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Performance-Based Seismic Design of Concrete Buildings: State of the Practice

Editors:
Jeff Dragovich, Mary Beth Hueste, Brian Kehoe, Insung Kim

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Performance-Based Seismic Design of Concrete Buildings: State of the Practice

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PREFACE

Performance-Based Seismic Design of Concrete Buildings: State of the Practice

Performance-Based Seismic Design (PBSD) of reinforced concrete buildings has rapidly become a widely used alternative to the prescriptive requirements of building code requirements for seismic design. The use of PBSD for new construction is expanding, as evidenced by the design guidelines that are available and the stock of building projects completed using this approach. In support of this, the mission of ACI Committee 374, Performance-Based Seismic Design of Concrete Buildings, is to "Develop and report information on performance-based seismic analysis and design of concrete buildings."

During the ACI Concrete Convention, October 15-19, 2017, in Anaheim, CA, Committee 374 sponsored three technical sessions titled "Performance-Based Seismic Design of Concrete Buildings: State of the Practice." The sessions presented the state of practice for the PBSD of reinforced concrete buildings. These presentations brought together the implementation of PBSD through state-of-the-art project examples, analysis observations, design guidelines, and research that supports PBSD.

This special publication reflects the presentations in Anaheim. Consistent with the presentation order at the special sessions in Anaheim, the papers in this special publication are ordered in four broad categories: state-of-the-art project examples (papers 1-5), lateral system demands (papers 6-8), design guidelines (papers 9-10), and research and observed behavior (papers 11-13).

On behalf of Committee 374, we wish to thank each of the authors for sharing their experience and expertise with the session attendees and for their contributions to this special publication.

Editors

Jeff Dragovich
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Performance-Based Seismic Design of the Tocumen Airport Terminal 2

Xiaonian Duan, Andrea Soligon, Jeng Neo, and Anindya Dutta

Synopsis: The new Terminal 2 at the Tocumen International Airport in Panama, currently essentially completed, will increase the airport's capacity to 25 million passengers per year. It has a doubly curved steel roof supported on reinforced concrete columns. The gravity force-resisting systems in the superstructure include long span precast and prestressed double tee decks, topped with cast-in-place concrete diaphragms and supported on a combination of unbonded post-tensioned girders and special reinforced concrete moment frame beams. The seismic force-resisting system includes special reinforced concrete moment frames and perimeter columns, special reinforced concrete shear walls and diaphragms, all detailed in accordance with ACI 318. Located in a region of moderately high seismic hazard, the building is classified as an essential facility and requires a non-conventional seismic design approach to maintain operational continuity and to protect life. Adopting the performance-based seismic design methodology and the capacity design principle, the structural engineering team designed an innovative reinforcement detail for developing ductile hinges at the top of the reinforced concrete columns to protect the structural steel roof which is designed to remain essentially elastic under MCE shaking. The structural engineering team's design has been reviewed by internationally recognised experts and three independent peer review teams.

Keywords: nonlinear pushover analysis, nonlinear response history analysis, performance assessment, performance-based seismic design, Tocumen Terminal 2

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Revitalizing a Community Space Using Performance-Based Seismic Design

Saeed Fathali, Bret Lizundia, and Francisco Parisi

Synopsis: This paper summarizes the benefits and challenges of implementing performance-based seismic design (PBSD) for two concrete buildings of the Lower Sproul Plaza Redevelopment Project in one of the busiest areas of the UC Berkeley campus. The project included new construction of Eshleman Hall and the additions to Martin Luther King (MLK) Hall, and the seismic retrofit of the existing MLK Student Union as a result of the expansion. The peer-reviewed PBSD implemented three-dimensional nonlinear response history analyses at two levels of seismic hazard. The analytical simulations using pairs of near-fault ground motions, scaled to match the site-specific spectrum, were intended to establish the expected seismic behavior of the buildings under rare and frequent earthquakes. The choice of PBSD over code-prescriptive procedures was prompted by multiple layers of complexity of the project. Several challenges including those related to the horizontal and vertical irregularities, or connecting new and existing concrete buildings with different lateral force-resisting systems would have made a code-prescriptive design a cumbersome analytical endeavor without providing reliable insight about the expected seismic behavior of the buildings. The PBSD, however, proved a powerful framework to design for a reliably predictable seismic behavior with sufficient ductility, and a designated ductile hinge zones with sufficient confinement and shear capacity. The PBSD methodology also enabled the designers to avoid unnecessary conservatism to deal with the complexities, when designing drift- and acceleration-sensitive elements including the cladding system. Finally, the PBSD methodology allowed the design to consider all potential modes of failure of concrete elements retrofitted by FRP material including the debonding failure between FRP material and substrate.

Keywords: performance-based seismic design, acceptance criteria, fiber-reinforced polymer (FRP), hazard level, nonlinear response history analyses (NLRHA), reinforced concrete, seismic design, seismic evaluation

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First Performance-Based Seismic Design Tower in Oakland, California

Devin Daniel and Ian McFarlane

Synopsis: The use of a Performance-Based Seismic Design (PBSD) approach to design buildings that exceed 240-feet (73.2 m) tall has been common among many west coast cities. More recently, Oakland, California has been an epicenter of development that has created a market for taller buildings. The residential tower at 1640 Broadway, which is currently under construction, is the first tower designed using PBSD exceeding 240-feet (73.2 m) tall in Oakland. This is notable in terms of establishing the implementation of PBSD in a new jurisdiction. This is also notable because of the near fault location of Oakland, given that the Hayward fault is less than 3.1 miles (5 km) from the downtown region, which raises new issues such as fault normal/fault parallel ground motion scaling issues and designing for extremely high demand levels. Due to these extreme demand levels, the project consisted of high reinforcement ratios within the walls and embedded steel coupling beams. Finally, the foundation conditions were challenged by the proximity to BART tunnels and therefore consist of a hybrid mat foundation supported on deep soil mixed panels and cased steel piles. A summary of the unique aspects of the building are presented and compared with typical code compliant and PBSD towers.

Keywords: performance based seismic design, near-source, soil-structure interaction

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Efficient Design of Slender Core-Only Tower Using PBSD

Mark Sarkisian, Eric Long, and David Shook

Synopsis: Performance based seismic design (PBSD) has created new opportunities for enhanced performance, improved cost efficiencies, and increased reliability of tall buildings. More specifically, flexibility with initial design methods and the utilization of response history results for design, not just verification, have emerged. This paper explores four refined design methods made available by the employment PBSD to influence seismic performance and identify areas of importance. First is the initial proportioning of reinforcement to encourage plastic hinge behavior at specific locations. Second is the initial proportioning of wall thicknesses and reinforcements to encourage a capacity-based design approach for force-controlled actions. Third is the mapping of observed strain demands in shear walls to specific detailing types such as ordinary and special boundary zones. Fourth is an efficient envelope method for the design of foundations. Through these design methods, initial proportioning can be conducted in a more refined way and targeted detailing can result in cost savings. A case study of a recently designed high-rise residential building demonstrates that cost savings can be achieved with these methods.

Keywords: performance based seismic design, tall buildings, concrete design, nonlinear time history analysis

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Performance-Based Seismic Design in Reinforced Concrete Tall Buildings in Indonesia

Sugeng Wijanto, Nelson M. Angel, José I. Restrepo, and Joel P. Conte

Synopsis: The rapid development of tall building construction has taken place in Indonesia over the last decade, especially in its capital, Jakarta. Reinforced concrete has been the preferred material of choice used for these buildings because it is economical and is easily handled by local contractors. Along with this rapid development, the Indonesian codes for structural design practices have experienced major changes, following the latest development of USA building design codes and performance-based design guidelines, especially those related to seismic design. This paper describes the latest seismic code in Indonesia and presents the state-of-the-practice for the design of tall buildings there. It also discusses the use of performance-based seismic design as an alternative method of design, considering the risk-targeted maximum and service earthquakes, in the structural design of a tall residential tower in Jakarta.

Keywords: dual systems, nonlinear analysis, performance-based seismic design (PBSD), tall buildings

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Analysis and Design of Reinforced Cast-in-Place Concrete Diaphragms

Drew A. Kirkpatrick, Leonard M. Joseph, J. Ola Johansson, and C. Kerem Gulec

Synopsis: The distribution of forces through floor diaphragms is critical to the overall behavior and performance of buildings during both wind and seismic events. Simplified methods commonly employed by design engineers establish approximate magnitudes and distributions of inertial and transfer forces within floor diaphragms. Such methods can be appropriate for regular low-rise buildings without significant transfer forces. However, for design of complex structures with large stiffness discontinuities in vertical or horizontal directions, a more detailed investigation and modeling of diaphragm behavior is usually required. Common situations in high-rise projects include a tower stack meeting a podium base with supplemental shear walls and a tower stack meeting a grade-level slab enclosed by basement walls. Large diaphragm transfer forces typically occur at these levels of abrupt stiffness changes. Using examples from recent projects and parametric studies following performance-based seismic design (PBSD) principles, this paper describes the use of strut-and-tie models in commercially available software (PERFORM-3D) to provide a better understanding of complex diaphragm behavior. Results can aid the designer in making decisions regarding floor thickness and reinforcing layout, including at chords and collectors. While the need for enhanced modeling techniques and understanding of diaphragm behavior has been highlighted by the increased use of PBSD, the findings presented in this paper may be applicable to projects based on traditional (code-based) approaches as well.

Keywords: performance based seismic design (PBSD), non-linear response history analysis (NLRHA), diaphragms, concrete, tall buildings, PERFORM-3D

Seismic Shear Force Amplification in Concrete Shear Walls for Buildings Under 240' (73m) – Performance Based Seismic Design vs Code Level Design

Tom C. Xia and Doug Lindquist

Synopsis: Performance based seismic design (PBSD) has been widely used for tall buildings as a code alternative design method for concrete shear wall structures. However, most PBSD studies are done for buildings taller than 240' (73 m). Very few studies have been done for buildings shorter than 240' (73 m) because PBSD is not required for buildings under 240' (73 m). It is unclear if and how the shear demand increases observed in typical PBSD analysis should be applied to buildings shorter than 240' (73 m). This study includes two buildings in the Seattle area that are designed per current codes. The study compares the shear demands predicted by the elastic analysis method with the demands predicated by the nonlinear time history analysis used in PBSD method. The intent of this study is to examine the merits of the new Seattle requirement using Ω_o factor to amplify the shear demand for buildings designed at code level and for the building height in the range of 160' (48.8 m)-240' (73 m). It also explores the proper ϕ factor to be used in ACI 318 to determine the shear wall capacity.

Keywords: reinforced concrete shear walls, seismic shear amplification, performance based seismic design, code level design, overstrength factor

Trends in Demands for Concrete Performance-Based Seismic Design Towers

Kevin Aswegan and Ian McFarlane

Synopsis: The use of a Performance-Based Seismic Design (PBSD) approach to design buildings whose heights exceed 240 ft (73 m) has become common in many West Coast cities. This paper studies trends across 14 special reinforced concrete shear wall PBSD towers designed within the last 5 years. The primary purpose of evaluating these trends is to compare demands calculated using a linear elastic design approach (i.e. for Design Earthquake or Service Level shaking) to the demands (average results from 7 or 11 ground motions) determined through nonlinear analysis (i.e. for Maximum Considered Earthquake shaking). The specific demands evaluated include core wall shears and foundation overturning moments. The paper also demonstrates that shear and moment amplification are significant phenomena for concrete buildings, and are believed to be primarily due to nonlinear behavior, material over-strength, higher mode effects, and damping and stiffness assumptions. The results present a useful range of trends to provide an engineer guidance on the expected demands and the level of variability between projects. The paper highlights some of the reasons for the variability in these trends, and provides general proportioning recommendations.

Keywords: concrete shear walls, PBSD, performance-based seismic design

Assessment of a 12-story Reinforced Concrete Special Moment Frame Building Using Performance-Based Seismic Engineering Standards and Guidelines: ASCE 41, TBI, and LATBSDC

Mustafa K. Buniya, Andre R. Barbosa, and Siamak Sattar

Synopsis: A 160-foot (≈ 49 m) tall 12–story reinforced concrete special moment frame building is designed following ASCE 7-16 and ACI 318-14, and assessed using three Performance-Based Seismic Engineering (PBSE) standards and guidelines including ASCE/SEI 41, the Tall Buildings Initiative (TBI) guidelines for performance-based design of tall buildings, and the Los Angeles Tall Buildings Structural Design Council (LATBSDC) procedures. The assessments are performed at the combination of two performance and hazard levels including Collapse Prevention (CP) at the risk-targeted maximum considered earthquake (MCE_R) hazard level and Immediate Occupancy (IO) at a frequent ground motion level with 50 percent probability of exceedance in 30 years, *i.e.* serviceability performance level. Based on the recommendations of each of the three PBSE documents, nonlinear finite element models are implemented in OpenSees. Through nonlinear time-history response analyses, the finite element models are subjected to eleven ground motions that are selected following the ground motion selection recommendations in ASCE 7-16. Assessment results indicate that for the serviceability performance level, the code-compliant building meets the design requirements of the three PBSE documents for the interstory drift ratio and inelastic deformation of the structural components. At the MCE_R hazard level, although the building essentially satisfies the design requirements for the peak interstory drift ratios and inelastic deformation, the mean of the residual interstory drift ratios as well as the envelope of the residual drift ratios do not meet the limits of the TBI and LATBSDC guidelines. The results indicate that the newly designed building meets the ASCE 41 acceptance criteria but does not meet the design requirements set in TBI and LATBSDC guidelines.

Keywords: ASCE/SEI 41, LATBSDC, nonlinear modeling, performance-based design, reinforced concrete, special moment frame, TBI

Guidelines for the Performance-Based Seismic Design of Seismic Category 1 Concrete Structures in Nuclear Power Plants

John S. Ma[1]

Synopsis: The U.S. Nuclear Regulatory Commission (NRC) defines seismic Category 1 structures as the structures (buildings) that should be designed and built to withstand the maximum potential earthquake stresses for the particular region where a nuclear plant is sited. Seismic Category 1 structures have been designed for ground-shaking intensity associated with a safe-shutdown earthquake (SSE) – the intensity of the ground motion that will trigger the process of automatic shutdown of the reactor in operation. The SSE generates floor response spectra at different floor elevations in a building, and these spectra and their associated forces are used for the design of piping and piping anchors and equipment and equipment anchors at their floor locations. The NRC policy requires that the seismic Category 1 structures whose collapse could cause early or/and large release of radioactive materials into the atmosphere to be analyzed/designed for "no collapse" during the ground-shaking intensity of a review-level earthquake (RLE), which is 1.67 times that of an SSE. Most seismic Category 1 concrete structures, such as containment and shield buildings (curved cylindrical wall; see Figs. 1 and 2 in the next section) and containment internal structures (straight wall; see Fig. 1), use walls to resist earthquakes.

This paper presents guidelines for the performance-based seismic design for these wall-type structures that could meet the NRC policy. The method consists of (1) proportioning wall thickness based on shear stress of $6\sqrt{f_c'}$ **(**$0.5\sqrt{f_c'}$ megapascals (MPa)) generated by SSE ground motions, (2) limiting vertical compressive stress in walls to less than 0.35 fc', (3) providing minimum percentage of reinforcement of 1.0 percent to prevent steel reinforcing bar fracture, (4) subjecting the building design to nonlinear dynamic response analyses under RLE ground motions, (5) identifying any members and their connections in the building that have failed or collapsed during the RLE ground motions, (6) increasing reinforcement or wall thickness, or both, to provide additional strength or/and ductility for the failed or collapsed members and their connections, and (7) resubjecting the revised building design to the nonlinear dynamic response analyses as stated in step (4) until there is no collapse of the building and its members and their connections. This performance-based seismic design method is a direct, transparent, and scientific answer to whether these important seismic Category 1 structures meet the NRC's policy that they will not collapse during the RLE ground motions. Examples of using the nonlinear dynamic response analyses are cited and described. Guidelines for the performance-based seismic design of seismic Category 1 concrete structures are listed at the end of this paper.

Keywords: containment building, containment internal structures, earthquake, performance-based design, safety, seismic design, and shield building

Recommendations for Modeling the Nonlinear Response of Flexural Reinforced Concrete Walls Using Perform

Laura N. Lowes, Dawn E. Lehman, and Carson Baker

Synopsis: The PERFORM-3D software package is used commonly in engineering practice to conduct nonlinear dynamic analyses of reinforced concrete walled buildings to their seismic response. However, few studies have evaluated or improved on common modeling approaches for structural concrete walls. The research presented here was conducted to establish best practices for modeling the full nonlinear response of walls exhibiting common flexural failure modes. First, an experimental data set consisting of eight planar concrete walls was collected; these walls were spanned a range of length-to-thickness ratios, shear stress demands, axial load ratios, and longitudinal reinforcement configurations. For each wall specimen, a reference numerical model was created using typical modeling methods as proposed by Powell. Comparison of simulated and measured cyclic response histories show that typical modeling techniques result in relatively inaccurate simulation of cyclic response and very inaccurate simulation of drift capacity. To improve the model accuracy, experimental data were used to determine appropriate values for the steel and concrete material model cyclic response parameters. Experimental data and mathematical definitions for the concrete compressive energy were used to develop recommendations for defining concrete post-peak stress-strain response to achieve accurate, mesh-independent simulation of drift capacity. Finally, recommendations for the minimum number of elements were examined. Comparison of simulated and measured cyclic response histories show that the new modeling recommendation result in accurate, mesh independent simulation of cyclic response, including drift capacity. Future work will evaluate the proposed modeling approach for asymmetric and flanged walls.

Keywords: structural walls, finite element modeling, seismic response, flexure

Interaction of Sliding, Shear, and Flexure for Earthquake Design of Reinforced Concrete Shear Walls

Burkhart Trost, Harald Schuler, and Bozidar Stojadinovic

Synopsis: Sliding failure of reinforced concrete shear walls was observed after the Chilean earthquakes in 1985 and 2010, during shaking table tests, and in many quasi-static cyclic shear walls tests. Sliding may occur along cold joints or flexural cracks that remain open due to permanent deformations induced during cyclic loading. If it occurs, sliding can significantly reduce the horizontal force resistance and change the deformation mechanism of reinforced concrete shear walls, and thereby markedly affect the seismic performance of shear wall buildings.

This study provides the interaction diagrams intended to help reinforced concrete shear wall designers exclude the sliding failure mode. Regions where sliding, shear, and flexural failure modes are expected are delineated according to the shear wall shear span to length ratio, the axial force, the horizontal and vertical reinforcement ratios, and the concrete strength. These interaction diagrams are derived using a cyclic reinforced concrete wall response model that considers flexure, shear and sliding load-deformation relationships and the interaction between them. The interaction diagram is used to develop design recommendations on how to avoid the sliding failure of reinforced concrete shear walls under earthquake loading.

Keywords: sliding, shear walls, crack, flexural crack, cold joint, friction, aggregate interlock, pushover

Seismic Performance of Full-Scale Reinforced Concrete Beam-Column Connections Extracted From Earthquake-Damaged Buildings

Giulio Leon Flores, Reza V. Farahani, Hussien Abdel Baky, and Paul C. Rizzo

Synopsis: This paper presents the structural testing of four full-scale reinforced concrete beam-column connections, extracted from reinforced concrete buildings that suffered minor damage from the Canterbury Earthquakes in New Zealand. Two connections are extracted from a moment frame comprising the secondary seismic-resisting system of a concrete building; two are extracted from moment frames of the primary seismic-resisting systems of a precast concrete building. The seismic performance of the connections is evaluated from the test results and compared to recommendations in ASCE 41 (2013) for the evaluation of existing buildings. Due to the size of the specimens, the tests were stopped when the actuator reached its maximum stroke, at interstory drifts between 2.5% and 3. The cast-in-place connections showed moderate damage after the tests, at ductility levels above 2.9, and their initial lateral stiffness was approximately 80% of the lateral stiffness of numerical models representing the undamaged state. The precast connections exhibited extensive damage along the construction joint between the precast beams and the cast-in-place beam-column joint, at ductility levels above 3.4. The plastic mechanism was governed by sliding shear of the precast beams, which caused severe stiffness deterioration at the end of the tests. The measured stiffness in this case was approximately half of the stiffness predicted by numerical models in which nonlinearity is considered in the form of flexural plastic hinges only. This unexpected behavior is attributed to the low quantity of reinforcing steel crossing the construction joint, and presumably earthquake damage.

Keywords: seismic performance, full-scale seismic test, measured lateral stiffness, beam-column connections, precast concrete frames