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Welded Continuous Frames and Their Components

Progress Report 7

WELDED PORTAL FRAMES TESTED TO COLLAPSE

by

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ABSTRACT

The testing apparatus, measurement techniques and testing procedure for the investigation of the ultimate carrying capacity of welded portal frames are described. Two frames of uniform cross-section (8WF40 and 8B13, respectively) were tested, the loading being carried through the plastic range to failure. Some typical results are given.

A method of providing lateral support to the frames and a simple device for measuring the change in curvature of structural members. are presented.

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INTRODUCTION

The investigation of welded portal frames, the test equipment for which is described in this paper, is part of a current study of "Welded Continuous Frames and Their Components" being conducted at Lehigh University in the Fritz Engineering Laboratory. The type of frame considered is shown in Fig. 1. The research is sponsored jointly by Welding Research Council through the Lehigh Project Subcommittee of its Structural Steel Committee, and the Department of the Navy.

The objectives of the Lehigh study of welded structures are to determine the behavior of steel beams, columns, welded continuous connections, and frames, and on the basis of this knowledge to explore the possibilities of improved methods of analysis and design, due regard being taken of limitations such as large deflections, local and lateral buckling, and fatigue.

Under this program, a study of the plastic behavior of wide flange beams was completed in 1948 (1). A program of tests of columns under combined thrust and moment commenced in 1946 under sponsorship of the American Institute of Steel Construction. The test equipment used in this study is described in an earlier paper of these Proceedings (2). The problem of connections for welded continuous portal frames is treated in three papers (4).

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(1) Numbers refer to bibliography at the end of the paper.

Following these investigations of the component parts of continuous structures, full size portal frames were tested. The principal purposes were:

1) to check the behavior of various frame components (such as connections, columns and beams) with the numerous isolated tests which have been performed.
2) to check actual deformations and internal forces with those predicted by various analytical treatments.

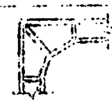
This report is a description of the testing apparatus used in the frame tests. Some representative test results are presented as typical examples of the data collected or to demonstrate the effectiveness of the equipment. In a forthcoming report the complete test resultswill be presented.

Testing procedures used in other full-scale frame investigations are reported upon in Ref. 7, 9-13, all of which list further references. Ref. 7 also presents a survey of related research abroad. However, only a limited number of such tests have been performed in which the loads were carried to complete failure.

TEST PROGRAM AND SPECIMENS

The first test program for portal frames includes three specimens, two of which have been tested. The physical details are shown in Table I.

TABLE I:-TEST FRAME DIMENSIONS

Test Frame	Span	Column Height	Loading	Beam	Column	Connection Type	
1	14'	7'	3/8-pt.	8WF40	8WF40	8B	
2	14'	7'	3/8-pt.	8B13	8B13	8B	
3	14'	7'	To be selected			2B	

All three specimens have the same over-all dimensions. The sections were chosen to agree closely with the previous test specimens of component frame parts. In an earlier program of continuous beam tests (5) a portal frame of the type shown in Fig. 1 was simulated by a three-span continuous beam (span lengths 7', 14' and 7'), the outer supports corresponding to the column bases in actual frame tests. The effects of corner connections and of axial loads are absent in such simulated frame tests. In the previous connection test program the 8B13 section and the same corner connection types were used.

An over-all view of Frame 1 is given in Fig. 2. The welded corner connection type used in Frame 1 and 2 is shown in Fig. 3. Connection type 2B, planned for Frame 3 is a commonly used haunched knee (Table I.).

The loading consists of two equal concentrated vertical loads applied to the beam in the plane of the frame at points 1/4 of the span apart and symmetrical about the frame center-line. This 3/8-point loading was selected to eliminate plastic failure due to shear force. This was not completely successful as some shear failure occurred at the beam ends of Frame 1 (Figs. 2, 3).

Since side-sway and lateral buckling of the beam would cause undesirable complication of the analysis of the tests, such factors were excluded by providing both longitudinal and lateral supports as described in the following. The testing equipment was designed with sufficient capacity to develop the full plastic hinge moments of the rolled section.

DESCRIPTION OF TEST APPARATUS

General views of the test apparatus with Frame 2 in position are shown in Figs. 4 and 5. The main parts of the test apparatus are:

1) Frame column supports
2) Base beam
3) The horizontal reaction assembly fixing the distance between column bases.
4) The longitudinal support preventing side-sway.
5) The supports preventing lateral movement.
6) The loading assemblies by which concentrated loads on the frame beam are applied and measured

Column Supports

The frame columns are welded to heavy base plates (Figs. 5 and 6), which rest on knife-edge supports. Longitudinal movement of the support points is not allowed but rollers are provided at one support. The distance between supports is held constant by means of the horizontal reaction assembly which also makes possible the measurement of the horizontal reaction.

Horizontal Reaction Assembly

On each side of the heavy column base plates pinned connections are provided near the axis of the knife-edge supports (Fig. 6) for two round bar ties which extend between the ends of the columns as shown in Fig. 7. In the side view of the test apparatus, Fig. 5, only the far tie is shown. The longitudinal distance between supports as indicated by the dial gages, Fig.7, is maintained constant throughout the test by means of turnbuckles. Ring dynamometers, one on each tie and supported on three steel balls, enable the measurement of the horizontal force. In Fig. 8 this measured reaction is plotted versus the corresponding load on the frame beam.

Longitudinal Support

Since side-sway is not desired in these introductory tests, it is prevented by a longitudinal support at one frame knee as shown in Figs. 5 and 9. The support is provided by a round flexible bar welded to the frame. The cross-section is reduced near both ends to eliminate undesirable restraints. The same basic type of bar is also used for the lateral supports described below.

Lateral Supports

As indicated in Fig. 5, lateral support is provided at four points along the frame beam in locations where severe plastic straining is expected. In addition, the corner connections are held laterally at the top and bottom points of the diagonal stiffener. Earlier separate tests of corner connections (4) indicated the necessity of securing both these points.

The large deflections of the frame beam in the plastic range would cause an appreciable slope in the lateral supporting bars if means of vertical adjustment were not provided. The resultant force would pull the frame out of alignment. A method was developed to provide for adjusting these bars and is shown in Fig. 10. The corners of the frame do not deflect appreciably, and no vertical adjustment of lateral support is needed at these points, (Fig. 11). The right-hand connection for the corner bars as shown in this figure is too flexible; the bars should have been welded directly to the I-beam.

During testing the lateral support rods were adjusted at intervals so that their fixed ends were 1" below the ends connected to the frame. A further deflection of 2" of the frame beam at the point of lateral support could then be tolerated before a new adjustment became necessary. The extreme horizontal deflection of the frame due to slope of these bars is less than 0.002".

Loading Assemblies

Loads were applied to the frame beam by means of manually operated hydraulic jacks. Aluminum tube dynamometers of 85,000-lb. capacity were used for load measurement on Frame 1 (8WF40 shape). For Frame 2 (8B13 shape) the expected maximum loads were appreciably smaller, and ring dynamometers of 30,000 lbs. capacity were used as shown in Fig. 12.

The concentrated loads were transferred to the frame beam through load-carriers welded to the beam web and flanges as described in Ref. 1. The loading assemblies are pin-connected to the load-carriers at the top and to the base beam at the bottom (Fig. 5). A spherical bearing inserted between the dynamometer and the frame further ensures pure tension in the loading assemblies and simplifies the procedure for aligning the frame prior to test.

The maximum stroke of the hydraulic jacks is 12". In Frame 1 resetting of the jacks was necessary since the test was carried on to a center deflection of more than 13 in. On the second test only about half of one stroke was required to bring about collapse.

Loading schemes used in other frame tests [7, 9-13] are pictured in Fig. 13. The use of dead loads precludes a study of frame behavior at deflections greater than that at the maximum load since the assembly collapses when the maximum load is reached. The use of a testing machine usually limits the frame size or type of loading that may be applied. The use of hydraulic jacks is advantageous for testing full-size frames to determine ultimate strength and load-deformation relationships beyond the maximum load.

Longitudinal Loading Device

In a future test program. it is planned to investigate the effect of combined vertical and side loading in the plane of the frame. The side loading would be applied as concentrated third-point loads on one column with a direction causing compressive axial load in the frame beam. Such a loading simulates the actual condition of side-sway caused by wind or blast forces on the windward column. This loading is somewhat more complicated to simulate in the laboratory than a simple tensile force applied along the extension of the beam-axis, as used in earlier tests by other investigators [7] (Fig. 13). However, the difference between these two methods of producing side-sway is important. Application of single tensile force will superimpose tensile stresses across the beam section, whereas application of a compression load on the windward side is more realistic and results in an added compressive stress in the beam which would cause it to buckle laterally at a lower load.

For inclusion of side-sway in future frame tests, the test apparatus may be altered as indicated on Fig. 14. The vertical loading assembly would be adjusted at each load increment to maintain its vertical position. The same horizontal reaction assembly as described above would be used to measure the horizontal reaction at the roller-supported column base. By subtracting this reaction from the total horizontal load applied, the other horizontal reaction at the anchored support may be found.

MEASUREMENT TECHNIQUES

Dynamometers

As indicated above, ring dynamometers fitted with dial gages were used to determine the applied loads on Frame 2 (Fig. 12), and to measure the horizontal reactions in both tests (Figs. 2 and 5). The Bourdon tube pressure gages attached to the hydraulic pumps were used only as a rough check on the applied loads.

The expected magnitude of loads on Frame 1 (P_{max} = 55 kips) required larger capacity dynamometers than were available with rings. Dynamometers of 85 kips capacity were fabricated from 8 1/2" diameter 61S-T6 aluminum tubing (Figs. 2 and 5). The details of the tube dynamometers are shown in Fig. 15. These dynamometers, designed for the tests reported in Ref. 5, are similar to those described in an earlier Progress Report [2]. Four SR-4 strain gages, Type AD-1, are mounted on each tube in an arrangement which eliminates the effects of temperature variations and cancels any bending stress. A similar application of SR-4 strain gages on aluminum torque-meters is described in Ref. 8.

Deflections

Deflections along the beam and columns were measured at locations shown in Fig. 16. Dial gages (1/1000) were mounted on a stiff deflection dial bridge supported on the frame at the intersections of the beam and column axes. At one connection the bridge rests on a knife-edge support (Fig. 16, Detail "A"). At the other knee a roller support is provided (Fig. 16, Detail "B") to allow for shortening of the beam during the test. Vertical deflections of the beam are thus measured relative to a line connecting the frame corners; column deflections are measured relative to the longitudinally fixed knee.

Local Buckling of Flange

Dial gages were mounted between flanges at critical locations (Fig. 17) to indicate flange buckling. Fig. 17 also shows details of a "local buckling dial gage" in use. In the later stages of the test the deformation becomes quite pronounced, an example of which is shown in Fig. 3.

Rotations

Fig. 18 gives the typical locations of these measurements. The rotations of cross-section at the various points along the frame are measured by level bars of the type shown in Fig. 19. The level bars are attached to the frame by means of brackets of the same type as used for the lateral supports, Fig. 10, the effect of shear distortion in the web being eliminated by welding the brackets to the flange-web fillets. This method of attachment also gives the best average of the cross-section rotation due to bending.

Curvature

For purposes of structural analysis it is important to know the relation between the moment M and the angle change Ø, for a unit length of member. From this M-Ø relationship slopes and deflections may be computed both in the elastic and the plastic range. The direct measurement of the curvature Ø is therefore an important part of the experimental investigation.

The center portion of the frame beam is subjected to a uniform moment. The curvature Ø at the centerline has been determined in the past by three different methods:

1) Deflection readings from three dial gages (Fig. 20).
2) Data from SR-4 strain gages mounted above and below the neutral axis of the beam (Fig. 20).
3) Change in slope as determined by means of two level bars.

For several reasons it was desirable to improve this technique. Method 1 is often insensitive in the elastic range, and for dependable results it requires that a considerable length of the member be under uniform moment. Method 2 gives a rather localized picture of the M-Ø relationship, is expensive in use of SR-4 gages, and unless post-yield gages are used does not provide an adequate range of measurement.

A device called a rotation indicator was therefore developed to measure the relative rotation of two neighboring cross-sections. This device may be used repeatedly on successive tests and for installation only requires the welding of the attachment device to the specimen. This rotation indicator is pictured in Fig. 20. It consists of two parallel steel lever arms rigidly welded to the beam at the fillets and symmetrically placed on each side of the section at which the curvature is to be measured. Brackets similar to those used for lateral support and described above, Fig. 10, joined the lever arms to the beam. The relative rotation of these arms is measured by means of two dial gages mounted at a known distance (12 1/2") above and below the frame axis. The curvature of the beam between the arms equals the measured angle change divided by the distance (4") between the two arms. Denoting the simultaneous dial reading differences as R_1 and R_2, respectively, the curvature ϕ is given by

$$\phi = \frac{R_1 - R_2}{4x25} = 0.01 \ (R_1 - R_2)$$

The curvature as measured by this rotation indicator is sensitive to about 10^{-5} radian, or 2 seconds which is quite sufficient for all practical purposes.

A comparison of results obtained by using the four methods for determining ϕ is given in Fig. 21. The four methods give results which agree closely. The rotation indicator provides the largest range of rotation and the dials may be reset if necessary.

The rotation indicator will also give satisfactory results at sections where the moment has a gradient; one dial was applied at the top of the column in a region of strain-hardening. While the strain-gage technique may also be used under these conditions, method 1 is not feasible.

Another function of the rotation indicator is to measure the rotation in the connections. In the past this has been accomplished with the aid of level bars [4], a procedure that was also used on Frame 1. On Frame 2, however, rotation indicators were used on both corner connections, replacing the level bar technique (Fig. 18). The rotation indicator is attached to the end of the beam and the top of the column, adjacent to the connection using the same brackets as were previously used for level bar supports. The indicator thus extends across the connection and measures the total rotation due to shear and moment.

Strains

Strains were measured by means of SR-4 gages, typical locations being indicated in Fig. 18. Many gages were used on the corner connection to determine, (1) the thrust transmission from flange to web and, (2) the shear stress carried by the web compared to direct stress in the stiffeners. These readings will provide comparison with the previous tests of corner connection [4].

As noted above, A-11 type gages in pairs at points 2" on either side of the frame axis yielded information on the curvature of the beam and the columns at various points.

TESTING PROCEDURE AND REPRESENTATIVE RESULTS

Test Set-Up

After erection of the test frame on the knife edges and roller bearings, attachment of the longitudinal and lateral supports to the frame, and mounting of loading assemblies and the horizontal reaction assembly, a set of zero readings was taken on all deflection dials, local buckling flange dials, level bars, rotation indicators, and strain gages. The initial readings of the horizontal dial gages shown in Fig. 7 which indicate the distance between column bases are the basis for maintaining a constant distance between supports. After each load increment the turnbuckles were used to return the column base mounted on rollers to its initial position. The test thus simulated a pin-end condition, and the loading and moment diagram for the frame is as shown in Fig. 23.

If simply supported, the frame beam of Fig. 23 would experience a maximum moment of

$$M_s = \frac{3}{8} PL \tag{1}$$

The horizontal reaction H at the column bases causes a restraining haunch moment

$$M_h' = Hh_1 \tag{2}$$

and the beam moment between load points is decreased by this amount:

$$M'_b = M_s - M'_h = \frac{3}{8} PL - Hh_1 \tag{3}$$

The horizontal reaction H is carried by the beam as an axial compressive force. In the plastic range the beam deflection δ becomes large and the additional beam moment due to this axial force,

$$M_b = H\delta \qquad (4)$$

can no longer be neglected. The magnitude of this correction, in percent of the total moment at the beam (Frame 1), is:

0.6% at working load, $\frac{P_y}{1.65}$,	$P = 26^k$, $\delta = 0.5''$
1 % at calculated yield load,	$P = 39^k$, $\delta = 0.9''$
11 % as shown in Fig. 24 for.	$P = 50^k$, $\delta = 7.2''$
20 % at the ultimate load,	$P = 55^k$, $\delta = 12.4''$

A correction may also be considered due to the friction force αP at the roller base, where α is the coefficient of rolling friction. The haunch moment Eq. (2), corrected for this influence, becomes (Fig. 23)

$$M_h = Hh_1 - \alpha Ph_2 \qquad (5)$$

The value of α can be taken as 0.01*, and its effect on the critical moments at the haunch and the beam center is then between 2.3 and 3.0 %. An error in the assumed value of α will therefore be of small consequence.

The maximum moment in the beam including the effect of beam deflection and roller friction, neglecting the small product $\alpha \cdot \delta$, finally becomes (6)

$$\underline{M_b} = M_s - M_h + (H - \alpha P)\delta = \underline{P\left(\frac{3}{8}L + \alpha h_2\right) - H(h_1 - \delta)}$$

*0.005 for each contact surface. See Marks' MECHANICAL ENGINEERING HANDBOOK, 5.Ed., 1951, p. 223.

At the knee, the critical moment occurs in the beam or the column next to the comparatively rigid corner connection. For the loading and proportions of these frames the critical section is in the column at a distance $\frac{d}{2}$ from the theoretical corner (d = depth of the rolled section). From Eq. (5) this moment M_r is given by

$$M_r = H(h_1 - \frac{d}{2}) - \alpha P(h_2 - \frac{d}{2}) \qquad (7)$$

As the test is carried into the plastic region, yielding must be expected to develop due to these two critical moments M_b and M_r, Eqs. (6) and (7). The 3/8-point loading, dictated by the consideration of avoiding plastic shear failure, caused the center moment to be the larger of the two. In the absence of residual stresses and stress concentrations, plastic deformation would therefore first occur in the center portion of the beam and would be followed by plastic deformation near the top of the columns. Since both stress concentrations and residual stresses were present, location of the first yield line would probably not follow the predicted pattern. Ultimately, however, significant plastic deformations would be expected both at the center portion of the beam and at the haunches. This behavior was verified by tests, as pictured in Figs. 25 and 3.

Testing Procedure

After frame alignment was completed and before the actual test was run, a "friction test" was performed, the purpose of which was to give a check on the complete test set up. Readings on all gages were taken during a loading up to about one-third of the load calculated to give initial yield. The observed deflections, rotations, etc. were plotted in comparison with the corresponding theoretical curves; discrepancies would indicate the need of further alignment of the frame or adjustment of the gages.

The main test was then carried out. In the elastic range, load was applied simultaneously at the two load points until the dynamometers indicated the desired load. The horizontal translation of the roller support during load application was then eliminated by means of the turnbuckles on the horizontal reaction assemblies, and the necessary readigns, photographs, and yield line sketches were taken. Due to stress concentrations and residual stresses, local yield was expected and did occur at loads below the theoretically predicted initial yield load.

The initial load increments for Frame 1 were 2.5 kips or 10% of the load expected to cause initial yield. After yielding had occurred, the increments were reduced to 1.0 kips, or 2% of the ultimate load. For the weaker Frame 2, load increments of 0.5 kips were applied throughout, corresponding to about 4% of the initial yield load.

In the plastic range appreciable deformations take place under constant load for some time after the application of a load increment. This is due to the penetration of yielded zones ("wedges") into the specimen. A criterion is therefore needed to indicate when such plastic creep has ceased to be of importance, and when readings can be taken. The adopted criterion was as follows: When the increase of deflection of the frame centerline over a 15-minute period was no greater than 0.0015", it was assumed that sufficiently stable conditions had been reached, and readings were taken. Curves showing the increase in center deflection under constant load are plotted for various load increments in Fig. 26. This criterion was selected on the basis of previous experience with continuous beam tests employing the same cross-section and involving similar moment distribution. It appears to be adequate also in these frame tests. With the adoption of this criterion, however, a considerable amount of time was required for performance of each test. This may be seen from Fig. 26.

The possibility of reducing the criterion requirement without introducing appreciable experimental error is of interest. For the present, the selection of the criterion is rather arbitrary, being selected for each particular member. In each case, the criterion to be adopted will be a function of the length of member yielding, the type and size of cross-section, and length of span. The attainment of a general criterion applicable to a variety of conditions will require further study.

After the maximum load was reached the test was continued through larger deformations in order to study the effects of excessive rotation at critical sections and to observe the ability of the frame to deform and at the same time to carry an appreciable percentage of the maximum load. For example, the energy absorption is an important factor in studying the response of structures to blast loading. There is an obvious difference in behavior of the two frames whose load-deflection relationships are plotted in Fig. 27.

Experimental points on the "unloading" portion of the load-deflection curves are determined by deforming the frame until a pre-determined centerline deflection has been reached. After allowing the frame to come to equilibrium, readings of load and deflection were then obtained. This procedure is being followed currently on tests at the Fritz Laboratory, deformation of the structure being increased until the load has dropped below about 70% of the maximum value recorded during the test.

Test Results

A report of test results and analysis will be presented in a separate article. Only a few representative results related to the testing technique are presented here.

The frame tested is statically indeterminate to the first degree. By measuring the horizontal force applied to each column base, the test frame becomes determinate, and statics may be used to determine the moment distribution. However, in more complicated types of frames it may not be possible to measure all reactions, with the result that the frame as tested may also be indeterminate.

The question of interest to the experimental is as follows: with what accuracy may the distribution of stresses around the frame be predicted on the basis of measurements of strains, rotations and deflections? It is probable that little difficulty would be experienced in the elastic range. However, in the plastic range the measured relationship between moment and deformation in as-delivered steel members does not correlate well with available theory [5].

It therefore seems that the strains, rotations or deformations from which the stress distribution around the frame would be deduced should be measured on parts of the frame which remain in the elastic range throughout the test. If forces and moments can be predicted from the above-mentioned measurements alone, then more complicated frames may be tested with assurance that the measurements would afford some means of explaining the behavior observed.

As a partial answer to this question, the moment distribution around Frame 2 is calculated on basis of SR-4 strain gage readings at locations A, B, and C, Fig. 28. These strain gages remain in the elastic range throughout the test. Each pair of these gages permits the determination of curvature at the corresponding frame cross-section, from which the moments are computed as shown by dotted lines in Fig. 29 for four load levels during the test. These moments agree well with the actual moment distribution as determined from the applied loads P and the measured horizontal reactions H. Thus, the moment distribution could have been determined with sufficient accuracy without measuring H.

A similar evaluation of the axial force in the members from the SR-4 strain gage readings gave a poor agreement with the actual values. This deficiency is ascribed to the fact that both gages in all the pairs (Fig. 28) were mounted on the same side of the web, thus including strain due to bending of the members about its weak axis. Such bending is introduced by the lateral support rods during deflection of the beam, and by possible eccentricity of the horizontal reaction assembly. In cases when the SR-4 gages would be depended upon also to indicate axial forces they should be mounted in pairs on both sides of the web.

Fig. 21 shows the relation between the moment M and the curvature ϕ at the mid-point of the beam. The four curves, as mentioned earlier, correspond to the four different methods of measuring ϕ. Following the proportionality between moment and curvature in the elastic region, the curvature increases greatly in the plastic range with practically no increase in moment, until strain hardening occurs and causes further increase in moment-carrying capacity of the section.

Fig. 30 shows the deflection at mid-span of the beam as a function of the load P for Frames 1 and 2. The calculated and the observed initial yield loads are indicated. Both frames demonstrate an appreciable reserve strength above this load.

SUMMARY

A testing technique is described for investigating the behavior of full-size welded portal frames (Fig. 1) through the elastic and plastic range to collapse.

The frame tests described are part of an investigation of welded continuous frames and their components. The complete results of the tests will be presented in a paper now in preparation. This report describes and evaluates testing methods and equipment summarized below:

1. The test set-up (Fig. 5), and the technique used for measuring deflections (Fig. 16), slopes (Fig. 19), curvatures (Fig. 20), strains (Fig. 18), and loads (Figs. 7, 12, 15) are described in detail. The performance of the test equipment proved satisfactory.
2. The loading device (Fig. 12) made it possible to apply loads through the elastic and plastic range and also to determine the load-deformation relationship beyond the maximum load.
3. The scheme shown in Fig. 14 is recommended for tests including side loading.
4. A rotation indicator (Fig. 20) used for the first time in these tests allows the measurement of curvature of structural members and may also be used to determine corner connection rotations (Fig. 22). This device has a larger range, is simpler and more economical in use than combinations of deflection dials, level bars, or SR-4 gages.

5. The distribution of moment around the test frames may be predicted with satisfactory engineering accuracy by means of SR - 4 gages mounted on parts of the frame which remain in the elastic range throughout the test (Fig. 29).
6. Representative results from the test of two full-size portal frames are shown in Figs. 8, 21, 27 and 30.

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STRENGTH OF RIVETED AND WELDED STEEL RIGID FRAMES
Journal of Research, National Bureau of Standards; three papers:
Vol. 21, 1938, p. 269, Research Paper No. 1130
Vol. 21, 1938, p. 853, Research Paper No. 1161
Vol. 23, 1939, p. 145, Research Paper No. 1224

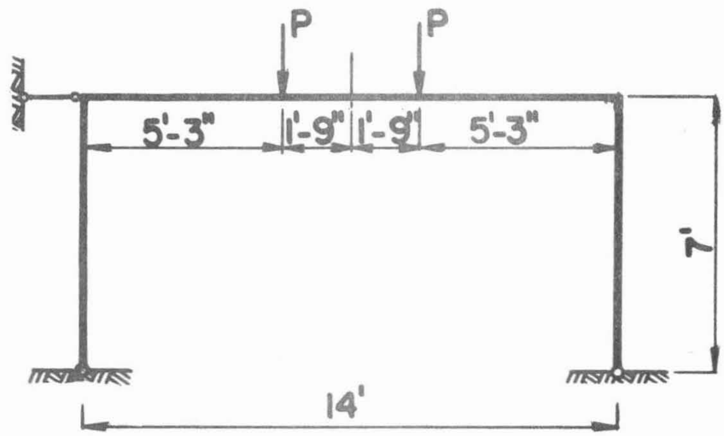


FIG. 1. TYPE OF FRAME AND LOADING

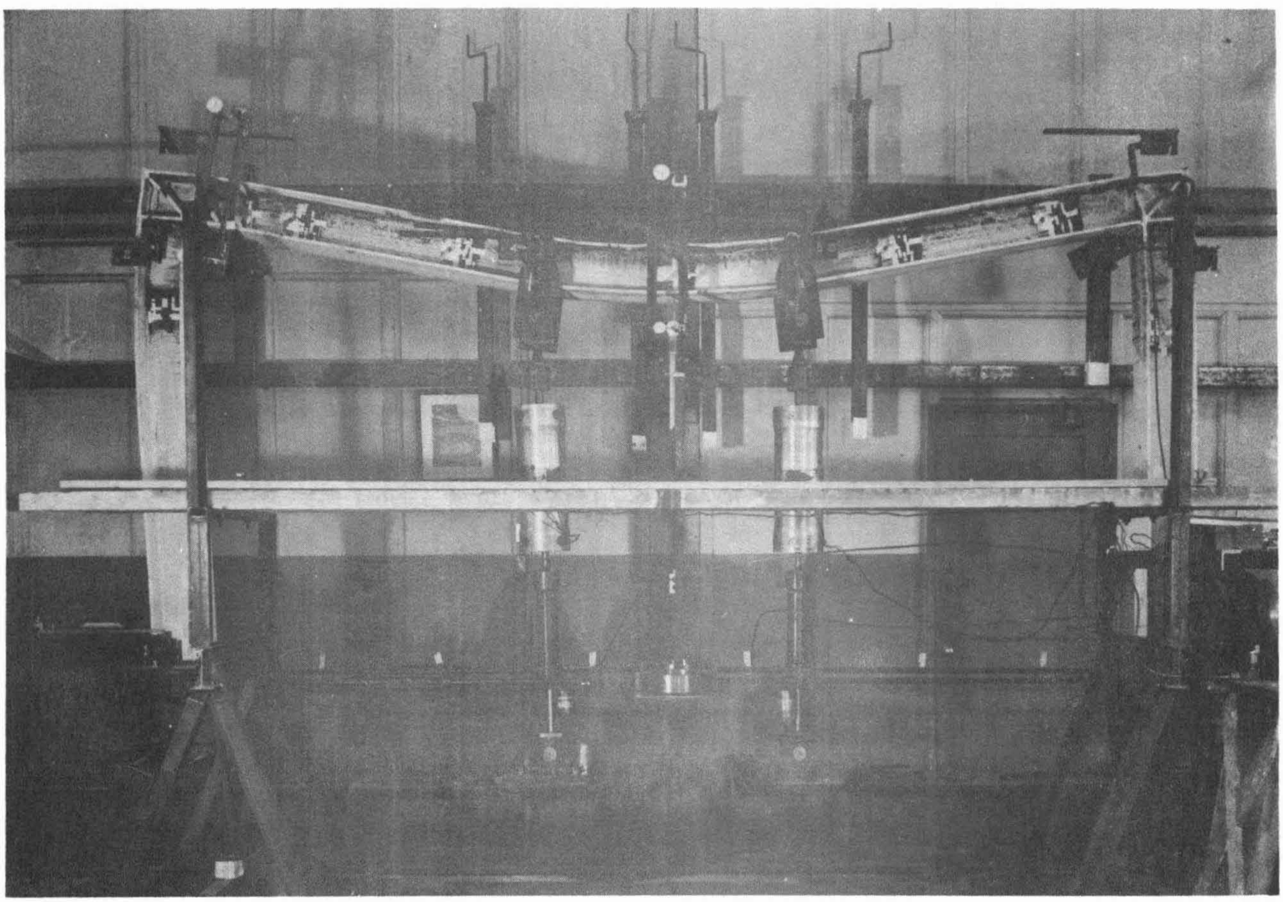


FIG. 2. OVER-ALL VIEW OF TEST APPARATUS WITH FRAME I TESTED TO COLLAPSE.

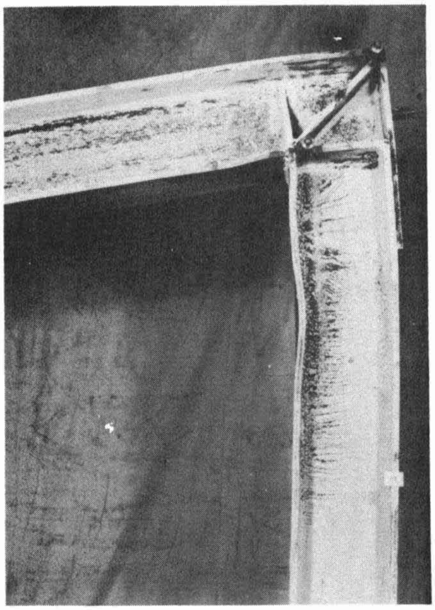


FIG. 3. CORNER CONNECTION TYPE 8B AFTER COLLAPSE OF FRAME. CUT-OFF TRANSVERSE AND LONGITUDINAL LATERAL SUPPORTS SHOWN, ALSO END SUPPORT FOR DEFLECTION DIAL BRIDGE. NOTE YIELD LINES IN WHITEWASH AND LOCAL BUCKLING OF COLUMN FLANGE

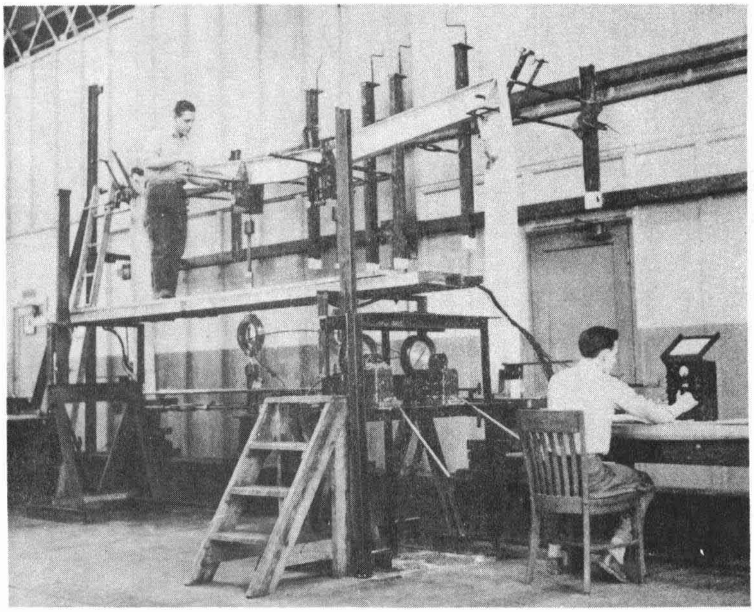


FIG. 4. GENERAL VIEW OF TEST SET-UP, SHOWING HYDRAULIC PUMPS FOR LOADING JACKS, AND SR-4 STRAIN INDICATOR

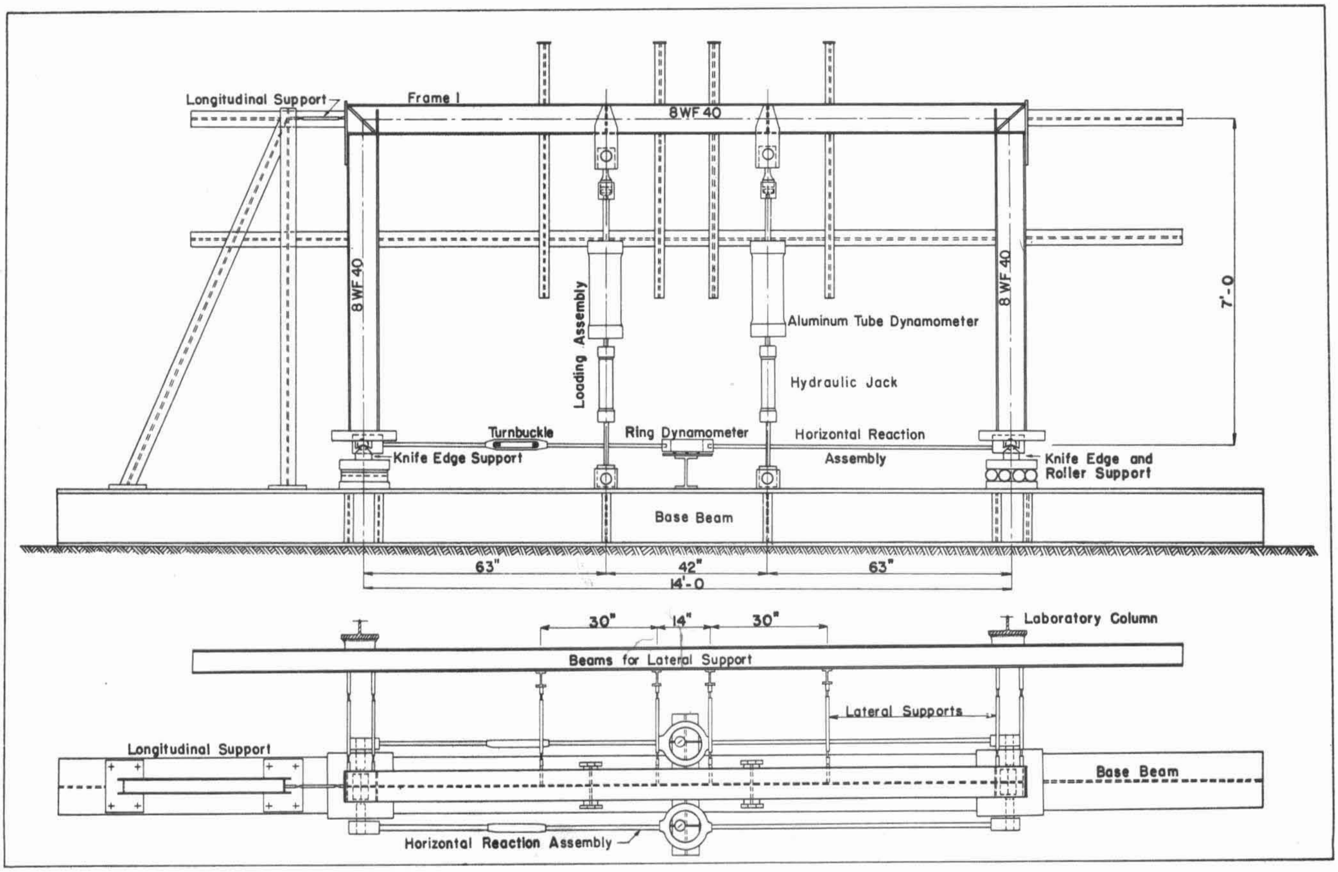
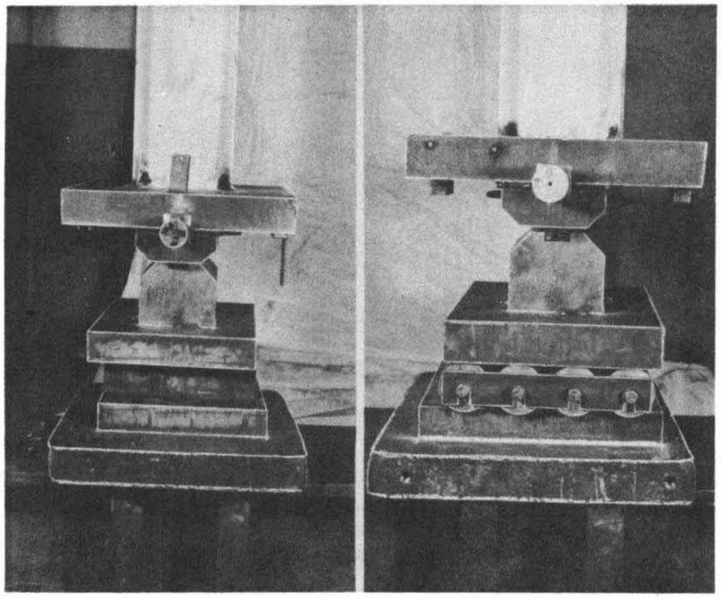


FIG. 5. TEST SET-UP



KNIFE EDGE SUPPORT   KNIFE EDGE AND ROLLER SUPPORT

FIG. 6. FRAME COLUMN SUPPORTS

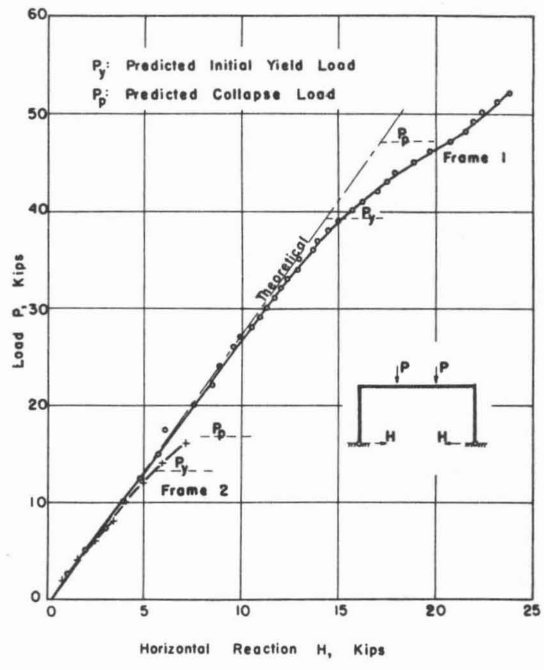


FIG. 8. HORIZONTAL REACTION AT COLUMN BASES

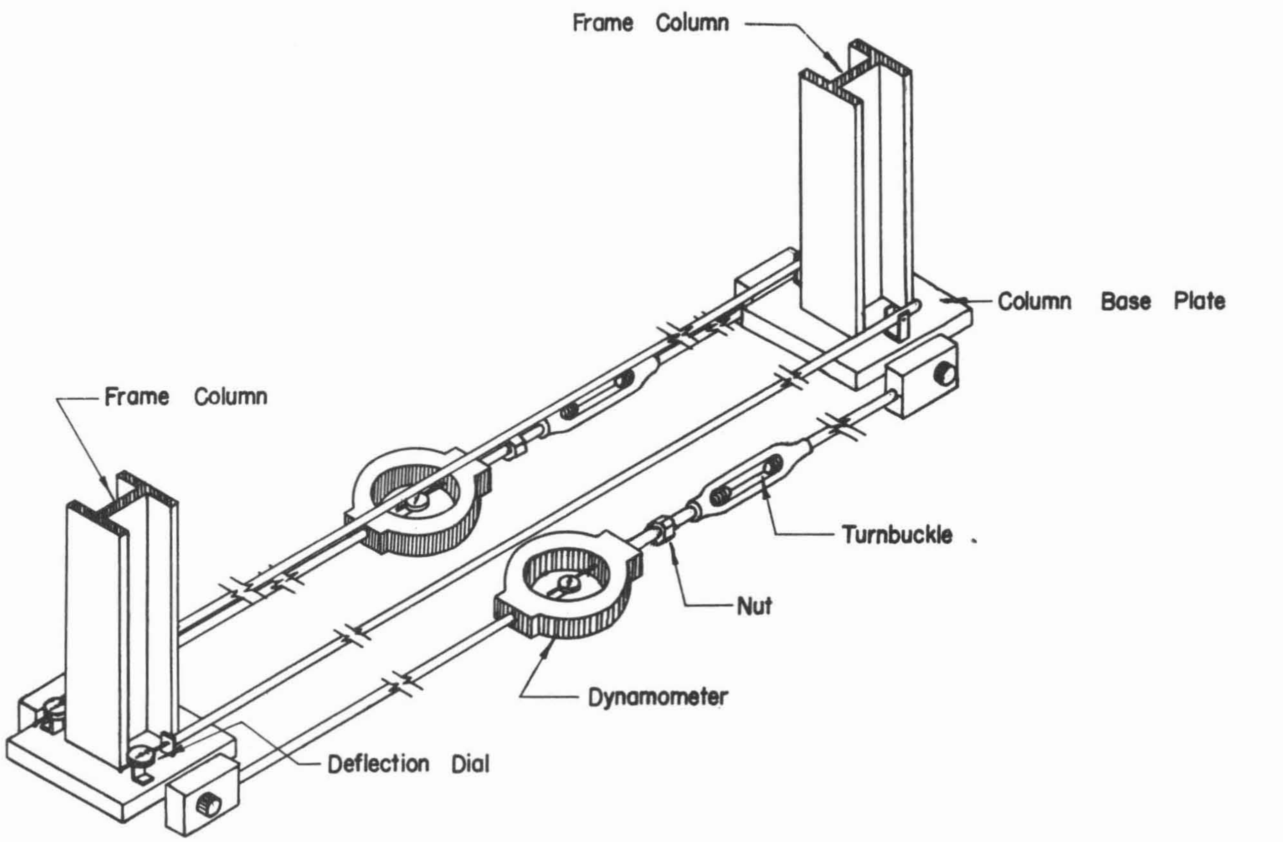
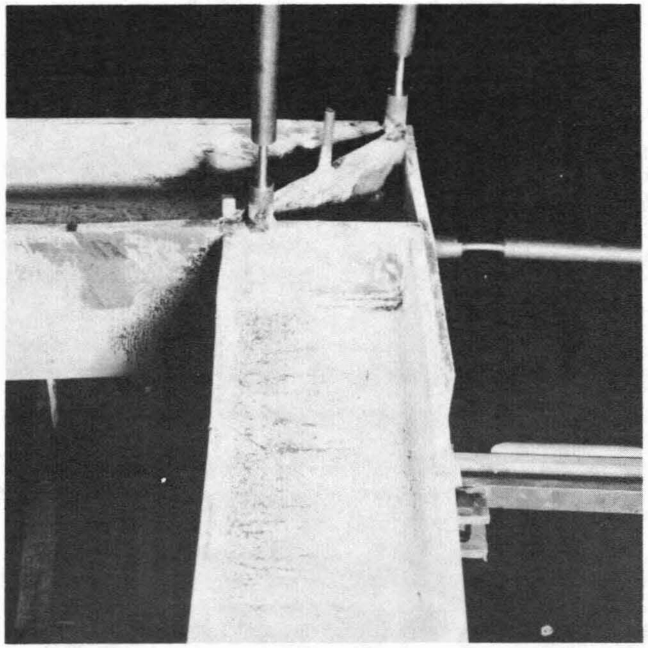


FIG. 7. HORIZONTAL REACTION ASSEMBLY



LONGITUDINAL AND TRANSVERSE LATERAL SUPPORTS

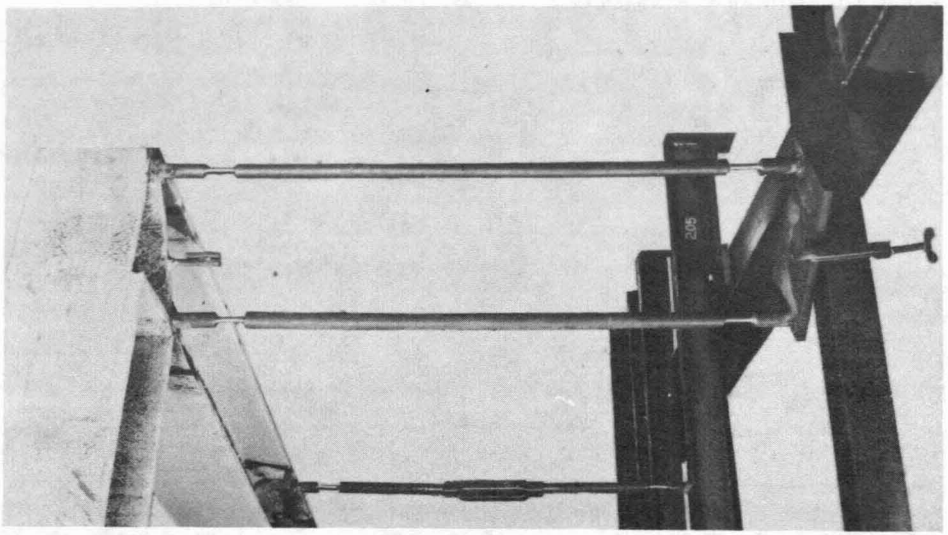


FIG. 11. LATERAL SUPPORT AT CORNER CONNECTION AND ALONG FRAME BEAM

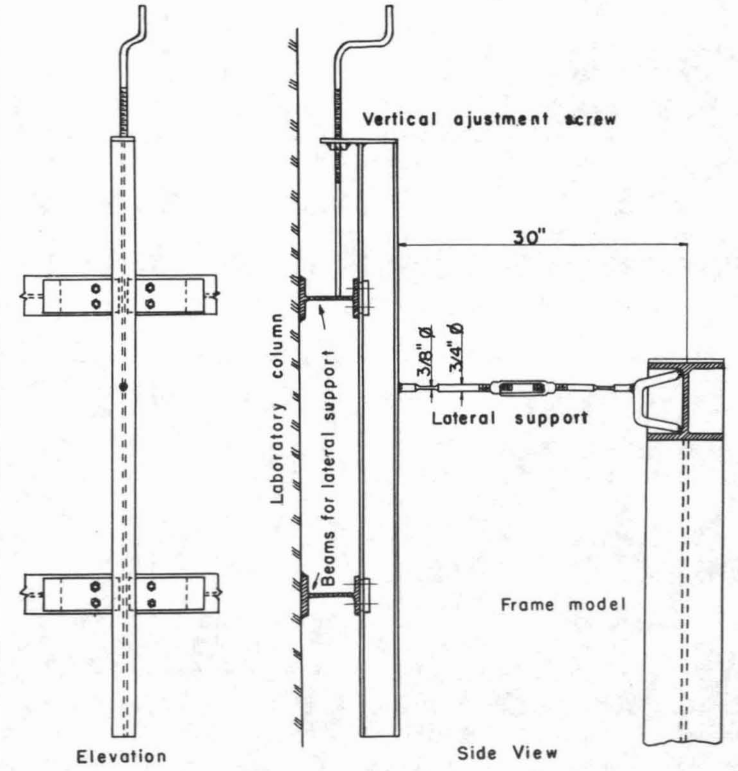


FIG. 10. LATERAL SUPPORT

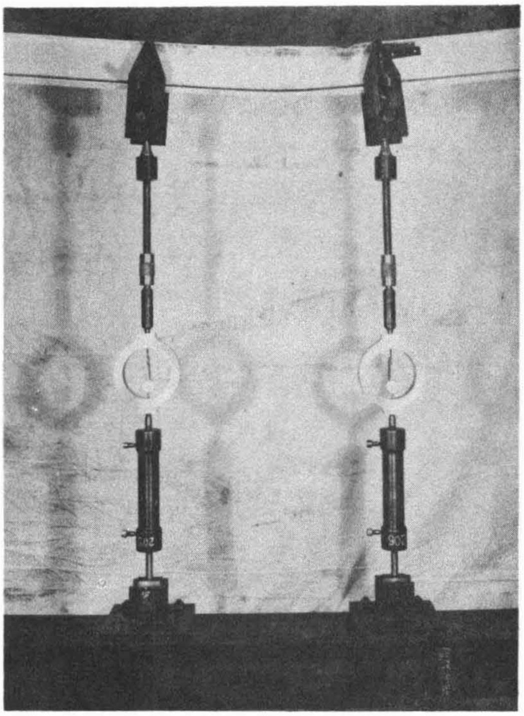
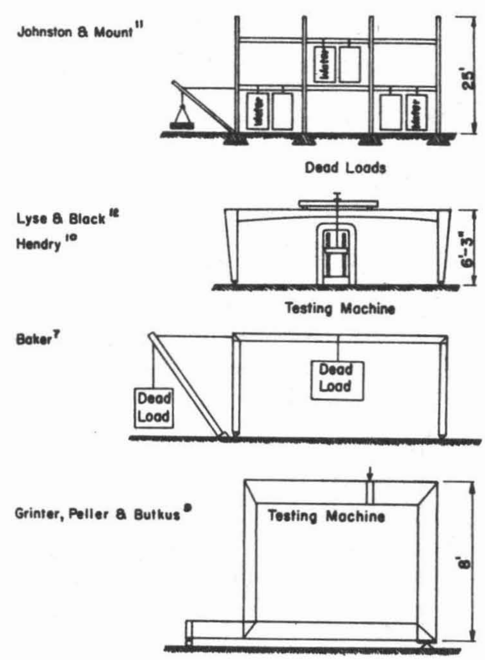


FIG. 12. LOADING ASSEMBLIES FOR FRAME 2. HYDRAULIC JACKS AND RING DYNAMOMETERS

FIG. 13 LOADING SCHEMES USED IN FRAME TESTS



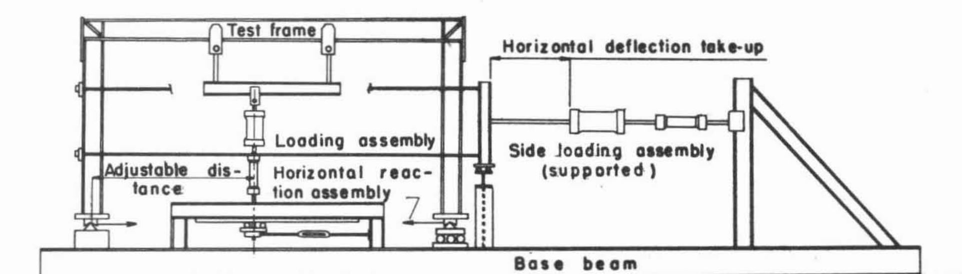


FIG. 14. COMBINED VERTICAL AND LONGITUDINAL LOADING DEVICE

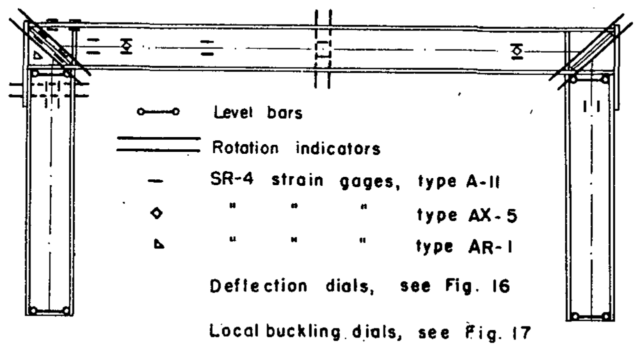


FIG. 18. LOCATION OF GAGES ON FRAME 2.

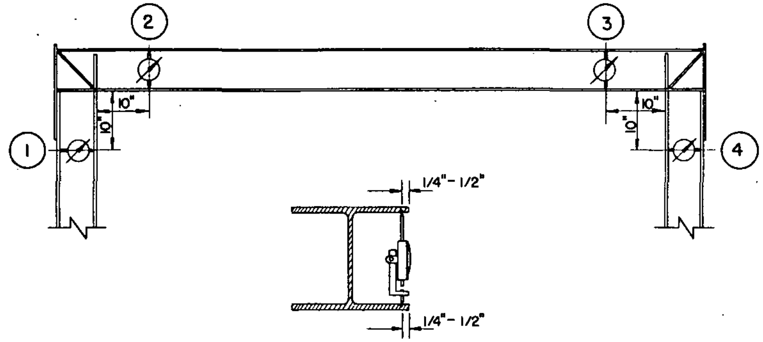


FIG. 17. LOCAL FLANGE BUCKLING DIALS

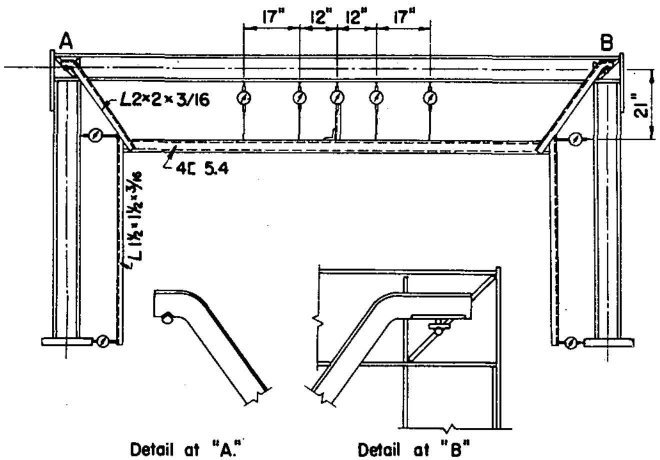


FIG. 16. DEFLECTION DIAL SUPPORT

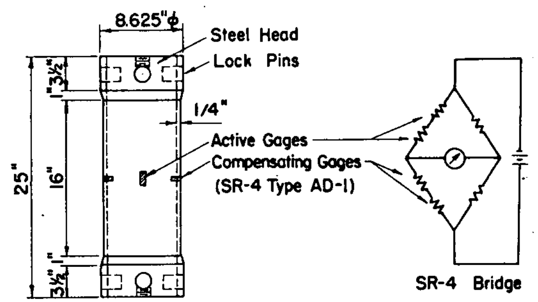


FIG. 15. 85-KIP ALUMINUM TUBE DYNAMOMETER

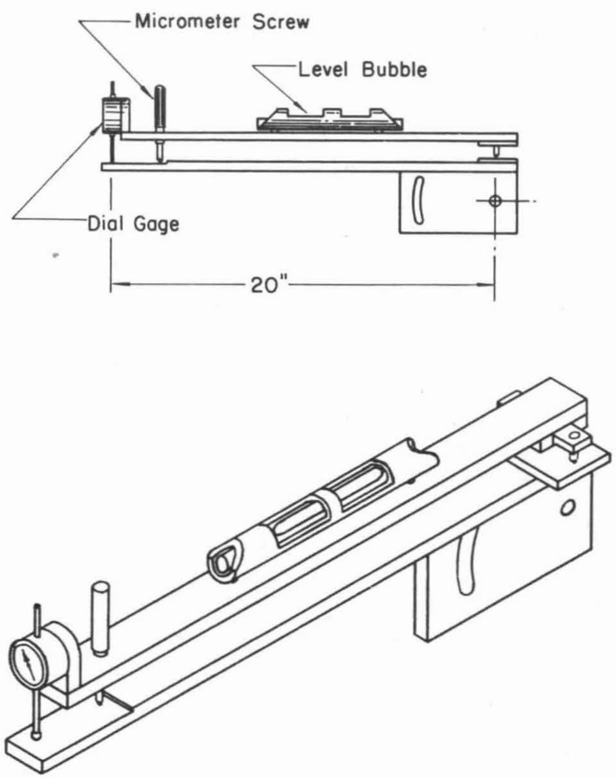


FIG. 19 LEVEL BAR

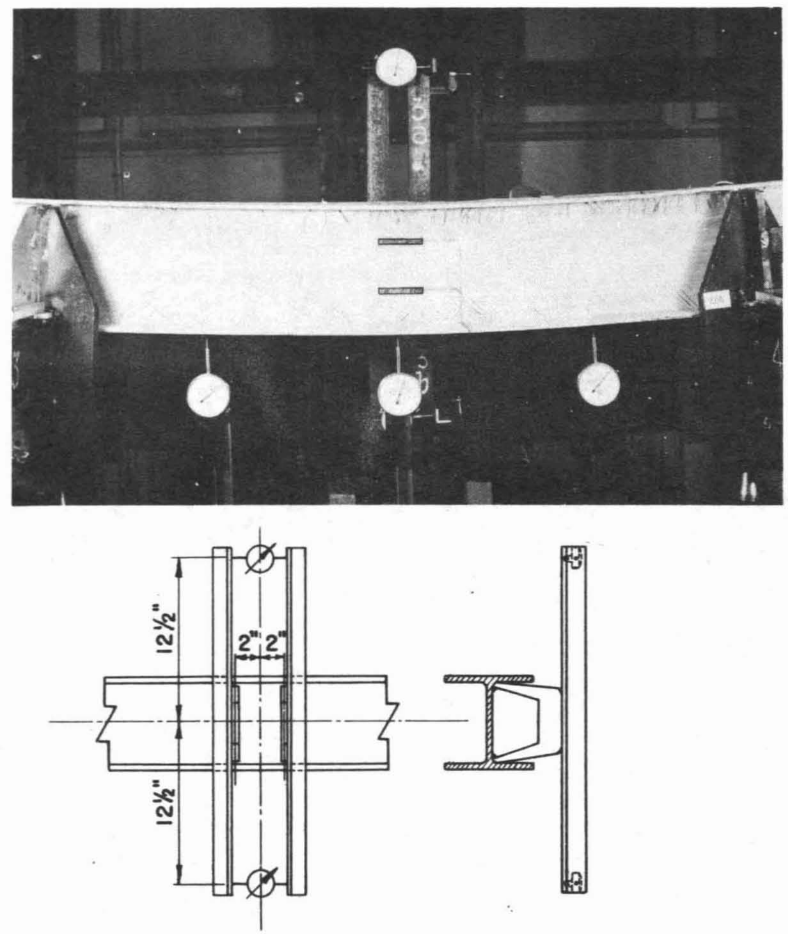


FIG. 20. THREE MEANS OF MEASURING CURVATURE

a) Three deflection dials

b) Two SR-4 gages

c) A rotation indicator

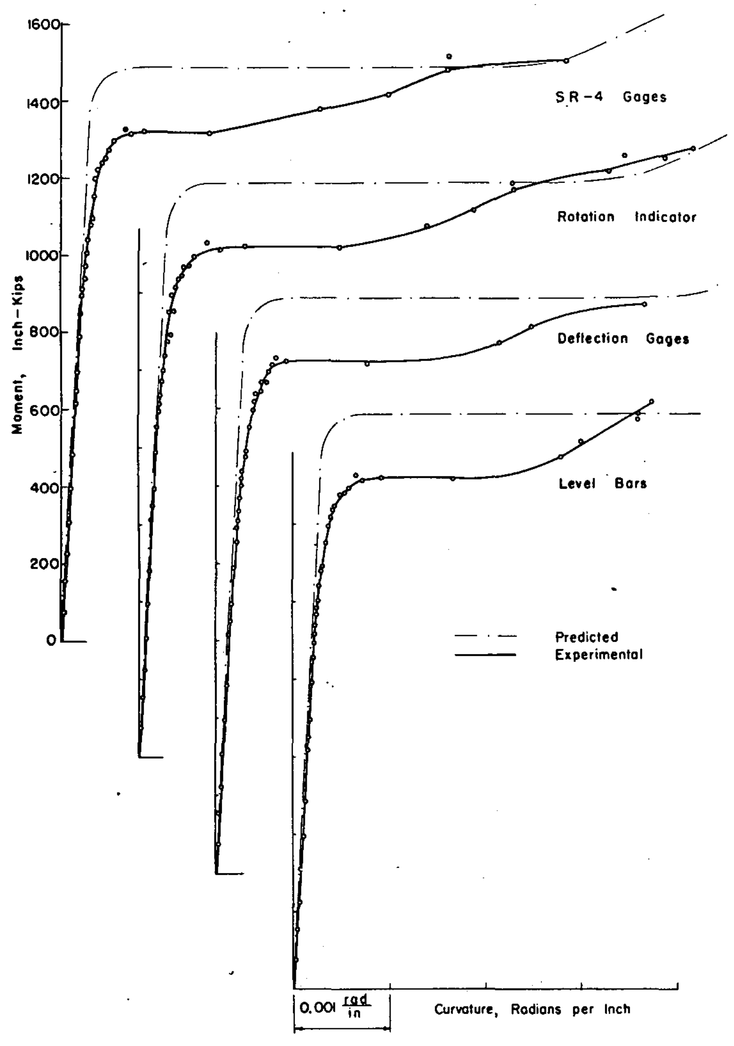


FIG. 21. MOMENT-CURVATURE RELATIONSHIP AT MID-SPAN OF BEAM, FRAME 1

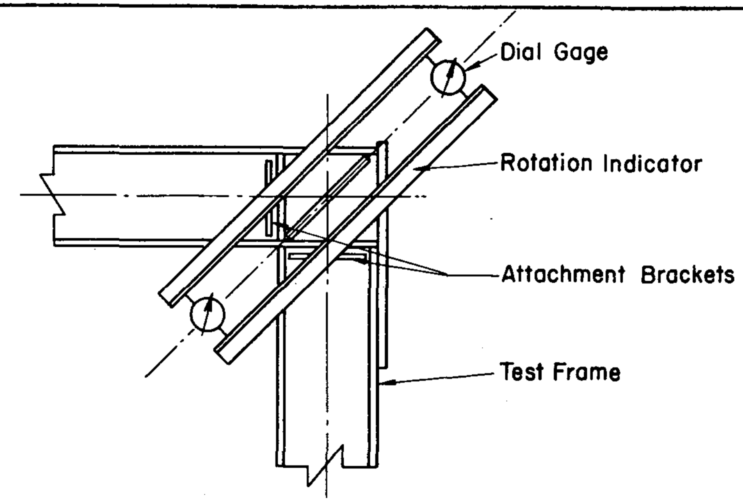


FIG. 22. CORNER CONNECTION ROTATION MEASURED BY ROTATION INDICATOR

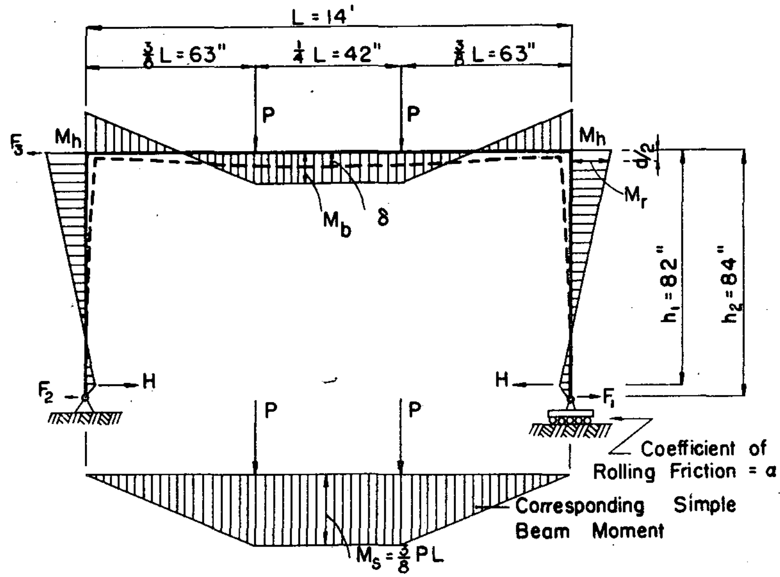


FIG. 23. TEST LOADS AND MOMENTS

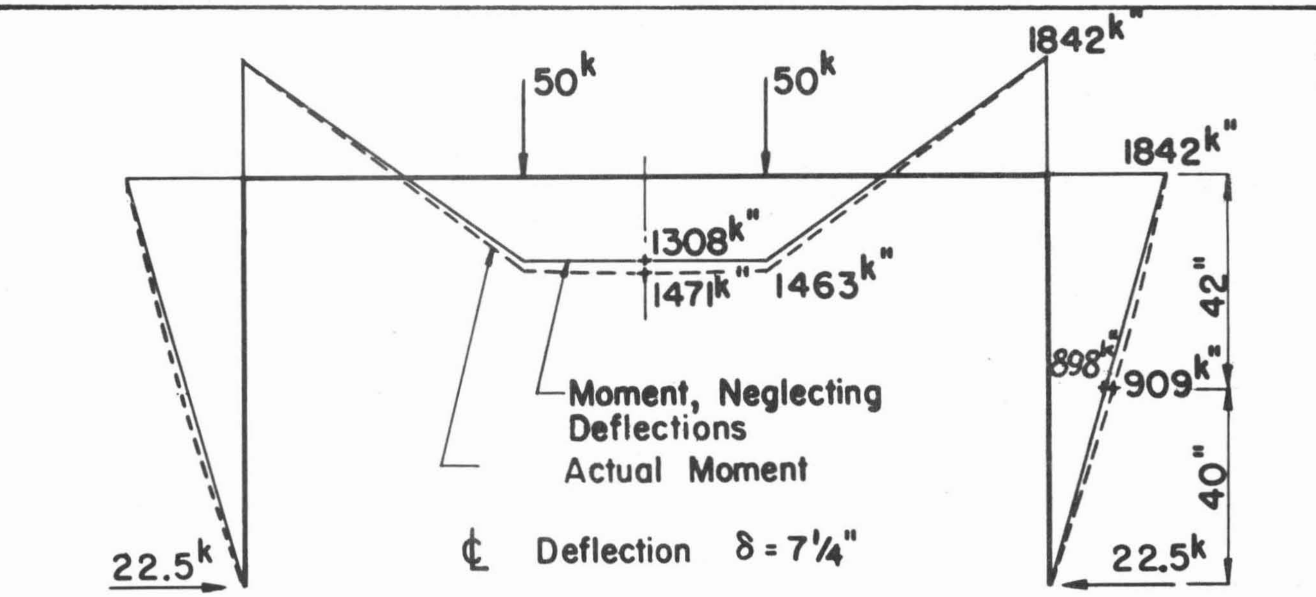


FIG. 24. INFLUENCE OF DEFLECTION ON THE MOMENT DISTRIBUTION, FRAME 1

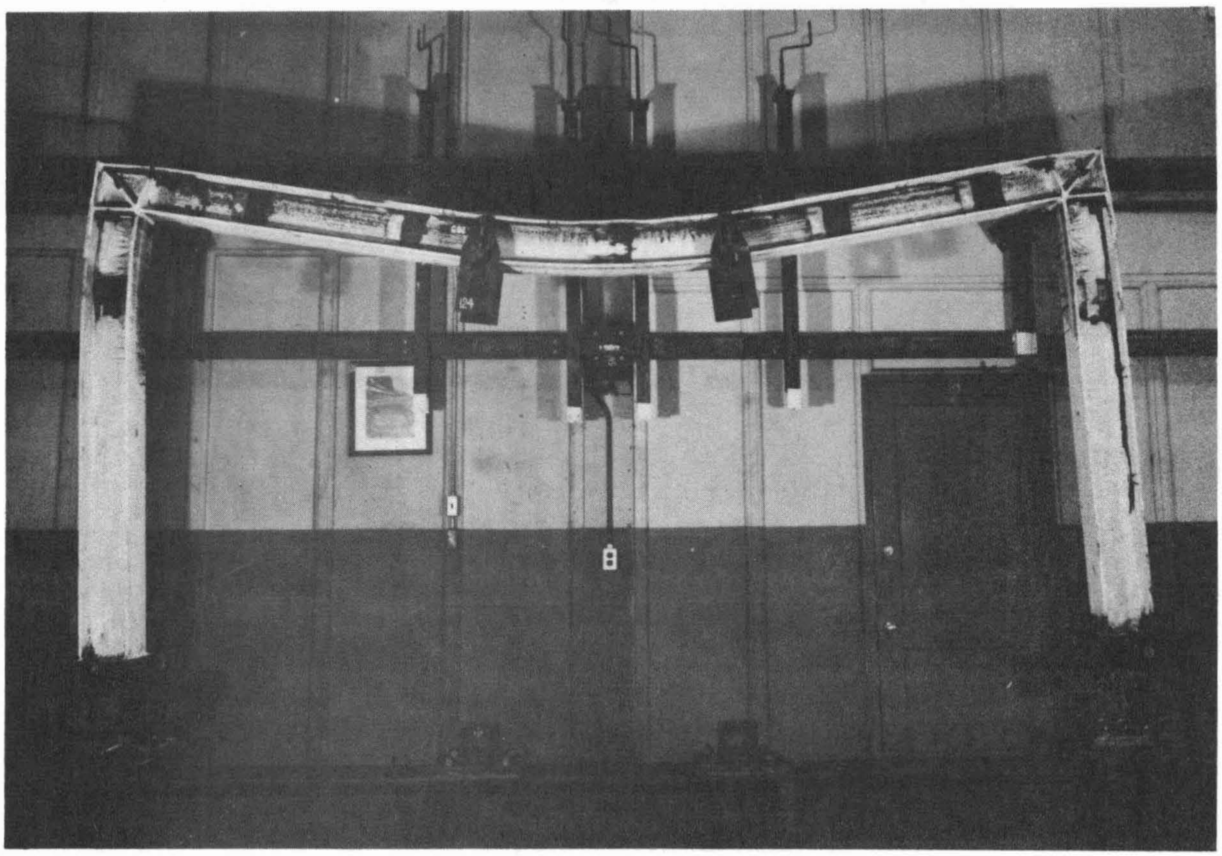


FIG. 25. FRAME 1 TESTED TO FAILURE

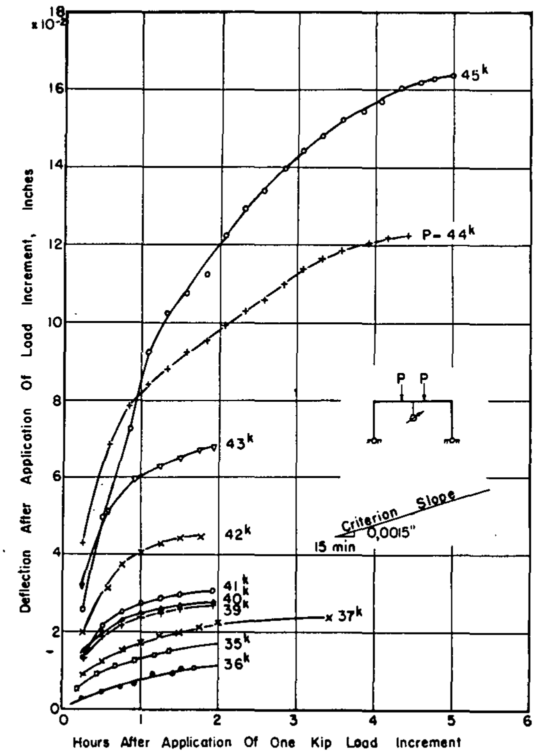


FIG. 26. CRITERION DEFLECTION, FRAME 1

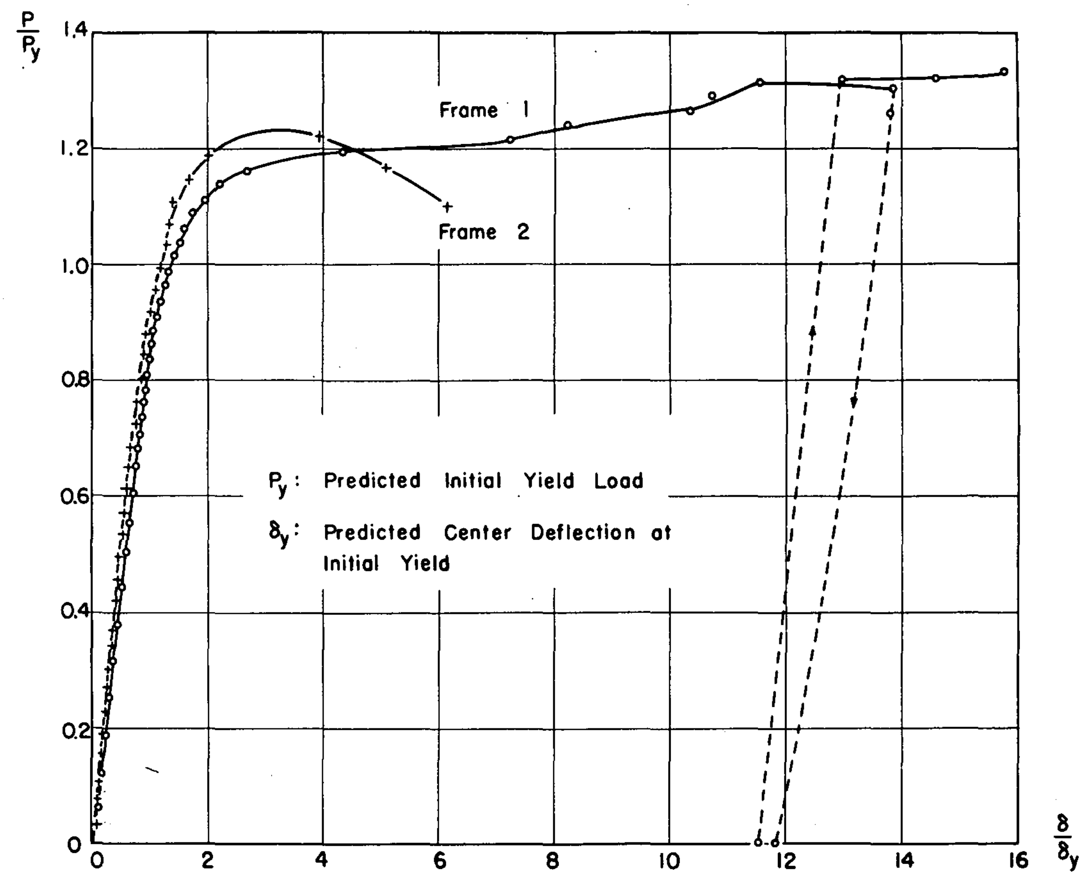


FIG. 27. COMPARATIVE LOAD-DEFLECTION RELATIONS FOR FRAMES 1 AND 2

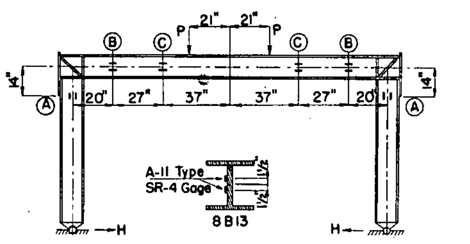


FIG. 28. STRAIN GAGE PAIRS AT LOCATIONS ON FRAME 2 WHICH REMAIN IN ELASTIC RANGE THROUGHOUT TEST

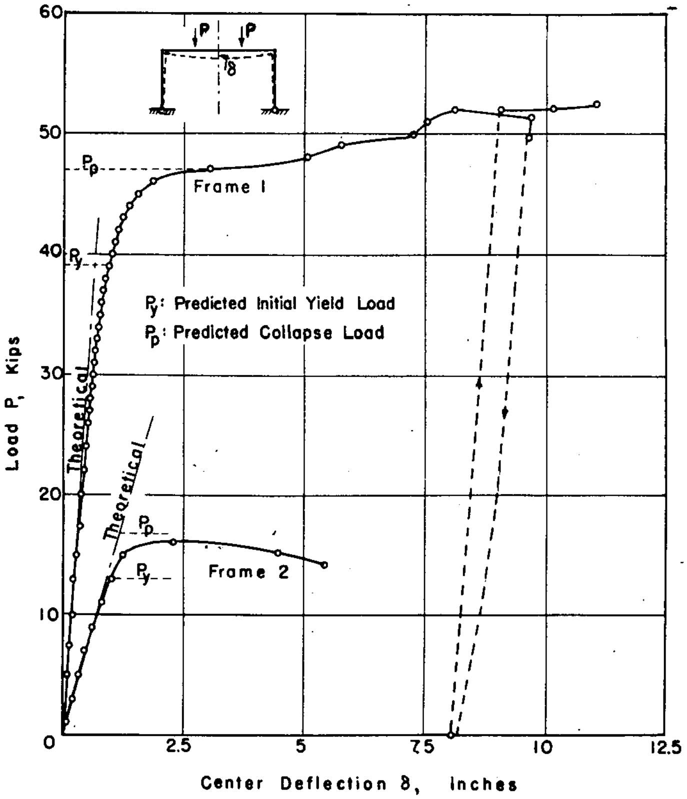


FIG. 30. DEFLECTION AT MIDSPAN

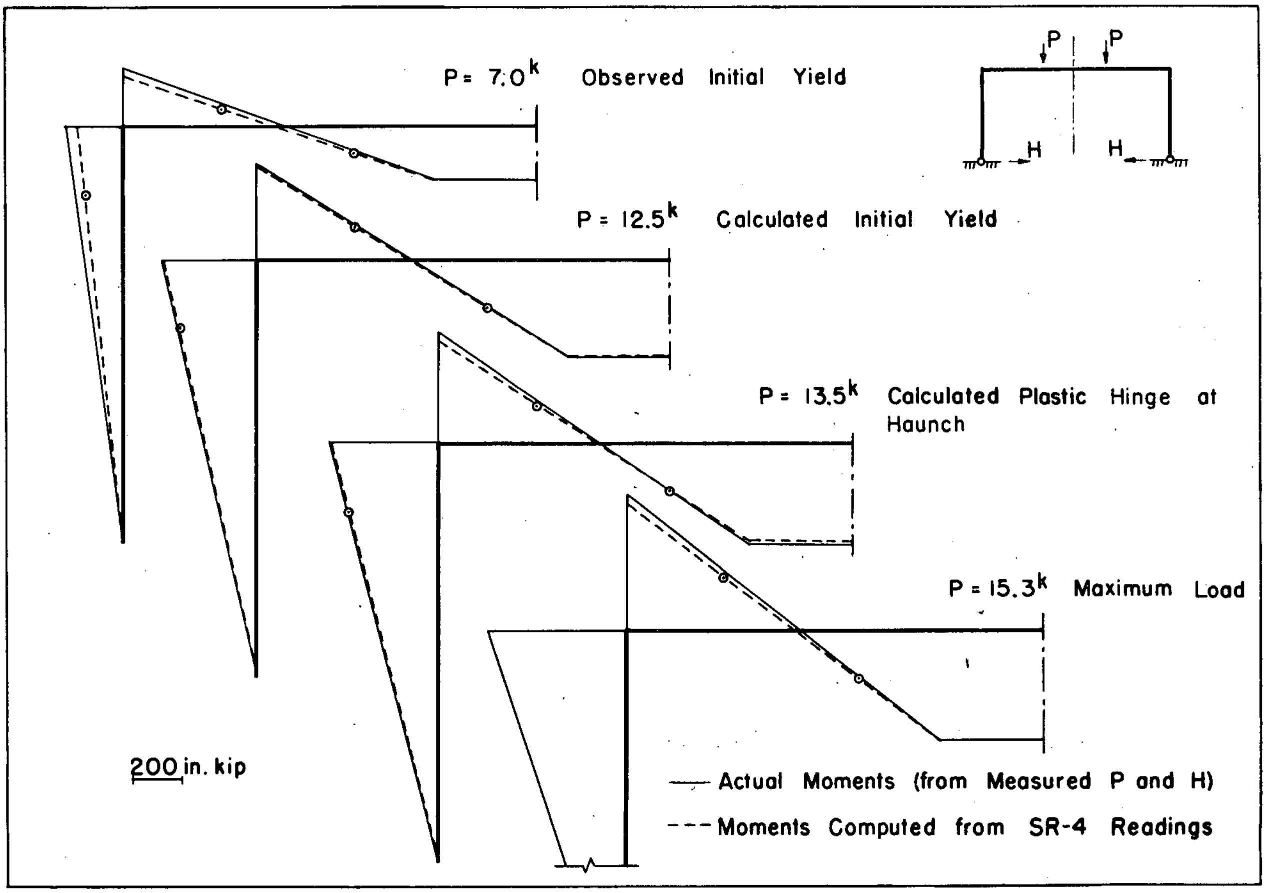


FIG. 29. EXPERIMENTAL MOMENTS DETERMINED FROM LOAD MEASUREMENTS AND FROM STRAIN READINGS