Committee Report: JCI-TC233A

Technical Committee Report on Comparison of Performance-based Seismic Design Practice of Concrete Structures in the US and Japan

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Abstract

In the United States, structural design codes for buildings and other structures, including IBC, ASCE 7, and ACI 318, began to undergo extensive revisions in the 2000s. These updates were coordinated to implement nonlinear response history analysis into standard seismic design practice. In addition, a range of technical documents intended for use by practical designers has been developed. Performance-based seismic design was implemented in the 2010s, leading to a surge in reinforced concrete ultra-high-rise housing construction in California. The research committee focused on the engineering practice of seismic design using nonlinear response history analysis for reinforced concrete structures in the United States. The structural design processes, provisions, and technical documents of the US and Japan are compared in the activity of JCI-TC233A to highlight their differences and similarities. This report covers the activities of the JCI-TC233A research committee from 2023 to 2025.

Keywords: Nonlinear response history analysis, Performance based seismic design, Nonlinear modeling, Seismic provision

1. Introduction

Non-linear response history analysis was first included in U.S. seismic building codes in the 2000s, later evolving into performance-based seismic design in the 2010s. This led to the development of reinforced concrete ultra-high-rise residential buildings with core wall structural systems, many of which are currently found in Los Angeles and San Francisco, California.

In Japan, engineers started using nonlinear response history analyses of steel moment-resisting frame structures in practice, with simple mass-spring models combined with nonlinear springs as early as the 1960s. In the 1990s, the Ministry of Construction developed a method for use it in reinforced concrete buildings. The development of ultra-high-rise residential buildings using reinforced concrete two-way moment-resisting frames subsequently drove the construction boom. In the 2000s, despite significant improvements in computer performance, there were no technological changes or innovations except for consideration of long-period seismic motion. There are observable differences in the practical application of nonlinear response history analysis between Japan and the United States recent years. In Japan, application of nonlinear response history analysis has mostly been developed in private closed circles, with limited open discussion among engineers and little public drive to advance future design methods. Furthermore, difference in application of nonlinear response history analysis has not been discussed between architectural engineers and civil infra engineers.

The objective of research committee (Table-1) is to compare Japan and the United States regarding the current use of nonlinear earthquake response analysis in seismic design, aiming

Table 1 Committee Members

Chair	Hitoshi Shiohara, The University of Tokyo
Secretaries	Shuichi Fujikura, Utsunomiya University
	Toshikazu Kabeyasawa, Tokyo Metropolitan University
	Koichi Kusunoki, The University of Tokyo
	Tomohiro Miki, Kobe University
	Hikaru Nakamura, Nagoya University
Members	Mitsuyoshi Akiyama, Waseda University
	Shuei Ikeda, Takenaka Corporation
	Masaaki Isa, Hanshin Expressway
	Ko Kashima, Mitsubishi Jisho Design Inc.
	Hiroshi Itoh, Kume Sekkei Co., Ltd.
	Kazuhiro Kawaguchi, JIP Techno Science Corporation
	Tsutomu Komuro, Taisei Corporation
	Fumio Kusuhara, Nagoya Institute of Technology
	Akitsugu Muramatsu, Taisei Corporation
	Takuya Nagae, Nagoya University
	Joji Sakuta, Horie Engineering and Architectural Research Institute
	Yasushi Sanada, Osaka University
	Tomoya Takahashi, Musashino University
	Yoshikazu Takahashi, Kyoto University
	Tatsumasa Watanabe, Tokyo Electric Power Services Co. Ltd.
Associate members	Garrett R. Hagen, Degenkolb Engineers
	Parham S. Pizadeh, Degenkolb Engineers
	Tomoyasu Nishida, Taisei Corporation

to improve Japan's design practice and promote international cooperation.

2. Current situation of performance-based earthquake-resistant design in the United States

Since the 2000s in the United States, building codes like ASCE 7[1)] and ACI 318[2)] have been updated to align with nonlinear response history analysis until now. Technical documents of concrete structures for structural engineers continue to be released to support these provisions. Since the 2010s, non-linear response history analysis has been practically used in seismic design, making performance-based earthquake-resistant design for new buildings refer to this approach. As of the 2020s, ongoing revisions are being implemented to further refine the regulations concerning nonlinear response history analysis within ASCE 7[1)] and ACI 318[2)].

2.1 Earthquake resistance design standards for new buildings and input seismic movement

In the United States, the latest version of ASCE 7[1)] was revised in 2022 and sets the minimum standard for new buildings. Nonlinear response history analysis using ASCE 7[1)] input base acceleration time histories equivalent to MCE_R (the largest class of seismic motion considering collapse) evaluates whether collapse occurs and how frequently it happens. Seismic performance is evaluated by determining the probability of collapse using the ratio of observed number of collapse cases. The MCE_R seismic action level for determining collapse is represented by the maximum acceleration seismic response spectrum with 5% damping, as indicated on the earthquake hazard map in ASCE 7[1)]. Soil conditions at the site are addressed by adjusting the spectrum. Time histories of input base acceleration equal to or greater than 11 are selected for use in nonlinear response history analysis. To align with the target maximum acceleration response spectrum of the MCE_R earthquake within the relevant period range of the structure, adjustments such as applying a magnification factor to observed seismic motions are made.

2.2 Input base acceleration and nonlinear response history analysis

The nonlinear response history analysis uses 3D models with member-based elements, assigning each appropriate nonlinear restoring force properties and accounting for the P-Delta effect. For all base acceleration motions, ensure deformation stays within permitted limits in plastic zones, stress does not exceed capacity in non-plastic zones, and verify that collapse probability meets the target threshold. The nonlinear response history analysis method can be applied without limitations on building height or structure type. Accurate modelling of the nonlinear behavior of the component is required. The scope is determined by the availability of technical information and experimental materials for specific types of components. There is potential for further research to broaden these applications. Nonlinear response history analysis also applies to seismic design of buildings with base isolation or energy dissipation devices.

2.3 Limitation to maximum story drift response

When nonlinear time history response analysis is used, it is required to ensure the collapse probability is below the specified limit, component plastic deformation and stress are within acceptable levels, and maximum story drift remains limited, regardless of the structural system.

According to the latest ASCE 7 1), for input motions with 11 or more waves, the average story drift ratio R — defined as the horizontal displacement of a floor divided by its height from the ground — must be less than the value calculated using the formula below. Furthermore, the maximum value of any individual story deformation angle must not surpass 150% of the calculated average value.

$$R = 4.71 - 0.0234\, h_{n.} \quad (\%) \qquad (1)$$

Here, R: If the calculated R is below 0.03 h_n, it is 0.03 h_n, where the building height is in meter.

2.4 Mechanical properties and structural details of members

Structural member details follow standards set by relevant organizations, such as the American Concrete Institute for reinforced concrete and the American Institute of Steel Construction for steel, based on the material used. For instance, when considering a reinforced concrete earthquake-resistant structural system featuring a special moment frame, it is essential to adhere to seismic regulations that are defined according to component type—including columns, beams, shear walls, and joints—as specified in Chapter 21 of ACI 318 2). These provisions must be diligently observed to ensure adequate protection.

The method for determining the modeling of the nonlinear mechanical properties of members is desirable to be described in ACI 318 2), but the description of the latest ACI 318 2) is insufficient and is scheduled to be revised in the future. Therefore, at this time, ASCE 7 1) cites the standard for seismic diagnosis and seismic reinforcement of existing buildings called ASCE 41[4)] and requires the application of the modeling of the nonlinear mechanical properties of the members specified therein.

2.5 Disclosure of various technical materials

The ACI 374 Committee focuses on developing technical resources for performance-based seismic design of reinforced concrete buildings. In 2017, the technical report[3)] titled "An ACI Handbook - Compilation of Performance-Based Seismic Design Recommendations and Stand" also referred to as "HB-12 (17)," was published. This publication summarizes key technical resources for structural designers seeking up-to-date knowledge on nonlinear time history seismic analysis and performance-based seismic design of reinforced concrete structures.

3. A comparison of proto-designs for RC 10-story buildings in Japan and the United States

A key focus of this research committee is comparing Japanese and U.S. methods for seismic design using non-linear time history earthquake response analysis. Chapter 2 of the report provides a detailed explanation; the following is a summary.

3.1 Background of the Japan-U.S. Workshop

The Japan-U.S. workshop aims to examine seismic design approaches using non-linear response history analysis for concrete buildings in structural design practice from an international viewpoint, with particular attention to comparisons between Japan and the United States, and to identify issues and suggest possible improvements. The structure referenced in the proto design is based on full-scale 10-story reinforced concrete building shaking table tests carried out in 2015 and 2018 at the 3D shaking table facility (E-Defense) of the National Institute of Disaster Prevention Science and Technology in Miki, Hyogo, Japan. The proto designs for Japan and the United States followed standard practices in each country regarding structural systems, material strengths, and cross-sections. Current seismic design provisions and standard engineering practices were applied.

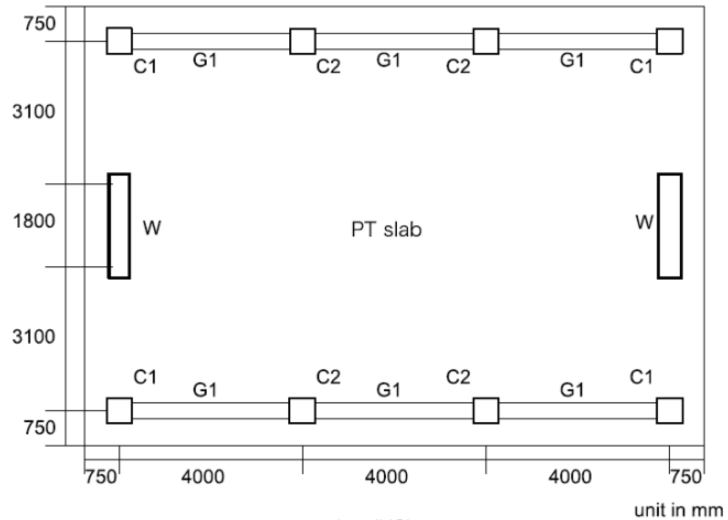
At the 1st Japan-U.S. Workshop in September 2023, teams from ACI and JCI agreed to compare seismic design practices. Dr. Komuro's group led for JCI, while Mr. Garrett Hagen, the chair of the ACI 374 committee, represented the ACI side. At the 2nd workshop in June

2024, held during the JCI Annual Conference in Matsuyama, results of the joint proto design were presented and discussed.

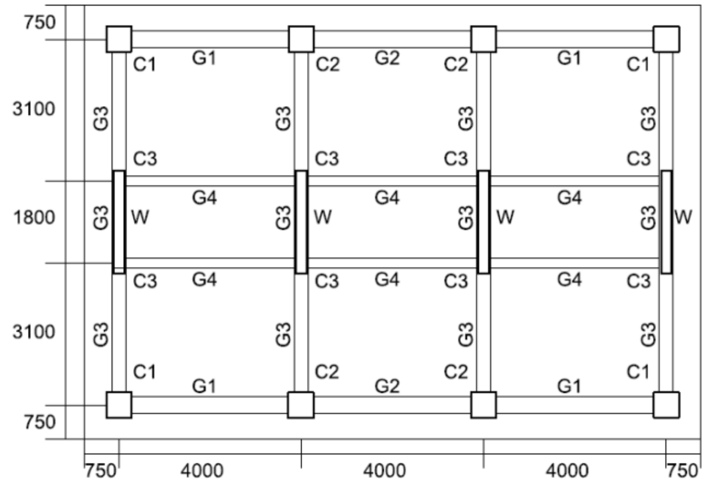
3.2 Proto-design building

Figures 1 and 2 show the proto design key plans and elevations for both the Japanese and American sides.

The Japanese proto design includes four shear walls, same as E-Defense shaking table test specimens. On the other hand, the U.S. proto design has two shear walls, considering securing the larger internal space in the building.



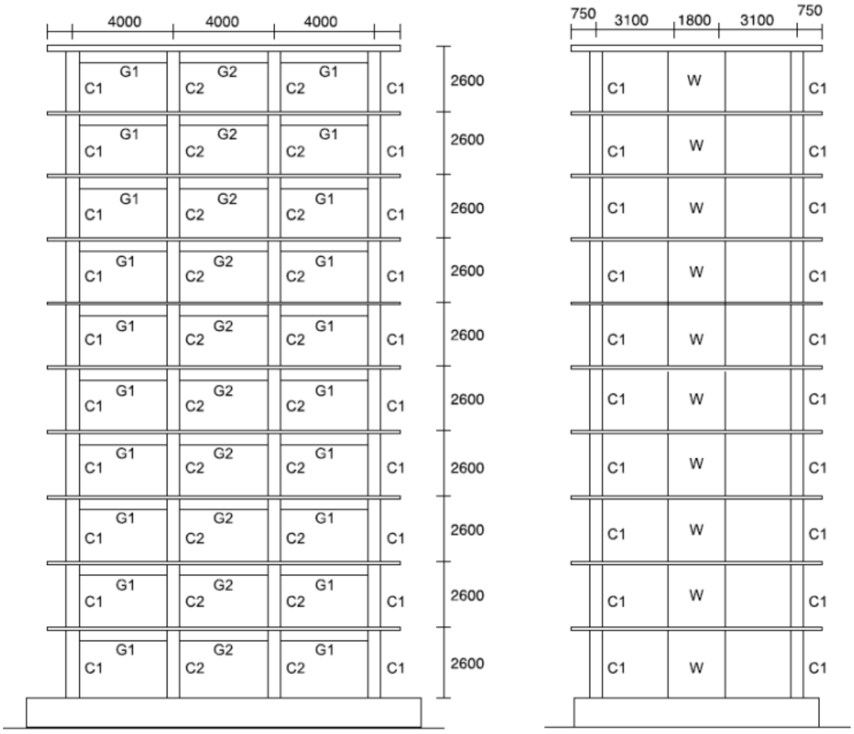
plan (US)



plan (Japan)

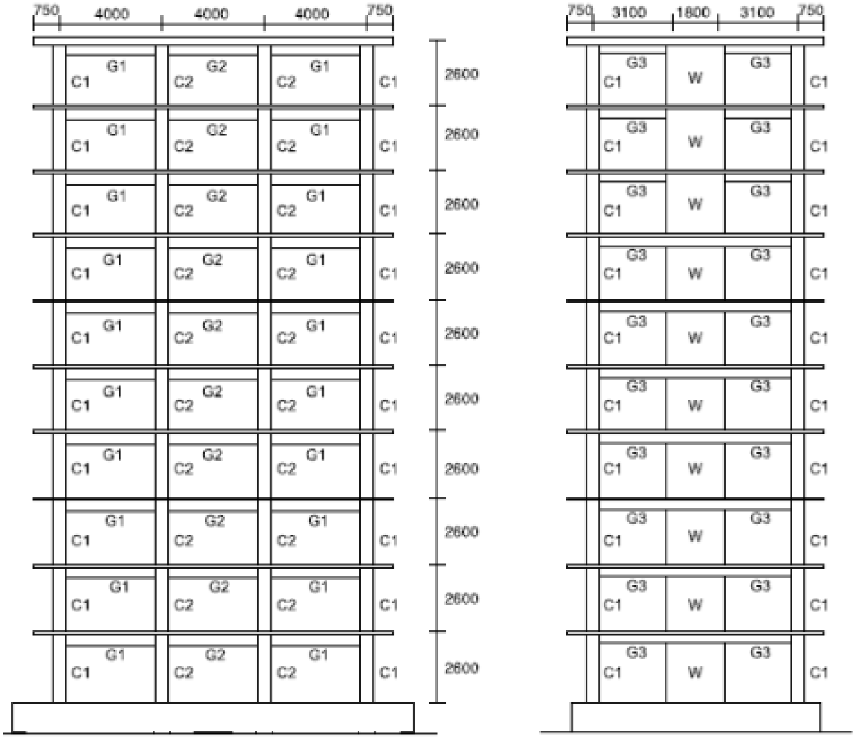
Figure 1 – Proto design of RC 10 story building plan

（upper：US，lower：Japan）



elevation (US)

unit in mm



elevation (Japan)

unit in mm

Figure 2 – Proto design of RC 10 story building elevation

（upper：US， lower：Japan）

3.3 Input Ground Motions

To compare the input ground motion on both side the, target maximum acceleration spectrum are plotted in Figure 3. In the Japanese proto design, both Level 1; damage limit, and the Level 2; safety limit, were assessed using three recorded base motions and three artificial base motions, following the time history response procedure for earthquake-resistant design.

The recorded base motions are normalized such that, irrespective of the building's specific period, the maximum response speeds for Level 1 and Level 2 are set at 0.25 m/sec and 0.50 m/sec, respectively. The target spectrum of artificial base motions matches the required spectra ratio in allowable stress design to lateral capacity design, which is set at 0.2.

In U.S. prototype design, earthquake resistance is assessed using nonlinear time history response analysis, with the number of input seismic motions determined according to ASCE 7 requirements. To ensure that the probability of building collapse remains at 10% or less, 11 waves are required if one or fewer instances of collapse occur. In the proto design, 22 base motions are typically used, particularly for high-rise buildings, due to the significant effect of higher-order modes. Eleven waves are scaled for short periods, and another eleven for long periods. Seismic motion scaling methods include amplitude scaling, spectral matching, and hybrid approaches. In this U.S. proto design example, amplitude scaling was first applied but resulted in excessive short-period seismic motions, so the hybrid approach was adopted instead. Figure 3 illustrates both the target spectrum for 11 waves and the elastic maximum acceleration response spectrum of the seismic input.

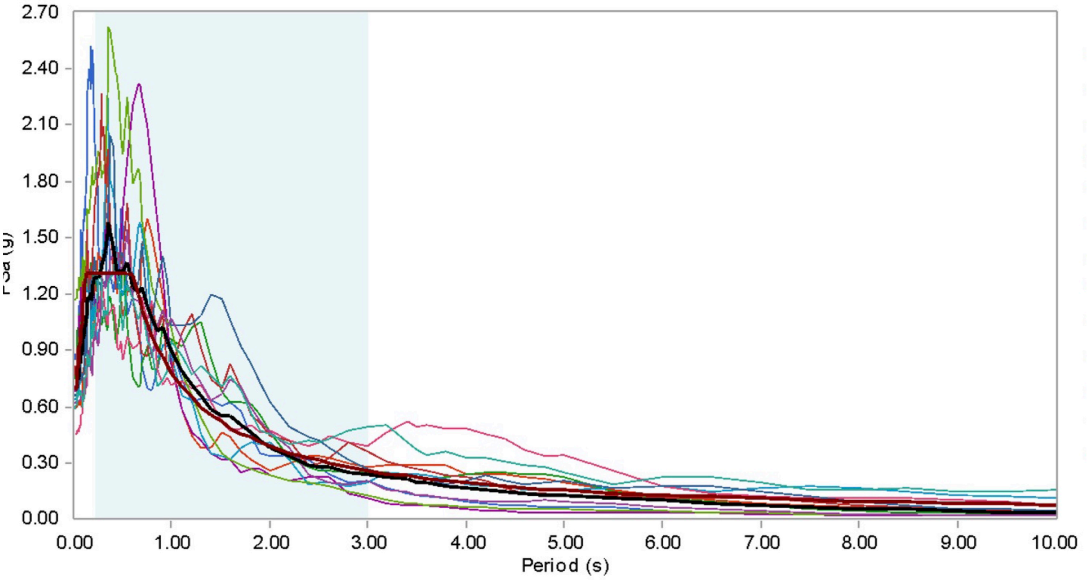


Figure 3 – Maximum response spectra of 11 input ground motions for US proto

3.4 Japanese proto design

In the Japanese proto design, performance assessment through non-linear time history response analysis is anticipated to yield significantly larger cross-sections compared to those designed using the lateral load carrying capacity method. This outcome arises from the characteristics of buildings with short periods. To satisfy the nonlinear response history analysis requirements, the cross-sectional dimensions were increased to ensure that the lateral carrying capacity is approximately twice as large, together with an increase in design material strength. The findings indicate that by permitting the maximum story drift criteria to be doubled, the section dimensions determined using the lateral load carrying capacity method meet the standards originally established in Japan and the United States.

In Japan, time history response analysis has primarily been applied to high-rise buildings. When this method is used for medium- and low-rise structures, it results in notable differences in the cross-sections determined compared to those derived from the conventional horizontal load calculation design method.

With respect to deformation limits, the Japanese proto design stipulates that the maximum story drift ratio under Level 1 ground motion input must not exceed 1/200, while for Level 2 input, the ratio must remain within 1/100. Additionally, for Level 2 input, the permitted ductility ratio for story drift is set below 2.0, and the allowable member ductility factor is specified as 4.0. To comply with these deformation constraints, the cross-sectional dimensions and material strength of the members were enhanced from the outset.

Japan's performance-based seismic design standards do not specify the required demand-to-capacity ratio to prevent brittle failure in structural members; instead, engineers set these margins using their experience with material strength gains and differences between static and dynamic stresses. Because this way of judgement depends on subjective assumptions, engineers may have differing judgments. There are no established guidelines for applying response analysis results to distribute seismic forces across levels in static elastic-plastic analysis.

3.5 U.S. proto design

Because performance-based seismic design adopts nonlinear time history response analysis, determining cross-sections and reinforcement remains necessary. For this purpose, the conventional equivalent lateral force method and the *R* factor design approach, as specified in ASCE 7[1)], are applied. The proto design structure is analyzed using linear elastic methods with the modified horizontal force, and cross-section design follows accordingly. As the result of nonlinear response history analysis indicated that the earthquake response was excessive and did not satisfy the structural criteria, the design was revised. For U.S. design, deformation criteria in nonlinear response history analysis use the average maximum response under MCE_R base motions—1.5 times larger than lateral load design spectra. Collapse probability is set by risk category. Engineers typically consider a 3% story drift ratio as the collapse threshold, 2% for functional recovery, and less than 1.5% as elastic range.

For components expected to undergo plastic deformation, each member type has defined skeleton curves and limit deformations that reflect reduced load capacity.

4. Outline of the Committee report

This report reviews seismic design with non-linear response history analysis in the U.S. and Japan and compares proto design between Japan and the U.S. The table of contents of the committee report is listed in Table 2. The detailed results of the Japan and the U.S. proto designs are also shown in the report.

The authors wish it serves as a resource for understanding differences in design philosophy at an overview level.

5. Concluding Remarks

This committee's findings provide an overview of the reliability of seismic design using non-linear response history analysis in Japan and the United States and help identify future challenges.

6. Acknowledgement

In the preparation of U.S. prototype design in the activities of this committee, we were supported by the contribution of Mr. Garrett Hagen, Chair of ACI 374 Committee, Degenkolb Engineers and Mr. Parham S. Pirzadeh, Degenkolb Engineers. The task of U.S. proto design in the report was unattainable without their contribution. We would like to express our sincere gratitude to them and the support of American Concrete Institute.

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5. 6 The role of structural design codes in society

5. 7 The role of structural engineers participating to committee activity

5. 8 The importance of technological transparency

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