The Long Road

Advancing First-Generation Performance-Based Seismic Design for Steel Buildings
Part 1: Background and Motivation

By Matthew Speicher, Ph.D., and John Harris, Ph.D.

First-generation performance-based seismic design (PBSD) principles are outlined in the latest edition of the American Society of Civil Engineers and the Structural Engineering Institute's ASCE/SEI 41-17: *Seismic Evaluation and Retrofit of Existing Buildings* referred to herein as ASCE 41. These PBSD principles have evolved since being introduced in the Federal Emergency Management Agency's FEMA 273: National Earthquake Hazards Reduction Program (NEHRP) *Guidelines for the Seismic Rehabilitation of Buildings* (FEMA 1997). ASCE 41 provides analytical procedures and performance criteria to evaluate an existing building for a defined performance objective and to design seismic retrofit strategies if the criteria are not satisfied. This ability to explicitly define a performance objective and then assess a building against that objective has led practitioners to adopt ASCE 41 for use in new building designs to meet the intent of ASCE 7: *Minimum Design Loads for Buildings and Other Structures*, of which the latest edition is ASCE/SEI 7-16.

Using ASCE 41 for existing building assessment and new building design has created interest amongst researchers and design professionals about the consistency between ASCE 41 and ASCE 7 (NIST 2009). Partially motivated to address this matter, the National Institute of Standards and Technology (NIST) initiated a study in 2010 to evaluate the first-generation principles of PBSD as applied to newly constructed steel buildings. A critical aspect of the NIST study was investigating whether the standards for designing new steel buildings and assessing existing steel buildings provide consistent performance levels. With the desire to advance performance-based design, the correlation between the performance of a building designed with the prescriptive provisions of ASCE 7 and assessed with the performance-based provisions of ASCE 41 was largely unknown.

Part 1 of this three-part series provides background on the history of PBSD, compares PBSD with traditional design approaches, and gives an overview of the motivation and outcomes of the NIST study. This overall series will discuss the past, present, and future work done at NIST to spur the advancement of PBSD.

Performance-Based Seismic Design

ASCE/SEI 7-16 Section 1.3 essentially allows two options for the design of a building: 1) a strength-based (or its alternative stress-based) procedure that follows the provisions provided in ASCE 7, or 2) an alternative performance-based procedure. The stated goal of the latter procedure is to give a system "reliability" generally consistent with targets intended to be achieved in the first option; these targets are given in ASCE 7. Since the provisions for the strength-based procedure are prescribed in ASCE 7, this type of design is commonly referred to as *prescriptive design*.

ASCE 7 prescriptive design requires a building to have adequate strength and stiffness to preclude various limit states (e.g., buckling, yielding, fracture, etc.) and other unacceptable serviceability or functionality performance goals. Along with the prescriptive design designation, this type of design approach is commonly referred to as a *limit state design*. Moreover, since these attributes are assessed via performance requirements, in the pure sense, prescriptive design can be thought of as a type of performance-based design. ASCE 7 can be considered a *performance standard* since it prescribes minimum design loads and associated performance criteria. As such, for a defined hazard, prescriptive design represents one point on the performance continuum for a building.

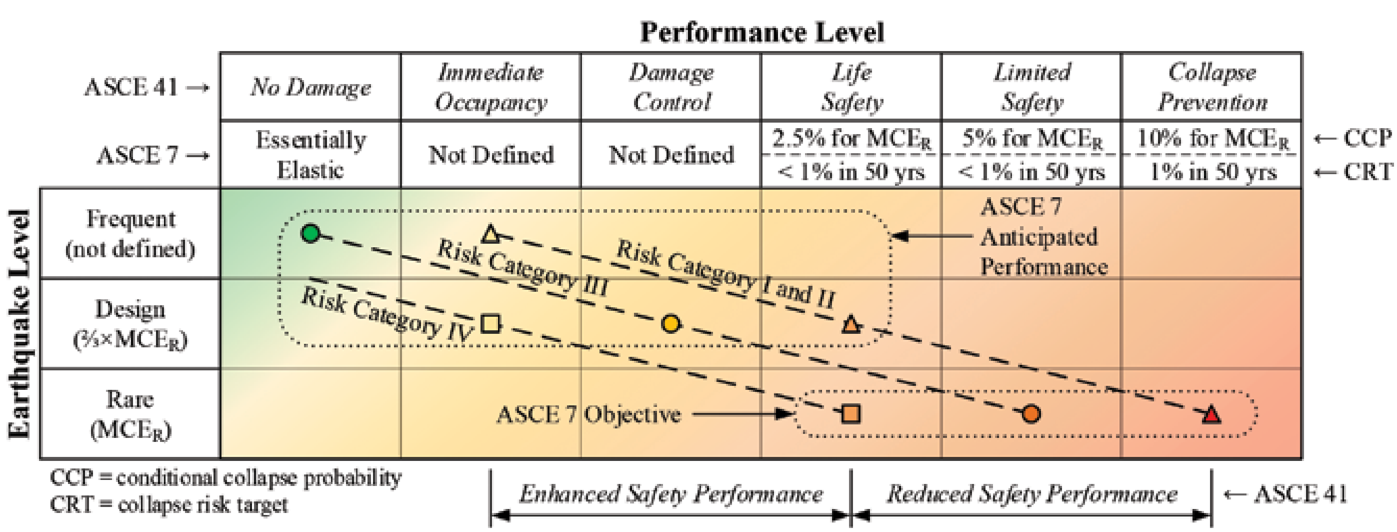

Figure 1. Mapping of ASCE 7-10 and ASCE 41-13 seismic performance objectives based on risk category.

Similarly, performance-based design is also a limit state design. In particular, for PBSD, a building is designed with defined reliability levels so as not to be damaged beyond certain limit states at specified seismic hazard levels. These limit states are determined based on fundamental mechanics, experimental and field observations, and engineering judgment considering the *consequences* of the damage associated with these limit states. Generally, consequences are categorized in terms of deaths, dollars, and downtime to assess the following risks implicitly or explicitly:

- total or partial collapse of a building;
- loss of life or life-threatening injuries to building occupants or the public-at-large;
- interruption of building function or occupant mission, either short- or long-term; and
- direct economic losses from damage to the building and/or its contents and indirect losses by interruption of provided services.

In the heuristic sense, PBSD provides a way to understand the design of a building and the associated risks that such a design may pose, thus giving a rational estimate of building performance in a future earthquake. PBSD explicitly enables the upfront selection of performance targets at specific earthquake hazard levels, which results in a clearer expectation of the outcome and greater flexibility in the design process (*Figure 1*).

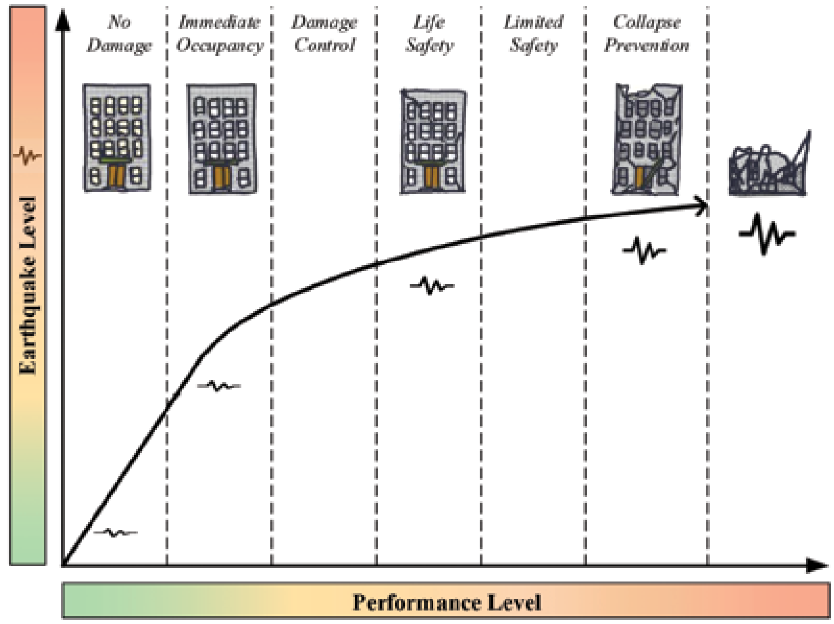

Figure 2. Illustration of building performance when subjected to increased earthquake intensities.

Understanding the link between the performance objectives of ASCE 7 and ASCE 41 is an integral part of the discussion. In *Figure 1*, the seismic hazard used by ASCE 7 (2010 edition and later) is ground motions producing a 1% probability of total or partial collapse in 50 years, referred to as the risk-targeted maximum considered earthquake (MCE_R). This hazard has a conditional probability of 10% collapse, given that an MCE_R event occurs. As such, protection against loss of life by preventing a collapse of the structural system is the primary life safety objective (referred to as *collapse prevention*). ASCE 7 then takes two-thirds of this hazard as the "design earthquake." At this level, the secondary life safety objective is that the performance of non-structural components is critical to protect life and injuries, and there exists a margin of safety against collapse (referred to as *life safety*). It is inferred that a building will have a higher performance level than life safety for earthquakes occurring more frequently than the design earthquake.

ASCE 41 uses the same terms to define the target performance of the structural system but uses different terms to define the target performance of the non-structural system. Therefore, if one wants to equate the objectives of the two standards, collapse prevention at the MCE_R is the common performance objective, as the two-thirds factor does not result in uniform risk across the nation. Furthermore, ASCE 7 focuses on the performance at the system level, whereas ASCE 41 focuses on the performance at the component level. Consequently, in the context of linking the two standards, a valid question is what percentage of components need to fail the collapse prevention performance level defined in ASCE 41 to achieve a 10% probability of collapse given an MCE_R event? Questions like this may help enhance how PBSD can support risk assessment.

State-of-Practice of PBSD

ASCE 41 continues to be the go-to standard for implementing first-generation PBSD principles to evaluate existing buildings. The standardization of first-generation PBSD principles in ASCE 41 can be traced from FEMA 273 as follows:

- FEMA 356, *Prestandard and Commentary for Seismic Rehabilitation of Buildings* (FEMA 2000)
- ASCE/SEI 41-06 *Seismic Rehabilitation of Existing Buildings*
- ASCE/SEI 41-13 and 41-17 *Seismic Evaluation and Retrofit of Existing Buildings*
- ASCE/SEI 41-23 *Seismic Evaluation and Retrofit of Existing Buildings* (under development)

The performance continuum utilized in ASCE 41 is illustrated in *Figure 2*, with each performance level associated with a damage state.

In practice, ASCE 41 is one of the referenced standards in the *International Existing Building Code* (IEBC) (ICC 2021) to assess the seismic performance of an existing building. ASCE 41 is also utilized in some cases in the design of new buildings. For example, ASCE 41 is referenced in the following documents:

- ASCE 7-16, Chapter 16
- *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region* (LATBSDC 2020)
- *Guidelines for Performance-Based Seismic Design of Tall Buildings* (PEER 2017)
- PBS-P100: *Facility Standards for the Public Buildings Service* (GSA 2018)

ASCE 41 is a deterministic type assessment procedure; either something does or does not satisfy the criteria. In recognition of this, FEMA supported the development of "next-generation" PBSD principles, published in FEMA P-58, *Seismic Performance Assessment of Buildings* (FEMA 2015). FEMA P-58 focuses on evaluating performance "in terms of the probability of incurring casualties, repair and replacement costs, repair time, selected environmental impacts, and unsafe placarding." FEMA P-58 provides a probabilistic performance assessment framework that can be used to explicitly evaluate seismic risks, relying on fragility and consequence data.

Both ASCE 41 and FEMA P-58 continue to evolve to advance PBSD of buildings. For example, ASCE 41 is currently making refinements to component modeling parameters and capacities for buildings identified in *Recommended Modeling Parameters and Acceptance Criteria for Nonlinear Analysis in Support of Seismic Evaluation, Retrofit, and*

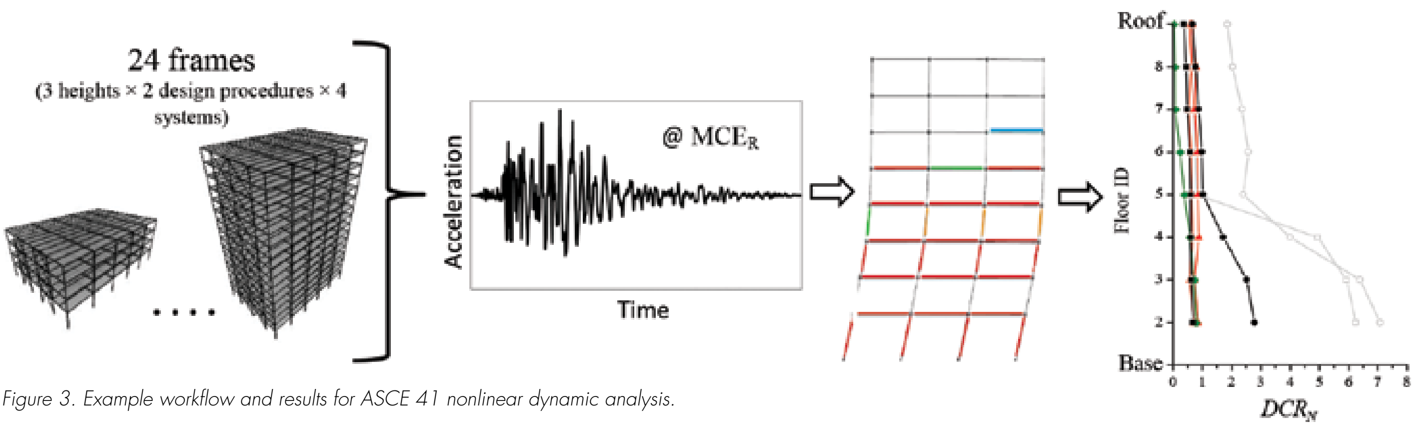

Figure 3. Example workflow and results for ASCE 41 nonlinear dynamic analysis.

Design (NIST 2017). Similarly, as new component performance data is generated, updated fragility and consequence functions enhance FEMA P-58. Still, comprehensive efforts to support the application of these two approaches within ASCE 7 are needed.

NIST PBSD Study

The NIST study started by designing a set of archetype steel buildings utilizing the prescriptive methods prescribed in the then-current ASCE/SEI 7-10. The archetype design space consisted of 4, 8, and 16-story buildings utilizing special moment frames (SMFs), special concentrically braced frames (SCBFs), eccentrically braced frames (EBFs), and buckling restrained brace frames (BRBFs) as the seismic force-resisting system (SFRS). The buildings are assumed to be in an area of high seismicity and are assigned to Seismic Design Category D as defined by ASCE/SEI 7-10. Each system was designed twice, once with the equivalent lateral force procedure and another with modal response spectral analysis.

The next part of the study involved evaluating the performance of the same structural systems using the different assessment procedures prescribed in ASCE 41. The current standards were used at the time of the respective portions of the NIST study; thus, ASCE/SEI 41-06 was used to assess the SMFs, SCBFs, and EBFs, and ASCE/SEI 41-13 was used to assess the BRBFs. A comparison of the assessment outcomes relative to the level of analytical sophistication was made using the linear static, linear dynamic, nonlinear static, and nonlinear dynamic procedures. Ultimately, the data generated was intended to spur improvements to future editions of ASCE 41, encouraging more confidence in its application. Detailed information regarding this study can be found in the NIST Technical Note 1863 series, *Assessment of First Generation Performance-Based Seismic Design Methods for New Steel Buildings* (Harris and Speicher 2015a, 2015b, 2015c; Speicher and Harris 2020).

In general, assessment using ASCE 41 (using the respective editions as noted above) tended to show the SFRSs had several challenges in meeting each performance objective. For example, in several cases, the nonlinear dynamic procedure indicated the SMFs had unacceptable performance, illustrated in *Figure 3*. This finding begs the question of whether the ASCE 41 assessment is overly conservative or if the ASCE 7 design is deficient. To this end, a follow-up study was conducted to verify the probability of collapse of the archetype buildings using FEMA P695, *Quantification of Building Seismic Performance Factors* (FEMA 2012). Investigating the performance of the SMFs, Speicher et al. (2020) demonstrated that the structural designs do, in fact, meet the objective of ASCE 7-10, suggesting that the respective version of ASCE 41 (in this case, ASCE/SEI 41-06) is conservative for the buildings studied.

Conclusions

PBSD is being used in practice to assess the seismic performance of existing buildings and is increasingly used to design new buildings to satisfy multiple performance levels to meet or exceed the intent of ASCE 7. This article highlights several points of discussion related to the similarities and differences between prescriptive design and performance-based design. Prescriptive design using ASCE 7 can be thought of as one point on a performance-based design continuum. Assessment using ASCE 41 enables access to more points on this same continuum.

However, the two standards differ in that ASCE 41 evaluates the performance of components, and ASCE 7 designs components for system performance. The starting point for identifying inconsistencies between the two standards is most logical at the collapse prevention performance level considering the maximum considered earthquake. The constraint of modern design techniques is that a system is defined as the sum of its components. Consequently, component-based limit state design can be inadequate in conveying the consequences of component performance on system performance, limiting its applicability to risk assessment.

The NIST study provides quantitative data demonstrating the inconsistencies between ASCE/SEI 7-10 and ASCE/SEI 41-06 or ASCE/SEI 41-13. The steel archetype building assessments are found to often result in conservative outcomes when ASCE 41 is applied. Ultimately, this research has helped spur a critical assessment of the provisions of ASCE 41 and motivated further research to advance the state of practice of PBSD.

Part 2 in this series will detail the NIST study's technical results, which looked at the four structural steel systems introduced previously. Part 3 will discuss the future of PBSD in practice, including its relationship to resilience-based design, which aims to quantitatively support community resilience. With the rise in interest in designing for functional recovery after an earthquake, PBSD will likely be a critical methodology to evaluate the impact of service interruption on the building occupants and the community that the building serves.▪

Full references are included in the online PDF version of the article at **STRUCTUREmag.org**.

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