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American Society of Civil Engineers

Seismic Analysis of Safety-Related Nuclear Structures and Commentary

This document uses both Système International (SI) units and customary units.

NUCLEAR REGULATORY COMMISSION 169

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$\{\dot{X}\}$ = column vector of relative velocities ($n \times 1$);
$\{\ddot{X}\}$ = column vector of relative accelerations ($n \times 1$);
$\{U_b\}$ = influence vector; displacement vector of the structural system when the support undergoes a unit displacement in the direction of the earthquake motion ($n \times 1$);
n = number of dynamic degrees of freedom;
$\ddot{u}_g$ = ground acceleration.

(b) Eq. 3.2-1 may be solved using the modal superposition or direct integration time history methods.

3.2.2.2.1 Modal superposition

(a) The modal-superposition method may be used when the equations of motion (Eq. 3.2-1) can be decoupled using the transformation:

$$\{X\} = [\phi]\{Y\} \qquad \text{(Eq. 3.2-2)}$$

where

$[\phi]$ = normalized mode shape matrix; $[\phi]^T[M][\phi] = [{}^{\backslash}1_{\backslash}]$ [This is an ($m \times m$) identity matrix];
$\{Y\}$ = vector of normal, or generalized, coordinates ($m \times 1$);
m = number of modes considered.

(b) The transformation of Eq. 3.2-2 will decouple the equation of motion (Eq. 3.2-1) when terms like $\{\phi_i\}^T[C]\{\phi_j\}$, $i \neq j$, are small and can be neglected. This approximation is used in most practical cases including the structural systems with composite damping described in Sections 3.1.5.2 and 3.1.5.3. When experience shows that such an approximation is inappropriate, or a more accurate analysis is desired, a method which accounts for nonclassically damped systems may be used.

(c) The decoupled equation of motion for each mode may be written as:

$$\ddot{Y}_j + 2\lambda_j\omega_j\dot{Y}_j + \omega_j^2Y_j = -\Gamma_j\ddot{u}_g \qquad \text{(Eq. 3.2-3)}$$

where

Y_j = generalized coordinate of jth mode;
λ_j = damping ratio for the jth mode expressed as fraction of critical damping;
ω_j = circular frequency of jth mode of the system (rad/s);
Γ_j = modal participation factor of the jth mode;

$$= \frac{\{\phi_j\}^T[M]\{U_b\}}{\{\phi_j\}^T[M]\{\phi_j\}} = \{\phi_j\}^T[M]\{U_b\} \qquad \text{(Eq. 3.2-4)}$$

(when mass normalized so denominator equals one).

The single-degree-of-freedom equations shall be integrated using a proven technique, such as those listed in Table 3.2-1.

(d) The techniques used for determining mode shapes and frequencies shall have convergence checks to ensure accuracy.

(e) It shall be sufficient to include all the modes in the analysis having frequencies less than the ZPA frequency, provided that the residual rigid response due to the missing mass is calculated from Eq. 3.2-5 and is combined algebraically with the response from Eqs. 3.2-2 and 3.2-3.

$$[K]\{X_o\} = -[M]\left\{\{U_b\} - \sum_{i=1}^{m}\Gamma_i\{\phi_i\}\right\}\ddot{u}_g \qquad \text{(Eq. 3.2-5)}$$

(f) Alternatively, the number of modes included in the analysis shall be sufficient to ensure that inclusion of all remaining modes does not result in more than 10% increase in total responses of interest.

3.2.2.2.2 Direct integration

(a) Direct integration of the equations of motion (Eq. 3.2-1) may be used. Either implicit or explicit methods of numerical integration may be used to solve the equations of motion.

3.2.2.3 Nonlinear Methods

(a) When performing a nonlinear analysis, the following shall be considered:

1. Geometric nonlinearities that significantly alter the effective system geometry, such as large displacements or significant gaps;
2. Material nonlinearities, such as plasticity or friction, in the range of response under consideration.

(b) The direct-integration and modal-superposition procedures (when appropriate) are acceptable methods to use for solution.

(c) Nonlinear analyses, shall, in general, consider all three components of earthquake motion, which shall be considered to act simultaneously unless it can be shown that individual component responses are uncoupled.

(d) In general, more than one set of acceleration time histories, meeting the requirements of Section

2.3, should be used, and the results of the analyses shall be averaged.

3.2.3 Response Spectrum Method

3.2.3.1 Linear Methods

(a) When the response spectrum method is used, the basic equations of motion given by Eq. 3.2-1 shall be uncoupled using the linear coordinate transformation of Eq. 3.2-2 and represented by the uncoupled, individual equation for each mode as given by Eq. 3.2-3.

(b) The generalized response of each mode shall be determined from:

$$Y_j(\max) = \Gamma_j \left(\frac{S_{aj}}{\omega_j^2}\right) \qquad \text{(Eq. 3.2-6)}$$

where S_{aj} is the spectral acceleration corresponding to frequency ω_j.

(c) The maximum displacement of node i relative to the base due to mode j is:

$$X_{ij}(\max) = \phi_{ij} Y_j(\max) \qquad \text{(Eq. 3.2-7)}$$

(d) In performing the calculations using Eqs. 3.2-6 and 3.2-7, and in calculation of the response quantities, the signs of the participation factor, Γ_j, the maximum generalized coordinate, $Y_j(\max)$, the maximum displacement of node i relative to the base due to mode $j, X_{ij}(\max)$, and other response quantities, shall be retained.

(e) Include all the modes in the analysis having frequencies less than the ZPA frequency or cutoff frequency, provided that the residual rigid response due to the missing mass calculated from Eq. 3.2-8 is added.

$$[K]\{X_o(\max)\} = M \times \left\{\{U_b\} - \sum_{i=1}^{n} \Gamma_i\{\phi_i\}\right\} S_{A\max} \qquad \text{(Eq. 3.2-8)}$$

where

$S_{A\max}$ = highest spectral acceleration in the interval between the cut-off frequency and ZPA.

Alternatively, the number of modes to be included in the analysis shall be determined as in Section 3.2.2.2.1(f).

(f) For modal combination purposes the residual rigid response $\{X_o(\max)\}$ shall be considered as an additional mode having a frequency equal to the ZPA or cutoff frequency.

(g) Individual modal and component responses shall be combined in accordance with the requirements of Section 3.2.7.

3.2.3.2 Nonlinear Methods

The response spectrum method cannot be applied in a rigorous manner to nonlinear multi degree-of-freedom systems because superposition of modes is no longer valid; however, there are approximate methods which may be used with adequate accuracy.

3.2.4 Complex Frequency Response Method

3.2.4.1 General Requirements

When the complex frequency response method is used for seismic time history analysis, the following requirements shall be met:

(a) The time interval for the input time history shall be chosen so that the maximum frequency of interest is retained.
(b) The frequency interval for calculation of transfer functions shall be selected to accurately define the transfer functions at structural frequencies.
(c) A quiet zone (trailing zeros) shall be added to the excitation time history. The quiet zone shall be long enough to damp out the transient response to ensure zero initial conditions.
(d) The transfer functions shall be established at a minimum 150 points in the 0 to ZPA frequency range unless the use of a lesser number of points or a lower upper frequency limit is justified.

3.2.4.2 Response Time History

When the complex frequency response method is used, the response time history, $R(t)$, may be expressed as:

$$R(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} R(\omega) e^{i\omega t}\, d\omega \qquad \text{(Eq. 3.2-9)}$$

where $R(\omega)$ is the response in the frequency domain and is given by:

$$R(\omega) = T(\omega)\ddot{u}_x(\omega) \qquad \text{(Eq. 3.2-10)}$$

where

$T(\omega)$ = transfer function for the structure at circular frequency ω;
ω = circular frequency;

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