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De-aggregation of community resilience goals to obtain minimum performance objectives for buildings under tornado hazards

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ABSTRACT

The paradigm of performance-based engineering (PBE) provides a framework for engineers and planners to achieve desired levels of performance and functionality of building clusters and civil infrastructure systems that are essential for community resilience and well-being. While it is recognized that resilience of a community must be supported by individual buildings and engineered facilities, the relation between community resilience goals and minimum performance criteria of individual structures enabling such goals through engineering practices does not yet exist. In this study, we first propose a path forward to establish this relation in a quantitative manner. We then illustrate the feasibility of the proposed framework by de-aggregating the resilience goals of a community residential building cluster through an inverse multi-objective optimization formulation to obtain the minimum performance objectives for residential buildings, for tornado hazards. Once the minimum building performance criteria are determined, they can be utilized as the target building performance for new constructions, pre-event strengthening or post-event reconstruction. The overarching aim of this framework is to relate engineering design and retrofit practices to socioeconomic expectations of a community as a whole, and to provide a vehicle for risk-informed resilience-based decision-making under natural hazard events.

1. Introduction

The resilience of a community is defined by its ability to adapt to changing conditions and to return to a level of normalcy within a reasonable time. Community resilience depends on the performance of the built environment and on supporting social, economic and public institutions which are essential for immediate response and long-term recovery within the community following a disaster (NIST, 2015) [21]. The built environment of a community is susceptible to damage due to extreme environmental and geophysical hazards, such as hurricane wind storms and floods, tornadoes, earthquakes, tsunamis, and wildfires. The economic losses and social disruptions caused by failure of the built environment are often disproportionate to the physical damage incurred. The aftermath of recent disasters has highlighted the importance of disaster-mitigation policies that focus on resilience of the community as a whole, rather than those that only address safety and functionality of individual structures and engineered facilities.

Many communities across the U.S. have initiated community-level resilience planning. The National Institute of Standards and Technology (NIST) guide [21] provides a methodology for local communities to bring together relevant stakeholders and incorporate resilience into their long-term development planning process, focusing on the role played by the built environment in the community-level hazard preparedness and recovery. The San Francisco Bay Area Planning and Urban Research Association (SPUR) [25] identified a suite of resilience metrics and goals under "expected" earthquakes for San Francisco. Such resilience goals emphasize the performance of the community built environment in addition to life safety, which has been the traditional basis of performance-based building design (e.g. [2]). Furthermore, there have been recent initiatives to implement large-scale, building cluster retrofit programs, either mandatory or voluntary, to enhance resilience of underperforming community building portfolios, e.g., mandatory seismic retrofit programs in San Francisco and Los Angeles [5,11] and a non-mandatory program for mitigating hurricane losses in Florida [8].

Despite these efforts, the risk management of the built environment, which is a key factor in community resilience, has been largely determined by codes and standards. These codes, standards and other regulatory documents traditionally have been applied to the design of individual buildings and local facilities, and more importantly, they have been developed by different organizations

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with different objectives and performance expectations. This lack of system perspective and coordination has led to a situation where the performance of individual buildings or lifeline components under demands from extreme natural hazards is not consistent within the performance expectations of building portfolios or lifeline networks, let alone cross all physical systems of a community built environment. A fundamental change must occur, as a starting point, in the way that code and standard-writing groups approach the problem of stipulating design requirements for buildings and other engineered facilities. Clearly-defined minimum performance objectives to which individual structures should achieve in supporting community-level resilience goals have yet to be developed.

In this study, we illustrate that it is possible to develop such risk-informed performance criteria for individual buildings and local facilities in a systematic manner that can be matched to community resilience goals. In a concurrent study [19], we further demonstrate that such performance criteria can be met in performance-based design through carefully identified and parameterized building attributes.

2. De-aggregating community resilience goals to obtain performance objectives for buildings

In this section, we introduce a path forward towards developing performance-based design (PBD) requirements for the built environment aimed at achieving community resilience goals. Specifically, we seek to transform resilience goals articulated for building clusters[1] supporting different vital community functions (e.g., residential buildings, commercial facilities, schools, healthcare facilities) into requirements that are practical to implement from an engineering perspective. We will show that at its highest level, resilience-driven PBE begins with community resilience goals expressed in terms of social and economic metrics. These goals are then used to differentiate subsystem performance objectives for a spectrum of building clusters and lifeline systems, and ultimately lead to PBD criteria for individual buildings of different occupancies and for system components of lifelines. The overarching aim is to relate engineering design and practices to socioeconomic performance expectations and to provide a vehicle for risk-informed decision-making in natural hazard events.

The resilience of a community is supported by its physical infrastructure, as illustrated in Fig. 1. Community resilience assessment requires bottom-up, multilayered analysis at different spatial and temporal resolutions. First, we estimate the performance of individual buildings and infrastructure network components. We then ***aggregate*** the performance of these individual structures on spatial and temporal scales to obtain the performance of the community's physical subsystems – building clusters and infrastructure networks – which are then further ***aggregated*** with the socioeconomic attributes of the community to obtain overall measures of community resilience as a whole.

Now, to identify the performance objectives for individual buildings and lifeline components that would collectively enable a set of pre-defined overarching community resilience goals to be achieved, the assessment process is reversed, creating the top-down, multilayered cascading "de-aggregation" framework shown in Fig. 2. Ideally, this multilayered de-aggregation analysis begins with a policy-driven process that sets the overarching community resilience goals expressed in terms of socioeconomic metrics. Through an ***upper-level de-aggregation*** (ULD), this set of overarching community resilience goals is de-aggregated to a set of performance goals for physical subsystems (i.e. building inventories and infrastructure networks) that serve the social and economic functions of the community. This ULD can be formulated as an inverse multi-objective optimization problem (MOOP), where we simultaneously search for the minimum performance goals for each subsystem that collectively enable the overarching community resilience goals to be achieved. This optimization must operate on an analysis model that estimates the overarching community resilience metrics of interest using community's subsystem performances as input. For example, if the overarching community resilience goals are articulated in terms of economic measures, e.g. job, income, gross domestic product, among others, an economic computable general equilibrium (CGE) model (e.g. [28]) can be integrated in the MOOP for the ULD. This ULD is performed at the community scale, and it decouples the interdependencies among the subsystems for the subsequent analysis. Once the set of minimum resilience goals are obtained for the subsystems, they are de-aggregated further in a ***lower-level de-aggregation*** (LLD) to obtain the minimum performance objectives for the individual components in each subsystem. The LLD is also formulated as an inverse MOOP and must operate on subsystem analysis models, i.e., residential building cluster resilience assessment model, transportation network resilience assessment model, etc. For example, Lin et al. [15] developed a cluster analysis model to assess the robustness and recovery of residential building clusters. Such model can be integrated in MOOP to obtain the minimum performance criteria for individual residential buildings that enables the residential cluster resilience goals obtained from ULD to be achieved. Finally, once the performance objectives for individual structures are established, ***performance-based design*** and retrofit can be implemented at the individual facility scale, in which building (or lifeline component) attributes can be identified and parameterized to meet the performance objectives resulted from the LLD.

As discussed in the NIST Resilience Guide [21], community resilience goals include two temporal components – robustness goals and recovery goals. For a community subsystem, the robustness goal usually is an acceptable level of damage or loss due to immediate impact of a hazard with particular level, while the recovery goal, on the other hand, is often stipulated as an acceptable recovery target at selected points in time after a hazard occurrence. The robustness of a community subsystem, e.g. a building cluster, (measured in terms of direct loss ratio, mean damage ratio, etc.), is exclusively affected by the existing physical condition of its buildings, which is directly tied to building design code levels. Recovery of a building cluster, however, has been shown to be conditional on initial damage and is collectively determined by the preparedness (e.g. the speed of damage inspection, the process of design and permitting, the availability of finances) and resourcefulness (e.g. contractors, construction material and equipment) of a community, among many other factors, as systematically modeled in Lin and Wang [16,17]. Accordingly, we emphasize that while de-aggregation of the robustness goals yields improvements in design criteria for buildings and lifeline components, de-aggregation of the recovery goals leads to useful organizational and preparedness guidelines for community resilience planning, such as, target insurance percentage, target inspection speed, etc. The focus of this study is on deriving design criteria for buildings.

In this study, we focus on illustrating the feasibility of the LLD, using a residential building cluster as the testbed subsystem, as highlighted in the dash-line box in Fig. 2, considering the tornado hazard. The analysis flow is illustrated in Fig. 3.

[1] We use the term cluster to refer to a group of buildings or a building portfolio, in the same sense as it is used in the *NIST Community Resilience Planning Guide* [21]. The buildings in a cluster need not be located in proximity to one another.