Development of Automatic MIMO System Identification Program to Analyze the Seismic Response Data from Taiwan Building Array

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Abstract

A major component in an automatic post-earthquake safety evaluation method for buildings is automated system identification. While there are a variety of different system identification methods that can be applied to building seismic records, the most important issue is to establish a set of criteria to guide the automated process for identification so that the results are within acceptable bounds. In this paper two automated programs for system identification processor were described. They were applied to the seismic response data of Taiwan Building Array of the Control Weather Bureau (CWB). Using such automated MIMO system identification programs as basis, safety evaluation of buildings using instrument data can be made in the near future.

1 Introduction

A large number of high quality strong-motion records of building responses have been obtained during recent earthquakes in Taiwan and elsewhere. The interest in using actual records for structural model verification becomes more and more strong in engineering community. Because of the availability of multi-channel records at various locations of a building, a multiple input-multiple output (MIMO) building system identification procedure has been utilized to analyze some of these records [1,2]. The system identification was based on the least-square-output-error method and the model parameters of the dynamic system were identified in the time domain. The time varying behaviour of the building can be studied using the time window approach.

One of the major problems in this kind of building earthquake record evaluation is the time-consuming data transmission and signal processing. This undesirable situation is changed by the advent of a PC-based seismic recording system. The system is originally developed by U.S. scientists but found its first large scale deployment in Taiwan in more than forty buildings. Thus, automated recording of acceleration data in a form suitable for subsequent analysis in an achieved fact with such a PC-based system. The stage is then set for the development of an automated post-earthquake-safety evaluation method that fully utilizes the advantages of this PC-based system. An automated system identification processor can satisfy such a need for the safety evaluation of the building. The basic elements of the automated identification processor have been tested against the records of several buildings [3,4]. The structural model of this method is assumed to be a multi-degree-of-freedom discrete system of second order. The earthquake response of the system is obtained by superposing the dominant vibrational modes of the system.

In this paper the framework of two quick post-earthquake system identification methods for buildings equipped with a PC-based seismic recording system is described including one based on the discrete-time filtering approach [5,6,7]. These records are applied to the seismic response data of Hsin-Kwon Building and Tai-Power Building.

2 Automated System Identification Applied to Hsin-Kwon Building Record

A major component in an automated safety evaluation method for buildings is the automated system identification. As the response is measured at several levels of a building and the ground motion consists of at least three major components, longitudinal, transverse and torsional ground floor motions, the system has multiple-input and multiple-output (MIMO). The identification results are more reliable if all the output records are matched at once so that a single set of parameters are obtained as the solution to the inverse problem. Thus, this becomes a MIMO system identification problem. The success of this identification process depends very much on the initial guess of the parameters. The iterative process may not converge or it may converge to a set of parameters that are outside of the bounds of physical sense, e.g. damping ratio being negative. Thus, repeated trials may be necessary before an acceptable set of parameters is obtained. To have an automated process for system identification means a set of criteria must be used to judge whether the system identification results are acceptable and if not, a new iteration cycle must be started automatically. Conceptually, the process of this automated system identification can be represented by the diagram shown in Fig. 1, under the heading of main-processor.

The 1994-6-5 earthquake of northern Taiwan triggered the seismic building array of a 50-story building, Hsin-Kwon Building, located in the Taipei basin. Figure 2 shows the instrumentation layout of the building. Including the ground level as the first level, six levels of measured acceleration time history at heights 0, 6.4, 86.7, 143.2, 206.1 and 223.6 m, respectively, are used. At each level, the original time histories are regrouped into three motions: longitudinal, transverse, and torsional motions at the geometric center of the building in an effort to separate the coupled motions. Thus, 23 original time histories are combined into 18, three for each level. Furthermore, only 30 seconds of relatively higher responses are included for identification. Three time windows each with 10 seconds are used in the identification.

The AMIMO program (Automated MIMO) was used not on-line, since the time histories were obtained off-line. The AMIMO was used several times until the initial guesses were close enough to get very good results. This points out the need for extensive study of a building before the AMIMO is used because no system identification program can guarantee good results without some pre-knowledge of the building characteristics. This should not be a problem in practice, because we can always use previous earthquake records, as we have been doing for the Hsin-Kwon building, to get the building vibration frequencies, etc., to prepare for the next earthquake. Figure 3 through 6 show the comparison between the calculated and the recorded time history at level four and level 4 in both longitudinal and transverse directions. As shown in Fig. 7, the torsional motions were small and not included in the system identification.

The identified frequencies (in Hz) of the first three modes in the longitudinal direction are 0.26, 0.65 and 1.14. The frequencies for the first three modes in the transverse direction are 0.22, 0.55 and 1.02. THe fourth mode frequency in each direction was also identified but not considered accurate since the modal contribution was very small. The first three modes are reliably identified because the error in acceleration as very small (less than 15 to 20% for each 10 seconds of time history) and the modal contributions were strong. The modal damping ratios are all smaller than 1.5%. Figure 8 shows the three identified mode shapes of the building, obtained by simply connecting the mode shape components at the instrumented levels by straight lines.

3 Discrete-Time Filters Applied to Tai-Power Building

Instead of using the multi-degree-of-freedom discrete system of second order, the discrete-time filter to represent the input-output relation of the dynamic system was used. The simplest input-output relationship is obtained by describing it as a linear difference equation:

$$y(t) + a_1\, y(t-1) + \cdots + a_{n_a}\, y(t-n_a) \\ = b_1\, u(t-1) + \cdots + b_{n_b}\, u(t-n_b) + e(t) \tag{1}$$

where the white-noise term $e(t)$ here enters as a direct error in the difference equation. The adjustable parameters are in this case

$$\hat{\theta} = \left[a_1\,,\, a_2\,,\, \cdots\,,\, a_{n_a}\,,\, b_1\,,\, b_2\,,\, \cdots\,,\, b_{n_b}\right]^T \tag{2}$$

If we introduce

$$\begin{aligned} A(q) &= 1 + a_1\, q^{-1} + \cdots + a_{n_a}\, q^{-n_a} \\ B(q) &= b_1\, q^{-1} + \cdots + b_{n_b}\, q^{-n_b} \end{aligned} \tag{3}$$

We shall have a model description:

$$y(t) = \frac{B(q)}{A(q)}\, u(t) + \frac{1}{A(q)}\, e(t) \tag{4}$$

This model can be called as ARX model, where AR refers to auto-regressive part, $A(q)\, y(t)$ and S to the extra input, $B(q)\, u(t)$. The ARX model can also be extended to Multi-variate version. Consider the ARX-model, shown in Eq. (4), here $y(t)$ and $u(t)$ are ny- and nu-dimensional column vectors and $A(q)$ is an $ny \times ny$ matrix polynomial, and $B(q)$ is an $ny \times ny$ polynomial matrix:

$$A(q) = \begin{bmatrix} a_{11}(q) & \cdots & a_{1ny}(q) \\ \vdots & \ddots & \vdots \\ a_{ny1}(q) & \cdots & a_{nyny}(q) \end{bmatrix} \tag{5}$$

where the entries a_{ij} are polynomials in the delay operator q^{-1}:

$$a_{kj}(q) = \delta_{kj} + a^{1}_{ks}\, q^{-1} + \cdots + a^{na_{kj}}_{kj}\, q^{-nq_{kj}} \tag{6}$$

Once the vector $\hat{\theta}$ is determined, the transfer function of the system is completely known. In order to determine the modal properties of the structure, we use partial fraction expansion of the transfer function. We first determine the poles (the roots of the denominator polynomial) and then expand the transfer function in partial fractions as

$$\begin{aligned} H(z) &= \frac{b_1\, z^{-1} + b_2\, z^{-2} + \cdots + b_{2n}\, z^{-2n}}{1 + a_1\, z^{-1} + a_2\, z^{-2} + \cdots + a_{2n}\, z^{-2n}} \\ &= \textstyle\sum_{k=1}^{2n} \dfrac{r_k\, z^{-1}}{1 - p_k\, z^{-1}} \end{aligned} \tag{7}$$

For stable system, $p_k\, s$ are all in complex conjugate pairs, and have modulus less than one. By combining the pair of terms corresponding to pairs of complex-conjugate poles, we can have

$$H(z) = \sum_{k=1}^{n} \left(\frac{r_k\, z^{-1}}{1 - p_k\, z^{-1}} + \frac{r_k^*\, z^{-1}}{1 - p_k^*\, z^{-1}} \right) \tag{8}$$

where $*$ denotes the complex conjugate. The modal frequencies and damping ratios can be expressed in terms of the poles of the discrete system [?] while the mode shape and the phase can be determined from the complex value of r_k.

To determine the story drift and the base shear of a building during earthquake, the displacement (or acceleration) at any floor must be recovered from the identified modal parameters. The mode shape and the participation factor are the two important parameters in relating to these response quantities. It is necessary to find the complete mode shape ϕ_{kj} for every k-th floor. It is assumed that the mode shape of any building frame with or without walls may be estimated by a combination of the shear and flexural modes. Based on the identified modal parameters and the above-mentioned assumption the mode shapes of the structure can be constructed. The horizontal elastic force can be expressed simply as the summation of the modal contributions $\sum \omega_j^2\, M\, \phi_j\, y_j(t)$. It represents the elastic force at each floor level, and from which the story shear and overturning moment are calculated.

The seismic response data of Tai-power office building on the 1996-3-5 earthquake was used for the study of identification using discrete-time filter. There are four levels of measured acceleration time history. Figure 9 shows the identified first three modes in the longitudinal direction. The theoretical mode shapes of the shear type and the flexure-type cantilever beam were also shown in this figure. The identified frequencies (in Hz) of the first three modes are 0.372 Hz, 1.096 Hz, 2.020 Hz. Figure 10 shows the response contribution of the first three modes. Comparison between the calculated and the measured acceleration represent at the 4th level (27th floor) is also shown in this figure. The calculated story drift (in cm) at each floor is shown in Fig. 11.

4 Calculations

This paper described two methods of building identification. The automated MIMO program was developed and written in window based computer program. This program has been tested on the CWB array data of Hsin-Kwon BUilding. The second method was written under MATHLAB to perform the identification. Both methods can be applied to sequential system identification so that the time-varying modal parameters can be estimates.

Acknowledgements

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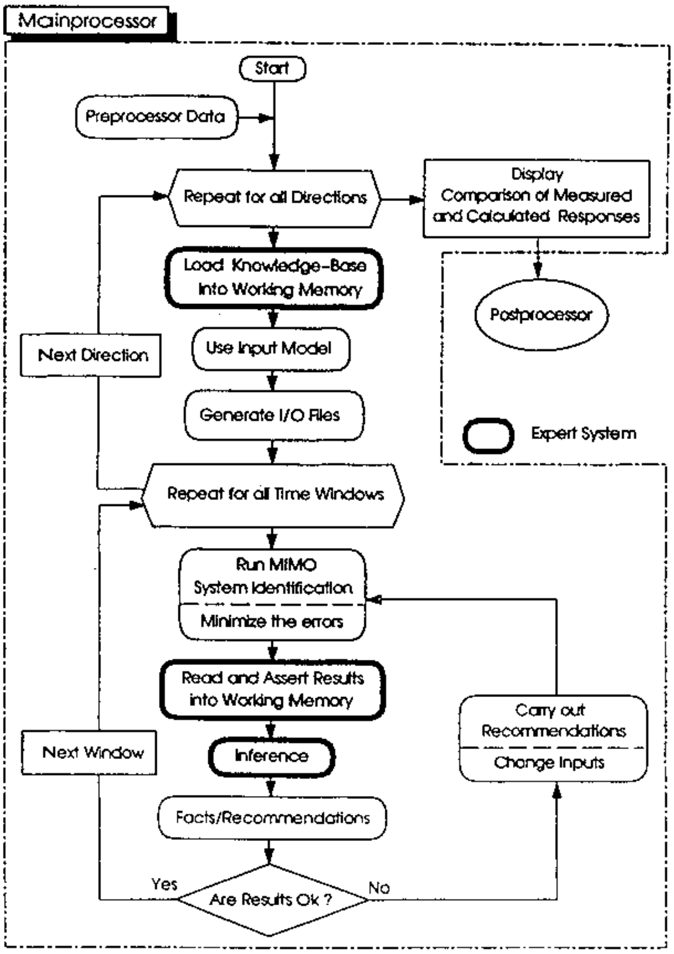

Fig.1: Flow diagram of the main-processor executing system identification.

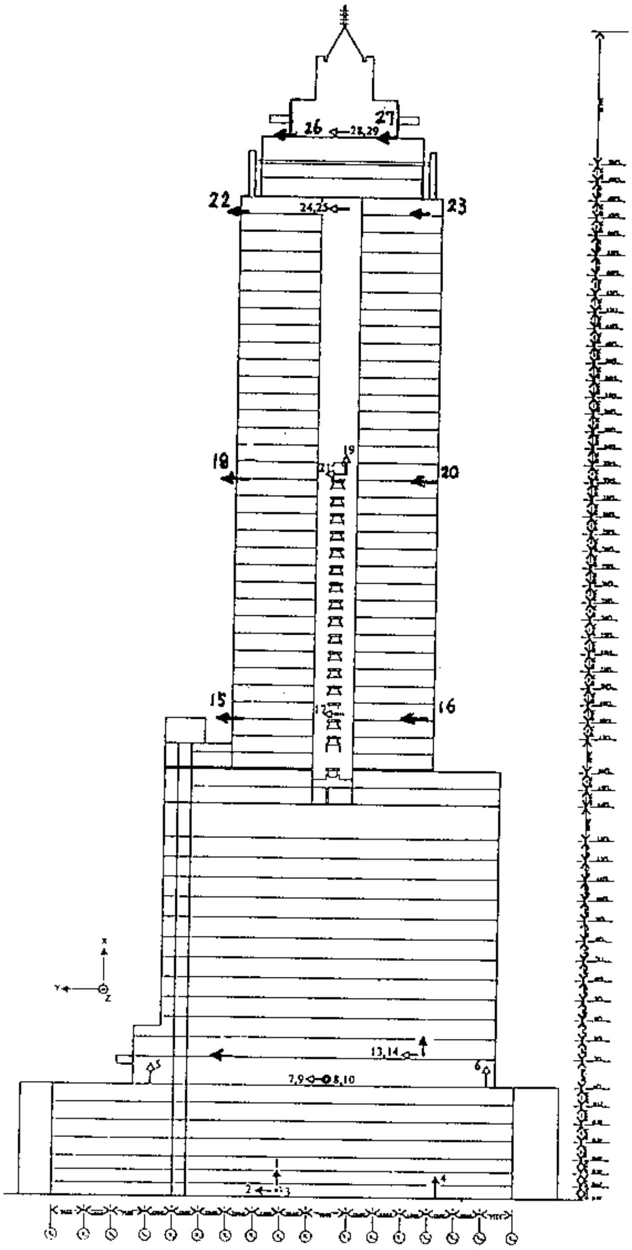

Fig.2: Seismic instrumentation layout at Hsin-Kwon Building.

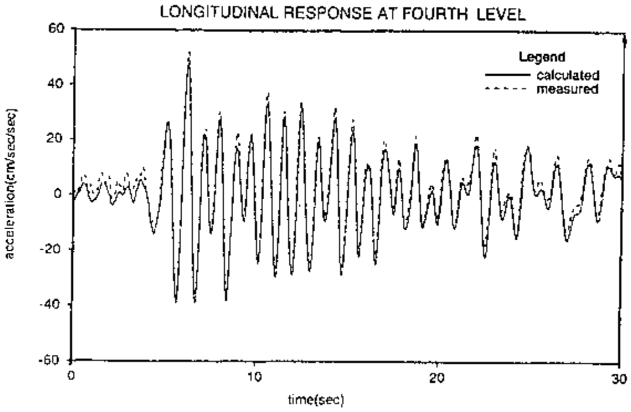

Fig.3: Comparison between calculated and recorded longitudinal acceleration at 4th-level (Hsin-Kwon Building).

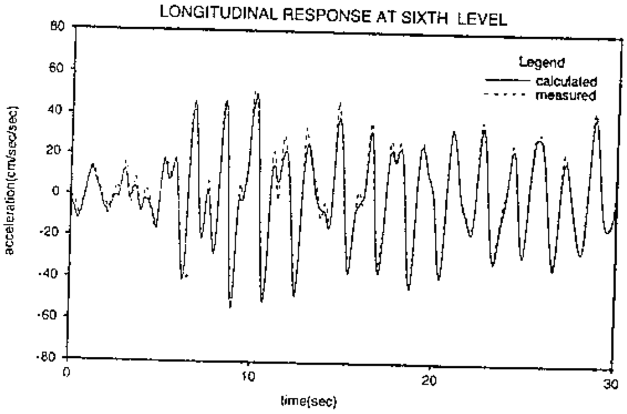

Fig.4: Comparison between calculated and recorded longitudinal acceleration at 6th-level (Hsin Kwon Building).

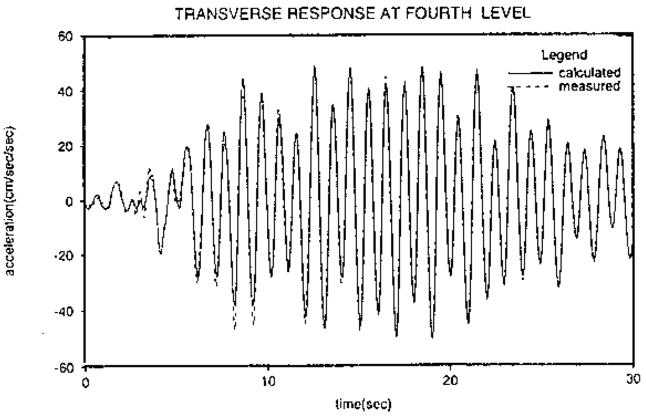

Fig.5: Comparison between calculated and recorded transverse acceleration at 4-th level (Hsin-Kwon Building).

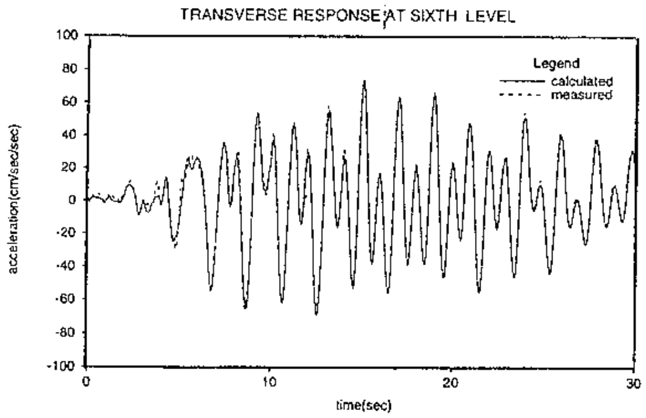

Fig.6: Comparison between calculated and recorded transverse acceleration at 6-th level (Hsin-Kwon Building)..

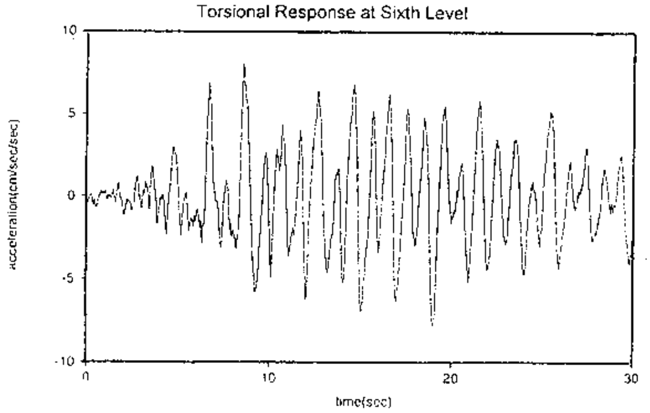

Fig.7: Plot of measured torsional response at 6-th level of Hsin-Kwon Building.

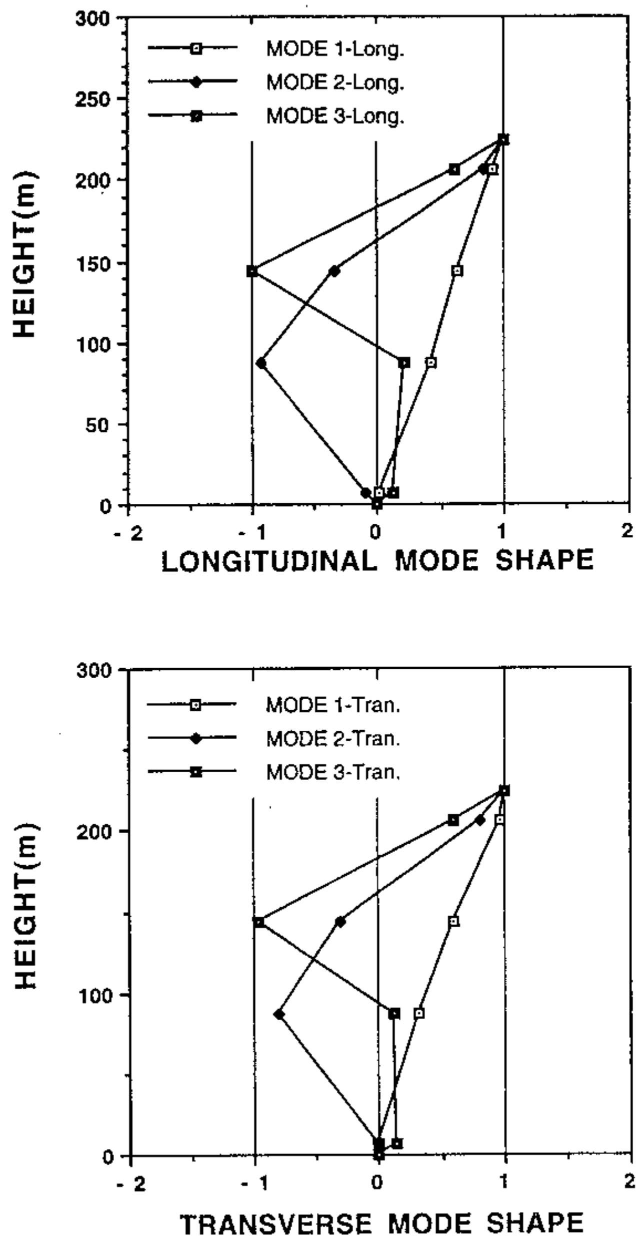

Fig.8: Plot of the three identified mode shapes of the Hsin-Kwon Building.

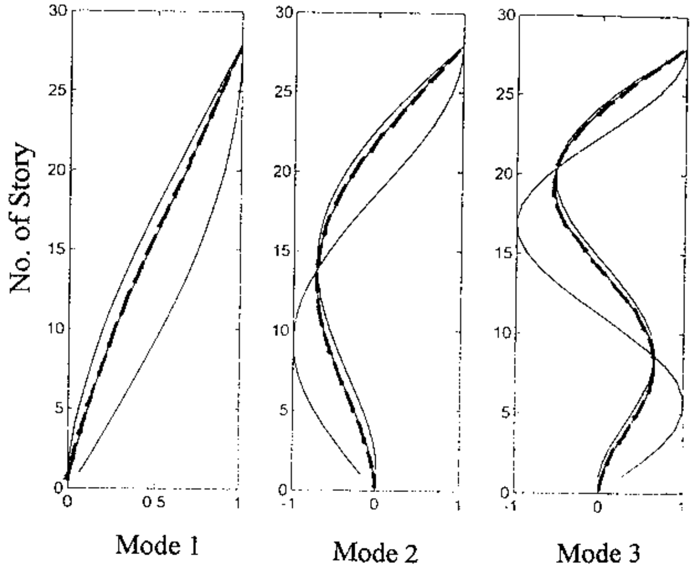

Fig.9: The Identified first three mode shapes of Tai-power office building (1996-3-5 earthquake).

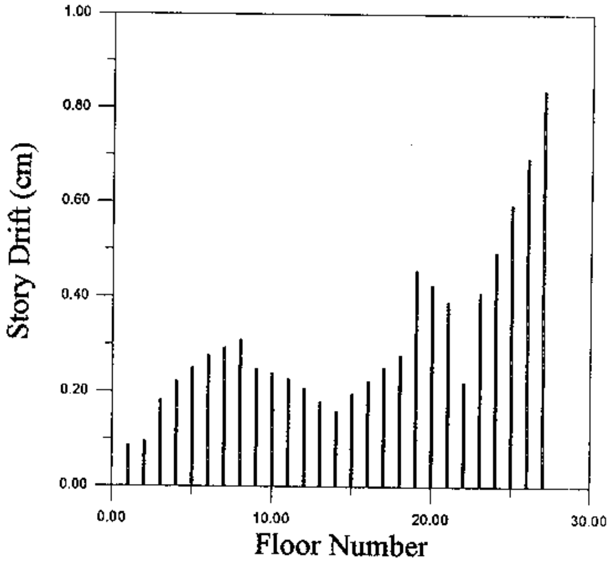

Fig.11: Estimated story drife (cm) of Tai-power Office building during the 1996-3-5 earthquake.

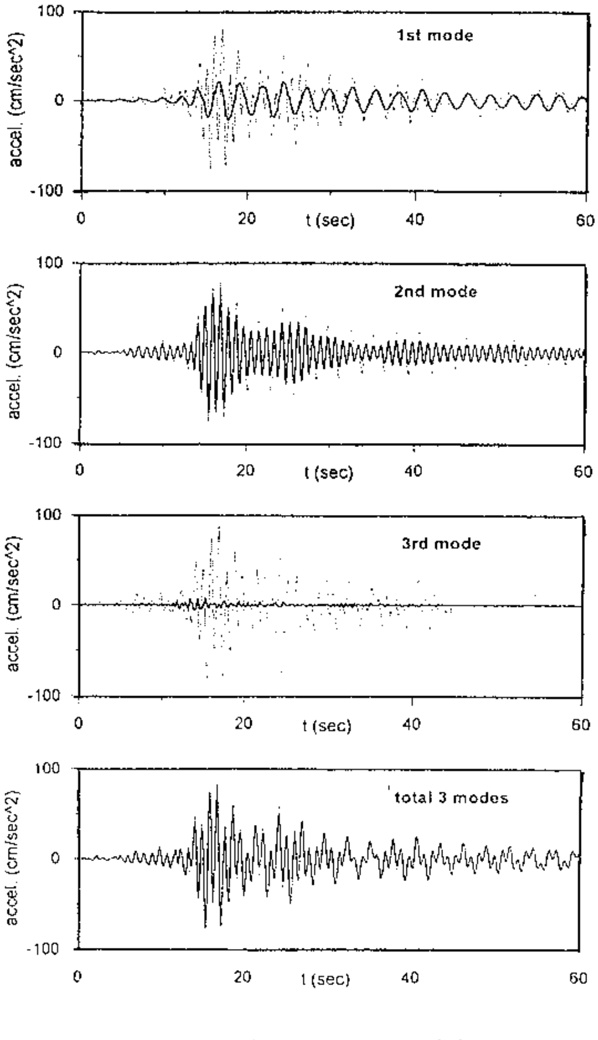

Fig.10: Contribution of first three modal responses and the comparison between calculated and recorded acceleration in the transverse direction (1996-3-5 earthquake).