Seismic Soil-Structure Interaction Including Non-Synchronous Motion Effects for Structures with Torsional Eccentricities

Dan M. Ghiocel, Ph.D.
Advanced Computational Software Inc., New York, USA
dghio@aol.com

ABSTRACT

The paper addresses the seismic behavior of buildings with torsional eccentricies to a complex seismic wave environment. Specifically, the paper investigates the effects of nonsynchroneus seismic motion on a L-shaped building with significant torsional eccentricity. The building represents a typical concrete-steel composite industrial structure sitting on a soft soil deposit with a shear wave velocity of 1000 fps. The foundation consists of isolated foundations under the walls and columns. The incoherent seismic motion at the foundation level is idealized by a homogeneus stochastic field with isotropic/anisotropic correlation structure. The directional wave passage effect is introduced by time lags between the soil motions at different locations. The seismic SSI analysis was performed using the ACS SASSI computer code which includes the capability of considering nonsynchroneus input excitations.

Introduction

The severe effects of nonsynchroneous seismic motions, including incoherency and wave passage effects, on torsional response of buildings have been repeatedly remarked from field observations after earthquakes. Many buildings with high lateral stiffness but with small torsional stiffness suffered significant damages. Typically, the perimeter columns were heavily damaged. These field observations were more obvious for buildings with torsional eccentricities than without. For these buildings, torsional modes of were excited by the nonsynchroneous input motion. When SSI effects were present, these input motion effects can be more drastic.

The present paper is focused on these aspects which are of great significance for seismic design. Using a refined computational tool the paper quantifies the torsional structural effects produced by a nonsynchroneous seismic input motion on a L-shaped industrial building structure. The SSI analysis was performed using the ACS SASSI computer code (Lysmer et. Al. 1981, Ghiocel, 1997). This computer code includes options for motion incoherency and wave passage effects based on a stationary/homogeneous stochastic field model of soil motion.

Nonsynchroneus Seismic Motion Model

Assuming that the seismic wave field, U, can be modeled by a plane wave motion, the cross-spectral density of motion stochastic field for two points i and k, can be expressed by

$$S_{Ui,Uk}(\omega) = [S_{Ui,Ui}(\omega) S_{Uk,Uk}(\omega)]^{1/2}\,Coh_{Ui,Uk}(\omega) \qquad (1)$$

where $S_{Uj,Uk}(\omega)$ is the cross-spectral density function for point motions Ui and Uk, and $S_{Uj,Uj}(\omega)$, j = i,k is the auto-spectral density for location point j. Inversely, from equation (1), the coherence between the two arbitrary motions can be derived as a complex function of frequency:

$$Coh_{Uj,Uk}(\omega) = \frac{S_{Uj,Uk}(\omega)}{[S_{Uj,Uj}(\omega) S_{Uk,Uk}(\omega]^{1/2}} \qquad (2)$$

The coherence is a measure of the similarity of the two point motions, including both the amplitude spatial variation and the wave passage effects. Most commonly in engineering applications, the so-called “lagged” coherence is used (Abrahamson et al., 1990). The lagged coherency includes only the amplitude randomness and removes the wave-passage randomness. From physical point of view, the lagged coherence represents the fraction of the total power of seismic motion which can be idealized by a single deterministic plane wave motion called the coherent motion. In the current earthquake engineering language, the lagged coherence is often called simply coherence. More generally than the “lagged” coherence, the “unlagged” coherence includes the wave-passage random effects. The “unlagged” coherence, $Coh_{U\,Ui,Uk}(\omega)$, including both the amplitude spatial variation and wave-passage random effects, is defined in terms of the “lagged” coherence, $Coh_{L\,Ui,Uk}(\omega)$ by:

$$Coh_{U\,Ui,Uk}(\omega) = Coh_{L\,Ui,Uk}(\omega)\exp[i\,\omega(X_{D,i} - X_{D,j})/V_D] \tag{3}$$

The term $\exp[i\omega(X_{D,i} - X_{D,j})/V_D]$ in equation (3) represents the wave passage effect in the direction D, which is expressed in frequency domain by a phase angle between the two motions at two locations with coordinates X_i and X_j in horizontal plane. The parameter V_D is the apparent horizontal seismic wave velocity that is given by the projected distance between the two motion locations on D direction over the horizontal propagation time.

Based on the experimental evidence of different records of past earthquakes, and assuming the seismic motion field U is homogeneous, the following analytical forms for the "lagged" coherence function were considered herein:

(i) Luco-Wong model (Luco and Wong, 1986), defined by

$$Coh_{L\,Ui,Uk}(\omega) = Coh(|X_i - X_j|, \omega) = \exp[-(\gamma\omega|X_i - X_j|/V_s)^2] \tag{4}$$

in which γ is the coherence parameter and V_S is the shear wave velocity in the soil. The above analytical expression compared with others given in the technical literature based on experiment fitting (Hoshiya and Ishii, 1983, Harichandran and Vanmarcke, 1986, etc.) has the advantage of a theoretical support based on the analytical formulation of shear wave propagation in random media (Uscinski, 1977). Luco and Wong, 1986, suggested that the coherence parameter has generic values in the range of 0.10 to 0.30.

(ii) Abrahamson model (Abrahamson, 1990), defined by

$$Coh_{L\,Ui,Uk}(\omega) = Coh(|X_i - X_j|, \omega) =$$

$$Tanh\{(a1 + a2|X_i - X_k|)[\exp[-(b1 + b2|X_i - X_k|)\frac{\omega}{2\pi}] + \frac{1}{3}(\frac{\omega}{2\pi})^{-c}] + k\} \tag{5}$$

where a1, a2, b1, b2 and c are model parameters. The values of the fitting parameters based on Lotung field data records are a1=2.55, a2=-0.012, b1=0.115, b2=0.00084, c=0.878 and k=0.35 (Abrahamson, 1990).

Using the ACS SASSI code, the “lagged” incoherent motion field can be assumed isotropic or anisotropic. In the last case, the coherence function for the horizontal and vertical motion components can be different. In the horizontal plane the input motion field can be defined as being anisotropic along a predefined direction D arbitrarily oriented. Using a Luco-Wong model, the coherence along the line D is adjusted by changing its parameter γ. The coherence parameter “adjustment” is based on the following relationship:

$$\gamma_D = \gamma(1 - a|\cos(\alpha_{i,j} - \alpha)|) \tag{6}$$

where the parameter a is a scale factor and in the difference $(\alpha_{i,j} - \alpha)$ is the relative angle between the horizontal line defined by point locations i and j (with inclination angle $\alpha_{i,j}$) and the direction D (with inclination angle α). The scale factor a has values between zero and one.

A zero value of the scale factor a corresponds to isotropic horizontal motion field, i.e. same coherence parameter for all horizontal directions, while an unit value corresponds to an anisotropic horizontal motion field with coherent motions along the direction D, i.e. cylindrical coherence with a coherence parameter of zero along D.

To implement the stochastic field model of incoherent soil motion, the "lagged" coherence matrix was decomposed using a spectral factorization. Each element of coherence matrix was expressed using the eigen-expansion

$$Coh_{Ui,Uk}(\omega) = \sum_{n}^{N} \lambda_n(\omega)\Phi_n(X_i,\omega)\Phi_n(X_k,\omega) \qquad (7)$$

in which λ_n and Φ_n represent the eigenvalues and eigenvectors of the coherence matrix. Then, the directional wave passage effect is included in the soil motion frequency representation by the complex amplitude factor $\exp(i\omega(X_{D,i} - X_{D,k})/V_D)$.

The nonsynchroneous amplitude in frequency domain, U, at any location Xi, including both motion incoherency and directional wave passage effect is approximated by

$$U(X_i,\omega) = U_o(\omega)[\sum_{n=1}^{N} \sqrt{\lambda_n(\omega)}\Phi_n(X_i,\omega)]\ \exp(i\,\omega X_{D,i}/V_D)) \qquad (8)$$

where $U_0(\omega)$ is the coherent seismic motion in frequency domain and $X_{D,i}$ is the projected coordinate of motion location on direction D (with respect to control motion point). The ACS SASSI code uses the equation (8) for defining the nonsynchroneous input motions in conjunction with the flexible volume substructuring method for SSI analysis.

Illustrative Example

The illustrative example shows the effects of nonsynchroneus seismic motion on a L-shaped building with significant torsional eccentricity. The building model shown in Figure 1, represents a typical concrete-steel composite industrial structure sitting on a soft soil deposit with a shear wave velocity of 1000 fps. The foundation consists of isolated foundations under the walls and columns. The incoherent seismic motion at the foundation level was idealized by a homogeneus stochastic field with an isotropic and respectively, anisotropic correlation structure. The control motion was the El Centro NS accelerogram input along X axis of the building. The wave passage effect was also introduced by time lags on the soil motions at different foundation locations along the preferential horizontal direction of the earthquake. The incoherent-wave passage soil-structure interaction analysis was performed using the ACS SASSI computer code.

The computed results indicate patterns of very complex effects due simultaneous effects of motion incoherency and directional wave passage effects. Different values of motion incoherency parameters or wave passage parameters influence significantly the building torsional response. Motion incoherency was modeled using a Luco-Wong model. Herein, are presented only the results computed for an “upperbound” of motion incoherency defined by a coherence parameter of 0.4.

Figure 2 and 3 shows the amplitude transfer functions of the acceleration response at the building roof for two opposite diagonal corners. These two roof corners are the roof corner (node 31 in Figure 1b) above the “stiff” concrete part of the building, and the roof corner (node 45 in Figure 1b) above for the “flexible” steel part of the building. The computed transfer functions indicate a large response amplification at the “flexible” corner. The spectral peaks of transfer functions are at different frequencies, 7.83 Hz and 3.90 Hz, due to the nonuniform lateral stiffness distribution of the building at the first floor level. The seismic responses in a perpendicular direction, not shown in here, were significant, indicating a strong torsional response. The spectral peaks of transfer functions at the two roof corners, “stiff” corner (node 31) and “flexible” corner (node 45), were 30% and 60%, respectively, higher for incoherent soil motion than for coherent soil motion.

For the base corner column under the “flexible” roof corner (connecting nodes 66 and 69 in Figure 1b) the maximum bending moment increases by approximately 50% due to effects of motion incoherency. The wave passage effects were of less significance for an apparent horizontal wave velocity of 1000 fps.

Concluding Remarks

The paper illustrates that the effects of nonsynchroneous seismic motion can be severe for buildings with significant mass eccentricities. The illustrative example shows that for the investigated L-shaped industrial building the effects of motion incoherency may increase the bending moments in the corner columns up to 50%. Further future research investigations of these effects of great significance for seismic design are very needed.

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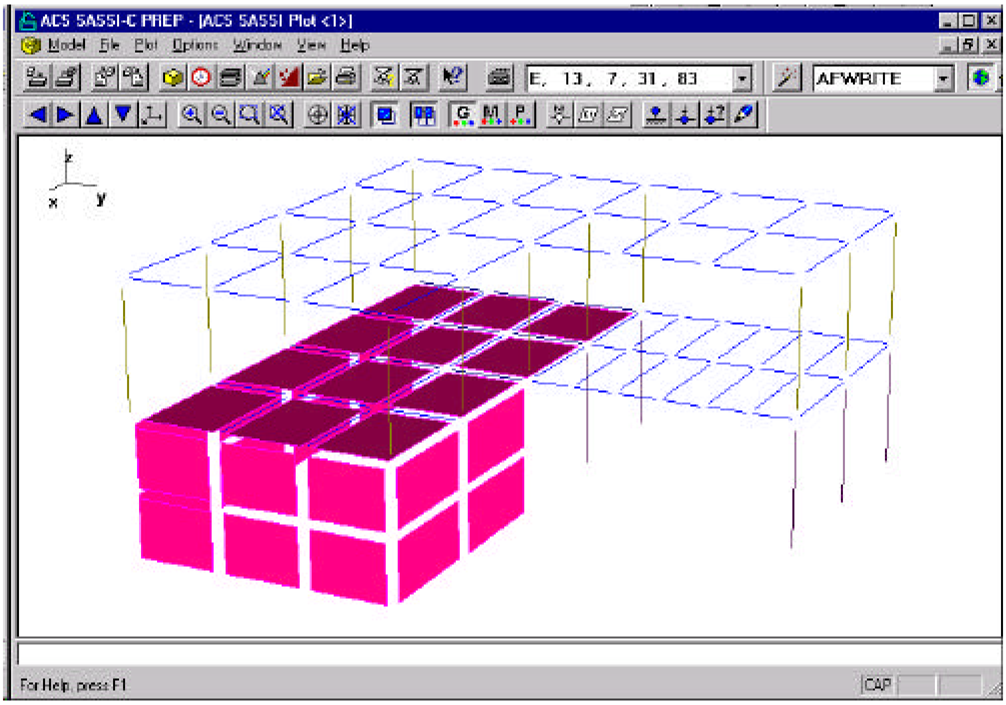
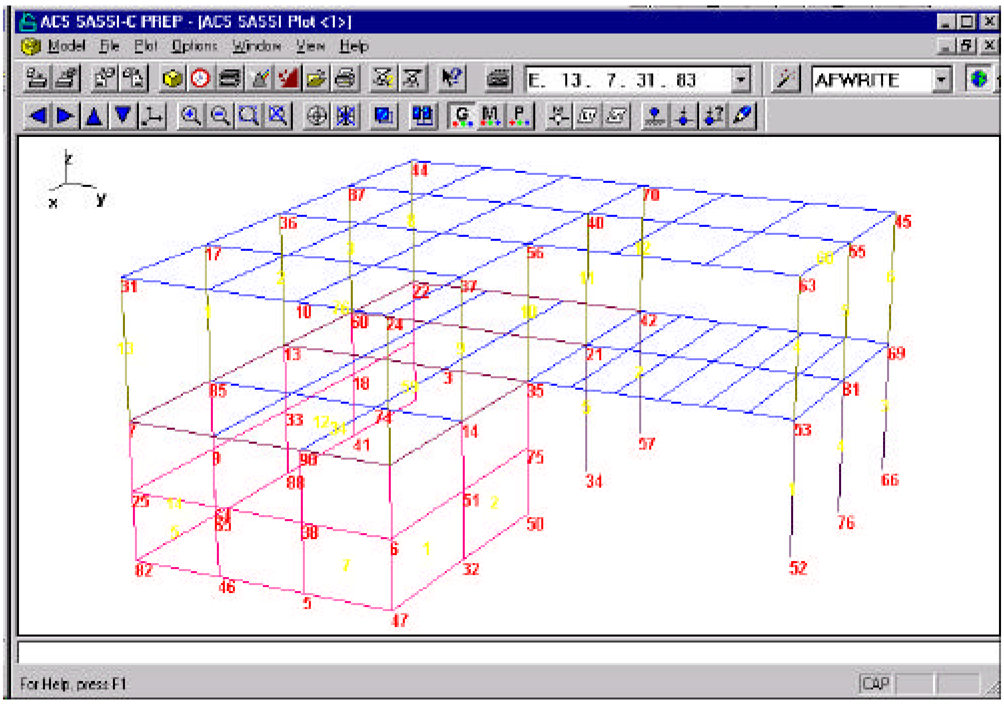


a) L-shaped Building Model



b) Node Numbering

Figure 1. L-shaped Building

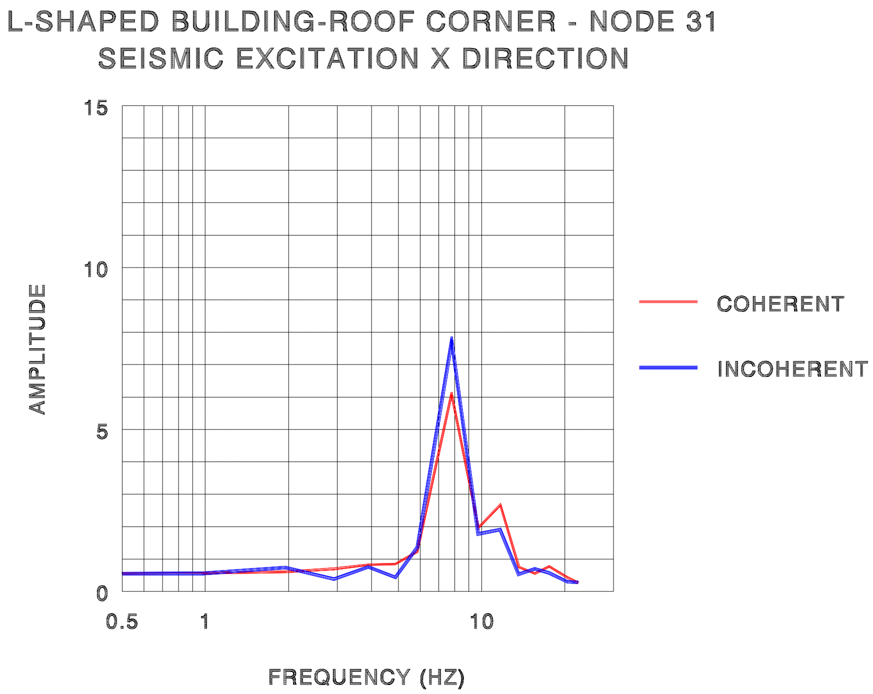


Figure 2. Horizontal Transfer Functions at the “Stiff” Roof Corner, Node 31

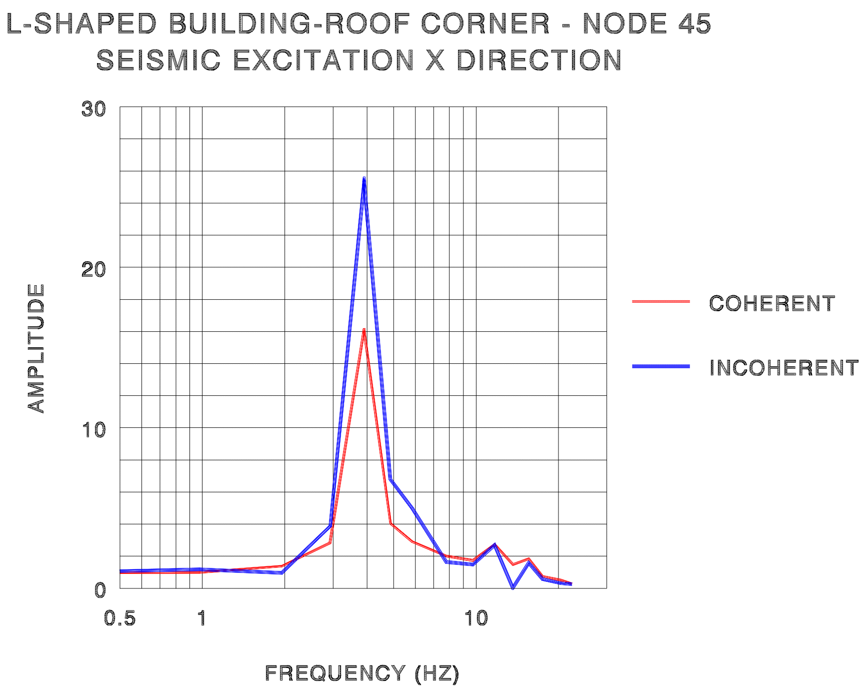


Figure 3. Horizontal Transfer Functions at the “Flexible” Roof Corner, Node 45