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PSEUDO-DYNAMIC TESTING OF WALL STRUCTURAL SYSTEMS

by

Vitelmo V. Bertero, Egor P. Popov
Toneo Endo and Tsan-Yuan Wang
Department of Civil Engineering
University of California, Berkeley

INTRODUCTION

In building construction, structural walls are generally used in conjunction with moment-resisting frames. Survey of structural damage after earthquakes reveals that by increasing the area per story of well designed and constructed structural walls, the degree of damage will decrease (Fig. 1) [1]. The interaction between wall and frame, particularly during the hysteretic behavior of buildings under severe earthquake-like conditions, is not very well understood at present and has led to disagreements among researchers and professional engineers regarding the way that walls should be designed. This disagreement is manifested in significantly different requirements for the design and analysis of structural walls as specified by different American codes.

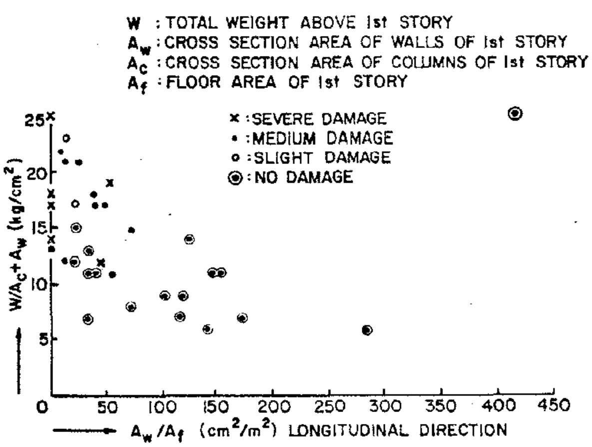


Fig. 1 Degree of Damage vs. Wall Area

The main concern of aseismic design is to achieve a ductile hysteretic behavior. Thus, walls should be designed so that its hysteretic behavior and mechanism of failure are controlled by flexure. In the case where geometric proportions dictate that shear control behavior (e.g., squat walls), the wall should be designed to absorb all the earthquake energy input in its elastic range and to prevent large diagonal or flexural openings of cracks. Present code provisions do not distinguish between shear (or squat) walls and flexural (or slender) walls.

While the UBC and SEAOC recommend increasing the value of earthquake forces in calculating shear stresses in shear walls of buildings without a 100% moment-resisting frame, the ACI does not. Although it is convenient to have a greater safety factor against nonductile shear failures, it is not believed that merely increasing the value of the design seismic loads is the best way of achieving this [2]. The actual shear stress developed during response to a severe ground shaking not only depends on the distribution of the code static equivalent lateral forces, but also, on (1) the flexural capacity built into the structure; (2) the actual distribution of inertial forces throughout the height of the building; (3) the interaction between frame and wall components; and (4) the actual hysteretic behavior of each of these components and their connections.

A slender flexural wall can be effectively achieved by designing it against the maximum shear that can be developed according to the actual flexural capacity (as affected by the axial force) of its critical region and considering the critical moment-shear ratio that can exist at such a region. Even if the maximum shear can be estimated with sufficient engineering accuracy, there still remains the problem of designing against it.

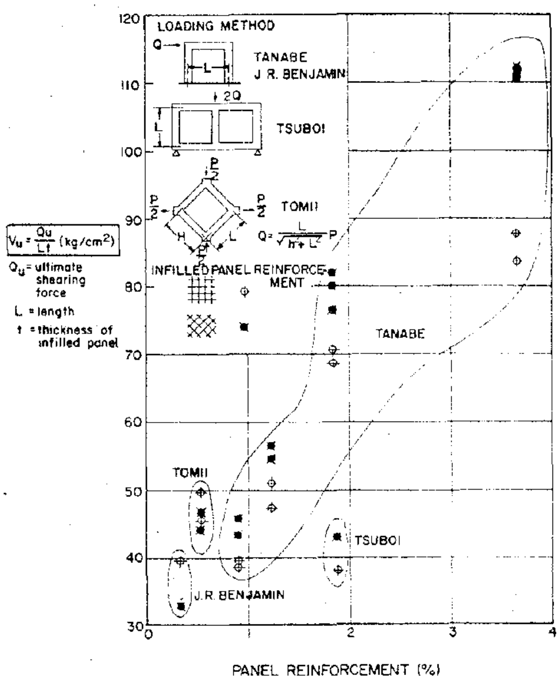


Fig. 2 Loading Methods and Test Results on R/C Walls

Up until 1970, most of the available experimental results on the behavior of wall elements were obtained from tests of one- or two-story reinforced concrete (R/C) walls, or infilled R/C frames which were subjected to simplified loading conditions. Although some of these studies investigated the seismic behavior of wall components in medium-rise buildings, the loading conditions under which most of the tests were conducted (Fig. 2) did not simulate the actual effects of earthquake excitations; rather, they simulated excitations that could have developed in wall systems used for shelters against nuclear weapons. The strength and deformational behavior of the walls tested were controlled by shear; hence, they have been designated accordingly as shear walls.

Only in some recent investigations [3,4, 5] have simulated loading conditions resembled those expected in ductile walls. Consequently, present methods of predicting the mechanical behavior of wall systems are of a very approximate nature. The need for improvements in this area has led to the initiation of the investigation partially described herein.

<u>Objectives and Scope</u>. - The ultimate objective of this investigation is to develop practical methods for the aseismic design of combined frame-wall structural systems. To achieve this objective, integrated analytical and experimental studies have been conducted to determine the actual mechanical behavior of wall systems subjected to earthquake-like excitations.

In this paper emphasis is placed on the discussion of the design, construction, and performance of the testing facility used in the experimental studies. Only those analytical results needed for planning the design of the facility and the experimental program, for checking the facility's performance, and for judging the possible aseismic design implications of the behavior observed in these experiments will be briefly discussed.

SELECTION, DESIGN AND CONSTRUCTION OF TESTING FACILITY

Different types of testing facilities for earthquake loadings are discussed in Ref. 6. Since the main objective of the experimental studies is to investigate in detail the mechanical behavior of frame-wall systems, it was decided to develop a new structural loading facility capable of simulating earthquake effects rather than to use the existing facility for determining a structure's overall response to specific time-history ground motions.

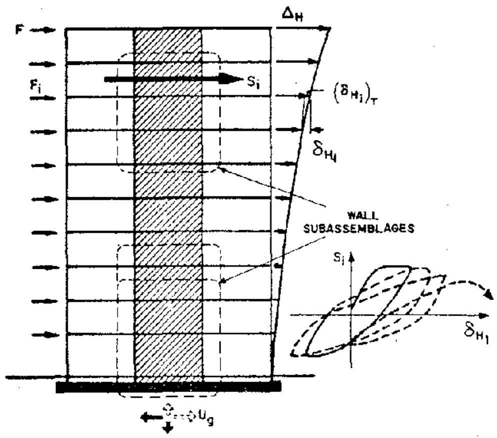


Fig. 3 Wall Subassemblages and Lateral Shear Displacement Relationship

For economic reasons, it was decided to test significant subassemblages of the structural system rather than large-scale models of entire buildings. Predicting the in-plane seismic behavior of frame-wall systems requires information on the variation of the lateral shear-displacement relationship for each story (Fig. 3). In order to correctly simulate the actual boundary conditions of a particular story, it was decided to test subassemblages of at least two or three stories (Fig. 3) [7].

To design the testing facility and to select the larger scale models which could be tested, two buildings, 10- and 20-stories, 61 ft x 180 ft, each, were designed according to present UBC provisions. From analyses of the response of the 10-story building (Fig. 4) to different ground motions, it was possible to estimate the relative intensity of the forces acting on the bottom three story subassemblages. The results led to the design of a facility capable of testing 1/3-scale models of this type of subassemblage.

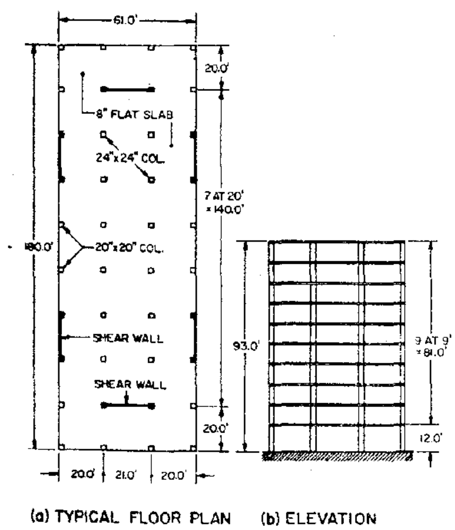


Fig. 4 Prototype Building

The principal feature of this facility is its ability to pseudo-statically simulate the dynamic loading conditions which could be induced in subassemblages of buildings during earthquake ground shaking (Fig. 5). Assuming that the wall alone resists most of the lateral inertial forces, it would not only be necessary to apply lateral forces, but also, forces which would simulate the effect of overturning moments and gravity loads existing above the top floor of the subassemblage [Fig. 5(c)]. This is required because the principle of superposition is not applicable in studying inelastic behavior. Therefore, to simulate the actual inelastic behavior of this subassemblage when it forms part of the whole wall, the synchronized shear, overturning, and axial forces must be applied simultaneously.

In the facility built at Berkeley, the walls are tested in a horizontal position (Fig. 6). The testing facility consists of set of reaction blocks, loading

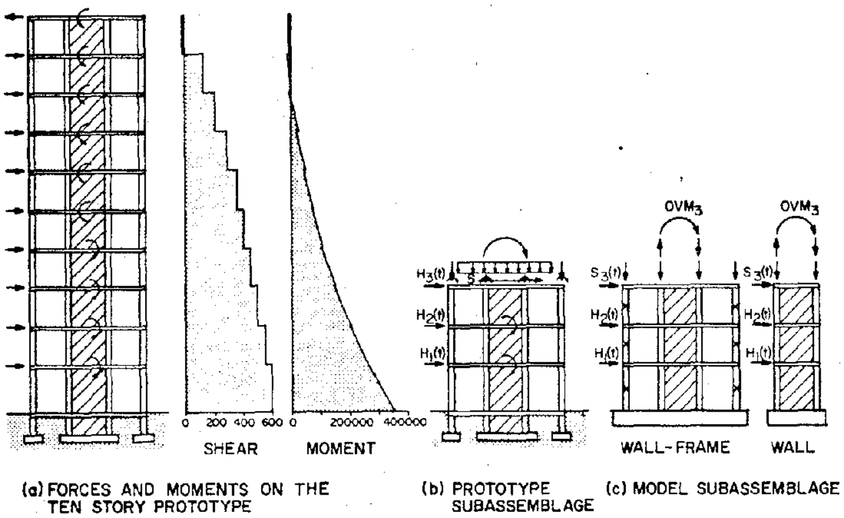
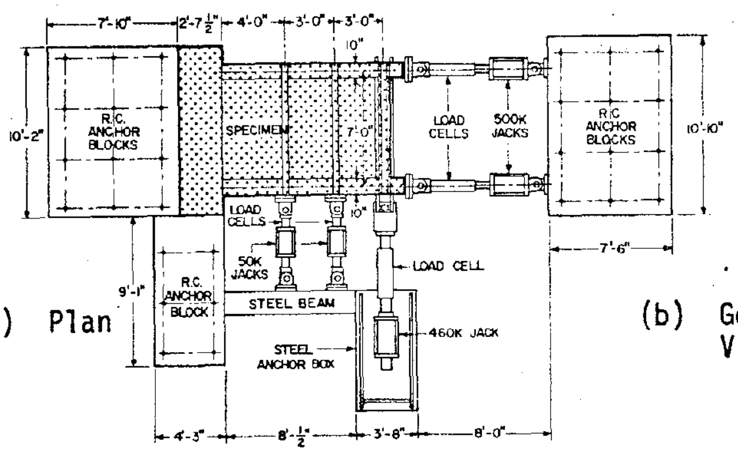


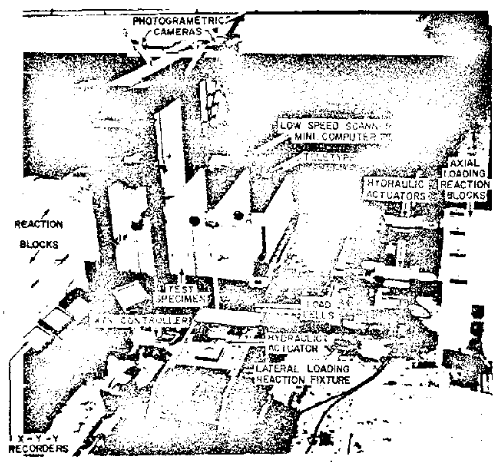
Fig.5 Comparison of Actual and Simulated Loading and Support Conditions

devices, ancillary devices, instrumentation, and data acquisition system.

Reaction Blocks. - These include: R/C anchor blocks supporting the test specimen; R/C anchor blocks supporting the servo-hydraulic actuators used to simulate the axial load and overturning moments; and a steel anchor box supporting the actuator that supplies the main lateral force. All these reaction fixtures are anchored by means of prestressed rods to the laboratory tie-down slab. A reaction steel beam supported



(a) Plan



(b) General View

Fig. 6 Plan and General View of Testing Facility

at the steel anchor box and an R/C anchor block serves to support the actuators which simulate the lateral inertial forces at each floor level.

Loading Devices. - The load and deformation are applied using a servo-hydraulic system. This shown, shown schematically in Fig. 7, consists of hydraulic actuators with load cells and servo-valves; hydraulic power supply; servo-controller system; input to the servo-controller system; and read-out.

All the actuators are standard double-acting hydraulic jacks. The jack used to supply the main story shear force at the top of the specimen has a loading capacity of 460 kips. When operation at 3000 psi pressure of the laboratory hydraulic system, its capacity is 346 kips. Each of the jacks supplying simulated axial loads and overturning moments has a maximum static force of 500 kips. At 3000 psi, push and pull loading capacities are 460 kips and 346 kips, respectively. The jack simulating shear force has a maximum stroke of 12 in. (± 6 in.), and those for axial loads and overturning moments, 10 in. (± 5 in.). Load cells of different

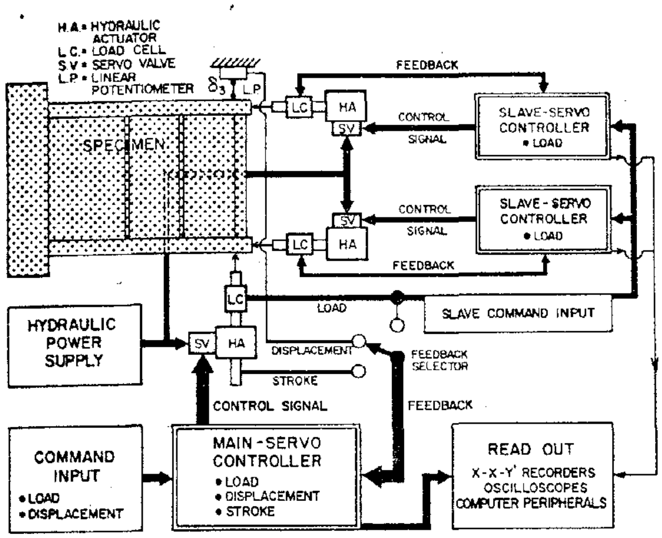


Fig. 7 Servo-hydraulic System

capacities can be added at the loading end of the piston rods. Jacks for simulating inertial forces at each floor are of 50-100 kip loading capacities (Fig. 6).

The necessary energy input for the actuators is supplied by the central power station whose hydraulic equipment is capable of providing 320 gpm of hydraulic fluid at 3000 psi.

One electrically controlled 16-10 DYVAL servo-valve is attached to each actuator. The maximum flow rating is 10 gpm at a 1000 psi drop across the valve. Each of the valves is controlled by an MTS 406.11 servo-controller. A detailed description of this controller given in the MTS operator's manual [8].

After going through transducer conditioners, the output from the load cell measuring the lateral force and that from the linear potentiometer (LP) measuring the lateral displacement, δ_3, of the specimen at the top floor level, are used as input to the feedback selector the main servo-controller. Thus, the lateral actuator can be operated under load or displacement control. The signal from the load cell is also used as program input to the controllers of the axial loading actuators. Each of the servo-valves of these axial loading actuators is therefore automatically controlled by the amount of force generated by the lateral loading actuator. For this reason, the servo-controllers for each of these axial actuators have been denoted as "slave," (Fig. 7). Provided the ratio between the axial and lateral forces remains constant during the whole or certain range of the test, once the slave controllers for the axial actuators have been set for this ratio, the operation of the whole system will be controlled by an input function to the servo-controller of the lateral actuator. Thus, this controller is referred to as the main servo-controller. At present, the main servo-controller is operated manually.

The ouput of the LP is continuously plotted by the Y-channel of an X-Y recorder and the output of the load cells of the axial loading actuators, by Y- and Y'-channels of an X-Y-Y' recorder. The X-channels of both X-Y and X-Y-Y' recorders are driven by the output signal from the load cell of the lateral loading actuator.

Ancillary Devices. - These devices can be classified as: transfer loading devices, model deformation guidance devices, and actuator supporting devices.

Transfer Loading Devices. - Simulation of ground shaking effects on wall subassemblages requires application of lateral and axial forces [Fig. 5(c)]. Because $S_3(t)$ represents the story shear transferred by the wall above the subassemblage plus the inertial force transmitted by the upper floor slab, the former is usually considerably larger than the latter. Therefore, $S_3(t)$ should be applied through the wall rather than the slab. This has been achieved by transferring the concentrated force applied by the lateral actuator through the wall by means of four steel channels which are bolted to a thickened part of the upper floor slab immediately adjacent to the wall (Fig. 8). On the other hand, as $H_2(t)$ and $H_1(t)$ represent the inertial forces developed at, and transferred by, the floor slab of each story, the concentrated forces supplied by the smaller lateral jacks are transferred to the slab at a certain distance from the wall by bolting four steel channels to the slabs (Fig. 8).

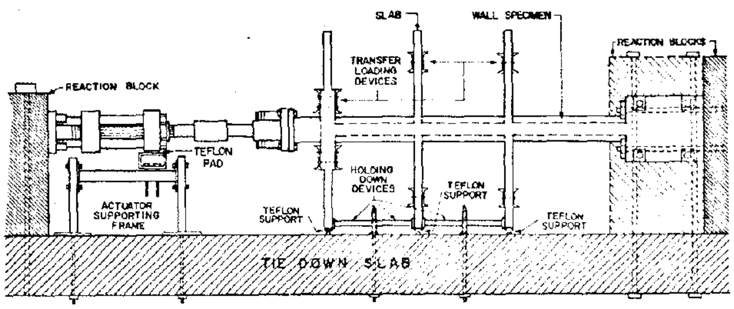


Fig. 8 Ancillary Devices

Model Deformation Guidance Devices. - Because only the bottom part of the model is anchored to the supporting reaction blocks (Figs. 6 and 8), considerable bending moments can occur due to the model's weight and the weight of the transfer loading devices. This can be averted by supporting the specimen against the tie-down slab at certain points along the edges of the slab (Fig. 8). To minimize friction, special steel plates are anchored to the edge of the slab. These plates slide on teflon pads attached to the slab. Special holding-down devices were added to prevent the upward movement of the specimen.

Actuator Supporting Devices. - According to the arrangement of the loading system selected (Fig. 6), as long as the shafts of the actuators are not connected to the specimen, they will remain hanging as cantilevers from their supports at reaction blocks. Because of their large weight, they are supported by auxiliary frames (Fig. 8). By sliding on teflon pads attached to these frames, the actuators can be rotated around their pin-connections at the reaction blocks. This enables the actuators to be displaced from their testing position, thereby facilitating the installation and removal of the specimens.

Instrumentation. - To obtain the necessary information for studying the hysteretic behavior of the selected subassemblages, the testing facility and specimen are extensively instrumented.

Testing Facility. - As illustrated in Fig. 7, the control of the loading or deformation of the specimen requires the installation of a load cell in the loaded end of each actuator shaft, and an LP of Linear Variable Differential Transformer (LVDT) to measure either the stroke of the lateral actuator or the displacement of the upper floor of the specimen. A series of mechanical gages were installed around the reaction blocks to detect their possible movement during a test.

Specimen. - Extensive external and internal instrumentation were used. Most of the external instrumentation is shown in Fig. 9. The lateral displacement at each floor level as well as the total axial deformation at the wall edges is measured by an LP or LVDT. The relative shear deformation of each story wall is measured through diagonally arranged wires connected to LP's. Axial deformation at the wall edges is measured by clip gages. Similar gages are also used to measure relative rotations between horizontal sections of the wall and the average strain distribution along the bottom horizontal section of the wall. In some specimens, additional clip gages are placed at 45° angles near the bottom corners

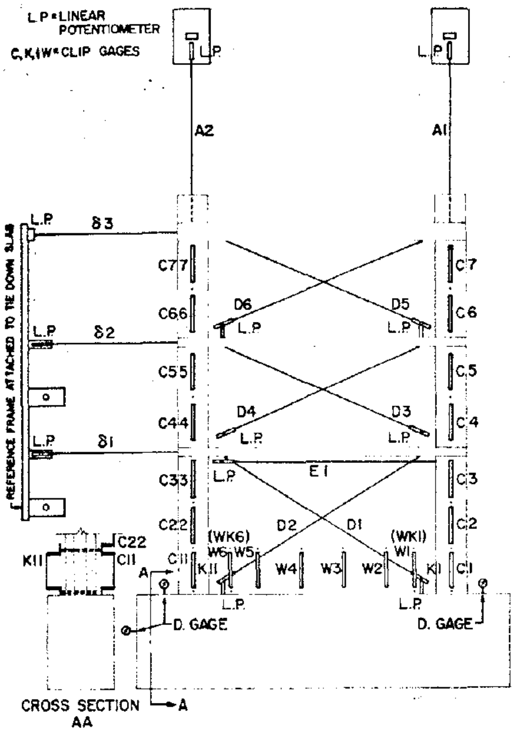


Fig. 9 External Instrumentation

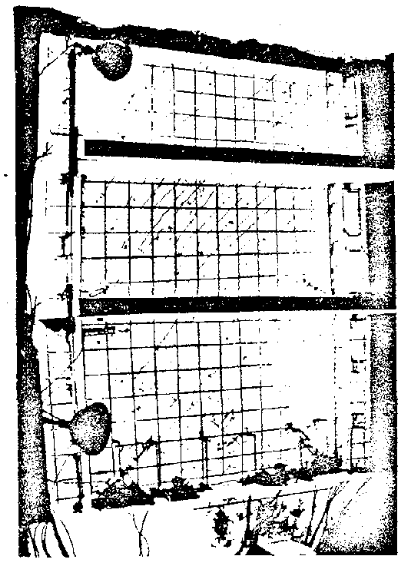


Fig. 10 Photogrammetric Grid

of the first story wall panel.

Long wire electrical resistance gages are glued to the concrete surface to measure average concrete strains. Dial gages are placed around the foundation of the wall to measure any possible movement which might occur. The upper surface of the specimen in its testing position is marked with a rectangular grid (Fig. 10) used for measuring large deformations through a photogrammetric technique. Two wires stretched between fixed supports completely independent of the specimen were placed above and across the first and second stories. These wires served as reference lines. Targets are attached at every intersection of the grid lines and at several points along the reference wires to assist the reading of the deformation. The internal instrumentation consisted of wire resistance gages welded to the reinforcing bars of the columns and wall panels.

Data Acquisition System. - The lateral displacement at each floor level and the variations of other applied forces are automatically plotted against the lateral shear force applied at the top of the specimen using X-Y-Y' recorders. The relative shear deformation of each story, average curvatures at different cross-sections of the wall, axial deformations along the edges of the walls, and strains of some of the reinforcing bars located in the expected critical regions are plotted automatically against the applied shear force by X-Y-Y' recorders. Numerous strain gages placed on reinforcing bars and clip gages for measuring the relative deformation along 12 in. to 16 in. base lengths are read at selected stages of the test directly through a low-speed data acquisition system whose heart is a NOVA minicomputer.

The progress of crack formation in the specimens is carefully observed and recorded. In addition, photogrammetric pictures are taken with two cameras mounted on a rigid frame [Fig. 6(b)]. These pictures provide a unique qualitative record of the deformational behavior of the wall at selected loadings, as well as accurate information on the movement of the cracked mosaic of the wall.

PERFORMANCE OF TESTING FACILITY

A series of tests on R/C wall subassemblages, R/C ductile moment-resisting frame subassemblages and similar frame subassemblages of infilled masonry have already been conducted. The performance of the facility was excellent as can be seen from the results of these tests. Results of tests on two 1/3-scale wall component models of the bottom three stories of the 10-story frame-wall system are briefly described.

Test Specimens. - The specimens consisted of a 4-in. thick wall framed by two 10-in. square columns (Fig. 11). The total width of the specimen was 7 ft x 10 in. and the total height, 13 ft x 7 in.

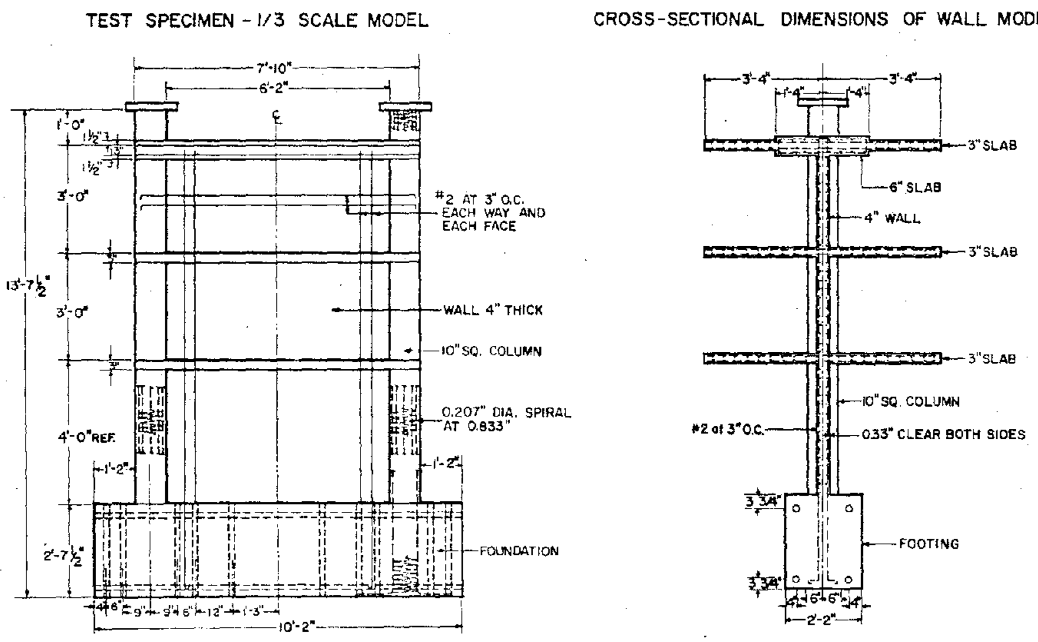


Fig. 11 Dimensions and Details of Wall Specimens

Loading Conditions. - The prototype was designed for critical combinations of gravity and seismic loads as specified by the 1973 UBC code. Although the forces induced by these loads could have easily been simulated in the testing, it was decided to subject the models to a more critical force combination that could develop during actual earthquakes. Rational selection of the actual critical combination requires integrated analytical and experimental studies because it varies depending upon the main parameters under study.

To determine the adequacy of present code specifications for avoiding brittle shear failures, specimens were tested under the loading combination inducing the largest shear force at the first story according to results from different linear elastic analyses. After applying the forces required for simulating the effect of gravity loads, the two specimens were tested under different patterns of lateral and matching overturning forces required to simulate the effects of seismic loads.

In the first specimen, the lateral force and the change in column axial forces needed to reproduce the corresponding change in overturning moments were increased

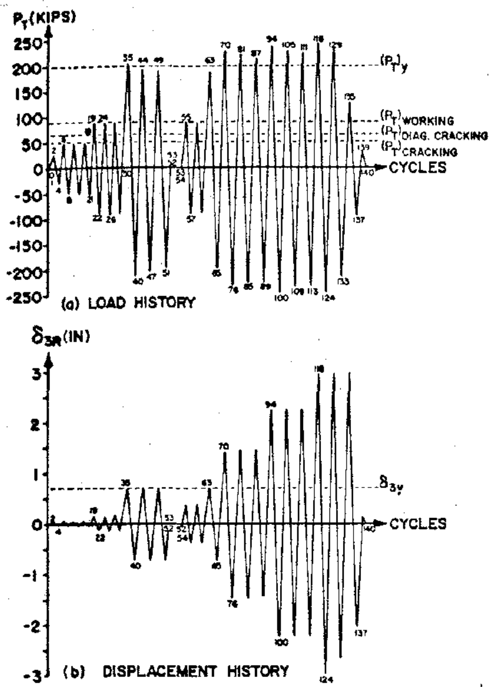


Fig. 12 Loading Program - Wall 2

monotonically until a reduction in the lateral resistance could be observed. Then, a closed large hysteretic loop was generated. The second specimen was subjected to a loading program considered to be one of the worst as far as shear resistance is concerned. In this program, the history of lateral shear and matching overturning moment induced gradually increasing cycles of full displacement reversals. As illustrated in Fig. 12, several cycles were applied at each displacement amplitude.

Test Results. - The instrumentation of the testing facility and specimens provided necessary data for studying the overall hysteretic response of the specimen as well as the variation of the contribution of the different sources of deformation to the displacement at each floor level. Some main results are presented herein to illustrate the type of information that can be obtained using the developed testing facility. For a detailed discussion of the experimental results, see Refs. 7, 9, and 10.

Overall Response. - The overall seismic response of a structural system is usually measured by the lateral displacement of the top floor versus the base shear force. Figure 13 is a composite graph illustrating the overall response for the two specimens. Comparison of this response enables some conclusions to be drawn regarding the effect of cyclic versus monotonically increasing loads. The curve obtained under monotonically increased loading for Wall 1 provides an approximate envelope for the hysteretic behavior obtained from the cycles of reversed displacement introduced to Wall 2. Wall 1 deformed up to 4.3 in. before any significant reduction in strength was observed, giving a displacement ductility, δ/δ_y, of about 6.1; with Wall 2, the maximum δ/δ_y was 4.2. It can therefore be concluded that while repeated reversals of lateral loads did not affect the strength of the wall, they did reduce the ductility by about 35%. Analysis of the hysteretic loops for Wall 2 (Fig. 13) indicates that each time the absolute value of peak deformation was increased, there was a degradation in the initial stiffness and energy dissipated during the following cycle.

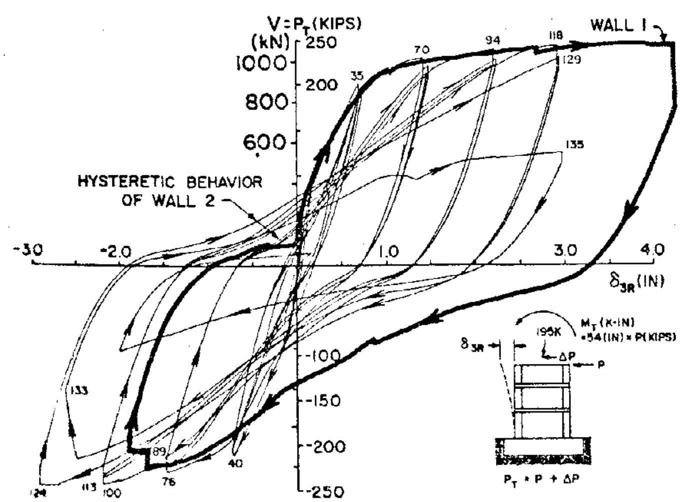


Fig. 13 Shear Force vs. Displacement Diagrams for Walls 1 and 2

Shear Deformations. - Shear deformation was recorded at each story. After yielding of the wall, most of the shear deformation was concentrated at the first story. Furthermore, just before failure, there was a considerable increase in the shear deformation

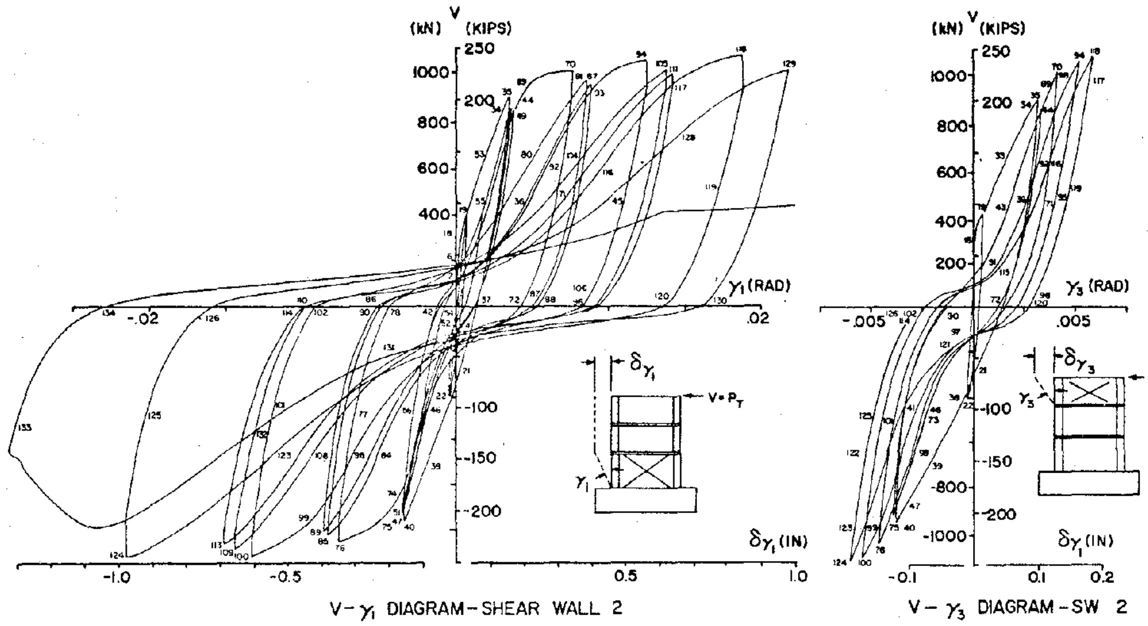


Fig. 14 Shear Force vs. Shear Distortion - Wall 2

of the first story upon repetition of cycles having the same peak displacement (compare Figs. 13 and 14).

<u>Contribution of Different Sources of Deformation</u>. - The contribution to floor displacements is shown in Fig. 15. From the photogrammetric readings, it is possible to detect the overall pattern and sources of deformation. For example, Fig. 16 shows the deformation pattern of the first story of Wall 2 when it was deformed for the first time to a δ/δ_y of 3. Some significant shear slippage along the construction joint of the wall at the foundation was observed. Besides the concentration of shear deformation in the lower rows of the grid, the columns, particularly the left one, began deflecting in a double curvature shape, leading to the failure mechanism shown in Fig. 17. This type of failure mechanism throws some doubt on the validity of the present code design philosophy of so-called dual bracing structural systems.

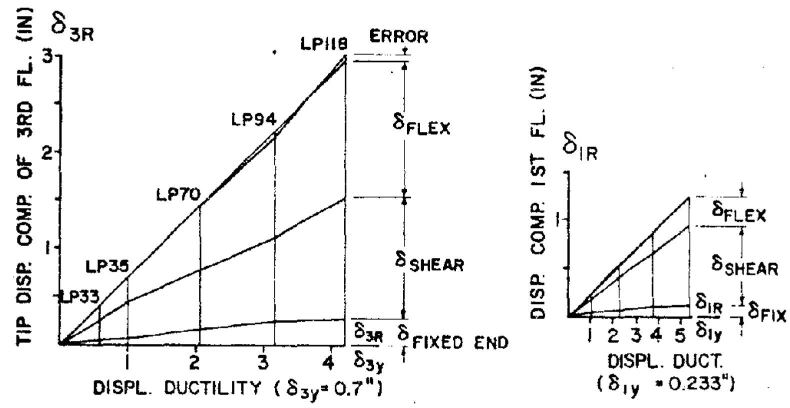


Fig. 15 Contribution of Different Sources of Deformation

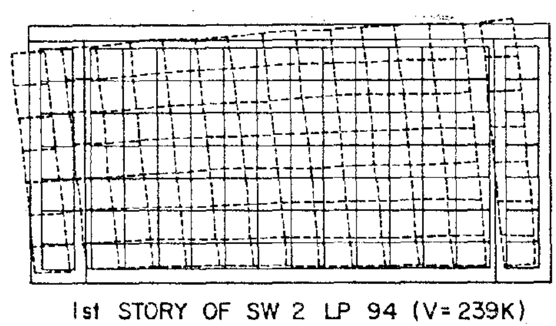


Fig. 16 Photogrammetric Deformation Pattern

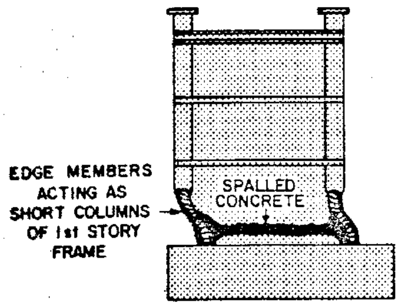


Fig. 17 Mechanism of Failure

ASEISMIC DESIGN IMPLICATIONS OF EXPERIMENTAL RESULTS

Despite the limited amount of specimens tested, analysis of the data obtained enables the following observations to be formulated. These observations, however, should be considered tentative and subject to modification as more data become available.

1. It is possible to design structural wall components capable of developing large ductilities even when subjected to full deformational reversals inducing nominal unit shear stresses up to $11\sqrt{f'_c}$.

2. Although the total lateral displacement ductility was reduced due to reversals, it was still considered large enough to permit the development of energy absorption and energy dissipation capacities exceeding even those that would be demanded in the case of very severe earthquake shaking. Furthermore, the confined core of the columns remained sound and capable of resisting both the effects of axial forces imposed by gravity loads and of lateral loads in the working load range.

3. Present code specifications for design forces, load factors, and design and detailing of critical regions can lead to a wall design which considerably underestimates the amount of shear that can actually develop. The design of flexural walls against shear should be based on the maximum shear that can be developed according to the flexural capacity of the critical region, and on the largest possible shear/bending moment ratio according to the expected dynamic response of the entire building to severe ground motions of different dynamic characteristics. To emphasize the importance of this observation, consider the results shown in Fig. 18. This figure shows the diagrams of the story shear, developed when the base shear reached its maximum value, as well as the corresponding moments acting on the wall components of the 10-story prototype when the building was subjected to static and dynamic excitations. The shear capacity, ϕV_u, and flexural capacity, ϕM_u, of the wall are calculated according to the UBC. THe symbols, V_{max}, M_y, and M_{max}, denote the actual shear capacity, yield moment, and moment capacity of the wall, respectively, corresponding to the test data. Although the base shear and moment of the

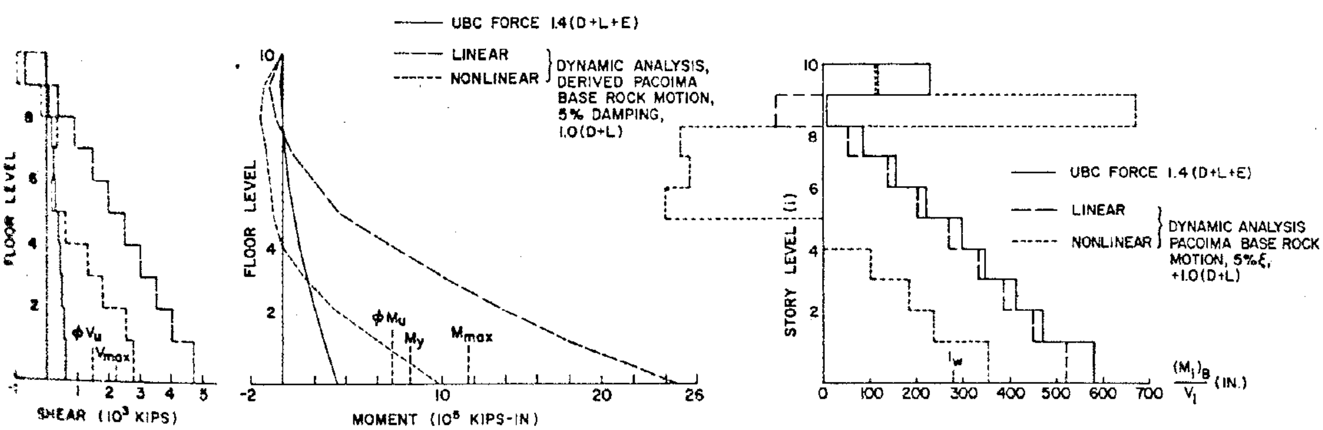


Fig. 18 Shear, Moment and Moment-shear Ratio According To Different Loadings and Analyses

wall corresponding to the UBC are very small, the shear and moment capacities of the designed wall are twice as large. Reasons for this increase are given in Ref. 7.

As shown in Fig. 18(c), the most critical ratio found assuming elastic behavior was M_B/V_B = 518 in. This ratio is more critical than that obtained using the UBC lateral loads, M_B/V_B = 581 in. After the test, several nonlinear dynamic analyses assuming an infinitely ductile model of the prototype were carried out according to the experimentally obtained stiffness and strength of the wall. The results obtained reveal that the shear force in the first two stories of the wall exceeded its shear capacity before the base moment of the wall reached its moment capacity, M_B/V_B = 354 in.: a value much lower than the one obtained in the elastic analysis. Thus, the shear and overturning moment ratio used in the experiments was unconservative.

CONCLUDING REMARKS

The performance of the developed pseudo-earthquake simulator has been excellent. Data obtained in the tests of wall subassemblages have not only clarified the complex hysteretic behavior of this structural component, but have also enabled us to formulate important observations for future research programs regarding the aseismic design of frame-wall structural systems.

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7. Author(s)
V.V. Bertero, E.P. Povov, T. Endo, and T.-Y. Wang

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
University of California at Berkeley
Department of Civil Engineering
Berkeley, California 94720

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15. Supplementary Notes
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16. Abstract (Limit: 200 words)

The objective of this investigation is to develop practical methods for the aseismic design of combined frame-wall structural systems. To achieve this objective, integrated analytical and experimental studies have been conducted to determine the actual mechanical behavior of wall systems subjected to earthquake-like excitations. Rather than using the existing facility for determining a structure's overall response to specific time-history ground motions, a new structural loading facility capable of simulating earthquake effects, was developed. Significant subassemblages of the structural system were tested rather than large-scale models of entire buildings. Predicting the in-plane seismic behavior of frame-wall systems requires information on the variation of the lateral shear-displacement relationship for each story. In order to correctly simulate the actual boundary conditions of a particular story, subassemblages of at least two or three stories were tested. The principal feature of this facility is its ability to pseudo-statically simulate the dynamic loading conditions which could be induced in subassemblages of buildings during earthquake ground shaking.

17. Document Analysis a. Descriptors

Dynamic structural analysis	Seismic waves	Loads (forces)
Earthquake resistant structures	Framed structures	Shear properties

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

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