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Response-History Analysis for the Design of New Buildings: A Fully Revised Chapter 16 Methodology Proposed for the 2015 NEHRP Provisions and the ASCE/SEI 7-16 Standard

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ABSTRACT

This paper is the result of a multi-year effort to rewrite Chapter 16 of the ASCE/SEI 7-10 Standard, which is entitled *Seismic Response-History Procedure*. This paper documents the newly-proposed Chapter 16 requirements, as well as the rationale and logic behind the requirements. The goals of this paper are to: (a) explain the rationale for the newly proposed requirements, for those interested in why changes are being proposed; and (b) provide detailed explanation of the new requirements, to help future users properly apply the requirements in the design of new buildings. This effort was initiated by the Building Seismic Safety Council (BSSC) Provisions Update Committee (PUC) who formed an Issue Team with the specific mandate of proposing a fully rewritten version of Chapter 16. This newly proposed Chapter 16 will become a part of the 2014 National Earthquake Hazard Reduction Program (NEHRP) Provisions and then will be considered for inclusion in the ASCE/SEI 7-16 Standard.

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1. Introduction

This paper is the result of a multi-year effort to rewrite Chapter 16 of the ASCE/SEI 7-10 Standard, which is titled *Seismic Response-History Procedure*. This effort was initiated by the Building Seismic Safety Council (BSSC) Provisions Update Committee (PUC) and a draft version of the updated Chapter 16 was produced and published in Part III of the 2009 National Earthquake Hazard Reduction Program (NEHRP) Recommended Seismic Provisions (NEHRP 2009). The BSSC PUC then formed an Issue Team with the specific mandate of finalizing the effort and proposing a fully rewritten version of Chapter 16. This newly proposed Chapter 16 is

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in the process of becoming a part of the 2015 NEHRP Provisions (an update to NEHRP 2009) and then will be considered for inclusion in the ASCE 7-16 Standard. More complete documentation of this effort can be found in Haselton et al. (2014).

2. Literature Review

The literature review for this effort included many contemporary standards and resource documents (ASCE/SEI, 2010; ASCE/SEI, 2007; (LATBSDC, 2011; AB-083, 2008; and PEER, 2010). This literature review is more fully documented in Haselton et al. (2014).

3. Goals and Evaluation Process in ASCE/SEI 7

3.1 Fundamental Goal

ASCE 7-10 defines the collapse performance goals sought by the Standard. Table 2 replicates a portion of ASCE 7-10 Table C.1.3.1b and shows that, when a building is subjected to Maximum Considered Earthquake (MCE_R) ground motion, the Standard seeks to provide not more than a 10% probability of collapse for Risk Category I and II structures. For Risk Category III and IV structures, these maximum collapse probabilities are reduced to 6% and 3%, respectively.

Table 1. Performance Goals in ASCE/SEI 7-10.

Risk Category	Tolerable Probability of Collapse	Ground Motion Level
I or II	10%	MCE_R
III	6%	MCE_R
IV	3%	MCE_R

3.2 Explicit Evaluation of Goals

Given that the collapse performance goals are now defined in ASCE 7-10, it is conceptually desirable to create a Chapter 16 RHA design process that explicitly evaluates the collapse probability and ensures that the performance goal is fulfilled. However, explicit evaluation of collapse safety is a difficult task requiring (a) a structural model that is able to directly simulate the collapse behavior, (b) use of hundreds of nonlinear response-history analyses, and (c) proper treatment of many types of uncertainties. This process is excessively complex and lengthy for practical use in design. Therefore, the updated Chapter 16 maintains the simpler approach of *implicitly* demonstrating adequate performance through a prescribed set of analysis rules and acceptance criteria (as discussed in the next section).

3.3 Implicit Evaluation of Goals

As discussed in the previous section, the proposed Chapter 16 RHA procedure evaluates collapse safety *implicitly* through the use of a prescribed set of analysis rules and acceptance criteria. The proposed Chapter 16 criteria require demonstration that the building has predictable and stable response under maximum considered earthquake (MCE_R) ground motions, that deformation and strength demands on elements are in the range of modeling validity and acceptable behavior, and that story drifts are within specified limits.

4. Framework of the Structural Design Procedure Using Response-History Analysis

Based on the literature review, the following framework is proposed for design using the updated Chapter 16 RHA procedure:

- Perform a code-level evaluation (modifications noted below). The purpose of this step is to enforce minimum levels of strength and stiffness, including the enforcement of the minimum base shear requirement imposed in Chapter 12 of ASCE 7. The following modifications are proposed for the code-level evaluation (because these items are handled in the MCE_R-level evaluation):
  - For Risk Category I, II, and III structures, the drift limits of Section 12.12.1 do not apply.
  - For Risk Category IV structures, the drift limits shall be 125 percent of the drift limits specified in Section 12.12.1.
  - The overstrength factor, Ω_0, is permitted to equal 1.0 for the seismic load effects of Section 12.4.3.
  - The redundancy factor, ρ, is permitted to equal 1.0.
- Perform an MCE_R-level evaluation. The goals of this step are to (a) to demonstrate that the building has predictable and stable response at MCE_R ground shaking levels and (b) to determine forces for the design of force-controlled (brittle) components. This step, and fulfillment of the associated acceptance criteria, demonstrates that the building has equivalent or better durability and seismic resistance as compared with designs using the basic Chapter 12 requirements.

5. Ground Motions

5.1 Ground Motion Intensity Measure

The ASCE 7-10 Standard now defines the spectral acceleration values in terms of a maximum direction spectral acceleration (Sa_{maxDir}, which is the maximum acceleration in any horizontal direction) rather than the previous definition which used a geometric mean spectral acceleration ($Sa_{g.m.}$, which is likely to be exceeded in some directions of response). The maximum direction spectral acceleration is typically about 10% larger than $Sa_{g.m.}$ at short periods and 30-40% larger at long periods (NEHRP 2009 Table C21.2-1).

The structural assessment should not depend on what type of spectral acceleration definition is being used to quantify the ground motion, provided that each step of the RHA process is completed in a manner that is consistent with the chosen spectral acceleration definition (i.e. selection, scaling, application to the structural model, and interpretation of response predictions). Given that the maximum direction spectral acceleration is now being explicitly used in the ASCE 7 Standard, the steps in the proposed Chapter 16 RHA procedure, as discussed in this paper, have been developed carefully so as to specifically account for this definition and to not enforce undue conservatism in the RHA procedure.

5.2 Level of Ground Motion

In the proposed Chapter 16 RHA procedure, the MCE_R-level evaluation is done at the MCE_R ground motion level, as the name implies, rather than the design ground motion level (which is 2/3 of MCE_R). The MCE_R level is used because this is a more direct approach for evaluating adherence to the collapse safety goals of Table 2. This approach is also consistent with other recent codes and guidelines for performance-based design procedures (per Table 1).

5.3 Definition of the Target Response Spectrum

This section starts by defining the various target spectra used in practice and then explains why two different options are proposed for inclusion in the updated Chapter 16 RHA procedure. These two proposed options are then explained in detail.

5.3.1 Explanation of Various Possible Target Spectra

Uniform Hazard Spectrum

The Uniform Hazard Spectrum (UHS) has been used as the target spectrum in design practice for the past two decades. The Uniform Hazard Spectrum is created for a given hazard level by enveloping the results of seismic hazard analysis for each period (for a given probability of exceedance). Accordingly, it will generally be a conservative target spectrum.

MCE_R Spectrum

Except in areas close to major active faults, where a deterministic expression of the MCE_R occurs, the MCE_R spectrum can roughly be thought of as a UHS with an approximate 2% probability of exceedance in 50 years.

Conditional Mean Spectra (CMS)

The Conditional Mean Spectrum (CMS) (and the Conditional Spectrum) is an alternative target spectrum to the Uniform Hazard or MCE_R spectra and can be used as a target for ground motion selection in performance-based engineering (Baker, 2011; Lin et al. 2012a and 2012b). To address the above problem that Uniform Hazard Spectrum overstates the hazard at many response periods, the Conditional Mean Spectrum instead conditions the spectrum calculation on a spectral acceleration at a single period, and then computes the mean (or distribution of) spectral acceleration values at all other periods. This conditional calculation ensures that the resulting spectrum is reasonably likely to occur, and that ground motions selected to match the spectrum have an appropriate spectral shape consistent with naturally occurring ground motions at the site of interest. Figure 1 provides examples of the Conditional Mean Spectrum for an example site in Palo Alto, California, anchored at four different candidate periods which may be appropriate for a 20-story frame building (with a fundamental period of 2.6s). The Uniform Hazard Spectrum for this example site is also provided for comparison.

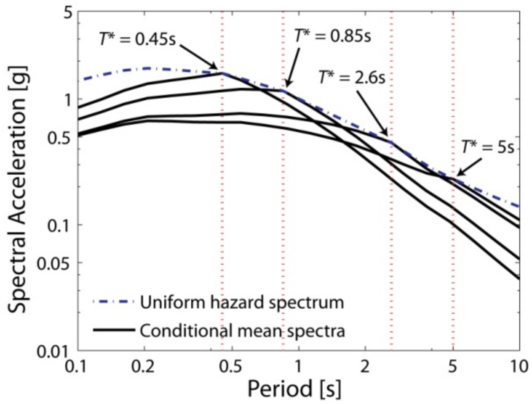

Figure 1**.** Example Conditional Mean Spectra for the Palo Alto site anchored for 2% in 50-year motion at T = 0.45s, 0.85s, 2.6s (fundamental mode), and 5s. (NIST, 2011a)

Conditional Spectra (CS)

The CMS was initially proposed with an emphasis on the mean spectrum and less attention was paid to the variability in the spectrum. A comparable target spectrum that also considers variability is termed a "Conditional Spectrum" (CS) and is not discussed in detail in this paper.

5.3.2 Proposed Methods for the Chapter 16 RHA Procedure

In the proposed Chapter 16 RHA procedure, the MCE_R target spectrum is retained (as a simpler and more conservative option) and the CMS/CS target spectra approach is also included as a new alternative (as a more appropriate approach for representing expected ground motions). These two alternative approaches are termed Method I and Method II, respectively, in the proposed Chapter 16 RHA procedure. This dual-method strategy is consistent with the approach taken in the PEER-TBI Guidelines (PEER 2009).

5.4 Ground Motion Selection

5.4.1 Minimum Number of Ground Motions

The required number of ground motions was not studied in detail in this project and remains to be an open need for future work. In the meantime, a minimum of eleven motions are proposed for the update Chapter 16 RHA procedure. This decision of eleven motions balances the desire for more statistically reliable estimates of mean structural responses (through use of more motions) with the desire to keep the required number of motions lower, to both reduce computational effort and to enable the use of multiple scenarios (such that the multiple scenarios of Method II can be used with a tractable total number of motions). Overall, it is expected that the total level of effort in the proposed Chapter 16 RHA procedure is actually lower than the current ASCE 7-10 RHA procedure.

5.4.2 Components of Ground Motion

The framework of the proposed Chapter 16 RHA procedure is such that a ground motion is typically comprised of two horizontal ground motion components, but the framework also includes the possibility of a vertical ground motion component for the unusual cases that vertical dynamic responses are clearly important (as discussed in the later modeling section).

5.4.3 Selection of Ground Motions for Sites that are not Near-Fault

The selection of recorded motions typically occurs in two steps. In the first step, the following criteria should be utilized to filter out ground motions that should not be considered as candidates in the final selection process: source mechanism, magnitude, duration, site-to-source distance, site class, and useable frequency of the ground motion. Once the filtering step has been completed, the second step is to select the final set of ground motions from the larger candidate set. The criteria for this step are spectral shape, scale factor, a maximum number of motions from a single event, and near-fault effects. Further discussion of ground motion selection is available in Haselton et al. (2014) and in the ATC-82 report, published as NIST GCR 11-917-15 (NIST 2012).

5.5 Ground Motion Scaling

5.5.1 Period Range for Scaling

In the proposed Chapter 16 RHA procedure, the ground motion level has been raised from the design ground motion level (which is 2/3 MCE_R) to the MCE_R ground motion level. Since greater inelastic response is anticipated at this level, it is proposed that the upper-bound period be raised to 2.0T, where T is redefined as the *maximum* fundamental period of the building (being the maximum of the fundamental periods in both translational directions and the fundamental torsional period). For the lower-bound period, it is proposed that the 0.2T requirement also be supplemented with an additional requirement that the lower-bound also should capture the periods needed for 90% mass participation in both directions of the building.

5.5.2 Basic Scaling Approach for Horizontal Components of Ground Motion

The proposed Chapter 16 RHA scaling procedure adopts the above ASCE 7-10 procedure, but with two changes. Firstly, scaling is based directly on the maximum direction spectrum, rather than the SRSS spectrum. This is proposed for consistency with the ASCE 7-10 MCE_R ground motion now being explicitly defined as a maximum direction motion. Secondly, the approach of enforcing that the average spectrum "does not fall below" the target spectrum is replaced with requirements that (a) the average spectrum "matches the target spectrum" and (b) the average spectrum does not fall below 90% of the target spectrum, within the period range of interest. This proposal intends to remove the conservatism associated with the average spectrum being required to *exceed* the target spectrum at *every* period within the period range.

5.5.3 Use of Spectral Matching

When spectral matching is used with this procedure the average of the spectra from all ground motion components, in a given horizontal direction, shall not be less than the target response spectrum. This is intentionally a more stringent requirement, as compared to the requirement for scaled unmatched motions, in order to compensate for the potential un-conservatism in responses obtained from spectrally matched motions. Spectral matching is not allowed for near-fault sites, unless the pulse characteristics of the ground motions are retained after the matching process has been completed. This is based on the concern that, when common spectral matching methods are utilized, the pulse characteristics of the motions may not be appropriately retained.

5.6 Application of Ground Motions to the Structural Model

5.6.1 Orientation of Ground Motions in Plan

The manner in which the two horizontal ground motion are oriented when being applied to the structural model is critically important and there is both little and inconsistent guidance for how this should be done. The recent debates about the appropriateness of various ground motion intensity measures (e.g. geometric mean versus maximum direction Sa) arguably hinge on how the ground motions are oriented when being applied to the structural model.

Sites that are not Near-Fault

For the proposed Chapter 16 RHA procedure, the maximum direction spectral acceleration is being used to describe the ground motion intensity (per ASCE 7-10). This spectral acceleration definition causes a perceived directional dependence to the ground motion. However, the direction in which the maximum spectral acceleration occurs is random in the far-field (Huang et al., 2008) and does not necessarily align with a principal direction of the building. Accordingly, for the RHA procedure to result in an unbiased prediction of structural response, the ground motions should still be applied to the structure *in a random orientation*.

Near-Fault Sites

For near-fault sites, there is a tendency for response spectra to be larger in the fault-normal direction than in the fault-parallel direction. For such sites, the fault-normal and fault-parallel components of the recorded ground motions should be maintained and applied to the corresponding orientations of the structure.

5.6.2 Application of Ground Motions over Subterranean Levels

The recent PEER TBI guidelines (PEER TBI 2009) and the recommendations contained in the ATC-82 NIST GCR 11-917-14 report (NIST 2011) both recommend inclusion of subterranean building levels in the mathematical model and the Chapter 16 RHA procedure similarly requires that this be done. More detailed guidance on soil-foundation-structure interaction, including both soil-foundation modeling guidelines and treatment of kinematic interaction effects, can be found in the ATC-82 NIST GCR 11-917-14 report (NIST 2011).

6. Modeling and Analysis

Nonlinear analysis models have been successfully used for many years. Computing power now provides analysis speeds that allow a larger number of earthquakes simulations to be run in a matter of days instead of weeks. The effort to revise Chapter 16 focused on providing clarity to the designer regarding fundamental assumptions in building nonlinear computer models and analyzing the results. Specific recommendations for modeling approaches were intentionally omitted to allow designers to utilize data from other documents and ongoing physical testing. More discussion of modeling and analysis requirements are presented in Haselton et al. (2014).

7. Interpretation of Structural Response Predictions

In the proposed Chapter 16 RHA procedure, eleven ground motions are selected and then scaled using an average-spectrum-based scaling procedure. This overall approach only provides meaningful information about the mean structural responses.

It is also often desirable to predict the variability in structural response (e.g., the standard deviation, σ) to help judge margins against undesirable performance. Even though predicting the variability in structural response is desirable, it is also difficult to accomplish in any statistically meaningful manner without running dozens of simulations.

8. Acceptance Criteria

The acceptance criteria are intended to ensure that the building conforms to the collapse performance goals shown in Table 2. Some of the acceptance criteria have been specifically developed with this objective (e.g. criteria for strength of brittle components) and some of the acceptance criteria are more historically-based and only loosely related to the collapse performance goals (e.g. story drift criteria). A future research study is warranted to redevelop each of the acceptance criteria to be more closely linked to the Table 2 collapse goals.

8.1 Global Acceptance Criteria

8.1.1 Average Story Drifts

It is proposed that the average story drift be limited to 2.0 of the typical ASCE 7-10 Table 12.12-1 limits. This limit comes from a factor of 1.5, to reflect the analysis being completed at the MCE_R ground motion level rather than at 2/3 of the MCE_R level, and a factor of 1.25, to reflect an average ratio of R/Cd. This story drift limit is simply based on consistency with other ASCE 7 design procedures and is not clearly linked to the collapse safety goals of Table 1; it would be useful if a future research effort could more clearly link this story drift acceptance criterion to the intended safety goal.

8.1.2 Maximum Story Drifts

The PEER-TBI guidelines (PEER 2009) include a requirement that limits the maximum story drift that can be observed from any ground motion in the set of motions. It is proposed that such a requirement not be included in the updated Chapter 16 RHA procedure for two reasons: (a) some reasonable limits are already imposed for unacceptable responses and (b) the maximum story drift is difficult to predict reliably and the value will depend heavily on the details of the ground motion set (see earlier section on interpretation).

8.1.3 Residual Story Drifts

It is proposed that such a requirement not be included in the updated Chapter 16 RHA procedure because a residual drift acceptance criterion is not needed for enforcing the Table 1 collapse safety goal. Limiting residual drifts is an important consideration for post-earthquake operability and for limiting financial losses, but such performance goals are not included in the scope of the ASCE 7 Standard.

8.1.4 Treatment of Collapses and Other Unacceptable Responses

In many cases it is desirable to predict the maximum likely structural response from the set of ground motions or to predict the percentage of ground motions that cause structural collapse or an unacceptable structural response. For this purposes of this paper, and the proposed Chapter 16 RHA procedure, “unacceptable responses” are defined as follows:

> *Unacceptable Response = dynamic instability collapse <u>or</u> non-convergence <u>or</u> response significantly exceeding valid range of modeling <u>or</u> force demand that exceeds the mean strength of a critical force-controlled component*

The proposed Chapter 16 RHA procedure requires, for Risk Category I-II structures and the use of scaled (non-matched) ground motions, that not more than one motion of the eleven produce an unacceptable response. When spectral matching is used, the reduced ground motion variability results in a more restrictive requirement that zero of the eleven produce an unacceptable response. Similarly, for Risk Category III-IV structures, the more stringent collapse probability targets (6% and 3%, respectively) also result in the more restrictive requirement that zero of the eleven produce an unacceptable response.

It must be made clear that these unacceptable response acceptance criteria are not the primary acceptance criteria that ensure adequate collapse safety of the building; the primary acceptance criteria are the story drift criteria of Section 8.1.1 and the element-level criteria of Section 8.2. These unacceptable response acceptance criteria were developed to be a secondary protection to supplement the primary acceptance criteria. The acceptance criteria were intentionally structured in this manner because there is high variability in unacceptable responses (as described in Section 7.3) and the other primary acceptance criteria are much more stable and reliable (because they are based on mean values of 11 motions rather than the extreme response of 11 motions).

8.2 Element-Level Acceptance Criteria

The element-level acceptance criteria follow the approach of PEER TBI (PEER 2009) and require that each element action first be classified as either a force-controlled action or a deformation-controlled action. The deformation-controlled actions are those that have reliable inelastic deformation capacity without substantial strength decay, whereas the force-controlled actions pertain to brittle modes were inelastic deformation capacity cannot be assured. Based on how the acceptance criteria are structured, any element action that is modeled elastically must be classified as being force-controlled.

8.2.1 Acceptance Criteria for Force-Controlled Actions

The proposed acceptance criteria for force-controlled actions follow the framework established by the PEER TBI guidelines (PEER 2009), shown in Equation 1 below.

$$\lambda F_u \leq \phi F_{n,e} \quad (1)$$

where λ is a calibration parameter explained in this section, F_u is the mean demand for the response parameter of interest, ϕ is the strength reduction factor from a material Standard, and $F_{n,e}$ is the nominal strength computed from a material standard considering expected material properties.

Equation 2 shows the final acceptance criterion proposed for critical force-controlled components in the Chapter 16 RHA procedure.

$$2.0F_u \leq F_e \quad (2)$$

where F_u is the mean demand for the response parameter of interest and F_e is the mean expected strength of the component. In some cases, the $F_{n,e}$ strength prediction is conservative and the mean strength of the component, F_e, is greater (as in the case of reinforced concrete shear walls will limited flexural ductility).

For purposes of comparison, the above Equation 4 requirement is comparable to the PEER TBI acceptance criteria value (PEER 2009) of Equation 3, for the case that ϕ = 0.75 and F_e = 1.0 $F_{n,e}$.

For non-critical force-controlled components, it is proposed that the Chapter 16 RHA procedure be consistent with the PEER TBI guidelines and allow that λ = 1.0 and ϕ = 1.0 be used for the case of a non-critical component where failure of the component does not result in collapse of the building.

8.2.2 Acceptance Criteria for Deformation-Controlled Actions

Table 2 provides are summary of the final acceptance criteria, including acceptance criteria for when test data exist (to evaluate deformation capacity) and an alternative approach for when data do not exist and one must use ASCE 41 limits. The acceptance criteria are structured such that the mean inelastic deformation should not exceed the limits shown in this table.

Table 2. Acceptance Criteria Limits for Deformation-Controlled Components

Classification	Limit When Data Available	Limit Based on ASCE 41 (When Data Not Available)
Critical, no redistribution	$(0.3/I_e)\theta_{LVCC}$	$(0.5)\theta_{ASCE41}$
Critical, with redistribution	$(0.5/I_e)\theta_{LVCC}$	$(0.75)\theta_{ASCE41}$
Ordinary, no redistribution	$(0.5/I_e)\theta_{LVCC}$	$(0.75)\theta_{ASCE41}$
Ordinary, with redistribution	$(0.7/I_e)\theta_{LVCC}$	$(1.0)\theta_{ASCE41}$
Non-critical	No limit	No limit

where I_e is the importance factor as prescribed from ASCE 7-16 Section 11.5.1, θ_{LVCC} is the mean inelastic deformation that would result in the loss of ability of the component to carry gravity loads (i.e. the mean value observed from test data), and θ_{ASCE41} is the ASCE 41-13 Collapse Prevention acceptance criterion for Secondary Components.

8.3 Treatment of the Gravity System

The proposed Chapter 16 RHA procedure requires that the basic deformation-compatibility requirement of ASCE 7-10 Section 12.12.5 be imposed for gravity-system components, which are not part of the established seismic force-resisting system, using the deformation demands predicted from response-history analysis under MCE_R-level ground motions.

9. Summary and Recommendations for Future Study

This paper has summarized the result of a multi-year effort to rewrite Chapter 16 of the ASCE/SEI 7-10 Standard, which is entitled *Seismic Response-History Procedure*. Throughout this process, many needed items of future work have been identified, but for brevity this paper does not cover this summary of future work; these are discussed in detail in Haselton et al. (2014).

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