# SEISMIC PERFORMANCE AND DESIGN CONSIDERATION OF A LONG-SPAN SUSPENSION BRIDGE

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## ABSTRACT

A 3D analytical model of the Vincent Thomas Bridge is calibrated using the measured structure responses during the 1987 Whittier Narrows earthquake. Vibrational characteristics which are sensitive to multiple-support excitations were identified.

An analytical model for the ground motion incoherency was evaluated based on motions recorded at 10 stations at Caltech during the earthquake. The motions at four stations were selected as input to the bridge supports whose spatial variation is consistent with the coherency model. A multiple-support response spectrum method is described to illustrate the application to long structures.

## INTRODUCTION

The seismic performance of major long-span bridges during a strong earthquake shaking would have significant effects on the regional economy and activities of the population. This was evidenced following the 1989 Loma Prieta earthquake. For important structures, not only collapse failure must be prevented, but also that the extent of damage due to an earthquake must be limited and the function of the bridge must be restored quickly. The new requirement for maintaining functionality following a major earthquake poses a greater demand on the seismic evaluation technology:

- A sufficiently detailed analytical model to capture the essential 3D vibrational characteristics of the structure;
- A clear understanding of the ground motion input to the structure supports; and
- A methodology to conduct seismic evaluation efficiently under the multiple-support excitation input.

The available instruments on the bridge site are not sufficient to define the multiple support ground motion input. To supplement the existing instrumentation, the ground motions recorded at the Caltech array during the 1987 earthquake (processed by CDMG) were used to establish the spatial variations as described by the coherency function. Ground motions recorded at four stations were selected for use in the direct-integration, multiple-support-excitation, time history analysis. Given the response spectrum and the coherency function consistent with the ground motion time histories, the applicability of the multiple-input response spectrum method can be evaluated.

## THE VINCENT THOMAS BRIDGE

**Description of the Bridge –** The Vincent Thomas Bridge on State Sign Route 47 spans the main channel of Los Angeles Harbor between San Pedro on the west and Terminal Island on the east. Its 6060 foot length is made up of the 1500 foot suspended main span, two 507 foot long suspended side spans and 19 steel plate girder approach spans of from 150 to 230 feet in length. The suspended span consists of two stiffening trusses, transverse floor trusses, and a lower-chord wind bracing system of the K-truss type. The vertical sag of the cable at midspan is 150 feet. Roadway width is 52 feet between 2-foot wide curbs.

At the time of construction (1961-'63) it was thought to be the only suspension bridge in the world supported entirely on piles. The 14 BP 117 steel H-piles used at the anchorages, cable bents and main towers were driven to Elevation -75 at the Terminal Island Tower and -135 at the San Pedro Tower. Indicated bearing value was 145 tons for each pile.

The towers each consist of two steel box section legs fabricated in seven vertical segments with five lateral truss members separating the legs. Cross section of each leg is roughly that of a cross with the inside vertical and the outside tapering uniformly from the base elevation of 25.00 feet to the top elevation of 360.67 feet. Individual segments are made up of welded 3/4-inch plate, and segments are bolted to one another with one inch diameter high strength bolts. The base segment is held to the pier with 78 2-1/2-inch diameter steel rods, each stressed to 360,000 pounds.

The suspender ropes do not hang vertically as they do on some suspension bridges. Center-to-center spacing is 66'-6" at the top of main towers, 59'-2" at the cable bents and 55'-0" at the cable anchorages. The elevation and plan views of the cable are shown in Figure 1.

**Description of the Instrumentation –** Figure 2 shows the layout of the strong-motion instrumentation installed on the bridge (CSMIP Station No. 14406). A total of 26 sensors are used including: 13 sensors on the stiffening-truss deck; 3 sensors on top of the east tower; and 10 sensors at the base level (East anchorage, East Tower and West Tower).

**Analytical Model –** A 3D analytical model of the suspension bridge was developed as shown in Figure 3. The stiffening trusses and transverse floor trusses were represented by statically equivalent girders located at appropriate locations as shown in Figure 3b. The stiffness matrix derived from the idealization involving equivalent girders and bottom K bracings was evaluated against the "exact" generalized stiffness matrix for the actual 3D truss structure. Very close correlation was obtained for all diagonal as well as off-diagonal terms in the stiffness matrix indicating that all essential behavior of the original truss system is captured by the idealized model.

The model of the tower is shown in Figure 3c. All members in the transverse trusses were included in the model. At the intersection of the tower and the deck, both main-span and side-span trusses are free to slide longitudinally within a guided bearing assembly passing through the tower shaft, are supported vertically by hangers, and are restrained in the transverse direction. All rotational degrees of freedom at the tower-deck connection are unrestrained.

## VIBRATION CHARACTERISTICS OF THE TOWER

The instrumentation layout was apparently devised to monitor the vertical,. lateral and torsional responses of the truss system. To this end, detailed correlation studies were carried out by Niazy (1991) to correlate analytical predictions with measured responses during the Whittier earthquake.

For the transverse vibration of the towers, there are three transducers installed at the top of the tower shaft (channel 8), the roadway level (channel 6), and the top of the pier (channel 9). The tower vibration in the transverse direction is strongly affected by the lateral vibration of the cable. Three types of modes are calculated as shown in Figure 4. There are a number of modes calculated which have essentially the same deformed configuration of the tower as shown in Figure 4a, but have periods ranging from 1.36 to 2.26 seconds depending on the participation of lateral cable vibration. From the measured data, similar modes were identified with periods 1.5 and 1.7 seconds. The second transverse mode with a period of 0.85 seconds involves the bending of the tower shaft starting at the roadway level as shown in Figure 4b. The corresponding measured mode was identified with a period of 0.79 seconds. The third transverse mode with a period of 0.47 seconds (Figure 4c) was not identified from the measurements.

Because of the high cable tension, the top of the tower where two transducers were located is essentially stationary. Therefore, longitudinal vibration modes of the towers can only be derived from the analytical model. Eight modes involving significant tower longitudinal vibration are shown in Figure 5:

- Modes 23 and 24 (T = 1.58 seconds) involve the longitudinal vibration of the two towers, respectively, and the in-phase motion of the adjacent side span (Figures 5a and 5b).

- Modes 31 and 32 (T = 1.27 seconds) involve similar vibration of the towers, but with out-of-phase motion of the side span trusses (Figures 5c and 5d).

- Modes 25 and 26 (T = 1.53 seconds) involve the simultaneous longitudinal motion of both towers. The two towers are in-phase for mode 25 and out-of-phase for mode 26 (Figures 5e and 5f).

- Mode 62 (T = 0.64 seconds) and Mode 67 (T = 0.58 seconds) involve the higher-order tower vibration with two towers vibrating in-phase and out-of-phase, respectively (Figures 5g and 5h).

These closely-spaced vibration modes are very important if the bridge structure is subjected to out-of-phase input motions at multiple supports.

## MULTIPLE-SUPPORT-EXCITATION SEISMIC ANALYSIS

For long structures extended over many supports, the spatial variation of ground motion may induce structural responses in the following ways:

1. quasi-static responses, and
2. vibrational responses.

If the seismic ground motion input at the multiple supports is completely defined in terms of ground acceleration and displacement time histories, the most direct method is the direct-integration time history analysis method. However, this is rarely the case. Typically, there is high uncertainty in the ground motion specifications. A response spectrum analysis method that will account for the spatial variation of the seismic input would be very desirable.

**Multiple-Support Ground Motion –** The spatial variations of ground motion can be attributed to attenuation effect, wave passage effect, ray-path incoherency and extended source effect. (Abrahamson et al, 1991) The spatial incoherency is expressed as a complex-valued function of frequency and separation distances. Given recorded ground motions at closely spaced stations, the coherency function can be quantitatively determined. In practice, the empirically derived coherency functions are used to define ground motion input. By varying the parameters involved, the sensitivity of the structural response to the spatial variation of ground motion can be assessed rather quickly using the multiple-support response spectrum method.

**Multiple-Support Response Method –** This method was recently developed by Der Kiureghian and Neuenhofer (1992) that would account for the multiple-support input. This is a direct extension of the CQC modal combination method under uniform input. (Der Kiureghian, 1980) Based on random vibration theory, the mean value of maximum responses (any displacement and member force component) can be expressed in terms of:

- peak ground displacements at each support,
- response spectrum at each support, and
- several cross-correlation coefficients.

In equation form, this is expressed as the sum of three terms as follows:

$$E\left[\max|z(t)|\right] = \left\{ \sum_k \sum_l a_k a_l \rho_{u_k u_l} u_{k,\max} u_{l,\max} + 2\sum_k \sum_l \sum_j a_k b_{lj} \rho_{u_k s_{lj}} u_{k,\max} D_l\left(\omega_j, \xi_j\right) + \sum_k \sum_l \sum_i \sum_j b_{ki} b_{lj} \rho_{s_{ki} s_{lj}} D_k\left(\omega_i, \xi_i\right) D_l\left(\omega_j, \xi_j\right) \right\}^{1/2}$$

where

$z(t)$ = response quantities of interest.
$a_k$, $a_l$ = effective quasi-static influence factors associated with supports k and l, respectively.
$b_{ki}$, $b_{lj}$ = effective modal influence factors for mode i (j) and support degree of freedom k (l).
$u_{k,\max}$ = peak ground displacement at support k.
$D_k(\omega,\xi)$ = displacement response spectrum associated with support k.
$\rho_{u_k u_l}$, $\rho_{u_k s_{lj}}$, and $\rho_{s_{ki} s_{lj}}$ = cross-correlation coefficients.

The three terms in the above equation account for:

1. the quasi-static effect,
2. the coupled quasi-static and dynamic effect, and
3. the dynamic effect.

The cross-correlation coefficients used account for the effects of spatial ground motion variation and the cross modal correlation. The method has been used in the study of the Golden Gate Bridge (Nakamura et al, 1993). The data flow diagram for the multiple-support response spectrum analysis is summarized in Figure 6.

In this study, an evaluation of the ground motion coherency model was carried out based on measured time histories. The time histories were selected to conduct the time history response analysis using the calibrated structural model. The coherency model and the ground motion response spectra are used to derive all necessary correlation coefficients. The multiple-support response spectrum analysis will be carried out to compare with the time history analysis results.

## ACKNOWLEDGMENTS

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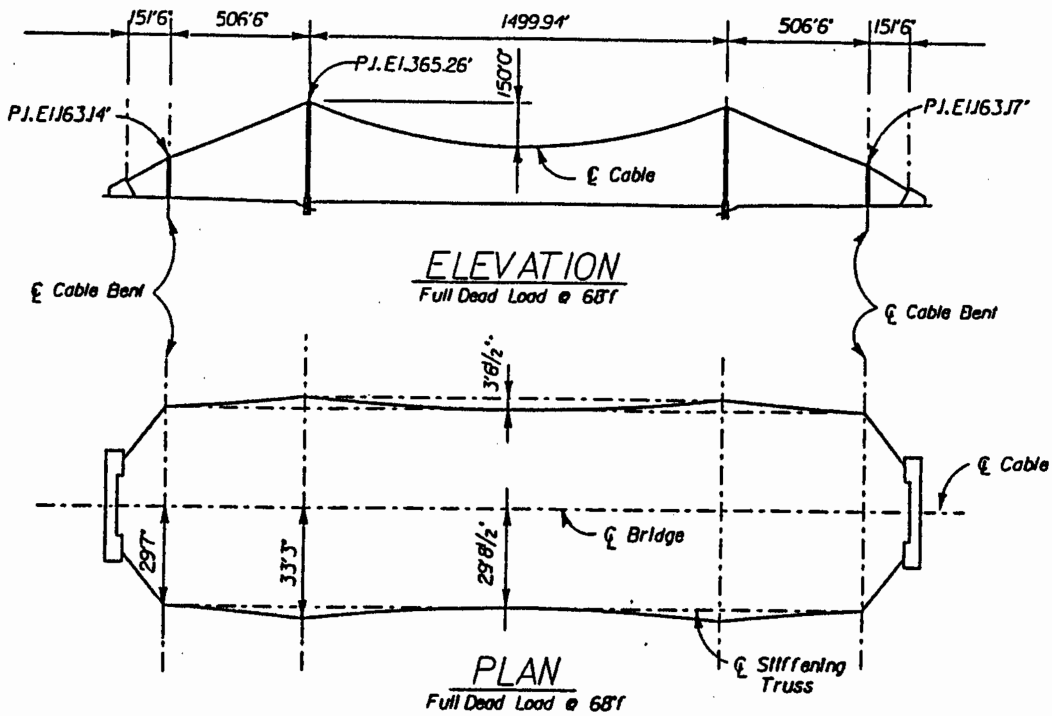
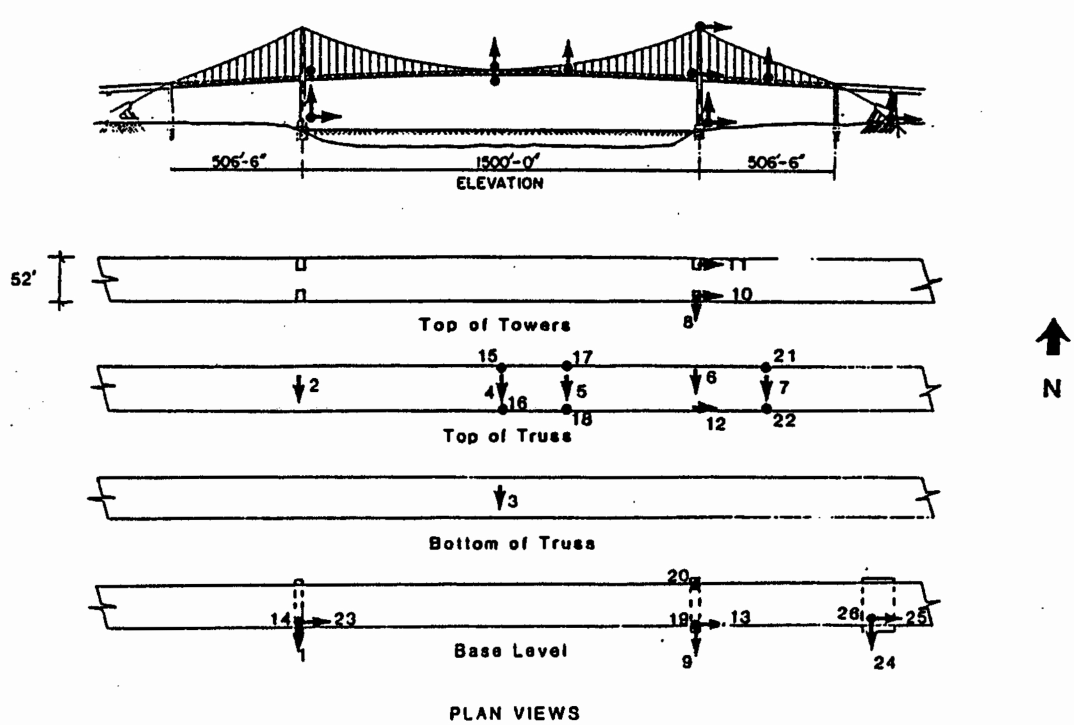



Figure 1 Cable Profiles-Vincent Thomas Bridge

Figure 2 Sensor Layout

Los Angeles – Vincent Thomas Bridge

(CSMIP Station No. 14406)



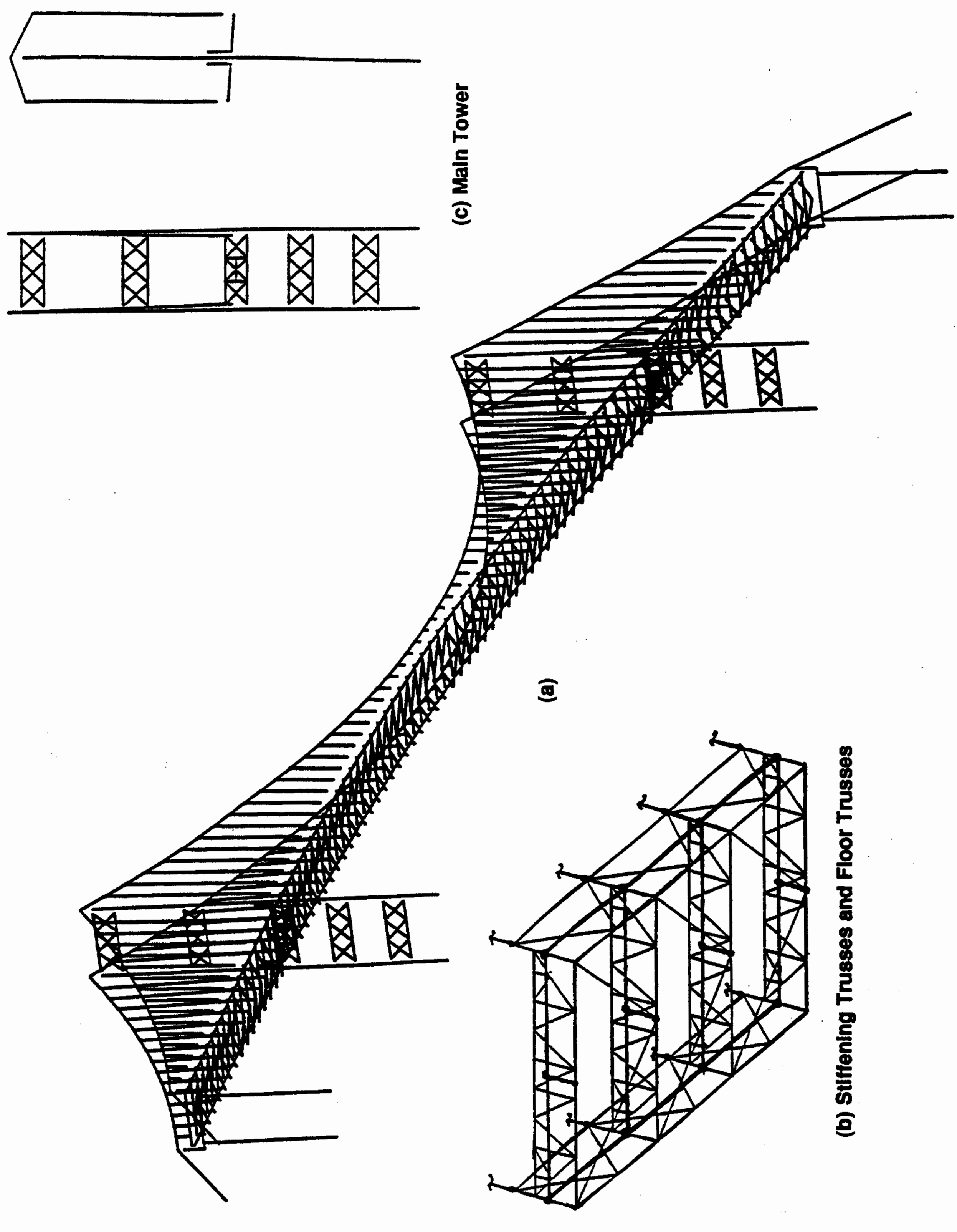
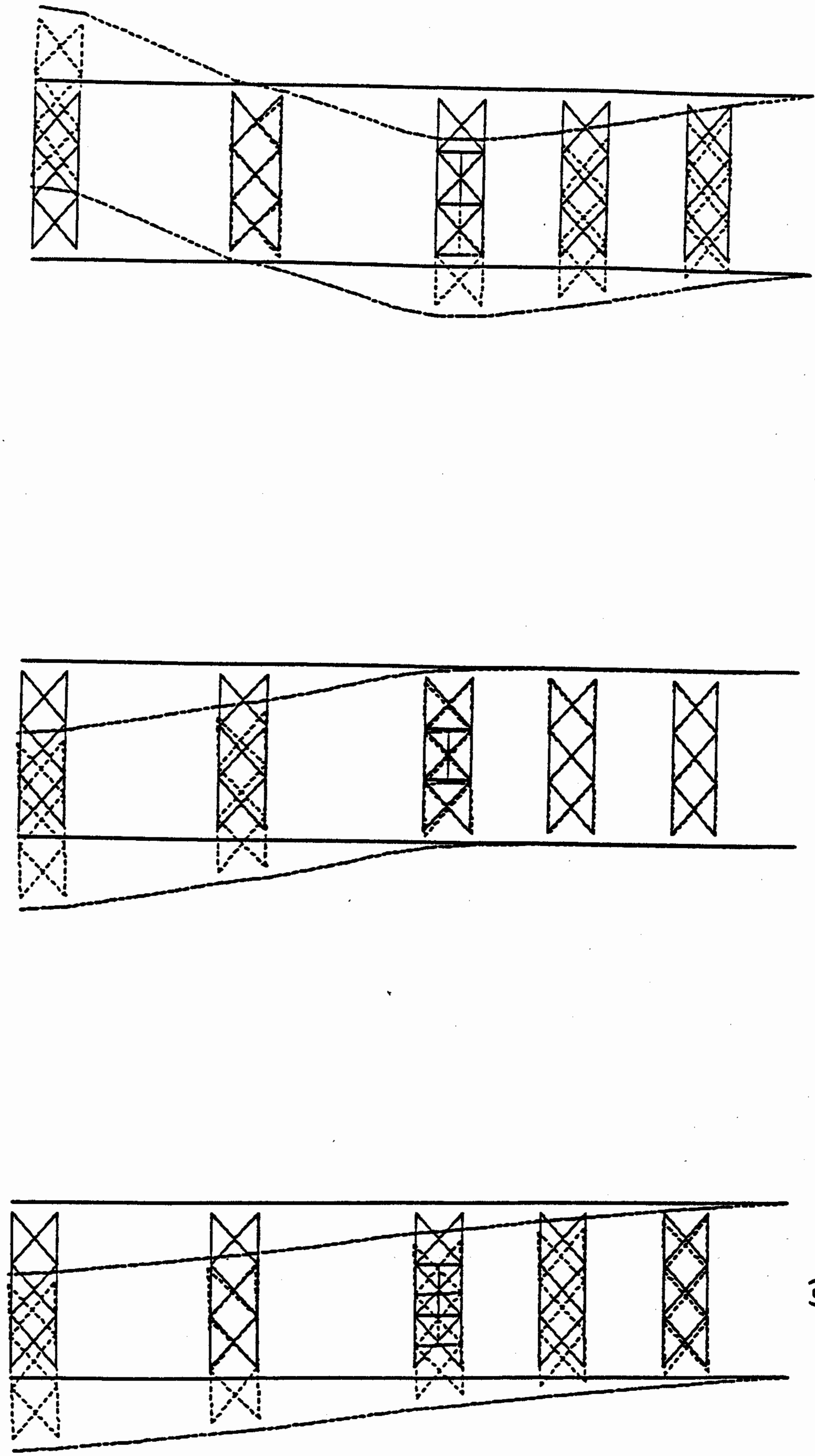



Figure 3 3D Model of the Vincent Thomas Bridge



(a)
Model : T=1.36 to 2.26 sec.
Measured: T= 1.5 & 1.7 sec.

(b)
Model : T=0.85 sec.
Measured: T= 0.79 sec.

(c)
Model : T=0.47 sec.

**Figure 4 Transverse Vibration Modes - Vincent Thomas Bridge**

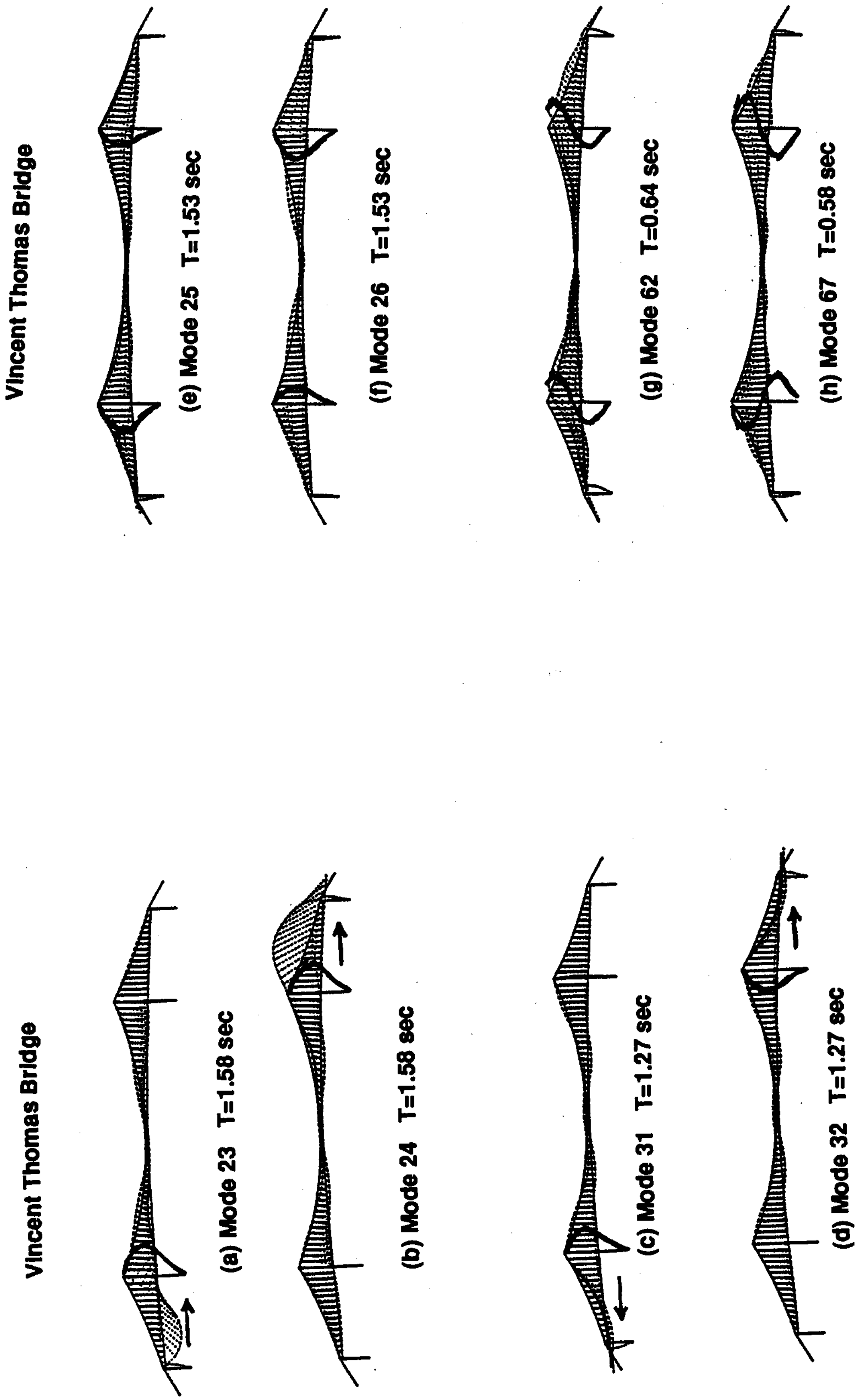



Figure 5 Longitudinal Vibration Modes

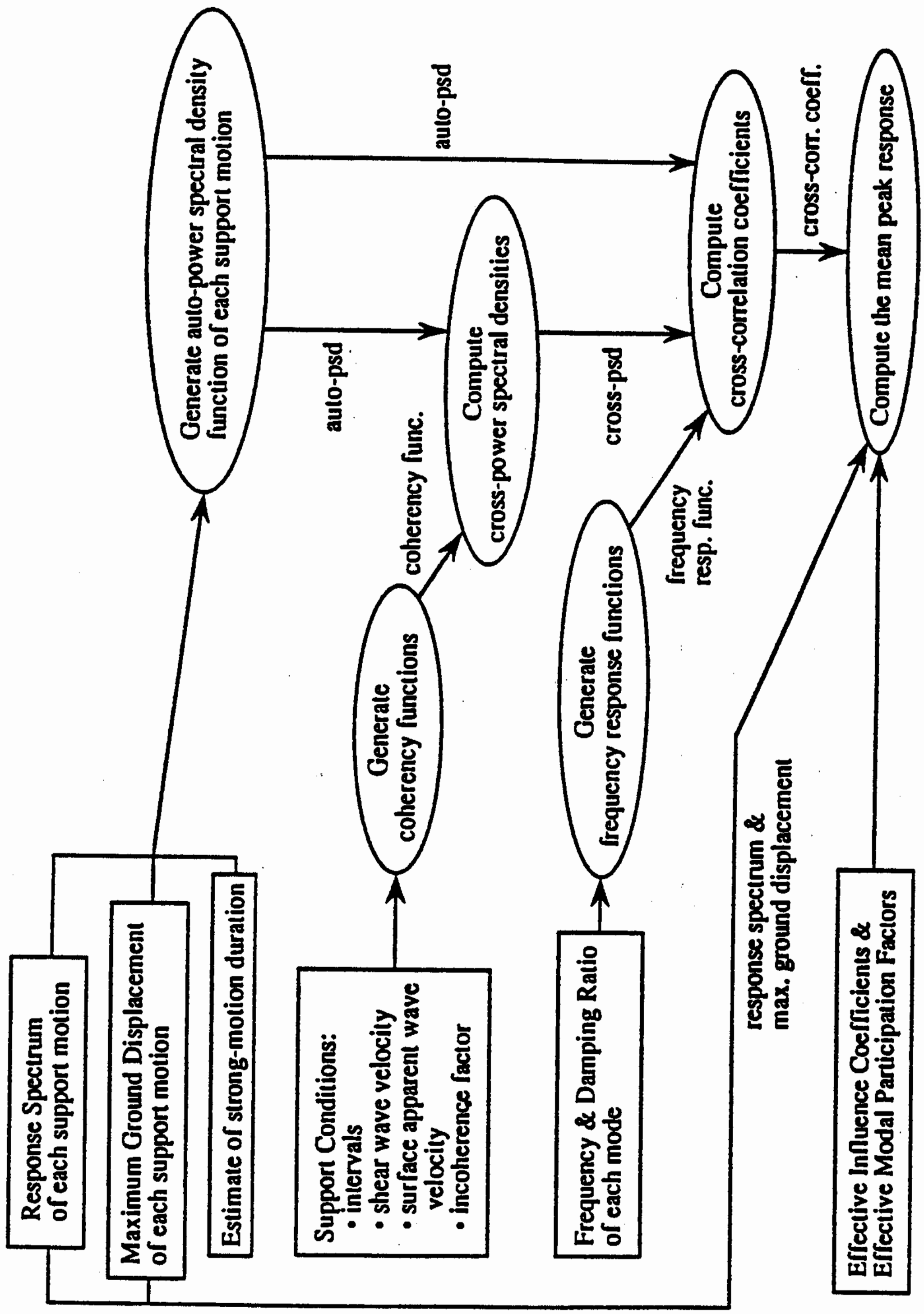



**Figure 6 Data Flow Diagram for Multiple-Support Response Spectrum Analysis (Nakamura, et al 1993)**