SUSTAINABLE DESIGN CONSIDERATIONS IN EARTHQUAKE ENGINEERING

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ABSTRACT

The primary goal for seismic-resistant design of ordinary structures is to prevent collapse and loss of life. Thanks to extensive experimental, theoretical and computational research, engineers are able to design wide array of structures capable of withstanding numerous cycles of inelastic deformation during strong earthquakes with minimal probability of collapse. However, this approach, while providing a high degree of life safety, is expected to result in substantial structural and nonstructural damage. The economic and social impacts of this anticipated damage could be far-reaching and profound; and likely contrary to the basic principles of sustainable development increasingly advocated by many owners, architects and policymakers. However, a range of quantitative tools, such as performance-based evaluation, and advanced structural system concepts, can easily extend current earthquake engineering design practices consistent with and supportive of emerging trends related to sustainable design. This paper discusses some of the underlying issues and highlights several approaches to achieve structural systems that are more sustainable.

KEYWORDS: Sustainable design, Seismic isolation, Rocking foundations, Self-centering structures

1. INTRODUCTION

A large ductility capacity is generally required of structures located in regions of high seismicity to ensure economical designs with adequate protection against collapse. For a design level or larger earthquake, this approach results in significant damage to structural and other elements, and permanent offsets -- damage that can impede post-event functionality, and require costly, dangerous and disruptive inspections, repairs and, in some cases, demolition. Thus, a challenge increasingly posed to earthquake engineers is to maximize post-event operability and minimize repair costs and other impacts, while protecting public safety.

One approach to this problem is to simply design stronger and stiffer structures, thereby limiting dependence on inelastic action and reducing displacements. This approach increases the quantity of materials required, but may utilize simpler and cheaper construction details. Since many structures are constructed on poor soil conditions, the need for greater superstructure strength and stiffness can disproportionately increase the complexity and cost of foundations. Similarly, stiffening and strengthening a structure would likely increase in-structure accelerations, increasing damage to nonstructural elements and contents, or necessitating more costly nonstructural elements and details.

Another approach is through performance-based design where the various performance objectives are characterized in terms of loss of life, disruption to operation, and direct and indirect losses. Engineering principles and risk management concepts are applied to evaluate how well stated goals are achieved. While this approach provides a powerful quantitative tool for assessing a particular structure, and for comparing the likely performance of alternative structural concepts, performance-based engineering as currently used is more of an evaluation technique than a coherent design strategy.

Similar problems are encountered in the planning of critical infrastructure systems and the architectural design of individual structures. The holistic framework articulated in 1987 by the UN's Brundtland Commission is increasingly used to address such issues [Brundtland, 1987]. This framework advocates "meeting the needs of present generations without compromising the ability of future generations to meet their needs." Numerous approaches to sustainable development have evolved from this report, but nearly all emphasize maintaining a balance among resource efficiency, environmental responsibility, well being of occupants, and community sensitivity. To many, sustainable design or so-called green construction focuses on selection of materials and energy efficiency, but as applied in the context of earthquake engineering, includes: durability and longevity; reparability, particularly following an earthquake; more efficient and lower impact construction; efficient use of materials through improved materials, more efficient design methods, and more efficient structural systems and layouts; consideration of material re-use and disassembly for reuse; use of recycled materials; integration of structural forms to help achieve the needs of other disciplines; and reducing the impacts of abnormal events such earthquakes by minimizing the need for repair and disruption of service [Kren, 2006].

Numerous efforts are being carried out by structural engineers throughout the world to realize these objectives. For example, efforts are underway on precast and prefabricated construction to reduce environmental impacts, reduce disruption caused by shoring and false work, and speed construction. Greater use is being made of fly ash, slag, recycled steel and concrete, and high performance materials. Several investigators have examined replaceable plastic hinges to facilitate post-earthquake repair. Several other existing and emerging approaches to earthquake resistant design appear ideal when considered from the perspective of sustainable design.

In this paper, three approaches under investigation at UC Berkeley are highlighted that permit durable structures to respond to earthquakes in a controlled nonlinear manner (resulting in cost savings), but that require less or no repair, and suffer only small residual displacements, following an major earthquake. These relate to (1) seismically isolated structures, (2) structures that rock on spread footings or pile foundations, and (3) fixed based structures that self-center as a result of the presence of unbonded longitudinal post-tensioning. Each approach is shown to be effective in reducing design forces compared to designing the structure to remain elastic, and each reduces post-earthquake residual displacements and damages due to drift and acceleration.

2. SEISMIC ISOLATION

Seismic isolation has been widely used in many parts of the world to retrofit existing seismically vulnerable structures and to design major new ones. This technology is especially easily to implement for bridges where tradition or environmental conditions result in the decks being attached to the supporting columns and abutments via elastomeric or other bearings. To develop improved understanding of the behavior of seismically isolated bridges and gain confidence in design methods a series of tests and analyses of isolated bridges has been recently completed at Berkeley (e.g., Anderson, 2003). These studies include a variety of different isolator types, bridge dynamic properties, and earthquake characteristics. Three generic types of isolator bearings were considered, including lead rubber bearings, high damping bearings, and friction pendulum bearings. Extensive studies were made to characterize bearings subjected to 3D loading, and to assess the effects of aging. Bridge systems tested ranged from simple span to two span bridges, having substructure periods ranging from nearly zero to more than 2 seconds. More than a dozen bridge configurations were tested to assess the effects of mass eccentricity, stiffness eccentricity, bridge substructure period, bearing type, in-situ variations in bearing properties, yielding of supporting columns, and earthquake excitations. Some of the bridge models tested appear in Fig. 1. In total, more than 1000 experiments were performed.

Such experimental results were used to develop improved numerical models of the isolation bearings, and to assess the sensitivity of system response to different design parameters, and to uncertainties in these parameters. In particular, various provisions of the AASHTO Guideline Specification [1999] were assessed. For example, issues related to treatment of bidirectional excitations are covered in Anderson and Mahin [2003, 2004]. Overall, good performance was noted for all of the isolated systems studied.

It has been noted that the design of isolated buildings and bridges can be problematic due to the apparent over-conservativeness of some design provisions, but also because of challenges encountered when designing isolated systems to resist intense near-field ground motions. Various efforts to make design procedures more transparent, based on performance-base engineering concepts, are underway worldwide.

Fig. 1 Shaking Test specimen of simple supported bridge with different substructure stiffness

To resist large near-fault ground shaking, relatively large and strong isolators are often necessitated to control displacements and maintain isolator stability. In these cases, isolators may not act effectively, especially for small events, and require relatively large design forces and trigger excessive accelerations in the superstructure [Morgan and Mahin, 2007]. Thus, efforts are underway to improve isolation for small events, limit displacements for larger events, and reduce floor accelerations.

Several approaches are being pursued at Berkeley, including novel combinations of elastomeric isolators and nonlinear viscous dampers. Another promising approach is the newly developed Triple Pendulum Slider [Earthquake Protection Systems, 2007]. This device has three independent pendulum mechanisms (Fig. 2). By strategically selecting friction coefficients for each mechanism, hysteretic characteristics can be optimized for occasional, rare and very rare events. Tests (Fig. 2) and analyses demonstrate that the devices can be designed to achieve about the same isolator displacements for a large event, but with smaller drifts and accelerations in the superstructure and with a far greater degree of isolation during smaller events (Fig. 3) [Morgan and Mahin, 2007].

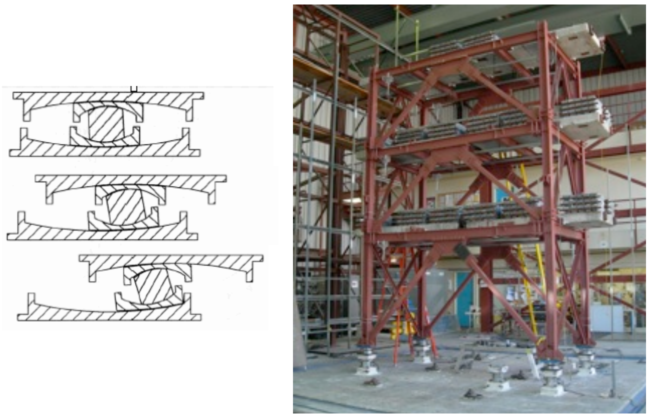


Fig. 2 Triple pendulum slider and test specimen

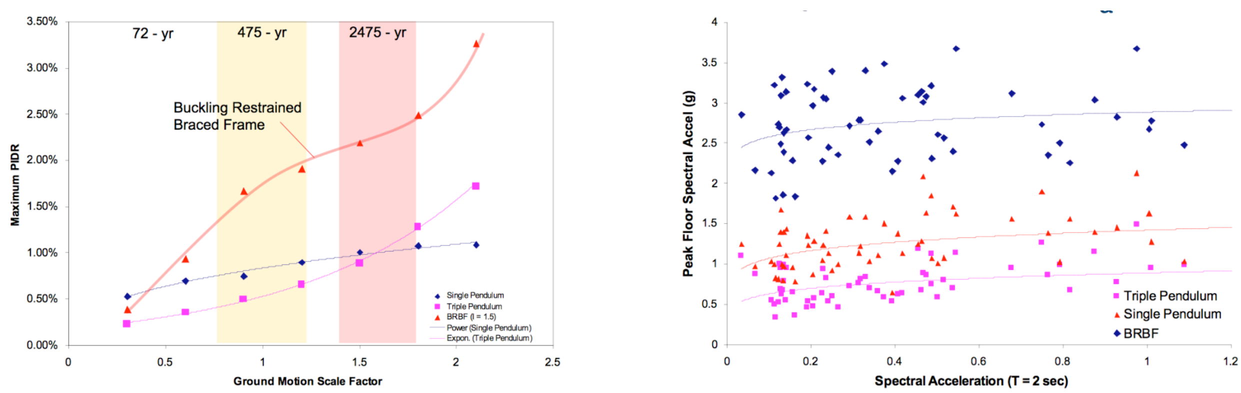


Fig. 3 Interstory drift ratio and floor spectral acceleration for isolated structures with TPS and conventional bearings and buckling restrained braced frames (BRBF) [Morgan *et al*, 2007]

3. ROCKING FOUNDATIONS

Most structures are designed to have a fixed base. For example, conventional bridge structures residing on competent soil are typically designed with rectangular spread footings proportioned to allow for a fixed base response. This generally leads to inelastic behavior at or near the column to footing interface during design level earthquakes. This mode of behavior dissipates input energy, but results in damage to the column and potential permanent lateral displacements. By permitting the bridge piers to rock or uplift on the supporting soil introduces other modes of nonlinearity (rocking) and energy dissipation (soil inelasticity). Explicit consideration of rocking as an acceptable mode of response can reduce the required footing sizes. Also, the simultaneous rocking of a properly designed foundation and flexural deformation of the supported column appears to eliminate, or substantially reduce, damage in the column and residual displacements in a bridge with moderate to long fundamental periods following a major earthquake. Of the three approaches discussed in this paper, rocking of bridge foundations relies the most on conventional design and construction methodologies.

Many previous studies have investigated the benefits of allowing a column and footing system to uplift (e.g., [Chopra and Yim, 1985; Housner, 1963]). Analytic studies of bridge column response to one horizontal earthquake component have illustrated the combined effects of rocking and column flexural displacements [Alameddine and Imbsen, 2002; Kawashima and Hosoiri, 2003]). Recent earthquake simulator tests [Sakellaraki et al, 2005] on small-scale steel columns subjected to unidirectional excitation have also demonstrated the feasibility and benefit of the rocking mechanism in resisting seismic effects.

Because of the potential economic and performance benefits of using rocking in new construction, and the desirability of developing reliable analysis procedures for evaluating existing bridge structures, a series of experimental and analytical investigations has begun at UC Berkeley and UC Davis with funding from Caltrans. These studies focus on developing guidelines for the design of bridge piers foundations allowed to uplift during severe earthquakes. The work at UC Berkeley focuses on development of design procedures, and validating these via more refined structural analyses and earthquake shaking table tests of moderate-scale models of reinforced concrete bridge columns under multidirectional earthquake excitations. The work at UC Davis focuses on validating this work through a series of geotechnical centrifuge tests. Consideration is limited to good soil conditions where the factor of safety under gravity loads alone exceeds three. Some to the models used in the tests and analyses are shown in Fig. 4.

Fig. 4 Simplified analytic model, UC Berkeley shaking table tests and UC Davis centrifuge tests used to study rocking foundations.

For the shaking table model, a series of tests examine the effect of one, two and three components of excitation for a simple 1:4.5-scale column on a spread foundation supported on a 50 mm thick neoprene (Duro-60) pad. This pad highly idealizes the soil beneath the footing. The column has a diameter of 410 mm, a longitudinal reinforcement ratio of 1.2%, and spiral reinforcement. Tests have been carried out with columns having a footing width of 3 and 5 times the column width (D_c) and having gravity loads equal to 3% and 10% of $A_g f'_c$. Two near-fault ground motion recordings having several frequency and amplitude scalings were used in the tests. For tests with a $3D_c$ footing width, the column remained elastic, even though comparable fixed based columns would likely suffer substantial damaged. For bridges with moderate to long fundamental periods, the overall displacement of the mass is similar to or smaller than expected of a fixed base column. For the $5D_c$ wide footing simultaneous yielding of the column and uplift of the footing occurred with similar overall top displacement but reduced plastic hinge rotation demands compared to the fixed base case.

The effect of two and three components of excitation was of special interest in these tests. When a footing lifts about a corner under two horizontal components of motion, it may tend to (1) 'roll' towards one edge or the other, resulting in irregular 3D response, or (2) pivot about a vertical axis due to the eccentricity of the reaction point and the center of mass. Where footing rotation was unrestrained about a vertical axis, after about 30 runs there was a permanent rotation about the vertical axis of about 2%. The bridge deck and soil surround the footing would tend to restrain this rotation. The results in Fig. 5 show that a vertical or a second horizontal component of excitation can increase column tip displacement, and improved methods for estimating this response have been developed.

Several models were developed for predicting uplift and rocking behavior using the computational framework OpenSees [2003]. The baseline model is a lumped mass fiber column resting on an elastic footing and nonlinear vertical springs. In addition, full 3D finite element models and a generalized bending, rocking and sliding plastic hinge model were also developed [Kutter *et al*, 2006]. Good correlation between computed and test results was achieved for both types of numerical models.

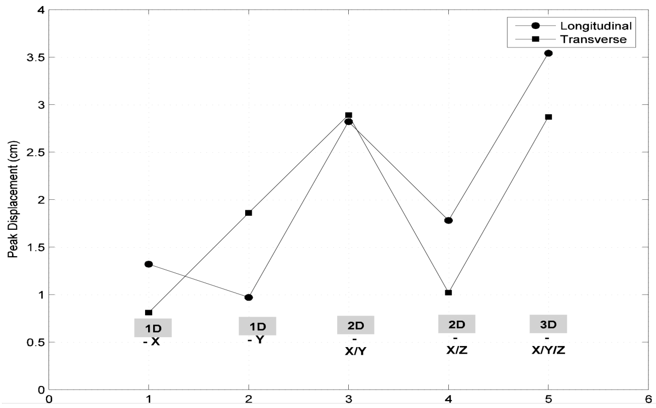


Fig. 5 Peak displacements for five combinations of Los Gatos records (35%g)

Experimental and analytical investigations indicate that this rocking mechanism provides a viable means of resisting earthquake effects. Except for short period structures, column displacements were similar to or smaller than would be expected for a comparable elastic or yielding pier with a fixed foundation, and the column showed no signs of damage and re-centered following the end of the ground shaking. For cases where column yielding occurred, the damage and permanent displacements are greatly reduced. It is recognized that rocking of spread footings may not be possible in many important situations (e.g., poor soil conditions). In such cases, development of special foundation details that permit rocking on pile-supported foundations may be feasible. Extension of these concepts to braced frame buildings is currently under investigation.

4. SELF-CENTERING REINFORCED CONCRETE COLUMN SYSTEMS

Where the base of a bridge column is fixed by large spread footings or piles, a modification of conventional ductile reinforced concrete columns is possible that can greatly improve post-earthquake operability and reduce the extent of necessary repairs. In this case, some of the reinforced concrete column's (RC) longitudinal mild reinforcement is replaced by unbonded post-tensioning strands (typically located in a central conduit). The seismic performance of such partially prestressed, reinforced concrete columns (PRC) is being investigated by the Pacific Earthquake Engineering Research Center through quasi-static and dynamic analyses and shaking table tests of single columns and simple bridge systems. The design approach used for these columns [Jeong and Mahin, 2007; Sakai and Mahin, 2004; Sakai et al, 2006] is to reduce the amount of longitudinal reinforcement needed for a conventional ductile design [Caltrans, 1998] by about half, but to add unbonded post-tensioning strands and adjust the amount of transverse confinement such that the envelop of stiffness and strength under loading conditions is similar to that used for a conventional ductile column. However, under unloading, the columns exhibit a characteristic hourglass or center-oriented hysteretic loop shape. This can be seen in Fig. 6.

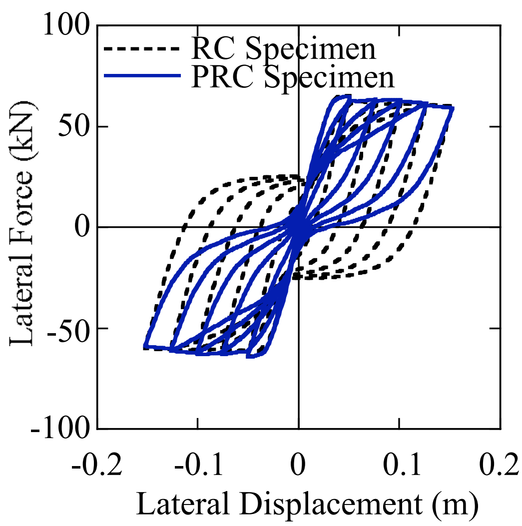
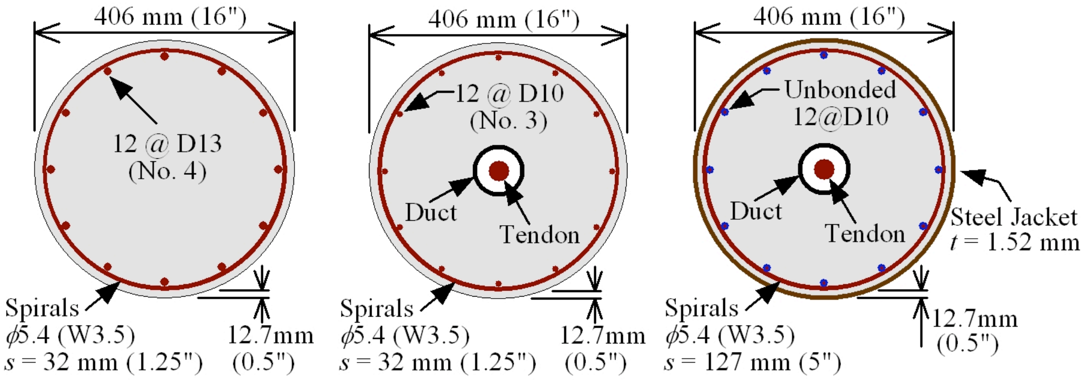


Fig. 6 Comparison of hysteretic loops

Six nearly identical columns have been tested to date [Sakai *et al*, 2006]. The baseline ductile column is shown in Fig. 7(a), whereas a corresponding self-centering column is shown in Fig. 7(b). In Specimens PRC and PRC-2 all of the mild reinforcement is fully bonded to the surrounding concrete. In PRC-U, the mild rebar are debonded locally over a length of $2D_c$ in the plastic hinge region to help reduce steel strain concentrations. In Specimen PRC-U2, the rebars are also debonded, but the level of post-tensioning is increased by about

75% to try to improve re-centering tendencies. Lastly, Specimen PRC-J was constructed with locally unbonded mild reinforcement, the lower baseline prestress force, and a steel jacket (to help confine the plastic hinge region and reduce visible damage in the plastic hinge region following an earthquake). For all of the partially prestressed columns, the post-tensioning was debonded over the full length of the column. All specimens were subjected to two horizontal components of the Los Gatos record from the 1989 Loma Prieta earthquake scaled to yield, design and maximum excitation levels. This motion typically results in large permanent residual drifts.



(a) RC specimen (b) PRC specimens (c) PRC specimen with jacketing

Fig. 7 Cross sections considered for self-centering column investigation

As expected, the conventional column proved to be quite ductile (with ductility demands in excess of 12 during the maximum considered event), but permanent lateral displacements developed during the design and maximum level events, requiring a premature termination of the tests (see Fig. 8(a)) at the end of the maximum level tests where the permanent lateral displacements were more than 10% of the column height. Even at the design level event (displacement ductility of 7.5) the permanent lateral displacement in the ductile column is more than 1%, which would be problematic for continued traffic flow (Fig. 9(a)). In contrast, the basic self-centering column at the Design Level excitation had the same or smaller peak displacements, but the permanent offset was very small (Figs. 8(b) and 9(b)).

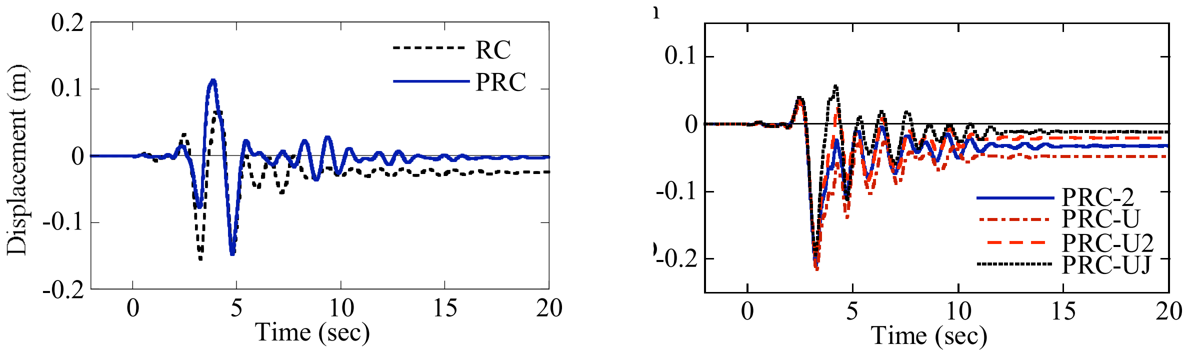
To improve the self-centering characteristics of the partially prestressed concrete columns, several design modifications were attempted, as mentioned above. As can be seen in Fig. 9(b), these reduced the residual displacements significantly. For the design level events, the residual displacements were essentially insignificant for all of the modified designs. For the maximum considered event (MCE), the displacement ductility demands were quite similar (greater than 10). While unbonding of the mild reinforcement in Specimen PRC-U reduced peak steel strains, it softened the column, some of the longitudinal bars buckled slightly and residual displacements increased somewhat in comparison to Specimen PRC-2 for the MCE. By increasing the level of prestressing in Specimen PRC-U2, the residual displacements under the MCE became smaller than for PRC-2, but the column suffered significant spalling and more buckling of the longitudinal steel. As such, these columns perform better than conventional reinforced concrete columns, but may still require repair following very large shaking.

On the other hand, self-centering column with steel jacketing (Specimen PRC-J), behaved quite well under the MCE, with permanent lateral displacements less than 0.6% of the column height, and no apparent damage (except a small local buckle at the bottom of the steel jacket attributed to insufficient gap between the jacket and footing). Thus, this column would appear to minimize the need for post-earthquake repair, and remains plumb enough to avoid reduced traffic flow. Extension of these concepts to the design of concrete cores in building structures is currently under investigation.

A series of numerical simulations has been undertaken to evaluate and improve analytical models and assess the cost and performance of self-centering systems [Jeong and Mahin, 2007; Lee and Billington, 2006]. Design guidelines for self-centering columns have been developed [Jeong and Mahin, 2007; Sakai *et al* 2006].

(a) Specimen RC (b) Specimen PRC

Fig. 8 Residual displacements of specimens after maximum level test



(a) Design Level (b) Maximum Considered Level

Fig. 9 Response of Test Specimens to Los Gatos Records from 1989 Loma Prieta Earthquake

5. CONCLUDING REMARKS

The technology and design approaches described in this paper provide several alternative ways to achieve durable building and transportation structures that increase post-earthquake serviceability and reduce the need for repair. By permitting structures to undergo significant inelastic deformations during seismic events, yet suffer little damage that would require post-earthquake repairs and impair operability, structural engineers can achieve designs that are durable, dependable, and economical in terms of initial construction cost and the potential losses that might occur in the event of a damaging earthquake. As such, these approaches address the basic principles articulated by sustainable design.

Additional research is needed to refine these concepts, especially with regards to (1) reducing cost and increasing speed of construction, (2) reducing the societal and ecological impacts of construction, (3) and refining concepts such as those presented herein and developing more generally applicable design guidelines. In addition, these design approaches require study to assess reliably the ability of the structure to withstand future seismic events. While typical visible forms of damage may not develop, some forms of damage are hidden (e.g., compaction of soil yielding beneath foundations), dynamic characteristics may have changed, and the remaining ability to dissipate energy may be reduced due to low cycle fatigue. Similarly, the deformed shape of structures designed in using these concepts may differ from conventional fixed base structures, requiring special consideration for the design of architectural, mechanical, electrical and plumbing elements.

Experimental research is an essential aspect of developing such new structural concepts, not only to improve understanding of their behavior and to validate numerical models, but also to provide a critical proof of concept.

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REFERENCES

AASHTO (1999). "Guide Specifications for Seismic Isolation Design", American Association of State Highway and Transportation Officials, Washington, D.C.

Alameddine, F., and Imbsen, R.A. (2002). "Rocking of Bridge Piers Under Earthquake Loading." *Proceedings,* Third National Seismic Conference & Workshop on Bridges and Highways.

Anderson, E. (2003). "Performance-Based Design of Seismically Isolated Bridges," *Doctoral Thesis,* University of California, Berkeley, CA, 881 pp.

Anderson, E. and Mahin, S. (2004). "An Evaluation Of Bi-Directional Earthquake Shaking On The Provisions of the AASHTO Guide Specifications For Seismic Isolation Design," *Proceedings,* 13WCEE, Vancouver.

Brundtland, G. (1987). *Report of the World Commission on Environment and Development: Our Common Future,* United Nations.

Caltrans (1998). *Seismic Design Criteria,* version 1.1, Calif. Dept. of Transportation, Sacramento, CA.

Chopra, A. K. and Yim, C. (1985). "Simplified Earthquake Analysis of Structures with Foundation Uplift." *Structural Engr.,* ASCE, **111:4**.

Earthquake Protection Systems (2007). *Product Description,* Mare Island, CA.

Housner, G.W. (1963). "The Behavior of Inverted Pendulum Structures During Earthquakes." *Bulletin of the Seismological Society of America,* **52:2**.

Kawashima, K. and Hosoiri, K. (2003). "Rocking Response of Bridge Columns on Direct Foundations," *Proceedings,* Symposium on Concrete Structures in Seismic Regions, Paper No. 118, FIB, Athens.

Kren, A. (2006). *Personal communication*.

Kutter, B., Jeremic, B., Stephen Mahin, S., Ugalde, J., Gajan, S., and Hu, G. (2006). "Seismic Energy Dissipation by Foundation Rocking for Bridge SFS Systems," *Proceedings,* Fifth National Bridge Seismic Conference, San Francisco, CA.

Jeong, H. and Mahin, S. (2007). "Evaluation of Self-Centering Reinforced Concrete Columns by Shaking Table Tests and Numerical Simulations," *PEER Report*, University of California, Berkeley, CA.

Lee, W. and Billington, S. (2006). "Performance based assessment of a self-centering bridge pier system for seismic regions," *Proceedings*, 100th Anniversary Earthquake Conference. EERI, Oakland, CA.

Morgan, T. and Mahin, S. (2007). "Enhancing the performance capabilities of seismically isolated buildings using multi-stage friction pendulum sliding bearings," *Proceedings*, World Forum on Smart Materials and Smart Structures Technology (SMSST '07), Chongqing & Nanjing, China.

OpenSees Development Team (1998-2003). "OpenSees: open system for the earthquake engineering simulations" *http://opensees.berkeley.edu/*.

Sakai, J. and Mahin, S. (2004). "Analytical investigations of new methods for reducing residual displacements of reinforced concrete bridge columns." *PEER-2004/02*, Pacific Earthq. Engrg. Res. Center, Univ. of California, Berkeley, CA.

Sakai, J., Jeong, H. and Mahin, S. (2006). "Reinforced Concrete Bridge Columns That Re-Center Following Earthquakes," *Proceedings,* 8NCEE, EERI, San Francisco, CA.

Sakellaraki, D., Watanabe, G. and Kawashima, K. (2005). "Experimental Rocking Response of Direct Foundations of Bridges, *Proceedings,"* 2nd Int. Conf. on Urban Earthquake Engineering, March 7-8, 2005, Tokyo Inst. of Technology, Tokyo, Japan.