THE RESPONSE OF MODEL FRAMES SUBJECTED TO DYNAMIC LATERAL LOADS

By

CHARLES L. WILKINSON
and
F. L. HOWLAND

Approved by
N. M. NEWMARK

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University of Illinois
Urbana, Illinois
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I. INTRODUCTION

1. Introductory Statement

Most of the investigations of inelastically deformed structures have been concerned with static tests with very little attention being given to the dynamic inelastic behavior. Structures under slowly applied loads behave quite differently from the same structures under dynamic loads, although a common procedure is to treat a dynamic load in terms of an equivalent static load. This procedure becomes very complicated for rapidly applied loads such as those caused by wind gusts, impact or earthquakes, and is practically impossible to use in the inelastic range.

In order to study the inelastic response of a structure to dynamic loads, the dynamic resistance of the structure must be evaluated. Before the dynamic resistance can be predicted, investigations are necessary to define the parameters which affect this resistance.

The principal objective of this investigation was to determine the inelastic resistance of model frames subjected to dynamic lateral loads. In this study, the observed dynamic resistance of the model frames is compared to the theoretical and observed static resistance. This comparison of the dynamic resistance to the static resistance helps in the evaluation of the parameters which determine the static and the dynamic resistance. A study was made of assumed forms of the dynamic resistance of the frames on the basis of the relationship between the energy inputs and the maximum deflections. This was a simple and
convenient procedure from which many of the trends of the dynamic resistances could be determined.

2. **Summary of the Investigation**

Four model frame specimens were tested by subjecting each specimen to a dynamic lateral load applied along the axis of the top girder. The specimens were essentially ideal frames with fixed column bases, and column sections which were one-quarter scale models of a 6 WF 25 section.

The applied load, accelerations, deflections and maximum fiber strains were recorded during each test. The magnitude of the applied load varied from 1.68 to 2.77 times the theoretical static elastic limit load. These loads produced deflections from 13.29 to 50.42 times the theoretical static elastic limit deflection.

The dynamic resistance of each specimen was computed from the observed loads, accelerations and deflections by assuming them to be single-degree-of-freedom systems. The dynamic resistance curves of all frames had an elastic slope less than the theoretical static resistance, but approximately the same as the observed static resistance. The dynamic resistance was greater than the static resistances when general yielding occurred and retained this increase until a deflection of from 8 to 11 times the theoretical static elastic limit deflection was obtained. After this deflection had been reached, the dynamic resistances fell close to the theoretical static resistance for the remainder of the test.
The increase in the observed dynamic resistance over the theoretical static resistance has been predicted reasonably well by consideration of the strain rates in the frame.

3. **Acknowledgment**

The experimental work described in this report was performed in the Engineering Experiment Station, Department of Civil Engineering, University of Illinois, and sponsored by the Wright Air Development Center, Department of the Air Force, under Contract AF 33(616)-170.

The author wishes to thank his advisor, Dr. N. M. Newmark, Research Professor of Structural Engineering, for his advice and direction of this investigation, and W. H. Munse, Research Associate Professor of Civil Engineering for his helpful suggestions. He also wishes to express his appreciation to F. L. Howland, Research Associate in Civil Engineering, for his immediate supervision and encouragement during this investigation.

The author wishes to acknowledge the assistance of: R. J. Mayerjak, Fellow in Civil Engineering, in preparing and conducting the tests and in the interpretation of the test results; W. Egger and R. F. Wojciezak, Research Assistants in Civil Engineering, for their helpful suggestions.

The recording instruments were assembled and operated by V. J. McDonald, Research Assistant Professor of Civil Engineering, and R. J. Craig, Senior Electrical Technician.
II. TEST SPECIMEN

1. Description of Specimen

The model frames which were tested as part of this investigation were two-column bents with a rigid top girder. The column sections were approximately one-quarter scale models of a 6 WF 25.0 section. The lengths of the columns and the distance between their center-lines were 5 in. The dimensions of the test specimens are shown in Fig. 1.

The columns were oriented in the strong direction with respect to the applied load and were rigidly connected to both the top girder and the base plate. The connection to the top girder was made by extending the columns 1 1/4 in. into a recess in the top girder and placing stiffening blocks between the flanges. Both the column and the blocks were then welded to the top girder in order to provide the rigid connections. Figure 2 shows one of the connections after it had been welded. The bases of the columns were connected by brazing stiffening blocks into and around the columns, which were then welded to the base plate to complete the rigid connection. This type of connection can be seen in Fig. 3.

The top girder of the frame was a 3 x 1-7/8 in. rectangular steel bar, with a stiffness 20 times the stiffness of the columns. Therefore, the test specimen can be considered an ideal frame with fixed column bases.
. **Column Sizes**

The column sections tested were one-quarter scale models of a standard 6 WF 25.0 section, except for slight modifications made to facilitate machining. All flanges were made of constant thickness and the depth of the columns was increased approximately 0.01 in. These modifications allowed easier and more efficient machining of the specimens. The length of the columns was 17 1/2 in., of which 2 1/2 in. were used to make the rigid end connections. This length was chosen because it provided the longest specimen which could be easily handled by the laboratory's existing machine tools.

The average dimensions of the column sections for each test specimen are shown in Table 1. The frames tested as part of this investigation are designated as frames No. 6, 7, 8, and 9. Frame No. 3 was tested statically by R. J. Mayerjak and the author, previous to this investigation\(^{(1)}\)*, and is included in this report only for comparison. The dimensions listed in Table 1 as theoretical are the values used in computing the theoretical static moment-curvature relationship, and are the average values of all the column sections tested.

5. **Properties of the Material**

All column sections were machined from 2 in. square blocks. These blocks were adjacent strips, cut from a 2 in. thick ASTM A-7\(^{(2)}\)

* Numbers in parentheses refer to corresponding numbered entries in the Bibliography at the end of this report.
steel plate. To relieve the residual stresses which would cause warping during the machining operation, the strips were stress relieved before machining of the column members was begun. This was done by heating the strips at a temperature of 1300°F for three hours, and allowing them to cool in the furnace. It is believed that this process also provided a more homogenous material.

Blocks were cut from each end of the stress relieved strips for tension test specimens. These tension coupons were 0.505 in. in diameter, had a 2 in. gage length, and were machined from the center of each block according to ASTM specifications. The stress-strain relationships obtained from these coupon tests fell within a narrow band. Therefore, the stress-strain relationships of all the coupons were averaged for use in computing a theoretical moment-curvature relationship. This band and the computed average stress-strain curve are shown in Fig. 4. This figure shows that the average yield strength was 44.7 ksi, the average ultimate strength was 82 ksi, strain hardening began at an average strain of 0.012 in./in., and the average final elongation was about 31.8 percent.

The coupon tests were made in a 120,000 lb Baldwin-Southwark hydraulic testing machine. The strains were recorded with a 2-in. micro-filmer type strain gage which enabled the strains to be recorded automatically, to rupture. All tests were run at a strain rate of approximately 0.0004 in./in./sec.

Figure 5 shows the variation in the stress-strain relationships obtained from the tension coupons of frame No. 3, and the average
relationship which was used to compute the theoretical moment-curvature relationship.

7. Fabrication of the Test Specimen

In order to provide uniformity among all four specimens, a special rig was made in which the members of the specimen could be clamped during fabrication. This insured that the columns of each frame were in the same position with respect to the top girder, and also maintained their center line perpendicular to both the longitudinal and lateral axis of the top girder.

The fabrication of the frame was begun by welding the columns to the top girder, as described previously and as shown in Fig. 2. At the same time, the base stiffening blocks were brazed to the base end of the columns. This U-shaped structure was then allowed to cool, so that any movement which might result from temperature differentials would occur before the columns were attached to the base plate. The 1-1/4 in. base blocks were then welded to the base plate, as shown in Fig. 3, to complete the fabrication of the frame.

Static tests of this type frame have shown that residual stresses and stress concentrations exist in these frames because of the fabrication and the restraint conditions of the boundaries. The relative magnitudes of these two effects could not be determined from these tests; but, since a very small amount of heat was transferred to the columns during the welding of the base blocks, it is believed that the residual stresses produced in the frame are minimized by using the above
method of fabrication. Since the base blocks were brazed to the column, the properties of the material were altered by the heat of the welding only at that section of the column which was welded to the top girder.
III. TEST APPARATUS

The apparatus used to test the specimens of this investigation can be divided into six basic parts: the basic frame, the loading unit, the lateral restraint system, the restraining system, the deflection age mount, and the instrumentation. Figure 6 is an overall view of his testing apparatus with the specimen in place.

. The Basic Frame

The basic framework consisted of an 8 WF 67.0 beam supported t each end by two 6 I 12.5 beams. Each support was connected to a tie-own in the laboratory floor to prevent relative movements between the pparatus and the floor. The test specimen was fastened to the 8 in. WF eam by bolting the base plate of the specimen to the bottom flange of he beam with six 3/4 in. bolts. To prevent slippage between the base late and the bottom flange of the base beam, a bar was welded to the lange and two 3/4 in. set screws were inserted in this bar parallel to he flange. After each specimen was set into place, the set screws wereightened against the front edge of the base plate.

. Loading Unit

The lateral load was applied by a 20 kip pulse loading achine, (3) which is a pneumatic loading unit. A complete description f the operation of this unit is given in Reference (3).
The loading unit was connected to the basic frame by a framework bolted to the two forward support beams. This framework was made approximately 3-1/2 ft. long in order that the loading unit could be placed at a great enough distance from the specimen to prevent any damage to the unit by lateral or vertical movements of the specimen.

The load was transmitted to the test specimen through a 3-1/4 in. round steel rod. This rod was connected to both the loading unit and the specimen by clevises which allowed the rod to rotate in the vertical direction. The applied lateral load was measured by a dynamometer, of 0 kips capacity, located in this loading rod. Figure 7 shows the end of the load dynamometer and the connection of the loading rod to the specimen.

3. Lateral Restraint System

Whenever beams are loaded in the strong direction of resistance, there is a tendency for these beams to buckle laterally because of in-homogenity of material, initial crookedness, local instability, or variances in their cross-sections. For beams inelastically deformed, lateral buckling is very prominent and, therefore, a lateral restraint system was devised for these tests.

The top girder of the specimen was supported laterally at the center line of each column. This support was furnished by 1/2 in. rods which were threaded into the girder at one end and bolted to the lateral

The forward part of the apparatus is designated as that toward which the specimen moves during the test.
 restraint frame at the other. An aluminum dynamometer, of 1 kip capacity, as coupled into each supporting rod to measure the magnitude of the required lateral restraining force. In addition, each rod contained a double clevis, which allowed the specimen to rotate freely in both the horizontal and vertical directions.

Since one end of the lateral support rods was fixed in position to the lateral restraint frame while the other end moved with the specimen during the test, the rods moved through an arc as the frame deflected. However, only small losses in lateral restraint occurred during this movement since the angle through which the rods traveled was small compared to the length of the rods. To compensate for some of the effect of this rotation, prior to a test the specimen end of the rods was set 1/2 in. behind the fixed end.

1. Restraining System

In order to stop the test specimen before the piston of the loading unit reached the end of its travel, a restraining system was designed which stopped the specimen at any desired deflection. This was accomplished by means of a stop, connected to the rear of the specimen, which would strike a stationary plate at some predetermined deflection.

The initial position of the stop could be set with respect to the stop plate, allowing a predetermined deflection to be reached before the lip of the stop made contact with the stop plate. Upon contact of the lip with the plate, a restraining force was applied to the top girder of the specimen. This force was transmitted to the specimen through an
3-in. long steel yielding bar whose center section was machined down to a diameter of 1/2 in. With an expected maximum restraining force of 3 kips, the frame would be stopped in a distance of about 1/2 in. The magnitude of the restraining force was measured by an aluminum dynamometer, of 10 kips capacity, placed between the yielding bar and the specimen.

The connection of the steel stop to the test specimen was made with a clevis, which allowed the specimen to rotate in the vertical plane. This connection can be seen in Fig. 8.

\[2. \text{ Deflection Gage Mount}\]

The deflection gage was supported by a 6 in. diameter steel pipe, welded to the rear support of the basic frame. As shown in Fig. 6, this pipe extended back and down at an angle of 25 deg., so that the deflection gage would clear the restraining system, and still be aligned with the center line of the top girder of the specimen.

It was necessary for the link between the deflection gage and the specimen to go around the restraining system. To provide this connection, the restraining system was straddled by a rectangular frame, fabricated from aluminum tubing. This frame was connected to both the deflection gage and the specimen by ball joints which allowed a rotation of 115 deg.

For a lateral deflection of the frame of 3 in., a 3/8 in. shortening of the columns was expected. To reduce the effect of this vertical movement, the center line of the deflection gage, as well as
the loading unit and lateral restraint systems, was initially placed 3/16 in. above the center line of the connection to the top girder.

13. Instrumentation

The applied load, the deflection of the top girder, and the maximum fiber strains at various sections of the columns, were recorded with magnetic oscillographs. A diagram of the load and strain-recording system is shown in Fig. 9.

The applied load and restraining forces were measured by means of an SR-4 strain indicating bridge, which was formed from SR-4 type A-7 strain gages located at the center section of each dynamometer. The loads were obtained from the effective strains by calibrating the dynamometers statically.

With the exception of frames 6 and 7, the maximum fiber strains were measured at four sections of each specimen. These sections were located, on each column, 1 in. from both the top girder and the base plate. For frames 6 and 7, the strains on the rear column 1 in. from the top girder were not recorded. The strains were measured by means of two electrical resistance strain gages which were placed on the tension and compression flanges at each section. The output of the bridges formed with these gages was proportional to the average of the maximum tension and compression fiber strains.

The deflections of the top girder were measured with a slide wire resistance gage. This gage and a diagram of the deflection recording system can be seen in Fig. 10. During the test, the electrical
contact was pulled along the wire whose resistance for various positions of the electrical contact had been calibrated statically.

The accelerations were measured by a Hathaway AMS 20-A accelerometer which was mounted just in front of the top girder on the loading rod clevis. The accelerometer and its mount are shown in Fig. 7.

Each trace was recorded as a function of time. The timing signal was 500 cps, and was recorded by a galvanometer in each oscillograph. The timing and synchronizing systems can be seen in Fig. 11.

Since the load and acceleration records obtained in these tests contained a large amplitude high frequency component that was close to the upper bound for the frequency response of the recording system, an estimate was made of the possible error or percentage deviation from the reported magnitudes which might have resulted. These frequency components were such that the recorded amplitudes may have been in error by approximately plus or minus 10 percent, particularly during the initial portions of the records. However, by taking the mean of the peaks and valleys of the high frequency component, an average load and acceleration record was obtained in which the high frequency components were small and the error in the average record was probably negligible.

In addition to possible errors from the recording system, consideration must be given to the errors resulting from the calibration of the instruments and the reading of the records. The static calibrations of the deflection and load measuring instruments indicate that the calibration values used are probably in error by no more than 0.2 percent. The accelerometer calibration was not this satisfactory; the error was
probably within about plus or minus 2 percent.

The error associated with the reading of the records is probably the most significant. Because of the high frequency component present in the load and acceleration records, it was difficult to determine the location of the trace at any given time. This uncertainty, in combination with an error associated with the scaling of the trace deflection, may have resulted in the largest total error. The deflection records, however, which did not contain the higher frequencies, were more easily measured and the errors in the values were probably considerably smaller. Estimates of the possible error in reading the records were made from the amplitude of the trace deflections. For the deflection traces, the reading error may have been as much as plus or minus 0.5 to 1 percent of the maximum deflection and for the load traces the reading error was probably slightly greater, approximately plus or minus 1 to 2 percent. However, the average load used in the interpretation of the test results was probably not in error by more than plus or minus 1 percent. The acceleration record may have contained the greatest error because of the large amplitude frequency components and the small trace deflections which occurred after the initial transients ended. Nevertheless, it is estimated that the average accelerations used are not in error by more than plus or minus 5 percent.

In the interpretation of the test results, the quantities measured have been combined in various ways. Thus, the estimated maximum errors resulting from the combinations were: for the energy input, which is a function of the load and deflection, plus or minus 2 percent, and
for the resistance, which is a function of the load and acceleration, plus or minus 7 percent. These errors are approximate but indicate reasonable bounds for the reported results.

14. Test Procedure

Before each test was begun, the instruments were checked and the calibration of each circuit was recorded. The calibrations of the load and strain circuits were obtained by shunting the bridge arm with a known resistance. The deflection trace was calibrated by changing the resistance of one arm of the bridge. The acceleration record was calibrated by recording the trace produced by the accelerometer when it was subjected to a known acceleration. This known acceleration was produced by a Somntag Universal Fatigue Testing Machine, model SF10-U. After the calibrations were recorded, a zero trace reading was taken and the zero readings of the lateral restraint dynamometers were recorded. When the pressure in the loading unit had reached the desired level, the oscillographs were started and the load immediately applied. After the test, the final positions of the traces were recorded and the final readings of the lateral restraint dynamometers taken.
IV. THEORETICAL STATIC MOMENT-CURVATURE AND LOAD-DEFLECTION RELATIONSHIPS

This section presents the procedures used to obtain the theoretical relationships between bending moment and curvature and between load and maximum deflection for the type of frame tested in this investigation.

15. Assumptions

These theoretical relations are based on the following assumptions:

(a) The material is homogeneous with identical properties in tension and compression.

(b) The strain in any fiber of the column is directly proportional to the distance of the fiber from the centroidal axis.

(c) The stress-strain relationship in the column is the same as that determined from a static tension test of a coupon of the material.

16. Moment-Curvature Relationship

The theoretical moment-curvature relationship was obtained by considering the moment on a section of the column determined from the following equation:

\[ M = \int_A ydA \]

where:

- \( M \) is the sum of all the moments of the external forces
- \( A \) is the area of the cross-section of the member
\( dA \) is an element of area in the cross-section of the member

\( \sigma \) is the unit stress at this element of area

\( y \) is the distance from the centroidal axis to the element of area

The stress across a section of the column can be determined from the assumption that the strain varies linearly across the section of the column and from the stress-strain relationship obtained from coupon tests. From the same assumption, the curvature can be defined as the extreme fiber strain divided by its distance from the centroidal axis.

The value of the moment when yielding is impending, may be computed from the elastic relationship of moment and stress:

\[
M = \frac{\sigma_e I}{c}
\]

where:

\( \sigma_e \) is the stress at which yielding occurs

\( c \) is the distance from the extreme fiber to the neutral axis

\( I \) is the moment of inertia of the area of the section

In the inelastic range the moment was obtained by numerically integrating the general equation for the moment. This was begun by choosing an extreme fiber strain and determining the stresses corresponding to this extreme fiber strain from the average stress-strain curve shown in Fig. 4. The moment and the curvature corresponding to the
xtreme fiber strain were then computed. This procedure was repeated for different values of extreme fiber strain to obtain the moment curvature relationship presented in Fig. 12.

7. Load Deflection Relationship

For small deflections, the following relationship exists:

$$\alpha = \frac{d^2 \delta}{dx^2}$$

here:

$\alpha$ is the curvature and is equal to the extreme fiber strain divided by its distance from the centroidal axis

$x$ is the coordinate along the length of the column

$\delta$ is the deflection of the column

In the elastic range, the curvature can be evaluated quite simply since the curvature is expressed as $M/EI$. When inelastic action begins within the member, the curvature is no longer a linear function of the bending moment, but has to be determined from the theoretical curvature relationship given above. In the computation of the moments along the column, the shortening of the moment arm resulting from the lateral deflection of the column, was taken into account. The deflections of the column were computed by numerically integrating the curvatures obtained from the theoretical moment-curvature relationship.

The deflections caused by the effect of shear were not considered in this procedure.

A complete discussion of this procedure is given in Part 2 of reference (1).
V. DISCUSSION OF THE TEST RESULTS

8. General Statement

To fulfill the objectives of this investigation, four model frames were tested. These frames were two column rigid bents whose column sections were one-quarter scale models of a 6 WF 25 section. Each frame was subjected to a dynamic lateral load which was applied long the axis of the top girder. With the exception of the magnitude of the applied load, each frame was tested under similar conditions.

One of the objectives of this investigation was to compare the dynamic test results to the static test results. Frame No. 3, which was tested statically previous to this study, was used to make this comparison. The static response of frame No. 3 is compared to its theoretical response in Fig. 13. The test of this frame and the results obtained are discussed completely in reference (1), however, a brief discussion will be presented here. The test of this frame was conducted by increments of deflection and was performed over a period of four to five ours. Two test curves are shown in Fig. 13. The top curve (high load) as obtained by recording the load necessary to obtain each new deflection. After this deflection was reached, the load which was required to maintain this deflection decreased because of a relaxation and redistribution of stresses. In a few minutes the load became stable. This load as recorded as the low load.

The test curve falls below the theoretical curve, probably because of local buckling and twisting of the columns. The drop in the
Load at the end of the test was caused by the tearing of the tension flange of the rear column. This tear occurred at the junction of the column and the top girder, and is believed to have resulted from the welding.

The elastic slope of the observed curve is less than the elastic slope of the theoretical curve. This can probably be attributed largely to stress concentrations and residual stresses in the frame, which are the result of the fabrication of the frame and the boundary conditions. To substantiate this explanation, a model column, similar to the columns tested in this investigation, was tested as a simple beam loaded in the center. In this test, the model beam was loaded to a value just exceeding the elastic limit and then the load removed. The beam was then reloaded to failure. The results of this test are presented in Fig. 14. The first loading curve was compared to the theoretical curve and it was noted that the observed elastic limit deflection was 1.74 times the theoretical elastic limit deflection. During the first loading, the residual stresses were redistributed and most of the stress concentrations relieved; and, therefore, when the beam was reloaded the observed elastic limit deflection was only 1.3 times the theoretical. Also shown in Fig. 14 is the theoretical curve with a correction for shear deflections, which accounts for over half of the error in deflections noted for the second loading. The remaining error is attributed to the residual stresses and stress concentrations still in the beam, errors in the measuring apparatus, and variances in the section.
9. Test Results

The maximum value of the applied dynamic load, the maximum deflection and the time required to reach the maximum deflection are shown in Table 2 for each test. Also shown in this table is the energy input, and the lateral restraint force existing at the end of each test.

Continuous recordings were made of the applied load, accelerations, deflections, and strains as functions of time during each test. Figures 15 through 19 show the load-time, acceleration-time and the deflection-time relationships for the frames tested. Because of a slippage of 0.1 in. in the deflection gage apparatus after the first few milliseconds of loading in the test of frame No. 6, a correction of this amount had to be applied to the deflection-time relationship of this frame. This correction was applied proportionally from 4 milliseconds to 8 milliseconds. After 8 milliseconds, the entire correction of 0.1 in. was applied for the remainder of the test. This slippage did not occur during any of the subsequent tests.

All specimens were subjected to only one load pulse with the exception of frame No. 8. In order to study the effect of a second loading on the dynamic response of the frames, two load pulses were applied to frame No. 8. The load-time, acceleration-time and the deflection-time relationships for the second load pulse is shown in Fig. 18. Since all the strain gages had ruptured during the application of the first load, strains were not measured during the second loading.

It should be pointed out that when the strain gages rupture during a test, there is a possibility that the change in resistance in
The circuit, caused by this break, will change the zero value of the remaining channels. Although gage breaks did not affect the zero values of either frame 6 or 7, there was a zero shift during the test of both frames 8 and 9. In these latter cases, only the load trace was affected enough to warrant a correction. For frame No. 8, this zero-shift correction reduced the trace values of load by 0.6 kips, and was applied only to the first load pulse. For frame No. 9, the load was reduced by 0.5 kips. It was impossible to determine the exact time that this shift occurred, but the approximate time of rupture of the strain gages could be found from the strain-time records. Realizing that the shift must have occurred very close to this time, one can apply the correction to all subsequent load values. This correction was applied after 6 1/2 milliseconds for frame No. 8 and 5 milliseconds for frame No. 9.

Only the second loading of frame No. 8, and the test of frame No. 9 produced deflections large enough to require the restraining system. The restraining system was set for a deflection of 3.2 in. during the second loading of frame No. 8, and for a deflection of 3.1 in. during the test of frame No. 9. These deflections occurred at 16 and 22 milliseconds, respectively. The effect of the restraining force on the load-time, acceleration-time and the deflection-time relationships can be seen in Figs. 18 and 19.

The sharp peaks and depressions in the load-time and acceleration-time curves are caused by the higher frequencies of the system. However, if these peaks and depressions are averaged and a curve drawn through the average points, a smooth curve can be obtained. The average load and acceleration curves are indicated in Figs. 15 through 19 by a dashed line.
An attempt was made to derive the deflection-time relationships by integrating the average observed accelerations. The deflections which were derived using a numerical integration procedure were in good agreement with the observed deflections. During the first part of the test, the derived deflections were smaller than the observed deflections. However, in the latter part of the test they rose above the observed deflections and were always larger at the time of maximum deflection. The derived deflections varied from the maximum observed deflections by 1.38 percent, 17 percent, 9.23 percent and 9.24 percent for frames 6, 7, 8 and 9, respectively. In each of the tests, it was found that after a time of approximately 9 milliseconds, the difference between the observed and the derived deflections was very close to a linear variation. Therefore, if an initial correction had been made to the derived velocities and deflections at approximately 9 milliseconds, very close agreement between the derived and observed deflections would have been obtained. This correction can be justified because the observed accelerations in the early portion of the tests may not be accurate. This inaccuracy is attributed to the large initial acceleration and its rapid rate of rise and decline.

Reference to Table No. 2 shows that no lateral buckling occurred in frames No. 6 and 8 and only a small amount occurred in frames 7 and 9. Since time is required for buckling to develop, this result should be expected. The slight buckling which did occur probably developed during the end of the dynamic test or possibly during the static portion of the test which occurred before the load could be removed.
Figures 20 through 23 show the final deflected shapes of the test specimens. A small amount of local buckling may be noticed in frames 8 and 9 of Figs. 22 and 23.

20. Comparison of Experimental and Theoretical Results

By using the average values of load and acceleration in the computations of the dynamic resistance of the test specimen, a smooth resistance curve was obtained. The experimentally determined dynamic resistance for the frames tested are compared to the theoretical static resistance in Figs. 24 through 27. The theoretical static curve was obtained by the procedure explained in Part IV of this report.

By assuming that the test specimens could be represented by a single-degree-of-freedom system, the dynamic resistances of the specimens were computed from the following expression:

\[ Q = P - ma \]

where:

- \( Q \) is the resistance of the specimen at any time \( t \)
- \( P \) is the average dynamic lateral load at time \( t \)
- \( a \) is the average acceleration of the top girder at time \( t \)
- \( m \) is the sum of the moving mass to the rear of the lateral load dynamometer plus one-half the mass of the columns

Knowing the deflections as a function of time, Figs. 24 through 27 were obtained by plotting the resistance at a certain time against the deflection at that time. These curves have been plotted
in a dimensionless form in order that the experimental results, as well as the theoretically determined relationships, could be compared more conveniently. The resistance and deflection values corresponding to the theoretical beginning of yielding are indicated on the figures. Their values are 3.25 kips for \( Q_e \) and 0.0695 in. for \( \Delta_e \).

The resistance functions were computed to the maximum deflections for all specimens except frame No. 9 and the second loading of frame No. 8. Because of the large vibrations in the load and acceleration after the application of the restraining force, accurate points could not be obtained for this region of the resistance curve.

A check was made of the observed resistance functions by deriving the response of each specimen using a step-by-step numerical integration procedure (5). The observed resistance function and the average applied load were used in each calculation. The derived response agreed with the observed response reasonably well except for frame No. 7. The difference in maximum deflections was 10.6 percent, 16.7 percent, 9.05 percent, and 2.5 percent for frames 6, 7, 8 and 9, respectively. The maximum deflections of the derived response were found to be larger than the maximum deflections of the observed response for all specimens except frame No. 9.

The comparison of the resistance for all test specimens is shown in Fig. 28. Also shown in this figure is the theoretical static resistance and the observed static resistance. Since the stress-strain relationship for the material in frames 6, 7, 8 and 9 differed from that of the material in the frame tested statically (frame No. 3), the
observed resistance of frame No. 3 had to be adjusted in order to obtain a static resistance which could be compared with the dynamic resistance of frames No. 6, 7, 8 and 9. To make this adjustment the ratio of the observed resistance of frame No. 3 to the theoretical static resistance, determined from the stress-strain relationship for frame No. 3, was obtained for various values of $\frac{\Delta}{\Delta_e}$. The required static resistance, corresponding to a static test of a frame similar to frames 6, 7, 8 and 9, was assumed to be equal to this ratio times the theoretical static resistance obtained using the stress-strain relationship for frames 6, 7, 8 and 9 at the same values of $\frac{\Delta}{\Delta_e}$.

Since the observed load is subject to the same inaccuracies during the early portion of the test as the inaccuracies previously explained for the acceleration, no accurate points of the resistance curves could be obtained before five milliseconds. Consequently, only one or two points could be used in determining the elastic region of the dynamic resistances. However, the observed dynamic elastic slope was approximately the same as the observed static elastic slope for all specimens except frame No. 7 (See Fig. 28). Therefore, the elastic resistance of frames No. 6, 8 and 9 is believed to be very close to the true resistance, but frame No. 7 is possibly in error because of the inaccuracies explained above. As was explained for the static case, the difference between the dynamic elastic slope and the theoretical static elastic slope is probably a result of the stress concentrations and the residual stresses in the frames.

Figure 28 clearly shows that the dynamic resistance of all the specimens was greater than the theoretical static resistance before
general yielding began. This occurs because of the raised yield level of the material when loaded dynamically. The magnitude of this increase has been shown by previous investigations\(^6\) to depend upon variables such as the strain rate and the excess stress.

To determine the effect of the strain rates on the dynamic resistance after yielding, for the frames tested in this investigation, the increase in the dynamic resistance over the theoretical static resistance was computed on the basis of the strain rates. This increase was computed using the results of tests performed on structural steel by Fry\(^7\) and on 0.21 carbon steel by Morrison.\(^7\) These results are given in the form of a curve which has been reproduced in Fig. 29. The tests in reference \(^7\) were conducted only to a strain rate of 1 in./in./sec. Therefore, this curve was extrapolated for use in this study. Since a large variance in the strain rate results in a small change in stress, this extension was considered to be reasonable. Also shown in Fig. 29 is the resistance function computed for a 30 percent increase in the static yield stress. Referring to the extension of Fry's curve, we see that this corresponds to a strain rate of approximately 3 in./in./sec.

The increase in the dynamic resistance computed from the theoretical strain rates is compared in Figs. 30 through 33 with the observed increase. Also presented in these figures are the theoretical strain rates as functions of deflection. Since the strains could be measured only to a deflection of 6 to 7 times the theoretical static elastic limit deflection, the theoretical strains in the frame, instead of the observed strains, were used to compute the strain rates. In order to obtain a more exact comparison between the observed and computed dynamic
resistances, the computed dynamic elastic resistance was assumed to have the same slope as the observed dynamic elastic resistance. The increase of the dynamic yield stress above the static yield stress was found from the strain rates by using the curve shown in Fig. 29. The increase in the dynamic resistance above the theoretical static resistance was then computed by assuming the dynamic resistance to have the same shape as the resistance function shown in Fig. 29 for a 30 percent increase in yield stress, but proportionally higher or lower depending upon the strain rates. Since the strain rates in this investigation varied little in the range of deflections considered, this was found to be a very good assumption. Figures 30 through 33 show that the increase in the dynamic resistance of the frames tested in this study can be approximated closely if the strain rates are taken into account.

The dynamic resistance of all specimens returned to approximately the theoretical static curve at deflections of 8 to 11 times the elastic limit deflections and then closely followed the static curve until the end of the test. At these larger deflections, the maximum strains have reached a value which produces a static strain hardening stress larger than the raised yield stress. It is possible that this return to the static curve is caused by the strain rates having a smaller effect in the strain hardening region.

21. The Dynamic Resistance by Energy Relationships

A study was made of three assumed forms of the dynamic resistance, considering the relationship between the energy input and the maximum deflection of the test frames. The three shapes of the
resistance functions considered were: an elasto-plastic resistance, a resistance considering strain hardening, and a resistance which approximated the shape of the observed dynamic resistance. The last resistance was assumed to be elastic to some raised yield stress. After yielding, a pure plastic region was assumed until the theoretical static curve was reached, and from this point to the maximum deflection, the static curve was used. In this procedure, the dynamic resistance is considered to be of the same form as the resistance function corresponding to some raised yield level. The magnitude of the raised yield stress was determined from the energy equation which states that the energy input corresponding to the maximum deflection of each frame must be equal to the area under the assumed resisting function from zero deflection to the corresponding maximum deflection.

The energy input for the test frames was obtained by integrating the applied load-deflection relationships from the initial deflections to the maximum deflections. The magnitude of this energy is presented for each specimen in Table 2. For convenience in comparing results, the energy input and the maximum deflections have been reduced to a dimensionless form.

In Figs. 34, 35 and 36 are shown the energy input-maximum deflection relationships for the assumed resistance functions. These values were obtained by integrating the area under the assumed resistance-deflection curves from zero deflection to the maximum deflections. The increased yield stress, corresponding to each curve, is indicated on the figures based on an elastic limit yield stress of 44.7 ksi. In these figures, the points corresponding to the tests of frames 6, 7, 8 and 9 are also shown.
Figure 34 shows the results for an assumed elasto-plastic resistance. It can be seen that the yield stress must be raised as the energy input increases. Therefore, if an elasto-plastic resistance function is used, a different yield level must be assumed for each test. Since strain hardening causes a large increase in the load-carrying capacity of the test frames, a true comparison cannot be made using only the elasto-plastic case. To show the effect of strain hardening and how it alters the results, the theoretical static resistance of the test specimens was approximated by an elasto-plastic condition and is shown in Fig. 34 by a dashed line. Thus, it is seen that the yield stress must be raised a considerable amount to account for the increased capacity produced by strain hardening, but only a small increase is necessary to account for the dynamic effect.

If the assumed resistance function includes strain hardening, the results shown in Fig. 35 will be obtained. These results show that as the energy input increases, the increase in the yield stress decreases slightly and, therefore, the dynamic resistance approaches the theoretical static resistance. However, the dynamic resistance for all frames can be closely approximated by an assumed yield stress of 1.07 times the static yield stress. It is interesting to note that as the energy input increases, the theoretical curves become closer to the static curve and the error in using the static curve decreases.

Figure 36 presents the results for an assumed resistance function which approximates the observed dynamic resistance. For this form of the resistance function, the yield stress required for the energies to
be equal changes only the elastic limit and the plastic resistance level. Therefore, as the deflection exceeds approximately 5 times the yield deflection, the theoretical curves converge. For large deflections, the dynamic resistance function is essentially the same as the theoretical static resistance function. From the test results, it is found that the yield stress increases as the energy input increases and that the observed dynamic response can be approximated reasonably well by this procedure if a resistance function is used which includes strain hardening as well as a raised yield stress.

22. General Summary

The dynamic response of the model frames tested was determined by subjecting the model frames to a dynamic lateral load, and recording the applied load, accelerations, and deflections. The recorded loads and accelerations were found to contain large oscillations, which, when averaged, produced a smooth relationship. These average curves were used in obtaining all experimental and theoretical results.

A check of the accuracy of the observed accelerations was made by comparing the observed response of each frame to the response obtained by integrating the average accelerations. This procedure was found to give an excellent correlation after the first 2 or 3 milliseconds of the tests. The initial accelerations were erratic because of their large magnitudes and their rapid rate of rise and decline.

The dynamic resistance of the test specimens was obtained from the observed loads and accelerations by representing the test frame as a
single-degree-of-freedom system. This is considered a valid assumption since the weight of the columns is only 5.7 percent of the total weight of the system. To verify the observed resistance functions, the responses of the test frames were computed from the observed loads. These responses, computed by the step-by-step numerical integration procedure, agreed reasonably well with the observed responses.

The observed dynamic resistance was lower than the theoretical static resistance in the elastic region, possibly because of residual stresses and stress concentrations in the specimens. The dynamic resistance was found to be above the theoretical static resistance during the initial portion of the inelastic response but, for deflections greater than 8 to 11 times the elastic limit, the dynamic resistance approximates the theoretical static resistance. The increase in the dynamic resistance over the theoretical static resistance during the initial portion of the inelastic response can be accounted for by the increase in yield stress which accompanies high strain rates.

If a resistance function which approximates the shape of the observed dynamic resistance is assumed, the dynamic yield stress can be predicted reasonably well by consideration of the relationship between the energy input and the maximum deflection of the test frames.
VI. CONCLUSIONS

The dynamic resistance of the frames tested in this investigation was found to be higher at yielding than the static yield resistance. After yielding occurred, the inelastic resistance approached the theoretical static response and in the latter stages of loading the dynamic resistance can be considered to be the same as the theoretical static resistance. For large deflections, the theoretical static curve is a good approximation for the dynamic resistance since the increase in the dynamic resistance at yielding contributes a small amount to the total energy.

The dynamic resistance was found to be significantly higher than the observed static resistance since the local buckling and twisting of the columns, which reduced the capacity of the frame in the static tests, did not have time to occur during the dynamic tests.

Although these tests do not provide enough information to enable us to determine the response of any frame, they do give a general picture of the response of frames and show what can be expected under the conditions used in these tests.
BIBLIOGRAPHY


TABLE 1
DIMENSIONS OF COLUMN SECTIONS

<table>
<thead>
<tr>
<th>Specimen</th>
<th>b</th>
<th>2c</th>
<th>f</th>
<th>w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical</td>
<td>1.522</td>
<td>1.607</td>
<td>0.116</td>
<td>0.104</td>
</tr>
<tr>
<td>Frame No. 6</td>
<td>1.521</td>
<td>1.606</td>
<td>0.115</td>
<td>0.08</td>
</tr>
<tr>
<td>Frame No. 7</td>
<td>1.522</td>
<td>1.607</td>
<td>0.116</td>
<td>0.107</td>
</tr>
<tr>
<td>Frame No. 8</td>
<td>1.521</td>
<td>1.607</td>
<td>0.116</td>
<td>0.102</td>
</tr>
<tr>
<td>Frame No. 9</td>
<td>1.522</td>
<td>1.607</td>
<td>0.116</td>
<td>0.100</td>
</tr>
<tr>
<td>Frame No. 3</td>
<td>1.522</td>
<td>1.606</td>
<td>0.115</td>
<td>0.08</td>
</tr>
</tbody>
</table>
### TABLE NO. 2

**SUMMARY OF TEST RESULTS**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum Value of Applied Load</th>
<th>Maximum Deflection</th>
<th>Time of Max. Deflection</th>
<th>Lateral Restraint Force at End of Test</th>
<th>Energy-Input</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{P(t)}{Q_e}$ kips</td>
<td>$\frac{\Delta m}{h_e}$</td>
<td>$\Delta m$ in.</td>
<td>Milliseconds</td>
<td>kips</td>
</tr>
<tr>
<td>Frame No. 6</td>
<td>1.68</td>
<td>5.47</td>
<td>13.29</td>
<td>0.924</td>
<td>22</td>
</tr>
<tr>
<td>Frame No. 7</td>
<td>1.83</td>
<td>5.96</td>
<td>19.33</td>
<td>1.344</td>
<td>27</td>
</tr>
<tr>
<td>First Load</td>
<td>2.13</td>
<td>6.87</td>
<td>25.22</td>
<td>1.754</td>
<td>27</td>
</tr>
<tr>
<td>Frame No. 8</td>
<td>2.81</td>
<td>9.13</td>
<td>25.97</td>
<td>1.806</td>
<td>19</td>
</tr>
<tr>
<td>Second Load</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame No. 8</td>
<td>2.77</td>
<td>9.00</td>
<td>50.42</td>
<td>3.50</td>
<td>27</td>
</tr>
</tbody>
</table>

* Natural period of each specimen is approximately 0.012 sec.
FIG. 1 TEST SPECIMEN

Scale - 3/16" = 1"

Rigid Top Beam

15" Rigid Top Beam

Welded

Silver Brazed

Welded

6 Holes - 1" Dia. for Mounting
FIG. 2 CONNECTION OF COLUMN TO TOP GIRDER

FIG. 3 CONNECTION OF COLUMN TO BASE PLATE
At Rupture:
Elongation = 31.8%
Stress = 69.8 ksi

FIG. 4  STRESS-STRAIN RELATIONSHIP FOR FRAMES 6, 7, 8 AND 9
FIG. 5  STRESS-STRAIN RELATIONSHIP FOR FRAME NO. 3
FIG. 7 CONNECTION OF LOADING ROD TO TOP GIRDER

FIG. 8 CONNECTION OF RESTRAINING SYSTEM TO TOP GIRDER
Calibrated Resistors

Bridge supply 5000 CPS regulated

Hathaway MRC 18 strain measuring system (modified) Note 2

Carrier filter system

Hathaway Sl4-C oscillograph (Hath. group 23 OC-2 each)

Other similar bridges
Note 1

Note 1
For Frames No. 6 and 7, 6 channels of strain equipment were used; for Frames No. 8 and 9, 7 channels. In all tests, 2 channels were used for load and 1 for acceleration measurements.

Note 2
Standard Hathaway MRC 18 unit modified to reduce cross-talk between channels and to provide carrier supply oscillator with approximately 0.01% regulation.

FIG. 9 LOAD AND STRAIN MEASURING CHANNELS
Note 1

Connections to B, C, and D for calibration purposes. Nominal values: B = 0.5"; C = 2.0"; D = 4.0". Precise values taken from gage calibration curves. "A" is the balance position at zero deflection.

Note 2

Recording galvanometer is a Hathaway Type OC2, group 23 units used in Hathaway Sl4-C magnetic oscillographs.
Note 1

G1 and G2 are Hathaway OC2 group 23 galvanometers. One galvanometer is located in each Hathaway Sl4-C oscillograph.

Note 2

Switch driven at synchronous speeds modulating the amplitude of the timing signal with steps every 0.02 min. and a step omitted once each 0.1 min.

FIG. 11 TIMING AND SYNCHRONIZING TRACES
FIG. 13  OBSERVED STATIC RESISTANCE OF FRAME NO. 3

\[ \frac{Q}{Q_0} = \text{Resistance / Elastic Limit Resistance} \]

\[ \frac{\Delta}{\Delta_0} = \text{Deflection / Elastic Limit Deflection} \]

- \( Q_0 = 2.7 \) kips
- \( \Delta_0 = 0.058 \) in.

High Load
Low Load
Theoretical Static Resistance
Observed Static Resistance
FIG. 14  LOAD DEFLECTION RELATIONSHIP FOR COLUMN NO. 12

Load - Kips

Center Deflection - in.

\( Q_0 = 2.42 \text{ kips} \)

\( \Delta_0 = 0.027 \text{ in.} \)
FIG. 15 OBSERVED DATA FOR TEST OF FRAME NO. 6
FIG. 16  OBSERVED DATA FOR TEST OF FRAME NO. 7
FIG. 17  OBSERVED DATA FOR FIRST LOAD PULSE ON FRAME NO. 8
FIG. 18  OBSERVED DATA FOR SECOND LOAD PULSE ON FRAME NO. 8
FIG. 19  OBSERVED DATA FOR FRAME NO. 9
FIG. 20 FINAL DEFLECTED SHAPE OF FRAME NO. 6

FIG. 21 FINAL DEFLECTED SHAPE OF FRAME NO. 7
FIG. 22 FINAL DEFLECTED SHAPE OF FRAME NO. 8

FIG. 23 FINAL DEFLECTED SHAPE OF FRAME NO. 9
Theoretical Static Resistance

Observed Dynamic Resistance

\( Q_e = 3.25 \text{ kips} \)

\( \Delta_e = 0.0695 \text{ in.} \)

\( \frac{\Delta}{\Delta_e} = \text{Deflection} / \text{Elastic Limit Deflection} \)

FIG. 24 OBSERVED RESISTANCE OF FRAME NO. 6
Figure 25: Observed Dynamic Resistance of Frame No. 7

$Q_e = 3.25$ kips

$\Delta_e = 0.0695$ in.

- Theoretical Static Resistance
- Observed Dynamic Resistance

$\Delta / \Delta_e = \text{Deflection} / \text{Elastic Limit Deflection}$
FIG. 26 OBSERVED DYNAMIC RESISTANCE OF FRAME NO. 3

\[ \frac{Q}{Q_0} = \text{Resistance} / \text{Elastic Limit Resistance} \]

\[ \frac{\Delta}{\Delta_0} = \text{Deflection} / \text{Elastic Limit Deflection} \]

- Theoretical Static Resistance
- Observed Dynamic Resistance

\( Q_0 = 3.25 \text{ kips} \)
\( \Delta_0 = 0.0695 \text{ in.} \)
\[ Q / Q_0 = \text{Resistance} / \text{Elastic Limit Resistance} \]

\[ \Delta / \Delta_0 = \text{Deflection} / \text{Elastic Limit Deflection} \]

- \( Q_0 = 3.25 \text{ kips} \)
- \( \Delta_0 = 0.0695 \text{ in.} \)

---

**FIG. 27** OBSERVED DYNAMIC RESISTANCE OF FRAME NO. 9
FIG. 28  OBSERVED DYNAMIC RESISTANCE OF FRAMES NO. 6, 7, 8 AND 9

\[
\frac{q}{q_0} = \text{Resistance / Elastic Limit Resistance}
\]

\[
\frac{\Delta}{\Delta_0} = \text{Deflection / Elastic Limit Deflection}
\]

- \( q_0 = 3.25 \) kips
- \( \Delta_0 = 0.0695 \) in.

- Theoretical Static Curve
- Observed Static Curve
- Frame No. 6
- Frame No. 7
- Frame No. 8
- Frame No. 9

Second Load
Fig. 29  Dynamic Resistance from Dynamic Yield Stress
\[ \frac{\Delta}{\Delta_0} = \text{Deflection} / \text{Elastic Limit Deflection} \]

FIG. 30 INCREASE IN DYNAMIC RESISTANCE OF FRAME NO. 6
\[ \Delta / \Delta_0 = \text{Deflection} / \text{Elastic Limit Deflection} \]

\[ \Delta / \Delta_0 = \text{Deflection} / \text{Elastic Limit Deflection} \]

**FIG. 31 INCREASE IN DYNAMIC RESISTANCE OF FRAME NO. 7**
\[ \Delta / \Delta_e = \text{Deflection} / \text{Elastic Limit Deflection} \]

**FIG. 32 INCREASE IN DYNAMIC RESISTANCE OF FRAME NO. 8**
FIG. 33 INCREASE IN DYNAMIC RESISTANCE OF FRAME NO. 9
Shape of Resistance Function

\[ \frac{\Delta}{\Delta_e} \] vs. \[ \frac{Q}{Q_e} \Delta_e \]

\( \sigma_e = 44.7 \text{ ksi} \)
\( q_e = 3.25 \text{ kips} \)
\( \Delta_e = 0.0695 \text{ in.} \)

- Frame No. 6
- Frame No. 7
- Frame No. 8
- Frame No. 9

**FIG. 34 ENERGY INPUT - MAXIMUM DEFLECTION RELATIONSHIP**
FIG. 35 ENERGY INPUT - MAXIMUM DEFLECTION RELATIONSHIP

\[ \frac{\Delta}{\Delta_e} \text{ vs. } \frac{\text{Energy Input}}{Q_e \Delta_e} \]

- \( \sigma_e = 44.7 \text{ ksi} \)
- \( Q_e = 3.25 \text{ kips} \)
- \( \Delta_e = 0.0695 \text{ in.} \)
- Frame No. 6
- Frame No. 7
- Frame No. 8
- Frame No. 9

Shape of Resistance Function
Shape of Resistance Function

\[ \Delta / \Delta_e \]

Energy Input / \( Q_e \Delta_e \)

\( \sigma_e = 44.7 \text{ ksi} \)
\( Q_e = 3.25 \text{ kips} \)
\( \Delta_e = 0.0695 \text{ in.} \)

- Frame No. 6
- Frame No. 7
- Frame No. 8
- Frame No. 9

FIG. 36 ENERGY INPUT - MAXIMUM DEFLECTION RELATIONSHIP