DYNAMIC PROPERTIES OF PREFABRICATED APARTMENT BUILDINGS

by

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SYNOPSIS

The paper describes the results of experimental forced and ambient vibration studies of a 12-story apartment building, constructed with prefabricated wall panel and slab elements. Dynamic characteristics, such as resonant frequencies, vertical and horizontal mode shapes and damping capacities of the structure are presented and correlated with analytical studies using the computer program TABS. The fundamental periods of this structure and of an 8-story apartment building with basically the same floor plan and construction are also presented.

INTRODUCTION

For the last 15 years, a number of full-scaled tests using both forced and ambient vibration techniques have been conducted on multistory structures with distinctly different structural systems (1,2). The collected dynamic data have been used to evaluate the accuracy of analytical modelling and computer programs used in predicting the structural response to known vibration inputs. This led to improved computational procedures and resulted in more reliable predictions of the structural response to actual earthquake ground motions. In order to gain information about the dynamic behaviour of prefabricated apartment buildings, field tests have been performed on the 8-story Los Partales Building and the 12-story Wesley Manor Building located in Oakland and Campbell, California, respectively.

DESCRIPTION OF THE WESLEY MANOR BUILDING

The 105 foot high building (Fig. 1) has an overall plan of approximately 80 by 164 feet. It is designed as a housing development and is therefore modular in concept. The foundation layout and typical floor plan are shown in Figures 2 and 3, respectively. The building is serviced by two elevators, located in the center, and two stairwells on the north side at either end of the structure. The structure is a "Forest City Dillon" prefabricated building system. The vertical and horizontal load-carrying system consists of reinforced concrete shear walls in both the transverse and the longitudinal directions. These walls rise from the first floor and run upward to the roof in the same dimensions. On the first floor, there are some openings in the walls as noted by solid lines on the foundation plan (Fig. 2). These wall elements rest on spread footings which in turn are placed on 24" diameter piles varying in length from about 30 to 52 feet.

The "Forest City Dillon" system uses solid reinforced floor elements and hollow wall elements. The floor elements have a thickness of 4" and plan dimensions of 8 by 22 feet. At the site, a 4" concrete topping is placed on these elements, with reinforcing at the joints between single floor elements. Preassembled kitchen and bathroom units have an 8" thick slab and are constructed so that reinforcing bars protrude enough to tie into the 4" topping of the adjacent floor panels. The cells of the wall panel elements are reinforced and filled with concrete. Fig. 6 shows a

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typical wall panel element with reinforcing. Examples of an exterior and interior joint are shown in Fig. 7.

EXPERIMENTAL STUDIES

Forced vibrations were produced by two rotating mass vibration generators mounted on the twelfth floor at the center of the east and west sides of the building. Linear accelerometers ($\pm 0.25g$) were used to measure the horizontal floor accelerations. Frequency-response curves were determined by increasing the frequency incrementally and measuring the vibration response of the structure at each step. Frequency-response data for different forcing directions and levels of excitations are shown in Figure 4. Using the bandwidth method damping capacities may be found from the normalized frequency-response curves near resonances as $\zeta = \Delta f/2f$, were f = resonant frequency, and Δf = frequency difference of two points on the response curve with amplitudes of $1/\sqrt{2}$ times the resonant amplitude. Once the resonant frequencies have been found, the mode shapes at each of these frequencies may be determined. Typical mode shapes are shown in Fig. 5. The vertical mode shapes in Fig. 5 show the relative motions at the center and the west end of the building. The horizontal floor modes for the 6th and 12th story are plotted to the right of the corresponding vertical mode shape. Six accelerometers were used to detect the horizontal mode shapes. The floor slab behaved basically as a rigid diaphragm; an observation used specifically in the development of the analytical model of this structure.

The ambient vibration study of dynamic properties uses field measurements based on wind and micro-tremor induced vibrations. An assumption in the analysis technique is that the exciting forces are a stationary random process possessing a reasonably flat frequency response spectrum. A structure subjected to this input will respond in all its normal modes. Wind produces the largest ambient vibrations for multistory structures. The wind induced vibrations were measured using Seismometers. Modal frequencies were obtained by seismometers placed near the outer walls on the north, south, east, and west sides of the 12th floor of the building. The orientation of the seismometers on the north and south sides allowed evaluation of the E-W frequencies; those on the east and west sides the N-S frequencies. In this way, translational frequencies were obtained by averaging the sum of the seismometer readings and torsional frequencies by averaging the difference of those readings. For measurement of the translational and torsional modes, two of the seismometers remained at the twelfth floor and two were placed in pairs at each successive floor. As in the case for determining the modal frequencies, the sum of the two seismometers was averaged to give the translational modes and the difference of the seismometers was averaged to give the torsional modes. Fourier transforms were used to analyze the low level structural vibrations and, thus, to identify the modal frequencies. Comparing vibration amplitude and phase for various floor levels provides an estimate of the mode shape.

The resonant frequencies obtained from the forced vibration tests are in the average 3% smaller than those from the ambient vibration tests and are compared in Table 1. This nonlinear aspect may be due to larger excitations under forced vibrations. The ambient vibration tests gave an equivalent viscous damping factor, determined by using the bandwidth method, of about 1%.

ANALYTICAL MODEL

An analytical computer model of the Wesley Manor Building was developed to assess the dynamic characteristics. The model was formulated using both a rigid and a flexible base. TABS, a general purpose computer program, was used to calculate the frequencies and mode shapes of the structure. The program considers the floors to act as rigid diaphragms with zero transverse stiffness. All elements are assembled initially into planar frames and then transformed, using the rigid-diaphragm assumption to three degrees of freedom (2 translational and 1 rotational) at the center of rigidity or each story level.

The basic model of the building was formulated as a system of frames and shear wall elements interconnected by floor diaphragms which were rigid in their own plane and fixed at the first floor level. All walls were treated as "wide columns". This required a reduction of properties (I, A) to the elastic centroid of each wall. Moments of inertias of the shear walls included flange areas, with a maximum effective width of one third of the building height or 35'. A value of 4,000 ksi was used for the modulus of elasticity of the concrete and 29,000 ksi for the reinforcing steel. The reinforcing steel area was included in calculating the moment of inertia of the shear walls. Wherever shear walls were positioned in one line parallel to the direction of motion, it was assumed that those walls would be coupled by a portion of the floor slab, which was chosen to be 18 times the thickness of the floor. The effective span of the coupling girders were identical to the clear distance between the walls. Also, the effective height was taken as the clear height between two stories. Fig. 9 shows how two panel elements were idealized for the analytical model.

During the experimental phase of the work, significant horizontal motion was recorded at the first floor level. Therefore, a second analytical model was developed to reflect the flexible base condition. Based on the measurements of the horizontal ground accelerations and the base rotations, estimated from the mode shapes, the following approach was used. The measured floor accelerations times the floor masses gave the elastic forces for each floor level, from which the base shear and the overturning moment could be computed. Comparing base shear and moment with the experimentally determined displacement and rotation at the first story allowed an assessment of the translational and rotational stiffness of the foundation for both directions. An additional dummy base story with stiffness properties as calculates was added to the structure to account for foundation and soil flexibility.

The frequencies for the rigid base model, as well as for the flexible base model, are compared with the experimental results in Table 1. Good agreement with the experimental frequency values can be noted for the model with flexible base, although it seems that the real foundation is stiffer than the "dummy story".

CONCLUSIONS

The results presented herewith clearly show that forced and ambient vibration studies can be carried out effectively. In comparing experimental and analytical solutions, good agreement can be noted for frequencies and mode shapes. Only the three fundamental modes of vibration could be found from the forced (up to 6.75 H_z) and ambient vibration tests (up to 20 H_z), thus indicating that the building would respond in a first mode motion to seismic excitation. The predominant feature which came out of the dynamic tests was the high coupling between E-W and torsional modes. This highly coupled response indicates the need to revise the floor plan in order to separate the modes. The same behavior was observed during the tests of the 8-story Los Portales Building with almost the same floor plan. The periods of the two structures are plotted versus building height and reveals, as shown in Fig. 8, an almost linear increase with height.

The frequencies for a standard code analysis, based on overall building dimensions, are 22% low in the N-S (transverse) direction and 40% high in the E-W (longitudinal) direction. These inconsistent results clearly indicate the need for a detailed dynamic analysis, considering the actual wall layout, stiffness distribution, and foundation conditions. Neglecting the foundation flexibility, as done in the rigid base model, yields an overestimation of the frequencies by 30% to 50%. Thus, in the analysis of rigid structures on flexible foundations, the soil-structure interaction must be considered.

ACKNOWLEDGEMENT

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TABLE 1

	Experiment		Analysis		
Forcing Direction	Forced Vibration	Ambient Vibration	Rigid Base	Flexible Foundation	Code
E-W/Torsion	1.76	1.82	2.27	1.67	—
E-W/Torsion	2.08	2.14	2.74	2.15	2.44
N-S	2.18	2.24	3.14	2.12	1.69

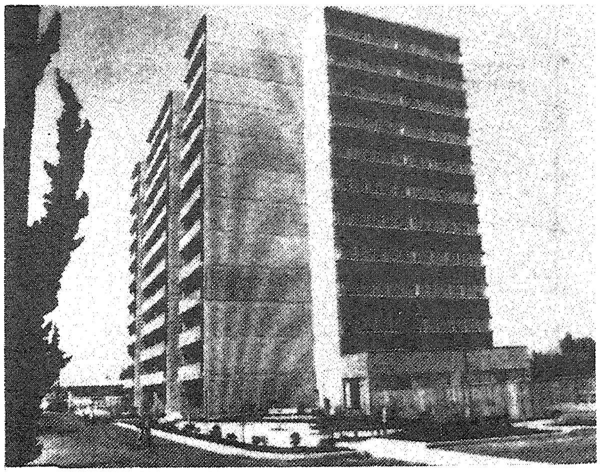

FIG. 1 WESLEY MANOR BUILDING, CAMPBELL, CA

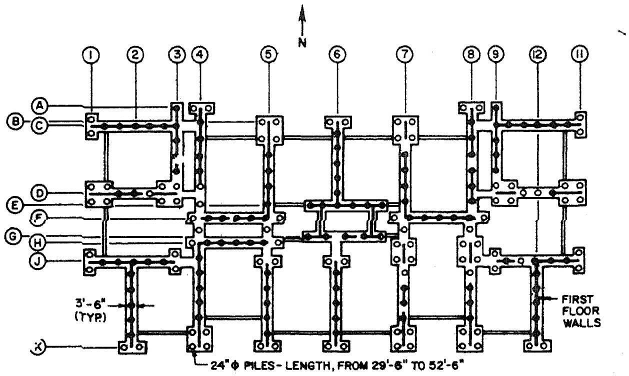

FIG. 2 FOUNDATION PLAN

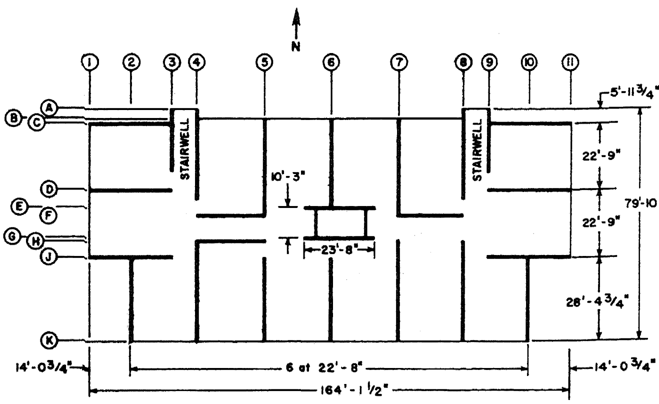

FIG. 3 TYPICAL FLOOR PLAN - 2ND THRU 12TH FLOORS

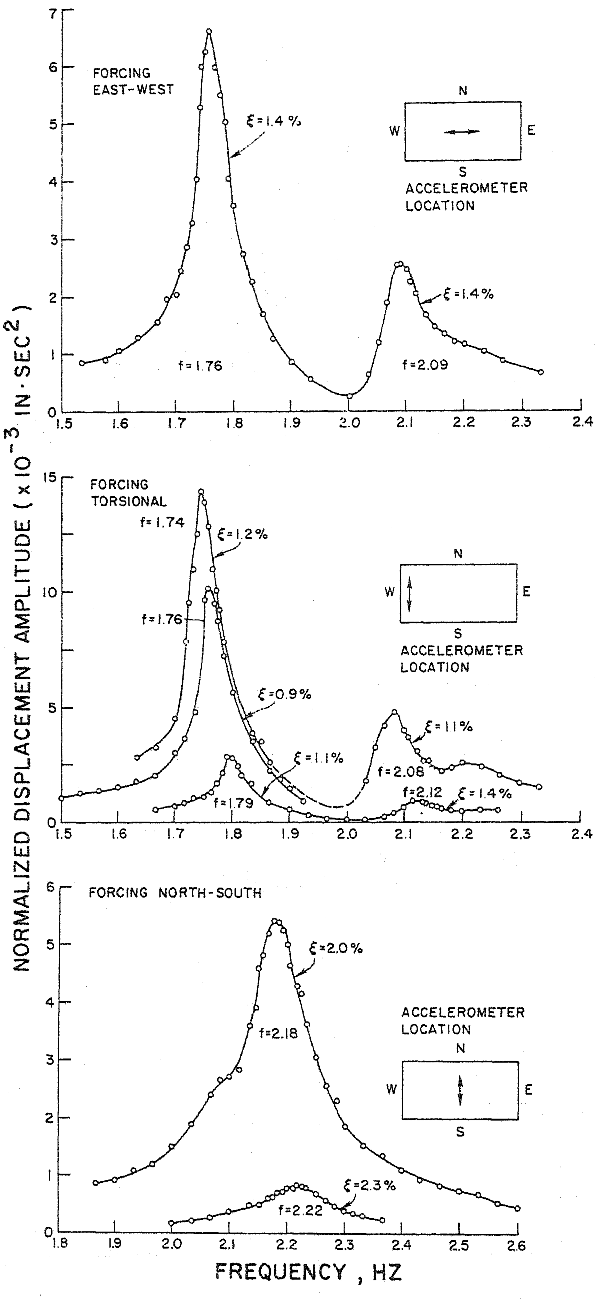

FIG. 4 FREQUENCY RESPONSE CURVES

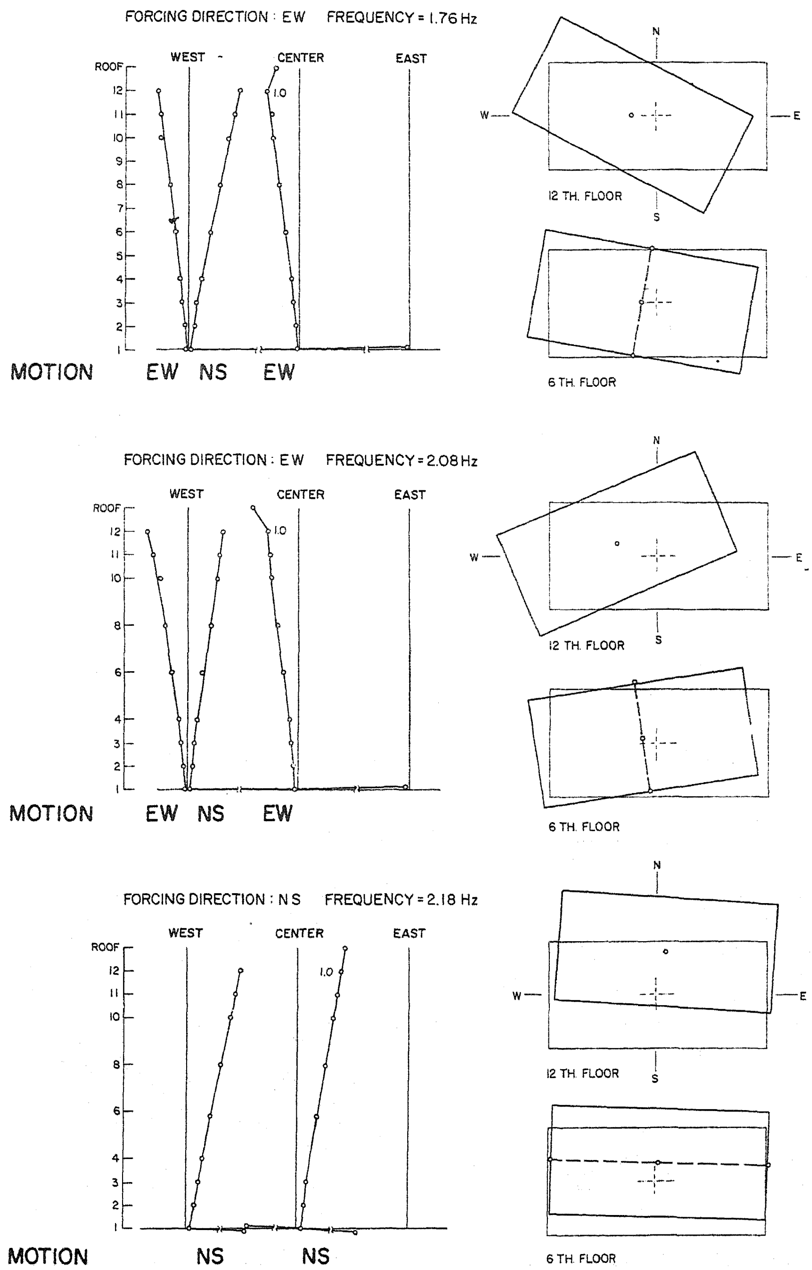

FIG. 5 TYPICAL MODE SHAPES

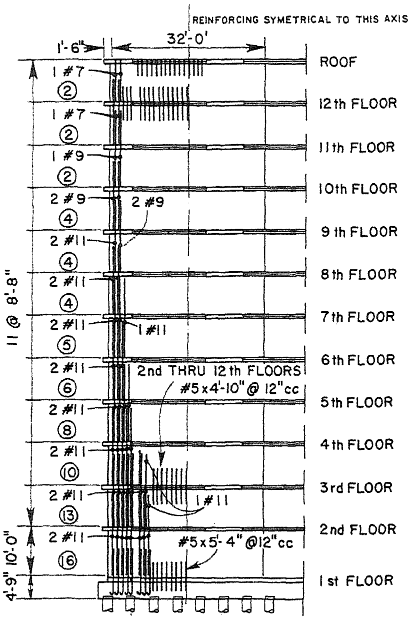

FIG. 6 TYPICAL WALL-FLOOR JOINT CONNECTION

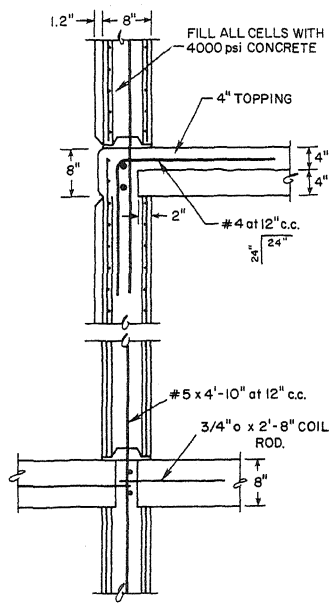

FIG. 7 TYPICAL WALL PANEL ELEMENT

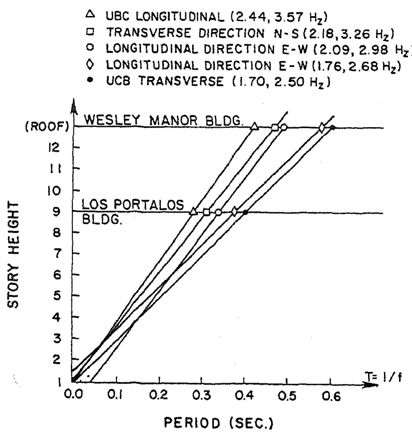

FIG. 8 PERIOD VS STORY HEIGHT

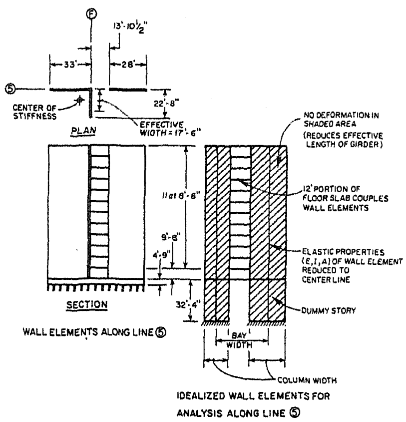

FIG. 9 TYPICAL WALL ELEMENTS