Strength of Beam-and-Column Subassemblages in Unbraced Multi-Story Frames

EXPERIMENTS ON UNBRACED ONE- STORY ASSEMBLAGES

by

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>2. EXPERIMENT DESIGN</td>
<td>6</td>
</tr>
<tr>
<td>3. MECHANICAL AND CROSS-SECTION PROPERTIES</td>
<td>9</td>
</tr>
<tr>
<td>3.1 Tensile Coupon Tests</td>
<td>9</td>
</tr>
<tr>
<td>3.2 Cross-Section Properties</td>
<td>9</td>
</tr>
<tr>
<td>4. TEST SETUP AND PROCEDURE</td>
<td>10</td>
</tr>
<tr>
<td>4.1 General</td>
<td>10</td>
</tr>
<tr>
<td>4.2 Load Application</td>
<td>11</td>
</tr>
<tr>
<td>4.3 Instrumentation</td>
<td>13</td>
</tr>
<tr>
<td>4.4 Alignment Procedure</td>
<td>14</td>
</tr>
<tr>
<td>4.5 Test Procedure</td>
<td>15</td>
</tr>
<tr>
<td>5. TEST RESULTS</td>
<td>16</td>
</tr>
<tr>
<td>5.1 Welding Residual Moments</td>
<td>16</td>
</tr>
<tr>
<td>5.2 Initial Gravity Load Moments</td>
<td>17</td>
</tr>
<tr>
<td>5.3 Experimental Behavior</td>
<td>18</td>
</tr>
<tr>
<td>5.3.1 Assemblage SA-1</td>
<td>18</td>
</tr>
<tr>
<td>5.3.2 Assemblage SA-2</td>
<td>20</td>
</tr>
<tr>
<td>6. THEORETICAL ANALYSIS AND DISCUSSION</td>
<td>22</td>
</tr>
<tr>
<td>6.1 Theoretical Prediction</td>
<td>22</td>
</tr>
<tr>
<td>6.2 Analysis of Behavior</td>
<td>23</td>
</tr>
<tr>
<td>6.2.1 Test Assemblage SA-1</td>
<td>23</td>
</tr>
<tr>
<td>6.2.2 Test Assemblage SA-2</td>
<td>26</td>
</tr>
<tr>
<td>6.3 Effect of Variation of Column Loads</td>
<td>28</td>
</tr>
<tr>
<td>7. SUMMARY AND CONCLUSIONS</td>
<td>33</td>
</tr>
<tr>
<td>8. ACKNOWLEDGMENTS</td>
<td>35</td>
</tr>
<tr>
<td>9. NOMENCLATURE</td>
<td>36</td>
</tr>
<tr>
<td>10. TABLES AND FIGURES</td>
<td>37</td>
</tr>
<tr>
<td>11. REFERENCES</td>
<td>68</td>
</tr>
</tbody>
</table>
ABSTRACT

Tests were conducted on two full-sized one-story two-bay assemblages. One test assemblage was designed to simulate a story near the top of an unbraced multi-story frame. The other assemblage was designed to simulate a story near the bottom of a frame. In each test the total gravity loads applied to the beams and columns was maintained constant as drift increments were given to the assemblage. However, the distribution of gravity loads to the columns was varied linearly with the applied drift. This loading condition thus represented a realistic combined loading condition for an unbraced frame in a high-rise building. The lateral-load versus drift behavior of the assemblage was compared with predicted load-drift behavior computed from sway subassemblage theory. The predicted behavior of the assemblages was in very close agreement with the experimental behavior.
1. INTRODUCTION

The sway subassemblage method of analysis was developed to determine the approximate second-order elastic-plastic behavior of individual stories of an unbraced multi-story frame.\(^{(1,2,3,4,5)}\) In the method, a story, called a one-story assemblage is isolated from the frame. Using sway subassemblage theory, the complete lateral-load versus drift curve for the one-story assemblage is then determined for either proportional or non-proportional loads up to or beyond the stability limit load. The load-drift relationship for the one-story assemblage is obtained by superimposing the load-drift relationships for each sway subassemblage in the one-story assemblage. A sway subassemblage consists of a restrained column plus one or two restraining beams.

A two-phase experimental program was undertaken at Lehigh University to provide an experimental evaluation of restrained column theory and sway subassemblage theory.\(^{(6,7)}\) In Phase I, three restrained columns were tested and the results reported.\(^{(8)}\) The tests showed that good correlation with predicted behavior was obtained. These studies therefore provided an important first step in the experimental verification of sway subassemblage theory. Phase II of the program is an experimental investigation of two one-story assemblages and a comparison of the test results with predictions obtained from a sway subassemblage analysis.
The column axial loads in an unbraced frame subjected to combined loads, whether proportional or nonproportional, vary with increasing lateral load and drift. The variation for a particular story column is the summation of the variations in each column directly above the column considered. In the sway subassemblage method of analysis the actual variation in axial loads can not be exactly accounted for. Therefore some assumptions are required regarding the magnitude and distribution of the total gravity loads to the columns within the one-story assemblage.

In an analysis considering nonproportional loads, where the gravity loads are held constant, it is assumed that the column axial loads in the one-story assemblage are constant. The sum of the column axial loads by statics is equal to the total of all the gravity loads above the one-story assemblage. The distribution of the total gravity loads to each column of the one-story assemblage is taken as that obtained from a moment-balancing solution for the frame corresponding to the frame mechanism condition.\(^{(3,9)}\) An analysis considering proportional loads would also eventually arrive at the same column loads but would arrive there after several proportional increments of loading starting with zero gravity and lateral loads.

Analytical studies indicated that within the range of expected axial load ratios in a frame the behavior of a one-story assemblage is insensitive to the distribution of the axial loads to the columns. In fact these studies indicate that one-story assemblage behavior is unaffected by the distribution of the total gravity loads to the columns providing that no plastic hinges form in the columns.
The reasoning for this is as follows: First, an examination of the equilibrium equations for a one-story assemblage show that overall equilibrium is dependent only upon the magnitude of the total gravity loads and not on their distribution. (4) Second, the primary effect of the axial load for any particular column is to establish the magnitude of the reduced plastic moment capacity \( M_{pc} \) for that column. Thus in the absence of plastic hinges in the columns a variation of the total gravity loads to the columns will not change the one-story assemblage response.

Two tests of one-story assemblages were conducted in Phase II. Each assemblage consisted of three columns and two beams forming two equal bays of 15-ft. and a story height of 10-ft. The assemblages were tested under non-proportional loading, which is considered to be the more realistic case for practical frames. The total gravity load applied to the columns was maintained constant, as were the gravity loads applied to the beams. The lateral load was applied to the top the interior column using a horizontal screw jack. The data obtained from the tests was reduced to determine all stress resultants and deformations. The load-drift behavior was compared to predictions from sway subassemblage theory.

The results of the Phase II studies are reported herein. Experimental evaluation of sway subassemblage theory, as applied to the two one-story assemblages is reported, and includes an evaluation of the effect of variations of the total gravity loads to the columns.
Each assemblage was subjected to approximately two cycles of reversed loading to fairly large values of drift following the initial tests discussed above. These results are not presented in this report.
2. EXPERIMENT DESIGN

Since only two assemblages were to be tested a decision was made that one should be designed to simulate the expected behavior of a story close to the top of an unbraced frame, in the vicinity of the stability limit load. The other would simulate the expected behavior of a story near the bottom of the frame. Such simulations can be achieved by selecting beam and column sizes and loading such that near the stability limit load, the plastic hinge locations in the test assemblage are similar to the expected locations in the corresponding stories of the frame. At the same time, in order to facilitate some comparison with the results of the Phase I studies it is desirable to maintain the same story and bay dimensions and member sizes as closely as possible. (8)

The dimensions and member sizes selected for the two test assemblages reported herein are shown in Fig. 1. Assemblage SA-1 is designed to simulate the behavior of a story near the top of a frame, while SA-2 is designed to simulate the behavior of a story near the bottom of a frame. ASTM A36 steel is used throughout. All sections are oriented for strong axis bending. The ratios of strong axis moments of inertia are typical of those found in the upper and lower stories of unbraced frames.

Figure 2 shows the beam and column loads selected for each test assemblage and the expected plastic hinge locations. For assemblage SA-1 plastic hinges are expected to occur in the windward beam and at the tops of the interior and leeward columns. This is a typical
plastic hinge pattern for a story close to the top of an unbraced frame. The plastic hinges in assemblage SA-2 are expected to occur only in the beams which is typical for a story located near the bottom of a frame.

The concentrated beam loads shown in Fig. 2 are maintained constant and simulate the effect of a constant uniformly distributed gravity floor loading. The column axial loads are varied according to a pre-selected program to simulate constant gravity loading above the assemblage but the distribution to the columns is varied as would be expected to occur during application of the lateral loads. This is discussed further in Chapter 4. Since assemblage SA-2 is designed to achieve a mechanism with plastic hinges occurring only in the beams the effect of varying the column loads is expected to be detected only from the SA-1 test results.

The ranges of variation of the columns axial load ratios, \( \frac{P}{P_y} \), shown in Fig. 2 are chosen to represent as closely as possible a practical range, as well as to be within the capabilities of the available laboratory testing equipment. The column loads shown in the figure are computed using measured mechanical and cross section properties. Referring again to Fig. 2, each assemblage is designed to be subjected to increments of drift applied to the tops of the interior columns in a west to east direction. The relationship between the resulting lateral force \( Q \) (shown positive to the right) at the column top and the drift \( \Delta/2 \) measured at the center of the interior joint is used to describe the behavior of an assemblage. The column tops are connected by a pinned strut (shown dashed in the figure) designed to maintain a nearly constant distance between the column tops.
In the design calculations, plastic hinges at the ends of the beams are assumed to form at the column faces. Plastic hinges in the columns are assumed to occur at the centers of the joints.
3. MECHANICAL AND CROSS-SECTION PROPERTIES

3.1 Tensile Coupon Tests

A total of thirty-two tension tests were performed to determine the mechanical properties of the ASTM A36 steel used. The static yield stress level, ultimate stress and percent elongation were determined from eight tension coupons cut from each section, four from the flanges and four from the web. A summary of the data obtained from the tension tests is given in Table 1. A numerical average for each of the three properties was determined for the webs and flanges separately for each section. Based upon these average values, the plastic moment capacity $M_p$ and the axial yield load $P_y$ of each section were calculated.

3.2 Cross-Section Properties

The cross-section dimensions of each shape were determined at various locations along the length of each beam and column using micrometers and calipers. Measurements of web thickness were taken only at the cut ends of each length. The average cross-section properties of each shape are given in Table 2 and compared with the corresponding handbook values. There were no significant differences between the measured and handbook properties. The measured values were used to determine the area $A$, the moment of inertia $I_x$, and the plastic section modulus $Z$ for each section. The value of the calculated plastic moment capacities $M_p$ and axial yield loads $P_y$ are also shown in Table 2.
4. TEST SETUP AND PROCEDURE

4.1 General

The overall view of the test setup used for the two assemblage tests is shown in Fig. 3. Figure 3 actually shows assemblage SA-1 after two cycles of reversed loading and shows the frame displaced in a westerly direction. In the tests reported herein drift was applied in an easterly direction. A more detailed view of the west bay of SA-1 during testing is shown in Fig. 4. The test assemblage is shown in white. The darker members are all part of the testing equipment. A gravity load simulator applying loads to the columns can be seen at the left and right edges of Fig. 4.

Figure 5 shows the pinned connections that were used at the ends of the column and the strut joining the column tops. The strut consisted of two channels spaced about 12-in. apart. Large roller bearings were used to ensure that there would be no bending moments at the ends of the columns. A more detailed view of the strut between an interior and an exterior column is shown in Fig. 6. At the middle of each strut (near the top of Fig. 6) four small steel rods were inserted and provided with strain gages so that the lateral force in the strut could be calculated during testing. A close-up view of these rods is shown in Fig. 7.

Planar motion of each test assemblage was ensured by means of specially designed lateral bracing perpendicular to the plane of the test specimen as can be seen in Figs. 4 and 5. The bracing
prevented lateral and torsional movement of the beams but did not offer restraint to in-plane deformation. The braces for the beams were placed at the locations recommended for use in plastic design. The beams were also braced in accordance with the requirements for reverse cyclic loading, the results of which are not reported herein. Six braces were used for each beam. The columns were braced using the same type of bracing members. Each column was braced at the level of the beams as shown in Fig. 4. All braces were in turn attached to an independent supporting frame.

4.2 Load Application

Vertical beam loads were applied approximately at the quarter points of each beam through a spreader beam which was attached at its mid-point to the tension jack of a gravity load simulator as shown in Figs. 3 and 4. Tension dynamometers were used to connect the spreader beam to the test specimen and also to measure the applied loads. The tension jacks of the two simulators were connected to a common hydraulic line to ensure that the same loads would be applied in both spans. Once the beam loads were applied, they were maintained constant for the duration of the test.

Each column load was applied to the top of the column by means of tension rods connected to two gravity load simulators placed on either side of each column, as shown in Fig. 8. The tension rods were provided with strain gages and calibrated so that the load applied by each simulator jack could be calculated. A common hydraulic line was connected to each pair of simulator jacks at each column. The column loads could
therefore be controlled by adjusting the hydraulic pressure in each pair of jacks and checked by taking readings on the tension rods.

The column loads were varied as discussed in Chap. 2 to maintain the desired axial load ratio $P/P_y$ in each column at every stage of the test. In order to accomplish this a loading program was determined for each column for each test assemblage. Figure 9 shows the column loading program used for the two subassemblies. For SA-1, the calculated drift corresponding to the theoretical mechanism condition was divided into ten drift increments. The load was adjusted at the end of each drift increment in order to maintain the desired axial load ratios in the columns. The open circles in Fig. 9(a) show the desired values of $P/P_y$ for each column for each drift increment. The column load used during each drift increment was the average of the desired axial load ratios at the beginning and the end of each increment. All strain and deflection readings were taken at the mid-point of a drift increment.

The column loading program for assemblage SA-2 is shown in Fig. 9(b). For this test the column loads were varied up to and somewhat beyond the mechanism condition. This was to account for the effect of strain hardening which can occur in the beams in the lower stories of a frame after the stability limit load is reached.

The drift increments at the top of the interior columns were applied by a mechanical screw jack mounted horizontally at the top of the interior column as shown in Figs. 6 and 10. The jack was pin connected to the column top through a dynamometer used to measure the lateral load applied by the jack. The jack was also pin connected to the independent supporting frame.
4.3 **Instrumentation**

The instrumentation used in the tests was designed to obtain strain data which could be used to (1) calculate the applied loads, (2) determine deformations and (3) calculate the internal stress resultants in the assemblages. Calibrated dynamometers were used to measure all applied loads.

Strains in the beams and columns were obtained from SR-4 electrical resistance strain gages. Four strain gages were used at each instrumented cross-section so that the axial force and bending moment at the cross-section could be calculated. Four cross-sections were gaged on each column and six were gaged on each beam as shown in Fig. 11. In addition another four gages were mounted on the beam webs at six instrumented cross-sections of each assemblage. These cross-sections were chosen near the locations of potential plastic hinges so that some strain measurements would be available after the occurrence of yielding in the flanges at those cross-sections.

Electrical displacement gages were used to measure drift and vertical beam deflections at the locations indicated in Fig. 12. A transit was also used to measure drift at the level of the beams by reading a scale attached to the face of each column.

Rotations were measured using electrical rotation gages. These gages were placed at the top and bottom of each column, at the joints and at either side of the concentrated beam loads as shown in Fig. 12.
Each test assemblage was whitewashed prior to testing in order to observe the progression of yielding. All electrical SR-4 strain gages, electrical displacement and rotation gages and dynamometers were read by a multi-channel strain gage recording system and punched automatically onto computer cards. This procedure enabled a systematic data reduction to be performed using a computer program.

4.4 Alignment Procedure

During erection of an assemblage the three columns were first placed on their pin-base supports, lightly attached to the surrounding framework at the beam level and aligned with transits to ensure that each beam was horizontal, in the correct position and in the plane of the assemblage. After all alignment was complete and all instrumentation in place, the initial set of strain and deflection readings were taken. Then the beams were welded to the columns. After the welding was completed, the lateral bracing in place and the temporary attachments removed a second set of readings was taken to isolate the effect of welding. At this point the horizontal struts between the column tops were loosely fitted so that no stresses would be developed in the columns above the beam level.

After erecting and aligning each assemblage, it was necessary to adjust the positions of the load hangers on either side of the columns (Fig. 8) to eliminate any eccentricity of the applied column load. Strain readings were taken at several small column load levels. Based on the strains obtained, the positions of the load hangers were adjusted to reduce the eccentricity of column load. The adjustment was continued for each
column until all column loads were applied with negligible eccentricities. At this point the horizontal struts were fitted snugly between the column tops by adjusting the rods at the center of each strut.

4.5 Test Procedure

At the start of each test and with the assemblage in a zero drift position one-half of the initial column loads (Figs. 2 and 9) and the full beam loads were gradually applied simultaneously. The columns loads were then gradually increased to their full values while the beam loads were held constant. After all the vertical loads had been applied all strain and deflection readings were again recorded to isolate the effect of the initial gravity loads.

From this initial stage the drift of the interior column was incremented following the predetermined program using the horizontal screw jack at the interior column top. A particular drift increment was applied in two steps. First, one half of the drift increment was applied with the column loads maintained equal to the average value desired for that interval. Then, all strain and deflection readings were taken. After taking all readings, the second half of the required drift increment was applied. At the end of the increment, the column loads were adjusted to the average value required for the next increment in the load program. These procedures were repeated until the total drift exceeded the drift corresponding to the stability limit load for the assemblage.

When inelastic action was evident in an assemblage, all readings were taken after approximately a ten to thirty minute waiting period in order to allow the yielding process to stop and the assemblage to come to static equilibrium.
5. TEST RESULTS

5.1 Welding Residual Moments

Since the fabricated assemblages are statically indeterminate, the welding operation can introduce residual stresses into the beams and columns. The calculated moments resulting from the welding are shown plotted in Fig. 13 on the tension side of each member. No particular welding order was maintained. The moments shown in the figure apply only to the test assemblages and could be entirely different in a one-story portion of an actual frame.

A certain amount of error is evident since the residual moments shown in the figure should theoretically be in self equilibrium. This error can be attributed mainly to (1) experimental accuracy; strains were recorded to an accuracy of about ± 5 micro-inches, and (2) probable restraints provided by the attachments used to align the members prior to welding.

Even though the absolute error indicated in Fig. 13 is fairly large the relative error is probably small. For instance, the largest residual moment at a potential plastic hinge location in a beam is about 0.09 M_p, and for a column, about 0.12 M_pc. The probable error in the residual moments is likely to be somewhat smaller than this. Therefore the measured residual moments are considered to be sufficiently accurate to include in Chap. 6 where a detailed analysis of all the test results is made.
5.2 Initial Gravity Load Moments

The constant gravity loads which were actually applied to the two test assemblages are shown in Figs. 14 and 15. These loads are to be compared with the design loads which are shown in Fig. 2. During each test the constant gravity loads were maintained using calibrated pressure gages which determined the oil pressure delivered to the several hydraulic jacks. The differences between the design and actual loads arise mainly from the accuracy with which the pressure gages could be read. The actual gravity load carried by an assemblage was calculated after the test using data recorded from the calibrated tension dynamometers previously discussed in Chapter 4. The average applied gravity load during a test is shown in Figs. 14 and 15.

The bending moments for each test assemblage corresponding to the initial constant gravity loads are also shown in Figs. 14 and 15. The theoretical bending moments which are shown in parentheses and the theoretical moment diagrams which are shown dotted were obtained from an analysis of each assemblage using the loads shown in the figures. The solid lines represent the bending moments computed from the strains measured on the beams and columns. Fairly good correlation was obtained between the theoretical and experimental values except mainly in the interior region of the beams. However, some differences can be expected to occur since the theoretically computed moments do not take into account deformations of the members (column shortening, initial crookedness of the columns, etc), slight eccentricities of load or slight variations in cross-section dimensions. The experimentally obtained moments are used in Chapter 6 where a detailed analysis of the test results is made.
5.3 Experimental Behavior

The experimental behavior of the two test assemblages will be discussed with reference to Figs. 16 to 22 inclusive. Comparison with theoretical predictions and a detailed analysis of the test results will be presented in Chapter 6.

The experimental load-drift behavior of each assemblage is shown by the solid lines in Figs. 16 and 19. The numbered circles on these curves correspond to the numbered drift increments (DI) shown on Figs. 18 and 21 respectively. Two theoretical load-drift curves for each assemblage, as determined by two sway subassemblage analyses are shown by the dashed curves in Figs. 16 and 19. These analyses were performed prior to testing and were used during testing to gage the progress of the tests. These two curves differ only in the assumed location of beam plastic hinges adjacent to the columns. Further discussion of these analyses is deferred to Chapter 6.

5.3.1 Assemblage SA-1

The experimental load-drift behavior of assemblage SA-1 is shown in Fig. 16. The onset of yielding was first observed in the flanges of the windward (west) beam adjacent to the windward face of the interior column at drift increment number 3 (DI3). At DI4 yielding was also observed in the flanges at the top of the leeward (east) restrained column, (ie: below the joint). At DI5 a considerable amount of yielding was observed in the flanges and webs at both of these locations.

Yielding of the flanges at the top of the interior restrained column was first observed at DI10, followed by initial yielding of the
flanges of the windward beam under the windward loading point at DII1. At this point the maximum applied lateral load Q of 25.75 kips was reached. Between DII1 and DII3 the lateral load decreased slightly. The test was terminated at DII3. No lateral-torsional or local buckling was observed prior to DII3. Four plastic hinges were observed to form in the sequence predicted by Analysis 1 and in the same locations (Fig. 16). Yielding was also observed in the beam between the windward column and hinge location 4.

The deflections of the assemblage at three stages of the test are shown in Fig. 17. Even though the figure shows the measured deflection points connected by straight line segments, the angle changes at the locations of the plastic hinges are quite noticeable. This is particularly evident at the locations of the first three plastic hinges.

The experimental variations in the axial load ratios $P/P_y$ for each of the three columns of assemblage SA-1 are shown in Fig. 18(a). These ratios were computed using the applied loads $P$ determined from the calibrated tension dynamometers connected to the gravity load simulators and the calculated values of $P_y$ shown in Table 2. The applied loads were also checked with the axial loads indicated by the column strain gages.

Figure 18(b) shows the experimental variation in shear at the top of each column of assemblage SA-1. These values were computed using the calibrated dynamometers in the horizontal struts between the column tops and checked with the shears indicated by the column strain gages.
The shear $H_A$ taken by the windward column reversed directed as expected. In addition the shears taken by the windward and leeward columns reached their maximum values and began to reduce prior to the drift increment corresponding to the maximum load carrying capacity of the assemblage. The total applied lateral load $Q$ is the sum of the individual column shears, $H_A + H_B + H_C$.

5.3.2 Assemblage SA-2

The experimental load-drift behavior of assemblage SA-2 is shown in Fig. 19. The onset of yielding was first observed at DI3 in the flanges of both beams adjacent to the windward faces of the interior and leeward columns. At DI5 yielding was also observed in the flanges of the beams at the windward loading points of both beams.

Yielding of the flanges and webs of the beams at all four locations steadily progressed from DI5 until DI12 when the maximum load carrying capacity of 15.69 kips was reached. At this point a few yield lines were also visible in the leeward flanges at the tops of all three restrained columns. Between DI12 and DI15 the applied lateral load gradually reduced. The test was terminated at DI15. No lateral-torsional local buckling was observed prior to DI15. Four plastic hinges were observed to occur in the sequence predicted by Analyses 1 and 2 and in the same locations (Fig. 19). Yielding was also observed in the beams between the windward and interior columns and hinge locations 3 and 4.

The deflections of the assemblage at three stages of the test are shown in Fig. 20. The columns remained essentially straight while
the angle changes in the beams at the locations of plastic hinges are particularly noticeable.

The experimental variations in axial load ratios $P/P_y$ for the three columns of assemblage SA-2 are shown in Fig. 21(a). These values were computed using the applied loads $P$ determined from the calibrated tension dynamometers connected to the gravity load simulators and the calculated values of $P_y$ shown in Table 2. The applied loads were also checked with the axial loads indicated by the column strain gages.

Figure 21(b) shows the experimental variation in shear at the top of each column of assemblage SA-2. These values were computed using the calibrated dynamometers in the horizontal struts between the column tops and checked with the shears indicated by the column strain gages. The shear $H_A$ taken by the windward column reversed direction as expected. In addition the shear $H_C$ taken by the leeward column reached a maximum value then began to reduce prior to the drift increment corresponding to the maximum load carrying capacity of the assemblage. The total applied lateral load $Q$ is the sum of the individual column shears, $H_A + H_B + H_C$. 

6. THEORETICAL-ANALYSIS AND DISCUSSION

6.1 Theoretical Prediction

Several sway subassemblage analyses were performed for each assemblage using the SMOA computer program previously developed at Fritz Engineering Laboratory.\textsuperscript{(14,15)} In the analyses the lengths of the columns were taken as the total distance between the pinned ends. However, the clear span length (face to face of columns) was assumed for each beam. These assumptions were based on the results of the Phase I studies.\textsuperscript{(8)}

Plastic hinges in the test assemblages actually develop over a certain finite length due to the effects of strain hardening whereas in the analysis the plastic hinges are assumed to occur only at a particular cross-section. To account for this difference three separate analyses were performed for each assemblage. These analyses differed only in the assumed location of a plastic hinge forming in a beam cross-section adjacent to the columns. These cross-sections were assumed as follows:

Analysis 1: The cross-section at the face of a column.

Analysis 2: The cross-section located away from the face of a column a distance equal to the beam depth.

Analysis 3: The cross-section located away from the face of the column a distance equal to one-half the beam depth.

In each analysis plastic hinges in the columns were assumed to form in the cross-section at the center of a joint.
The actual mechanical and cross-section properties of the members, the actual dimensions of the assemblages, as fabricated and erected, and the actual applied beam and column loads were used in the SMOA analyses to determined theoretical load-drift behavior of each test assemblage. Analyses 1 and 2 were performed prior to carrying out the tests. Analysis 3 was performed after testing was completed.

6.2 Analysis of Behavior

6.2.1 Test Assemblage SA-1

The experimental load-drift curve for assemblage SA-1 is shown in Fig. 16. Also shown are two theoretical curves plotted from the results of Analyses 1 and 2 of the assemblage. The sequence of formation of the plastic hinges is shown on the theoretical curves and also on the sketch of the assemblage in the figure. Each of the two analyses predicts a slightly different plastic hinge sequence. Analysis 2 requires a larger moment at the interior joint that that required by Analysis 1. As a result, in Analysis 2, the first plastic hinge is required to develop in the leeward restrained column. The effect is to substantially increase the stability limit load predicted by Analysis 2.

Figure 16 shows that good correlation between the experimental and Analysis 1 load-drift curves was obtained up to about DI5. Beyond DI5 the assemblage carried substantially higher lateral load than that predicted by Analysis 1. The maximum load (25.75 kips) was only slightly higher than the stability limit load (25.20 kips) predicted by Analysis 2. However, the observed onset of yielding in the assemblage (Art. 5.3.1) indicated that the plastic hinge sequence was that predicted by Analysis 1.
In addition the lateral load did not reduce after a mechanism condition was reached as predicted by either analysis.

The major differences between the observed and the predicted behavior of assemblage SA-1 can be explained by examining Fig. 22. This figure shows the experimental bending moment versus drift relationships at each of the plastic hinge locations assumed in Analysis 1. The welding residual moments (Fig. 13) have been included together with the moments resulting from the applied lateral load. It is apparent that by DI5 the plastic moment $M_p$ of the beam was reached and slightly exceeded at hinge location 1. Similarly the $M_{pc}$ of the leeward column had been reached at hinge location 2 by DI7. It is evident therefore that up to about DI5 fairly good correlation between the observed and the predicted behavior from Analysis 1 can be expected. However between DI5 and DI7 the moments $M_1$ at hinge location 1 somewhat exceeded $M_p$ thus delaying the formation of the column hinge at location 2. Beyond DI7 the bending moments $M_1$ and $M_2$ at both locations exceeded the respective plastic moment capacities of the members. Since these hinge locations are within regions of high moment gradient this increase can be attributed to the effect of strain hardening. This effect was not directly considered in Analysis 1. Thus Analysis 1 predictions can be expected to underestimate the lateral load capacity and overestimate drift for all drifts in excess of DI5.

Analysis 2 considers the effect of strain hardening indirectly in an approximate way by requiring that the $M_p$ at plastic hinge location 1 be reached at a cross-section a beam depth away from the column face. This analysis more closely predicted the maximum load capacity of the assemblage which, of course, is affected by strain hardening.
Observations made during the tests indicated that yielding of the windward beam at hinge location 1 had spread to a distance about equal to the beam depth away from the column face. The extent of yielding at this location is shown in Fig. 23. On this basis Analysis 3 was performed in which the plastic hinge at location 1 was assumed to be more realistically concentrated at a cross-section one-half the beam depth away from the column face. The corresponding bending moment versus drift relationship which includes the welding residual moments is shown in Fig. 24. Since the moment $M_1$ at this cross-section more nearly approximates $M_p$ for drifts in excess of $DI5$ the results of Analysis 3 can be expected to more closely predict the test results if the effect of strain hardening is isolated and eliminated from the test results.

The experimental load-drift curve for assemblage SA-1 is again shown in Fig. 25, and compared with the theoretical curve obtained from the results of Analysis 3 for the assemblage considering the actual variation in the column loads (Art. 6.3.1). Also shown in the figure is an experimental load-drift curve where the effect of strain hardening has been eliminated. The increments of lateral load attributed to strain hardening were calculated for each drift increment based on the difference between the actual column moments at the centers of the joints and the computed values of $M_{pc}$ based on the actual applied column loads also taking into account the $P\Delta$ effect. It is evident from the figure that the correlation between the results of Analysis 3 and the modified experimental results is quite good.
6.2.2 **Test Assemblage SA-2**

The experimental load-drift curve for assemblage SA-2 is shown in Fig. 19. Also shown are two theoretical curves plotted from the results of Analyses 1 and 2 for the assemblage. The sequence of formation of the plastic hinges is shown on the theoretical curves and also on the sketch of the assemblage shown in the figure. The same plastic hinge sequence is predicted by both analyses.

Figure 19 shows that good correlation between the experimental and Analysis 1 load-drift curves was obtained up to about DI5. Beyond DI5 the assemblage carried a higher lateral load (15.69 kips) than that predicted by Analysis 1 (14.50 kips) but less than that predicted by Analysis 2 (18.05 kips). The lateral load did reduce somewhat after a mechanism condition was reached but not so abruptly as predicted by either analysis.

The major differences between the observed and the predicted behavior of assemblage SA-2 can be explained by examining Fig. 26. This figure shows the experimental bending moment versus drift increment relationships at each of the plastic hinge locations assumed in Analysis 1. Considering the effect of welding residual moments (Art. 5.1) it is evident that the $M_p$ of the beam was essentially reached at hinge locations 1 and 2 by DI5. This correlates well with the observed onset of yielding (Art. 5.3.2) which occurred simultaneously at both locations at DI3. A plastic hinge condition was not reached at hinge locations 3 and 4 until about DI13 and DI14.
It is evident from Fig. 26 that up to DIS good correlation between observed and predicted behavior can be expected. However beyond DIS the bending moments $M_1$ and $M_2$ at hinge locations 1 and 2 exceeded the respective plastic moment capacities $M_p$ of the beams. Since both hinge locations are in regions of high moment gradient this increase can be attributed to the effect of strain hardening. As mentioned in Art. 6.2.1, this effect was not considered in Analysis 1. Thus Analysis 1 predictions will underestimate the lateral load capacity and overestimate drift of the assemblage beyond DIS.

Analysis 2 considers the effect of strain hardening indirectly in an approximate way by requiring that the $M_p$ at plastic hinge location 1 and 2 be reached at a cross-section a beam depth away from the column face. Analysis 2 actually overestimates the lateral load capacity and underestimates drift beyond DIS.

Observations made during the test indicated that as in assemblage SA-1 yielding of the beams at hinge locations 1 and 2 had spread to a distance about equal to the beam depth away from the column face (Fig. 23(a)). On this basis Analysis 3 was performed in which the plastic hinges at locations 1 and 2 were assumed to be more realistically concentrated at a cross-section one-half the beam depth away from the column face. The bending moment versus drift relationships at hinge locations 1 and 2 are shown in Fig. 27. The residual welding moments at these locations have been considered. It is evident that the moments at these locations more closely approximates $M_p$ after DIS.
The experimental load-drift curve for assemblage SA-2 is again shown in Fig. 25, and compared with the theoretical curve obtained from the results of analysis 3 of the assemblage. Good correlation between experimental and theoretical results is obtained up to the maximum load level. Beyond that, the excess load capacity may be attributed to the effects of strain hardening in the beams, as was discussed in Art 6.2.1.

6.3 Effect of Variation of Column Loads

Sway subassemblage theory indicates that if the total gravity load carried by the restrained columns in a one-story assemblage is constant there will be no effect on the load-drift behavior of the assemblage due to variations in the distribution of the gravity load to the columns, providing that plastic hinges do not form in the restrained columns. Plastic hinges were predicted to form in the interior and leeward restrained columns of assemblage SA-1. Plastic hinges did occur in these columns during the test. An analysis of assemblage SA-1 and a comparison with the experimental results will indicate the significance of variations of the column loads on the load drift behavior of the assemblage.

Figure 29 again shows the experimental load-drift behavior of SA-1 modified to eliminate the effects of strain hardening in the columns (Art 6.2.1 and Fig. 25). The modified experimental results are compared in the figure with three theoretical load-drift curves computed using the Analysis 3 assumptions (Art. 6.1). The differences between the three analytical curves are entirely due to variations in the assumed column loads. In the analyses the axial load ratios \( P/P_y \) assumed for the
windward (column A), interior (column B) and leeward (column C), restrained columns of assemblage SA-1 were as follows (see also Fig. 18)

Analysis 3A: \( \frac{P_A}{P_y} = 0.35; \frac{P_B}{P_y} = 0.35; \frac{P_C}{P_y} = 0.36. \)

This corresponds to the assumption of a uniform distribution of total gravity loads. The ratios were computed from the average of the nearly constant total gravity loads in the restrained columns during the test. These ratios were maintained constant in Analysis 3A.

Analysis 3B: \( \frac{P_A}{P_y} = 0.11; \frac{P_B}{P_y} = 0.33; \frac{P_C}{P_y} = 0.65 \)

This corresponds to the distribution of the total gravity loads to the columns at the end of the test. These ratios were maintained constant in Analysis 3B.

Analysis 3C:

The load-drift curve in Fig. 29 was plotted from the results of 13 separate analyses, one for each drift increment (DI) used in the test. In each analysis the axial load ratio \( \frac{P}{P_y} \) selected for each column was held constant. The ratios selected for a particular analysis were those actually applied during the test at a particular drift increment. Thus the load-drift curve in Fig. 29 represents the effect of maintaining the total gravity loads constant but varying the distribution to each column as the drift was varied. This closely represents the practical loading case for an unbraced frame.

Also shown in Fig. 29 are the locations and sequences of formation of the plastic hinges predicted by each of the three analyses. The behavior predicted by Analysis 3C is identical to that predicted by Analysis 3A up to the second plastic hinge. At this point the moment at the top of the leeward restrained column also reached \( M_{pc} \) for that column (\( M_{pc} \) is steadily decreasing due to increasing \( \frac{P}{P_y} \) in the leeward
column). As the lateral load and drift continue to increase the magnitude of $M_{pc}$ at the top of the leeward restrained column continues to decrease (thus causing the moment at the end of the leeward beam to also decrease) and the second plastic hinge shifts from the beam to the top of the restrained column (hinge position 1 in Analysis 3B). With further increases in lateral load and drift the third plastic hinge eventually forms in the windward beam as indicated in the figure. At this stage the maximum lateral load capacity of 23.5 kips is reached. Beyond this point additional drift results in decreasing lateral load. The value of $M_{pc}$ at the top of the leeward restrained column still continues to decrease however because $P/P_y$ in that column is still increasing (Fig. 18), thus maintaining the plastic hinge at that point. Because of the reduction in moment at the leeward end of the leeward beam (joint equilibrium being maintained) the positive moment at the windward loading point of that beam continues to increase even though the bending moment in the beam due to the applied lateral loads is decreasing. Finally, the fourth plastic hinge develops in the leeward beam as predicted by Analysis 3B.

Comparison of the analytical results with the modified experimental load-drift behavior in Fig. 29 indicates that excellent correlation was achieved between the two curves. The difference between the observed location and sequence of plastic hinges (Art. 5.3.1 and Fig. 16) and that predicted by Analysis 3C above can be readily explained with reference to strain hardening of the interior and leeward restrained columns. In the absence of strain hardening the moments at the interior and leeward joints are somewhat smaller than the moments observed in the test. As a result the third and fourth plastic hinges form as predicted by Analysis
3B. Due to strain hardening the moment in each restrained column is increased above the theoretical values of $M_{pc}$. The redistribution of moments in the assemblage is altered so that the third hinge forms in the interior column instead of the windward beam. The fourth hinge finally forms in the windward beam as shown in Fig. 23(b).

The theoretical load-drift curve for assemblage SA-2 shown in Fig. 28 remains the same regardless of the distribution of gravity loads to the columns. This is a consequence of the fact that no plastic hinges are predicted to occur in the restrained columns. As shown in the figure fairly good correlation between the experimental and predicted load-drift behavior of assemblage SA-2 was obtained. The differences that did occur can be attributed partly to the slight strain hardening of the third plastic hinge beyond DI13 (Fig. 26), partly to assumptions used in the analysis which were not exactly attained in the experiment and partly to experimental error. In view of the major effect of the variation of column loads exhibited in assemblage SA-1, it can be concluded that the variation in column loads for assemblage SA-2 had little or no effect on the load-drift behavior of the assemblage.

The implication of the above results on the use of sway sub-assemblage theory to predict the load-drift behavior of one-story assemblages is as follows:

1. For assemblages in which column plastic hinges are not expected to occur use any reasonable distribution of the total gravity loads to the column when performing the analysis. For instance the distribution obtained under gravity loads alone could be used.
2. For assemblages in which column plastic hinges are expected to occur, or when it is not known if column plastic hinges will occur, consider the probable variation in column loads in the analysis. For the zero drift condition, the distribution of gravity loads to the columns will be for the gravity load alone case as in (1) above. For drifts in the vicinity of the stability limit load or the mechanism load, a reasonable estimate of the column loads can be obtained from a moment balancing solution of the frame or from a prior frame analysis if preliminary designs of the frame are being carried out. For intermediate values of drift the column loads can be obtained from a linear variation of the total changes in the column loads as was performed in this report.
7. **SUMMARY AND CONCLUSIONS**

Tests were conducted on two one-story assemblages. One assemblage was designed to simulate the expected behavior of a story close to the top of an unbraced multi-story frame. The other was designed to simulate the expected behavior of a story near the bottom of the frame. Several analyses of the assemblages were carried out by computer using a computer program (SMOA) previously developed from sway subassemblage theory. The analyses were used to obtain predicted lateral load versus drift curves for the assemblages. The several predicted load-drift curves differed in the assumed locations of beam plastic hinges adjacent to the columns and in the assumed distribution of the total constant gravity loads to each of the columns. Excellent correlation between experimental and predicted behavior was obtained, especially when the effect of strain hardening, neglected in the analyses, was accounted for in the experimental results.

The major conclusions based on the results of this investigation are as follows:

1. The load-drift behavior of each assemblage was essentially as predicted. The location and sequence of formation of plastic hinges were as predicted.

2. The experimental behavior of both assemblages compared best with predicted behavior when plastic hinges at the leeward ends of the beams were assumed in the analysis to form at a cross-section located one-half the beam depth away from the face of the column.
3. Strain hardening of plastic hinges at the top of restrained columns had a significant effect on the load-drift behavior of an assemblage. Neglecting strain hardening in the analysis had the effect of underestimating the lateral load capacity of the assemblage and overestimating drift.

4. Variation in the distribution of gravity loads to the columns as drift increases has a significant effect on the load-drift behavior of an assemblage only if plastic hinges occur in one or more restrained columns. This conclusion is in accordance with sway subassemblage theory.
8. ACKNOWLEDGEMENTS

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9. NOMENCLATURE

A  area of cross section;
b  flange width;
d  depth;
H  horizontal wind load;
I_x  moment of inertia about major axis;
M  bending moment;
M_p  plastic moment capacity of cross section;
M_{pc}  reduced plastic moment capacity considering axial load;
P  axial force in column;
P_y  axial yield load of cross section;
Q  horizontal force;
t  flange thickness;
w  web thickness;
Z  plastic section modulus about major axis;
Δ/2  joint deflection.
10. TABLES AND FIGURES
### TABLE 1 SUMMARY OF TENSION TESTS

<table>
<thead>
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<th>Section</th>
<th>Static Yield Stress (ksi)</th>
<th>Ultimate Stress (ksi)</th>
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TABLE 2 AVERAGE CROSS-SECTION PROPERTIES

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<th>t (in)</th>
<th>w (in)</th>
<th>A (in²)</th>
<th>Iₓ (in⁴)</th>
<th>Z (in³)</th>
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<td>3.97</td>
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<td>79.6</td>
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*Yield stress taken as 36 ksi
Note: Members for SA-2 shown in parentheses where different from SA-1.
Shapes correspond to those listed in AISC Manual of Steel Construction - 6th Edition
(a) Assemblage SA-1

(b) Assemblage SA-2

- Expected Plastic Hinge Locations

FIG. 2 DESIGN LOADS AND EXPECTED PLASTIC HINGE LOCATIONS
Fig. 3 OVERALL VIEW OF TEST SETUP

Fig. 4 VIEW OF THE WEST BAY OF SA-1 DURING TEST
FIG. 5 VIEW SHOWING PINNED CONNECTIONS AT THE ENDS OF THE COLUMNS AND THE STRUT JOINING THE COLUMN TOPS
FIG. 6 DETAILED VIEW OF STRUT BETWEEN COLUMN TOPS—
AN INTERIOR COLUMN IS IN THE FOREGROUND
Fig. 7 DYNAMOMETERS USED TO DETERMINE THE FORCE IN A STRUT
FIG. 8 TENSION RODS USED TO APPLY COLUMN LOADS
FIG. 9 COLUMN LOADING PROGRAMS
FIG. 10 HORIZONTAL SCREW JACK USED TO APPLY DRIFT INCREMENTS TO THE ASSEMBLAGES
FIG. 11 LOCATION OF ELECTRICAL RESISTANCE STRAIN GAGES
FIG. 12 LOCATION OF DISPLACEMENT AND ROTATION GAGE
(a) ASSEMBLAGE SA-1

(Bending Moments Plotted on Tension Side)

(b) ASSEMBLAGE SA-2

FIG. 13 WELDING RESIDUAL MOMENTS
(a) Initial Gravity Loads

(b) Bending Moment Diagram

Unit: kip-in

--- Theoretical (Moments in Parentheses)

- Experiment

(Note: Bending Moments Plotted on Tension Side)

FIG. 14 - SA-1: LOAD AND MOMENT CONDITIONS AT ZERO DRIFT
(a) INITIAL GRAVITY LOADS

\[ P_A = 94^k \]
\[ P_B = 139^k \]
\[ P_C = 92^k \]

(b) BENDING MOMENT DIAGRAM

Unit: Kip-in

--- Theoretical (Moments in Parentheses)
--- Experiment

(Note: Bending Moments Plotted on Tension Side)

(b) BENDING MOMENT DIAGRAM

FIG. 15 - SA-2: LOAD AND MOMENT CONDITIONS AT ZERO DRIFT
FIG. 16 - SA-1: LATERAL LOAD VERSUS DRIFT BEHAVIOR
FIG. 17 - SA-1: EXPERIMENTAL DRIFT AND BEAM DEFLECTIONS
FIG. 18 - SA-1: EXPERIMENTAL COLUMN LOADS AND SHEARS
First Yielding at Hinge Locations 1 and 2

Drift Increment - D1

Plastic Hinge Sequence

FIG. 19 - SA-2: LATERAL LOAD VERSUS DRIFT BEHAVIOR
FIG. 20 - SA-2: EXPERIMENTAL DRIFT AND BEAM DEFLECTIONS
FIG. 21 - SA-2: EXPERIMENTAL COLUMN LOADS AND SHEARS

(a) Column Axial Load Ratios $P/P_y$

(b) Individual Column Shears

Drift Increment - DI

INTERIOR JOINT DRIFT - $\Delta/2$ (in.)
FIG. 22 - SA-1: EXPERIMENTAL MOMENTS AT PREDICTED PLASTIC HINGE LOCATIONS
(a) EXTENT OF YIELDING AT PLASTIC HINGE LOCATION 1

(b) EXTENT OF YIELDING AT PLASTIC HINGE LOCATION 4

FIG. 23 PLASTIC HINGES IN THE WINDWARD BEAM OF ASSEMBLAGE SA-1
FIG. 24 - SA-1: EXPERIMENTAL MOMENT AT PREDICTED PLASTIC HINGE LOCATION 1
FIG. 25 - SA-1: COMPARISON OF EXPERIMENTAL AND PREDICTED LATERAL LOAD VERSUS DRIFT BEHAVIOR

INTERIOR JOINT DRIFT - $\Delta/2$ (in.)

LATERAL LOAD $Q$ (kip)

Experiment
Strain Hardening Effect
Experiment Less Effect of Strain Hardening
Analysis 3
(Analysis 3C in Fig. 29)
FIG. 26 - SA-2: EXPERIMENTAL MOMENTS AT PREDICTED PLASTIC HINGE LOCATIONS
FIG. 27 - SA-2: EXPERIMENTAL MOMENTS AT PREDICTED PLASTIC HINGE LOCATIONS 1 AND 2
FIG. 28 - SA-2: COMPARISON OF EXPERIMENTAL AND PREDICTED LATERAL LOAD VERSUS DRIFT BEHAVIOR
FIG. 29 - SA-1: EFFECT OF VARIATION OF COLUMN LOADS ON LATERAL LOAD VERSUS DRIFT BEHAVIOR
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