ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
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First Interim Progress Report
(Call No. 2)

PROCEDURES AND SPECIFICATIONS FOR EXPERIMENTAL DETERMINATION OF LOAD-DEFLECTION CHARACTERISTICS OF FULL-SCALE BUILDINGS

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Project 2328

DEPARTMENT OF THE AIR FORCE
AIR FORCE SPECIAL WEAPONS CENTER (SWRS)
KIRTLAND AIR FORCE BASE, NEW MEXICO
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FOREWORD

This is the first interim progress report for Call No. 2 on Project 2328, Engineering Research Institute, The University of Michigan. The project is under the auspices of the Department of Civil Engineering. The work was initiated on March 13, 1956, as Call No. 2, Task No. 10811, Contract No. AF 33(616)-2723, under the direction of the Wright Air Development Center, Wright-Patterson Air Force Base, but has now been transferred to the Air Force Special Weapons Center at Albuquerque, New Mexico. It is scheduled for completion by January 13, 1957.

Messrs. Eric Wang and Channing Pao are technical liaison representatives of the Air Force.

Professor Bruce G. Johnston is the project supervisor for Calls No. 1 and No. 2 of this contract. Mr. Glen V. Berg is now taking full responsibility for Call No. 1, and Mr. D. A. DaDeppo is in charge of Call No. 2.

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ABSTRACT

This is a report of the progress on Contract No. AF 33(616)-2723, Call No. 2, for the period March 1, 1956, through August 31, 1956.

This report covers studies that are being made with the aim of setting up specifications and procedures for conducting static and dynamic tests on full-scale structures. Material contained in this report is concerned with buildings in the 3- to 5-story range. Vibration, story shear, and pulldown tests are briefly discussed and a test schedule is presented. A preliminary design of test rigs, for the story shear and pulldown tests, is developed.

OBJECTIVES

The objectives of this program are clearly stated in Call No. 2:

"I. General

...

B. Purpose

The purpose of this Call is to set up procedures and specifications for determining the collapse loads and dynamic properties of full scale buildings.

II. Detailed Requirements

A. Specifications

The specifications will be divided into two major parts and will be set up for a maximum and minimum desirable program. The first part of the specifications will establish the requirement for inspection and modifications of the buildings. Provision for repair, removal or reinforcement of parts of the building will also be included.

The second portion of the specifications will pertain to the test procedure, including test descriptions, instrumentation, installation of loading and recording equipment, a system for recording and analyzing data and cost estimates when possible. In connection with this portion of the specifications, a literature search will be made in the field of full scale structural tests, including correlation with earthquake experience, and a summary report prepared.

B. Scope of Work

Structures to be considered in writing the specifications will be:

1. A three to five story steel frame office building.
2. A three to five story reinforced concrete frame office building.
3. A one story steel frame industrial building with trussed roof.
4. A one story reinforced concrete rigid frame industrial building.
5. A one story welded steel rigid frame industrial building.

Tests to be considered for inclusion in the specifications will include the following:

1. Vibration tests, to determine the natural frequencies of vibration in the important normal modes, and to study the damping in each normal mode in order to determine the extent to which the assumption of viscous damping is a satisfactory approximation.

2. Shock tests to determine the actual dynamic response to transient loads, if feasible means of applying sufficiently large impact or impulsive loads can be devised.

3. Story shear tests, to determine the load-deflection characteristics in each story in the elastic and early plastic ranges.

4. Pull-down tests, to determine the actual collapse loads and the load-deflection characteristics over the complete range of deformation. No actual testing of any full scale structure is to be performed as part of this call."

I. INTRODUCTION

During the course of highway development projects or new building construction, it is sometimes necessary to destroy existing buildings. With the cooperation of proper authorities these buildings may become available for the purpose of full-scale static and dynamic testing. Buildings which thus become available may be located in practically any region of the United States, and may be of virtually any type. The period of time available for conducting tests may be short. It is therefore necessary that testing parties have a general guide, in the form of specifications and test procedures, in order to expedite setting up and carrying out the tests.

After reviewing Call No. 2 for this contract, it was decided that initial efforts should be directed toward setting up the test procedures and specifications for buildings in the three- to five-story range. Work on the one-story structures would then follow. This report is a brief summary of initial studies of buildings in the three- to five-story range.

By far the most difficult buildings to be tested will be those in the three- to five-story range. A considerable amount of heavy testing equipment will be required for these structures. Skilled and unskilled labor and heavy construction equipment will be required to prepare for the tests. Instrumentation for testing these buildings will be much more extensive than that required for testing one-story structures. Load and read cycles will be much slower for the story shear and pulldown tests. Recording and checking of data for reliability will also be a much slower process for these buildings.

II. TEST STRUCTURES

TEST STRUCTURES IN THE THREE- TO FIVE-STORY RANGE

Buildings falling in this class may vary considerably both in plan and construction. They range from the simple virtually doubly symmetric rectangular office building, to the complicated F-shaped school building. To outline test procedures and specifications for all the possible buildings that might become available for testing is out of the question.

The present state of analytical knowledge of the dynamic and static behavior of multistory structures is limited to the case of buildings which are rectangular in plan and structurally symmetric. In the experimental field a considerable number of vibration tests have been made on full-scale structures of all types,[1-4] but most of these tests have been limited to the determination of natural periods of vibration. To our knowledge no attempts have been made to determine natural mode shapes and investigate the damping characteristics of the structures in their normal modes of vibration. A literature survey failed to turn up any recorded attempts at conducting story shear or pulldown tests in which an entire full-scale structure was involved.*

The combined lack of previous experimental background on the types of tests to be made and of analytical knowledge of structures necessitates confining the test program to simple structures where test results can be compared with analytical calculations. Of course, this means that at least the initial tests are to be restricted to buildings which are rectangular in plan, of uniform height, and structurally symmetric, or nearly so. Fortunately most buildings in the three- to five-story range will fall in this class, or can be made suitable for testing without requiring a long period of time or great expense. L-shaped buildings and buildings slightly more complicated in plan can also, in some instances, be put in condition for testing, but careful consideration must be given to the cost and time involved. Flat-iron buildings and buildings more complicated in plan are to be entirely avoided. As the testing program proceeds, buildings having only one plane of symmetry, such as E-, T-, and U-shaped structures, may also be tested.

In most cases, some alterations will be necessary to put a structure in a suitable condition for testing. Alterations are divided into two classes according to their purpose:

A. To maintain the safety of personnel and test equipment. Typical alterations which may be called for are:

1. Removal of:

   a. Parapet walls
   b. Suspended ceilings
   c. Windows and doors
   d. Heavy electrical and mechanical equipment.

2. Repair and/or reinforcement of structural members used to support or set up test equipment.

B. To check the relationship between the structure and the mathematical model that represents it, typical alterations may be called for as follows:

*Reference 5 contains a summary report of lateral-load tests made on a wing of a dental hospital in Johannesburg, South Africa.

1. Strengthening of connections.
2. Provision of lateral bracing for columns and beams.
3. Removal and replacement of defective structural members where repair is not feasible.
4. Removal of walls and partitions, in part, as testing proceeds.

TEST SEQUENCE

Tests which will be performed on any one structure are vibration, story shear, pulldown, and, if possible, shock tests. A considerable amount of information can be obtained from any one test structure, provided that these tests are carried out in the proper sequence. A tentative test sequence has been set up for buildings with structural-steel frames and is given in Table I, along with the information which can be obtained from each test. The test sequence given in Table I may be applicable to structures with reinforced-concrete frames. If the shear walls have no openings or very small openings, there is the possibility that a considerable amount of cracking may occur in the structural frame before the shear walls are very severely cracked. In this case Test 3 would be entirely omitted.

Materials tests are also to be made on samples taken from the test structure. Data taken from these tests are to be used in the analytical calculations necessary to compare experimental results with theory.

III. DYNAMIC TESTS

VIBRATION TESTS

A considerable number of vibration tests have been made on structures of all types. Summaries of these tests may be found in References 1-4. In most of these tests the objectives were to determine the fundamental frequencies of vibration and equivalent damping coefficients, without investigating the extent to which the assumption of viscous damping is valid. In these tests it has been customary to excite the structures in resonant vibration by means of a single vibrator, located on the roof of the structure. With proper instrumentation, excitation in this way permits the determination of the fundamental frequencies and yields sufficient data to permit the plotting of resonance curves. Viscous damping coefficients are calculated from the resonance curves. But the assumption of viscous damping must be made in order to make the calculation. This test procedure neither verifies nor disproves the validity of the assumption of viscous damping.

In order to determine the extent to which the assumption of viscous

TABLE I

TEST SEQUENCE

Test No.	Test Type	Information Obtained	Comments
1	Story Shear	Stiffness of structure including shear walls	Test carried to hairline cracking of shear walls
2	Vibration	Natural frequencies, damping coefficient, mode shapes	Forced vibration takes place in direction of shear walls
3	Story Shear	Cracking loads of shear walls	Test carried to severe cracking of shear walls
4	Story Shear	Stiffness of structural frame	All walls removed before this test is started
5	Shock	Actual dynamic response to mild shock loads	Test is dependent on the development of suitable shock-loading methods
6	Pulldown	Load-deflection characteristics of structural frame	Test carried to moderate plastic deformation
7	Vibration	Same as in test 2, but for bare frame only	
8	Pulldown	Same as in Test 7	Test carried to severe plastic deformation

damping is valid, it is necessary to obtain decay curves. The procedure is to excite the test structure in one normal mode only, then to cut off the exciting forces and observe the decay curves at dynamic pickup stations. If the damping is small and truly viscous, then the decay records should show:

1. That the decay curves at all stations are exponentially decreasing.
2. That there are no phase shifts between the various output stations (small or very slow phase shifts can be disregarded for all practical purposes).

In a multidegree-of-freedom system, the use of a single vibrator is generally not sufficient to produce a pure mode of vibration at higher natural frequencies. This is graphically illustrated in Fig. 9 of Reference 6. As shown in Reference 6, pure normal modes of vibration can be produced at all natural frequencies by using several shakers operating simultaneously.

The possibility of using a multiple-shaker system was discussed at length with Mr. R. T. McGoldrick and other members of the vibrations division at the David W. Taylor Model Basin. During the course of the discussion it was pointed out that the coupling of only two vibrators would be very difficult and expensive and that the use of a multiple-shaker system for buildings would be highly impractical. This method was therefore discarded.

Excitation of nearly pure first and second normal modes of vibration may be possible with a single vibrator, but obtaining decay curves, in accordance with 1 and 2 above, is virtually impossible, due to the construction of shakers which are suitable for use on buildings.*

No suitable experimental methods have been found which permit verification of the assumption of viscous damping on the basis of decay curves.

VIBRATOR REQUIREMENTS

Natural frequencies and equivalent damping coefficients will be experimentally determined as in the past, so a single shaker will be required. Vibration tests conducted in California[1] indicate that the range of the fundamental period of vibration, for buildings in the three- to five-story ranges, is from 0.14 sec to 0.95 sec, with an average period of about 0.40 sec. The shortest period of vibration, other than the fundamental, found in these tests was on a five-story reinforced-concrete building having brick walls and tile

*Vibrators, suitable for testing buildings, are of the counter-rotating eccentric-weight type. Excitation by these machines is cut off by removing the power to the machine and allowing it to coast to a stop. Once the frequency of the machine is below the natural frequency of the mode under investigation, all modes of vibration are again present.

partitions. This period was 0.03 sec.* Usually, however, periods other than the fundamental were found to be around a low of 0.10 sec. Based on the average periods, with a twenty-percent extension at the extremes, it was concluded that the vibrator should have a working frequency range of from 2 cps to 13 cps.

Since the buildings that will be made available for testing will be scheduled for razing, there should be no objections to heavy vibration testing. Depending on the construction of the test structures, shaker force amplitudes of a thousand pounds or more will be required over the full operating frequency range in order to produce large vibrational deflections (this force of 1000 pounds has been arbitrarily selected and pilot tests may be necessary in order to determine the adequacy of any particular shaker).

In order to satisfy the force and frequency range requirements, it is necessary to go to a heavy vibrator. One such machine is at the David W. Taylor Model Basin and possibly can be made available, on loan, for the test program.[7] This machine does have the disadvantage of being excessively heavy. The machine proper weighs 5600 pounds, and the combined weight of the machine and controls, when boxed for shipping, is 6500 pounds.

INSTRUMENTATION FOR VIBRATION TESTS

For the type of test program under consideration, it will be necessary to have two dynamic pickups at each floor level of a test structure in order to pick up both translational and torsional modes of vibration. Deflection measurements are to be made in the vibration tests. The measurements may be made with velocity meters or accelerometers, provided that suitable electronic integrating and amplifying circuits are used to give a final output signal proportional to deflection.[8]

PICKUP REQUIREMENTS

All pickups are to be of rugged construction suitable for field use and should be such that easy mounting and removal from an expendable base is possible. The linear range of frequency response, for all pickups, is to extend from 0 cps to 100 cps, since they may be used in shock as well as vibration tests. Instrument design is to be such that extraneous motion perpendicular to the direction of interest is not introduced into the test records. Pickups having fluid damping are to be provided with a damping adjustment device so that the frequency response range can be maintained under severe temperature conditions (30° to 100°F).

*In these tests all periods other than the fundamental are classified as "others" or "extraneous" and are not designated as second, third, etc.

METHOD OF RECORDING PICKUP OUTPUT

Pickup output from vibration and shock tests is to be recorded on an oscillograph. Galvanometers used in the oscillograph are to have a linear frequency response range extending from 0 to 200 cps.

IV. STATIC TESTS

STORY SHEAR TESTS

The objective of the story shear test is to determine experimentally the load-deflection characteristics in each story of the test structure, up to the early range of plastic deformation. These tests provide an experimental determination of the lateral stiffness matrix for the test structure.

The stiffness matrix can be found by either a direct or an indirect process. The direct method for experimentally determining the lateral stiffness corresponds exactly to that used in the analytical procedure. The structure is first given a unit lateral deflection at one floor level, the deflections at all other floor levels being held to zero. Then the forces necessary to maintain the structure in this configuration are recorded, thereby determining one column of the stiffness matrix. This process is repeated until all floor levels have been given the unit deflection, thus obtaining the complete stiffness matrix. This procedure is inherently difficult under field test conditions.

The indirect method is substantially the inverse of the direct method in that the flexibility matrix is found directly and the stiffness matrix is calculated by matrix inversion. The procedure here is to apply a unit load at one floor level, with no load at all other floors, and to record the corresponding deflections at all floor levels. This will determine one column of the flexibility matrix. The process is repeated for all floor levels, until the complete flexibility matrix is determined. This procedure is simple from the point of view of test operation.

PULLDOWN TESTS

The objective of the pulldown test is to determine experimentally the load-deflection characteristics of full-scale structures over the full range of deformation. Since the emphasis of the test program is on accumulating information which will be useful in the study of the dynamic response of structures, especially when subjected to blast loads, a reasonable procedure to follow is to force the structure through a deformation pattern based on a blast-response analysis, in which the structure just manages to survive. This is the procedure which is to be followed in the pulldown tests.

TEST-RIG DESIGN FOR STORY SHEAR AND PULLDOWN TESTS

Three rather severe requirements are imposed on the loading system for these tests. First, it must be capable of delivering horizontal forces in either sense along a straight line, at each floor level of the test structure. This requirement was set up as a result of multidegree-of-freedom analyses which show that the effective resistances, at each floor level, are active in the direction of the blast load as well as in the opposing direction.

The second requirement is that the system must be such that load application and resulting deformations can be controlled from remote positions to maintain the safety of test personnel and equipment.

Finally, the load system must transfer the loads to the test structure by means of tension members only. This requirement arises as a result of the fact that deflections encountered in the tests will be very large, on the order of from three to six feet or more. At deflections of this magnitude, the elevations of the various floor levels will drop from 6 inches to 1 foot below their original positions. Also, horizontal motion perpendicular to the direction of loading may occur. Under these conditions, extreme difficulty would be encountered in maintaining the alignment of compression members used to transfer loads to the structure. In addition, bending and possibly buckling of the extended portion of jacking devices may occur unless jacks of extremely heavy design are used.

In initial studies, the possibility of using an internal loading scheme, as shown in Fig. 1, was considered. This method of loading, however, was discarded on two counts. First, the loading jacks would be inside the structure where any local or general collapse would damage or ruin them. Second, the compressive loads transmitted to the building columns could become large enough to cause premature buckling of these columns.

The possibility of jacking against another structure was also considered. But the very conditions under which the test structures would become available eliminated this possibility, since

1. a nearby building, suitable for use as a loading frame, may not be available for that purpose,
2. there may not be a building close enough to be used as a loading frame, and
3. a building close enough to be used as a loading frame may not be oriented properly, or may not be strong enough for use as a loading frame.

The load system finally chosen for use in the story shear as well as the pulldown tests in schematically shown in Fig. 2. The system consists

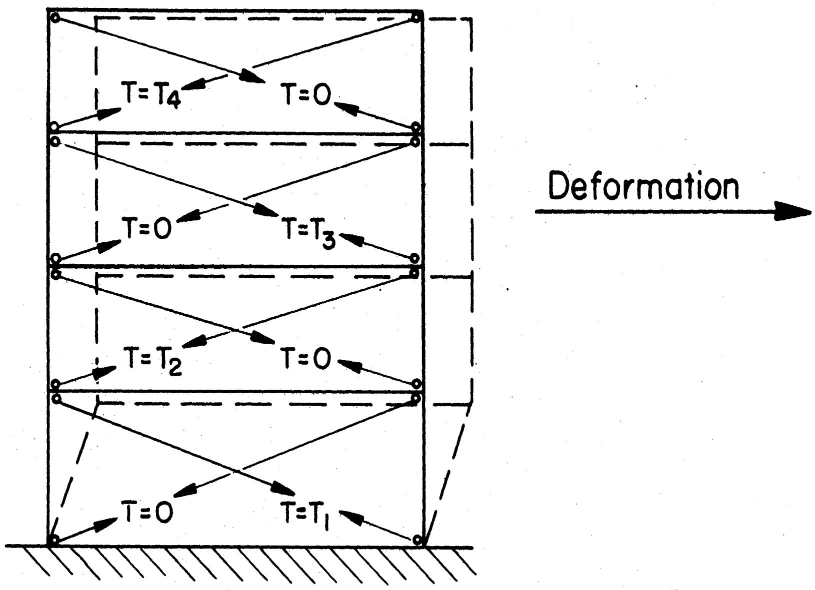

Fig. 1. Deformation by internal loading.

of a number of independent load rigs located on two sides of the test structure. Load transmittal is accomplished by means of wire ropes and hydraulic jacks used in tension only.* The use of hydraulic jacks will permit remote load control at all floor levels, when the jacks are operated by hydraulic pumps and electric motors. Also, with the test setup as shown, complete control of deformation is possible at all times. The seemingly out-of-balance condition of the load system is intended to be as shown. This is due to the fact that the loads required in the direction opposite to the deformation are somewhat smaller than those in the direction of deformation. The horizontal forces necessary to prevent the test rigs from sliding are developed by tying the test rigs into the first-floor columns of the test structure.

Bracing between test rigs, to prevent lateral buckling, is made up of horizontal wire-rope cables at the top and midheight of the vertical masts. Overall stability is maintained by guying the end masts at the top and midheight. Wire rope is used for bracing instead of rigid members since turnbuckles can be used to provide flexibility in the spacing of test rigs (bent spacing from one test building to the next can vary from 12 to 26 feet).

Figure 3 shows the design layout of one test rig. The loads indicated at the various floor levels of the four-story bent are approximately twice the maximum resistances the bent would develop, as calculated by a multidegree-of-freedom blast-load response analysis. Connection, stiffening, and other details are omitted for clarity. Figure 4 illustrates how the jacks are mounted to the test rigs to maintain axial loading in the jacks throughout the loading process.

*A manufacturer, already experienced in heavy-jack production, has stated his ability and willingness to manufacture tension jacks with an 8-foot stroke and a 200,000-pound force capacity.

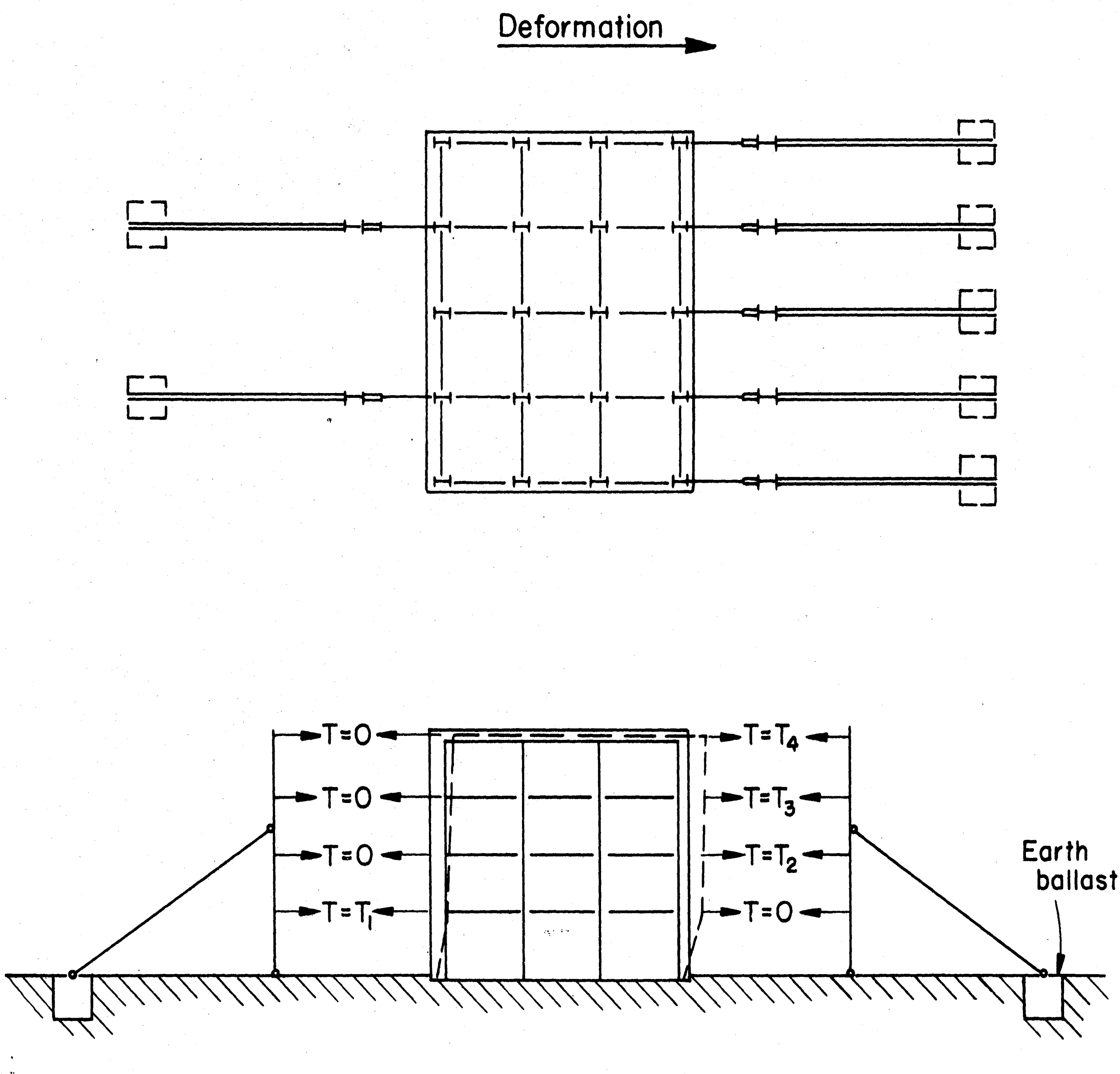

Fig. 2. Load system for story shear and pulldown tests (structure in near collapse condition).

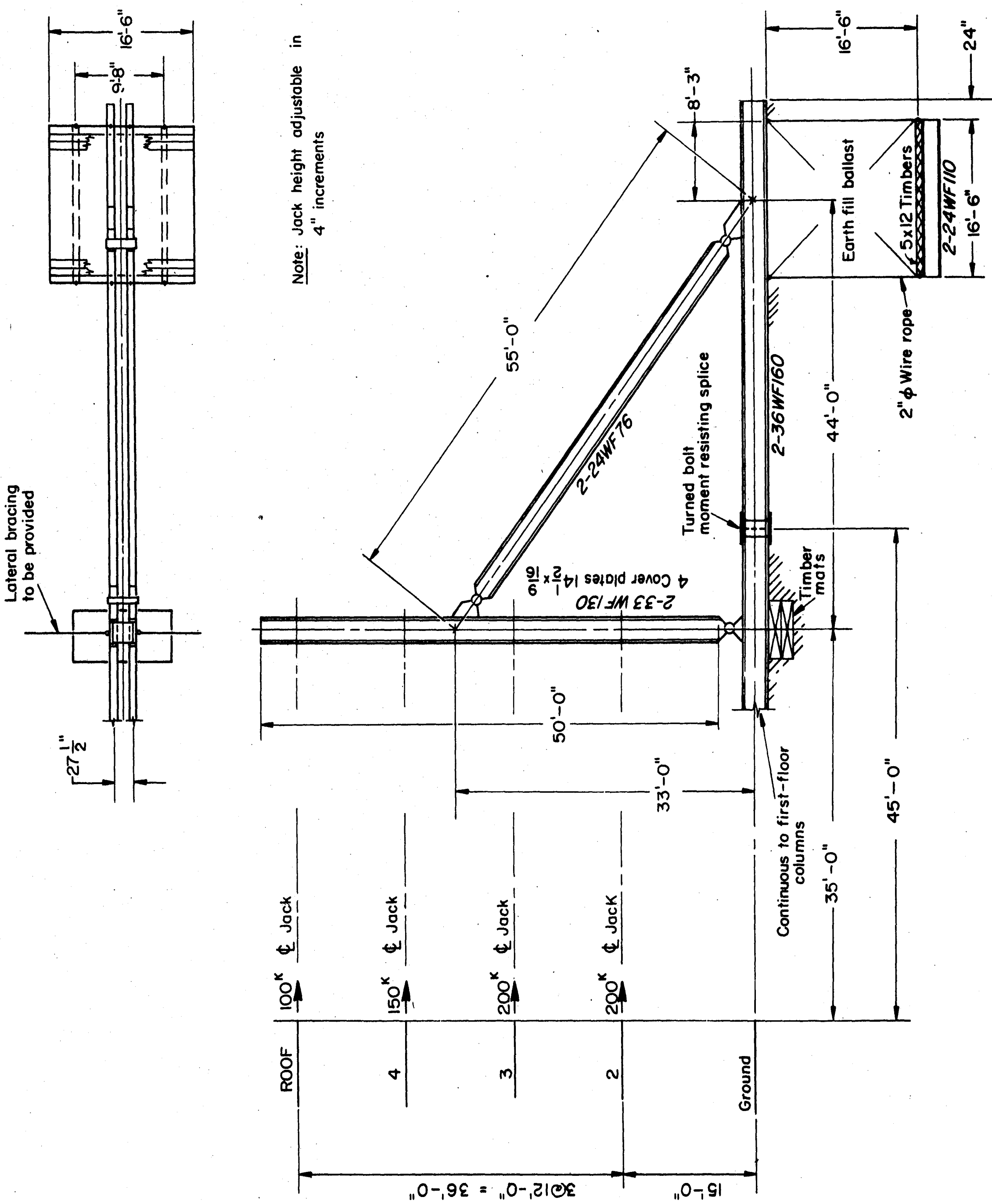

Fig. 3. Test-rig design

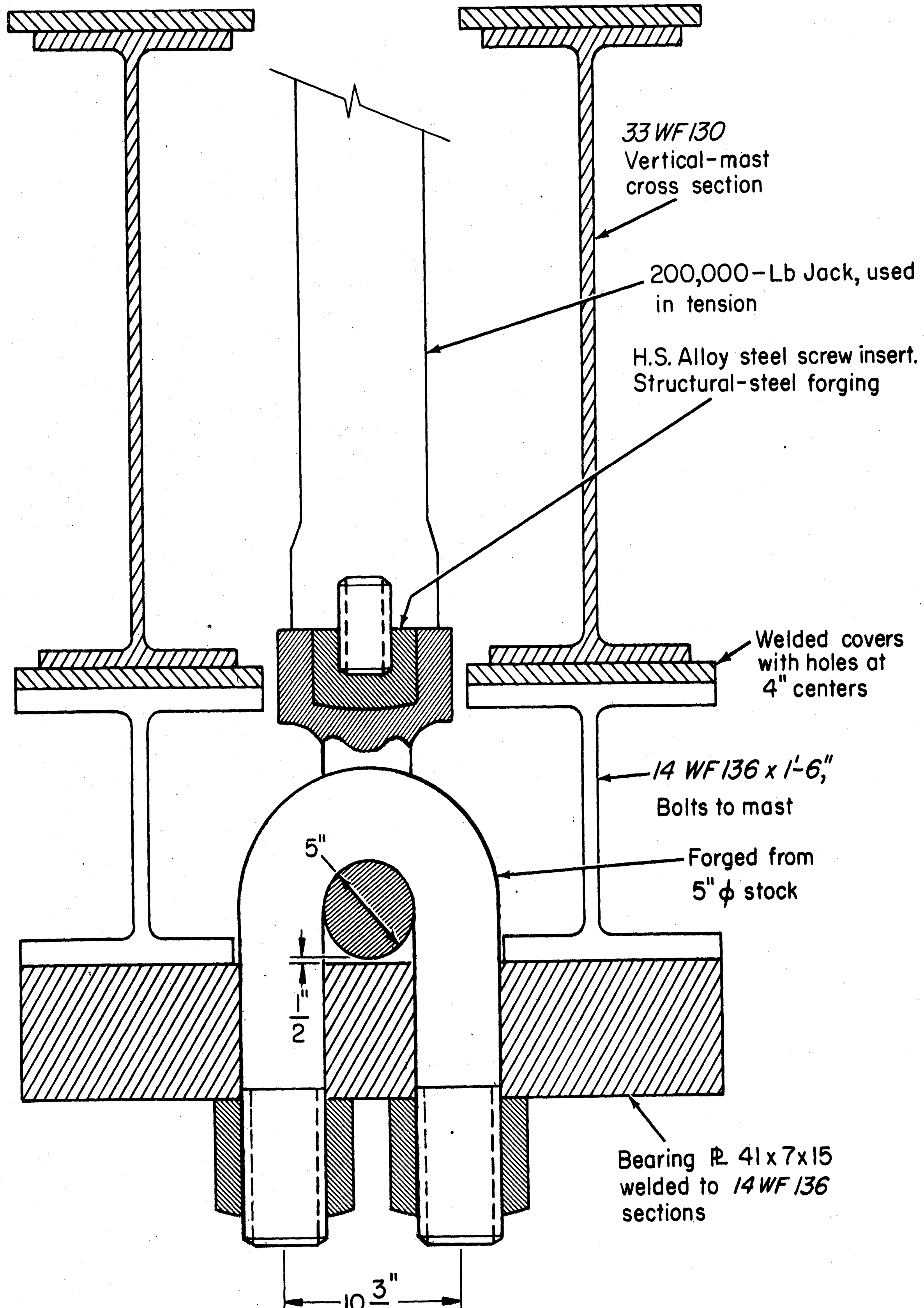

Fig. 4. Hydraulic-jack mounting.

The estimated weight of the steel required for one test rig is 37 tons, excluding the weight of the hydraulic jacks. Assuming a fabrication cost of about $0.20 per pound, the cost of one test rig is about $15,000.

INSTRUMENTATION FOR STORY SHEAR AND PULLDOWN TESTS

Data to be recorded in these tests consist of the loads and deflections at each floor level of the test structure.

Loads are to be recorded in two ways:

1. With aluminum-tube-type dynamometers.[9]
2. By means of pressure gages calibrated directly in pounds of force. Pressure-gage readings are to be used as a gross check on the loads calculated from dynamometer output.

Deflection measurements are to be taken at three equally spaced positions, at each floor level of the test structure. Ames dial gages with a minimum reading of 0.001 in. shall be used for fine measurements. Transit stations are also to be set up, to provide a gross check on dial-gage readings. As the capacity of the dial gages is exceeded, transits alone will be used to make further deflection measurements. All deflections will be recorded by observers stationed on a scaffold, to be erected alongside the test structure. A setup at an observer station is shown in Fig. 5.

In this portion of the test program, cameras will also be used to record such items as the cracking of wall panels and the behavior of connections. Cameras are to be set up such that, in the case of wall panels, for example, initial cracking will close an electrical circuit which controls the camera in such a manner that intermittent photographs are taken.

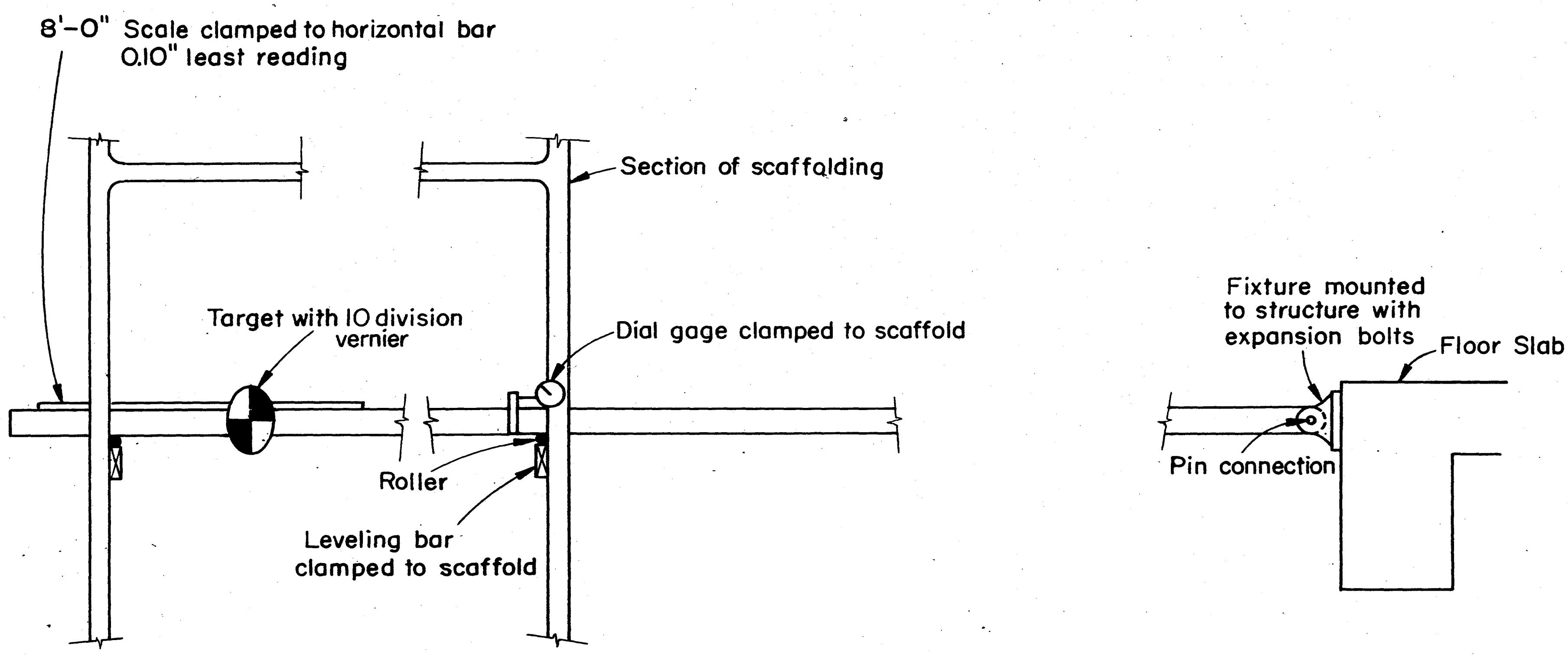

Fig. 5. Setup for measuring horizontal deflections in static tests.

REFERENCES

1. Earthquake Investigations in California 1934-1935, U. S. Dept. of Commerce, Coast and Geodetic Survey, Special Publication No. 201, 1936.

2. Hudson, D. E., and Housner, G. W., Vibration Tests of a Steel Frame Building, Seventh Technical Report, Contract N6 onr-244, Task Order 25, Project Designation NR-081-095, California Institute of Technology, July, 1954.

3. Alford, J. L., and Housner, G. W., "A Dynamic Test of a Four-Story Reinforced Concrete Building," Bulletin of Seismological Society of America, Vol. 43, No. 1, Jan., 1953.

4. Jacobsen, L. S., and Wells, W. M., Natural Frequencies of Structures 3.1.1, SC-2090(TR), Sandia Corp., Nov., 1951.

5. Ockleston, A. J., "Load Tests on a Three Storey Reinforced Concrete Building in Johannesburg," The Structural Engineer, Vol. XXXIII, No. 10, Oct., 1955.

6. Lewis, R. C., and Wrisley, D. L., "A System for Excitation of Pure Natural Modes of Complex Structure," Journal of the Aeronautical Sciences, Vol. 17, No. 11, Nov., 1950.

7. Robinson, Q. R., Vibration Machines at the David W. Taylor Model Basin, The David W. Taylor Model Basin, Report 821, NS712-013, July, 1952.

8. Perls, T. A., and Rich, H. L., Evaluation of Selected Shock Instruments, The David W. Taylor Model Basin, Report 720, NS711-110, Feb., 1951.

9. Beedle, L. S., and Johnston, B. G., "Tests of Columns Under Combined Thrust and Moment," Proc. SESA, Vol. VIII, No. 1 (1950).

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