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Special Issue on Resilience-Based Analysis and Design of Structures and Infrastructure Systems

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Although the notion of resilience has been maturing within a variety of disciplines over the past decade, including fields such as ecology, economics, sociology and engineering among others, only until recently it reached a tipping point where resilience for communities drives policy. In essence, the notion of community resilience has grown beyond academic circles to become the language of professional, political and public action. Disasters such as hurricanes Katrina or Sandy in the United States (U.S.) in 2005 and 2012, respectively, the 2009 L'Aquila earthquake in Italy, the 2010 Chile earthquake, the 2011 Tohoku earthquake in Japan, and the 2010-2011 earthquake sequence in New Zealand among others, have triggered the question about the capability of communities to function and rebound when their structures and infrastructural facilities are affected by disasters, especially when some of the events cannot be averted—only managed at best. Hence, the capability to rebound and function in the aftermath of extreme events and disasters is essential, and is understood across this special issue contributions as resilient behavior.

To advance from calls for action to actions themselves, funding has become available through a number of agencies, including the U.S. National Science Foundation (NSF), the National Institute of Standards and Technology (NIST), the Department of Homeland Security (DHS), and even more recently the Defense Advanced Research Projects Agency (DARPA) through its Complex Adaptive System Composition and Design Environment (CASCADE) program. All these initiatives seek fundamental understanding of the interdisciplinary science and engineering behind community resilience while also decidedly pursuing practical implementations. In parallel, the U.S. government declared November as the month for Critical Infrastructures Security and Resilience[1], and September as the month for National

[1] The White House, Presidential Proclamation: Critical Infrastructure Security and Resilience Month, 2014, Washington, D.C. URL: https://www.whitehouse.gov/the-press-office/2014/10/31/presidential-proclamation-critical-infrastructure-security-and-resilienc

Preparedness in 2014[2], with related endorsements at the highest levels of governments abroad[3]. These directives, fueled by reports and studies calling public officials, professionals, academics, and end users for action, are marshalling resources towards achieving resilience worldwide. These efforts, along with recent events reminding all parties involved about the imperative of community resilience, only make the need for understanding and quantifying community resilience more urgent. It is within this context that ASCE's Structural Engineering Institute (SEI) timely contributes new ideas and rigorous methods to assess the resilience of structures and infrastructure systems at the core of urban systems and the communities they span.

This special issue compiles a set of 19 original manuscripts by SEI academics and professionals at the forefront of resilience quantification and design today. The collection is intended to clarify how the technical, operational, social, and economic components of structures and infrastructure systems can be integrated, designed and planned for disaster resilience against multiple hazards. The papers in this issue reexamine the fundamental underpinnings of community resilience, especially in the SEI community which has embraced pioneering work by the Multi-Disciplinary Center for Earthquake Engineering Research (MCEER). The contributions span practical applications to achieve community resilience across low- to high-rise buildings of different materials, building portfolios, bridge systems, transportation networks, and other infrastructure systems, including electric power transmission, water distribution, storm water, and wastewater networks. Multiple hazards are explicitly addressed, many related to seismic events, but also blast loads, wind storms, fire, and life-time deterioration.

Overall, the collection of papers offer new forward-looking ideas for community resilience, including decision making support, rating systems, damage avoidance designs, portfolio analysis methods, system-level logic, modern control and automation as well as socio-economic considerations. Collectively they point at interdisciplinary efforts to formulate new approaches and metrics that jointly consider pre-event and during-event performance along with post-event functionality goals. Such considerations improve disaster resilience, improve lifetime functionality with respect to impact and losses, justify repair and retrofit interventions, and acknowledge evolving urban dynamics. Resilient structural and infrastructural systems also require considering interdependencies with other systems, and ultimately how they affect the aftermath of emergencies and disasters.

The contributions are grouped in three main sets: (1) conceptual papers that challenge current design paradigms, (2) quantitative technical papers focusing on structures, their resilience-based design, and their role as elements of a portfolio of structures that make up communities, and (3) quantitative technical papers that probe system-level methods and overcome challenges unique to the resilience of distributed infrastructure.

Foundations of Community Resilience

Conceptual papers re-examine the essence of what resilience is in our community. They establish connections to existing paradigms such as risk-based design and performance-based design meant to

[2] The White House, Presidential Proclamation: National Preparedness Month, 2014, Washington, D.C. URL: https://www.whitehouse.gov/the-press-office/2014/08/29/presidential-proclamation-national-preparedness-month-2014

[3] Cabinet Office, 2014, *A Summary of the 2014 Sector Resilience Plans*, United Kingdom; Ministry of Civil Defence and Emergency Management, 2015, *Guide to the National Civil Defence Emergency Management Plan 2015*, New Zealand; Public Safety Canada, 2014, *Action Plan for Critical Infrastructure (2014-2017)*, Government of Canada.

reduce direct and indirect losses, but propel the field forward to address contemporary socio-technical challenges designed to plan speedy recovery processes in case of disastrous events while maintaining lifetime safety and functionality. In this regard, Cimellaro et al. set the stage for contemporary resilience assessment with a framework for its evaluation which is aptly named PEOPLES, as an acronym that implies human-technical considerations that span population, environment, organizations, physical assets, lifestyle, economy, and social/cultural dimensions. They state that losses and recovery of the built environment after severe events cannot be addressed in isolation and that the multiple layers of PEOPLES' contributors vary across time and space. Adding perspective, McAllister puts the notion of community resilience within a known risk analysis framework to enable decision analyses and decision support. She shows how resilience is a means towards risk-based design goals, and identifies technical gaps in the field offering directives for future short- and long-term research.

Quantitative Approaches for the Resilience of Structural Systems and Portfolios

The resilience of structural systems and collections of them is investigated here, not only in design terms, but more importantly in terms of lifetime losses and return to functionality, thus sparking a number of original, affordable, and implementable ideas. For instance, Almufti et al. propose a rating system to evaluate resilience in practice, considering losses and time to functional recovery. They exemplify their approach with an archetype tall building in San Francisco, California, showing that some interventions require only a small increase in financial investment, but whose return is significant in terms of resilience improvement. Similarly, Hutt et al. show the effectiveness of structural and nonstructural interventions for improving the resilience of tall buildings, targeting the reduction of economic losses and downtime as measure of recovery.

Focusing on design practices, Tirca et al. investigate resilience-informed retrofits to concentrically braced frames (CBF) located in areas of medium and high seismicity, revealing that feasible interventions limit not only losses but also the rapidity of recovery that contributes to resilience. Also, Rodger et al. study innovative damage avoidance design (DAD) strategies to make structural systems resilient at the highest level without requiring restoration or repair.

As for contributions showing how resilience informs the decision making of owners and other stakeholders, Quiel et al. evaluate structural damage and changes in the topology/geometry of structures due to blast. They outline a decision-based framework by which the magnitude of the consequences to stochastic blast-induced local damage are evaluated, while guiding interventions that reduce functionality loss, and thus contribute to structural resilience. Expanding the scope, Bonstrom and Corotis study the robustness and restoration times of entire building portfolios. They use a practical approach based on first- and second-order reliability methods (FORM and SORM), but extended to quantify resilience and the effectiveness of pre-hazard and post-hazard interventions, thus supporting community-level decision making. More generally, Burton et al. developed a building-level methodology for the probabilistic assessment of recovery paths and functionality states, while also offering a systematic approach to quantify community-level resilience metrics that can be used to inform policy decisions.

Quantitative Approaches for the Resilience of Distributed Systems and Their Components

Novel methods for the study of infrastructure systems are necessary given the multiple scales required to describe them, as they include individual structures such as bridges or industrial facilities, transmission and distribution networks, and in many cases real-time operators and users. In particular,

optimization methods, including genetic algorithms (GAs) along with Bayesian Networks offer flexibility to include social and technical constraints. Also, insights from graph theory, statistical learning, system reliability, economic input/output, and control domains, inform algorithms to systematically study the complex problem of community resilience. Starting with the constituent components of distributed systems, Domaneschi and Martinelli evaluate the seismic performance of iconic cable stayed bridges with hysteretic energy dissipation devices. They quantify system performance when a control device deteriorates or malfunctions under a seismic event. They find that sensitivity is reduced (i.e., robustness increased and thus resilience too) when control actions compensate losses due to malfunctions, and suggest that automatic modifications of the system reduce recovery times. Similarly, Chandrasekaran and Banerjee analyze different retrofit strategies for bridges under earthquake and scour conditions so as to enhance their multi-hazard resilience in terms of optimally reduced losses and recovery times via GA schemes. Echevarria et al. also investigate retrofits for improved resilience of bridges in terms of recovery of functionality, but by increasing their robustness and confining losses in spite of extreme variation of loads. They evaluate the recovery time and costs related to the residual axial load capacity of concrete-filled-fiber-reinforced columns under multi-hazards, including blast, fire and earthquakes. More generally, Mackie at al. build upon performance-based earthquake engineering and design to include sustainability ideas in the context of resilience via repair costs, time, and carbon equivalents. They find that resilient systems may incur larger carbon costs than other systems without resilience, thus highlighting the need for life-cycle studies to clearly see the benefits of upfront investments.

At the network level, Kurtz et al. assess the performance of entire transportation systems by integrating advanced statistical learning, fragility analysis, and system reliability concepts. They study the effects of component deterioration and their correlations which affect the recovery dimension of resilience. The approximations embedded in their tools strike a balance between accuracy and the practical computability of system-wide resilience. Adding life-time considerations, Alipour and Shafei quantify the effects of bridge aging on the performance of transportation networks under seismic hazards. In particular, flow redistribution and bridge location/capacity within the networks along with their age and costs are all shown to help identify critical components otherwise missed when performing bridge-by-bridge rankings for resilience enhancement in terms of post-event functionality.

As for other lifeline systems, Matthews studies the disaster resilience of water transmission and distribution networks, spanning wastewater and storm water collection and treatment. He shows that while the loss of sources may occur in localized parts of the networks, the robustness and redundancy of alternative sources allow for continued supply and functionality during system-level recovery processes. He also explores interdependencies and various levels of cost-effectiveness to tackle multiple dimensions of resilience. Recognizing the complexity of system-level resilience, Cimellaro et al. explore a new resilience quantification approach that combines different performance dimensions. They define resilience in terms of customers served considering functional and environmental metrics, essentially quantifying how system configurations and associated socio-technical constraints affect loss, recovery and overall resilience. Then, tackling computational challenges at the system level, Mensah and Dueñas-Osorio investigate the timely restoration of spatially distributed power outages that contribute to system-wide functionality reduction. Computationally efficient algorithms for power transmission modeled as physics-constrained Bayesian networks represent probabilistic dependencies and are used to rapidly quantify power flow and outage distributions. These algorithms track the influence of resource mobilization practices which accelerate the restoration of functionality. Finally, Reed et al. present an alternative yet complementary model of resilience based on high-level input-output inoperability formulations. Resilience is related to the time-space variation of such inoperability, and it

is illustrated with an electric power delivery network during extreme storms including relevant correlations along with intra- and inter-dependent considerations.

As the field of community resilience continues to mature, a few gaps still require attention. These include developing resilience-based design guidelines for structural systems and infrastructural facilities, modeling and design of components and systems attendant to constraints at different scales, expanding probabilistic methods to propagate and quantify uncertainty (especially in life-time resilience studies), and broadening the perspectives of resilience to truly embrace its complex, adaptive, and socio-technical nature.

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