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Revised proposal for braced multi-story frame tests, February 1964

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Welded Continuous Frames and Their Components

REVISED
PROPOSAL
FOR
BRACED MULTI- STORY FRAME TESTS

by
Joseph A. Yura
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George C. Driscoll, Jr.

February 1964

Fritz Engineering Laboratory Report No. 273.14A
To: Members, Lehigh Project Subcommittee

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Subject: Revised Proposal for Braced Multi-Story Frame Tests

Gentlemen:

Enclosed is Fritz Engineering Laboratory Report No. 273.14A, "Revised Proposal for Braced Multi-Story Tests." This is a revised and expanded version of the proposal presented in F. L. Report 273.14 and approved at the September 23, 1963 meeting of the Lehigh Project Subcommittee in New York. The number of tests, system of loading, and type of lateral bracing have been changed in order to develop a setup for testing both braced and unbraced frames.

This report is sent to inform you of the progress to date in planning the tests on the multi-story frame project. It is expected that the testing of the frames will take place within the next few months.

George C. Driscoll, Jr.

GCD:mlc

Enclosures

cc: K. H. Koopman
Welded Continuous Frames and Their Components

REVISED PROPOSAL

for

BRACED MULTI-STORY FRAME TESTS

by

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Erol Yarimci
Le-Wu Lu
George C. Driscoll, Jr.

(Not for publication)

Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania
February 1964

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1. **INTRODUCTION**

In a steel structure subjected primarily to bending forces, simple plastic theory can generally be used to determine the ultimate strength. Extensive experimental work\(^1\) has been done on the components of such structures, that is, beams, columns, and connections. In addition, full-size frame tests have been used to study the interaction among the components and thus establish the plastic method of analysis experimentally.

Until recently the plastic method of analysis was restricted to structures composed of components primarily subjected to bending, such as one or two-story frames or the top stories of a multi-story frame. Members subjected to significant bending and axial force (beam-columns) introduce instability effects which had retarded the use of ultimate strength methods.

However, recent theoretical investigations\(^2\) at Lehigh University have solved the beam-column problem in that the load-deformation characteristics can be predicted to ultimate load and even after unloading. This solution has been incorporated in a method of analysis for the ultimate strength of a subassemblage\(^3\). A subassemblage consists of a beam-column and the other structural members framing into its ends. The ultimate strength of a subassemblage is not necessarily the same as, and is usually greater than, the ultimate strength of the individual beam-column. It represents a more rational approach compared to the design of isolated members in a multi-story frame.
Tests at Lehigh University have verified the method of analysis of subassemblages. In these tests isolated subassemblages with ideal end conditions were studied. However, a multi-story frame is composed of many subassemblages which are interdependent. In order to check the validity of the method for the ultimate strength design of multi-story frames, it is desirable to compare the theory with actual frame behavior. Unfortunately, no full scale tests have been conducted on frames in which axial force is significant.

Four tests on braced multi-story frames are proposed. The purpose of the tests is to provide experimental data on the ultimate strength of braced multi-story frames to compare with design methods. Important information on the interaction of subassemblages will be obtained in these multi-story frame tests which individual subassemblage tests cannot provide; the performance of bracing in multi-story frames will also be studied.

This is a revised and expanded version of the proposal presented in F. L. Report 273.14 and approved at the September 23, 1963 meeting of the Lehigh Project Subcommittee. The number of tests, system of loading, and type of lateral bracing have been changed in order to develop a setup for testing both braced and unbraced frames.
2. PROPOSED TEST PROGRAM

2.1 Test Frame

The proposed three-story, two-bay braced test frame is shown in Fig. 1. The columns are 15 ft center-to-center and 30 ft high. Standard welded construction will be used. This particular arrangement was chosen because it is composed of almost every type of subassembly, and it permits a checkerboard-type loading condition.

The column bases of the test frame will be fixed by means of prestressed anchorages, a detail of which is shown in Fig. 1. The bases are fixed in order to prevent failure at an early stage at an isolated point in the frame. If the bases were pinned, isolated failure of the interior column at the lower story would occur since a uniform column section is used.

The test frame is composed of three different cross sections as shown in Fig. 1; the exterior columns are 6WF20 (L/r=45), the interior columns are 6WF25 (L/r=45) and all the beams are 12B16.5. The columns are uniform from the base to the top story. ASTM-A36 steel will be used.

The column sections were chosen on the bases of realistic frame geometry and slenderness ratios commensurate with those in multi-story frames. Smaller column sizes would require a corresponding decrease in frame geometry which is not desirable.

Four tests are proposed. The frame will be the same for all tests, but the type of loading will vary.
2.2 Loading Conditions

The loading conditions for the four proposed tests are shown schematically in Fig. 2 (the bracing is not shown). In the figure, uniform loads are shown for clarity; actual test loads will be concentrated at the one-fourth points on the beams which simulates uniform loading and lateral loads will be concentrated at each story level.

The loading condition shown in Fig. 2a represents full dead and live loading on all floors. The axial loads will be relatively high in the interior column but the moments will be zero. There will be high axial forces and moments in the exterior columns. The exterior columns will be critical for this loading condition. Also, the loads on the top story are 0.75 of the loads on the lower two floors in order to prevent the formation of a beam mechanism in the top story.

A checkerboard loading arrangement will be used in the second frame test as shown in Fig. 2b. This loading will produce critical single-curvature bending in the interior columns. The loading condition simulates full dead load on all beams and full live load on alternate bays and floors. A uniform load approximating 0.50 of the ultimate load will be applied to all beams. Then, the additional loads to produce failure will be applied on alternate bays and floors.

The loading conditions shown in Figs. 2c and 2d are similar to that of the first two frames except for the addition of lateral load. This represents combined gravity and wind loading. These tests will provide information concerning the effect of bracing in resisting lateral loads, and the effect of lateral forces on the distribution of moments throughout the braced multi-story frame.
With the geometry shown, loads expected would correspond to a 170 psf vertical working load and a 20 psf working wind load. The ultimate load on each floor is expected to be approximately 80 kips. Also, the method of loading requires both the axial forces and the moments to be increased from zero to ultimate load. This is different from the individual subassemblage tests described previously in which an axial load was applied and kept constant during the test while the moment was increased from zero.

2.3 Test Setup

The setup for testing the braced frames is shown in Figs. 3 and 4. On all floors of both bays, vertical loads are applied to the test frame at the 1/4 points on the beam. Two equal concentrated loads are applied to beams through calibrated dynamometers (to measure the load) attached to the spreader beam which divides the single load supplied by the hydraulic loading system. Hydraulic cylinders (jacks) acting in tension have one end attached to the spreader beam and the other end connected to a gravity-load simulator. The gravity-load simulator is a device which permits the tension jack to remain vertical under lateral deflection in the plane of the test frame and provides very little restraint against lateral movement of the frame. The gravity-load simulator is supported by the loading frame which is fixed to the foundation. Lateral loads are applied at each floor level by hydraulic jacks acting in tension. Movement of the test frame out of its plane is prevented by lateral bracing which is supported by the loading frame. The test setup is similar in each bay and on every floor. The setup has been designed for use in tests of both braced and unbraced frames.
(1) **Gravity-Load Simulator.** In order to determine the forces in the bracing of the braced frame or the strength of an unbraced frame experimentally, the loading system must provide only negligible restraint to the frame. If large friction forces exist in the loading system, the frame would be braced by the loading system itself. A test frame loaded directly by dead weight is an ideal system because the dead weight does not restrain the frame. However, for the test frame proposed the dead weight method is impractical due to space and load requirements.

A mechanism has been developed which provides very little restraint to the test frame. It is called a gravity-load simulator because it approximates the behavior of actual dead weights. A schematic diagram of the mechanism is shown in Fig. 5. It is composed of three rigid members, two inclined straight arms connected by a rigid triangular member. Hinges are located at both ends of the inclined arms which makes the system stable only under upward loading. The triangular member permits one end of the tension jack to be connected at a certain point in space (load height) in reference to the fixed geometry of the mechanism (base width, top width and arm length).

For the type of mechanism shown, equilibrium requires that the line of action of the load pass through the instantaneous center, that is, the point of intersection of the two arms. The position of the instantaneous center changes as the mechanism is deflected as shown in Fig. 6. The line of action of the load must also be vertical if it is to simulate gravity load. For every deflected position, the load height can be calculated which satisfies these two conditions, namely, that the load pass through the instantaneous center and that the load is vertical.
The load height should not change from one deflected position to another for an ideal system. However, the calculated story height does change slightly from 3.065 ft to 3.027 ft for a corresponding lateral deflection of 16 in. for the geometry shown in Fig. 6. This geometry was chosen after numerous trials because it provided the necessary clearances for the test frame and permitted significant sidesway. A load height of 3.065 ft was chosen for the test setup. This causes a theoretical inclination of the load at large horizontal deflections. This load gradient, however, is approximately 1 to 400 for a deflection of 16 in. Thus if a load of 80,000 lb is applied to the mechanism, there will be a 200 lb horizontal component which is very small. In fact, this horizontal component will become negligible as the sidesway decreases. Thus, the system can be considered ideal for the testing of both braced and unbraced frames since large deflections are permissible.

Three different mechanisms are compared in Fig. 7 to show the effect of load height and geometry on the equilibrium system. In all cases the dotted lines represent the undeflected equilibrium position, and the solid lines represent an extreme deflected equilibrium position. Case (a) represents the ideal condition to be used in the frame tests. In the deflected position shown, the load gradient is 1 lb horizontal for every 400 lb vertical load (approximately 1 lb to 20,000 lb for a deflection of 6 in.). Case (b) shows the effect of changing the load height from 3.065 ft to 0.0 ft. The gradient becomes 1 lb to 1.4 lb which is unsatisfactory. Similarly, the arrangement using parallel arms shown in Fig. 7c also produces poor results.
The front elevation of the prototype gravity-load simulator is shown in Fig. 8. Roller bearings are used to provide the hinges at the ends of the inclined arms. A tube section is provided at the base to carry the horizontal component of the force in the inclined arms. It is also used to make the simulator a stable unit for ease in handling and erection in the test setup.

Six gravity-load simulators are required for the tests. One is currently under construction for use in conducting preliminary tests to check its actual performance. The simulator is designed to carry 100 kips.

(2) Loading Frame. The loading frame is shown in Figs. 4 and 9. The frame supports the gravity-load simulator and the out-of-plane bracing. It also provides a scaffold for instrumenting and examining the test frame. Two loading frames are provided, one on each side of the test frame. The loading frames consist of 12WF85 columns, 12WF27 beams on the first and second stories and 10WF25 beams at the top. Cross beams (10WF33) which directly support each gravity-load simulator tie the two frames together. Additional ties (10WF25) are provided at the top story. The frames are fixed to the foundation by means of anchorages.

The loading frame will be constructed almost entirely from existing stock and equipment. It will only be necessary to splice extensions to existing framing columns. The exterior columns will require 10 ft extensions using 12WF85 sections, while 15 ft extensions will be required for the interior columns. All beams and cross members will be fabricated from available material.
(3) **Bracing.** Lateral bracing is provided to prevent out-of-plane movement of the components of the test frame. This bracing should not be confused with the diagonal bracing which resists the unbalanced horizontal forces in the test frame.

Lateral bracing used in experiments usually have two undesirable characteristics. First, positive bracing attached to the specimen would provide restraint as the specimen deflects under load. Second, in a "slide" or "guide" type of bracing (point to be braced slides between rigid guides as the braced member deflects) friction between the guide and the specimen can cause forces which restrain the specimen. The first problem can be eliminated by adjusting the position of the bracing during the test. However, for the tests proposed, this method is not practical because of the number of braces required.

A self-adjusting bracing system has been developed and is proposed for the tests. This system, which does not require adjustment and does not restrain the test member, is shown in Fig. 10 for bracing of beams. At the point to be braced, an angle is clamped to the compression flange of the beam. A pivot arm rotates in a horizontal plane about a vertical pin attached to the bracing angle. The bracing members which consist of 2 in. pipe are attached to the ends of the pivot arm and the loading frame by ball-and-socket connections. The ball and sockets permit movement in any direction.
The original and deflected positions of the beam are shown in Fig. 10. The deflected position, shown dashed, represents a sidesway of 12 in. with a simultaneous beam deflection of 10 in. in the plane of the test frame. Because the length of the 2 in. pipe does not change (neglecting second order effects) the pivot arm rotates as the beam deflects. Positive lateral bracing is still provided in the deflected position. For bracing a column, two of these bracing arrangements must be used, one attached to each flange.

A prototype bracing arrangement which has been constructed has shown that the method of bracing is feasible. Rotations occur with very little restraint and play at the pin and the ball-and-socket connections.

(4) Hydraulic Loading System. Loads are applied to the test frame by hydraulic cylinders acting in tension; one end of the cylinders is connected to the test frame and the other end attached to the gravity-load simulator. A schematic diagram of the hydraulic system is shown in Fig. 11.

Oil is pumped from a central supply by a pump which operates on air pressure. The pump can maintain a given oil pressure automatically. The oil is distributed to the six cylinders by a control console which has six outlets. The arrangement at each outlet is the same. The amount of oil entering each outlet is controlled by a valve. This permits the six hydraulic cylinders to provide six different loads. A bleeder valve is provided because the system requires some manipulating to achieve the desired ratio of loads between the various hydraulic cylinders for the various loading conditions shown in Fig. 2. A 5000 psi gage measures the pressure in each line. High pressure hose, 1/4 in. diameter, carries the oil from the control console to the cylinder.
The hydraulic cylinders have a diameter of 6 in. and a stroke of 12 in. A cylinder can pull with a force of 118 kips at the maximum working pressure of 5000 psi. The maximum load expected during the tests is 80 kips.

2.4 Instrumentation

The test frame will be instrumented extensively with strain gages to reduce the frame to a determinate structure. Rotations will be measured at the critical joints by a bubble level. Other joint rotations will be measured by means of a calibrated dial attached to a joint at its center of rotation. A plum bob, also suspended from the center of rotation, will be used to indicate the rotation of the joint on the calibrated dial. The sidesway at each floor level will be measured. The deflected shape of every beam will be recorded by measuring the deflections at three points in every beam. These deflections will be recorded by a level reading scales suspended from the bottom flange of the beams.

Calibrated dynamometers will measure the load applied to the test frame and strain gages will measure the forces in the diagonal bracing. The sidesway of the gravity-load simulator will be recorded to check on possible restraint by the mechanism.
3. FINANCES

The estimated cost of the test program is shown below:

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four test frames (material, fabrication, physical properties)</td>
<td>$2,400</td>
</tr>
<tr>
<td>Base plates, spreader beams, wind bracing</td>
<td>400</td>
</tr>
<tr>
<td>Six hydraulic clinders with end fixtures</td>
<td>1,600</td>
</tr>
<tr>
<td>Hydraulic loading system (pump, console, hose)</td>
<td>800</td>
</tr>
<tr>
<td>Gravity-load simulator</td>
<td>1,000</td>
</tr>
<tr>
<td>Loading frame (column extensions, fabrication of beams)</td>
<td>1,000</td>
</tr>
<tr>
<td>Bracing</td>
<td>2,000</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>400</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$9,600</strong></td>
</tr>
</tbody>
</table>

The total cost of the test program is $9,600. Of this total, $6,800 is used to purchase and fabricate equipment which can also be used for tests on unbraced frames. Once this equipment is provided, each test can be conducted at a cost of $700 plus labor.

The test program on braced frames outlined previously was estimated to cost $6,400. An additional $3,200 is required for the test program proposed herein. The additional funds required are primarily due to the cost of the bracing and the gravity-load simulator, both of which can be used for tests of braced and unbraced frames.
Four tests on braced multi-story frames are proposed. The frames will be subjected to the combinations of vertical and horizontal loads shown in Fig. 2. A loading system which simulates gravity loading has been developed for the tests. A self-adjusting lateral bracing system has also been designed.

The four tests proposed will provide insight into the ultimate strength of braced, multi-story frames. Since tests of this scale have not been performed previously, they will also be an important contribution to structural knowledge in addition to providing experimental evidence for proposed ultimate-load design methods for multi-story frames.

Almost all types of connections which are encountered in welded rigid-frame design are represented in the test frame. Consequently, connection behavior can also be studied.

It is expected that the experience and results from these tests will be of value in preparation for the 1965 summer course in plastic design of multi-story frames.
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5. Lehigh Project Subcommittee
   MINUTES OF SEPTEMBER 23, 1963 MEETING, New York
FIG. 2

Note: Bracing not shown
FIG. 3

Test Frame

Calibrated Dynamometers

Spreader Beam

Gravity-Load Simulator

Hydraulic Jack (tension)

Loading Frame

Base Support For Gravity-Load Simulator

FIG. 4

Test Frame

Spreader Beam

Calibrated Dynamometers

Hydraulic Tension Jack

Gravity-Load Simulator

Column Beam

Loading Frame

Crossbeam
**FIG. 5**

- Arm Length (5.35ft)
- Top Width (3.25ft)
- Load, P
- Hinge
- Rigid Triangular Member
- Base Width (11.00 ft.)

**FIG. 6**

- Instantaneous Center
- Sidesway 16 in.
- Original position
- Deflected position
FIG. 7
2 roller bearings
1/2 φ pin

2-4/5 7.25
w/11 x 3/16 CovRe

6 x 13

8 x 6 x 1/4 Tube

FIG. 8

All columns 12WF85 (including extensions)

----- ----- Test frame location

FIG. 9
FIG. 11

Test Frame

Hydraulic Cylinder
6" bore
12" stroke
5000 psi Max.
Working Pressure

Gravity - Load Simulator

1/4" High Pressure Hose

High Pressure Oil to Tension Jack

5,000 psi Gage

1/4" Needle Valve

Bleeder Line

1/4" Shut Off Valve

High Pressure Oil

Oil Return to Supply Tank

Pump

Oil Supply

Air Pressure to Run Pump

FIG. 11