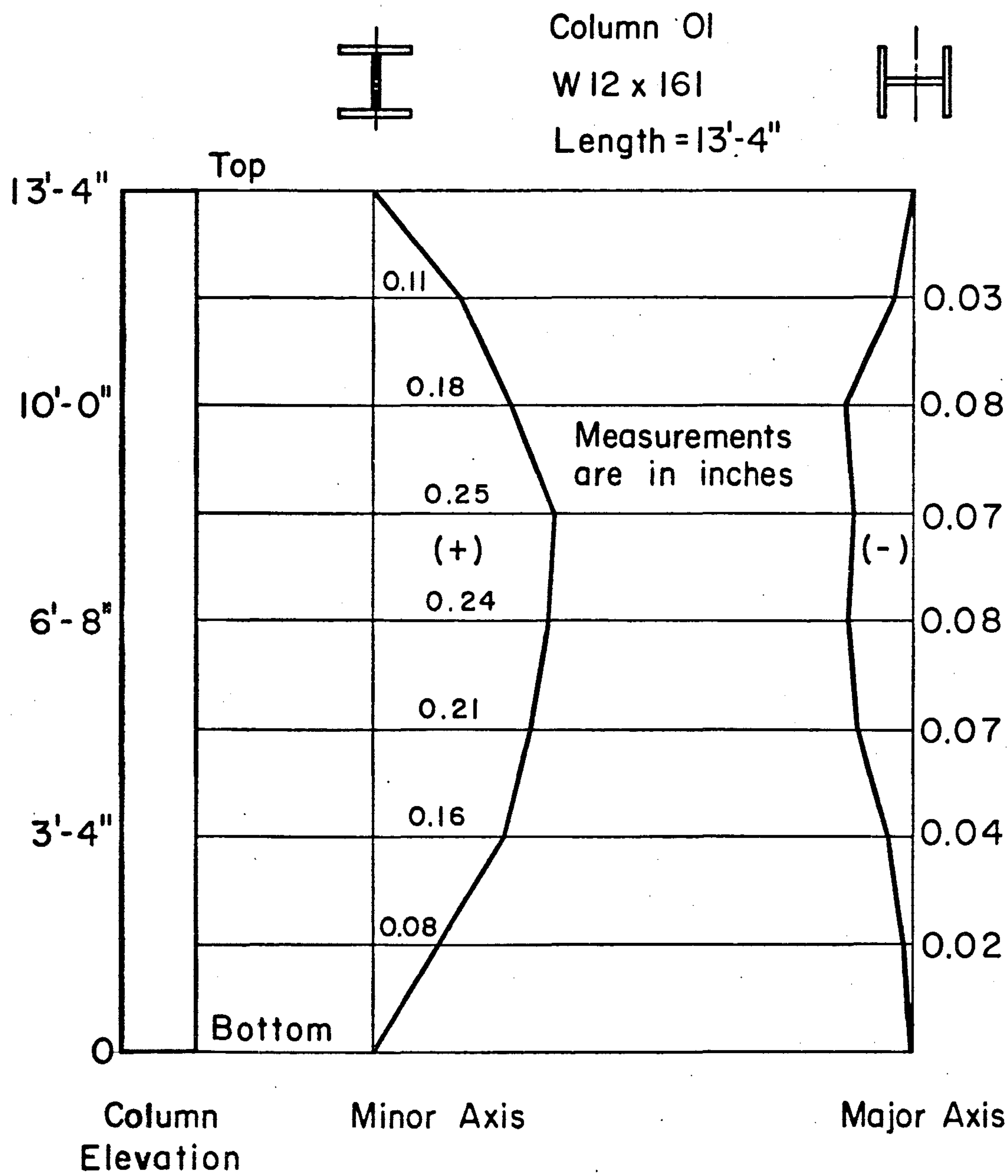


Fig. 9 Initial Out-of-Straightness about the Principal Axes of the Column

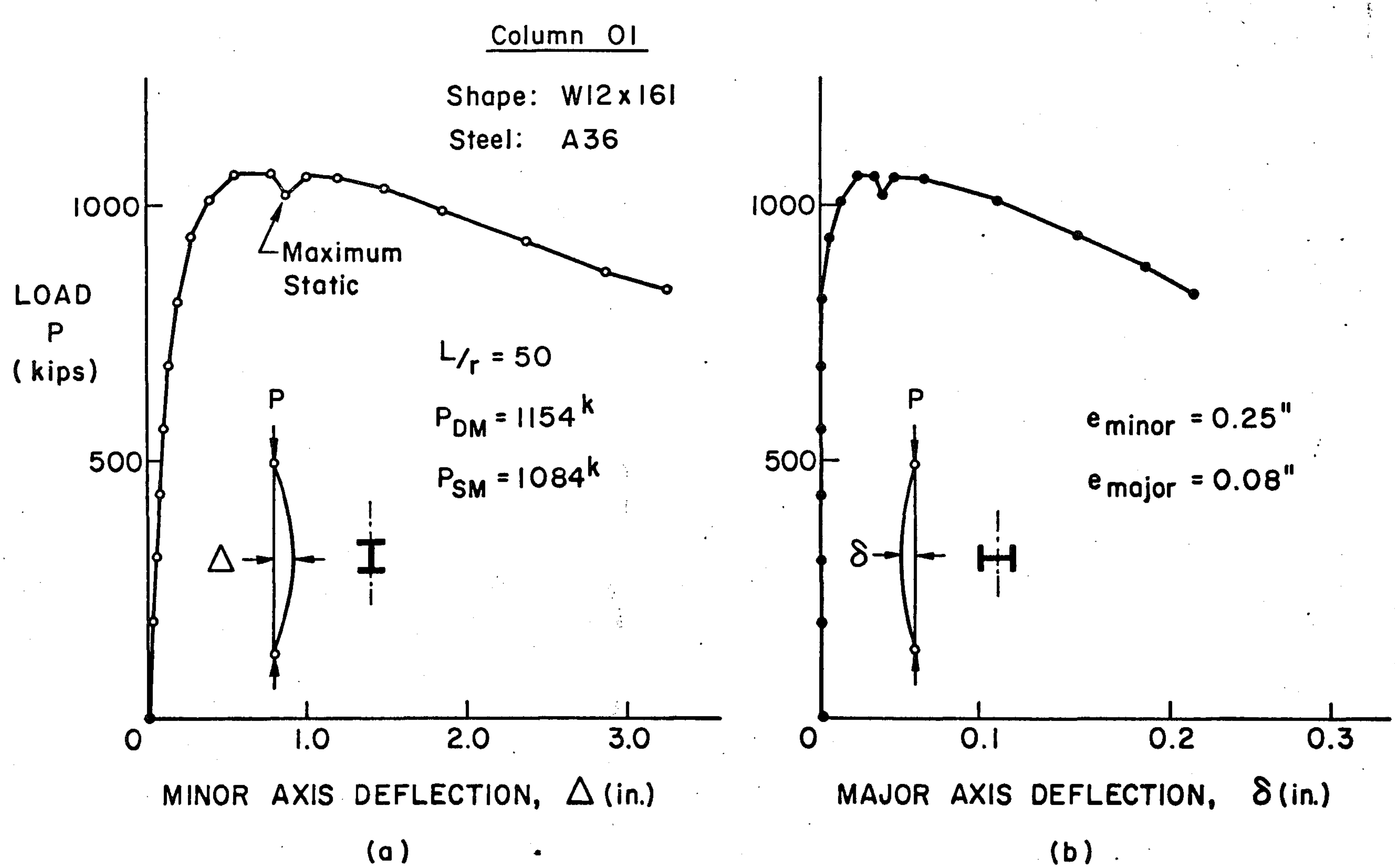


Fig. 10 Load-Deflection Curves

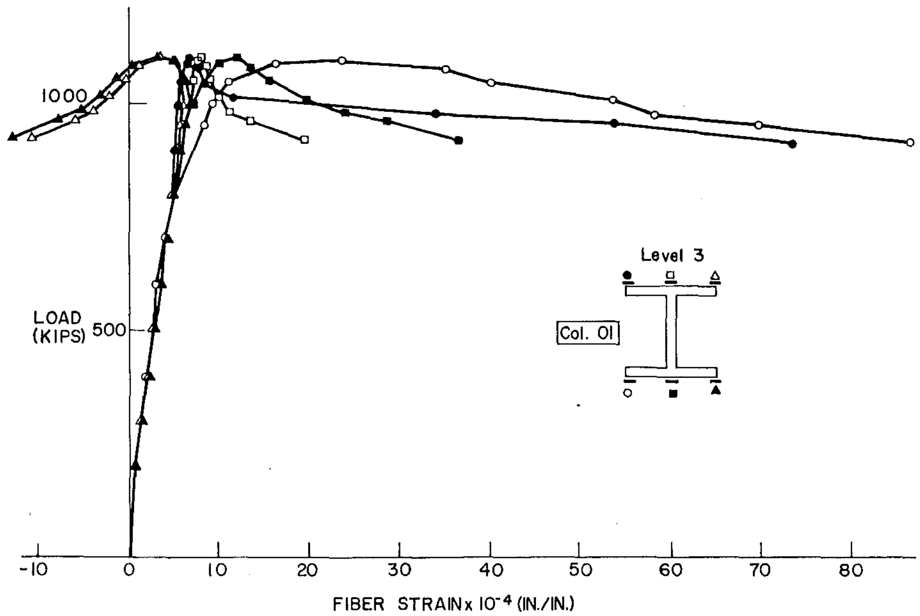


Fig. 11 Strain Measurements at Mid-Height Section Using Strain Gages

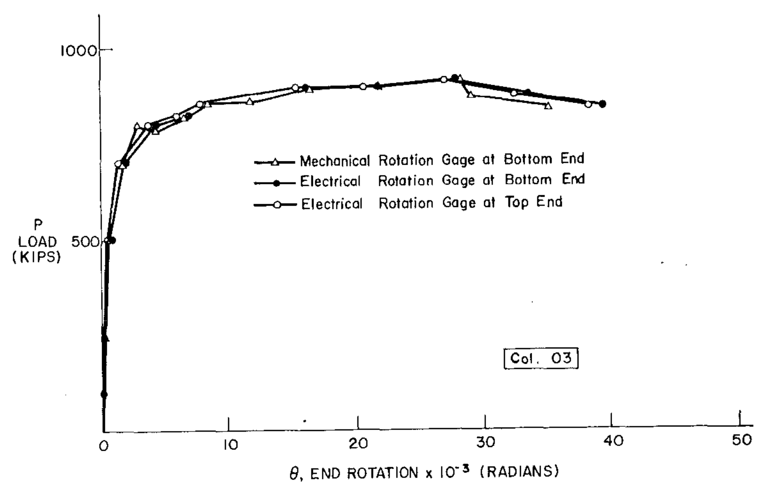
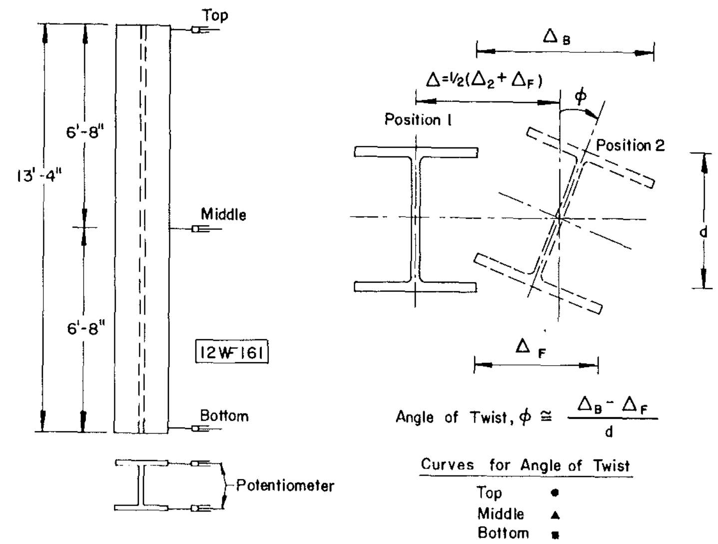


Fig. 12 End Rotations Using Mechanical and Electrical Rotation Gages



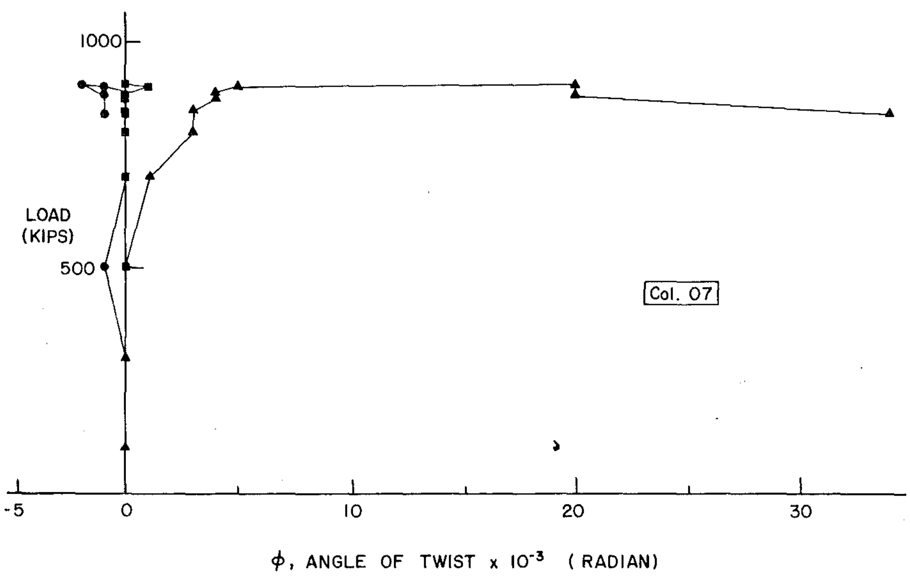


Fig. 13 Angles of Twist at Three Levels

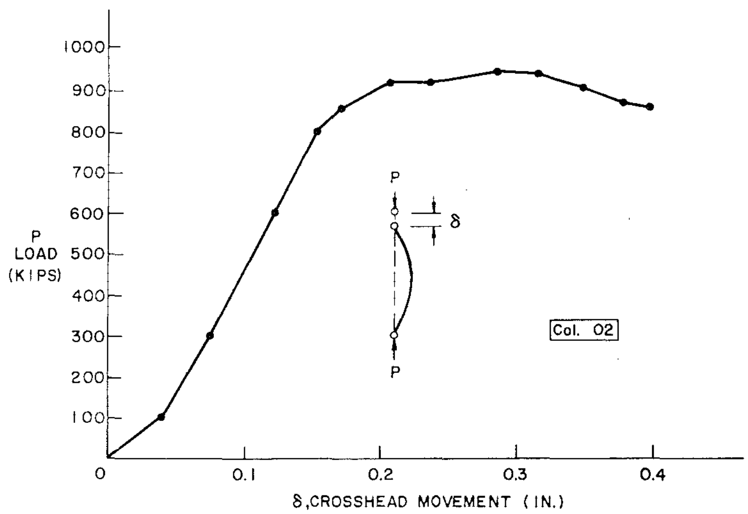


Fig. 14 Load Versus Overall Shortening Curve

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