On the behavior of a heavy steel column

ON THE BEHAVIOR OF A HEAVY STEEL COLUMN

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ABSTRACT

This report presents a theoretical and experimental investigation of the behavior and the strength of a heavy shape column built up from oxygen-cut plates. The theoretical part of the analysis includes two-dimensional in-plane column investigations by the tangent modulus concept and by the load-deflection approach, and a three-dimensional biaxial bending column analysis. The effects of residual stress, yield strength variations over the cross section, and initial out-of-straightness about the two principal axes, are considered in the theoretical analysis.

To obtain experimental data on the behavior and the strength of heavy built-up columns, a complete experimental investigation was conducted on one particular shape--H23x681, ASTM 36 steel. The experimental part includes the measurement of the yield strength levels and residual stresses over the cross section, a stub column test, and a full-size column test. The column tests were conducted at the National Bureau of Standards, Gaithersburg, Maryland in their 12-million pound testing machine.

Failure of the column was observed in biaxial bending with excessive bending about the major axis. The results of the column test and the theoretical prediction based on a three-dimensional biaxial bending column analysis are compared and good agreement is observed. The need for the biaxial bending analysis for centrally loaded heavy columns built up from flame cut plates is attributed to the particular pattern of residual stress distribution as well as to the initial out-of-straightness about the two principal axes which are inherent in such columns.

1. INTRODUCTION

At present, the design of heavy shape columns does not differ from that of small and medium-size shapes. Very little information is available on the strength and behavior of heavy columns, yet they are used extensively, for instance, in high-rise buildings, in major bridges, and in off-shore structures. The major problems associated with the design of heavy columns are the lack of data on residual stresses, yield strength variation over the cross section, and initial geometric imperfections of the columns.

The AISC column formula [1] is based on the CRC basic strength formula [2] which is developed from studies of small and medium-size shapes. Data for heavy column shapes have not been included in the strength formulas. Consequently, there exists a need for design rules that are applicable to heavy shape columns.

An extensive research program is currently underway at Lehigh University on residual stresses in heavy welded plates and shapes. A significant portion of the experimental phase--on the measurement of residual stresses in heavy shapes--has been reported in Refs. 3 and 4. Using these results, the theoretical strength of heavy columns built up from flame-cut plates can be predicted, and have shown an increase in strength when compared with lighter welded members and their rolled counterparts [3]. However, there are no full-size heavy column test results presently available to give experimental verifications.

This report presents a comprehensive experimental investigation performed on one particular shape--H23x681, ASTM A36 steel--whose slenderness ratio is within the range normally encountered in practice for such members. Failure of the column was observed in biaxial bending with excessive bending about the major axis. The results of the column test and the theoretical prediction based on the analysis of biaxially loaded columns are compared and good agreement is observed. The need for the biaxial bending analysis for centrally loaded heavy columns built up from flame-cut plates is attributed to the particular pattern of residual stress distribution as well as the initial out-of-straightness about both axes.

2. SCOPE OF TEST PROGRAM

Specimen

Heavy shapes are available in different steel grades and cross sectional forms. Rolled shapes are presently available to W14x730, the so-called "jumbo" shape. When the strength of the available rolled shape is insufficient for a particular application, the column may be strengthened by welding additional plates to it. Alternatively, and perhaps more conveniently, a heavy shape can be fabricated by welding together component plates; for instance, three plates can form an H-shape and four plates a box-shape. Heavy tubular columns, used extensively in offshore structures, are usually prepared from single plates. The residual stresses in such shapes are built up as a consequence of a superposition of residual stresses developed in the various phases of manufacturing and fabrication.

Herein, a comprehensive experimental investigation for one particular heavy welded shape, H23x681, is presented. It is the heaviest shape ever tested in column tests. The tests were performed in the newly installed 12-million pound capacity testing machine at the National Bureau of Standards, Gaithersburg, Maryland.

Fabrication

The test specimen was fabricated according to AWS specifications [5] by steel fabricators following the normal practices and procedures using automatic oxygen-cutting and submerged arc-welding equipment. The component plates were first obtained by oxygen-cutting from larger base metal plates of ASTM A36 steel. The H23x681 shape was welded using two tandem electrodes. Thus, it was possible to deposit the fillet welds simultaneously in one pass. After the first flange and web were joined together, the T-shape was turned over and the other flange was welded to form the final H-shape. A summary of the pertinent welding data is given in Table 1. A more detailed account of the fabrication of the H23x681 shape is given in Ref. [3]

Table 1 WELDING DATA FOR FABRICATION OF TEST SPECIMEN

	Type	Voltage (ohm)	Current (amp)	Speed (in/min)
1st Flange	DC	26	700	15
	AC	31	530	15
2nd Flange	DC	26	710	18
	AC	30	530	18

Preparation of Test Specimen

Figure 1 shows the layout for the preparation of the test specimens to carry out the supplementary tests and a full-size column test. The test pro-

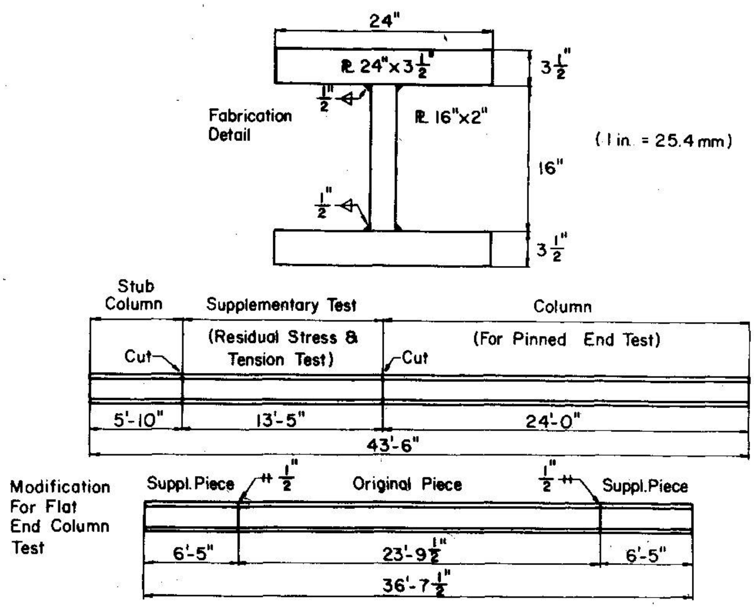


Fig. 1 Schematic Layout of Test Specimens

gram consists of: 1) Tension coupon tests; 2) Residual stress measurement; 3) Stub column test; 4) Full-size column test.

The column specimen was originally prepared to be tested under a pinned-end condition. At a later stage, it was decided to test the column under the flat-end condition to simulate fixed-end conditions. This change was made due to the limitations of the capacity of the available end-fixtures, and the considerable expense involved in preparing high-capacity end-fixtures. To maintain the same order of magnitude of slenderness ratio originally intended, the column was made longer by welding to it specimens at the two ends. The details of this modification are shown in Fig. 1.

3. SUPPLEMENTARY TESTS

Supplementary tests were conducted to determine the basic properties of specimens which are required to evaluate the theoretical column strengths. The following supplementary tests were performed:

Tension Coupon Tests

A total of twenty-four 2-inch gage length (ASTM A570) specimens were tested: fourteen from the flange and ten from the web. The specimens were cut at four different locations on the shape and five or seven specimens (from the web and flange, respectively) were taken across the thickness of each location (Fig. 2a). Results of the static yield strength defined by the stress at 0.005 strain are summarized in Fig. 2c. The recorded yield strength varies between 29.5 ksi (203.4 N/mm²) and 33.7 ksi (232.4 N/mm²) for the flange, and between 30.7 ksi (211.7 N/mm²) and 34.8 ksi (239.9

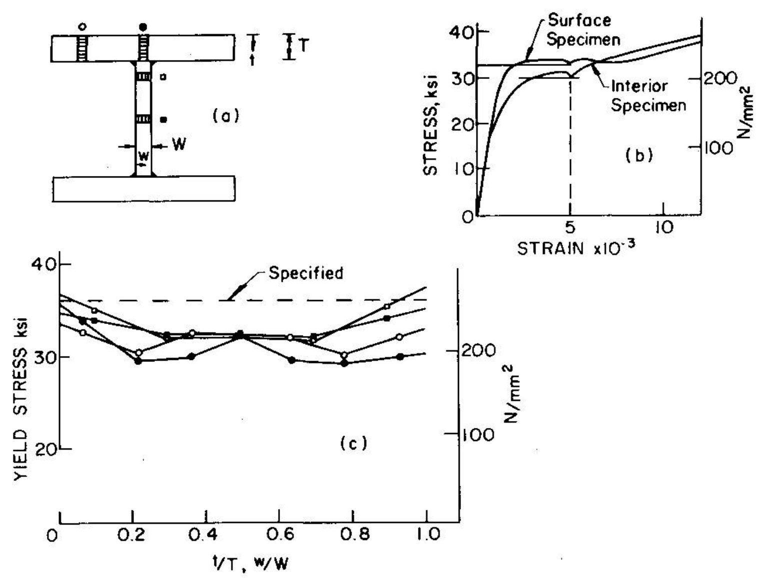


Fig. 2 Variation of Yield Strength for the H23x681

N/mm²) for the web. The average yield strengths are 31.0 ksi (223.7 N/mm²) and 32.5 ksi (224.1 N/mm²) for the flange and web, respectively. It was observed that the interior specimens had a lower yield strength and a gradual transition from the elastic to the strain hardening range, while the surface specimens exhibited a higher yield strength and a "flat" yield plateau and a marked onset of strain hardening usually observed in ASTM A36 tensile coupons (Fig. 2b) [6].

Residual Stress Measurement

The procedure used for the residual stress measurement was the sectioning method, involving longitudinal saw cuts across the width and through the thickness of the component plates. A detailed description of the sectioning method is given in Ref. [7].

The variation of residual stresses through the thickness was measured by employing the "slicing" technique. After the first set of saw cuts are performed (complete sectioning), additional gage points were laid along the

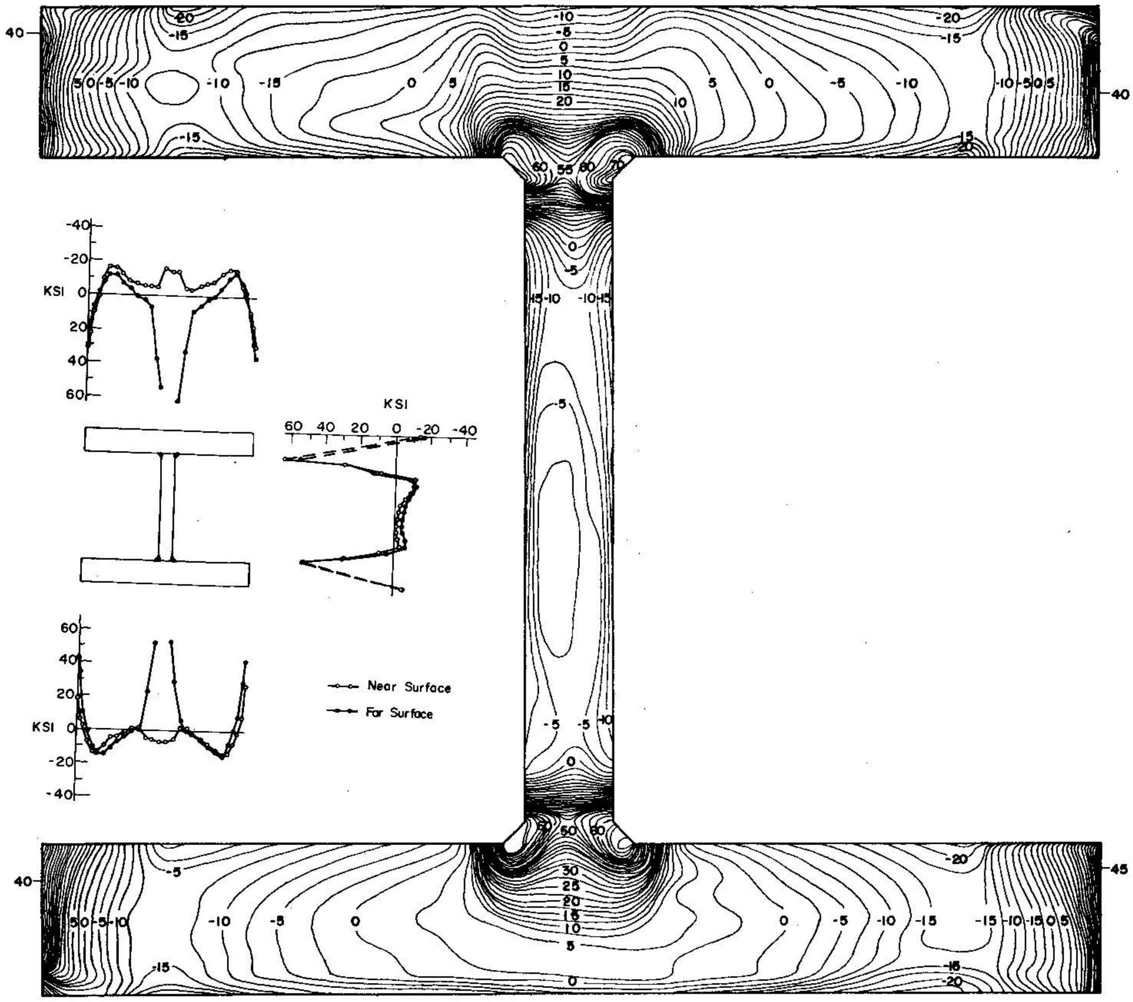


Fig. 3 Two-Dimensional Variation of Residual Stress in the H23x681 Shape

sides of the elements. New readings were then taken, followed by sawing the elements into strips across the thickness (slicing). The results for the H23x681 shape are shown in Fig. 3 where the residual stress distribution in ksi is represented in the form of an isostress diagram, that is, contour lines for constant stress [3].

<u>Stub Column Test</u>

The purpose of a stub column test is to determine the average stress-strain curve for the entire cross section, including the effects of residual stress and yield strength variation over the cross section. The most important data furnished by this curve is the tangent modulus. Hence, a smooth curve must be established above the proportional limit by taking test points at closer intervals.

The length of the stub column was selected such that it is sufficiently long to retain the original residual stress in the column but short enough to prevent any premature failure occurring before the yield load of the section is obtained. For the H23x681 shape considered, a length of 5 ft 10 in (1.78 m) was selected. The procedure used in testing the stub column is described in detail in Ref. [8].

After the specimen was aligned such that the deviation in strain did not exceed 5 percent of the average value, the specimen was loaded continuously with only one stop made at the yield plateau to determine the static yield strength level. A strain rate corresponding to a stress rate of 1.0 ksi/min (6.9 N/mm^2/min) was used throughout the test after it was established in the elastic range. The average stress-strain curve obtained from this test is shown in Fig. 4. The proportional limit, the elastic modulus, and the tangent modulus are the important data furnished by this curve.

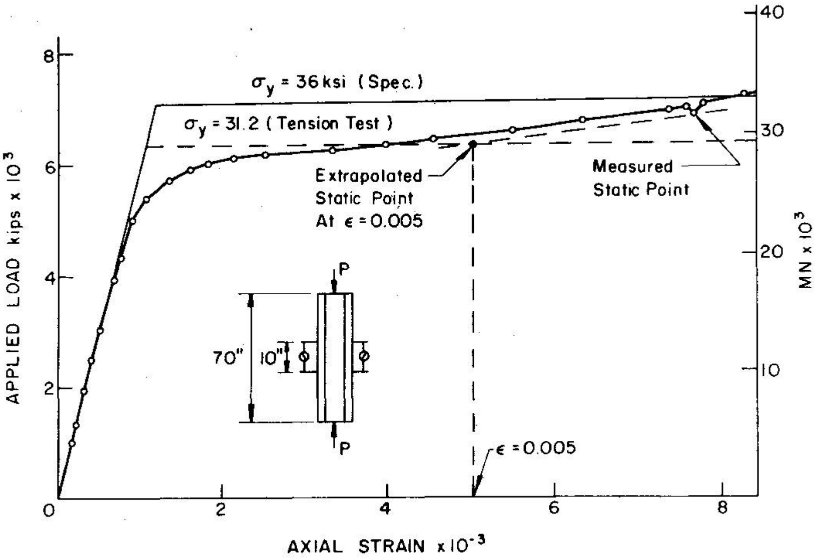


Fig. 4 Stub Column Test Result

Using the yield strength level criteria defined by the stress at 0.005 in/in strain [8], the static yield stress was found to be 31.3 ksi (216 N/mm^2), which indicates a close correlation to the weighted average yield stress determined by tensile coupons, 31.2 ksi (215 N/mm^2). The measured yield strength of the specimen was below the specified value of 36.0 ksi (248.2 N/mm^2).

4. COLUMN TEST

Pinned end conditions are frequently used in column tests, and, it is necessary to provide end fixtures for such a condition. For heavy columns, this condition introduces practical difficulties and considerable expense. Flat end conditions are, in comparison, easy to perform.

Theoretically, the effective length of a column tested in the fixed-end condition in one-half that of a pinned-end column. However, in testing columns under fixed-end conditions, there is a problem in determining the degree of end fixity since complete fixity cannot be attained in reality, since in effect, the column is usually tested in the flat-end condition. The amount of end fixity and, thus, the effective length of the column is not a constant but a function of the applied load. This effective length can be determined accurately by locating the positions of inflection points in the column test.

Column Testing

Prior to testing the column, initial measurements were taken of the geometric characteristics of the column specimen; these include the cross-sectional area and the initial out-of-straightness. Cross-sectional measurements were taken at five locations, at the ends, and at the quarter points

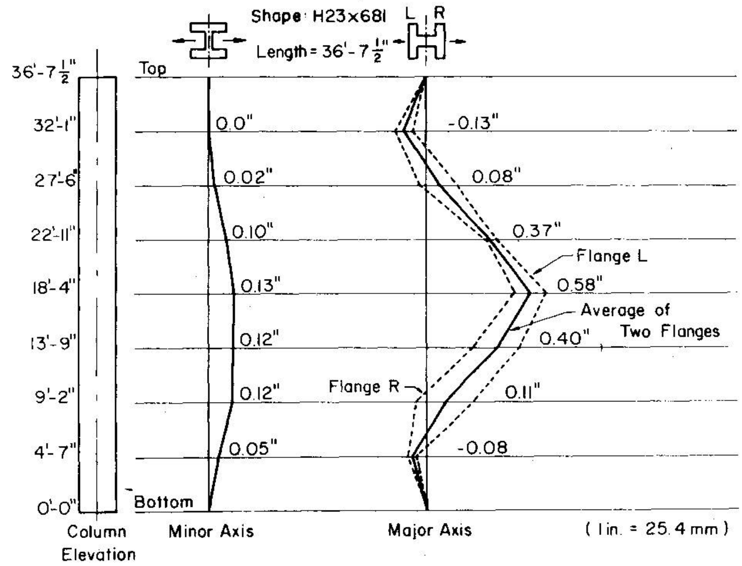


Fig. 5 Initial Out-of-Straightness of the Column Specimen

of the column length. The initial out-of-straightness of the column was measured at nine-levels, each spaced at one-eighth of the column length. Measurements were taken in the two principal axes and are shown schematically in Fig. 5. The maximum out-of-straightness was 0.58 inch (14.9 mm) at the column midheight about the major axis. The initial out-of-straightness of the column was symmetric for the major axis and unsymmetric for the minor axis (Fig. 5).

The column testing procedure described in Ref. 9 is then followed. The alignment of the column was performed geometrically by matching the end plate centers to the centers of the flanges at each support--the reference point was located at the midpoint of the line connecting the two centers of the flanges. The end plates were centered with reference to the centerline of the machine.

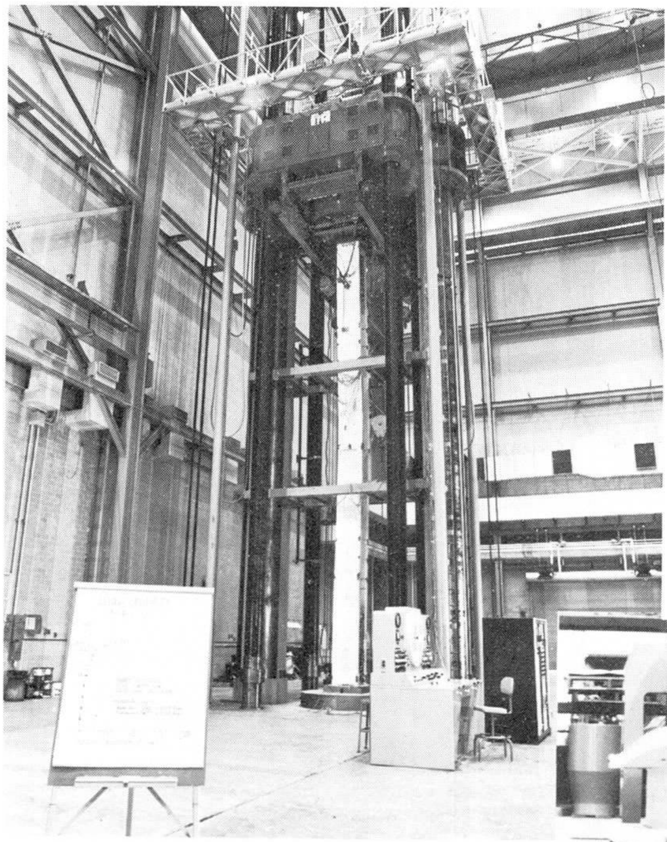
The instrumentation for the column test consists of potentiometers attached at quarter points to measure lateral deflections, electric resistance strain gages at characteristic points to measure strain and curvature variations along the column length, electrical rotation gages at the crosshead to measure end rotations about the two axes, and a dial gage to measure the overall shortening. The test set-up is shown in Fig. 6 under the 12-million-pound hydraulic testing machine.

The load was applied continuously at a rate of 1 ksi/min (6.9 N/mm^2/min) and all measurements were instantly recorded automatically at one minute intervals. The maximum "static" load was recorded as 6140 kips (27,300 MN) or 0.98 P_y by maintaining the cross-head movement until the load was stabilized. The loading was terminated when the midheight deflection was approximately seven inches, (180 mm). The specimen at the end of test is shown in Fig. 6.

Test Results

The measured load versus midheight deflection curves are shown by the small circles in Fig. 7 for the case of minor axis bending and in Fig. 8 for the case of major axis bending. The values shown at zero-load level correspond to the midheight initial out-of-straightness of the column. Also shown in these figures are the theoretical curves derived from the two dimensional in-plane column analysis as well as the three dimensional biaxial bending column analysis. A detailed discussion on these theoretical predictions is given later.

A substantial deviation of the measured curve from the linear behavior is seen to initiate approximately at the load P = 5400 kips (24,000 MN) or $0.865 P_y$. Beyond this load, the curve starts to bend very rapidly and this rate of bending falls steadily as the axial load increases. When the lateral deflection for the minor axis reaches the value approximately 0.8 inch (20 mm), the value of minor deflection becomes practically a constant until the end of the test (Fig. 8). The column finally failed with excessive bending about the major axis. Unloading of the column did not occur in the loading range of the test.



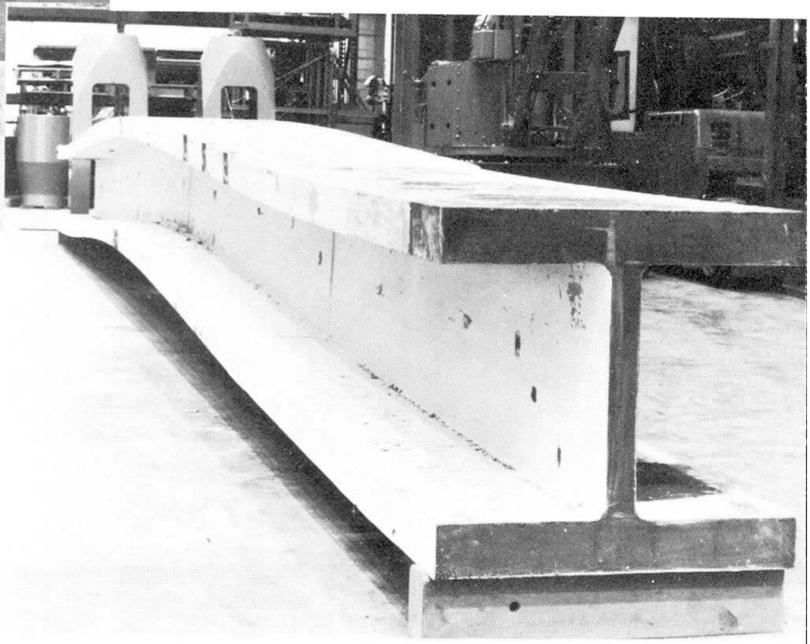


Fig. 6

a) Column Test Under the 12-Million Capacity Testing Machine
b) The Column Specimen at the End of Test

Rotation of the cross-head was measured using two electrical rotation gages oriented along the minor and major axes of the column cross section. Figure 9 shows the rotation measured at different load levels. A sharp

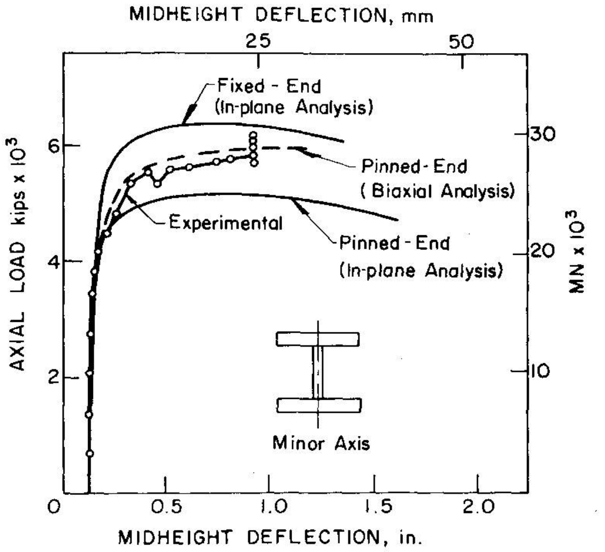


Fig. 7 Midheight Lateral Deflection About the Minor Axis

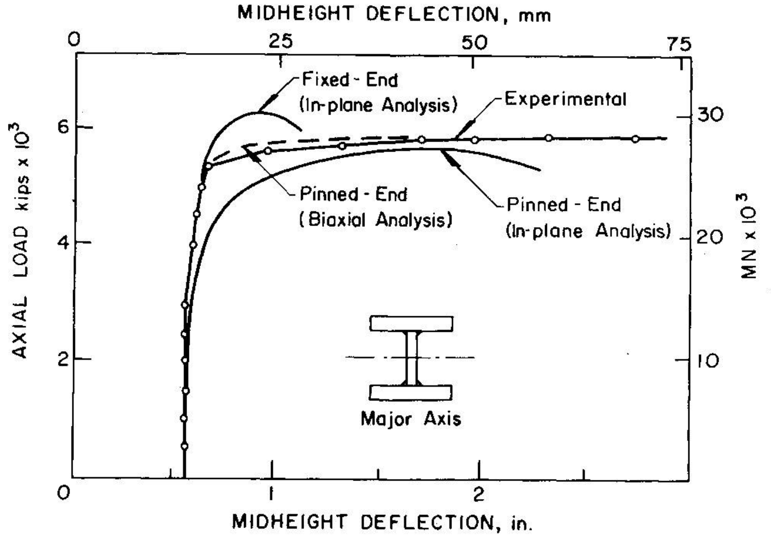


Fig. 8 Midheight Lateral Deflection About the Major Axis

deviation of the major axis rotation is observed at the initial stages of loading after which a fixed-end condition was maintained until the load reached 5500 kips (24,500 MN) or 0.880 P_y. The cause for the initial deviation is believed to be due to the adjustments of the cross-head. It is of interest to note that the shape of the load-rotation curves are very similar to that of the load-midheight deflection curves shown in Figs. 7 and 8. The two sets of curves are seen to start to bend very rapidly almost at the same load level.

The overall shortening of the column was obtained by measuring the cross-head movement using a dial gage. The load versus overall shortening curve is shown in Fig. 10. Similar to that of the load-rotation curves shown in Fig. 9, a deviation is also observed at the initial stages of the loading. The additional factor causing this deviation may be attributed to the deformation of the copper plates inserted between the end plates and the specimen. The stiffness of the column beyond the value of axial load P = 2000 kips (8900 MN) agrees very closely to the theoretical stiffness which is predicted by the formula AE/L where the value of AE is obtained from the stub column test.

Strain readings were recorded at selected points along the column lengths using electric resistant strain gages. Figure 11 shows the strain measurements at the column midheight for different load levels. Bernoulli's hypothesis on the linear strain distribution over the cross section is seen to be rather good up to the initiation and subsequent yield plastification of the cross section. However, when the cross section has been substantially plastified, a linear strain distribution assumption for the heavy shape column section may not be justified.

5. THEORETICAL ANALYSIS

The strength of an axially loaded column may be determined either by its bifurcation load or by its maximum load. For a perfectly straight column with concentric load application, the column remains straight under increasing load until the tangent modulus load is reached. Real columns, however, show an initial out-of-straightness, unsymmetric distributions in material properties, and residual stresses. This geometrical and material imperfection, along with the fact that the load can not be applied axially along the center line of the column, will cause the column to deflect immediately upon loading. Thus, all columns must be treated as beam-columns (deflection problem), not as straight columns (eigenvalue problem, tangent-modulus method).

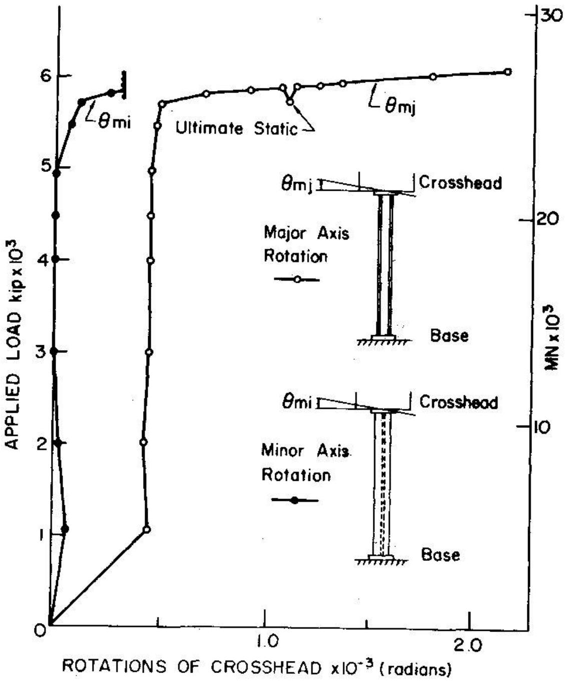


Fig. 9 End-Rotations of the Column at the Cross Head

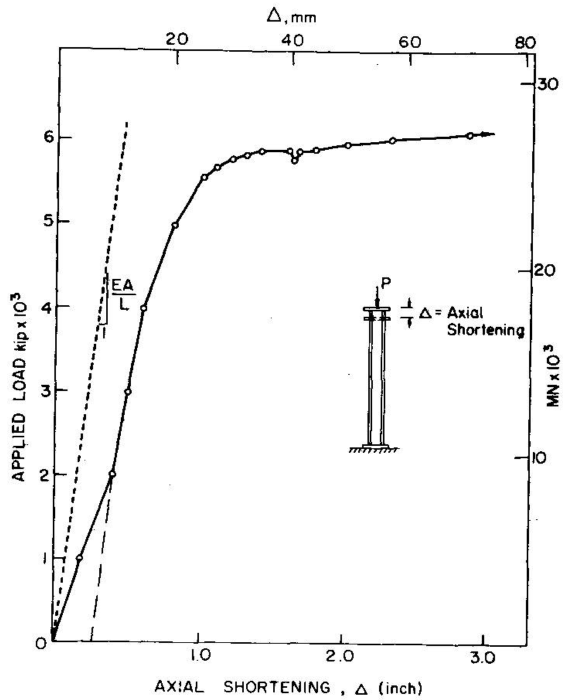


Fig. 10 Overall Shortening of Column

Several methods of solution exist to determine the behavior of such columns. However, in determining the behavior of heavy shape columns, the major problems are: (1) the variation in yield strength and residual stresses through the thickness of the component plates, and (2) the initial out-of-straightness in the two principal axes directions. The theoretical analysis presented herein considers both the two-dimensional in-plane column analysis and three-dimensional biaxial bending column analysis.

In-Plane Column Analysis--Tangent Modulus Load

The strength of a centrally loaded column based on the tangent modulus concept may be written in the form

$$P_T = \frac{\pi^2 E}{L^2} \int_A \left(\frac{E_T}{E}\right) y^2 \, dA \qquad (1)$$

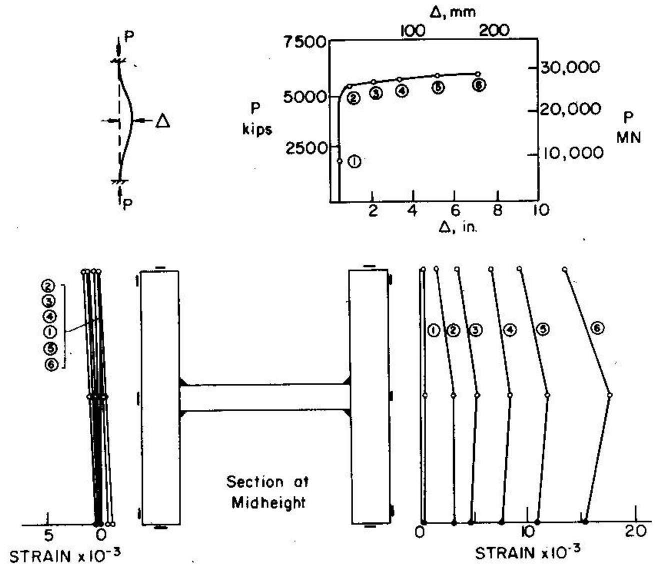


Fig. 11 Strain Variations at Midheight of Column

where P_T = tangent modulus load, E = elastic modulus, A = total cross sectional area, L = effective length of the column and E_T = effective tangent modulus of the shape. The tangent modulus load can be computed based on either measured residual stresses or the stress-strain relationship of a stub column test [10]. The stub column approach is adopted herein for the theoretical predictions. Figure 12 shows the tangent modulus load curves with bending permitted about the minor and major axes of the column.

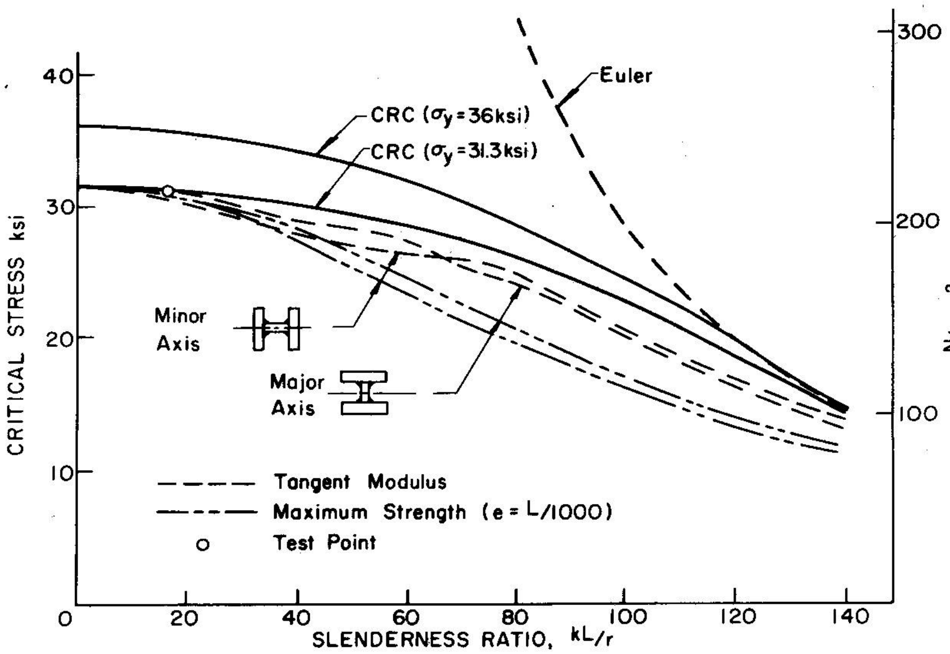


Fig. 12 Column Strength Curves

In-Plane Column Analysis--Maximum Load

The calculations become more involved for maximum strength predictions even though the underlying basic concepts are rather simple. The method adopted herein is based on the assumption that the initial as well as the deflected shape under increasing load can be described by a half-sine wave. The equilibrium condition at the midheight cross section may be written in the form

$$\Delta P_{int} = \int_A E_t \ \Delta\epsilon \ dA = \frac{1}{\delta_m} \int_A E_t \ \Delta\epsilon y \ dA = \frac{1}{\delta_m} \Delta M_{int} \tag{2}$$

where ϵ is the strain distribution in the cross section. By assuming linear strain distribution, Eq. 2 can be solved by using a numerical increments iterative procedure. The maximum load, under which the column assumes a state of neutral equilibrium, is then determined when the rate of resisting internal moment of the column approaches zero.

The in-plane behavior of the column was determined using a computer program (CDC 6400 Digital Computer) developed at Lehigh University [11]. The program computes the load-deflection relationship for a column with sinusoidal initial out-of-straightness. It also handles residual and yield strength variation through the cross section but constant through the thickness of the component plates.

In calculating the load-deflection curves for the H23x681 column the measured yield strength, residual stress variations, and initial out-of-straightness were used. The flanges and the web were subdivided into 50 and 30 segments, respectively. The average measured residual stress and yield strength values were used as the input data. Since the degree of end fixity during the test was unknown the two extreme end conditions were used in the analysis: pinned-end and fixed-end. Thus, the load-deflection curves obtained correspond to the upper and lower bound solutions to the problem. The calculated deflection curves are shown in Fig. 7 for the case of minor axis bending and in Fig. 8 for the case of major axis bending. In both figures the test results are seen to be bound between the two bounds. In Fig. 12 the maximum load column curves are shown. The curves are seen to be below the CRC basic column curve since the specimen had a yield strength lower than the specified value.

Biaxial Bending Column Analysis--Maximum Load

Several analytical procedures are available for the determination of the load deformation behavior of an isolated, initially imperfect column under biaxial bending [12]. Herein, the tangent stiffness method to the solution of the heavy shape column is adopted for the theoretical analysis [13]. The method is based on the analytical development of the linear relationship between the infinitesimal changes of the generalized forces $\{\delta f\}$ and displacements $\{\delta\Delta\}$. The derivation is based on the assumption that the initial as well as the deflected shape under increasing load can be described by a half-sine wave. It has the simple form

$$\{\delta f\} = [Q] \{\delta\Delta\} \tag{4}$$

The matrix $[Q]$ is defined as the tangent stiffness matrix as it represents the tangent of the force-deformation curve as well as the stiffness of the cross section. In this procedure the load is applied as a sequence of sufficiently small increments so that during the application of each increment the column is assumed to behave linearly. Thus, the nonlinear behavior is determined by solving a sequence of linearized equations

$$\{\delta\Delta\} = [Q]^{-1} \{\delta f\} \qquad (5)$$

An improved solution may be obtained by starting with an initial estimate of the displacement solution. This solution is then backsubstituted into the equations and the procedure is repeated until an accepted convergence or a prescribed tolerance is obtained. The iterational scheme is similar to the Newton-Raphson method, thus, the solution will generally converge within a few cycles even for larger load increments.

The load-deflection curves for the H23x681 column based on biaxial bending column analysis was performed using a computer program developed also at Lehigh University 14 . The program computes the relationship between the applied load and the three generalized displacements: lateral deflections in the two principal axes and twist of the cross section. The program can handle residual stress and yield strength variations throughout the cross section including the variations through the thickness of the component plates.

In the computation both the flanges and the web were divided equally into 30 segments through the width and 5 segments through the thickness. The average residual stress and yield strength (Figs. 2 and 4) at each segment was used as the input data. The calculated deflection curves are also shown in Figs. 7 and 8. It can be seen that the theoretical curves predicted by the biaxial bending column analysis are in good agreement with the results.

The effective length of the column was determined by plotting the curvature variation along the column length for different load levels. The curvature at each location is determined from the strain gage readings mounted at various levels and at opposite sides of the specimen. The curvature curves are shown in Fig. 13 for the minor axis bending and in Fig. 14 for the case of the major axis bending. It is noted that the point of inflection, that is, zero curvature points are not fixed but rather change with

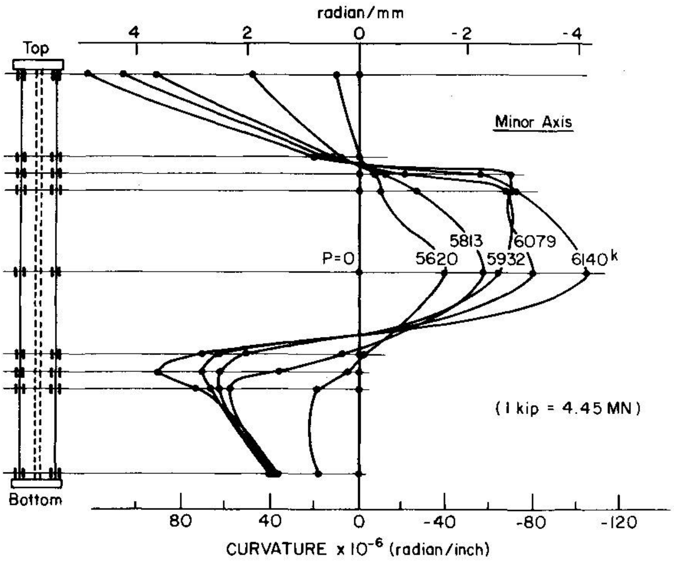


Fig. 13 Measured Curvature Curves about the Minor Axis

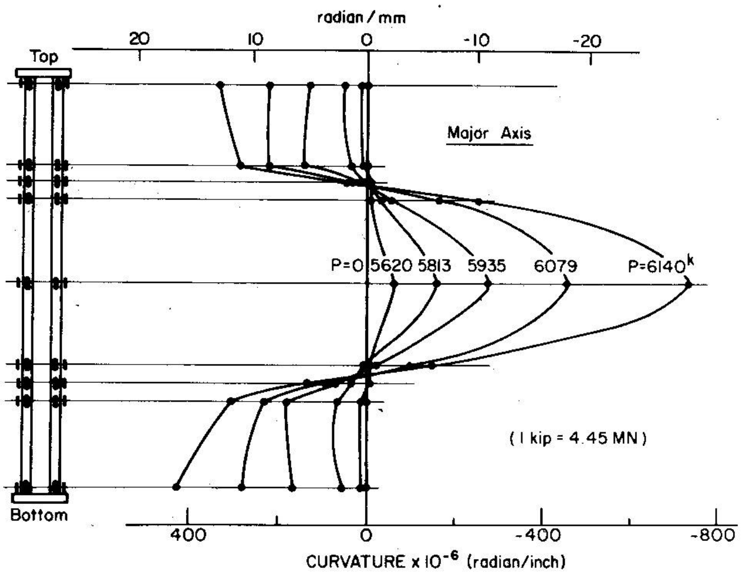


Fig. 14 Measured Curvature Curves about the Major Axis

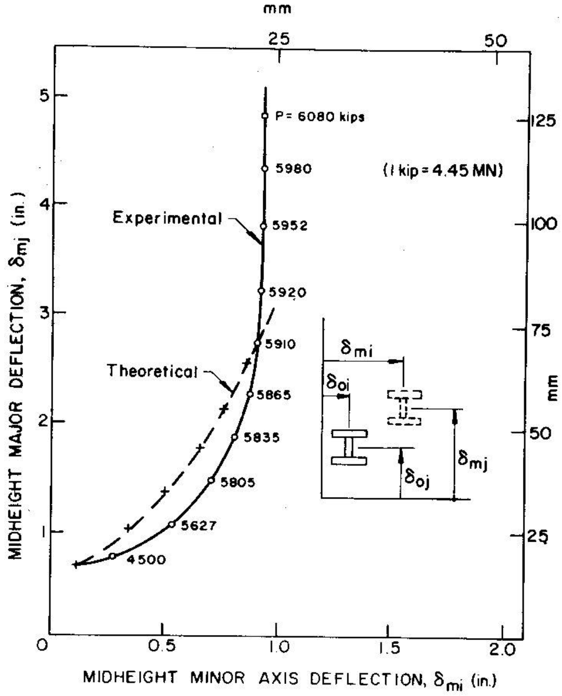


Fig. 15 Comparison of Experimental and Theoretical Load-Deflection Curves (Biaxial Analysis)

load for the case of minor axis bending and seem stationary for the major axis bending. The effective lengths determined from the experiment (Figs. 13 and 14) were used in the biaxial bending analysis of the column. The load versus the deflections in the two principal axes are compared in Fig. 15 and good agreement is observed.

6. SUMMARY AND CONCLUSIONS

This paper contains a theoretical and experimental analysis of the behavior and the strength of a heavy shape column built up from flame-cut plates. The theoretical part of the analysis includes two-dimensional in-plane column analyses by tangent modulus concept and by a load-deflection approach, and a three-dimensional biaxial bending column analysis. The effects of residual stress, yield strength variations over the cross section and initial out-of-straightness in the two principal axes are considered in the theoretical analysis. Comprehensive experimental investigation was performed to determine the strength and behavior of one particular heavy built-up shape--H23x681, ASTM A36 steel. The experiment includes: (i) measurements of yield stress levels in the cross section; (ii) measurements of residual stress distribution in the cross section; (iii) a stub column test; and (iv) a full-size column test.

Failure of the column was observed in biaxial bending with excessive bending about the major axis. The results of the column test and the theoretical prediction based on a recently developed three-dimensional biaxial bending column analysis are compared and good agreement is observed.

Based on this study the following conclusions may be stated:

1. The two-dimensional in-plane column analysis considering the geometric and material imperfection of the column can predict the maximum strength of the heavy shape columns with good accuracy; however, the method may give a false representation of the load deflection behavior of heavy shape columns.

2. Because of the particular pattern and variation in residual stress distribution in the cross section as well as the initial out-of-straightness along the two principal axes for the heavy shape columns, the three-dimensional biaxial bending column analysis is needed in order to predict accurately the load-deflection behavior of such columns.

3. The strengths of heavy shape columns built up from flame-cut plates are found to be higher than those of lighter welded whapes as well as their rolled counterparts.

4. Bernoulli's hypothesis on the linear strain distribution over the cross section of heavy shapes is found to be good up to the initiation of yielding and including the subsequent plastification of the cross section. However, when the cross section has been substantially plastified, the assumption of linear strain distribution may not be justified.

5. The AISC column formula or the CRC strength formula may be used to predict the maximum strength of a heavy column shape built-up from oxygen-cut plates of ASTM A36 steel.

7. ACKNOWLEDGMENTS

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