FULL SCALE, THREE-DIMENSIONAL TESTS OF STRUCTURAL DEFORMATIONS DURING FORCED EXCITATION OF A NINE-STORY REINFORCED CONCRETE BUILDING

by

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ABSTRACT

Full scale, forced vibration tests of the nine-story reinforced concrete Millikan Library building on the campus of the California Institute of Technology in Pasadena, California, were conducted during 1974. An eccentric weight vibration generator installed on the roof of the building was used to shake the building at resonance. The three-dimensional motion at approximately 50 points on each of six levels including the basement and at 100 points on the ground surrounding the building was measured. These tests were performed for shaking in both the transverse and longitudinal directions of the building. The tests revealed a substantial amount of deformation of the floor slabs and interaction between horizontal and vertical load carrying members. The tests also indicated that the deformation of the soil had a significant influence on the response of the building in the stiffer N-S direction.

INTRODUCTION

The analysis of stress and deformation for complicated structures such as high-rise buildings, bridges and dams is often accomplished by deriving a mathematical model of the structure. These models are based on the behavior of individual members such as beams, columns, plates and walls and on the assumed combined behavior of these elements as a structural system. Consequently, the results of these analyses are largely dependent upon the engineer's ability to model structural systems. This dependence has inspired numerous experiments to determine both the elastic and post-yield behavior of the individual elements. As a result, much is known about the static and dynamic behavior of structural components.

Although extensive experimental programs have been undertaken to determine the behavior of these structural components, relatively little has been done to test the assumptions regarding the behavior and interaction of these components when they are combined to form a structural system. Several attempts to study the dynamic behavior of assemblages of structural elements have been made using shake tables. Whereas these have provided valuable information, they are limited in size and composition. They do not contain many of the so-called non-structural members which may play a significant role in the overall behavior of a real structure; nor do they rest on a deformable foundation which may or may not influence the behavior of the system.

The development of the forced vibration generator(1) provided a means of doing full scale tests of existing structures(2-7). For the most part, these forced vibration tests have been used to determine the first few natural frequencies and mode shapes of one-dimensional representations of the structures. However, these tests tell us little about the validity of the assumptions that were made which initially allowed the one-dimensional modeling. In a sense, it has been a case of the modeling assumptions dictating which tests should be performed as opposed to the vibration tests verifying, or implying, which assumptions could be

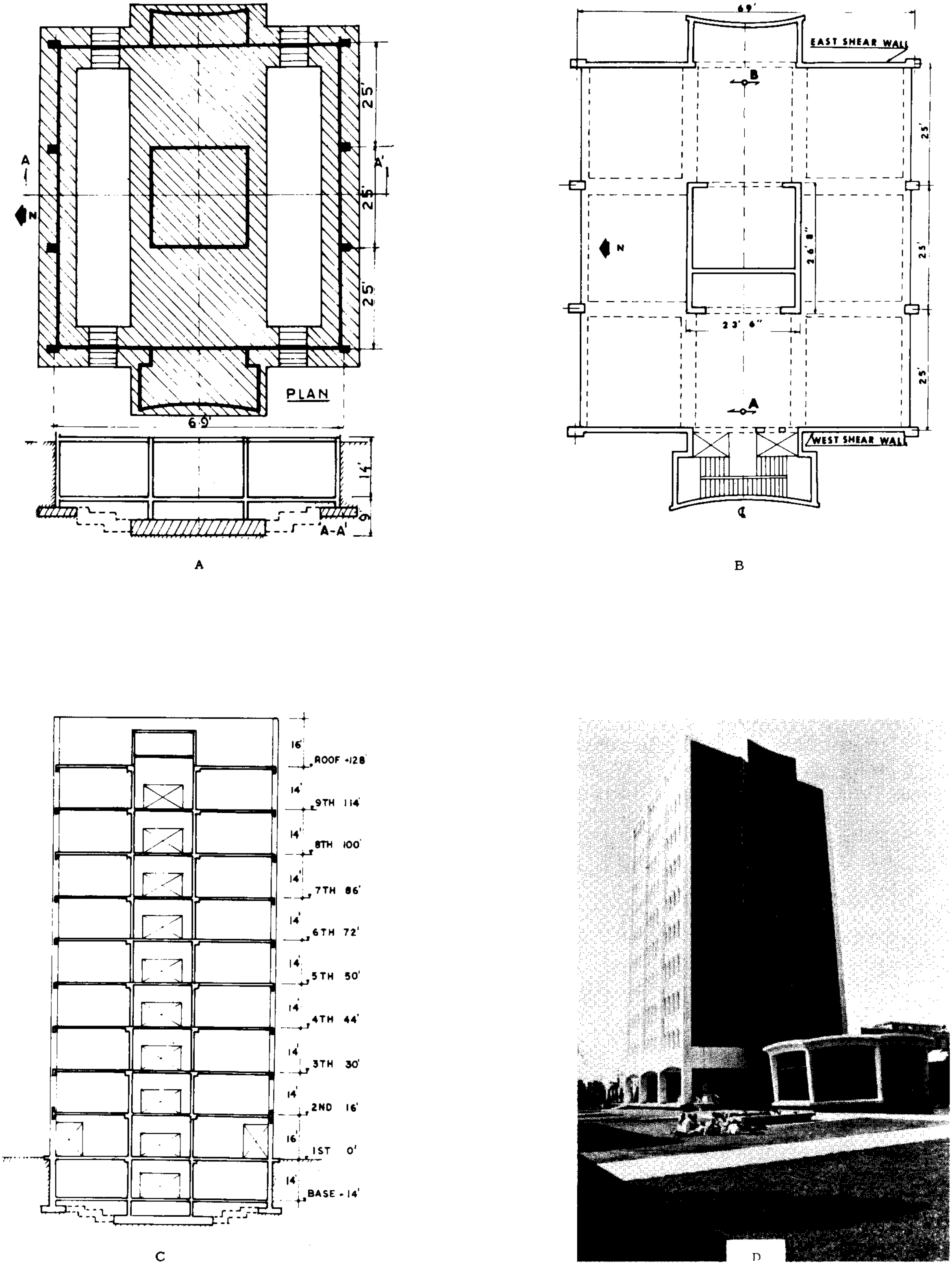

Figure 1. Millikan Library Building: (a) Foundation plan and N-S Section; (b) Typical Floor Plan; (c) a N-S Section; (d) View of Building Looking Northwest.

made. Consequently, it is the contention of these authors that more information about the behavior of structural systems can be gained using conventional testing equipment than has previously been obtained.

The purpose of this study was to ascertain the breadth of information that may be obtained from a forced vibration test of a multi-story building using readily available apparatus and simple data processing techniques. As a result, the information that was gained from this study revealed the nature of three-dimensional deformations that the soil-structure system experienced during dynamic excitations. The tests also provided a direct physical insight into the appropriate model that should be used to describe the building.

DESCRIPTION OF THE BUILDING, APPARATUS, AND EXPERIMENTAL PROCEDURES

The Robert Millikan Memorial Library is a nine-story, reinforced concrete building located on the campus of the California Institute of Technology in Pasadena, California. Since its completion in 1966, the building has undergone numerous tests and analyses (6-9). During and following its construction, the building has also experienced three earthquakes (Lytle Creek, Borrego Mountain, and San Fernando) which were recorded by strong-motion instruments located in the basement and on the roof. Therefore, the collection of all of these tests and analyses provides a valuable case study of a building subjected to loads of various types and intensities, as well as an indication of the accuracy to be expected from these types of measurements.

The library building is 69 × 75 feet in plan and stands 144 feet above grade and 158 feet above the basement level (see Figure 1). This includes an enclosed roof which houses elevator and air handling equipment. The majority of the lateral loads in the transverse (N-S) direction are resisted by 12-inch reinforced concrete shear walls on the east and west ends of the building. In the longitudinal direction the 12-inch reinforced concrete walls of the central core, which houses the elevators and emergency stairways, provide most of the lateral resistance. The foundation system is composed of a central pad 32 feet wide by 4 foot deep that extends from the east curved shear wall to the west curved shear wall. Also provided are beams 10 feet by 2 feet which run east-west beneath the rows of columns at the north and south ends of the building. These are connected to the central pad by stepped beams (see Figure 1).

A vibration generator(1) which provided a sinusoidal exciting force was mounted on the roof of the building. The steady state response of the building and surrounding soil was measured with four Model SS-1 Ranger Seismometers and a Model SC-1 signal conditioner and recorded by two Mark 220 Brush Recorders. Three of the seismometers were mounted on a board to facilitate the measurement of motion in three orthogonal directions. The fourth seismometer was placed in the basement of the building at a reference point located at the center of the north face of the central core wall where it remained throughout each test. Three-dimensional motions were measured for 51 locations on each of four floors, the roof and the basement for shaking in both the N-S and E-W directions. Three-dimensional motions for shaking in both directions were also measured at 100 locations on the ground outside the building. The amplitudes of the motion of these points relative to the reference point are shown in Figure 2 through Figure 5.

PRESENTATION AND DISCUSSION OF RESULTS

The three-dimensional motions of the basement, the second, fourth, sixth and eighth floors and the roof are shown in Figure 2 and Figure 3 for shaking in the N-S and E-W directions, respectively. The resonant frequencies were

1.76 Hz in the N-S direction and 1.21 Hz in the E-W direction. These motions indicate the degree of interaction and the coupling of the motions between the various load resisting elements in the structure.

The characteristics of the motions of the structure for shaking in the N-S direction were dominated by the behavior of the shear walls at the east and west ends of the building. Notice that the exterior edges of the slabs at the east and west ends of the building remained nearly straight lines as the structure deformed (see Figure 2). This indicates that, although the channel-shaped section joining the two portions of the east shear wall experienced a small amount of shearing-type deformation, the dominant behavior of the assemblage was more like that of a single Euler beam than two beams acting independently. This bending-type behavior was even more evident for the walls at the west end of the building where the stairs acted as a bracing element resisting shear deformation. This bending behavior of the shear walls produced vertical motions of the slab which reached a maximum at the ends of the walls. This maximum vertical motion was approximately 24% of the horizontal motion of the roof. It is clear from these figures that the assumption for design analysis that the slabs were perfectly flexible would have produced conservative estimates of stress in the shear walls but nonconservative estimates of stress for the columns. On the other hand, the assumptions of a perfectly rigid slab would have produced conservative estimates of stress for the columns but nonconservative estimates of bending stress for the shear walls. Of course, this is true only if one originally considered coupling of horizontal and vertical deformations in the design model. The actual behavior of the structure indicated that the columns acted as relatively rigid members that resisted the vertical motion of the edges of the slabs. This resulted in a significant amount of bending deformation in the slabs.

The building behaved quite differently in the E-W direction. There was little vertical motion of the slab around the perimeter of the building, but there was a substantial amount at the east and west ends of the central core. Consequently, there was a significant amount of deformation in the slabs. This result occurred because of the different types of load resisting elements in the system. The central core deformed like a bending beam, while the columns and the east and west shear walls acted as rigid members in the vertical directions. These results of the tests for both the north-south and the east-west directions indicate that the relationship between lateral deflection of the floors and stresses in the structural members would differ from those predicted by a one-dimensional model.

The maximum displacement of the basement slab for shaking in both directions is shown in Figure 4. It is clear that the slab did not behave as a rigid foundation. In fact, the deformation of the basement slab was not unlike that of the other floor slabs. Motion in the N-S direction, characterized by the relatively rigid east and west shear walls, caused a somewhat uniform rotation of the basement slab. The maximum vertical motion of the outside corners of the slab was approximately 200% larger than the average horizontal motion which was in turn approximately 4% as large as the maximum lateral motion of the roof. The average rotation of the basement slab produced a vertical motion at the north and south edges of the slab which measured approximately 145% of its horizontal motion. This average rotation contributed 25% of the measured horizontal roof motion. Consequently, deformation of the soil accounted for approximately 29% of the translation of the roof and approximately 45% of the rotation of the roof slab in the N-S direction (see Figure 6). These results vary markedly from those reported by Jennings and Kuroiwa(6) in 1968. Their results indicated that the deformation of the soil contributed less than 3% of the motion at the roof. The reason for this difference is not totally understood. The fact that the instruments for the Kuroiwa tests were located at the points of minimum vertical motion of the basement slab account for some of the difference. Further

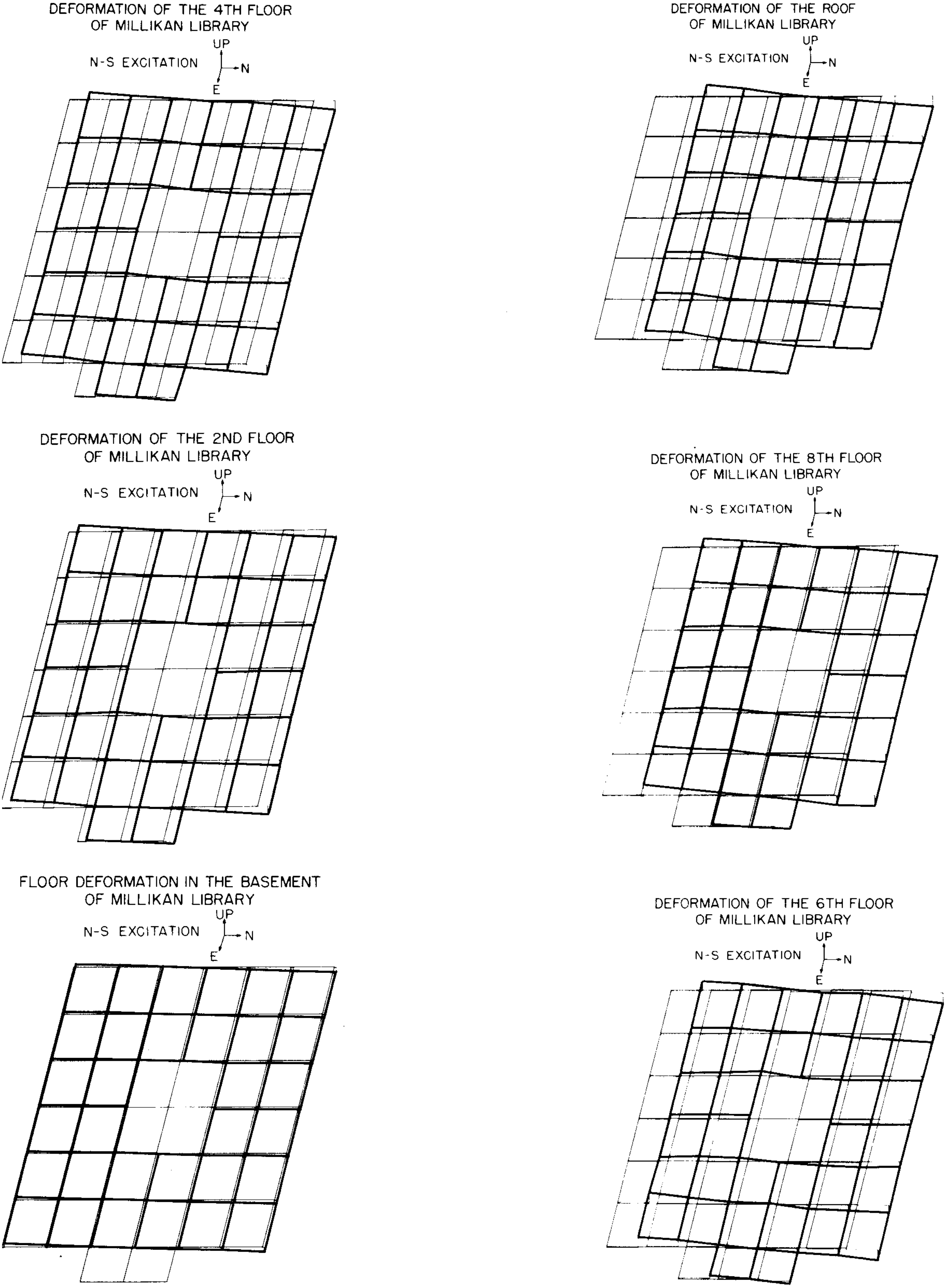
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Figure 2

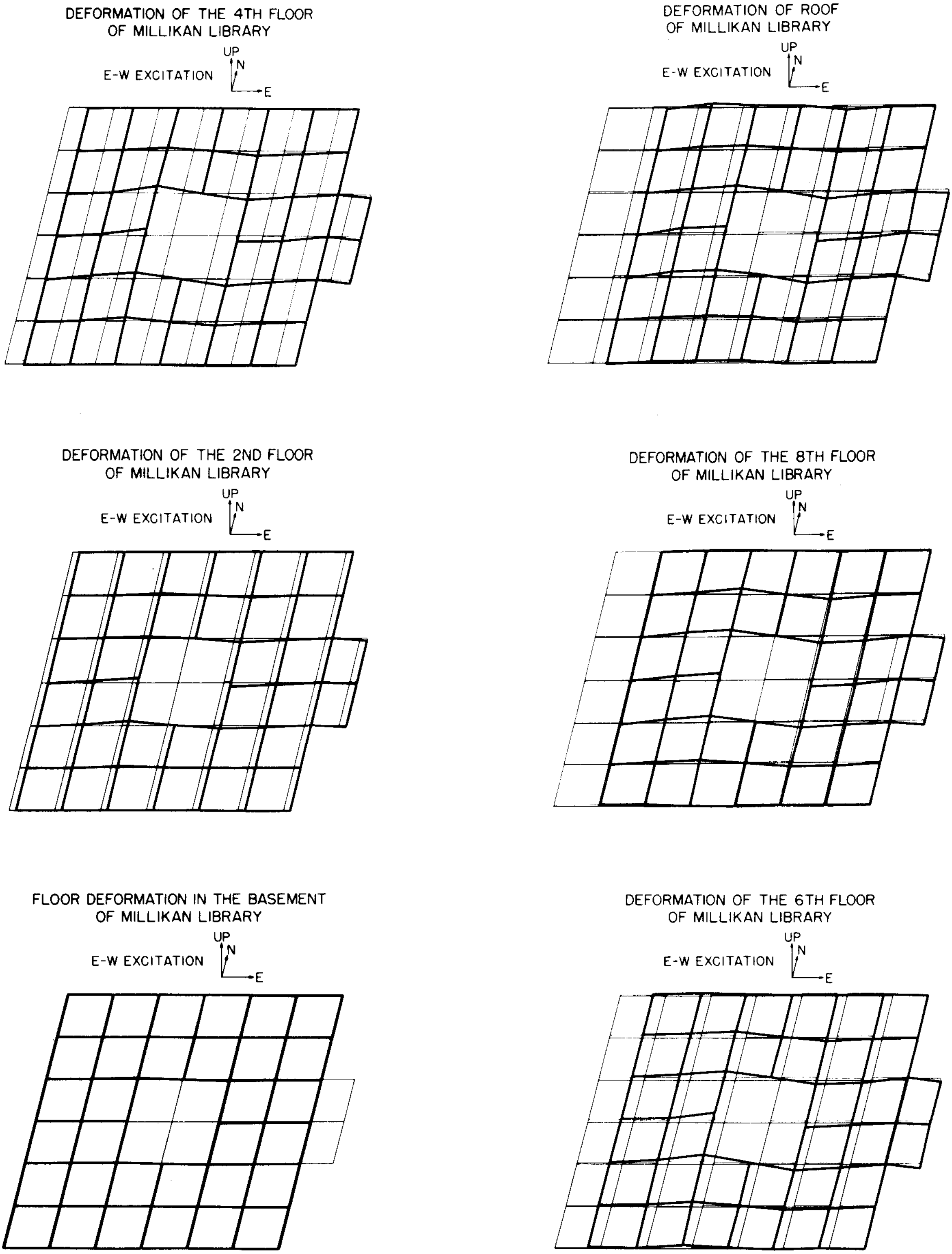
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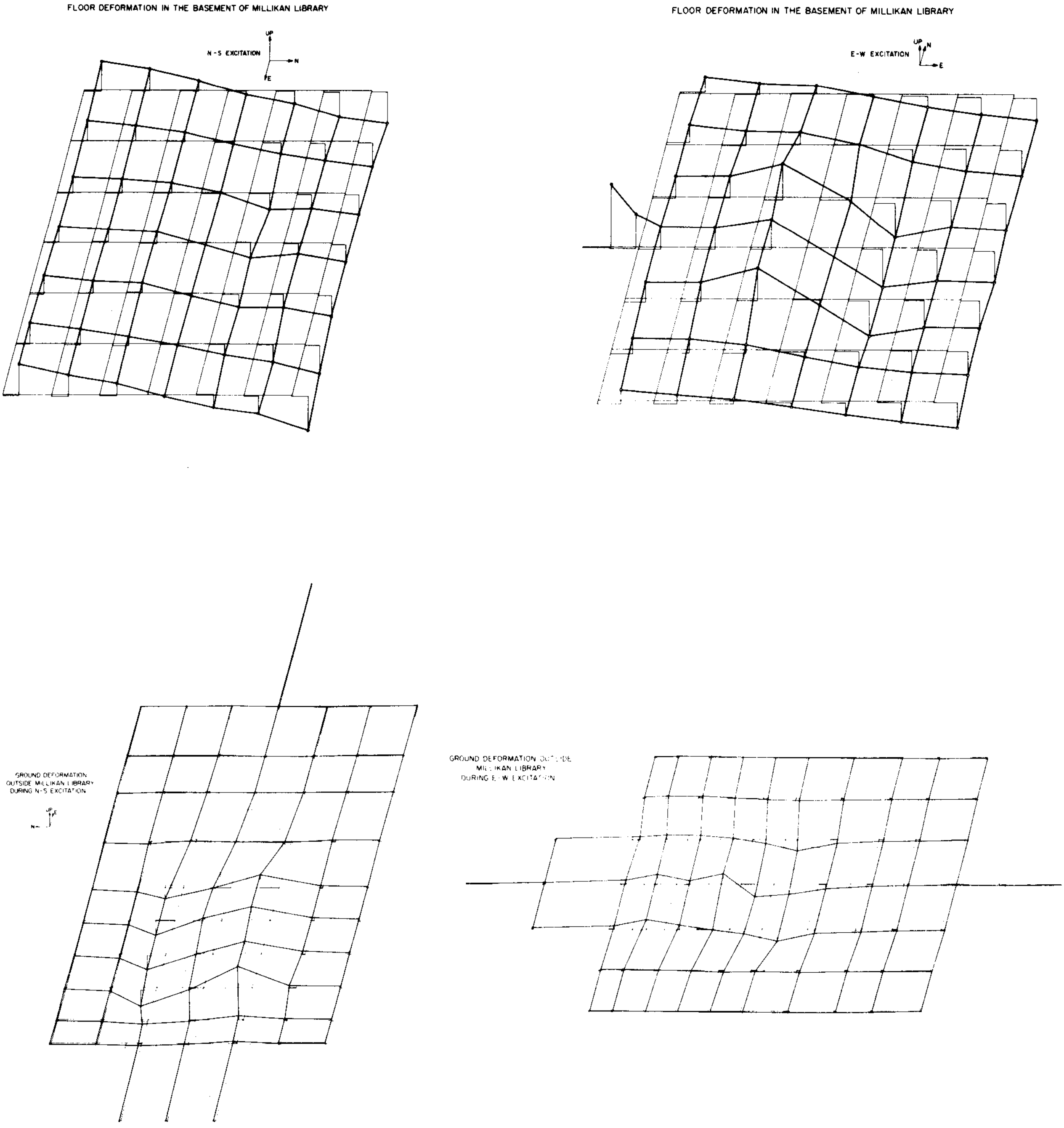
Figure 3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DURING N-S EXCITATION
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Figure 4

studies are being conducted to clarify these differences. For shaking in the E-W direction the deformation of the slab was concentrated around the central core as would be expected. In this case the horizontal displacement of the slab was approximately 2% of the displacement of the roof and the maximum vertical deformation was again roughly 200% larger than the average horizontal motion. Overall rocking of the building was not important in the E-W direction.

Figure 4 also shows the deformation of the ground around the structure for shaking in both directions. These results indicate that substantial deformation of the soil occurred as far away as several meters from the base of the building. As would be expected, the deformation of the soil was dependent upon the nature of the structural elements resisting motion in a particular direction. The largest motions occurred for shaking in the more rigid N-S direction.

The relative behavior of the various elements of the soil-structure system are illustrated in Figure 5. Figure 5a shows the relative displacements of a section through the central core for E-W shaking and Figure 5b shows the deformations along a section just inside the west shear wall for N-S shaking. It is doubtful that usual modeling techniques could properly describe the dynamic behavior of this system. The strain energy stored in the slabs and the energy radiated from the structure due to soil deformation should have a significant affect on the dynamic response of the structure. Also, it is doubtful that present modeling techniques could properly describe the relationship between horizontal and vertical motions of the floors. Clearly, a two-dimensional model which allowed coupling between horizontal and vertical deflection would be required in the E-W direction, and a model which included foundation deformation would be necessary in the N-S direction.

It may be rightfully argued that the information obtained from forced vibration tests is restricted to that obtained from low levels of excitation and is therefore of limited value. However, this study has shown that a variety of information may be gained from forced vibration tests of full scale structures. This is the most readily available means of determining the true interaction between various structural elements of a dynamical system. Many more interesting questions about the behavior of structural systems may be answered than the authors attempted in this paper. This paper represents just a sample of some techniques that may be used.

CONCLUSIONS

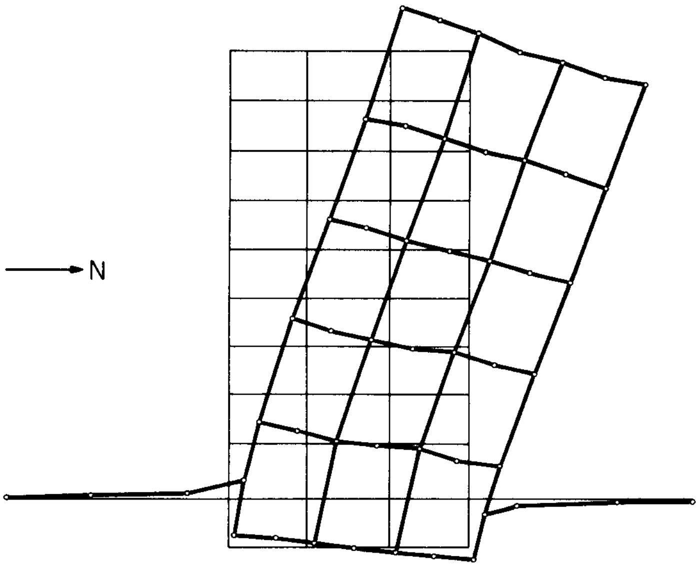
The following conclusions were drawn from the results of the tests reported here:

1. Much more information about the dynamic behavior than simple one-dimensional mode shapes and natural frequencies may be obtained from forced vibration tests.

2. The dynamic behavior and the distribution of stress in real structures subjected to earthquake motions may be substantially different than that predicted by models based on common assumptions.

3. Soil-structure interaction has a significant effect on the dynamic response of the Millikan Library Building. The effect is most pronounced in the N-S direction.

DEFORMATION OF SECTION ALONG WEST
SHEAR WALL OF MILLIKAN LIBRARY
N-S EXCITATION



DEFORMATION OF SECTION THROUGH CENTERLINE
OF ELEVATOR CORE OF MILLIKAN LIBRARY
E-W EXCITATION

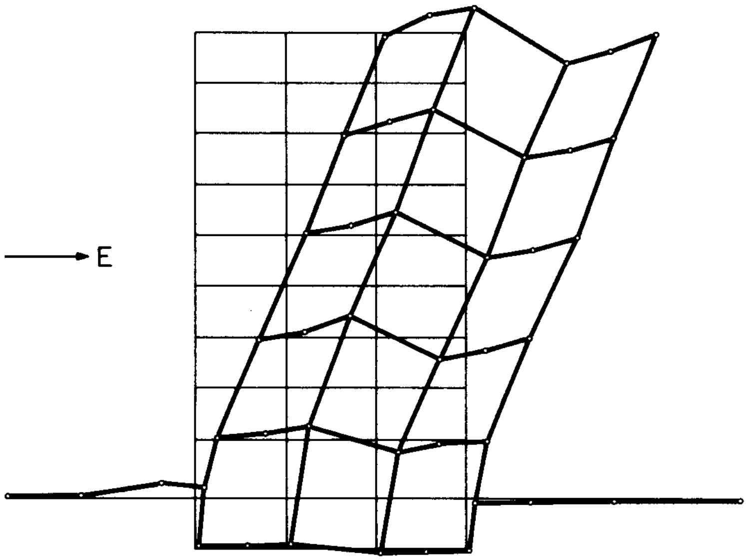


Figure 5

CONTRIBUTION OF FOUNDATION DEFORMATION
TO ROOF MOTION FOR N-S SHAKING

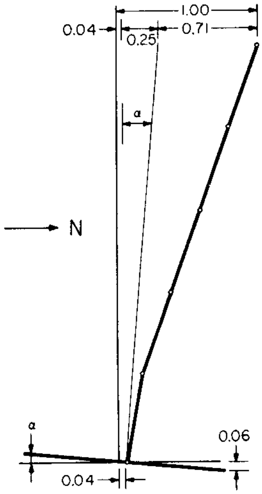


Figure 6

REFERENCES

1. Hudson, D. E., "Synchronized Vibration Generators for Tests of Full-Scale Structures," Earthquake Engineering Res. Lab., California Institute of Technology, Pasadena (1962).

2. Matthiesen, R. B. and Smith, C. B., "A Simulation of Earthquake Effects on the UCLA Reactor using Structural Vibrations," Department of Engineering, University of California, Los Angeles (1966).

3. Englekirk, R. E. and Matthiesen, R. B., "Forced Vibration of an Eight-Story Reinforced Concrete Building," Bull. Seism. Soc. Amer., 57, 421-436 (1967).

4. Nielsen, N. N., "Dynamic Response of Multistory Buildings," Earthquake Engineering Res. Lab., California Institute of Technology, Pasadena (1964).

5. Wood, J. H., "Analysis of the Earthquake Response of a Nine-Story Steel Frame Building during the San Fernando Earthquake," Earthquake Engineering Res. Lab., California Institute of Technology, Pasadena (1972).

6. Jennings, P. C. and Kuroiwa, J. H., "Vibration and Soil Structure Interaction Tests of a Nine-Story Reinforced Concrete Building," Bull. Seism. Soc. Amer., 58, 891-916 (1968).

7. Trifunac, M. D., "Comparisons between Ambient and Forced Vibration Experiments," Earthquake Eng. and Structural Dyn., 1, 133-150 (1972).

8. Jennings, P. C. and Iemura, H., "Hysteretic Response of a Nine-Story Reinforced Concrete Building," Earthquake Eng. and Structural Dyn., 3, No. 2, 183-202 (1974).

9. Trifunac, M. D. and Udwadia, F. E., "Time and Amplitude Dependent Response of Structures," Earthquake Eng. and Structural Dyn., 2, 359-378 (1974).