PROPOSAL 2-5—Revision 5 (2009) Part 3

SCOPE: Proposed New Chapter 16 for the *2009 Provisions*

Reason for Proposal:

1. When Response History Analyses (RHA) are used, they are commonly used as an MCE verification after a preliminary design has been completed. This code change adds a number of important requirements for RHA, to be conducted at the MCE level.
2. The code change also revises requirements to provide a better overview and organization to the chapter, provide consistency with and remove duplication of analysis requirements in Chapter 12, and avoid repeated language within Chapter 16
3. The chapter is reorganized to emphasize nonlinear RHA, although linear RHA remains an option.

The proposal extensively modifies and reorganizes Chapter 16. The entire chapter as proposed is shown below as new.

CHAPTER 16
SEISMIC RESPONSE-HISTORY ANALYSIS

16.1 GENERAL REQUIREMENTS

A response-history analysis (RHA) shall consist of an analysis of a mathematical model of the structure to determine its response, through methods of numerical integration, to suites of ground motion acceleration histories. The analysis shall be performed in accordance with the requirements of this chapter. Structures with elements of the seismic force-resisting system responding significantly beyond their elastic limit shall satisfy Section 16.3.12. Where the analysis is used to validate a design that uses the exceptions in Section 16.1.1, the ground motions shall be scaled to the MCE ground motion level per Section 16.2 and the acceptance criteria shall meet Section 16.4.

16.1.1 Design Requirements. The design of the structure shall meet all requirements of the equivalent lateral force procedure or modal response spectrum analysis in accordance with Section 12.6, except that specific exceptions to such requirements are permitted to be taken, provided the exceptions are:

1. clearly identified in the documentation submitted for Design Review, and
2. justified through rational application of the RHA.

16.1.2 Level of Ground Motion. The analysis shall be based on the MCE ground motions, defined in Section 11.4.

16.1.3 Occupancy Categories III and IV. For Occupancy Categories III and IV, the ground motion is per Section 16.1.2, but the acceptance criteria per Section 16.4are more restrictive compared to values applicable to Occupancy Categories I and II.

Where alternative acceptance criteria are used, they shall be demonstrated to be consistent with the importance factor I per Section 11.5.

Nonstructural elements shall be designed per Chapter 13 using I_p per Section 13.1.3.

16.2 GROUND MOTION

A suite of not less than seven appropriate ground motions shall be used in the analysis.

Appropriate ground motion acceleration histories shall be obtained from records of events having magnitudes, fault distance, and source mechanisms that are consistent with those that control the maximum considered earthquake. Where the required number of appropriate recorded ground motion records are not available, appropriate simulated or modified ground motion records are permitted to be used to make up the total number required.

Where applicable, the ground motion acceleration histories shall include near fault and directivity effects including direction of fault rupture and velocity pulses, as appropriate.

16.2.1 Duration. Each response-history analysis shall be run for the full duration of the ground motion, except that the first or last portion of the record provide that the truncation does not significantly modify either the frequency content or the number of cycles of ground motion with an amplitude sufficient to induce nonlinear response.

16.2.2 Two-Dimensional Analysis. Where two-dimensional analyses are performed, each ground motion shall consist of a horizontal acceleration history. The ground motions shall be scaled such that the average value, over all ground motions, of the 5 percent damped response spectra for the suite of motions is not less than the MCE response spectrum for the site for periods ranging from $0.2T$ to $1.5\ T$ where T is the natural period of the structure in the fundamental mode for the direction of response being analyzed.

16.2.3 Three-dimensional Analysis. Where three-dimensional analysis is performed, ground motions shall consist of pairs of appropriate horizontal ground motion acceleration components. For each pair of horizontal ground motion components, an SRSS spectrum shall be constructed by taking the square root of the sum of the squares of the five-percent-damped response spectra for the scaled components (where an identical scale factor is applied to both components of a pair). Each pair of motions shall be scaled such that for each period between $0.2T$ and $1.5T$, the average, over all component pairs, of the SRSS spectra does not fall below 1.3 times the corresponding ordinate of the MCE response spectrum by more than 10 percent.

16.3 MODELING AND ANALYSIS

Mathematical models shall conform to the requirements of Section 12.7. Design Review requirement are described in Section 16.5.

16.3.1 Interaction of Elements. The analysis shall consider the interaction of all structural and nonstructural elements that can adversely affect the response of the structure to earthquake motions, including elements not designated as part of the seismic-force-resisting system.

16.3.2 Identification of Nonlinear Response. Documentation submitted for Design Review shall identify the elements in the Seismic Force Resisting System that are designed for nonlinear seismic response. All other elements in the SFRS shall be demonstrated by analysis to remain essentially elastic; refer to 16.4.3.

16.3.3 Two-Dimensional Analysis. A 2-D analysis model is permitted to be used if Section 12.7.3 does not require a 3-D model, or if documentation submitted for Design Review demonstrates that the 2-D analysis captures all significant 3-D effects, including plan torsion, non-orthogonal earthquake response, engagement of overturning resistance through flange effects or transverse coupling, and non-orthogonal effects on strong-column weak-beam behavior.

16.3.4. Direction of Loading. Two-dimensional modeling shall account for direction of loading effects in accordance with Section 12.5

16.3.5 Diaphragm Modeling. Floor and roof diaphragms responding linearly shall be modeled according to Section 12.3.1.

Diaphragms responding beyond the linear range shall be modeled using nonlinear force-deformation relationships if required by Section 16.3.11

16.3.6 Seismic Mass. The masses used in the analytical model shall be as defined in Section 12.7.2. Where modal computation techniques are used for response history computation, Section 12.9.1 shall be satisfied and the results shall be multiplied by the ratio of the total mass to the mass participating in the modes included in the analysis.

16.3.7 Gravity Load. The modeling of and demands on elements in the analysis model shall be determined considering earthquake effects acting in the presence of expected gravity loads. For building structures with ordinary occupancies, expected gravity loads shall be taken as:

$$1.0D + 0.5L$$

For live loads subject to reduction on the basis of area per Section 4.8, the tributary area shall be permitted to be taken as the total floor area in the structure subject to that live load, and K_{LL} shall be set to 1.0.

For other occupancies or where the expected gravity load is not well represented by 1.0D + 0.5L or is highly variable, the analysis shall be modified accordingly.

16.3.8 P-delta effects. P-delta effects shall be included in the analysis, using the gravity loads defined in Section 16.3.7.

16.3.9 Inherent Plan Torsion. Inherent plan torsion shall be included per Section 12.8.4.1.

16.3.10 Accidental Plan Torsion. If the accidental torsion requirements of Section 12.8.4.2 are included in the determination of the strength of the nonlinear elements of the structure and in the analysis used to meet the requirements of Section 16.1.1, inclusion of accidental torsion in the RHA is not required.

16.3.11 Nonlinear Modeling. The mathematical model shall directly account for the nonlinear hysteretic behavior of the structural elements, where elements include members and connections.

The hysteretic force-deformation behavior of elements shall be modeled consistent with applicable laboratory test data and shall account for all significant yielding, strength degradation, stiffness degradation, hysteretic pinching, and interaction effects indicated by such test data. Strength of elements shall be based on expected values considering material overstrength, strain hardening, and hysteretic strength degradation, at the expected range of deformation. The behavior model shall not be extended to deformations beyond levels substantiated by test data.

Linear properties, consistent with the requirements of Section 12.7.3, are permitted to be used for those elements demonstrated by the analysis to remain within their linear range of response.

16.3.12 Stiffness. To the extent that such effects are significant for the MCE response, element properties shall account for the following:

1. Stiffness properties of reinforced concrete and reinforced masonry shall account for cracking and other phenomena that affect effective initial stiffness, including strain penetration, bond slip, joint and panel zone deformation, and tension shift associated with shear cracking.

2. Stiffness properties of steel or other connected elements shall account for connection stiffness, including for moment frames the effect of panel zone (beam-column joint) deformations.

16.3.13 Damping. The equivalent viscous damping level shall not exceed 5% of critical damping for any mode required to obtain the effective mass per Section 12.7.2, unless substantiated. Documentation submitted for Design Review shall identify how damping effects are included in the RHA to account for energy dissipation that is not considered directly in the nonlinear analysis model.

16.4 ANALYSIS RESULTS.

16.4.1 Design values. The calculation of design values shall account for the signs of response parameters and the combinations of response

parameters, such as axial force and bending moment, that can govern the design.

16.4.2 Analysis Results. The response parameters of interest shall be calculated for each ground motion used for the RHA. For peak value of each parameter shall be determined for each ground motion. The average of the peaks shall be used for checking acceptance criteria. Where a combination of response parameters is important, such as for elements resisting both flexural and axial forces, these results shall be captured to be consistent with the acceptance criteria.

16.4.3 Acceptance Criteria for Ductile Behavior. Element response that satisfies the definition for deformation-controlled actions in section 2.4.4.3 of ASCE/SEI 41 shall be evaluated on the basis of either nonlinear or linear behavior. If the calculated force in an element does not exceed 1.5 times its nominal strength, that element is permitted to be considered linear (essentially elastic).

16.4.3.1 Nonlinear Behavior of Ductile Elements. Member deformation shall not result in deterioration of its attainable member strength to less than 80 percent of the peak resistance. Deformation capacities shall be based on values tabulated in ASCE/SEI 41 or from laboratory test data for similar elements. Where ASCE/SEI 41 is used, the performance levels are to be used as follows:

1. Collapse prevention for Occupancy Categories I and II
2. Life safety for Occupancy Category IV
3. 80% of Collapse prevention, but not less than Life safety for Occupancy Category III.

Documentation shall be submitted for design review to substantiate the adequacy of individual elements and their connections to withstand the deformation demands from the RHA.

16.4.3.2: Linear Behavior of Ductile Elements. Calculated force demands shall not exceed 150% of nominal capacities divided by the I factor.

16.4.4 Acceptance Criteria for Nonductile Behavior. Any type of element response that does not satisfy the definition for deformation-controlled actions in section 2.4.4.3 of ASCE/SEI 41 shall be evaluated on a linear basis. The demands from Section 16.4.2 shall not exceed the expected strength. It shall be permitted to use the nominal strength in lieu of the expected strength.

16.4.5 Story Drift. The story drift ratio shall not exceed 1.5 times the limits of Section 12.12.1 for any story unless those elements not designated as part of the seismic force-resisting system are capable of undergoing the calculated story drift for each RHA without collapse of the portion of the structure supported by those elements.

16.4.6 Stability. The structure shall be shown to be stable for the MCE ground motions.

16.5 Design Review. A design review of the seismic force-resisting system, the structural analysis, and the documentation shall be performed by an independent team of registered design professionals in the appropriate disciplines and others experienced in seismic analysis methods and the theory and application of nonlinear seismic analysis and structural behavior under extreme cyclic loads. The design review shall include, but need not be limited to, the following:

1. Review of any site-specific seismic criteria employed in the analysis including the development of site-specific spectra and ground motion time histories.
2. Review of acceptance criteria used to demonstrate the adequacy of structural elements and systems to withstand the calculated force and deformation demands, together with that laboratory and other data used to substantiate these criteria.
3. Review of the preliminary design including the selection of structural system and the configuration of structural elements.
4. Review of the final design of the entire structural system and all supporting analyses.