The Science Behind Community Resilience Assessment: An Overview of the Center for Risk-Based Community Resilience Planning

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Abstract: Community resilience depends on the performance of the built environment and on supporting social, economic and public institutions that are essential for response and recovery of the community following a hazard event. The social needs of a community are not reflected in codes, standards, and other regulatory documents currently used to design individual facilities. A new approach is necessary, one which is interdisciplinary in nature and reflects the complex inter-dependencies among the physical, social, and economic systems on which a healthy and vibrant community depends. The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, and eight partner universities, was established by the National Institute of Standards and Technology to advance the measurement science for understanding the factors that make a community resilient, to assess the likely impact of natural hazards on communities, and to develop risk-informed decision strategies that optimize planning for and recovery from disasters. This presentation summarizes the approach taken by the Center's research teams during its first two years to advance the science underlying community resilience assessment and risk-informed planning and recovery strategies.

Keywords: Buildings, Civil infrastructure, Decision algorithms, Natural hazards, Risk.

1 Introduction

Community resilience depends on the performance of the built environment and on supporting social, economic, and public institutions that, individually and collectively, are essential for immediate response and long-term recovery within the community following a hazard event. The performance of the built environment, which is a key factor in community resilience, is largely determined by codes and standards, which are applicable to individual facilities and have the primary objective of preserving life safety under severe events. Current design standards, such as *ASCE Standard 7* [1], generally do not address facility performance in the period of recovery following an event. Moreover, the design of interdependent transportation systems, utilities, and communication systems currently is based on different performance criteria. Accordingly, there is no assurance that all systems required for community resilience will perform at a consistent level during and following an extreme hazard event. Furthermore, the resilience goals of a community are based on social needs and objectives that are specific to its character – its prior experience with natural hazards, the vulnerability of the population, economic and financial drivers and resources, and local building regulations and construction practices, all of which are factors that fall outside the purview of infrastructure design. Finally, much of the needed science only exists in rudimentary form at present. This includes science-based measurement tools to address deficiencies in current practices and to evaluate performance and resilience at the community scale, fully integrated supporting databases, and risk-informed decision frameworks to support optimal life-cycle technical and social policies aimed at enhancing community resilience [2, 3].

Natural and man-made disasters in the United States are responsible for over $55 billion in average annual costs in terms of injuries and lives lost, disruption of commerce and economic networks, property damaged or destroyed, the cost of mobilizing emergency response personnel and equipment, and recovery of essential services [4,5]. The losses due to such events are increasing more rapidly than the growth in population or the Gross Domestic Product. The potential exists for even larger losses in the future, given that population and infrastructure development in hazard-prone areas of the United States [as of 2010, 39 % of the U.S. population lived in a county that touches the coast (www.noaa.gov)] are increasing dramatically and that climate change may affect both the frequency and severity of the extreme events from natural hazards [6]. A new approach is needed, one that reflects the complex inter-dependencies among the physical, social and economic systems on which community well-being depends. The vast majority of research on community resilience in the past decade has focused on the impact of severe earthquakes on the physical infrastructure in communities [7, 8, 9, 10] or on the impact of hazard events on community social institutions [e.g., 11, 12]. Little attention has been paid to other natural hazards, including those that might be impacted by climate change [6, 13]. Resilience assessment has become a national imperative [5, 14], not only in the United States but in Europe and the countries in the Asia-Pacific Rim.

The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, was established by the National Institute of Standards and Technology (NIST) in 2015. The Center's overarching goals are to establish the measurement science for understanding the factors that make a community resilient, to assess the likely impact of natural hazards on communities, and to develop risk-informed decision tools and strategies that optimize planning for and recovery from hazard events and are consistent with local community financial constraints, values and preferences. In this paper, we introduce this ***Mini-symposium on Enhancing Urban Resilience Under National Hazards*** by presenting an overview of the Center's research activities during its first two years, including multiple hazards and their cascading effects on infrastructure, the role of supporting economic networks and social systems on community resilience and post-hazard event recovery, the impact of aging infrastructure, and the identification and articulation of performance metrics and requirements. We include several community resilience testbeds, which have been designed to allow Center research teams to initiate, test, and modify essential community resilience assessment models and algorithms early in the program and to facilitate the essential interdisciplinary collaborations and approaches to community resilience assessment that will be necessary for the Center's ultimate success. We conclude with a summary of significant challenges for community resilience research and Center research activities designed to address many of them.

2 Summary of Center Research Tasks

The Center is engaged in three major research thrusts to accomplish its programmatic goals: (1) developing the **i**nterdependent **n**etworked **co**mmunity **r**esilience modeling **e**nvironment (IN-CORE) to quantitatively assess alternative community resilience strategies; (2) instituting a standardized data ontology, robust architecture, and management tools to support IN-CORE; and (3) performing a comprehensive set of testbeds and disaster hindcasts to validate this advanced computational modeling environment and to lead to practical risk-informed decision tools for community resilience assessment and risk mitigation.

Thrust (1) Development of the IN-CORE modeling environment: Initial efforts within the Center during its first two years have focused on Thrust 1, on which all else depends. Thrust 1 consists of eight tasks, which are running concurrently, rather than sequentially: (1) Hazards modeling; (2) Damage, loss, and recovery of physical infrastructure systems modeling; (3) System modeling of community resilience; (4) Development of the IN-CORE modeling environment; (5) Model validation by hindcasting; (6) Development of performance metrics for community resilience; (7) Resolution and scalability studies; and (8) Development of optimization strategies and decision methods for community resilience.

Natural hazards considered include earthquakes and tsunamis, tornadoes, hurricane winds, coastal storm surge and inundation, riverine flooding, and wildfires. In some cases, the individual hazard formulations are reasonably well-understood, especially for earthquakes where the National Earthquake Hazard Reduction Program has produced advanced knowledge of earthquake hazards and civil infrastructure response over the past four decades. In other cases (riverine flooding, storm surge, tornado, and wildfires), improved models of the hazard and its impact on the built environment are required for quantitative community resilience assessment. Similarly, the state of the art regarding the performance of individual constructed facilities (e.g., buildings, bridges, buried piping, electrical transmission and distribution systems) and the integrity of individual infrastructure systems (electrical, gas, and water distribution systems) during hazard events is reasonably mature. Such systems are interconnected, however, and their functioning is dependent on the availability and functioning of other connected systems [15].

The distinctive features of each hazard (e.g., advance warning time, area affected, type and severity of damage, populations displaced) have caused hazard mitigation methodologies to be strongly hazard-dependent. Multiple hazards, and differences in community response to them, or synergies that might be achieved in policies to mitigate risk or enhance community resilience under multiple hazards, have received limited attention [16]. Furthermore, the performance of physical infrastructure systems during and following a hazard event may be positively correlated depending on the spatial scale of the hazard and the interconnected nature of their successful (or unsuccessful) operations within the community. These positive spatio-temporal correlations for physical systems must be considered in resilience assessment and combined with social and economic models which affect both the ability to prepare for and recover from an event. Finally, the numerous sources of uncertainties associated with the life cycle performance of infrastructure systems mandate a risk-informed decision-making approach to assess facility and community risks and to identify cost-effective strategies to enhance community resilience [17].

Accordingly, the first two years of the Center have seen the compilation of existing stochastic models for performance of the built environment in the form of hazards and multi-dimensional fragilities; the development of new stochastic models of infrastructure performance where none previously existed; consideration of interdependencies including physical, social, and economic interactions; development of computable general equilibrium models to assess the economic impacts of a specific hazard on a community in terms of job loss, declines in tax base, reductions in household income, and other measures of community well-being; inclusion of the effects of household demographics; and validation of the fundamental resilience assessment algorithms for specific communities and hazard scenarios with default stochastic models (summarized in Section 3).

Thrust (2) Development of standardized data ontologies, robust architecture, and management tools to support IN-CORE: IN-CORE is being designed to be an open-source, integrated multi-scale, multi-hazard computational modeling environment, providing extension points where software developers can add new modules to simulate response, interactions, and recovery of major infrastructure, social, or economic systems. Since community resilience assessment involves multiple domains of science, engineering, and socio-economics, defining a common language within those communities is essential. Databases in international resilience-related research are being developed by different users, using different methods and have different purposes. It is essential that these databases interface seamlessly in the IN-CORE environment. This task focuses on collecting and analyzing user requirements, metrics, and measurements within the user communities and stakeholders, at the same time that the algorithms being developed in Thrust (1) are coded into the computational modeling environment.

Thrust (3) Validation of the modeling environment from testbeds and hindcasts to develop decision tools: While thrust (3) must await the completion of IN-CORE Version 1, which is anticipated in year 3 of the Center, hindcasts and field studies have progressed in year 2, as described in Section 3.

3 Community Resilience Studies

The Center has several community resilience studies in progress to provide focus to Center engineers in developing the physical infrastructure models – hazards, fragilities, and infrastructure interdependencies – needed for community resilience assessment. These studies are intended to allow the Center's interdisciplinary research teams to initiate, test, and modify resilience assessment models and algorithms prior to the time IN-CORE becomes fully operational; to stress these assessment models in a controlled manner; to examine varying degrees of dependency between physical, social and economic infrastructure systems; to allow issues of scalability in modeling to be addressed; to inform the subsequent development of more refined community resilience assessment methods; and to facilitate interdisciplinary collaborations and approaches to community resilience assessment that will be essential for the Center to achieve its goals. Each of these studies, summarized below, has a somewhat different objective. We refer to some of these studies as *testbeds*; these are intended to study the impact of various scenario hazards on communities that have not yet been exposed to such hazards, and are used for purposes of algorithm and database development, to resolve issues of modeling interdependencies, scaling, and resolution, and to capture the interfaces between physical/social/economic systems. Other studies are referred to as *hindcasts*; in contrast to the testbeds, the hindcasts represent an attempt to reproduce *what actually happened* during an extreme hazard event, using the physics-based models of physics-based infrastructure behavior and integrated social and economic databases developed in other Center research tasks. The hindcasts requires careful treatment of data from past events to ensure they do not bias the development of the models. We view both testbeds and hindcasts as essential ingredients of validating the algorithms and databases in IN-CORE.

3.1 The Centerville Virtual Community Testbed (Earthquake and Tornado)

The Centerville Testbed involves a virtual community of about 50,000 in the Central United States. It is an average community in most respects (population demographics were obtained from the *American Community Survey*, published by the US Census Bureau), although there are pockets of low-to-moderate income residents who may be especially vulnerable to a natural hazard event. Its diversified economy includes commercial/retail, professional services, education/healthcare, industry and public sectors. The physical infrastructure includes a variety of residential, commercial and industrial buildings, bridges and transportation facilities, and utility networks, each of which represents a distinct spatial infrastructure topology [18, 19, 20, 21, 22]. Physical and socioeconomic systems are modeled in this testbed as interdependent; the performance of physical infrastructure under stipulated scenario hazards provides the initial conditions to the social and economic models needed to obtain a broad perspective of the impact of such hazards on community well-being. A recent issue of *Sustainable and Resilient Infrastructure* [23] is devoted to the Centerville Testbed. Topics covered include a description of Centerville, its building inventory, transportation network, coupled water and electrical power network, and its community economic and social demographics; a building inventory fragility analysis to support multiscale community resilience assessment; a multi-objective optimization approach for allocating retrofit resources to minimize population dislocation and economic losses; performance of electrical power networks during scenario tornadoes; performance of interdependent electrical and water systems under scenario earthquakes; and the use of computable general equilibrium (CGE) economic models for assessing impact of natural hazard events on a typical community.

3.2 Seaside, Oregon Testbed (Earthquake and Tsunamis)

In contrast to Centerville, Seaside, OR is a real community, a popular oceanfront resort of approximately 6,500 permanent inhabitants, situated on the Pacific coast about 80 miles NW of Portland, OR. The Oregon/Washington coast is approximately 120 km directly east of the Cascadia Subduction Zone, which is capable of generating Magnitude 9 earthquakes and producing a devastating tsunami of as much as 30 m in height that would reach the Oregon coast within 10 to 15 minutes. While seismic fragility analysis is relatively mature, the vast majority of fragilities for tsunami loading that have been developed are based on post-event observations, which are dependent on the site at which the tsunami made landfall and in which velocities are unknown. Accordingly, one of the Center research tasks developed a methodology to generate physics-based tsunami fragility functions using tsunami flow depth, flow velocity, and momentum flux, in various combinations, as intensity measures [24]. There has been an increase in interest in tsunami effects following the Great East Japan Earthquake and Tsunami of 2011, several papers on tsunami effects have been published recently, and the new *ASCE Standard 7-16* contains tsunami provisions for the first time.

3.3 Shelby County, TN Testbed (Earthquake, Riverine Flooding, and Climate Change)

Shelby County, TN is located in the southwest corner of Tennessee, and its western border is formed by the Mississippi River. Shelby County is a metropolitan area covering 2,033 km^2, with a population of approximately 940,000 inhabitants, and includes the City of Memphis, with a population of 660,000 inhabitants. Shelby County was selected for several reasons. First, it provides a realistic test of the Center's integrated engineering/social/economic models in IN-CORE for a reasonably large metropolitan area with a diverse economy and demographics. Second, a study of urban resilience under earthquakes from the New Madrid Seismic Zone in SE Missouri (about 50-60 km NW of Memphis and capable of generating Magnitude 8 earthquakes) was conducted a number of years ago by the Mid-America Earthquake Center (MAEC) (using less advanced models) [25] and can be used to benchmark the IN-CORE analysis. Third, a significant part of Shelby County lies within the Mississippi Embayment, where soil liquefaction is a significant problem and existing fragilities will have to be modified to model damage to the built environment. Fourth, the City of Memphis depends on the infrastructure provided by surrounding Shelby County, and the testbed will provide an opportunity to investigate how the resilience of a community depends on the resilience of the surrounding urban area. Fifth, unlike California, Shelby County is ill-prepared for a Magnitude 8 earthquake; older buildings and other infrastructure are not earthquake-resistant, e.g. unreinforced masonry. And finally, a large part of Shelby County falls within the Wolf River Basin drainage; one of the Center teams has initiated a study of the impact of climate change on riverine flooding in the Wolf River Basin for the remainder of the 21st Century [26], which will enable the Center to perform an analysis of competing risks and risk mitigation strategies for a major urban area.

3.4 Galveston and Bolivar Peninsula, TX (Hurricane and Storm Surge)

Galveston lies on a barrier island approximately 75 km southeast of Houston, TX on the Gulf of Mexico. It is a port city, with a population of approximately 50,000, and its economy depends on the viability of the port. The dominant hazards for Galveston are hurricane and coastal storm surge. The most recent hurricane was Hurricane Ike, which occurred in September, 2008, with wind speeds of 230 km/hr, $US 37.5 billion in damages, and 195 fatalities. The Galveston study is attempting to reproduce the impact of Hurricane Ike on the Galveston-Bolivar Peninsula using the physics-based hazard and infrastructure response models developed during the first two years of the Center's research program. It has elements of both a hindcast (the event has already happened) and a testbed (the coupled hurricane-storm surge models will attempt to reproduce the impact of Ike on the community).

3.5 Joplin, MO Tornado Hindcast

Joplin, MO is a community of approximately 50,000 inhabitants, within a surrounding Metropolitan Statistical Area of about 175,000 inhabitants. In May, 2011, it was struck by a catastrophic EF5-rated multiple vortex tornado, with wind speeds exceeding 320 km/hr. The tornado killed 158 people and caused nearly $US 3 billion in damage. It also ranks as the costliest single tornado in U.S. history. The Joplin, MO tornado prompted an investigation by the National Institute of Standards and Technology [27], which provided extensive documentation of the impact of the tornado on the community. A Center Team has recently initiated a hindcast of the Joplin tornado which utilizes many of the tools developed during the first two years of the Center including the tornado wind field model [28] and physical models of infrastructure [e.g. 29]. As part of the hindcast, researchers are focusing on a series of increasingly complex analysis starting with single sector damage validations, e.g. building damage, electrical power network disruption and damage, and then moving to coupled sector validations. A CGE model for the community is also under development, which will allow a yearly time stepping analysis to examine the economic recovery of Joplin using the functionality and recovery models that are being developed within the Center. The final validation step for the hindcast will be to model at least four physical infrastructure sectors, demographics and related population dislocation, and economic recovery from 2011 to the present day for direct comparison with what actually occurred.

4 Community Resilience Metrics

Community leaders and planners need to know how resilient their communities are in order to develop effective risk-informed public policy for enhancing community resilience. Community resilience metrics fall into two general categories: current and desired (future) resilience conditions. The current condition includes the resilience of existing systems before a hazard event, or physical damage, loss of functionality, and social and economic impacts after a hazard event. The future condition provides a goal for planning and recovery purposes. Resilience metrics need to address both categories for community systems, such as physical systems, economic vitality, and social well-being. Design codes and standards traditionally address the performance of individual facilities – buildings, bridges and roadways, utility systems - without considering how the interactions between these systems affect the welfare of the community as a whole. Functionality and recovery are not included in codes and standards; nor are economic vitality – attracting and retaining businesses and employment opportunities, revenue sources, household income, domestic economic output - or social well-being – safety and financial security, availability of food, water and shelter, population dislocation, access to health services. All are essential ingredients of community resilience.

The testbeds and hindcasts summarized in the previous section included direct damage to physical infrastructure – buildings, bridges and other transportation infrastructure, and water/wastewater and electrical power networks – as well as damages which present challenges to economic vitality and social well-being within the community. These different physical, social, and economic systems are integrated to provide quantitative measures of community resilience, including post-hazard measures, such as economic losses due to direct damage, loss of income and employment as a result of damage to residential, commercial/retail buildings, declines in the community tax base and population dislocation [30, 31, 32, 33]. The ability to assess such metrics quantitatively and to determine how changes in policy might affect them is essential, both in planning for a hazard event as well as in planning for post-event recovery.

5 Concluding Remarks

Community social needs and objectives (including post-hazard recovery) are not reflected in codes, standards, and other regulatory documents applied to design of individual facilities, necessitating an approach that reflects the complex inter-dependencies among the physical, social, and economic systems on which a resilient community depends. Modeling the resilience of communities and cities to natural hazards depends on many disciplines, including engineering, social sciences, and information sciences.

A review of the literature [e.g., 2, 3, 34] has identified a number of critical challenges confronting the development of a resilient built environment, among them: *(1) Quantitative metrics and tools for assessing community resilience* are required to improve resilience in the built and modified natural environment and should be tailored to the specific needs of each community; *(2) Community resilience plans and guidance* are needed to help communities plan for hazard-specific performance, and for restoring community infrastructure systems in a cost effective and timely manner; *(3) Existing building and infrastructure systems* must be considered in community resilience planning as well as new construction, recognizing that existing buildings (a) may not meet current codes and standards; (b) often cannot be modified economically to meet modern design and construction practices; and (c) may have deteriorated due to structural aging or a lack of maintenance; and *(4) Codes and standards* with consistent performance goals for all buildings and infrastructure systems are a key component for achieving a resilient community.

The Center's current work is addressing these challenges by refining existing community infrastructure models, modeling dependent or cascading multiple hazards, developing stochastic models of the recovery processes, considering algorithms for propagating deep uncertainties in hazards and community responses, including the impact of climate change, and developing decision support algorithms and practical decision tools.

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