DYNAMIC TESTS OF FULL-SCALE STRUCTURES

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SYNOPSIS

Dynamic tests of full-scale stuuctures provide a unique opportunity to verify the validity of analytical models used in analyses for design and research. In the study reported here, the present status of experimental verification of analysis is discussed; and newly applied experimental procedures, which involve closely spaced three-dimensional measurements of motion on selected floors of a building and the measurement of strain in structural members, are presented. These detailed measurements help resolve uncertainties which may arise in current modeling practices. Examples illustrating these points are drawn from recent forced vibration tests of a nine-story reinforced concrete building and a twelve-story steel frame structure. Suggestions regarding future experimental efforts are presented.

Introduction

The analysis and design of complex structures depends on the engineer's ability to model the behavior of structural systems and their constituent elements. Full-scale tests of structures are obviously an essential part of the experimental effort required to verify methods of analysis used in design. These tests are not so readily accomplished, however, since most civil engineering structures are much too large to be built in a laboratory.

The need for full-scale testing has long been recognized and vibration studies have been performed on multistory buildings in the United States for over 40 years. The requirement for full-scale tests is even more apparent today since the experimental verification of the highly sophisticated modeling techniques available to the engineer is far from complete for civil engineering structures.

To help provide some of this evaluation, a series of forced vibration tests of two buildings have been undertaken at the California Institute of Technology over the past 3 years. The object of the experiments was to demonstrate that forced vibration tests could be used to gain sufficiently detailed information concerning the interaction of the various structural and nonstructural systems in a building to evaluate critically the type of finite element models now used in structural analysis.

Tests of Millikan Library Building

Forced vibration tests were conducted during the fall of 1974 on the Millikan Library building, a nine-story reinforced concrete building located on the campus of the California Institute of Technology in Pasadena, California. A specially designed package of Ranger seismometers was

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placed at approximately 50 points on six floors of the structure including the basement. Three orthogonal components of motion at each point were measured for shaking of the structure at its fundamental frequencies in the N-S and E-W directions. More detailed descriptions of the instrumentation and structural system appear elsewhere.[1, 2, 5, 6]

The three-dimensional character of the two fundamental modes of the building is shown in figure 1. For N-S shaking, a section showing the deformations in the plane of the shear wall at the west end of the structure is shown in figure 1(a); and a plot of the three components of slab deformations is shown in figure 1(b). Similar results for E-W shaking are shown in figure 1(c) and 1(d).

Several interesting conclusions may be drawn from these tests regarding the overall behavior of the Millikan Library building. A surprising amount of soil-structure interaction is evident for N-S shaking. The translation of the basement slab contributed 4 percent and the average base rotation contributed 25 percent to the translation of the roof. Consequently, soil-structure interaction plays an important part in the behavior of the structure in the N-S direction. It was found that the behavior of channel-shaped shear walls at the east and west end of the building behaved much like Euler beams with shearing deformation included. This is seen in figure 1(a). For shaking in both directions, the vertical load carrying system interacted significantly with the lateral load carrying system. This is most evident in figure 1(c). Here the central core behaves as a bending beam; but the walls at the east and west ends of the building resist the vertical motion of the edges of the slab caused by the bending deformation of the core. The result is a pattern of deformation typical of shear wall-frame interaction. Thus, the results of these tests indicate that similar experiments could be used on some other complex structure to gain valuable information about the interaction of its various subsystems.

Tests of the Parsons Building

An extensive series of forced vibration tests of the Ralph M. Parsons Company World Headquarters building was completed in May 1976. This is a twelve-story steel frame building located in downtown Pasadena, California. Figure 2(a) is a picture of the east elevation of the buildings and figure 2(b) is a schematic plan view of the buildings. The headquarters is actually composed of three buildings. Two identical four-story satellite structures are located to the northeast and northwest of the main building. The main building is composed of a large four-story portion at the south and a twelve-story tower that is roughly octagonal in shape on the north side. Lateral loads are resisted by moment resisting steel frames indicated by heavy lines in figure 2(b). The vertical load carrying system is not shown. Natural frequencies and damping values for nine modes are listed in Table 1.

One phenomenon that is being studied through the tests of the Parsons building is modal interference. This occurs when natural frequencies, most often translation and torsion, lie close together. This has previously been observed experimentally[3] and its effects have been studied, to a certain extent, theoretically.[4, 5] One of the problems that arises due to modal interference is that torsional motions are excited as well as translational motions, even if only horizontal excitation is applied to the structure.

Considerably larger stresses may be experienced by the outer columns when this occurs. An example for the Parsons building occurred for E-W shaking near the third natural frequency for torsional motion which was about 2.0 Hz. It was observed that the north edge of the building moved at an amplitude of approximately seven times that of the south edge; and the amplitude at the north edge was nearly 75 percent of the amplitude it would have experienced had the building been shaking at its third E-W resonance frequency of about 2.6 Hz. This suggests that for earthquake response the outer columns might experience up to 75 percent higher stress due to these torsional motions than one might expect for purely translational response. It is uncertain whether current or proposed code provisions adequately account for effects of this type.

Figure 2(c) shows resonance curves measured at the geometric center of the roof for N-S shaking at five different force levels. The exciting force ranged in magnitude from about 15 pounds (SO-LO) to about 209 pounds (S4-L4). The peak in the resonance curve occurs at lower frequencies as the amplitude of the force increases. This indicates a softening nonlinear system. Similar curves were obtained for nine modes of the structure (three N-S, three E-W, and three torsional). Detailed measurements were taken on eleven floors for three levels of excitation to determine if the apparent three-dimensional mode shapes change with amplitude and resonant frequency measurements. These measurements included some at grade level which indicated linear foundation compliance in a preliminary analysis. A detailed analysis of the results is in preparation.[6]

One goal of these tests was to assess the reliability of current modeling practices to predict the stresses in structural members for a given loading condition. To aid in this assessment, measurements of strain in one of the columns were taken during forced excitation of the building. The strains were easily measurable with a linear variable differential transformer. The indicated stresses were approximately 20 psi. A comparison of measured values and some predicted mode shapes and frequencies for a finite element model of the N-S moment resisting frames are shown in figure 2(d). These results indicate that the observed first three natural frequencies are 20, 26 and 27 degrees higher, respectively, than the calculated values. The mode shapes are also somewhat different for the second and third modes. The differences are probably due to the complex interaction of the structural and nonstructural systems and possibly the influence of the satellite structures upon the response of the main building. The computed results may actually be more representative of the characteristics of the building during an earthquake, since it is not uncommon for the natural periods of a building to lengthen by 20 to 30 percent during the large amplitudes of vibration experienced during response to strong motion.

Concluding Remarks

These studies have indicated that considerably more knowledge concerning the overall dynamic behavior of full-scale structures may be gained from forced vibration tests than has previously been attempted. Using the discussed procedures, one could determine accurately the appropriate finite element model of a "clean" structural system. However, the presence of nonstructural systems, which add considerable stiffness at these low levels of excitation, preclude an accurate quantitative evaluation of a particular finite element model of the structural components of the building. Consequently, full-scale large amplitude tests are needed. With these tests we could evaluate the ability of linear finite element models to predict the behavior of a building up to the time of incipient yielding or damaging of its structural members. It would be even more beneficial to shake a well-instrumented structure to the point of collapse. The information gained about the collapse mechanism and the energy absorption capacity of a real structure would be extremely valuable to structural engineers. It is not possible, of course, to make large amplitude tests on many full-scale structures, but a few tests of this type are needed to serve as a focal point for dynamic tests on shaking tables, repeated load tests on structural elements and other experimental research directed toward understanding earthquake response of buildings.

References

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Table 1. Natural frequencies and damping coefficients for nine modes of vibration of the Ralph M. Parsons Co. World Headquarters Building.

N-S TRANSLATION			E-W TRANSLATION			TORSION		
Mode	Frequency Hz	Damping % Critical	Mode	Frequency Hz	Damping % Critical	Mode	Frequency Hz	Damping % Critical
1	.523	2.5	1	.566	4.1	1	.612	4.0
2	1.36	4.8	2	1.57	6.4	2	1.38	4.8
3	2.13	4.1	3	2.57	4.4	3	2.02	-I

I not able to determine due to modal interference

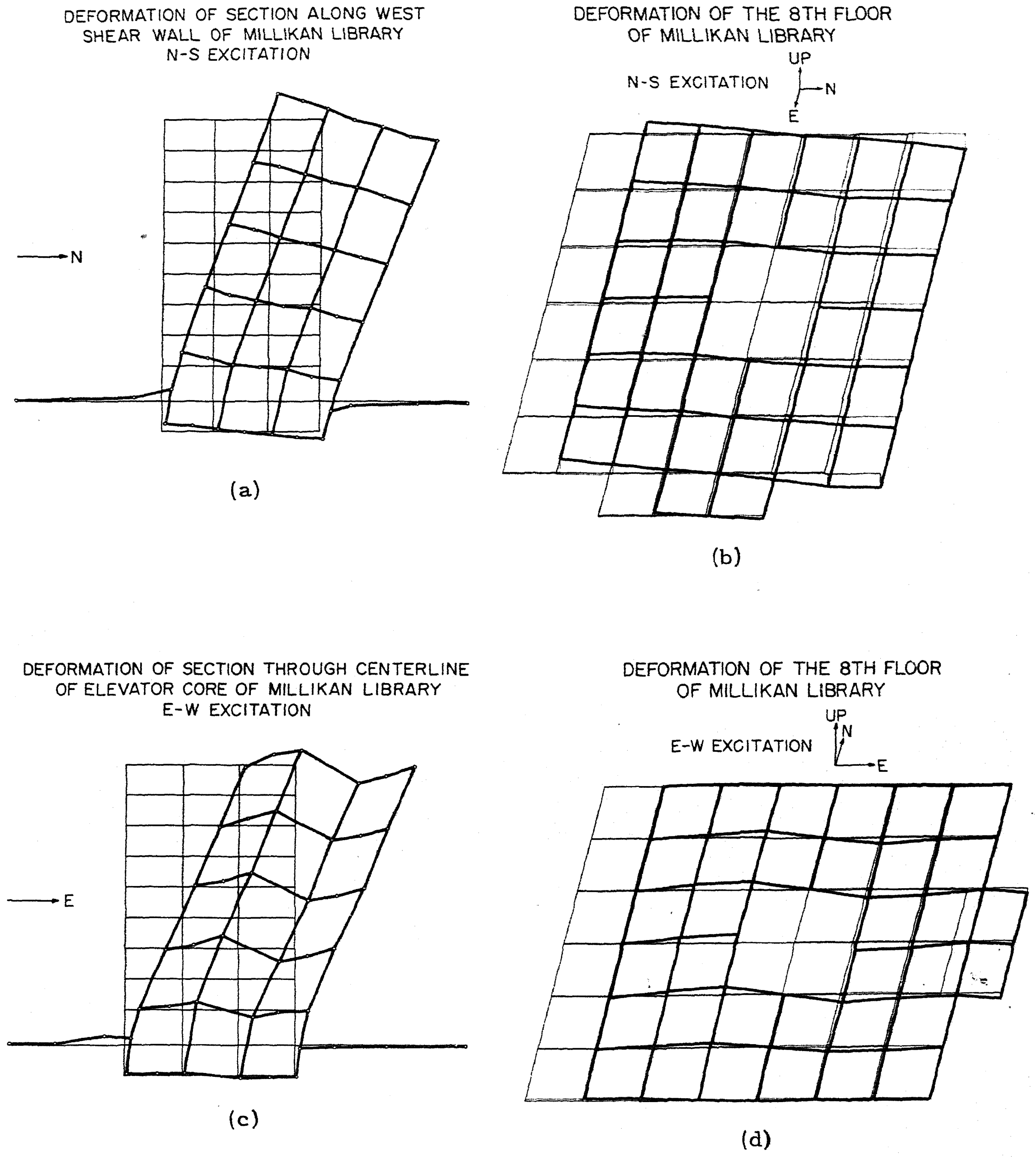
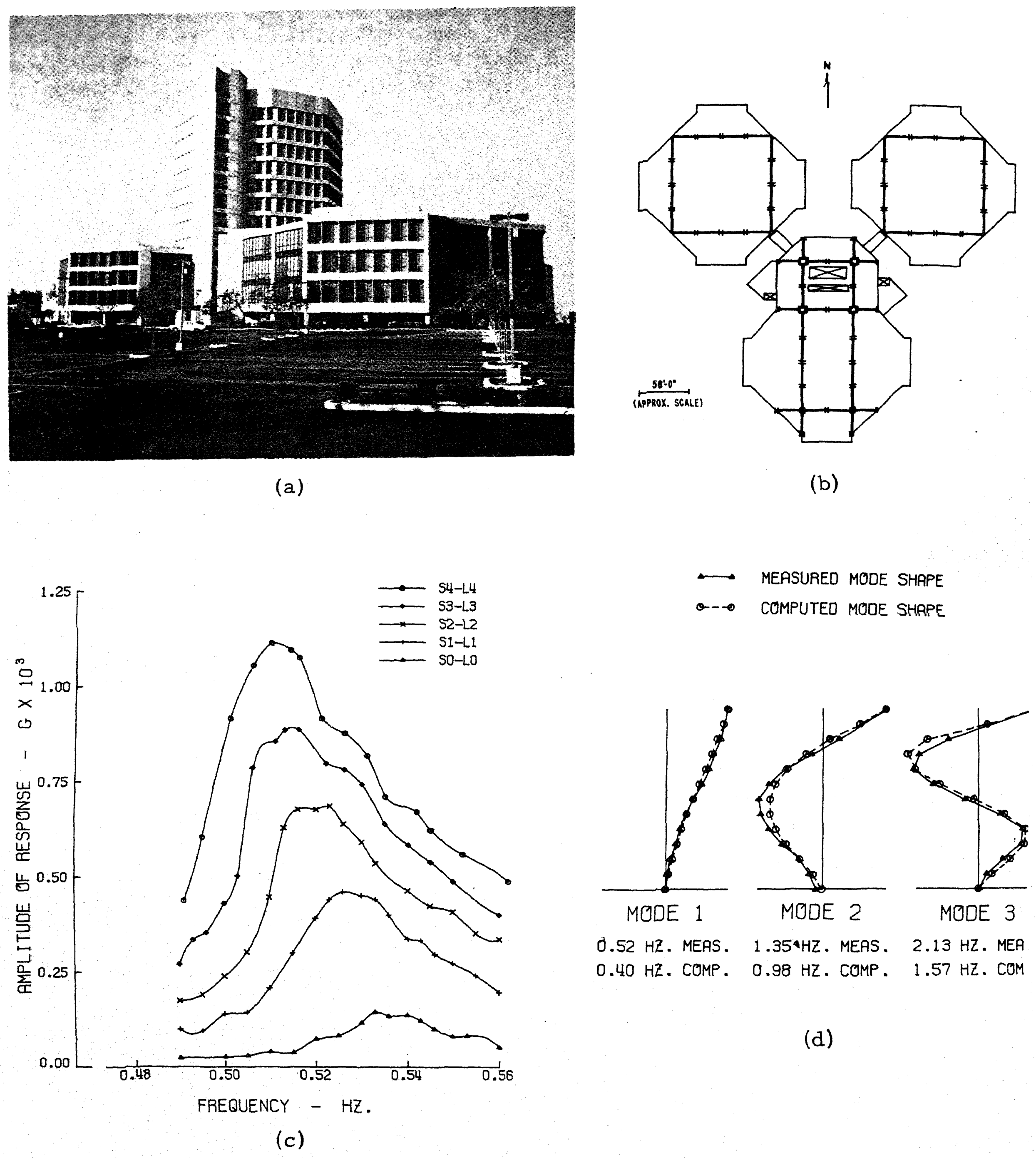


Figure 1. Plots of deformations measured during forced vibration tests of Millikan Library building.



(a)

(b)

(c)

(d)

Figure 2. (a) East elevation of Ralph M. Parsons Co. World Headquarters building; (b) Schematic plan view of Headquarters Complex; (c) Resonance curves measured at roof of tower for five levels of excitation in the N-S direction; (d) Comparison of measured and computed frequencies and mode shapes for the N-S direction.