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OVERVIEW AND KEY CONCEPTS OF THE FEMA P695 (ATC-63) METHODOLOGY

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ABSTRACT

This paper provides an overview of the ATC-63 project and the FEMA P695 methodology developed by this project - a wide-ranging combination of traditional code concepts and cutting-edge nonlinear dynamic analysis and collapse risk techniques. On one hand, the methodology remains true to the definitions of Seismic Performance Factors (SPF's) given in *ASCE 7-05* and the underlying pushover concepts described in the Commentary to the *NEHRP Provisions*. On the other, the methodology embodies state-of-the-art incremental dynamic analysis (IDA) and probabilistic methods to evaluate seismic-force-resisting system fragility, margins against collapse and appropriate values of SPF's.

Introduction

In September 2004 the Applied Technology Council (ATC) was awarded a "Seismic and Multi-Hazard Technical Guidance Development and Support" contract by the Federal Emergency Management Agency (FEMA) to conduct a variety of tasks, including a task entitled "Quantification of Building System Performance and Response Parameters" (ATC-63 Project). The purpose of the ATC-63 Project is to establish and document a new, recommended methodology for reliably quantifying building system performance and response parameters for use in seismic design. A key parameter to be addressed on the project is the Structural Response Modification Factor (*R* factor), but related design parameters that affect building system seismic response and performance are also addressed. Collectively these factors are referred to as "Seismic Performance Factors".

R factors are used to estimate strength demands on systems that are designed using linear methods but are responding in the nonlinear range. Their values are fundamentally critical in the specification of seismic loading. *R* factors were initially introduced in the ATC-3-06 report, *Tentative Provisions for the Development of Seismic Regulations for Buildings*, published in 1978 (ATC, 1978). Original *R* factors were based largely on judgment and qualitative comparisons of the known response capabilities of relatively few types of lateral-force resisting systems that were in widespread use at the time. Since then, the number of systems addressed in seismic codes and in today's *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (FEMA, 2004a) has increased dramatically. Many of these recently defined systems have somewhat arbitrarily assigned *R* factors and have never been

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subjected to any significant level of earthquake ground shaking. Their potential response characteristics and their ability to meet seismic design performance objectives are both untested and unknown.

During the course of the ATC-63 Project, 50%, 75% and 90% draft reports were developed and reviewed internally by FEMA and the project's oversight committee, and a series of external workshops (on the 90% draft) were conducted to present concepts and example applications of the methodology to potential users. The project received broad-based feedback from workshop participants which was used to finalize draft methods. In early 2009, the Federal Emergency Management Agency published the final report, FEMA P-695, *Recommended Methodology for Quantification of Building System Performance and Response Parameters* (FEMA, 2009).

Primary Objective of the Methodology

The primary objective of the FEMA P-695 Methodology (referred to simply as the Methodology) is to provide systematic methods for determining building system performance and response parameters for use in seismic design that,

> *when properly implemented in the design process, will result in the equivalent safety against collapse in an earthquake of buildings having different seismic force-resisting systems.*

The Methodology is intended for use with model building codes and resource documents to set minimum acceptable design criteria for standard code-approved seismic force-resisting systems and to provide guidance in the selection of appropriate design criteria for other systems when linear design methods are applied.

The Methodology also provides a basis for re-evaluation of existing tabulations of and limitations on code-approved seismic force-resisting systems for adequacy to achieve the inherent design performance objectives. It is possible that results of future work based on this Methodology could be used to modify or eliminate those systems or requirements that cannot reliably meet or do not relate to these objectives.

Scope and Basis of the Methodology

The scope of the Methodology is based on a few, key principles that are described in the following sections.

New Building Structures

The Methodology applies to the determination of seismic performance factors (SPF’s) appropriate for design of the seismic force-resisting system of new building structures. While the Methodology is conceptually applicable (perhaps with some limitations) to design of retrofit strengthening of seismic force–resisting systems of existing buildings, and possibly to systems of non-building structures, such systems were not considered by the ATC-63 project. The Methodology does not apply to the design of nonstructural systems.

NEHRP Provisions (ASCE 7-05)

The Methodology is based on, and intended for use with, applicable design criteria and requirements of the *NEHRP Provisions for Seismic Regulations for New Buildings and Other Structures (NEHRP Provisions)*, (FEMA, 2004a), reflecting incorporation of changes consistent with the seismic provisions of *Minimum Design Loads for Buildings and Other Structures*, *ASCE 7-05* (ASCE, 2005). The *NEHRP Provisions* recently adopted *ASCE 7-05* as the "starting point" for future updates and development. At this time, *ASCE 7-05* is the most current, published source of seismic regulations of model building codes.

ASCE 7-05 provides the basis for ground motion criteria and "generic" structural design requirements applicable to both existing and new (proposed) seismic force-resisting systems. *ASCE 7-05* provisions include detailing requirements for existing systems that may also apply to new systems. By reference, other standards may also apply to the system of interest. Unless explicitly excluded (and evaluated accordingly by the Methodology), the Methodology requires the seismic force-resisting system of interest to comply with all applicable design requirements of *ASCE 7-05*, including limits on system irregularity, drift and height. For new (proposed) systems, the Methodology requires identification and use of applicable structural design and detailing requirements of *ASCE 7-05* and development and use of new requirements, as necessary, to augment applicable provisions of *ASCE 7-05*.

Life Safety

The recommended Methodology is consistent with the primary "life safety" performance objective of seismic regulations of model building codes. As stated in the Commentary of the *NEHRP Provisions*,

> "the *Provisions* provides the minimum criteria considered prudent for protection of life safety in structures subject to earthquakes." (p. 2, FEMA, 2004b)

Design for performance other than life safety was not considered by the ATC-63 project. Accordingly, the Methodology does not address special performance or functionality objectives of *ASCE 7-05* for Occupancy III and IV structures.

Structure Collapse

The Methodology achieves the primary, life safety, performance objective by requiring an acceptably low probability of collapse of the seismic force-resisting system for maximum considered earthquake (MCE) ground motions.

In general, collapse of a structure would lead to very different numbers of fatalities, depending on the structural system type, the number of building occupants, etc. However, life safety risk (i.e., probability of death or life-threatening injury) is both difficult to calculate accurately, due to uncertainty in casualty rates given collapse, and even greater uncertainty in assessing the effects of falling hazards in the absence of collapse. Rather than attempting to provide uniform protection of "life safety", the Methodology provides approximate uniform protection against collapse of the structural system.

Collapse includes both partial (e.g., single story collapse) and global instability of the seismic force-resisting system, but does not include local failure of components not governed by the global SPF's (e.g., localized, out-of-plane failure of wall anchorage and potential life-threatening failure of non-structural systems).

The Methodology assumes that deformation compatibility and related requirements of *ASCE 7-05* adequately protect against premature failure of structural components not included in the seismic force-resisting system (i.e., gravity system components). Conversely, structural components not designated as part of the seismic force-resisting system (and non-structural components) are not used to resist collapse of the seismic force-resisting system.

MCE Ground Motions

The Methodology evaluates collapse under Maximum Considered Earthquake (MCE) ground motions, as defined by the coefficients and mapped acceleration parameters of the general procedure of *ASCE 7-05* (for various levels of ground motion hazard).

While the SPF's apply to the design response spectrum (i.e., two-thirds of the MCE spectrum), code-defined MCE ground motions are considered the appropriate basis for evaluating structural collapse. As noted in the Commentary of the *NEHRP Provisions*,

> "if a structure experiences a level of ground motion 1.5 times the design level, the structure should have a low likelihood of collapse," (p. 320, FEMA, 2004b).

Technical Approach of the Methodology

The technical approach taken by the ATC-63 project is a broad combination of traditional code concepts and cutting-edge nonlinear dynamic analysis and collapse risk techniques. On one hand, the Methodology remains true to the definitions of SPF's given in *ASCE 7-05* and the underlying pushover concepts described in the Commentary to the *NEHRP Provisions*. On the other, the Methodology embodies state-of-the-art nonlinear dynamic analysis and probabilistic methods to evaluate seismic force-resisting system fragility, margins against collapse and appropriate values of SPF's.

Elements of the Methodology

The Methodology recognizes that meaningful analysis requires valid (MCE) ground motions and representative nonlinear models of the seismic force-resisting system. Development of representative models requires both detailed design information on the system of interest, as well as comprehensive test data on post-yield performance of components or assemblies of the system of interest. Figure 1 illustrates the key elements of the Methodology.

Ground motions and analytical methods are generically applicable to all seismic force-resisting systems, and the Methodology fully defines appropriate characterizations of ground motions and applicable methods of analysis. Design information (e.g., detailing requirements) and test data will be different for each system (and may not yet exist for new systems). For new systems, the Methodology includes requirements for defining the type of design information and test data that is needed for developing representative analytical models.

Rather than establishing "minimum" requirements for design and test data, the Methodology encourages use of better "quality" design information and test data by rewarding systems that have "done their homework." Analytical models that are based on well-defined design requirements and comprehensive test data have inherently less uncertainty in their seismic performance and require less margin against collapse to achieve the same level of safety than systems with less robust data.

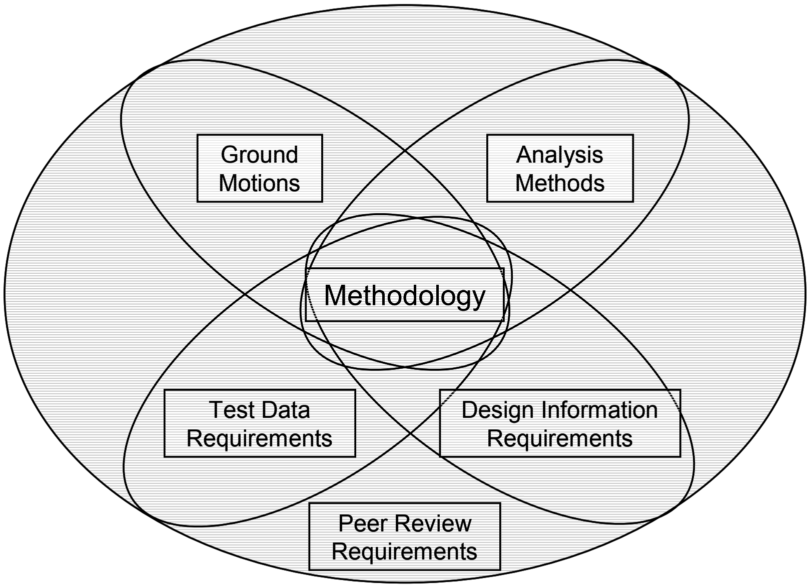

Figure 1. Key elements of the FEMA P-695 (ATC-63) Methodology

Finally, considering the complexity of nonlinear dynamic analysis, the difficulty in modeling inelastic behavior and the need to verify adequacy and quality of design information and test data, the Methodology requires peer review of the entire process.

Seismic Performance Factors

Global seismic Performance Factors (SPF's) include the response modification coefficient (R factor), the system over-strength factor (Ω_O factor) and the deflection amplification factor (C_d factor), values of which are given in Table 12.2-1 of *ASCE 7-05* for existing seismic force-resisting systems. Section 4.2 of the *NEHRP Provisions* Commentary provides background on SPF's.

The discussion in the remainder of this section utilizes Figures 2 and 3 to explain and illustrate the SPF's, and explains how they are used in the Methodology. The parameters are defined in terms of equations, which in all cases are dimensionless *ratios* of force, acceleration or displacement. The equations form the definitions. However, in attempting to utilize the figures to clarify and to illustrate the meanings of these SPF ratios, the two figures take graphical license in two ways. First, the SPF's are depicted in the figures as the increment difference between the two related parameters, rather than their ratio. In addition, as a consequence of being depicted as increment differences between two parameters, these dimensionless ratios (the SPF's) are shown plotted on an axis having units, when in fact they are dimensionless.

Figure 2, an adaptation of Figures C4.2-1 and C4.2-3 of the *NEHRP Provisions* Commentary, defines the SPF's in terms of global inelastic response (idealized pushover curve) of the seismic force-resisting system. In this figure, the horizontal axis is lateral displacement (e.g., roof drift) and the vertical axis is lateral force at the base of the base of the system (i.e., base shear).

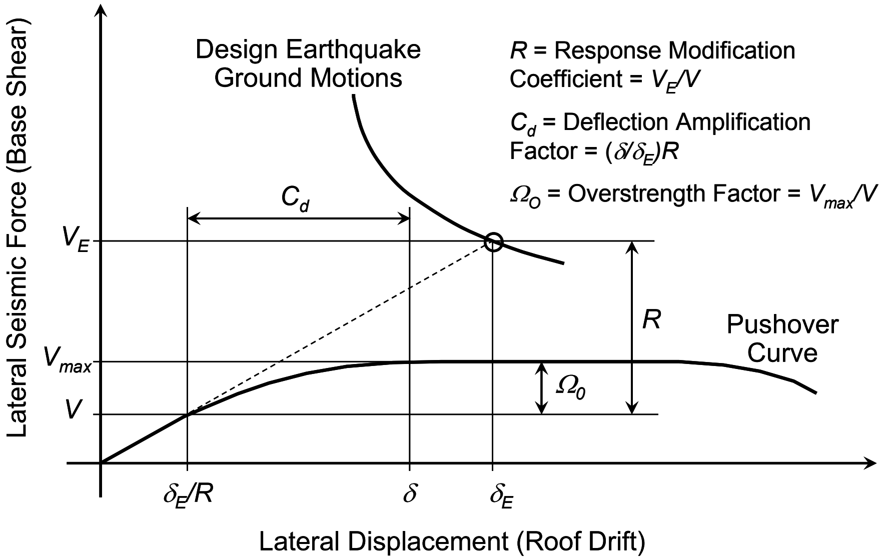

Figure 2. Illustration of Seismic Performance Factors (R, Ω_O and C_d) as defined by the Commentary of the *NEHRP Provisions* (FEMA, 2004b).

In Figure 2, the term, V_E, represents the force level that would be developed in the seismic force-resisting system, if the system remained entirely linearly elastic for design earthquake ground motions; the term, V_{max}, represents the actual fully yielded strength of the system; and the term, V, is the seismic base shear required for design. As illustrated in the figure, the R factor is the ratio of the forces that would be developed for design earthquake ground motions if the structure remained entirely linearly elastic to those prescribed for design:

$$R = \frac{V_E}{V} \tag{1}$$

and the Ω_O factor is the ratio of fully yielded strength to design base shear,

$$\Omega_O = \frac{V_{max}}{V} \tag{2}$$

In Figure 2, the term, δ_E/R, represents roof drift of the seismic force-resisting system corresponding to design base shear, V, assuming that the system remains essentially elastic for this level of force, and the term, δ, represents the assumed roof drift of the yielded system corresponding to design earthquake ground motions. As illustrated in the figure, the C_d factor is some fraction, typically less than 1.0, of the R factor:

$$C_d = \frac{\delta}{\delta_E} R \tag{3}$$

Figure 3 illustrates the SPF's defined by the Methodology and their relationship to MCE ground motions.

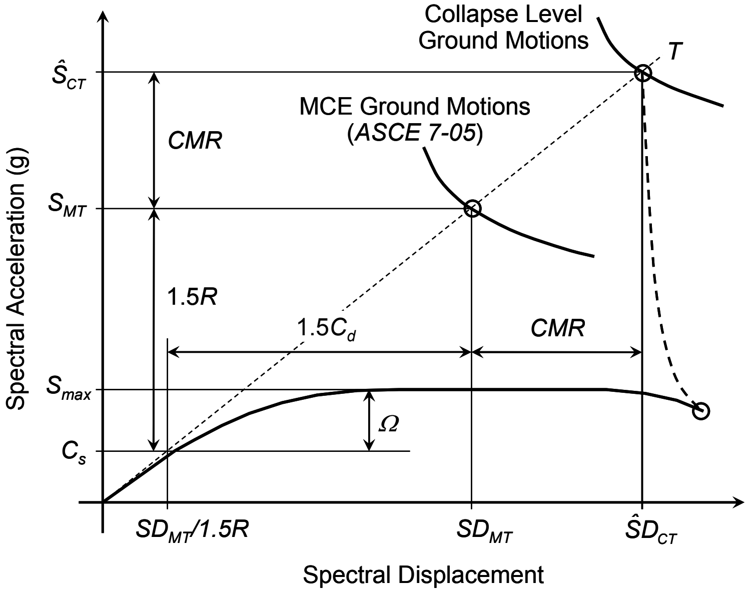

Figure 3. Illustration of Seismic Performance Factors (R, Ω and C_d) as defined by the FEMA P-695 (ATC-63) Methodology.

Figure 3 parallels the "pushover" concept shown in Figure 2 using spectral coordinates rather than lateral force (base shear) and lateral displacement (roof drift) coordinates. Conversion to spectral coordinates is based on the assumption that 100% of the effective seismic weight of the structure, W, participates in fundamental mode at period, T, consistent with Equation (12.8-1) of *ASCE 7-05*:

$$V = C_s W \tag{4}$$

In Figure 3, the term, S_{MT}, is the maximum considered earthquake (MCE) spectral acceleration at the period of the system, T; the term, S_{max}, represents the fully-yielded strength of the system (normalized by the effective seismic weight, W, of the structure); and the term, C_s, is seismic response coefficient. As shown in the figure, 1.5 times the R factor is the ratio of the MCE spectral acceleration to the design-level acceleration (i.e., seismic response coefficient):

$$1.5R = \frac{S_{MT}}{C_s} \tag{5}$$

In Figure 1-3, the overstrength parameter, Ω, is defined as the ratio of the maximum strength normalized by W (S_{max}) to the design base shear normalized by W (seismic response coefficient):

$$\Omega = \frac{S_{max}}{C_s} \tag{6}$$

The Methodology uses the overstrength parameter, Ω, based on pushover analysis, to distinguish calculated values of overstrength from the overstrength factor, Ω_O, of *ASCE 7-05* (e.g., required for design of non-ductile elements). In general, different designs of the same system will have different calculated values of overstrength. The Ω_O factor represents the value of calculated overstrength, Ω, considered to be most appropriate for design of the system of interest.

In Figure 3, inelastic system displacement at the MCE level is defined as $1.5C_d$ times δ_E/R and set equal to the MCE elastic system displacement, SD_{MT} ("Newmark rule"), effectively defining the C_d factor to be equal to the R factor:

$$C_d = R \tag{7}$$

The equal displacement assumption is reasonable for most conventional systems with effective damping approximately equal to the nominal 5% level used to define response spectral acceleration and displacement. Systems with substantially higher (or lower) levels of damping would have significantly smaller (or larger) displacements than those with 5%-damped elastic response. As one example, systems with viscous dampers have significantly higher damping than 5%. For these systems, the response modification methods of Chapter 18 of ASCE/SEI 7-05 are used to determine an appropriate value of the C_d factor, as a fraction of the R factor.

Collapse Margin Ratio

The Methodology defines collapse level ground motions as the level of ground motions that would affect median collapse of the seismic force-resisting system (i.e., one-half of the structures exposed to this level of ground motions would have some form of life-threatening collapse). As illustrated in Figure 3, MCE ground motions are substantially less than collapse level ground motions and affect a significantly smaller (and presumably acceptable) probability of collapse. The collapse margin ratio, *CMR*, is defined as the ratio of the median 5%-damped spectral acceleration (or displacement) of collapse level ground motions to the 5%-damped spectral acceleration (or displacement) of MCE ground motions at the fundamental period of the seismic force-resisting system:

$$CMR = \frac{\hat{S}_{CT}}{S_{MT}} = \frac{\hat{SD}_{CT}}{SD_{MT}} \tag{8}$$

Collapse of the seismic force-resisting system, and hence the collapse margin ratio, *CMR*, is influenced by many uncertain factors, including ground motion variability and various contributors to the uncertainty in design, analysis and construction of the structure. These factors are represented collectively by a collapse fragility curve that describes the probability of collapse of the seismic force-resisting system as a function of the intensity of ground motions.

Figure 4 illustrates the efficacy of collapse fragility curves for two hypothetical seismic force-resisting systems that have inherently different levels of collapse uncertainty. Both systems are designed for the same seismic response coefficient, C_S, using the same value of the response modification factor, R. However, differences in collapse uncertainty necessitate the two systems having different collapse margin ratios. In order to achieve the same design value for the R factor, System No. 1, with greater uncertainty and a “flatter” collapse fragility curve than System No. 2, is required to have a larger collapse margin ratio, CMR_1, than the collapse margin ratio, CMR_2, of System 2.

The Methodology defines acceptable values of the collapse margin ratio in terms of both an acceptably low probability of collapse for MCE ground motions and the uncertainty in collapse fragility. Systems, which have more robust design requirements, more comprehensive test data, and/or more detailed nonlinear analysis models, have less collapse uncertainty and achieve the same level of life safety with smaller collapse margin ratios.

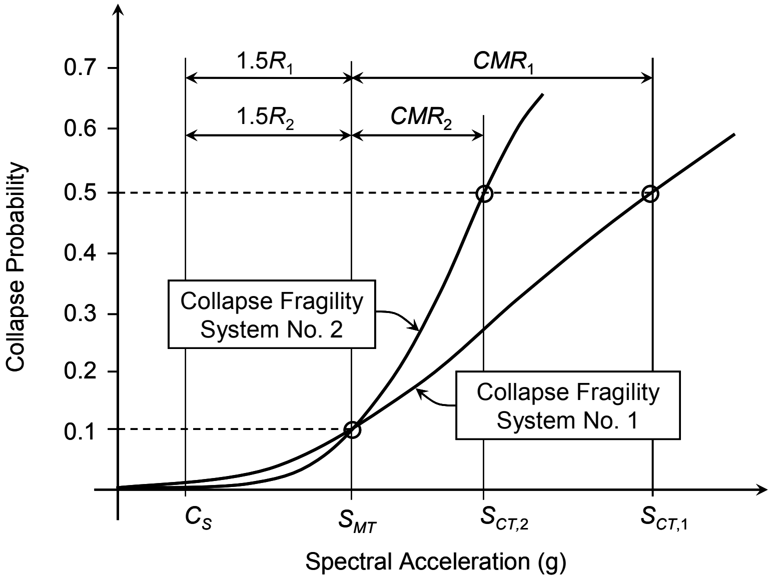

Figure 4. Illustration of fragility curves and collapse margin ratios for two hypothetical seismic force-resisting systems – same design level.

Archetypes and Nonlinear Analyses

The Methodology determines the response modification coefficient (R factor) and evaluates system over-strength (Ω factor) using nonlinear models of seismic force-resisting system “archetypes.” Archetypes capture the essence and variability of the performance characteristics of the system of interest. The Methodology requires nonlinear analysis of a sufficient number of archetype models (with different design, heights, etc.) to broadly represent the system of interest.

The Methodology requires archetype models to meet the applicable design requirements of *ASCE 7-05* and related standards, and additional criteria developed for new systems.

Archetype design assumes a trial value of the *R* factor to determine the seismic response coefficient, C_s. The Methodology requires detailed modeling of nonlinear behavior of archetypes, based on representative test data sufficient to capture collapse failure modes. Modes of collapse failure that cannot be explicitly modeled are evaluated using appropriate limits on the controlling response parameter.

For each archetypical model, nonlinear static (pushover) analysis is initially performed to establish the Ω factor, based on the ratio of normalized strength, S_{max}, to the seismic response coefficient, C_s, used for archetype design. Nonlinear dynamic analysis then establishes the collapse margin ratio using a suite for ground motion records scaled incrementally until median collapse is determined (50% of the records induce collapse of the archetypical model). The calculated value of the collapse margin ratio is compared with acceptable values of the collapse margin ratio that reflect collapse uncertainty, as described in the previous section. If the calculated collapse margin is large enough to meet life-safety objectives (acceptably small probability of collapse at the MCE), then the trial value of *R* factor used for design of the archetype is acceptable. If not, a new (lower) trial value of the *R* factor must be re-evaluated by the Methodology.

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