Behavior of Steel Frames Under Repeated Loading

PROPOSAL FOR AN EXPLORATORY STUDY ON
STEEL FRAMES SUBJECTED TO CYCLIC LATERAL LOADS

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1. INTRODUCTION

The research program proposed in this study is concerned with the elastic and inelastic behavior of steel frames under the action of constant gravity loads and cyclic horizontal loads. An understanding of the inelastic behavior of frames under these loads is necessary to correlate recent research in earthquake engineering which has centered around full-scale dynamic testing of buildings\(^1,2\) and computer studies of simple systems under recorded earthquake motions.\(^3,4,5\) And, in recent tests at Berkeley, cantilever beams were tested under cyclic loads to study the connection behavior under earthquake conditions.\(^6\)

The earthquake problem is essentially one of constant gravity loads and a variable horizontal acceleration (or displacement) of the base of the frame. The inertia forces are often replaced by horizontal forces applied at the floor levels in studying the dynamic effects of earthquakes. Currently available methods of frame analysis are adequate to predict the static behavior of frames under the combined effect of gravity and monotonically increasing horizontal loads.\(^7,8\) However, these methods were not adequate to describe the behavior of frames under reversed loading.
2. PROPOSED TEST PROGRAM

In order to gain maximum correlation with a previous test of a single-story frame\textsuperscript{7} and the results of the connection tests at Berkeley,\textsuperscript{6} the member sizes, bay spacing, and floor height were chosen to be similar for the single-story and the three-story frames which are proposed for this exploratory study.

Therefore, the frames were designed for a 15-ft. bay and bent spacing and a 10-ft. story height. In addition, the geometry and the resulting member sizes are compatible with realistic frame geometry and column slenderness ratios found in multi-story frames. The detailed procedure that was followed in the design of the test frames is outlined in Section 3 of this proposal. The final member sizes for the two frames are shown in Fig. 1. It is noted that the single-story frame is essentially the bottom story of the three-story frame. Both frames will be fabricated from ASTM A36 rolled steel sections using standard welded construction.

In conjunction with the frame tests, the material properties and residual stress distribution will be determined along with beam tests to determine the plastic moment capacity of the sections obtained. Additionally, cyclic load tests will be performed on several of the uniaxial coupons taken from these sections under
both static and dynamic conditions and various strain amplitudes. These cyclic coupon tests for the particular steel used in the frames will give the necessary material behavior under cyclic loading in the form of a cyclic stress-strain curve$^9$ and the shape and stability of the stress-strain loops.

This test series together with the theoretical work (described in Section 5) is aimed at finding an accurate accounting of the static load-deformation behavior of unbraced steel frames having relatively high column loads and cyclic horizontal loads proportioned for earthquake simulation. From these results will develop a method of analysis suitable to account for the behavior of steel frames under cyclic static horizontal load. And, following a study of the variables involved in a dynamic loading, and based on the static analysis, a prediction for frame behavior under dynamic conditions will be made.
3. TEST FRAMES

3.1 Design Loads

The working loads used in the design of the three-story frame are as follows:

Roof: \( W_L = 60 \text{ psf}; W_D = 70 \text{ psf} \)

Floor: \( W_L = 80 \text{ psf}; W_D = 90 \text{ psf} \)

Wind: 20 psf

The total loadings were computed based on a 15-ft. bent spacing. These loads are applied to the frame at floor level or at the quarter points of the beams to simulate wind or earthquake forces and uniform gravity loading, respectively.

The lateral forces used for determining the behavior of the frame under gravity plus earthquake loads were determined from the present lateral force requirements for aseismic design. The magnitudes used are based on dead load alone.

The column top loads in the single-story test will be the summation of the floor loads at levels one and two for the three-story frame.

In the design of the frame a load factor of 1.70 was used for the gravity load case and a load factor of 1.30 for the combined
loading cases.

The final load patterns and magnitudes are as shown in Figure 2.

3.2 Design Procedure

The three-story frame was initially designed plastically for wind plus gravity loading, keeping in mind the beam mechanism strengths under gravity loading alone.

The design method initially assumes no P-Δ effect and a likely-to-occur mechanism. From the resulting moment diagram and sections required, the Δ's are calculated and the P-Δ moments are found. Redesign then includes the P-Δ effect and the sections required initially are altered if necessary.  

Then using the same technique and the present lateral force requirements for design for earthquake loading, the frame was checked.

A stability analysis of the frame under gravity load alone (frame buckling condition) was made by the "α-method". This method applies light horizontal loads as a percentage of the floor loads and finds the load deformation characteristics of the structure. Then a different percentage is taken and a second
analysis made. Following this, a plot of the two percentages versus maximum loads attained is made and extrapolation is carried out to zero percent to find the maximum value of the gravity load acting alone. The "α-method" is a method of analysis which is a second order elastic-plastic analysis including the P-Δ effect. A second-order elastic-plastic analysis including the P-Δ effect was also carried out on the final frame under the two combined loading conditions to provide a check of the design and yield the load-deformation behavior of the frame under monotonically increasing lateral load. The results of these analyses are presented in Section 3.3.

Based on the stress resultants which the analyses yielded, the connections were designed by plastic design methods. Due to inadequate column web thickness to resist the joint shear, doubler plates were added to the joints. Even though a slightly more than adequate column web thickness against web crippling and column flange thickness against tension distortion are provided, stiffening the same size as the beam flanges was called for to reduce the distortion within the joint itself.

The final joint and weld detail is shown in Figure 3.
3.3 Analytical Behavior of Test Frames

Three-Story Frame

The three-story frame was first analyzed for gravity loading condition to determine its inelastic buckling load. This load is sometimes used as a reference load in plastic design and represents the load at which the symmetrical frame buckles side-wise into an anti-symmetrical deformation mode. The computer analysis using the "α-method" results in a buckling load of 

\[ P_{cr} = 34.4 \text{ kips}, \]  

which is about 98% of the beam mechanism load. This load compares favorably with the factored \( L.F. = 1.70 \) gravity load of 32.4 kips assumed in plastic design.

The frame was further analyzed for constant gravity loading and monotonically increasing lateral loading. The following three cases have been considered in the analyses:

1. Factored \( L.F. = 1.30 \) gravity load and monotonically increasing wind loads

2. Factored \( L.F. = 1.30 \) gravity load and monotonically increasing earthquake forces

3. Working level gravity load and monotonically increasing earthquake forces

The computer results obtained for the first two cases are presented in the form of lateral load vs. sway deflection
curves in Figure 4. The numbers shown on the curves and the
frames give the locations and order of formation of the plastic
hinges. Because of the instability effect caused by the P-Δ
moment, the frame fails prior to the formation of a failure mecha-
nism. Additional hinges will form if the frame is permitted to
deform further after the attainment of the maximum load. The
dotted hinges shown in Figure 4 represent the locations where the
next plastic hinges will form if additional deformation after the
maximum load is permitted.

For the case of factored gravity load and gradually in-
creasing wind loads, the analysis shows that the frame fails at a
maximum load, $H_{\text{max}}$, 3.8% less than the factored wind load (3.90
kips) assumed in the design. The frame may therefore be considered
satisfactory to resist the factored gravity and wind loads acting
simultaneously. The results given in Figure 4 show that the same
frame has approximately twice the strength required to resist the
factored earthquake force.

The results of analysis made for the case of working
level gravity load and increasing earthquake forces are given in
Figure 5. Frame instability again affects the load-carrying capacity
of the frame. The maximum load, $H_{\text{max}}$, that can be carried by the
frame is about three times the factored earthquake load. The
loading condition assumed in this analysis is considered to be the
most-likely-to-occur situation during an earthquake and will therefore be used in the testing program.

All the analyses described above were based on handbook values for cross-sectional properties and on an assumed yield stress level ($\sigma_y = 36$ ksi). The results may not be exactly correct for the test frame because of variations in cross-sectional and material properties. The same analyses will then be repeated after the test frame is fabricated.

**Single-Story Frame**

The behavior of this frame will be analyzed using the actual cross-sectional properties and yield stresses of the ordered material. The load-deflection relationship of this frame will not be the same as that for the lowest story of the three-story frame. The failure mechanism is expected to be a combined mechanism with the lee hinge forming at the top of the leeward column, because the plastic moment (reduced for the effect of axial force) of the column is smaller than that of the beam. The test will therefore provide information on the cyclic behavior of a double curvature column having plastic hinges forming at both ends.
4. TESTING TECHNIQUE

4.1 Loading Program

The gravity load (working value) will be applied first to the frame and then the earthquake lateral forces will be applied to the frame in a cyclic manner as shown in Figure 6. The figure shows loading program based on the load applied at level three and the number of cycles at different loads. The initial three cycles are for the elastic response of the system and then five cycle groups at higher loads will yield the inelastic response of the frame. The magnitudes were chosen at or just higher than the horizontal load at which new plastic hinges would form under the monotonic loading condition. In addition, the design magnitude will also be cycled.

4.2 Test Equipment

The initial gravity loading will be applied at the quarter-points of the beam through a spreader beam to which the jack (tension) of the gravity load simulator is attached. The gravity load simulator is attached to the independent loading frame.

The vertical loads on the column tops in the portal frame test will be applied through a loading beam set on rollers on the
column tops and connected symmetrically to two gravity load simulators on each side of the frame.  

The horizontal loading program for the frames will be accomplished by means of jacks on one side of the frame. These jacks will alternately push and pull the test frame in the two opposite directions. The jacks will be applied at the beam centerlines and the external reaction will be absorbed by the loading frame.

Planar motion of the test frames under load will be insured by lateral bracing perpendicular to the plane of the frame. The braces will be placed at the locations of the plastic hinges.

Enough equipment is available in the form of gravity load simulators and lateral braces, and the horizontal jacks and necessary equipment for lateral load will be adapted. Figures 7 and 8 show the general nature of the setup and the equipment to be used for the proposed tests.

4.3 Instrumentation

In addition to monitoring the line pressures to the various jacks by means of pressure gages, calibrated dynamometers will be used to measure the applied loads. The horizontal and vertical deflections of the structure will be attained from dial
gages and scales attached to the frame. The rotations at critical sections throughout the structure and at the base will be measured by means of electrical and mechanical devices. In addition, strain gages will be used extensively throughout the structure to reduce it to a determinate structure and measure the phenomena at the plastic hinge locations.
5. ANALYTICAL STUDIES

5.1 Initial Work

The initial portion of the work has been concerned with a survey of the literature concerning material behavior and frame response to cyclic loadings and a determination as to the type of testing that should be included in the project.

5.2 Analysis for Static Repeated Horizontal Loads

The initial theoretical investigations will be concerned with the analysis for static cyclic lateral loading of multi-story frames. The static approach will be used as a starting point and is almost necessary to gain a close account of the behavior of a frame under cyclic loading. Since the frame is designed for instability effects, the frame will act as a subassemblage of a multi-story frame and therefore the columns will have a reduced plastic moment capacity due to the high axial load. The static analysis will be basically second-order elastic-plastic with modifications to account for the effect of strain hardening and the true position of the plastic hinges.
5.3 Analysis for Dynamic Repeated Horizontal Loads

The analysis for dynamic cyclic lateral loading of multi-story frames may require merely the extension of the static method or a present dynamic method, or a completely new approach.

After a close study of the variables involved in the dynamic loading and based on the static analysis, a prediction of frame behavior under dynamic conditions may be possible. However, without a dynamic test of a frame, this extension will depend on the use of data obtained in the cyclic coupon tests which are to be conducted as part of the material properties tests and other references.

One simple approach has been to use a constant dynamic plastic moment capacity as some ratio of the static moment capacity and then proceed as in a static situation. ¹³

Perhaps the non-linear dynamic analysis under study at Michigan which uses the Ramberg-Osgood function to represent the force displacement characteristics of a single degree of freedom system should be correlated to the test frames. ⁵ And since the extension of this method to multi-story frames under the assumptions that the beams follow the R-O relationship and the columns remain linearly elastic, there will be limitations on such correlations which could be made. Note also that all secondary effects are
excluded since only flexural resistance of the members is considered in the above analysis.

The spectral response curve and a determination of the damping parameters of the structures tested can be made for correlation purposes with other frame tests. In the latter case, a mechanical system consisting of a mass, a linear spring, and a viscous damper which has its force proportional to the relative velocity to the first power is used to calculate various conventional damping parameters.
6. **FURTHER POSSIBLE EXPERIMENTS**

Further studies into the nature of frame behavior under earthquake conditions may include the following tests:

a. Two-bay three-story frames
b. Frames with weak axis framing
c. Frames with bolted connection details
d. Braced frames
7. SUMMARY

Two tests on steel frames with all-welded strong-axis framing, one single-story and one three-story, are proposed. These frames will be subjected to constant vertical loadings and cyclic lateral loading proportioned according to the present lateral force requirements for earthquake loading. A parallel theoretical study aiming at the development of methods for predicting the cyclic behavior of multi-story frames is also outlined.
8. FIGURES
FIG. 1 FRAME GEOMETRY AND BASE DETAIL
Working Loads

Gravity
\[ P = 19.1 \text{ kips} \]

Wind
\[ 2H_1 = H_2 = H_3 = 3.0k \]

Earthquake
\[ 2.42H_1 = 2H_2 = H_3 = 0.5k \]

FIG. 2 LOADING CONDITIONS
Use 1/4" Doubler I Ps
Both Sides (1/4" weld)

Beam Flanges Prepared
For Full Butt Weld

Use 3/16" Fillet Weld On
Beam Webs And
Stiffeners

FIG. 3 CONNECTION DETAILS
FIG. 4 LOAD-DEFLECTION RELATIONSHIPS OF THREE-STORY FRAME
(FACTORED GRAVITY LOAD)
FIG. 5 LOAD-DEFLECTION RELATIONSHIP OF THREE-STORY FRAME
(WORKING GRAVITY LOAD)
FIG. 6  LOAD CYCLING PROGRAM
FIG. 7 SINGLE-STORY FRAME TEST SETUP

FIG. 8 THREE-STORY FRAME TEST SETUP
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