

## **APPLICATION OF THE MODAL PUSHOVER PROCEDURE TO ESTIMATE NONLINEAR RESPONSE ENVELOPES**

**Kerri Tokoro and Charles A. Menun**

The necessary size and strength of a seismically-loaded structural component is often controlled by the simultaneous action of two or more loads and/or deformation demands (collectively called response quantities). For example, a column in a moment frame must be proportioned to resist an axial force and bending moment that act concurrently and vary in time. For any specified combination of responses, the adequacy of the element to resist those responses is usually ascertained using an interaction diagram, which defines the boundary between the safe and unsafe response combinations. Most of the commonly used interaction diagrams, such as those associated with moment-axial interaction in steel or reinforced concrete columns, have remained relatively unchanged for many years, suggesting that the capacity of structural elements subjected to interacting responses is well understood. However, to use these interaction diagrams effectively with seismically-loaded elements, the engineer must also have reliable estimates of the peak values of the responses and a model for the correlation that exists between them, since it is often observed that the critical response combination that occurs in an element during an earthquake does not include the peak value of any of the responses.

It is common in the current practice to estimate the peak values of seismic response quantities using the nonlinear static procedure (NSP) prescribed by FEMA 273; however, it is well known that this procedure is not well suited to responses that receive significant contributions from more than one mode of vibration. The modal pushover analysis (MPA) procedure was used to address this problem with the conventional NSP. For several response quantities commonly used to assess the seismic performance of a structure, the MPA procedure has a level of accuracy that is comparable to that of response-spectrum-based analyses performed on linear structures.

Unfortunately, neither the NSP nor the MPA procedure provides any indication of the correlation between two response quantities in time. Consequently, for elements controlled by response interaction, it is common in the current practice to use the estimates of the individual response maxima provided by the NSP or MPA procedures to construct a rectangular envelope, which is compared to the interaction diagram of the element. However, this practice, which implicitly assumes that the responses are perfectly correlated, can be overly conservative for structures responding in their linear-elastic range. To address this problem in linear structures, a response-spectrum-based procedure for predicting the envelope that bounds two or more seismic responses as they evolve in time has been previously developed. Modification of a linear response-spectrum-based envelope is used to extend the approach to structural systems possessing material nonlinearities by incorporating the results provided by MPA analyses.

To demonstrate the accuracy of the proposed procedure, envelopes that bound (1) the bi-directional inter-story drifts and (2) the axial forces and bending moments in selected columns of a three-story steel-moment-resisting-frame building are examined. Quantification of this accuracy is made by comparing the predicted envelope to the mean simulated response envelope obtained from an ensemble of nonlinear dynamic analyses. These comparisons serve to demonstrate that the proposed procedure, while not as accurate as the existing response-spectrum-based procedure available for linear structures, does provide a reasonable estimate for the envelope that bounds a pair of seismic responses in a nonlinear structure that is appropriate for structural design and analysis.