

# SMIP90 Seminar Proceedings

## EVALUATION OF LATERAL FORCE PROCEDURES FOR BUILDINGS

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### ABSTRACT

The recent edition of building codes for earthquake resistant design specify a dynamic analysis procedure for computing lateral forces on buildings with irregular plan or vertical irregularities. This paper presents the use of the instrumented response of two buildings to strong ground motion for determining vibration properties and distribution of lateral forces. The two buildings were selected for the irregular features in their configuration, and the results illustrate the difference in lateral force distribution for type of building and amplitude of earthquake response.

### INTRODUCTION

The determination of lateral earthquake forces acting on a building is a critical part of earthquake resistant design. The lateral forces depend on the dynamic characteristics of the building (mass, stiffness, strength, damping, and energy absorption) and the characteristics of the ground motion (amplitude, frequency content, and duration). The detailed modeling and analysis of a building for computing lateral forces is not practical, particularly in the early stages of a design. The current lateral force requirements developed by SEAOC [7] and incorporated in the 1988 Uniform Building Code [5] prescribe two methods for determining lateral forces:

- Static Lateral Force Procedure - Compute the maximum base shear using a design ground motion spectrum and distribute the base shear over the height of the building.
- Dynamic Lateral Force Procedure - Using a ground motion spectrum and a mathematical model of the building, compute the internal forces and displacements of the building from a response spectrum or time history analysis. For most buildings the response may be scaled such that the base shear is not greater than the base shear determined from the static lateral force procedure.

The dynamic lateral force procedure is a new requirement from earlier versions of the code. The new provisions recognize the poor earthquake performance of buildings with irregular configuration compared to buildings with regular configuration. The dynamic lateral force procedure is mandatory for buildings with a configuration that would invalidate the assumption that the response is primarily due to the fundamental mode of vibration, which is inherent in the static lateral force procedure.

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The Applied Technology Council committee 3-06 report, now incorporated in the NEHRP recommended provisions [6], introduced the concept of building configuration for determining lateral forces on buildings. An irregular configuration has significant discontinuities in the mass or stiffness of the lateral force resisting system, or eccentricity of mass or stiffness. For the purpose of evaluating configuration, structural irregularities are classified by features in the vertical direction or in plan; the code provides lists of specific irregular features. Other characteristics of the building and ground motion may invalidate the use of the static lateral force procedure, such as participation of higher vibration modes, different lateral force resisting systems in orthogonal directions, and directional effects of the ground motion, particularly in buildings with closely coupled vibration modes. Although the dynamic analysis provisions for buildings with irregular configurations is a positive development in seismic design, the equivalent lateral force procedure is not always rational even for buildings with uniform mass and stiffness because of the contributions of the higher vibration modes [1] or because of torsional response.

The purpose of this study is to use the recorded earthquake response of buildings to determine the distribution of lateral forces and compare the distribution to the building code provisions. This paper presents an evaluation of the earthquake response of two buildings.

### SELECTION OF INSTRUMENTED BUILDINGS

Seventy-one building/earthquake records from the California Strong Motion Instrumentation Program (CSMIP) of the Division of Mines and Geology were examined for configuration and earthquake response that may be characteristic of irregular buildings. Several parameters were collected for each building/earthquake including in the preliminary screening: number of stories and story heights, aspect ratio in plan, peak acceleration amplification factors between the roof and ground in each principal direction, classification of vertical and plan irregularity according to the code definitions [5,7], and observation of torsion, higher mode contributions or beating in the response records. Most the buildings instrumented by CSMIP are regular, however twelve buildings have at least one irregular feature, of which four had two irregular features. Two buildings were selected for detailed study; coincidentally both are hospitals.

### BUILDING ONE - FOUR STORY HOSPITAL

The four story medical center is located in South San Francisco. Figure 1 shows the structural configuration of the building. The gravity load system consists of a lightweight concrete slab on metal decking supported by floor beams. The lateral force resisting system is a structural steel moment resisting frame. The foundation for each column consists fifty to seventy foot piles; grade beams connect the pile caps and support an eight inch slab. The building is instrumented with eleven acceleration transducers at the locations shown in Figure 1.

The CSMIP documentation [2,4] describes the first floor walls as a "shear walls," which would constitute an vertical irregularity because of the abrupt

change in stiffness of the lateral force resisting system. Examination of the building plans, however, show that the wall is an architectural barrier and there is no structural connection between the wall and the moment resisting frame (there is transverse support for the wall) so there is no vertical irregularity in the lateral force resisting system. One of the interesting features of the earthquake response is whether the wall participates in resisting lateral forces as a nonstructural component; the earthquake response records shed some light on this question. In plan, the re-entrant corners are approximately 15% of the length in the longitudinal direction which is on the borderline of constituting a plan irregularity [5,7].

At the beginning of the study response records were available for the 1984 Morgan Hill earthquake [4]. During the course of the study, the instruments triggered in the 1989 Loma Prieta earthquake and the processed response records have just become available [2].

### Morgan Hill Earthquake

The unprocessed records are shown in Figure 2(a) and the peak total accelerations are listed in Table 1. Figures 3 and 4 show two sets of the transmissibility functions for total acceleration in each direction: (i) between the roof and ground level; and (ii) the second level and ground. The transmissibility functions are the ratio of the Fourier transform of the corrected acceleration records computed over two time windows. The first time window, zero to fifteen seconds, shows the response before the strong response, and the second time window, fifteen to forty seconds contains the strong ground motion and response. The transmissibility functions for frequencies less than one-half Hertz have not been considered in the interpretation.

The vibration periods and damping ratios for the lower mode in each direction are obtained using the half-power bandwidth method; the values are tabulated in Table 2. The periods lengthen slightly in the strong motion phase and the damping ratio in the longitudinal direction increases because of the larger amplitude of motion. Based on the strong motion response, the  $C_t$  coefficient is 0.029, compared to 0.035 for the code procedure for determining vibration period. The larger amplification of the response between the 2nd floor and roof and the lower vibration mode shapes (Figure 5) obtained from the transmissibility functions indicate that the nonstructural wall in the first level is providing some lateral stiffness for the relatively low amplitude response.

### Loma Prieta Earthquake

The unprocessed records from the Loma Prieta earthquake are shown in Figure 2(b) and the peak responses are also listed in Table 1 [2]. The ground motion and building response was significantly greater in Loma Prieta than in Morgan Hill, yet there was no damage to the structural or nonstructural components of the building<sup>1</sup>. The transmissibility functions computed from the processed records for two time windows are shown in Figure 4 for two time windows: (i) zero to nine seconds, and (ii) nine to twenty six seconds. Based

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<sup>1</sup> Personal communication with a structural engineer engaged who inspected the building after the Loma Prieta earthquake.

on these functions, the periods are listed in Table 2. The damping was larger than in the Morgan Hill earthquake as can be seen by comparing the peaks of the transmissibility functions between Figures 3 and 4, but the half-power bandwidth method does not give reliable values because of the closely correlated modes. The large amplitude of the response results in significantly longer periods than for the Morgan Hill earthquake, and the  $C_t$  coefficient of 0.036 compares favorably with the code value. The fundamental mode shape in each direction (Figure 6) clearly shows the first floor wall does not resist lateral forces because the shape is typical for the racking mode shape of a frame structure.

### Mathematical Model and Computed Response

A mathematical model of the linear response of the structural components has been developed based on the plans for the medical center. Although space limitations preclude presentation of the results, close correlation between the measured and analytical response was obtained when mass eccentricity is included. This appears necessary because the symmetrical distribution of stiffness does not explain the coupled modal response and beating apparent in the recorded response.

### BUILDING TWO - SIX STORY HOSPITAL

This six story hospital in Sylmar has a rectangular plan in the lower two floors and a cruciform plan in the upper four floors (Figure 7). The floor system is concrete slab on metal decks. The lateral force resisting system consists of concrete shear walls in the lower two stories and steel shear walls in the upper four stories. The structure has both plan and vertical irregularities according to the code definitions.

The building was instrumented with sixteen acceleration transducers in the 1987 Whittier earthquake (although one malfunctioned) [3]. The large stiffness of the lower two floor is clear from the mode shapes obtained from the transmissibility functions (Figure 8), where the relative amplitude of the vibration mode between the third floor and roof is larger than between the base and the third floor.

### CONCLUSIONS

The earthquake response records of two hospital buildings with irregular features illustrate the effect of lateral force distribution and the sensitivity to the amplitude of ground motion. More detailed results in the final report will show the correlation with analytical response and compare the lateral force distributions to the provisions of the building codes.

### ACKNOWLEDGEMENTS

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2. CSMIP Strong-Motion Records from the Santa Cruz (Loma Prieta) Earthquake of 17 October 1989, Report OSMS 89-06, California Department of Conservation, November, 1989.
3. CSMIP Strong-Motion Records from the Whittier Earthquake of 1 October 1987, Report OSMS 87-05, California Department of Conservation, October, 1987.
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5. International Conference of Building Officials, *Uniform Building Code*, 1988 Edition, May, 1988.
6. National Earthquake Hazards Reduction Program, "Recommended Provisions for the Development of Seismic Regulations for New Buildings," Part 1 and 2, FEMA/95, Federal Emergency Management Agency, February, 1986.
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Table 1 - Maximum Total Acceleration of Building One - Four Story Hospital in the 1984 Morgan Hill Earthquake and the 1989 Loma Prieta Earthquake

Earthquake	Maximum Response	Transverse Direction	Longitudinal Direction
Morgan Hill	Roof Acceleration (g)	0.17	0.11
	Base Acceleration (g)	0.03	0.02
	Roof/Base Acceleration	5.7	5.5
Loma Prieta	Roof Acceleration (g)	0.61	0.57
	Base Acceleration (g)	0.16	0.14
	Roof/Base Acceleration	3.8	4.1

Table 2 - Lower Vibration Mode Properties of Building One - Four Story Hospital in the 1984 Morgan Hill Earthquake and the 1989 Loma Prieta Earthquake

Earthquake	Time Window	Vibration Property	Transverse Direction	Longitudinal Direction
Morgan Hill	First	Period (sec)	0.54	0.54
	(0-15 sec)	Damping Ratio	0.028	0.028
	Second	Period (sec)	0.57	0.56
	(15-40 sec)	Damping Ratio	0.029	0.044
Loma Prieta	First	Period (sec)	0.65	0.61
	(0-9 sec)	Damping Ratio	(a)	0.055
	Second	Period (sec)	0.71	0.71
	(9-26 sec)	Damping Ratio	(a)	(a)

(a) Could not be determined because of closely spaced modes.

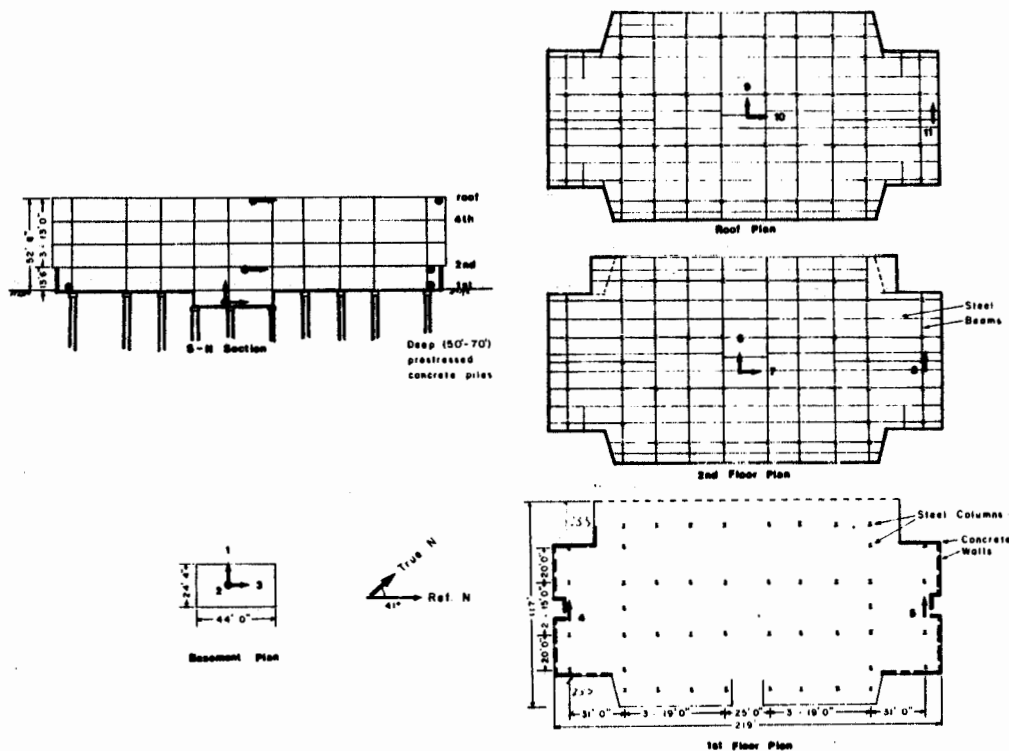
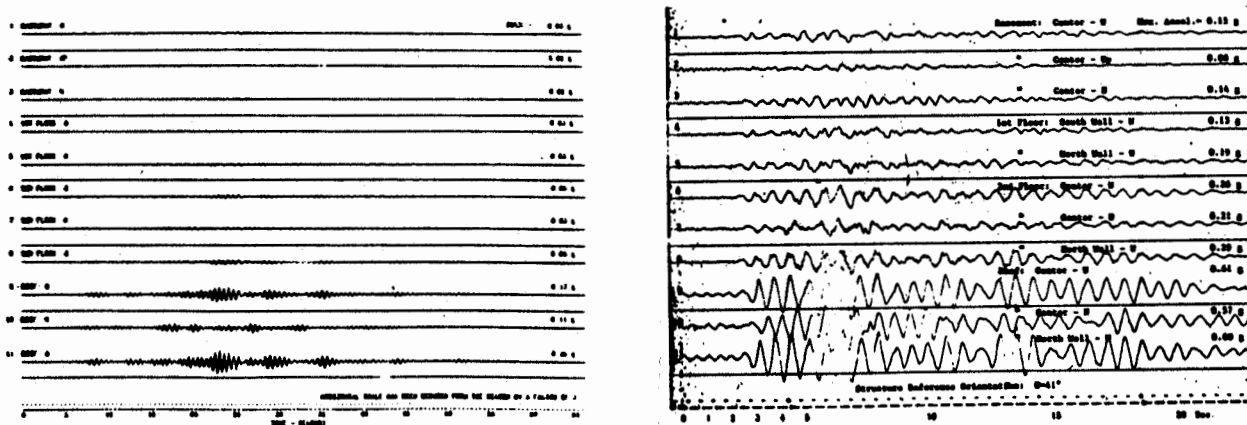


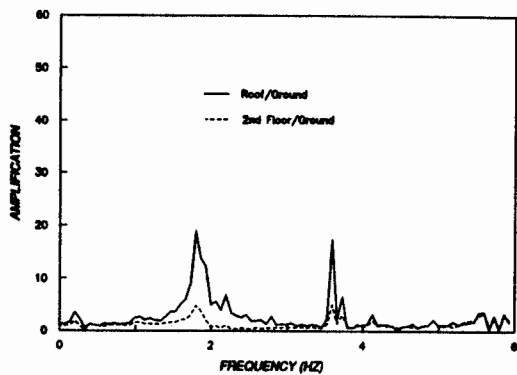
FIGURE 1. Structural Configuration and Instrumentation for Building One - Four Story Hospital [2,4]



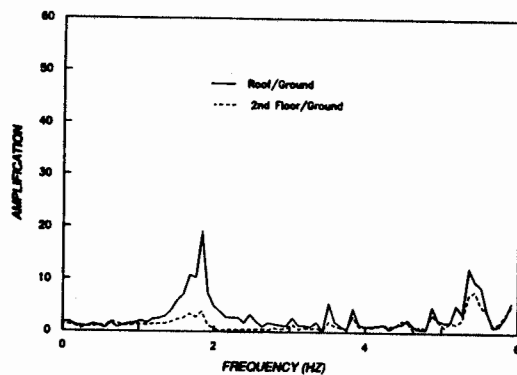
(a) 1984 Morgan Hill Earthquake [4]

(b) 1989 Loma Prieta Earthquake [2]

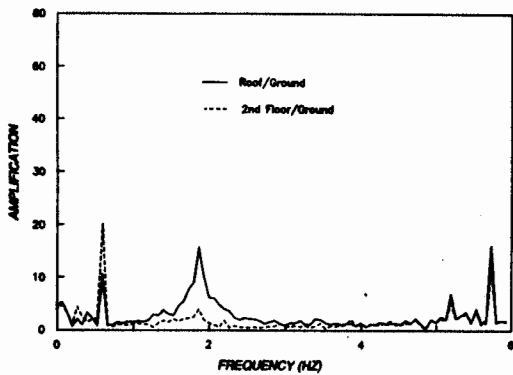
FIGURE 2. Unprocessed Response Records for Building One - Four Story Hospital



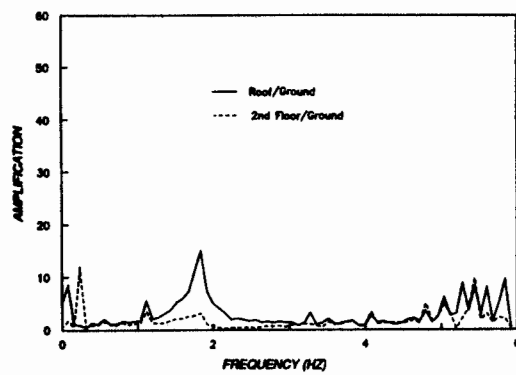
(a) Transverse Direction, 0-15 sec



(b) Transverse Direction, 15-40 sec

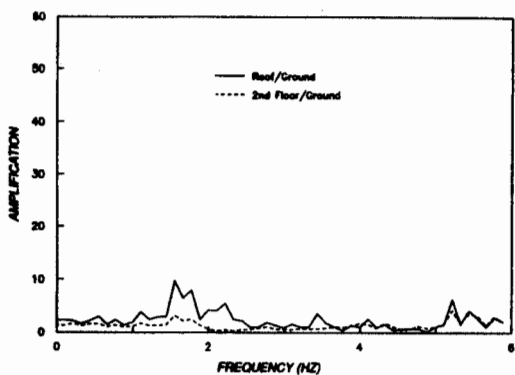


(c) Longitudinal Direction, 0-15 sec

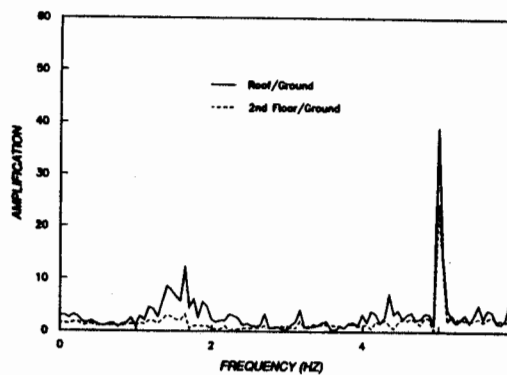


(d) Longitudinal Direction, 15-40 sec

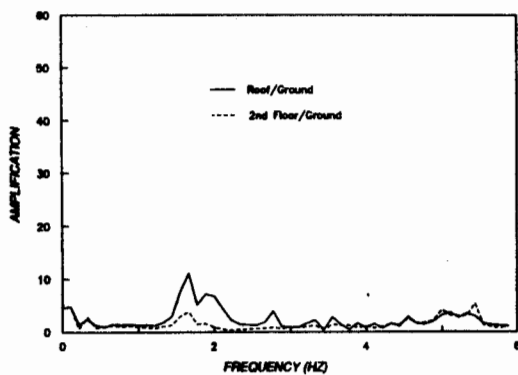
FIGURE 3. Transmissibility Functions for Building One - Four Story Hospital for the 1984 Morgan Hill Earthquake



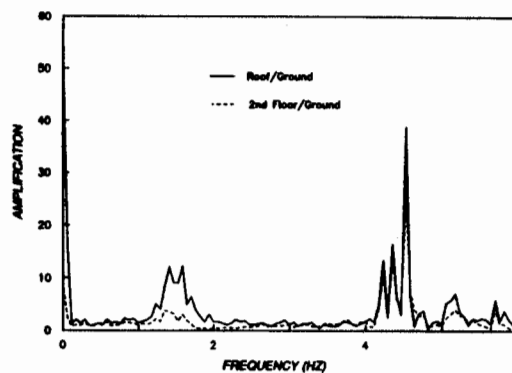
(a) Transverse Direction, 0-9 sec



(b) Transverse Direction, 9-26 sec



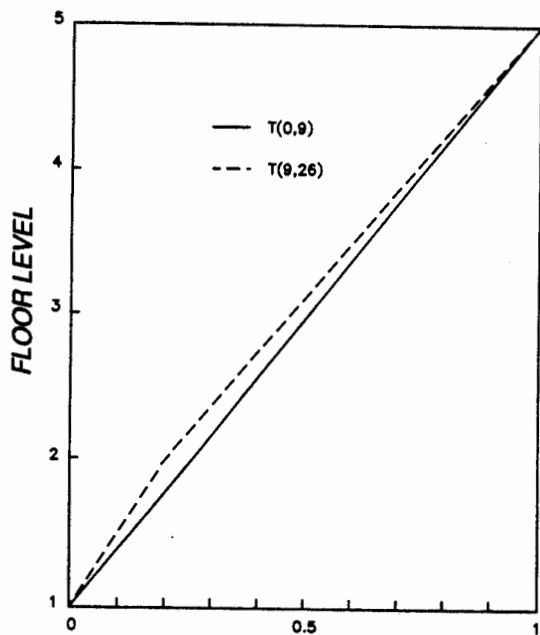
(c) Longitudinal Direction, 0-9 sec



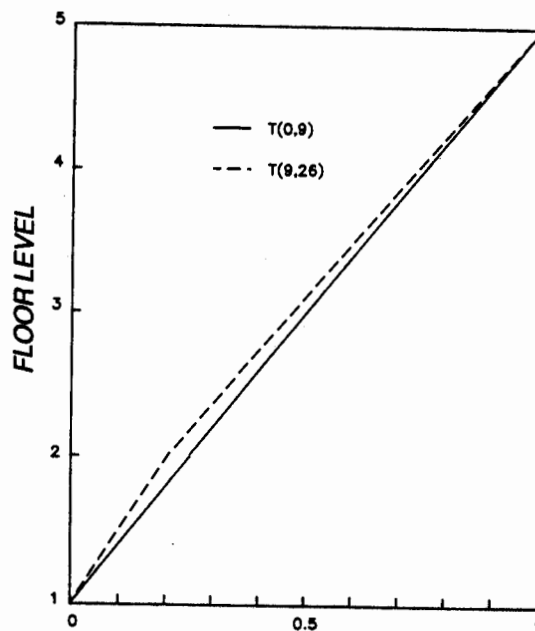
(d) Longitudinal Direction, 9-26 sec

FIGURE 4. Transmissibility Functions for Building One - Four Story Hospital for the 1989 Loma Prieta Earthquake



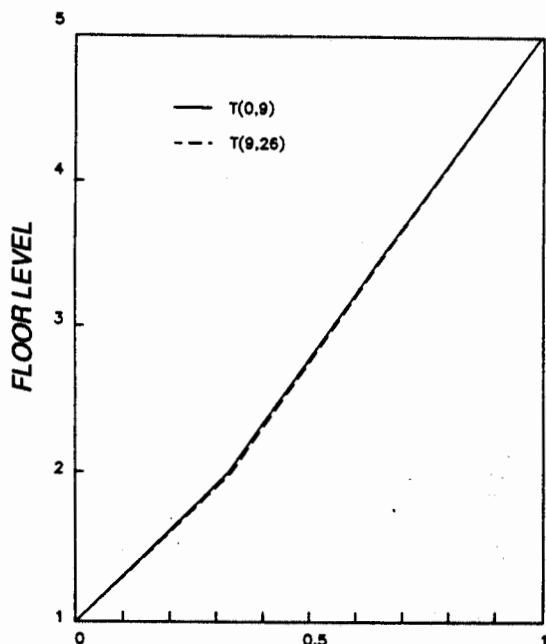


(a) Transverse Direction

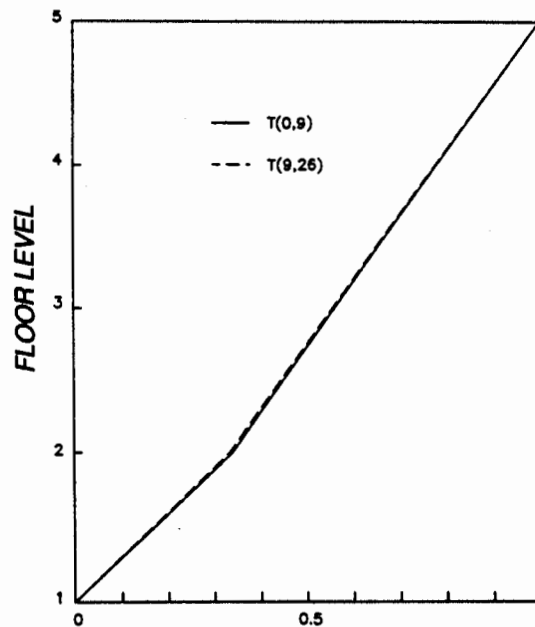


(b) Longitudinal Direction

FIGURE 5. Lower Vibration Mode Shapes for Building One - Four Story Hospital for the 1984 Morgan Hill Earthquake



(a) Transverse Direction



(b) Longitudinal Direction

FIGURE 6. Lower Vibration Mode Shapes for Building One - Four Story Hospital for the 1989 Loma Prieta Earthquake

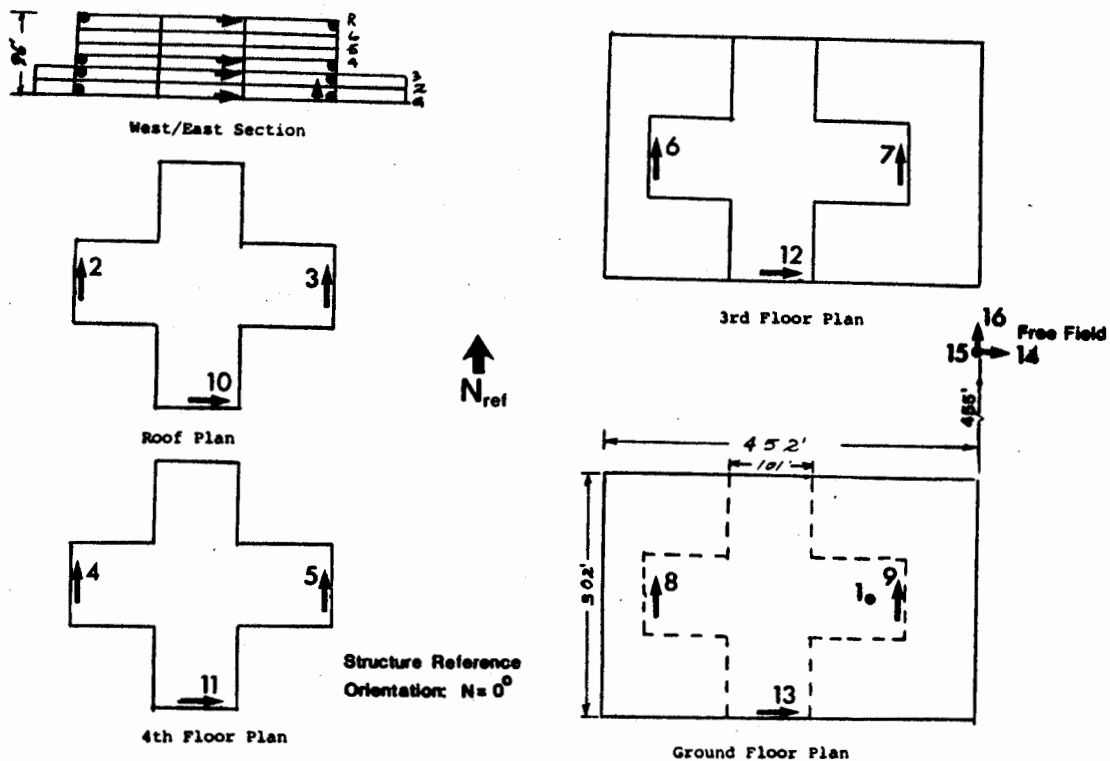


FIGURE 7. Structural Configuration and Instrumentation for Building Two - Six Story Hospital [3]

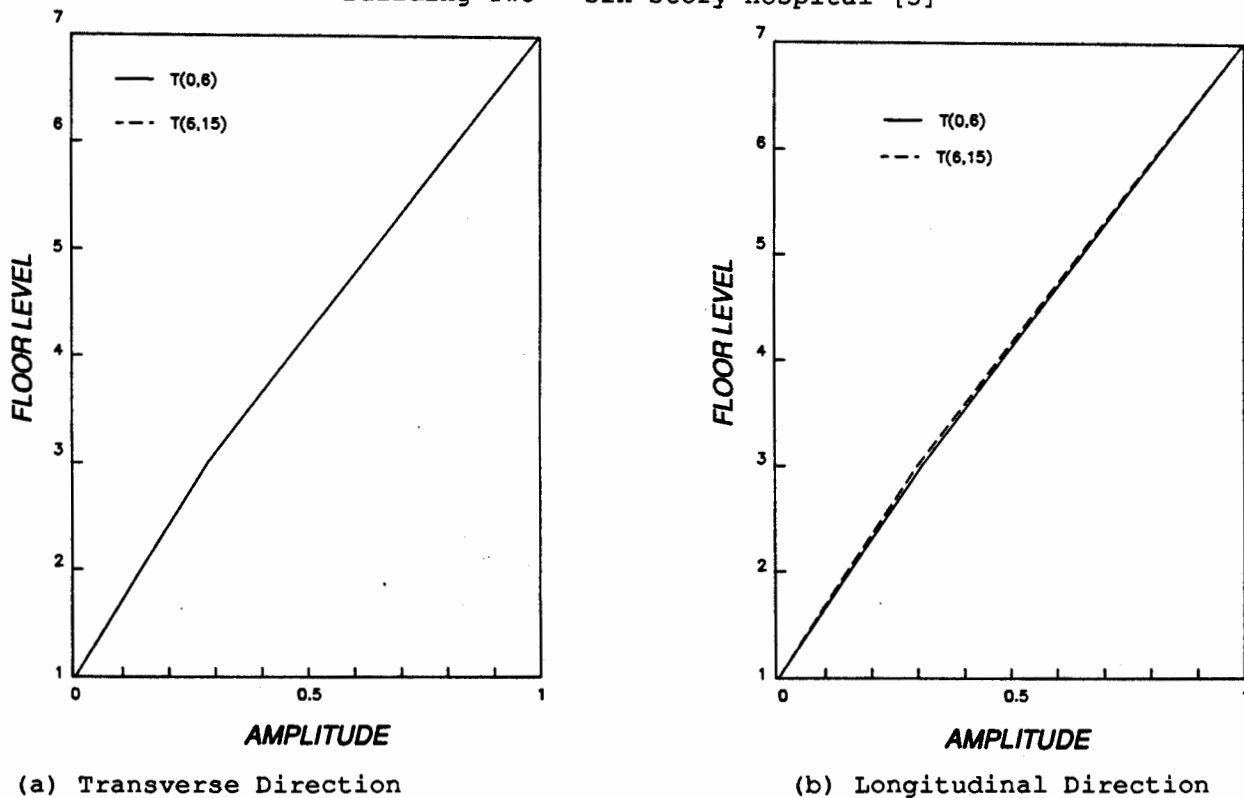


FIGURE 8. Lower Vibration Mode Shapes for Building Two - Six Story Hospital for the 1987 Whittier Earthquake