OVERVIEW OF A PROJECT ON RESILIENCE-BASED DESIGN OF BUILDINGS WITH ACCELERATED POST-EARTHQUAKE FUNCTIONAL RECOVERY

C. Franco Mayorga[1], Georgios Tsampras[1], Paolo Bocchini[2], and Sena Mursel[2]
1. University of California San Diego, La Jolla, California
2. Lehigh University, Bethlehem, Pennsylvania
USA

Abstract

With urban populations rising, the demand for multi-story buildings in seismic-prone areas like California is increasing. However, recent earthquakes have revealed that even newly designed multi-story buildings can collapse, resulting in fatalities, financial losses, non-functional communities, and significant environmental impacts due to debris. The U.S. National Earthquake Hazards Reduction Program (NEHRP) emphasizes national earthquake resilience, underscoring the need for buildings to recover functionality quickly after strong earthquakes to enhance community resilience. FEMA identifies the development of "better-than-code" structural systems as a key research need for future NEHRP Provisions. Supported by the NIST/NSF Disaster Resilience Research Program (2024-2027), our research focuses on developing resilience-based designs for buildings to ensure accelerated post-earthquake functional recovery. Specifically, we investigate buildings with rocking inelastic base mechanisms and practical force-limiting deformable connections strategically placed in the seismic load path. These systems are preferred over conventional designs due to their potential to achieve faster and more reliable post-earthquake functionality, owing to their limited seismic responses and reduced sensitivity to the variability in strong earthquake ground motions. This paper and corresponding presentation will provide an overview of the basis of the proposed research project.

Introduction

Despite advancements in seismic engineering, the last two decades have witnessed a troubling increase in earthquake-related fatalities and damages (CRED 2022; Tsampras 2016). This rise can largely be attributed to higher population densities in seismically active regions and the complexities involved in modern urban structures, particularly multi-story building constructions. Such trends underscore a critical shortfall in traditional building designs, which, while intended to preserve life, often fail to promptly restore building functionality, resulting in significant economic losses and community disruption. Recognizing this gap, there is a pressing need to rethink current design strategies and adopt resilience-based objectives that not only aim to protect lives but also ensure rapid functional recovery after earthquake events that exceed the design intensity level.

This paper discusses the shortcomings of current seismic design practice on community resilience; and introduces a comprehensive approach incorporating advanced structural solutions to enhance post-earthquake functional recovery of buildings.

National Earthquake Resilience. Chen et al. (2023) discussed the need for national earthquake resilience which is one of the priorities of the National Earthquake Hazards Reduction Program (NEHRP) (Congressional Research Service 2021; FEMA 2020). Designing buildings to recover a functional level promptly after a strong seismic event is required to contribute to community resilience and, as a result, enhance national earthquake resilience. Individual buildings can be designed to return to a target functionality state after a given period if resilience-based design methods are used (FEMA 2020).

Designing buildings for higher performance can mitigate the damage in the structural and non-structural components expected in conventional building designs.

FEMA P-58 (FEMA 2018) provides a methodology for designing buildings using performance-based seismic design principles including performance- and resilience-based design objectives. These objectives can include the damage that buildings may experience and its consequences considering potential casualties, loss of use or occupancy, and repair/reconstruction costs. ATC 138-3 provides a methodology for assessing functional recovery time (ATC 138-3 2021) . These methods are different from those included in the current seismic design provisions for conventional buildings, which are prescriptive and rely on ensuring life-safety performance levels (for Risk Category II buildings), and do not provide explicitly the means to design buildings for performance levels other than life safety (FEMA 2018; McAllister et al. 2022).

The FEMA/BSSC/PUC functional recovery planning committee addresses complex questions such as: "How can we reduce the risks of life and property from future earthquakes and increase the resilience of communities in the United States?" (FEMA/BSSC/PUC 2024). Addressing these important questions requires a clear definition of resilience metrics in the context of seismic design of buildings.

Design for Functional Recovery. The engineering community is shifting the seismic design criteria of buildings from life safety to pursuing more ambitious design objectives, such as immediate occupancy (Burton et al. 2016). Building occupancy is associated with a specific level of building functionality. So, it is necessary to implement methods to improve the functional recovery of buildings after a strong earthquake ground motion (Davis et al. 2022; FEMA P-2090 2021; Burton et al. 2016). Building resilience is rooted in the concept of building functionality (NASEM 2021); therefore, most resilience metrics are built on functional recovery curves that typically show the evolution of a building functionality metric over time (Bocchini et al. 2014). Functional recovery curves can be associated with each post-disaster damage state to determine the evolution of functionality over time and obtain a set of samples of restoration functions (Karamlou and Bocchini 2017b). This collection of samples can be used for the probabilistic assessment of resilience, which focuses not only on the expected (i.e., mean) recovery path but also on its variability (Karamlou and Bocchini 2017a).

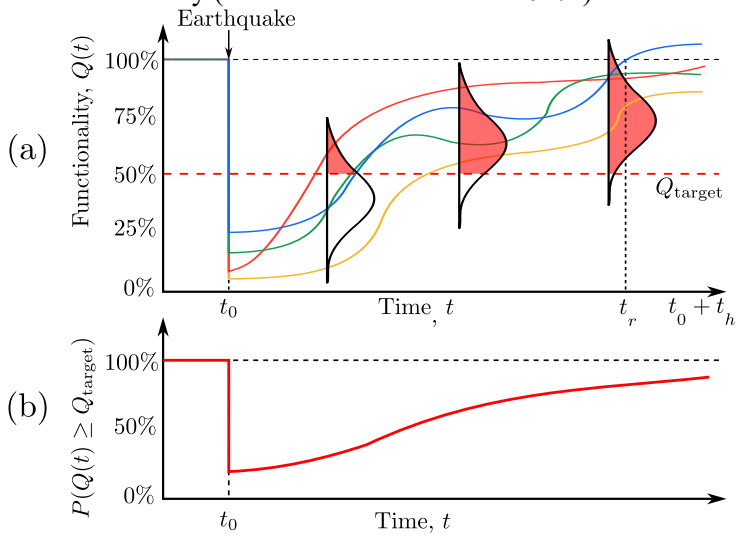


Figure 1. (a) Samples of functional recovery curves and (b) probability of exceeding a target functionality level.

Figure 1a shows samples of functional recovery curves where $Q(t)$ is a building functionality metric (e.g., percentage occupancy) and t is time. The repair actions will allow to safely reopen portions of the

building over time, and the functional recovery path will depend on the initial damage state and the effectiveness of the repair actions. The fact that the initial damage and the recovery curve are random yields a probability distribution for the functionality level at each point in time. One metric that is commonly used to capture this uncertainty is the probability of the functionality exceeding a certain target level (see Figure 1b) (Karamlou and Bocchini 2017a).

Metrics such as the one above can be used to design buildings for a target functional recovery. However, design for accelerated post-earthquake functional recovery for conventional buildings may be challenging considering the inherent performance requirements for structural and nonstructural components in conventional buildings (e.g., moment resisting frame systems, braced frame systems, bearing wall systems).

Challenges for Conventional Buildings. The current seismic design practice for conventional buildings focuses on practical and easy-to-implement methods that use design response spectra to represent the seismic demand. They can be classified as force-based design methods (Uang 1991; American Society of Civil Engineers 2022) that estimate the force demands of buildings using seismic design modification factors and design response spectra; displacement-based methods (Moehle 1992; M. Priestley et al. 1996; M. J. N. Priestley et al. 2007; Fardis 2018) that are performance-oriented and account for the nonlinear evolution of stiffness of an equivalent single degree of freedom system; or hybrid methods (Karavasilis et al. 2010; 2007; Tzimas et al. 2013; Tsampras 2011) that use performance-oriented displacement-based design principles framed in the context of force-based design. All these methods are approximate and include assumptions and limitations; however, they provide effective and efficient procedures to design buildings with different seismic force-resisting systems that meet mass and stiffness distribution, and height requirements.

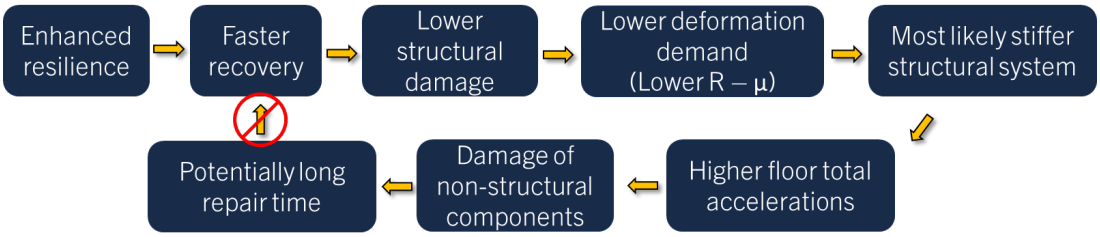


Figure 2. Flowchart of the trade-off between building seismic responses associated with structural damage and those associated with damage to non-structural components for conventional buildings

Although the current design methods for conventional buildings can provide reasonable seismic performance during an earthquake ground motion, researchers and engineers are trying to promote faster functional recovery after a strong earthquake ground motion to enhance the resilience of our community. However, there is a conflict in the ability to achieve faster functional recovery of conventional buildings after an earthquake since there is a trade-off between the building seismic responses associated with structural damage and those associated with damage to non-structural components. This trade-off can be explained using the flowchart shown in Figure 2. Consider for example a moment-resisting frame or a braced frame that inherently modifies the seismic response of buildings by allowing local inelastic response in deformation-controlled structural members. If this conventional building is designed using the current design methods to enhance the resilience of our community, it is required to aim for faster functional recovery after an earthquake. Therefore, the post-earthquake damage of the structural system needs to be below a certain limit. This implies a design for lower deformation demand that requires lower seismic response modification factors providing lower ductility demand. So, the building will most likely be stiffer, and as a result, higher floor accelerations are expected. The higher floor accelerations may produce increased damage to non-structural components and potentially longer repair time, which

prolongs the required post-earthquake recovery time and prevents the enhancement of seismic resilience. For this reason, there is a need to focus on "better-than-code" buildings to achieve resilience-based design objectives.

In addition, conventional buildings inherently tend to develop damage in locations that engineers typically do not design for. Consider for example a reinforced concrete (RC) wall building in which the earthquake-induced inertial forces are transferred through the floor diaphragms to the RC walls, which transfer these forces to the foundation system. The walls are designed to develop an inelastic flexural mechanism at the base of the walls. The inelastic flexural base mechanism region is carefully detailed to provide a ductile moment-rotation response at the base of the walls. However, other regions of the building such as the connections between floor diaphragms and the walls are not usually designed to take excessive deformation demands; therefore, damage is expected in these connections because of the kinematic compatibility between the connected components and the potential change in the force distribution over the height of the walls due to the higher-mode effects. This issue is present in more advanced building systems, as well. This was demonstrated by the experimental tests conducted by Sritharan et al. (Liu et al. 2018; Sritharan 2015). They tested a rocking wall system including a portion of the floor slabs, in which the wall was designed to rock at its base; therefore, the system developed a controlled rocking base mechanism instead of an inelastic flexural base mechanism typically associated with structural damage. The restoring moment at the base of the wall was controlled by post-tensioning and energy dissipation systems reducing or eliminating the structural damage at the wall base. However, excessive structural damage was observed in the connection between the floor diaphragm and the rocking wall. This structural damage that engineers do not design for, even for more advanced building systems, may result in increased uncertainty in the seismic response of buildings. Understanding that this challenge potentially leads to increased uncertainty in the seismic response and considering that there is variability in the characteristics of earthquake ground motions and variability in the evolution over time of dynamic properties of buildings, the level of confidence in the prediction of the seismic response of buildings through numerical earthquake simulation, and therefore the confidence in the resulting design of these buildings, is negatively affected.

To overcome the trade-off between the seismic responses related to structural and nonstructural damage aiming for resilience-based design objectives and mitigate or eliminate the damage in locations that engineers typically do not design for, it is recommended to use "better-than-code" building systems.

Buildings with Force-Limiting Connections. Researchers (Tsampras et al. 2016a; 2016b; 2017; 2018; Zhang et al. 2018) developed force-limiting deformable connections that consist of two components: (1) a limited-strength hysteretic component to limit the forces transferred through the connections, and (2) a bearing component to provide post-elastic stiffness to prevent excessive inelastic deformation in the connections and provide the out-of-plane stability to the seismic force-resisting system composed of planar structural elements. Figure 3 shows a schematic three-dimensional view, plan view, and connections between the gravity load-resisting system and the seismic force-resisting system of a RC rocking wall building with force-limiting connections. As observed in the plan view, including these force-limiting connections requires a gap between the slabs and the rocking walls (made through openings in the floor system) to allow relative motion between the two connected systems. These connections are designed to eliminate the damage expected due to the stress concentration in conventional monolithic floor-to-wall joints generated to provide kinematic compatibility between the connected structural components. The building also includes limited-strength hysteretic components in the rocking interface at the base.

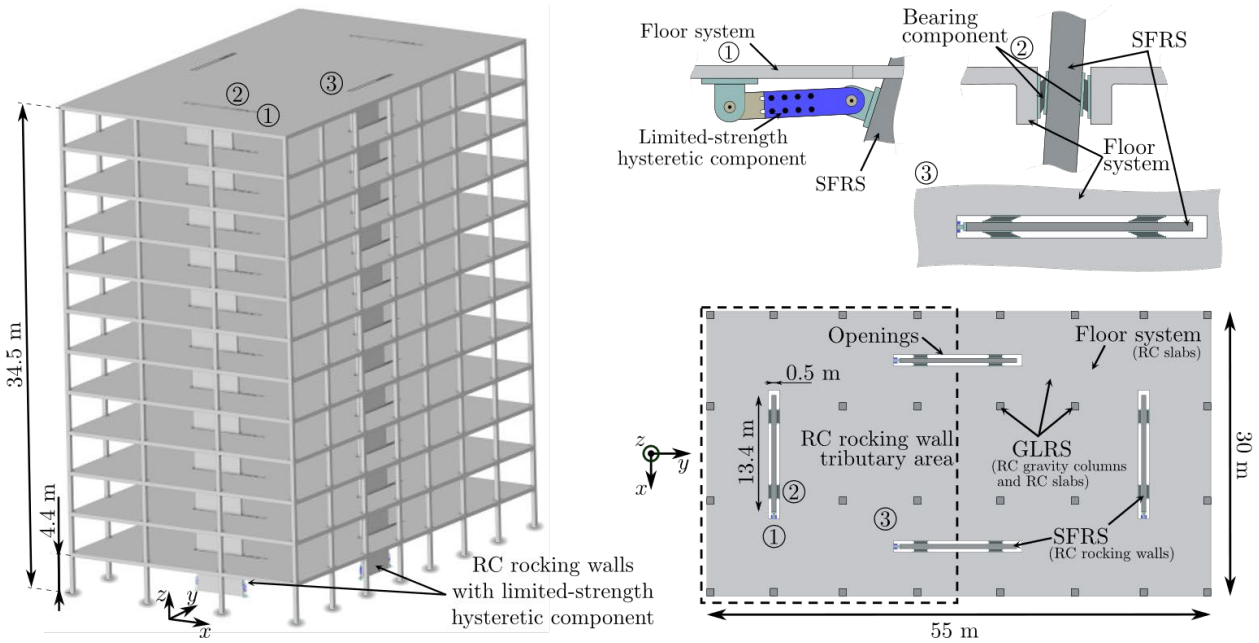


Figure 3. RC rocking wall building with force-limiting connections.

Tsampras and Sause (2022) proposed a force-based design method for the force-limiting connections. This method estimates the earthquake-induced inertial forces at the building floors and applies a reduction factor R_{DC} to control the ductility demand on the connections. However, this method is only for the connections. It does not consider the design of the building as a whole system and does not include performance- or resilience-based design objectives. Tsampras et al. (2016; 2022) and Lee et al. (2024) applied the force-based design method to RC wall building, self-centering rocking braced-frame building, and RC wall core building numerical models with force-limiting connections. They observed a reduction in the higher-mode shear-dominant acceleration and force responses as well as a reduction in their dispersion due to ground motion-to-ground motion variability. They also demonstrated the remarkable ability of these building systems of changing R_{DC} used to design the force-limiting connections to intentionally modify the global seismic response and the distribution of the ductility demand on the building numerical models. Mayorga and Tsampras (2024) observed a reduction in the dispersion of the distribution of the mean peak shear-dominant acceleration and force responses that may be developed due to the uncertainty in the material properties of the longitudinal reinforcing steel bars of RC wall-building numerical models with force-limiting connections. The ability to reduce this variability enhances the confidence in the numerical seismic response prediction of these building systems and, as a result, enhances the confidence in the development of future methods to design buildings with force-limiting connections considering resilience-based design objectives.

The use of force-limiting connections is a practical design solution for buildings with accelerated post-earthquake functional recovery, which contributes to national earthquake resilience. Nevertheless, there is currently no simple and practical design method available that provides the means for the holistic design of buildings with force-limiting connections to achieve targeted performance and post-earthquake functional recovery levels.

NIST/NSF Disaster Resilience Research Program Funded Project

In 2024, the authors initiated a research project that focuses on the design of buildings with a rocking inelastic base mechanism equipped with force-limiting connections strategically placed in the seismic load path. The project was funded by the NIST/NSF Disaster Resilience Research Program (Award No. 70NANB24H013). This building system is preferred over conventional designs due to their potential to achieve faster and more reliable post-earthquake functional recovery, owing to their limited seismic responses and reduced sensitivity to variability in strong earthquake ground motions. Additionally, it is expected that including force-limiting connections provides a solution for the trade-off between the seismic responses associated with structural damage and those associated with damage to non-structural components present in the design of conventional buildings aiming for faster post-earthquake functional recovery.

Figure 4 shows a schematic representation of the vision and goal of the project. The vision of the project is to advance the fundamental knowledge that will democratize the simple, efficient, rational, and practical design of high-performance buildings that even after earthquakes preserve the functions that are critical for the well-being of our society and reduce the immediate and long-term financial losses. The project aims to develop and validate a design method that will integrate performance and resilience criteria. It is expected that the proposed design method will popularize high-performance earthquake-resilient building systems designed to meet specific performance and resilience criteria.

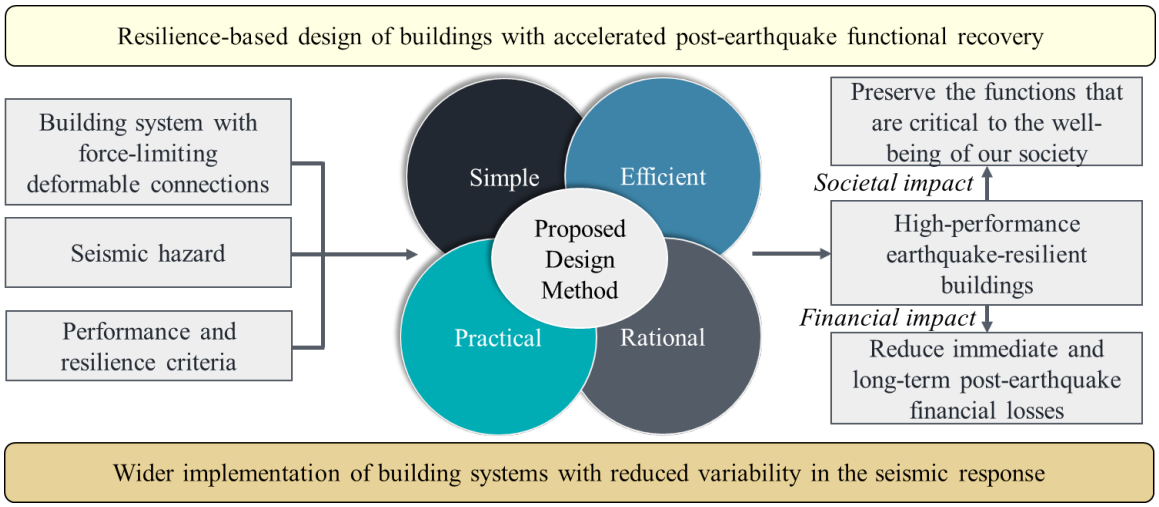


Figure 4 Vision and goal of the proposed project.

The scope of the project is to develop a procedure that will essentially integrate performance and resilience objectives. To do that, the seismic response modification factors for the force-limiting connections and seismic force-resisting system components along with the equivalent lateral forces that will be used for the proposed design method are going to be determined. The overstrength factors needed to apply the capacity design principles to protect the structural elements not designed for excessive inelastic deformation are going to be determined. Additionally, the expected inelastic demands in the force-limiting connections and seismic force-resisting system components are going to be estimated. Finally, the structural performance limits are going to be linked to functional recovery limits for a given level of hazard considering a probabilistic approach.

Conclusions

An introduction to the NIST/NSF-funded research project that focuses on the development of a resilience-based design method for buildings with accelerated post-earthquake functional recovery was provided. This research project is motivated by the critical need to reevaluate traditional seismic design approaches due to the fatalities, financial losses, non-functional communities, and significant environmental impacts due to debris after strong earthquakes. The development of a design method for buildings with accelerated post-earthquake functional recovery can contribute to the national earthquake resilience by reducing downtime and economic losses following seismic events.

Acknowledgments

The authors acknowledge the NIST/NSF for the support through the Disaster Resilience Research Program Award No. 70NANB24H013. The authors are also thankful for the contributions of Lawrence Burkett, Bruce R. Ellingwood, John D. Hooper, David Mar, Prasad Naik, and Mark Sarkisian who generously serve on the advisory board of the project.

References

American Society of Civil Engineers, 2022, "Minimum Design Loads and Associated Criteria for Buildings and Other Structures."

ATC 138-3, 2021, "Seismic Performance Assessment of Buildings Volume 8 – Methodology for Assessment of Functional Recovery Time. Preliminary Report," *Applied Technology Council*,

Bocchini, P., Frangopol, D. M., Ummenhofer, T., Zinke, T., 2014, "Resilience and Sustainability of Civil Infrastructure: Toward a Unified Approach," *Journal of Infrastructure Systems*, 20, (2): 04014004.

Burton, H. V., Deierlein, G., Lallemant, D., Lin, T., 2016, "Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience," *Journal of Structural Engineering*, 142, (8): C4015007.

Chen, K., Tsampras, G., Lee, K., 2023, "Structural connection with predetermined discrete variable friction forces," *Resilient Cities and Structures*, 2, (1): 1–17.

Congressional Research Service, 2021, "The National Earthquake Hazards Reduction Program (NEHRP): Overview and Issues for Congress."

CRED, 2022, "EM-DAT - The international disaster database."

Davis, C. A., Kersting, R., Nikolaou, S., Yu, K., 2022, "Recommendations toward Functional Recovery Performance of Lifeline Infrastructure Systems."

Fardis, M. N., 2018, "From Force- to Displacement-Based Seismic Design of Concrete Structures and Beyond," *Recent Advances in Earthquake Engineering in Europe: 16th European Conference on Earthquake Engineering-Thessaloniki 2018*, 101–22.

FEMA, 2018, "Seismic Performance Assessment of Buildings, Volume 1 -- Methodology, Second Edition."

FEMA, 2020, "Recommended Future Issues and Research Needs Identified During the Development of the 2020 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures."

FEMA P-2090, 2021, "Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time."

FEMA/BSSC/PUC, 2024, "Functional Recovery Planning Committee Report."

Karamlou, A., Bocchini, P., 2017, "Functionality-fragility surfaces," *Earthquake Engineering & Structural Dynamics*, 46, (10): 1687–1709.

Karamlou, A., Bocchini, P., 2017, "From Component Damage to System-Level Probabilistic Restoration Functions for a Damaged Bridge," *Journal of Infrastructure Systems*, 23, (3): 04016042.

Karavasilis, T. L., Bazeos, N., Beskos, D. E., 2007, "Behavior Factor for Performance-Based Seismic Design of Plane Steel Moment Resisting Frames," *Journal of Earthquake Engineering*, 11, (4): 531–59.
Karavasilis, T. L., Bazeos, N., Beskos, D. E., 2010, "A New Seismic Design Method for Steel Structures," *Advances in Performance-Based Earthquake Engineering*, 13, 161–71.
Lee, K., Tsampras, G., Mayorga, C. F., 2024, "Reinforced Concrete Core Wall Buildings with Modified Friction-Based Force-Limiting Connections: Connection Design Considerations and 3D Response to Bidirectional Ground Motions," *Journal of Structural Engineering*, Accepted.
Liu, Q., French, C. W., Sritharan, S., 2018, "Study of Interaction between a PreWEC System and Surrounding Structure," *Structural Journal*, 115, (5): 1407–18.
Mayorga, C. F., Tsampras, G., 2024, "Reinforced concrete wall buildings with force-limiting connections: Modeling effects and uncertainty propagation," *Earthquake Engineering & Structural Dynamics*, 53, (4): 1465–91.
McAllister, T. P., Walker, R. F. J., Baker, A., 2022, "Assessment of resilience in codes, standards, regulations, and best practices for buildings and infrastructure systems."
Moehle, J. P., 1992, "Displacement-Based Design of RC Structures Subjected to Earthquakes," *Earthquake Spectra*, 8, (3): 403–28.
NASEM, 2021, "Investing in Transportation Resilience: A Framework for Informed Choices."
Priestley, M. J. N., Calvi, G. M., Kowalsky, M. J., 2007, "Displacement Based Seismic Design of Structures."
Priestley, M., Kowalsky, M., Ranzo, G., Benzoni, G., 1996, "Preliminary Development of Direct Displacement-Based Design for Multi-Degree of Freedom Systems."
Sritharan, S., 2015, "Home > NEES-CR Rocking Wall Project."
Tsampras, G., 2011, "Parametric study of the inelastic response of plane flexural metal frames," Master's Thesis, University of Patras.
Tsampras, G., 2016, "Force-Limiting Floor Diaphragm Connection for Earthquake-Resistant Buildings," PhD Dissertation, Lehigh University.
Tsampras, G., Sause, R., 2022, "Force-Based Design Method for Force-Limiting Deformable Connections in Earthquake-Resistant Buildings," *Journal of Structural Engineering*, 148, (10): 04022150.
Tsampras, G., Sause, R., Fleischman, R. B., Restrepo, J. I., 2017, "Experimental study of deformable connection consisting of buckling-restrained brace and rubber bearings to connect floor system to lateral force resisting system," *Earthquake Engineering & Structural Dynamics*, 46, (8): 1287–1305.
Tsampras, G., Sause, R., Fleischman, R. B., Restrepo, J. I., 2018, "Experimental study of deformable connection consisting of friction device and rubber bearings to connect floor system to lateral force resisting system," *Earthquake Engineering & Structural Dynamics*, 47, (4): 1032–53.
Tsampras, G., Sause, R., Zhang, D., Fleischman, R. B., Restrepo, J. I., Mar, D., Maffei, J., 2016, "Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses," *Earthquake Engineering & Structural Dynamics*, 45, (9): 1473–94.
Tsampras, G., Sause, R., Zhang, D., Fleischman, R. B., Restrepo, J. I., Mar, D., Maffei, J., 2016, "Development of deformable connection for earthquake-resistant buildings."
Tzimas, A. S., Karavasilis, T. L., Bazeos, N., Beskos, D. E., 2013, "A hybrid force/displacement seismic design method for steel building frames," *Engineering Structures*, 56, 1452–63.
Uang, C.-M., 1991, "Establishing *R* (or Rw) and Cd Factors for Building Seismic Provisions," *Journal of Structural Engineering*, 117, (1): 19–28.
Zhang, Z., Fleischman, R. B., Restrepo, J. I., Guerrini, G., Nema, A., Zhang, D., Shakya, U., Tsampras, G., Sause, R., 2018, "Shake-table test performance of an inertial force-limiting floor anchorage system," *Earthquake Engineering & Structural Dynamics*, 47, (10): 1987–2011.