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Welding Research Council Bulletin Series

Tests of Columns Under Combined Thrust and Moment

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ABSTRACT

Under sponsorship of the American Institute of Steel Construction, test equipment has been developed in which various desired combinations of axial load and end moments may be applied to metal columns. Lengths of 8, 12, and 16 feet may be accommodated in the apparatus, which is designed to test steel columns up to an 8WF40 rolled section size.

Axial load is applied by a universal testing machine of 800,000 pound capacity. The end moments are applied separately through lever arms with tension-compression hydraulic jacks mounted in series with dynamometers which measure the thrust.

The behavior of test columns under load is determined by the use of four measuring techniques: (1) taut-wire and mirror deflection gages, (2) level bars, (3) SR-4 strain gages, and (4) whitewash. In addition, the moment-producing thrust is measured by aluminum tube dynamometers.

The test program is currently being sponsored by the Welding Research Council. Some of the test results obtained are presented to demonstrate the effectiveness of the apparatus. The objectives of the program are described, the principal one being to determine the ultimate strength of columns under varying combinations of end moments and direct load.

INTRODUCTION

For a number of years the American Institute of Steel Construction has sponsored research on the general column problem at the Fritz Engineering Laboratory of the Lehigh University Civil Engineering Department. A study of the local buckling of the flanges of WF columns was completed in 1942. This was followed by an investigation of the behavior of eccentrically-loaded columns. The previous work contains rather complete references to other theoretical and experimental studies of the column problem.

In 1946, the AISC commenced sponsorship of the current investigation of columns loaded with combined axial force and various end moments, simulating the loads acting on a column in a rigid frame. Two principal objectives are:

(1) to determine the ultimate strength of columns under combined axial load and end moment, and

(2) to determine the moment distribution carry-over and stiffness factors of steel columns in both the elastic and plastic range. A variation in the magnitude of compressive load will influence these factors.

Some similar tests have been conducted on small specimens. So far as is known to the authors, none approaching column sizes used in structures have been made in which a constant axial load could be maintained while the applied moment was varied, or in which the applied moment could be maintained constant during change in axial load. These, then, are the essential features of this investigation:

(a) the use of rolled structural steel members, and

(b) the ability to independently vary axial load and end moment.

The program is now coordinated with a five-year investigation of the ultimate strength of welded continuous frames sponsored by the Welding Research Council with financial support from the American Institute of Steel Construction, The American Iron and Steel Institute, the U. S. Navy bureau of Yards and Docks, and the U. S. Navy Bureau of Ships through a contract with the Office of Naval Research. The Column Research Council also supports the work in an advisory capacity.

In Fig. 1 are shown the forces applied by the test apparatus used in the current investigation. It will be seen that it is possible to apply axial load to the test specimen independently of end moments. The concentric force, P, is applied through knife edges with an 800,000 lb. Rhiele testing machine. Thrusts, F, applied hydraulically to lever arms, deliver the moment. Lateral support, H, is provided. Previous investigators have used some of the testing arrangements shown in Fig. 2, since their study was

*Progress Report No. 2 on the "Ultimate Strength of Welded Continuous Frames and Their Components"
### PROPOSED COLUMN TESTS

<table>
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<tr>
<th>Tests</th>
<th>Size of member</th>
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<th>r</th>
<th>l/r</th>
<th>Test conditions</th>
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<td>8</td>
<td>-</td>
<td>-</td>
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</tr>
</tbody>
</table>

P_cr = load predicted by Tan. modulus theory.

### CONDITION OF TEST

#### TABLE I
aimed at solution of one of the several problems there typified.

This report is a description of the testing apparatus. Herein is described the method of applying loads and moments, the details of end fixtures and alignment procedure, and measurements made on test columns. Representative test results are presented as a demonstration of the effectiveness of the equipment. In a progress report to be issued in the near future, the results of tests will be presented.

**TEST APPARATUS**

**Specimens**

Two different sizes were selected in the original program with variation in length to give a wide range in the slenderness ratio, \( l/r \). As shown in Table I, 4WF 13 and 8WF 31 columns are being tested in lengths of 8, 12, and 16-feet. The variation in \( l/r \) thus provided is from 27.6 to 111.5 when bending is about the strong axis. The pilot test column may be seen in Fig. 3.

**Axial Load**

In order to provide a means of applying known moments (or angle changes) at the column ends and at the same time to be able to determine accurately the magnitude of axial load, the general scheme shown in Fig. 4 was adopted. An 800,000 lb. Riehle testing machine is used to apply the load. The details of the bearing blocks, knife edges and end fixtures are described in the section "Column End Details" below.

**Application of End Moments**

End moments or end angle changes are accomplished by applying accurately measured forces at the ends of lever arms rigidly fixed to the ends of the specimen. Fig. 1 shows a typical system of forces in which moments of the same sense are applied at each end of the column. The system of horizontal forces is necessary to maintain equilibrium.

The Test Frame (or moment loading frame), Fig. 4, provides reaction support for the forces developed. Moment thrust, \( F \), is produced and measured with tension-compression hydraulic jacks connected in series with load-measuring dynamometers as described below. The adjustable cross beams of the frame accommodate the various lengths of columns, transmitting the thrust from the moment arm to the vertical frame members. Fig. 3 shows the special frame developed. This complete assembly is placed in the testing machine as shown in Fig. 5. The method of transferring lever arm thrust into moment in the column end is shown in Fig. 6. The upper arrangement of dynamometer, jack, and end fixture is the same as that used below but is inverted.

**Column End Details**

The COLUMN BASE PLATES (Figs. 7, 8a) are fully welded to both ends of the test column. They provide the means for securing the test column to the web of the end fixtures with Allen-head bolts.

The END FIXTURE (Figs. 8b, 6) serves to transmit the bending moment to the ends of the column and to provide a foundation for the knife edge seats. It consists of a stiffened 342 lb. WF-section to which is welded two channels as moment arms.

KNIFE EDGES, WEDGE BLOCKS, AND CYLINDRICAL BEARINGS are shown in Fig. 9. The double system of knife edges was developed so that the point of end rotation and application of axial load, the center of moment, point of lateral support, and end of the actual column section could be brought as close as possible to the same horizontal plane. This was accomplished for each of the above except the end of the column section. It is actually 5 3/4 inches above the knife edge. Compensation for the resulting error is made in analyzing the data. The knife edge seat is secured to the web of the end fixture by bolts. The length of a single edge is 8". The 90° angle at the edge proper is rounded to a radius of 1/16". Knife edges are greased.

The cylindrical bearings provide a plane surface which is common to both knife edge blocks. This is necessary since the knife edges rest on different members. The wedge blocks provide for an angular adjustment of the column so that it may be lined up with the axis of the testing machine as seen in Fig. 8c. In Fig. 9 will also be noted the wedge adjusting device by which the blocks are positioned and held in place.
FIG. 1 LOADS ACTING ON TEST COLUMN
while the end fixture and column are being assembled.

LATERAL TIE RODS (Fig. 9) are attached to the upper and lower end fixtures on the axis of rotation of the knife edges to carry in tension any lateral thrust, $H$, developed during the test. Friction in the upper and lower assemblies carries some of this lateral force. The rods are anchored at the edges of the moment loading frame (Figs. 4, 9). Upper tie rods have been fitted with flex-bars, since the load will push the upper end of the column downward with respect to the frame. Later in the program it was found that it was necessary to adjust these tie rods during a test. The insertion of thrust bearings made this more convenient.
The **UPPER DIRECT LOAD ASSEMBLY** (Fig. 10) is used at the upper end of the column in lieu of wedge blocks and cylindrical bearings installed at the bottom. The unit is held together loosely as a safety measure and to assist in placement, and under load such hangars and U-shaped rings do not bear against the rollers. An initial load is applied with the upper head of the testing machine through a bearing plate to the 4" roller. The wedge blocks are then installed to "fix" the column against bending about the weak axis in those tests where it is desired to bend the column about the strong axis.

**Erection and Alignment**

Fig. 11 shows the various assemblies and the sequence with which they are erected. With the test frame (1) on the laboratory floor, assembly (2) consisting of cylindrical bearings, wedge blocks, and knife edge blocks is placed in position. After the lower end fixture (3) has been approximately aligned, the column with upper end fixture attached (4) is then lowered down through the frame and held in position with a crane while the base plate is bolted to the lower fixture. Safety devices clamp the column and end fixtures to the frame while it is being placed in the Rhiele testing machine. Following alignment of the column, the upper load assembly (5) is positioned. After a slight initial axial load has been applied, the jacks and dynamometers are installed.

Numerous factors can affect the alignment of the test specimen, contributing to what is known as "initial eccentricity":

(a) the ends may be out of line,
(b) initial curvature may be present in the column,
(c) the ends may be out of square, or
(d) one end may be twisted with respect to the other.

A discussion of these factors is contained in an unpublished report (3) of the Committee on Design of Structural Members of the A.S.C.E. The accuracy of alignment achieved with the apparatus described herein is well within the limits set forth in the above report.

In securing this alignment, three axes of the various components must be made to coincide as shown in Fig. 12. Base plates are welded to the column ends in a jig, the column being supported along its length. The column center is taken as the intersection of diagonals joining opposite flange corners. No compensation is made for initial curvature. AISC tolerances allow 3/16" for the 16-foot member, and measurements on the specimens show them to be well within this limit. Likewise, no attempt is made to correct for initial twist of the member.

With the equipment in place, both ends of the

![Fig. 3. Test frame with column and hydraulic loading equipment in place.](image-url)
FIG. 4 - COLUMN TEST APPARATUS
EXPERIMENTAL STRESS ANALYSIS

column are separately centered between the vertical screws of the testing machine.

The knife edge seats, being rigidly attached to the end fixtures, act to automatically position the knife edge blocks which are supported with wedge blocks and cylindrical bearings, enabling them to shift to the proper position. The moment arm is centered in the test frame by adjustment of lateral tie rods.

Thus with the equipment described, the column is placed squarely in line with the testing machine axis, and the moment arm is positioned in the intended plane of bending, normal to the axis of knife edges.

Prior to an actual test, the alignment is checked using SR-4 gages and level bars at the ends. The SR-4 gages indicate the eccentricity at the ends (Fig. 7 is a typical arrangement), whereas the measured rotations tend to average all the eccentricities and constitute a more general indication of alignment. Thus far in the investigation, centering under load, (the process by which the column is shifted with respect to the machine screws or supports) has been used to a limited extent.* Extreme accuracy of alignment of the vertical axis is not necessary since a moment of considerable magnitude is applied at one or both ends in all tests.

Hydraulic Pumps, Jacks, and Dynamometers

As previously mentioned, the application of end moment is accomplished with tension-compression jacks in series with load measuring dynamometers. Two pumps are connected with high pressure tubing to each jack, one for use in tension, the other for use in compression.** The pumps, high pressure tubing and jacks were procured commercially***, the dynamometers having been designed and constructed at the Fritz Engineering Laboratory making use of SR-4 gages under license from Baldwin-Southwark Corporation. Fig. 6 shows the system in operation in the pilot test.

The dynamometers shown in the photographs consist of aluminum tubes with heavy ends threaded to receive the jack and pin connectors. Four SR-4 strain gages, type AD-1, were installed on each unit.

The arrangement of strain gages on the dynamometers is one in which both the active, “A”, and compensating, “D”, gages are mounted on the aluminum tubing, the “D” gages being * The use of this process by others has been described by Osgood.(4)

** In order to use the system at high compressive loads it is necessary to provide lateral support to the jacks. Thus far it has been possible to run tests using tension alone.

Fig. 6. Arrangement for applying end moments showing adjustable cross beam at upper right, calibrated dynamometer (SR-4 gages mounted beneath asphaltic-base adhesive), tension-compression hydraulic jack, connected with a pin to the moment arm and thus to the end fixture and into the test column. Note SR-4 gages at base of column and grouped gage leads.
mounted at right angles to the "A's". The use of the two gages in each direction provides temperature compensation and cancellation of any bending stresses.* Calibration is obtained with a Baldwin-Southwark type K strain indicator, loads being applied with a Baldwin-Southwark hydraulic testing machine. The calibration curve is checked and corrected from time to time. Unusual reproducibility has been observed. In order to use one strain indicator for both dynamometers, a household type four-pole double-throw switch is used. The dial gages (Bourdon type) attached to high pressure pumps (Fig. 5) are not used except as a rough check against the dynamometer loads as given by the strain indicator.

Measurements

The behavior of test columns under load is determined with the assistance of four measuring techniques. Lateral deflections at various sections are measured with a taut-wire and *Increased sensitivity may be achieved by using a bridge completely external to the indicator. This involves internal modification of the box.

mirror arrangement as shown in Fig. 13. Paper scales* were glued to mirrors which were themselves attached to the test column with "Miracle Adhesive". By lining up the wire with its mirror image, a reading could be made on the scale from which the lateral deflection of the point on the column with respect to its ends could be computed.

Four wires were arranged around the section so that deflections in both directions and torsional displacements could likewise be measured. The wire was anchored at the base of the column and strung over a pulley attached to the top. Weights were then hung at the free end of the wire to keep it taut. (Fig. 7)

Lateral deflections were determined with an arrangement of Ames dial gages on recent tests to improve the data obtained. On short column tests the mirror and taut-wire technique is somewhat insensitive. Deflection readings are referenced to the column "ends".

It will be noted that if torsional rotation is combined with relatively large lateral displacements there will be significant error in the measurement of deflection. Such displacements have not occurred as yet, but a modification of the system has been evolved to take care of such an eventuality.

The measurement of deflection is of use:
(a) to check end rotations,
(b) to determine the point of inflection when there is reversal of moment,
(c) to check with calculations of the deflection curve as predicted by elastic and plastic theory,
(d) to determine additional moment produced by the combination of axial load and column deflection, and
(e) predict buckling load by the Southwell method.**

From thirty to forty SR-4 gages are used on an average test. Type A-1 gages, 13/16" gage length are arranged on various sections depending on test conditions. Gages at the quarter point are seen in Fig. 13. In Fig. 5 may be seen the multiple selection box to which SR-4 leads from the column were connected.

Strain gage data will be of particular use in checking hypotheses. Among the uses of the

*Engine-divided scales procured in 18" lengths from Dietzgen Co. similar to K & E cat. No. 16773,

**Ref. 5, p. 177.
FIG. 8 - COLUMN END DETAILS

(8a) Base plates welded to column ends

(8b) End fixture with moment arm attached

(8c) End view of fixture showing alignment apparatus.

Knife edge blocks
Wedge blocks
Cylindrical bearings
data are the following:
(a) indicate initial eccentricity of axial load at the column ends,
(b) determine M-Ø characteristics at various sections,
(c) determine point of inflection when moments of the same sense are applied at opposite ends,
(d) to show strain distribution across critical sections, indicating whether or not there is a linear distribution,
(e) indicate shifting of "neutral axis" as plasticity in a section develops and increases,
(f) to show strain distribution along the test member, and
(g) to indicate initial yielding.
Level bars (Fig. 14) are used to indicate angle changes at tops and bottoms of test columns.

The level bar support bracket is attached as close as possible to the end of the column.
Under one condition of test (condition "b" of Table I) one end is held fixed and the level bar is used as an index of zero end rotation.
The measurement of angle change is one of the most important observations made on the column tests. Information is used to indicate moment-rotation characteristics of the member at the ends. This is an essential element of structural analysis. Comparison will be made with theory in the elastic range and with the results of frame tests. Since it has been necessary to make a connection at the column ends, rotations of end fixtures are also measured. This enables a more exact analysis of the results.
In order to observe the progression of yield-
ING in the test column, hydrated lime is applied as a white wash. The flaking of mill scale slightly above the yield point is then made apparent.

It should be mentioned in concluding this section that additional important measurements are those of axial load and end moment (as indicated by the dynamometers). These observations show the overall strength of test members.

TESTING PROGRAM AND PROCEDURE

Program of Tests

Table I outlines the investigation. It will be seen that the variables are:
(a) size of specimen (8WF31 and 4WF13),
(b) $P/P_{cr}$, the ratio of applied load to buckling load,
(c) $L/r$, the slenderness ratio,
(d) end moment condition, and
(e) flexure axis, $(x-x, y-y, 45^\circ)$.

In the pilot test, the member was also tested in compression without end moments. Also not included in the table are a series of tests intended to compare directly with compression members in frames to be tested in the future.

Coupons and Measurements

Prior to welding the base plates into position, the specimens were accurately measured, determining moment of inertia and area. Sections of the member which had been cut from representative portions of the rolling were fur-
Testing

The erection of test apparatus and column alignment have previously been described. It remains to describe the procedure of making tests of columns under the various end moment conditions. Thus far in the program, three different combinations have been used:

(a) axial load alone,

(b) moment applied at one end, with opposite end simply supported, and

(c) moment applied at one end, opposite end kept “fixed”. The features of each of these conditions are now described.

AXIAL LOAD

Below the critical buckling load readings of deflection are taken at the midheight so that an estimate of the Euler buckling load may be made by the Southwell method. In these tests the dynamometers and jacks are not connected to the moment arms.

END MOMENTS

The moment-producing thrusts have two effects on the axial load:

(a) They change the length of the member, either by tension, compression, or bending. This requires adjustment of the testing machine until the desired load values are reached.

(b) Thrusts apply a concentric force in addition to moment. For thrusts applied to the lower arm, no correction is involved. The load indicated by the machine is the axial load “P” in the column. However, corrections must be applied equal to the magnitude of the thrust when it is applied at the top.

Lateral adjustment of the column is frequently required. Since the moment frame is an elastic structure it will deflect under the horizontal forces, H, shown in Figs. 1 & 4. This will affect the axially of the central load, the end angle changes and the end moments, the error involved being dependent on the length of the column.

Subsequent to the initiation of the program, it was realized that these errors might be serious and steps were taken to correct the trouble. Thrust bearings were procured so that, after the application of an end moment increment, the end could be pulled back into

Finished by the fabricator. Test coupons were cut from these to determine tensile and compressive properties. Column ends were milled to length.
FIG. 12. ALIGNMENT OF COLUMN TEST ASSEMBLIES
position with nuts threaded on the lateral tie rods. A position control gage is referenced to the screws of the machine. This system has worked satisfactorily, although a further modification has been to install two hydraulic jacks in appropriate position to accomplish this same adjustment.

Moments Applied at One End

(Test Condition “d”, Table I)

The test procedure described below has been found to require the least amount of readjustment. Prior to the time of test an estimate is made of the conditions of $P$ and $M$ that will produce initial yielding and ultimate failure. In all tests the full magnitude of axial load is applied to the member (for one test the variable $P/P_{cr}$ is held constant), after which the moment is applied in increments. For test condition (d) thrust is applied downward at the top of the member.

For any increment of moment after the axial load is initially applied, the test procedure is as follows:

(a) Determine new testing machine reading for axial load by subtracting from the original $P$ the magnitude of the moment-producing thrust. This has been described previously. Balance machine at the new load.

(b) Apply additional increment of end moment with the hydraulic jack.

(c) Adjust testing machine as needed.

(d) Correct for lateral displacement of column ends by applying tension in appropriate lateral ties (described above).

(e) Re-adjust the axial load and moment to give the desired values.

(f) Take readings of angle change, deflection gages, strain gages.

A new increment of loading is then applied and the above procedure is repeated.

Moment Applied at One End, Opposite End “Fixed”.

(Test Condition “b”, Table I)

Under this loading system, the moment is applied at the top and the lower end is kept “fixed” by the use of the hydraulic jack system attached to the lower moment arm. Before any moment is applied, a level bubble is set up on a bracket attached to the column base (Fig. 14). After application of the upper moment incre-
ment, the end of the column is brought into the level or "fixed" position with the jack.

The test procedure is the same as described above, except as modified by the application of end thrust at the base to maintain the "fixed" position. Of course, one of the measurements made is the magnitude of this end moment, since the ratio of this value to the upper moment is the "carry-over factor".

Modification for Testing in the Plastic Region

After the material is strained beyond the elastic limit, a certain amount of "creep" or plastic flow occurs. The same phenomenon is observed in other tests involving plastic behavior, and is associated with yielding under constant load at a particular section of the member until strain-hardening occurs. Generally, the time required to reach equilibrium increases as the amount of plastic deformation increases. A "criterion" was selected, which, it is believed, gives a "flow curve" very close to what would be obtained with a dead-loaded system holding each loading increment for an indefinite period. Since the moment is applied at the upper end in the tests described here, the angle change is the greatest at this point. When the rate of yielding had decreased to the point where the rate of upper angle change was no greater than .00005 radians per minute, then it was considered that yielding had ceased and readings of deflection, strain, angle changes, and end moments were taken.

EVALUATION OF TEST DATA

Six tests have been conducted thus far as shown in the following table:

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<th>Test Number</th>
<th>Section</th>
<th>Length*</th>
<th>Test Conditions**</th>
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<td>.25 (b)</td>
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<td>d</td>
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<td>b</td>
<td>.8</td>
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Flexure axis on all tests: x - x

*Add 11/2" to obtain exact distance between knife edges

**See Table I for sketch of end condition

In the discussion which follows, all test results are not presented, the primary purpose here being to discuss the test apparatus. A description of test results will appear in a separate progress report. In this section is indicated typical data that can be obtained with the apparatus.

Axial Load Tests

In the pilot test axial load alone was applied until failure occurred, under condition "e". Fig. 15 presents the load-deflection curve, three values of the buckling load being shown as a check:

(a) the experimentally determined value,
(b) that obtained from the Euler equation,
(c) that predicated by the Southwell Method.

Column Loaded with Combined Thrust and Moment

If the connections between beams and columns in a structure are made continuous, i.e., capable of transmitting large bending moments from one member to the other, then the entire frame must be considered in determining the carrying capacity of the compression members. In recent years attention has been brought to the fact that the bending stiffness of a column decreases with increasing load, becoming zero at the critical buckling load, and finally reaching negative values if there are adjoining members to provide restraint. Tables are available for computing modified stiffness factors. In a frame composed of slender columns that buckle in the elastic range, published procedures are available for calculating the mo-
Fig. 14. Arrangement for angle change measurement at column base. Shown are the level bar, base plate and support bracket. Level bubble is adjusted by means of micrometer screw. Readings are indicated by dial gage at end.
TEST OF COLUMNS UNDER COMBINED THRUST AND MOMENT

Fig. 15 Column Deflection At Midheight --pilot test.

ment distribution at any load as well as the buckling load of the entire frame.

Consider the illustrative case shown in Fig. 16*. For an infinitely rigid column, case (a), the beam is “fixed” at the ends. For a more realistic column, case (b), the end moments in the beam are reduced over their “fixed-end” values. As the loads F are applied and increased, case (c), the moment at the ends of the column will decrease and finally become zero at the load which would produce buckling if it were not for the fact that the beams will tend to prevent end rotation. At higher loads, case (d), the column “tries” to buckle but is restrained from doing so by adjoining members. Note that greater than simple beam bending moment is developed at the center of the beam span. Finally, when the combined bending stiffness of the columns and beams framing into a particular joint reaches zero, the entire frame will buckle.

The foregoing procedure of analysis has been restricted principally to the elastic range. One of the purposes of this investigation is to determine to what extent similar procedures are applicable in the inelastic range.

The preceding discussion has been presented as a background for consideration of the experimental methods of obtaining collapse loads and stiffness factors of framed columns.

* The case described is one in which the column is initially deformed in single curvature.

Thus far in the experimental program these loads and factors have been determined for the case where the total axial load is less than $P_{cr}$ (Fig. 16b and 16c). This is also the type of loading acting on single span rigid frames or on the top floors of industrial buildings. In both instances the principal axial force comes from loads in the beams. Consideration of specific frames shows that a condition of negative stiffness would almost never be reached in practice unless additional load is applied directly to the column. Whether or not negative stiffness develops is determined as follows: compute the critical axial load under pin-end conditions for the column; then distribute this load to the beam and determine the maximum moment under simply-supported conditions. The beam will not provide restraint to the column if this moment is greater than the plastic hinge value of the beam.

Although no tests under restrained conditions have been conducted as yet, collapse loads under this type of loading can be determined with the apparatus, simulating different degrees of end restraint (variation in beam stiffness) and different magnitudes of initial load due to bending moment. As was mentioned previously, this is a situation approached in the lower floors of a high building or in any case where the total load on the compression member exceeds the critical buckling load for a pin-ended column.

In England, Professor J. F. Baker and his associates are conducting a program at Cambridge University entitled, “Investigation Into the Behavior of Welded Rigid Frame Structures” under the auspices of the British Welding Research Association. Numerous interim reports have been published by this group, a general report describing the work up to the present time having appeared recently. The behavior of the restrained column has received particular emphasis in their work and forms the basis for any future studies.

The Interaction Curve

The carrying capacity of the type of member under investigation is a function of applied axial force and end moment. Such an “interaction” curve is shown in Fig. 17. For zero axial load, $P$, the member is a beam and initial yield and ultimate collapse are determined from elastic and plastic beam theory. For zero moment,
FIG. 16 - BEHAVIOR OF RESTRAINED COLUMNS

(a) Fixed End Beam

(b) F = 0, P < P_{cr}

(c) F + P = P_{cr}

(d) Near Collapse

Loading

Moment Diagrams
we have a compression member whose ultimate strength is given by the tangent modulus theory. For points in between, that is, for combinations of axial load and end moment, theories are available, or are being studied to predict initial yield and ultimate strength.

Fig. 17 is constructed making use of the assumption that the stress-strain curve of the material consists of two straight portions -- a line with a slope of $E$, and a horizontal line at the lower yield point stress.

Two interaction curves are thus developed, one indicating initial yielding, the other, the locus of points where "collapse" occurs, (collapse meaning that the member will refuse to carry increased bending moment).

The experimental results for several tests, are shown, illustrating the agreement obtained. The figure also shows the method of test. The full magnitude of axial load was initially applied, followed by successive increments of bending moment until collapse occurred. Check tests will be made in which the moment is held to a constant value while axial load is increased. The former method is important, however, since it enables determination of carry-over and stiffness factors for constant axial load.

**Carry-Over Factor**

The observation of carry-over factor obtained in the pilot test is shown in Fig. 18. Attention is called to the fact that the last few points were observed under a gradually reduced magnitude of axial load.

**Whitewash**

An observation of the flaking of whitewash gives a qualitative picture of the yielding process. A photographic record is shown in Fig. 19.

**SUMMARY**

**Adequacy of Apparatus and Future Research Program**

**Alignment**

It is considered that the method of alignment is sufficiently accurate. In addition to measurements of actual eccentricity at the top and bottom of the column, a "Southwell plot" made during the application of axial load alone gives opportunity to determine effective eccentricity. In the pilot test of the 4" member, for example, the observations were:

(a) .023" (measured prior to test)
(b) .032" (observed from Southwell curve).

For tests of structural sections, this is considered quite adequate, particularly when large bending moments are to be separately applied at the ends.

**Hydraulic Jacks and Dynamometers**

The observed check of carry-over factor in the elastic region as shown in Fig. 18 is an indication that the general operation of this equipment was satisfactory. Questions frequently arise as to whether or not the loading system simulates dead load. There seems no doubt of this in the present instance as there was never any difficulty in maintaining constant load.

The operation of the check valve on the pumps presented occasional difficulties in the low elastic range. With but one exception, however, it has been found that check valves on the pumps increase in "holding power" as the load increases. Good operating characteristics were therefore obtained in the plastic range where constant load is important.

Dynamometers in one instance were checked after a 3-month interval and negligible changes in calibration constants were observed. Recent experience has indicated that certain strain indicators will "drift" after the switch is turned to the "on" position. Almost without exception the duration of test required that batteries be replaced in strain indicators. This is often accompanied by a change in reading under constant load.

Change of readings due to replacement of batteries will give significant error if only the low-load range of the dynamometer is used. Several ring dynamometers are available in Fritz Laboratory and are used when the range is suitable. "Zero" readings taken before a load series was commenced and after its completion give an indication of the reproducibility of the zero and hence the accuracy of the indicated loads. The following table gives such observations with error in moment-producing thrust indicated for observations made on various tests.
The above table shows that the percentage errors made with ring dynamometers are of the same order as the tube dynamometers. For the latter, the error may result from a loss of battery potential. So long as the dynamometers are used in their efficient design range, the error in “zero” is not serious. Several improvements will be made to a constant source of power to the strain indicator will be used, and readings of a reference bridge will be observed periodically so that any changes in the strain indicator may be corrected as the test progresses.

Deflection Gages

Mirror and taut-wire gages are effective on the 4" members of 12 and 16-foot length. When torsion is absent, Ames dial gages constitute an improved technique on the 8” WF sections. The wire gages are not sufficiently sensitive when used on these stiffer members, the deflections being relatively small. These gages are somewhat difficult to read in the testing machine set-up due to restrictions in space.

The “mirror” gages are always installed at two sections on all tests, to permit measure-

<table>
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<tr>
<th>Dynanometer Type</th>
<th>Test No.</th>
<th>Test Condition</th>
<th>Reading* at start (zero load)</th>
<th>Reading* at end (zero load)</th>
<th>Diff. (micro-inches)</th>
<th>Maximum Thrust During Test (kips)</th>
<th>Thrust Error (kips)</th>
<th>% Error</th>
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<td>150.0</td>
<td>0</td>
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</tbody>
</table>

*This is the dial reading of strain-indicator. In the case of ring dynamometers the “Reading” and “Diff.” are in hundred-thousandths of inches.
TEST OF COLUMNS UNDER COMBINED THRUST AND MOMENT

Fig. 17 - Interaction curves - initial yield & ultimate strength

Fig. 18 - Carry-over factor, its variation with stress

Fig. 19. "Yielding lines" on column after test.

Fig. 20. Knife edge friction test
ment of torsional displacements.

Level Bars

On the pilot test the readings were not reliable and both the technique and the gage base were improved. The measurement scheme is now quite satisfactory, reproducible results being consistently obtained.

Strain Gages

A relatively small number of gages have been used on the tests, and the results although not presented here seem to justify this procedure. Since the elastic behavior is not being emphasized in the investigation, the need for a large number of gages is not acute. After the yield point has been reached at a gage location knowledge of the exact magnitude of strain is not of prime importance.

Knife Edge Friction

From numerous separate observations it is concluded that knife-edge friction has never reached significant proportions. The observed buckling load in the pilot test was less than predicted, the opposite of which would have occurred had there been significant friction. Carry-over and stiffness factors in the elastic region of stress are in good agreement. In addition to this, a test was conducted to investigate any possible friction at the upper knife edge assembly. The results shown in Fig. 20 exceed expectations. The test was conducted by applying an axial load equal to 50% of the buckling load, then applying moment to the upper end taking readings of rotation at various increments. The evidence, then, is that the friction is negligible.

Under the maximum loading attempted thus far, knife edge force reached 16 kips per linear inch of edge.

FUTURE TEST PROGRAM

The general outline is contained in Table I, the investigation to proceed along the lines previously outlined. In the immediate future, the last three tests will be duplicated except on 4” members.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the helpful assistance of William Spraragen, director of the Welding Research Council, LaMotte Grover, chairman of the Structural Steel Committee and T. R. Higgins, chairman of the Lehigh Project Subcommittee. Members of this subcommittee also made valuable suggestions. Several of the recent tests were conducted by Messrs. C. H. Chen and J. M. Ruzek, Research Assistants at the Fritz Engineering Laboratory. Mr. Kenneth Harpel, foreman, directed the work of constructing the test frame and preparing test specimens, and his cooperative assistance and suggestions are appreciated.

BIBLIOGRAPHY

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