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EXPERIMENTAL STUDY OF STRUCTURAL RESPONSE TO EARTHQUAKES

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SUMMARY

The purpose of this paper is to describe the objectives, methods, and some of the principal results obtained from experimental studies of the behavior of structures subjected to earthquakes. Although such investigations are being conducted in many laboratories throughout the world, the information presented here deals specifically with projects being carried out at the Earthquake Engineering Research Center (EERC) of the University of California, Berkeley. A primary purpose of these investigations is to obtain detailed information on the inelastic response mechanisms in typical structural systems so that the experimentally observed performance can be compared with computer generated analytical predictions. Only by such comparisons can the mathematical models used in dynamic nonlinar analyses be verified and improved.

Two experimental procedures for investigating earthquake structural response are discussed: (1) the earthquake simulator facility which subjects the base of the test structure to acceleration histories similar to those recorded in actual earthquakes, and (2) systems of hydraulic rams which impose specified displacement histories on the test components, equivalent to motions developed in structures subjected to actual 'quakes. The general concept and performance of the 20 ft square EERC earthquake simulator is described, and the testing of a two story concrete frame building is outlined. Correlation of the experimental results with analytical predictions demonstrates that satisfactory agreement can be obtained only if the mathematical model incorporates a stiffness deterioration mechanism which simulates the cracking and other damage suffered by the structure. Several test facilities, based on servo-controlled hydraulic actuators, that have been developed for testing a variety of structural components are discussed. Tests of two types of components, a spandrel-wall-girder column assemblage and a three story shear-wall floor-slab system are selected for detailed discussion. Correlation of the results of these tests with analytical predictions has not yet been completed, so the validity of current modeling procedures for such components cannot be verified.

The principal conclusions to be drawn from these investigations is that the current state of the art ability to predict nonlinear earthquake response, particularly of reinforced concrete structures, is limited by insufficient knowledge of the actual seismic behavior. Additional experiments will be required to improve the mathematical idealizations employed in performing such analyses.

1. Introduction

Earthquakes are one of nature's greatest hazards to the works of man; each year on the average they cause the loss of thousands of lives and hundreds of millions of dollars in property damage. The terrible consequences of any major damage to a nuclear reactor system have made it necessary to impose very high seismic safety standards in the design of such structures when they are to be located in regions of earthquake activity, and a large part of their structural design effort may be expended in earthquake response analyses.

Presently available computer procedures are capable of predicting the dynamic earthquake response of highly complicated mathematical idealizations. However, the value of such analyses depends entirely on how well the mathematical model simulates the real structural behavior. If the seismic input is only of moderate intensity, so that the structure is not stressed beyond the elastic limit, it is not difficult to define a suitable linearly elastic mathematical model. On the other hand, if the earthquake is so severe that considerable damage is produced in the structure, the mathematical representation of the effective structural properties becomes very complicated. In this case, the force-deformation properties not only are nonlinear, they also are path-dependent; so the stiffness is a function not only of the current deformations, but also of the entire deformation history.

Because it is not economically feasible to design all structures to resist a great earthquake without damage, it is necessary to develop nonlinear analysis procedures which can be used to predict the extent of damage that will result from a given ground motion. However, the nonlinear behavior properties of the material and components included in the structural system cannot be evaluated mathematically; they must be determined by tests of similar materials and component configurations subjected to deformation histories that are equivalent to those experienced in an actual earthquake.

In order to obtain such test data, a group of faculty at the University of California, Berkeley, began ten years ago to develop test facilities for the study of nonlinear structural behavior under earthquake loadings, with financial support from the National Science Foundation (NSF). At present, 13 Berkeley faculty investigators are taking part in a research program on energy absorption characteristics of structural systems subjected to earthquakes, with an NSF budget of nearly one million dollars per year. The purpose of this paper is to describe some of the test procedures in use and the results being obtained in that program.

Two different testing procedures are being used at Berkeley to study the nonlinear earthquake behavior of structural systems: an earthquake simulator and controlled displacement hydraulic actuator systems. The earthquake simulator is a heavily reinforced concrete slab 20 ft. square which can be controlled to move both vertically and in one horizontal direction by servo-controlled hydraulic actuators. [1] Test structures which are fastened to the slab can be subjected to any desired base motion, such as those recorded during an actual earthquake, and the resulting earthquake response can be observed directly. The capacity of the simulator is ±5 in. displacement and 2/3 gravity acceleration in the horizontal direction together with ±2 in. displacement and 45% gravity acceleration vertically, with a full pay load of 50 tons. The earthquake simulator is a very effective testing device, but its principal disadvantage is the limited size and weight of the structures that can be tested.

A controlled displacement test system consists of a group of servo-controlled hydraulic actuators similar to those which drive the shaking table. In this type of testing, the actuators are arranged so that they impose a specified displacement history on the test specimens. Major advantages of this procedure are that very large forces can be applied to the test structure, and that the testing can be done at low speeds so that details of the damage process may be observed. However, the test input generally can only be specified arbitrarily; it does not simulate the response behavior during any actual earthquake.

In this paper one test on the earthquake simulator and two tests using controlled displacement systems will be described. The test specimens considered in these studies are of reinforced concrete, but the research program deals also with masonry and steel construction. The principal purpose of each test is to obtain data on the actual behavior of structures subjected to earthquake loadings. These data then are used to evaluate the reliability of nonlinear analysis procedures and to make improvements in the mathematical modeling. It is important to note that the objective is not simply to provide a performance test of a specific structural design, but rather to improve the ability to predict seismic performance by digital computer analyses.

2. Earthquake Simulator Test of a Concrete Frame [2]

The first reinforced concrete structure tested with the Berkeley earthquake simulator is the two story building frame shown in Fig. 1. It was intended to represent a segment of a small office building and was constructed according to standard seismic code requirements with a length scale of 0.7. 12 tons of concrete blocks were loaded on the floors to give the test structure a typical period of vibration and also to cause significant seismic forces during the tests. Lateral bracing was provided to constrain the building against any lateral or torsional motions.

Instrumentation installed to record the response of the test structure included accelerometers and displacement gages at each story and on the shaking table, strain gages on the reinforcing bars at the column bases where the maximum strains were expected, and displacement gages located to measure relative rotations (curvatures) at the ends of the columns and girders. In addition, force transducers calibrated to indicate moment, shear, and axial force were installed at mid-height of each column. A total of 98 channels of instrumentation were recorded during the test, using a mini-computer based data acquisition system. Each channel was sampled 50 times per second during the test and the data was stored in digital form on a magnetic disk. Subsequently the data was transferred to magnetic tapes for further computer processing and plotting.

The input motion for this test was one horizontal component of the earthquake recorded at Taft, California in July 1952; no vertical motions were considered. The excitation was applied with successively increasing intensities, starting with a peak acceleration of 0.07g in the first run and reaching a maximum run having a peak acceleration of 0.44g. The first run produced only elastic response, but the maximum test caused considerable damage. The input table displacements and the resulting average column shear force recorded during the maximum test are shown in Fig. 2.

After each test, the free vibration frequency and damping of the test structure was determined by suddenly releasing a 1000 lb. horizontal force applied at the first story level. The successive changes of these properties which are plotted in Fig. 3 demonstrate the extent of damage done to the structure in each test run.

As was stated earlier, the results of this test were used to evaluate the accuracy of available nonlinear response analysis procedures and to improve the mathematical indealizations employed in such analyses. A comparison of the second story displacement observed during the most intense test run with a computer analysis of the response to the same base motion is shown in Fig. 4. The mathematical model used in this calculation included a bilinear yielding hinge mechanism at each end of each member, combined with a global stiffness degradation mechanism based on the first mode response amplitude. The correlation obtained in this test is considered adequate for most design purposes, but undoubtedly could be improved further with a more refined type of mathematical model.

3. Spandrel Girder - Column Tests [3]

One of the controlled displacement test systems developed at Berkeley is used to study the nonlinear seismic behavior of spandrel girder frames. These frames frequently are used in the exterior walls of school buildings, and have been damaged extensively in many earthquakes. Their deep girders and short connecting columns provide good strength and stiffness, but they are notoriously lacking in ductility. The purpose of this test program was to evaluate the large amplitude cyclic displacement behavior of typical spandrel girder-column frames, and to develop improved schemes for reinforcing such structures.

A schematic view of a spandrel girder frame is presented in Fig. 5; the typical test component considered in the research program, consisting of two girders and a two-story column segment joining them, is shown in the circle. The facility which was designed to test this structural component is illustrated in Fig. 6. The test specimen, also shown in the figure, was constructed at half scale for reasons of economy and convenience. It was supported in a horizontal position on low-friction teflon pads. Loads were applied by hydraulic jacks inserted between the test structure and a system of five concrete reaction blocks which were fastened to the floor of the testing laboratory by prestressing rods. The principal loading units were a 150 ton jack which applied constant axial load to the column, and a 100 ton jack which produced lateral "sidesway" displacements equivalent to those resulting from an earthquake. Supplementary 60 ton jacks were installed between the ends of the spandrel girders. These were controlled electronically to maintain the same distance between the girder ends as was measured between corresponding points on the column, thus forcing the girders to remain parallel as the column was undergoing damage during tests.

Instrumentation used in these tests included load cells to measure the applied loads and reactions, potentiometers to measure the displacement of the load points, and clip gages to measure relative rotations (curvatures) at critical sections of columns and girders. In addition, strain gages were attached to some reinforcing bars to measure local strains for comparison with the average values indicated by clip gages. About 60 data channels were recorded digitally by a low speed (3 channels per second) data acquisition system; generally six channels also were recorded by oscillograph to visually monitor the behavior.

The test was conducted by applying cyclic sidesway displacements starting with small amplitudes (0.1 inch each way) and increasing by steps until failure occurred. Typically each step included five complete cycles at constant amplitude, applied at a rate of about 5 minutes per cycle. A composite plot showing the first cycle of input force vs. displacement for each step of a typical test is shown in Fig. 7. The successively changing shapes of these hysteresis loops demonstrate that the mathematical idealization of this behavior is exceedingly complex; the development of an appropriate mathematical model is still in progress.

4. Shear Wall Tests [4]

A second controlled displacement test system was constructed at Berkeley to study the seismic behavior of shear wall and braced frame construction. The test component for the first series of studies was a three story segment of a reinforced concrete shear wall. Such walls frequently are used in building frames to increase their lateral strength and stiffness. They consist of a solid reinforced concrete panel which is intended to resist shear, bounded at each side by columns which are designed for the static vertical loads plus axial forces induced by overturning moments.

The test system was designed to apply loads to the specimen equivalent to those that would act in an actual shear wall. The specimen was supported in a horizontal position on low-friction pads, and loads were applied by actuators positioned between the specimen and a set of reaction blocks anchored to the laboratory floor, as shown in Fig. 8. The test structure was a 1/3 scale model of the lowest three stories of a shear wall designed for a 10 story building. Its dimensions were 7'-10" wide by 13'-7" high; the columns were 10" square and spirally reinforced; and the shear wall was 4" thick. Floor slab "stubs" representing half of the adjacent floor slabs were cast with the shear wall. The model was made 3 stories high to minimize boundary effects in the behavior of the critically loaded bottom story.

As may be seen in Fig. 8, actuators were arranged to apply axial column loads to the specimen, simulating both the static gravity effects plus the dynamic alternating forces due to seismic overturning moments. Other actuators were provided to apply shear forces simulating the seismic shears acting on the stories above and the local lateral inertia forces; these were electronically coupled with the column actuators so that dynamic shears and overturning moments would act in phase. The instrumentation was designed to measure total and relative story-to-story lateral displacements, shear distortion of each wall panel, curvature of the entire wall section at its base, strains in some of the reinforcing bars, and all of the actuator forces. Readings from a large number of gages were recorded continuously by X-Y plotters. These plotted the most significant strains, displacements, and rotations (curvatures) against the lateral shear force applied at the top story of the specimen. As many as 18 X-Y plots were made permitting the response of the specimen to be followed during each test; supplemental data was recorded in digital form by a low speed data acquisition system. In addition, photogrammetric methods were used to record crack pattern formation and movements along the cracks, as well as the overall deformation behavior of the structure. The results obtained with the first two specimens (Walls 1 and 2) are compared in Fig. 9.

The loading of the first test specimen Wall 1 was increased monotonically at a low rate until a reduction of its strength was observed; then the loading was reversed and increased in the negative direction until the residual displacement at zero load was eliminated. Wall 2 was subjected to gradually increasing cycles of alternating displacements with two or three cycles at each amplitude. Fig. 9 is a composite graph showing the lateral force vs. displacement behavior of the two specimens. It is interesting to note that the monotonic loading of Wall 1 provides an approximate envelope of the results obtained from the alternating cycles of the second test. Wall 1 deformed up to 4.3 in. without any reduction of resistance, giving a displacement ductility factor of about 7; with Wall 2, the maximum displacement ductility factor under alternating cyclic loading was less than 5.

5. Conclusions

The dynamic response behavior demonstrated by reinforced concrete specimens discussed in this report shows how complex are the mechanisms of structural damage during earthquakes. The force-deformation properties of all these test structures were found to be nonlinear and history-dependent; moreover their behavior patterns were different so that they require different forms of mathematical idealization.

The only feasible way to develop suitable mathematical models of such systems and to establish numerical values for their properties is by experiment with physical models. Both the earthquake simulator system and the controlled displacement test systems described here have performed very well in demonstrating the damage mechanisms of typical structures subjected to severe seismic loading. Each type of system has advantages and disadvantages, consequently both are very useful in carrying out a complete research program in this field.

References

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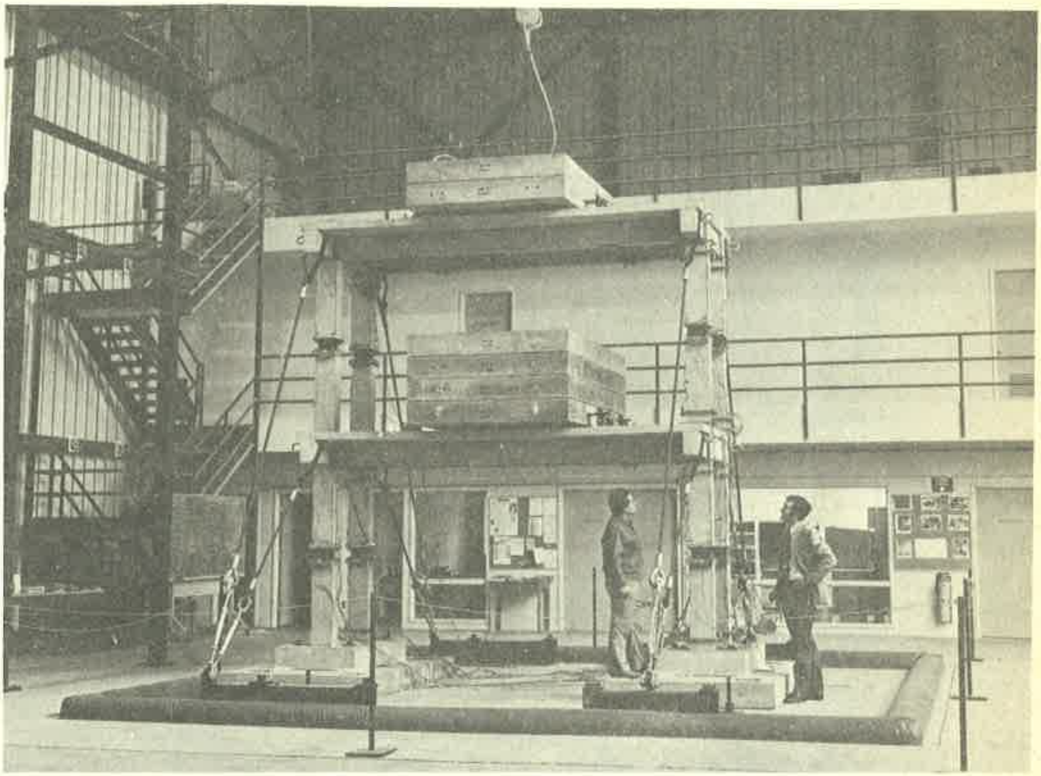
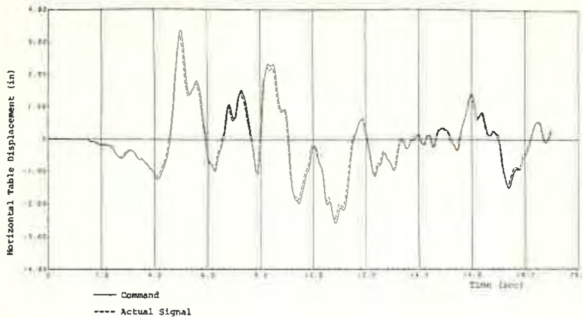
[2] Hidalgo, P. and Clough, R. W., "Earthquake Simulator Study of a Reinforced Concrete Frame", University of California Earthquake Engineering Research Center Report No. EERC 74-13, Berkeley, 1974.

[3] Kustu, O. and Bouwkamp, J. G., "Behavior of Reinforced Concrete Deep Beam-Column Subassemblages Under Cyclic Loads", University of California Earthquake Engineering Research Center Report No. EERC 75-11, Berkeley, 1975.

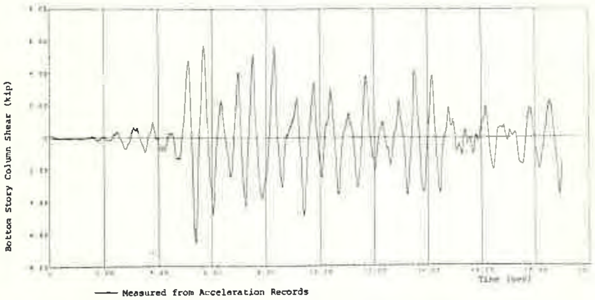
[4] Wang, T. Y., Popov, E. P. and Bertero, V. V., "Hysteretic Behavior of R. C. Framed Walls", University of California Earthquake Engineering Research Center Report, Berkeley (in preparation).



1. Two Story R/C Frame on Earthquake Simulator

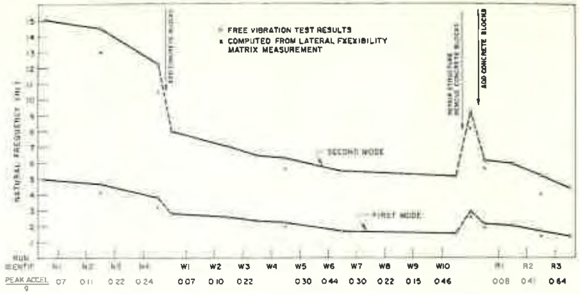


(a) Input Table Motions

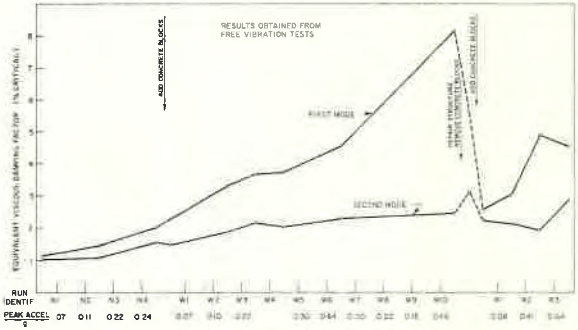


(b) Average Column Shear

2. Base Input Displacements and Average Column Shear Force, Run W6

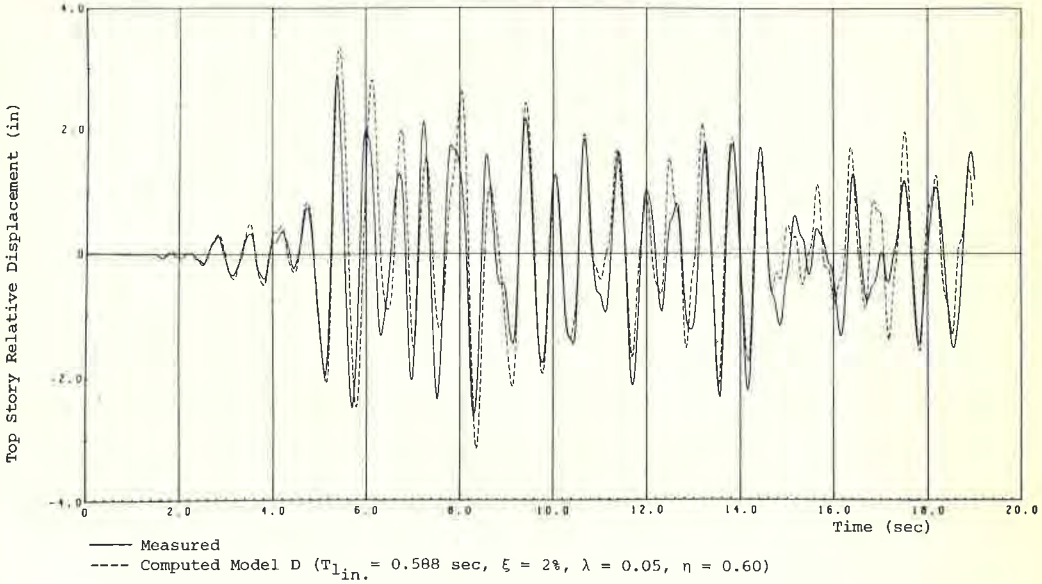


(a) Frequency Variation During Test Sequence

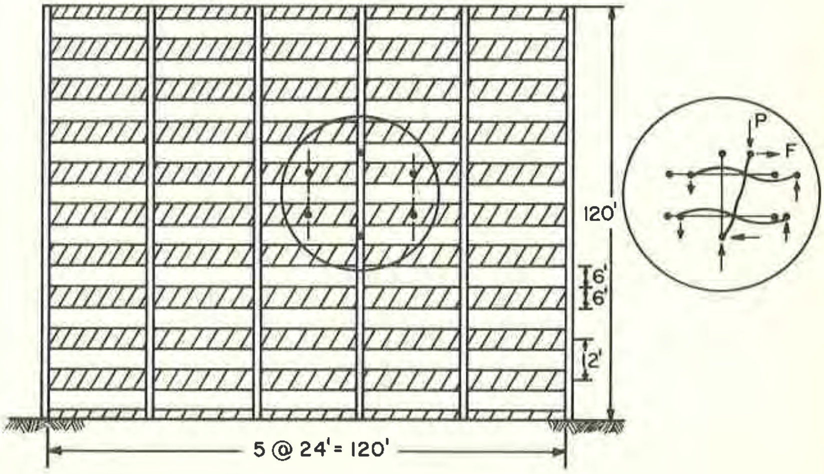


(b) Damping Variation during Test Sequence

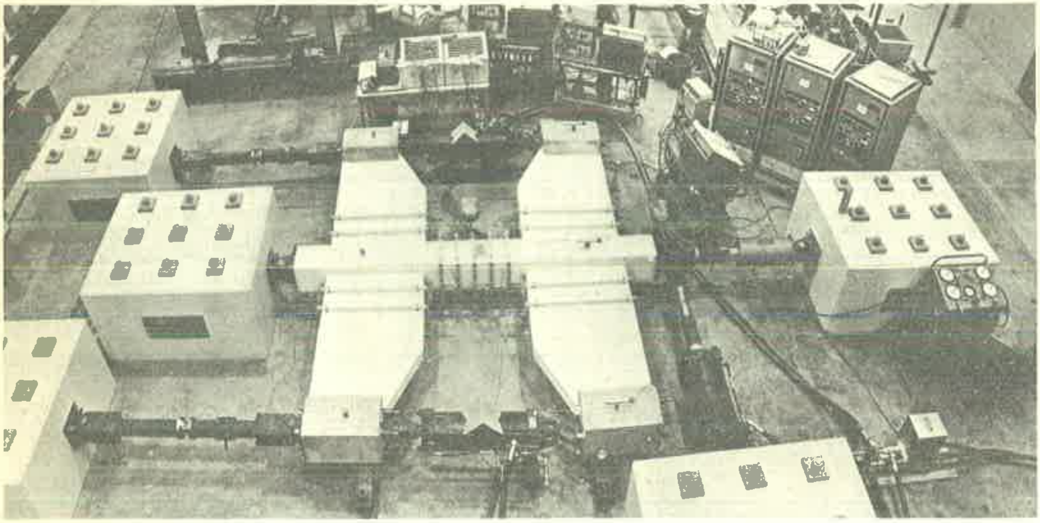
3. Changes of Free Vibration Frequencies and Damping during Test Sequence



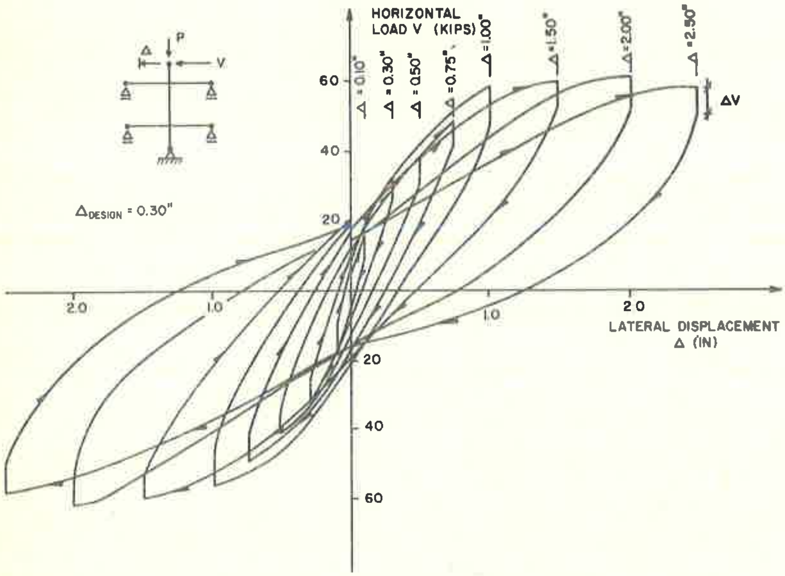
4. Correlation of Computed with Measured Top Story Displacement, Run W6



5. Schematic View of Spandrel Girder Frame and Test Subassembly



6. View of Spandrel Girder Specimen in Controlled Displacement Test Fixture



7. Composite of Typical Spandrel Girder First Cycle Load vs. Displacement Plots

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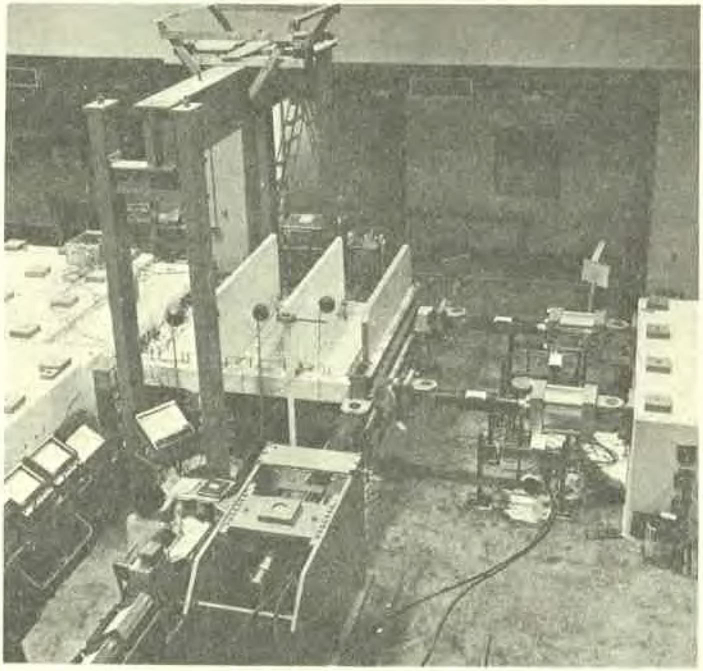
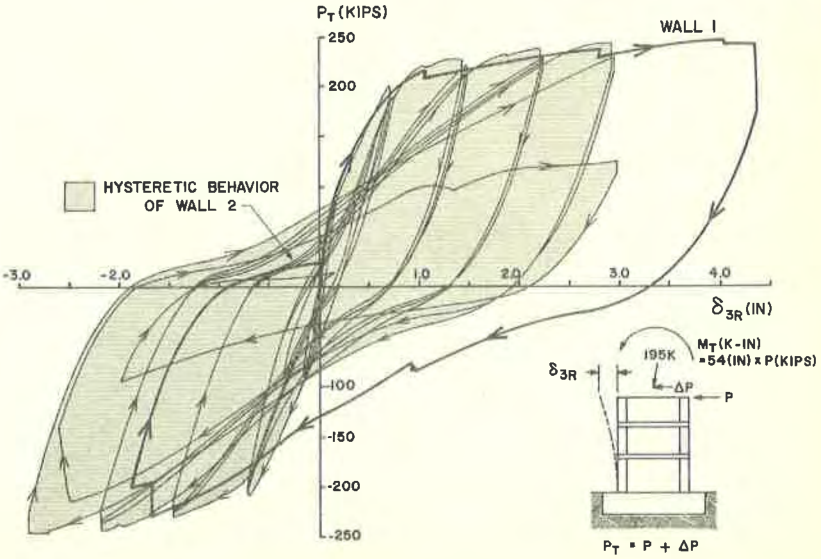


8. View of Shear Wall Specimen in Controlled Displacement Test Facility



9. Force vs. Displacement Plots for Shear Walls 1 and 2.