Building Vibration Characteristics From Recorded Data

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Abstract

This research project is devoted to interpreting the earthquake time history response records of three buildings that experienced strong motion during two recent Southern California temblors. The earthquake response interpretation has been aided by the information obtained from the ambient vibration tests of these buildings as well as developing a linear finite element model of each structural system. In addition some cursory building response results have been gleaned from the spreadsheet analyses of these earthquake records. The buildings and the earthquake records include:

a) Palm Springs Desert Hospital - Roof level excitation of 0.62g was recorded during the 8 July 1986 Palm Springs earthquake.

b) Burbank Pacific Manor - Roof level excitation of 0.54g was recorded during the 1 October 1987 Whittier Narrows earthquake.

c) UCLA Math-Science Building - Roof level excitation of 0.14g was recorded during the 1 October 1987 Whittier Narrows earthquake.

Building Descriptions

Some of the more significant details of each building include:

a) Palm Springs Desert Hospital - This 4 story, 126' x 78' rectangular building has a steel frame for its lateral force resisting system whereas the vertical load carrying system consists of 4"-5" reinforced concrete slabs supported by the steel frame. An elevation and plan sketch of the sensor locations are shown in Figure 1 [1]. Sensor 2 along the south roof wall experienced a peak acceleration of 0.62g whereas sensors 3 and 4 experienced 0.45g and 0.34g motions respectively. A recent site visit noted significant cracks in the basement walls which were attributed to the '86 earthquake.

b) Burbank Pacific Manor - This 10 story, 215' x 75' rectangular residence hall has pre-cast concrete shear walls in both directions for its lateral force resisting system whereas the vertical load carrying system consists of pre-cast and poured-in-place concrete floor slabs supported by pre-cast concrete bearing walls. An elevation and plan sketch of the sensor locations are shown in Figure 2 [2]. Note the plethora of shear walls in the two lateral directions. Sensor 10, located in the middle of the roof and oriented in the longitudinal direction, experienced a peak acceleration of 0.54g whereas the other roof accelerometers, sensors 2 and 3, experienced 0.33g and 0.34g motions respectively in the transverse direction.

c) UCLA Math-Science Building - This 5 story, 60' x 48' office/classroom addition to the Math-Science building has been the object of several prior experimental and analytical studies [3,4]. The lateral force resisting system consists of a 2 bay by 3 bay moment resisting frame that was added to the roof of an existing two story nuclear reactor building back in 1968. An elevation and plan sketch of the sensor locations are shown in Figure 3 [2]. Sensors 10 and 12 recorded, respectively, 0.14g and 0.11g at the roof level in the N/S direction whereas sensor 11, located in the middle of the roof and oriented in the E/W direction, recorded a peak acceleration of 0.05g.

Ambient Vibration Tests

Ambient vibration surveys represent a relatively inexpensive and rapid means of determining the modal properties of existing structures under low level excitation. The surveys can be used to "calibrate" linear, elastic analytical models as well as to obtain estimates of damping. These surveys are particularly straightforward and meaningful when one "taps" into the in-situ instrumentation network that CDMG has installed in a number of existing structures. Typically the sensors in these buildings have been placed at the most significant vibration locations and, most importantly, the tests can be conducted in an extremely low profile manner so as to provide minimum disruption to the building's occupants.

Such was the case in conducting the ambient vibration tests of the three candidate buildings. Whereas one can normally obtain reasonable information from a single channel recorder, a simple two channel analyzer affords one the opportunity to perform comparison studies such as in-phase and out-of-phase relationships. UCI has been fortunate in that over the last several months the research team has conducted over a dozen field vibration tests (forced and ambient) using its HP 3565 18-channel data acquisition/data reduction system. This prior field experience reduced the "exposure" time within each of the three buildings since most, if not all, strong motion channels could be recorded simultaneously. The HP 3565 system consists of two mainframes that house the input modules for data acquisition, an HP 9000/350 UNIX-based workstation that controls the data acquisition process, and associated peripherals such as plotters, printers, and disk/tape drives. Two experienced people and a pickup truck were sufficient to conduct the ambient vibration tests with the HP 3565.

Whereas the entire array of strong motion sensors can be recorded simultaneously, the "roof-top ambient vibration survey" [5] has been found to provide reasonable modal estimates particularly if one is attempting to "calibrate" a 3D analytical model with two translational modes and one torsional mode. Consider, for example, the roof-top ambient vibration measurements of the Palm Springs Desert Hospital shown in Figure 4. Clearly the common peak at 2.44 Hz for sensors 2 and 3 denotes a transverse mode whereas the peak corresponding to 2.75 Hz only in the sensor 2 response denotes a torsion frequency. Furthermore the single peak at 2.00 Hz from the sensor 10 measurement denotes the longitudinal fundamental frequency. Similar results for the Burbank Pacific Manor and the UCLA Math-Science Building were obtained.

A satellite calculation of the "roof-top ambient vibration survey" provides a means of determining the center of rigidity using ambient or earthquake recordings [6]. A center of rigidity estimate for the Burbank Pacific Manor was obtained from the autospectrums of sensors 2 and 3 (Saa(f), Sbb(f)) as well as their cross-spectrum (Sab(f)). The procedure assumes that the coherence between the translational and torsional motion is a minimum at the center of rigidity. Since the center of rigidity is not known, then one can express the coherence of the translational-torsional motion in terms of the measured auto- and cross-spectra as well as a non-dimensional length parameter $\underline{L}$ such that

$$|G(f)|^{2} = p(\underline{L})\mathrm{Sab}(f)\mathrm{S\overset{*}{a}b}(f)/[q(\underline{L})\mathrm{Saa}(f)r(\underline{L})\mathrm{Sbb}(f)] \qquad (1)$$

Here G(f) is the coherence function and $p(\underline{L})$,$q(\underline{L})$, and $r(\underline{L})$ are polynomial expressions (well, sort of) of the unknown non-dimensional length parameter. $\underline{L}$ is defined as the ratio of the center of rigidity distance from sensor 2 to the distance between the sensors. To eliminate a frequency dependent form of $\underline{L}$, the coherence function is integrated over the measurement frequencies to obtain a "coherence length" [6]. The center of rigidity is obtained from a curve such as the one shown in Figure 5 which depicts the coherence length versus $\underline{L}$. The curve's minimum corresponds to the location where the transverse and torsional vibrations have the least coherence.

Analytical Models

An ETABS model [7] of each building has been developed in order to predict the linear elastic response of these structure's to the earthquake ground motion recorded during the event. There are at least three obvious flaws in this procedure. First, the procedure uses the ground motion measured in the building rather than a free field set of records so that soil-structure interaction effects are ignored. Secondly, the linear elastic response may be inadequate for those buildings that experience significant structural motion. Lastly, the fundamental assumption within ETABS that the structure has a rigid diaphragm may distort some of the results.

Despite these flaws there is still merit in performing the analytical-earthquake correlation exercise by subjecting the analytical models to the earthquake ground motion and predicting their linear elastic response at strategic locations within the upper stories. Such studies, albeit linear theory for a potentially nonlinear structure, usually provide some insight into a building's response. Although ETABS provides the time history motion at the center of mass, the motion at key CDMG accelerometer locations within each building are determined by a post-processing calculation. This analytical effort is being conducted for each of the project's three buildings and is not yet concluded.

The elastic response issue of each building's recorded motion is being investigated from a restoring force-relative displacement diagram [8,9] of a SDOF oscillator. Consider a typical multistory building as shown in Figure 6. If one assumes that the relationship between the relative displacement of the building's roof acceleration ($\ddot{x}$) and the ground acceleration ($\ddot{z}$) can be represented by a SDOF oscillator, then the equation of motion of the building can be expressed as

$$M \ddot{x} + F(x,\dot{x}) = -M \ddot{z} \tag{2}$$

The $F(x,\dot{x})$ term in Equation (2) represents the restoring force due to the relative displacement (x) and relative velocity ($\dot{x}$) whereas M is an equivalent mass. Note that the generic form of $F(x,\dot{x})$ can permit a linear or nonlinear restoring force. Equation (2) is founded on the assumption that normally the first mode dominates the earthquake time history response of a building. Alternative forms of Equation (2) are

$$F(x,\dot{x}) = -M (\ddot{x} + \ddot{z}) = -M \ddot{y} \tag{3}$$

$$F(x,\dot{x}) / M = -\ddot{y} \tag{4}$$

Since CDMG provides records of $\ddot{x}$ and $\ddot{z}$ as well as the integrated displacement time histories, then it is a relatively routine matter to "import" these data into a spreadsheet for subsequent analysis. For instance, one need only "import" three records from the processed CDMG Volume 2 data into columnar format of a spreadsheet in order to construct a restoring force-relative displacement diagram; the required data include: (1) roof level acceleration, (2) roof level displacement, (3) ground level displacement. A spreadsheet could form a 4th column of data that is the opposite sign of the roof level acceleration whereas a 5th column would provide the difference between the roof and ground level displacements. A spreadsheet plot of the column 4 data versus the column 5 data thus provides a restoring force-relative displacement curve. Consider, for example, the restoring force-relative displacement diagram for the Palm Springs Desert Hospital shown in Figure 7. Despite the significant 0.62g accelerations experienced at the roof, one could conclude that the hospital's earthquake response was nearly linear with little damping. It should be noted that some earthquake records may have to be filtered in order to eliminate the effects of higher mode frequencies.

Conclusions

Definitive conclusions about the specific earthquake interpretation of all three buildings must wait until the project concludes in the next three months. However, the thrust of the earthquake record interpretation study to date has led the project team to make the following assumptions:

(1) structural engineers might be more inclined to "fiddle" with the CDMG Volume 2&3 data if it could be easily manipulated,

(2) structural engineers usually have access to an AT-class microcomputer for running ETABS and a LOTUS 1-2-3 type spreadsheet.

Given that the CDMG Volume 2&3 data **is** provided in a convenient microcomputer format, then some natural by-products of the current investigation will be public domain software that will enable others to process the earthquake records in much the same manner as reported herein. Calculations such as restoring force-relative displacement curves, relative displacements within a floor to check diaphragm rigidity, center of rigidity estimates, etc. can be performed by others from the Volume 2&3 data.

A provocative recommendation, that others will certainly disagree with, is that an ETABS model should developed for all ETABS-applicable, instrumented buildings within the SMIP network. Even though a building's response might be inelastic or that ETABS rigid diaphragm assumption might be violated, there is some merit in having a 3D elastic model - no matter how inappropriate it might be for a given study - that others could use directly or modify to suit their own needs. The development of such an ETABS model database could be done on a voluntary basis (read free) by those practitioners and researchers interested in advancing the state of SMIP's data dissemination program. The voluntary ETABS model development could be accomplished by assigning 1 building/per year to those consulting firms and universities willing to participate. The database would include an ETABS input and output file on floppy diskette format as well as a 4-5 page standard format report that identifies the modeling characteristics and unusual assumptions.

References

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8. McVerry, G.H., Beck, J.L., Jennings, P.C., "Identification of Linear Structural Models From Earthquake Records", Proceedings of the 2nd US National Conference on Earthquake Engineering, Stanford,CA, 1979, pp 515-524.

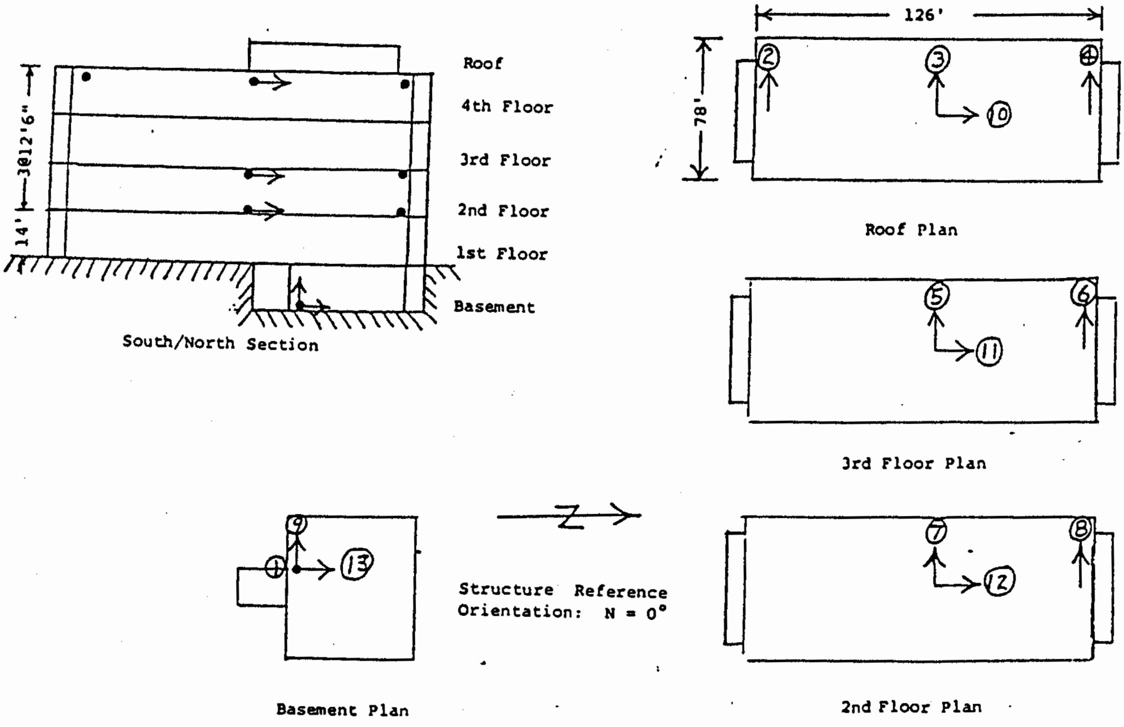

Figure 1 - Sensor Locations @ Palm Springs Desert Hospital

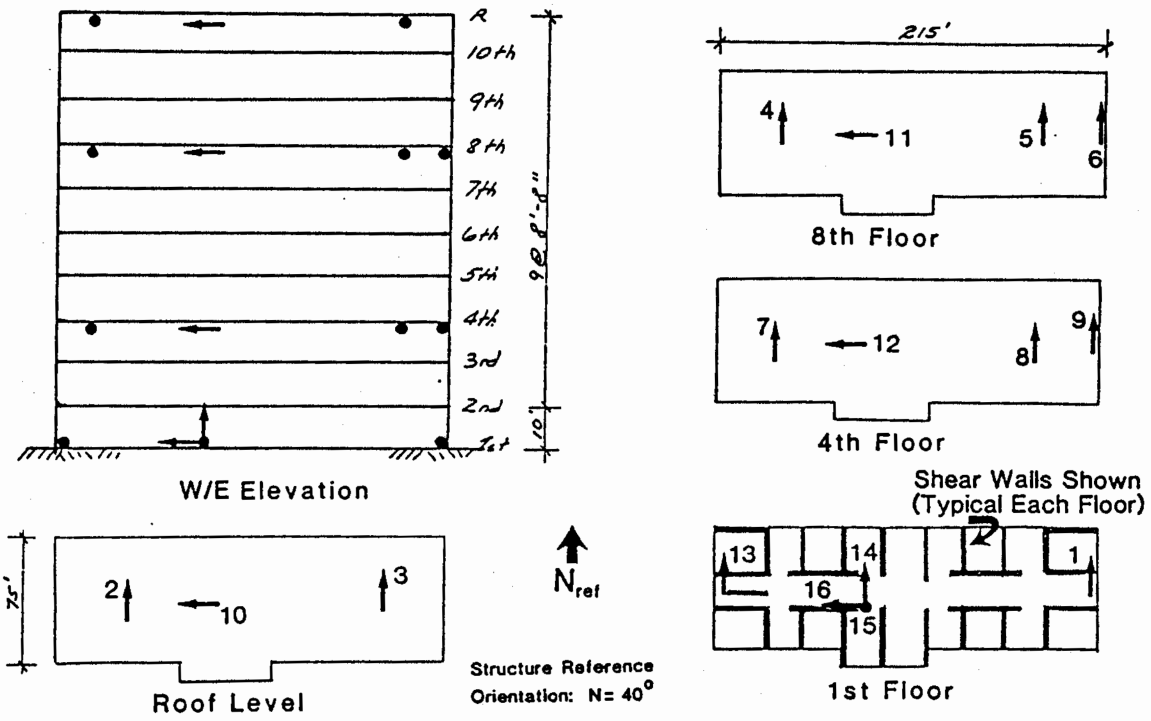

Figure 2 - Sensor Locations @ Burbank Pacific Manor

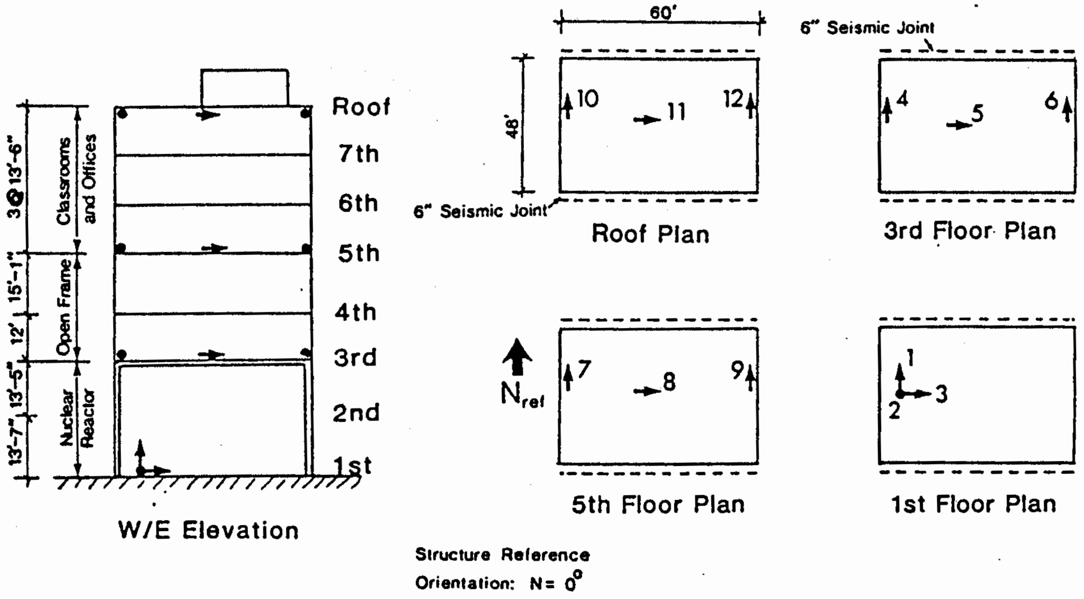

Figure 3 - Sensor Locations @ UCLA Math/Science Building

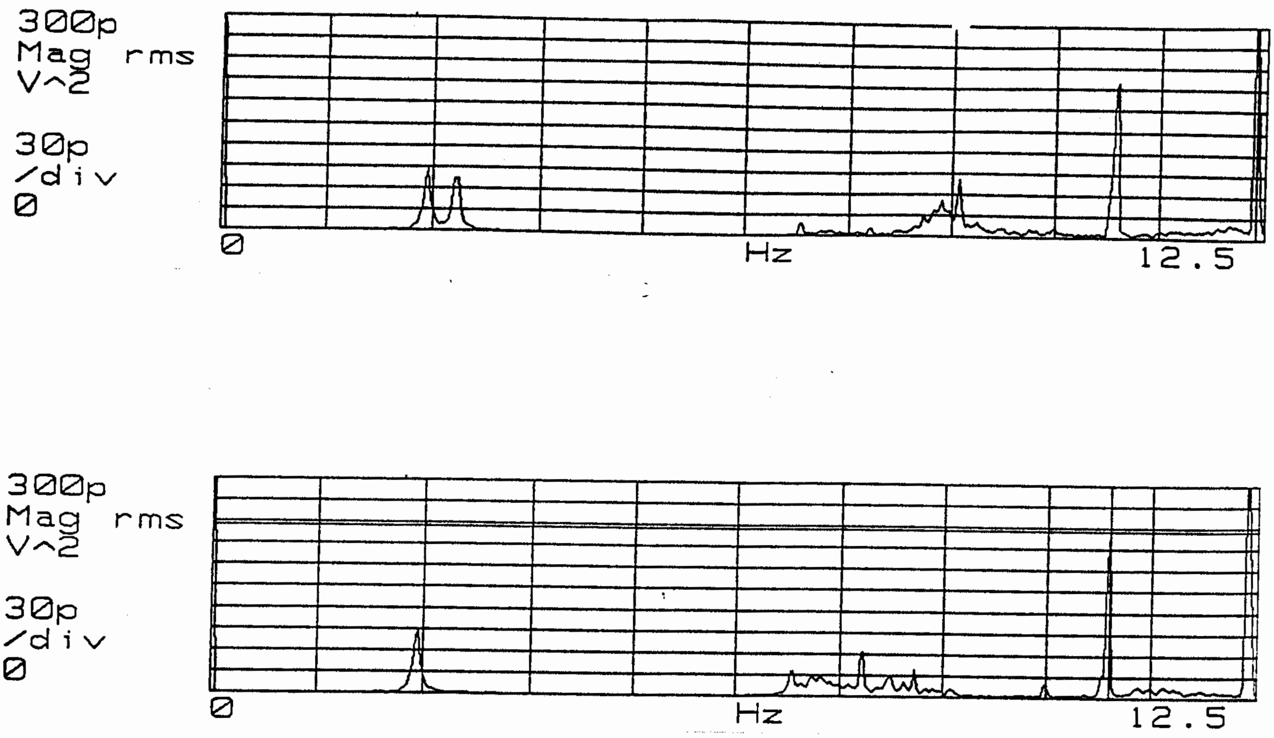

Figure 4a - AVS of Palm Springs Desert Hospital (Top: E/W Sensor @ Bldg Edge, Bottom: E/W Sensor @ Bldg Center)

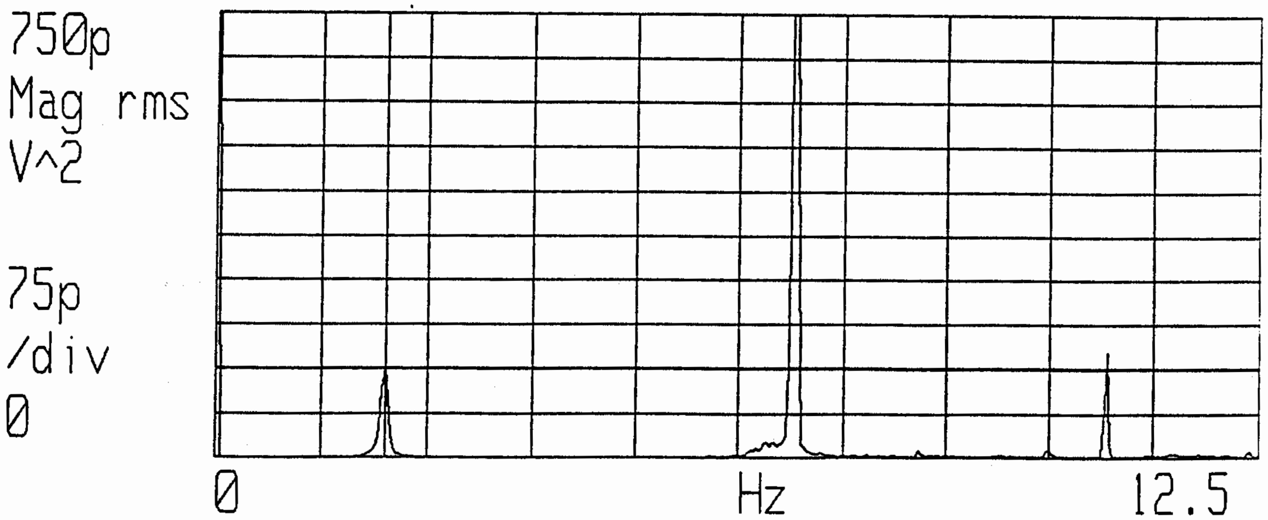

Figure 4b - AVS of Palm Springs Desert Hospital (N/S Sensor @ Bldg Center)

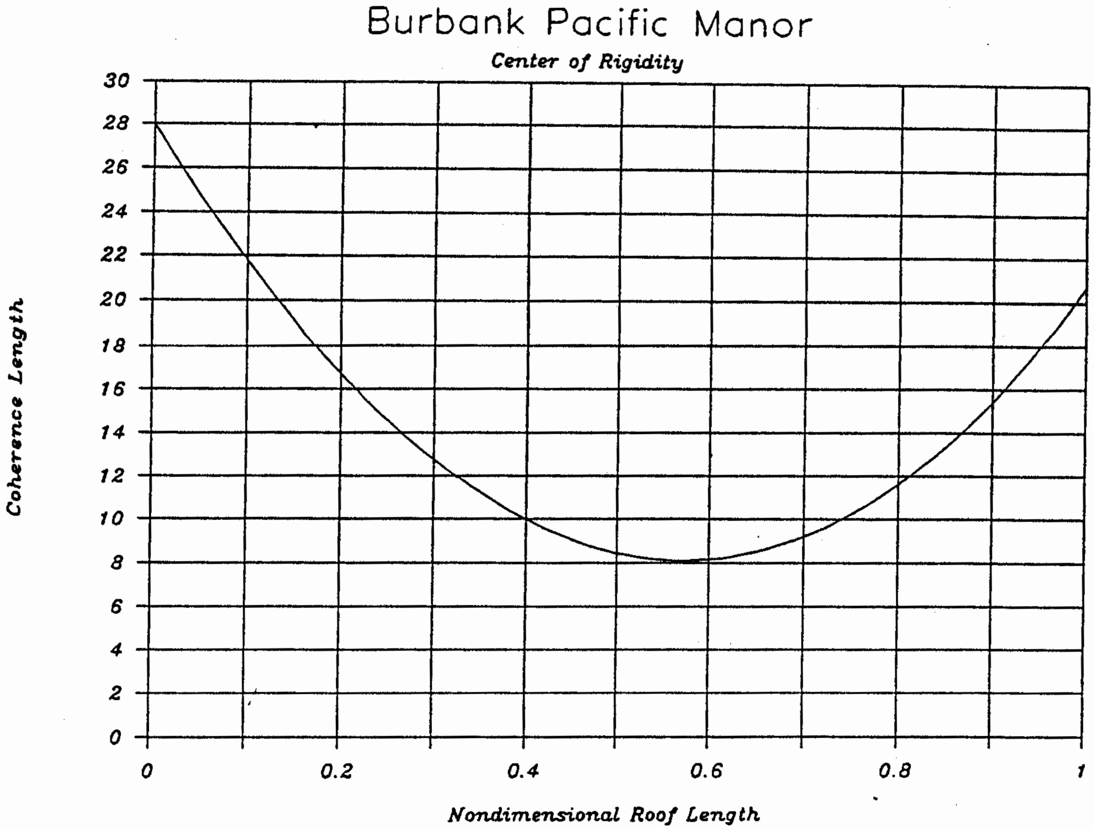

Figure 5 - Burbank Pacific Manor Center of Rigidity

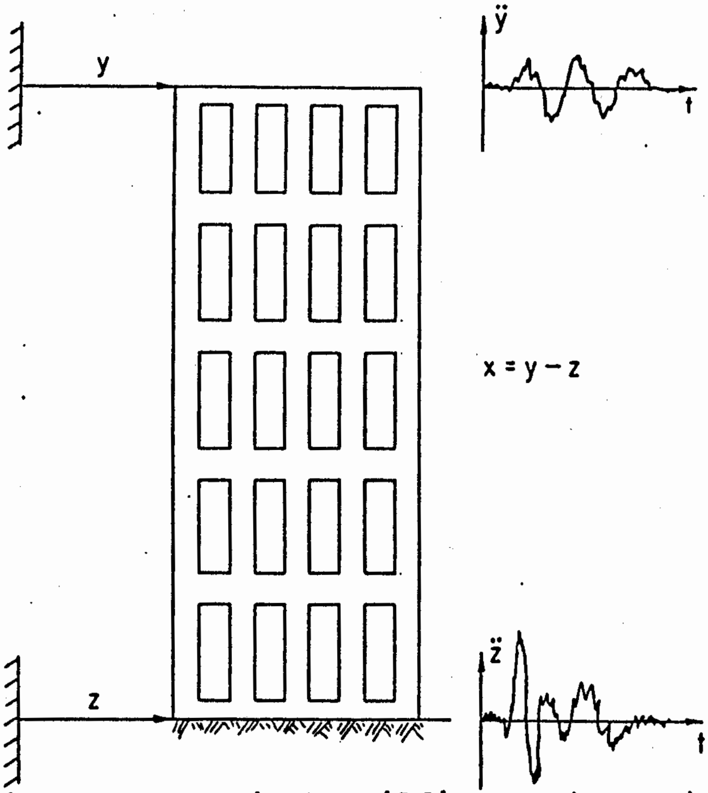

Figure 6 - Typical Building Instrumentation

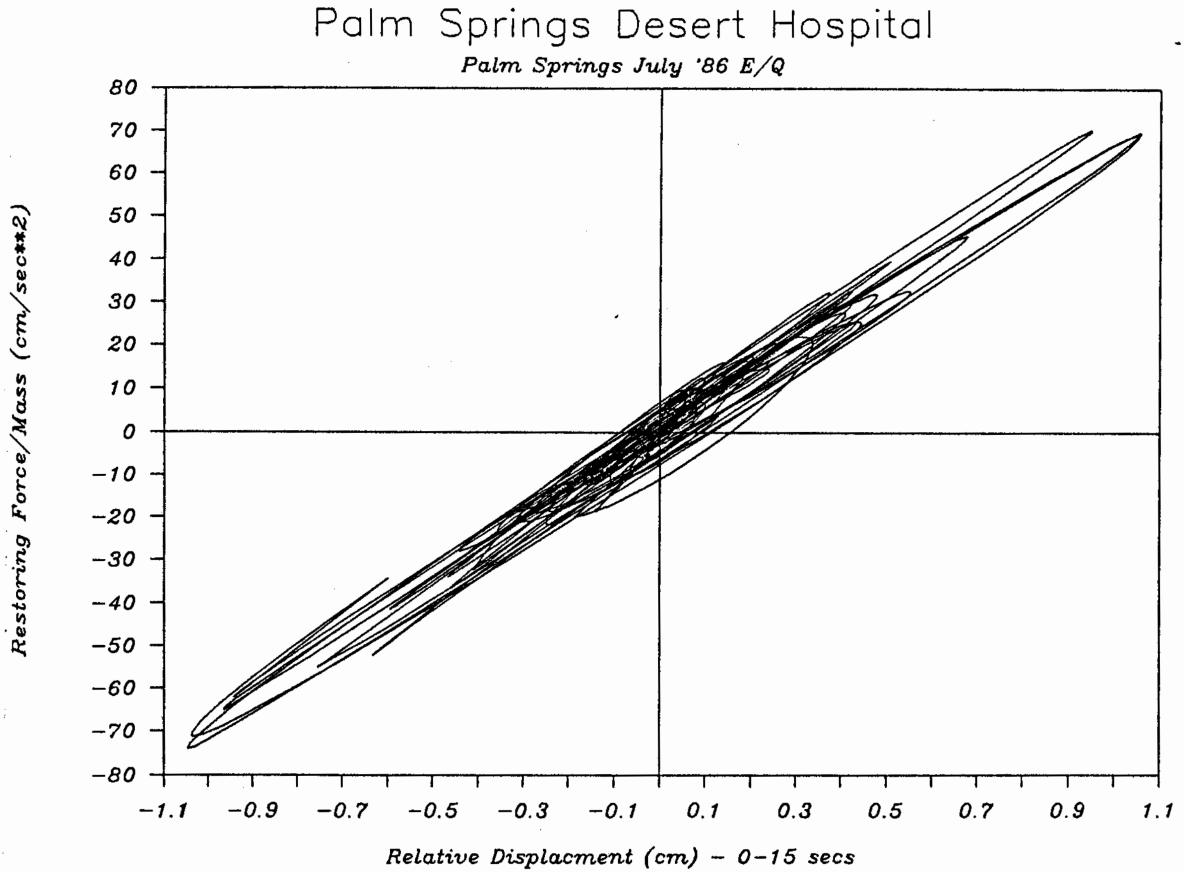

Figure 7 - Palm Springs Desert Hospital
Restoring Force vs Relative Displacement...July '86 E/Q