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Measuring and enhancing resilience of building portfolios considering the functional interdependence among community sectors

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ABSTRACT

Resilience is an attribute of communities, and is supported by community building sectors (occupancy types) with different functionalities. Evaluating community resilience and functionality requires the establishment of new metrics and their quantification. This study introduces a methodology to consider how the interdependencies in functionality among different building sectors impact community resilience. Four building sectors that provide essential functions to a community, i.e. housing, education, business and public services, are considered. The percentage of people in a community who dislocate following a disaster as a result of the physical damages to buildings is selected as the resilience metric in this conceptual study. A framework is further developed to determine the optimum strategies for retrofitting community building portfolios as a whole in order to achieve an overall community resilience objective expressed in terms of the threshold value of the community resilience metric identified above. Finally, the methodology to quantify community functionality and the associated retrofit optimization algorithm are illustrated using a simplified hypothetical community building portfolio in China exposed to potentially severe earthquakes, in which the objective is to achieve a predetermined functionality level when financial constraints may be present.

1. Introduction

Natural hazards, such as earthquakes and hurricanes, can damage the built environment, making it difficult for a community to function normally. The aftermath of recent hazard events has highlighted the need for a community to be prepared for and be able to recover rapidly from a sudden potentially disastrous event. Over the past two decades, the concept of community resilience has evolved and received considerable attention from researchers and policymakers. Many studies have considered definitions of resilience and the metrics necessary to measure it [5,28,38,12,30]. Presidential Policy Directive 21 [32] defines resilience as "*the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions*." More specifically, a resilient system should demonstrate the following characteristics: reduced failure probability, reduced consequence from failure, and reduced time to recovery [7].

Resilience is often regarded as an attribute of communities rather than a property of individual infrastructure components or systems [26,24,30]. A resilient community requires a resilient ***building portfolio*** that consists of different ***building sectors***, such as residential, commercial, education, government, etc., the functionalities of which are interdependent in maintaining the well-being of a community. For example, if a large percentage of housing in an urban area becomes unusable after an earthquake, a significant outmigration of residents may occur, which will impact the local businesses and the delivery of public services [27]. Therefore, an important aspect of community resilience assessment involves quantifying the interdependencies between building sectors in terms of their functionalities within the community and developing a methodology to determine the performance targets for each sector needed to support the overall community resilience goals [22]. Although research studies to date have considered numerous aspects of community resilience evaluation [5,7,2,12,31,4,24], the quantitative linkage between the overall community resilience and the functionalities of its building sectors has received only limited attention [27,22]. Moreover, a search of the resilience literature has failed to reveal methodologies to account for the interdependencies among building sectors in assessing community resilience, as well as in designing community building inventory retrofit plans.

This paper proposes a methodology to establish the linkage between the overall community resilience goals and the

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functionalities of its supporting building sectors in which the performance of individual sectors as well as their intrinsic functional interdependencies are considered. A methodology to determine the optimal community inventory retrofit plans is developed to enable an existing community to achieve an overall community resilience goal that is supported by the above-mentioned functionalities facilitated by different building sectors. Finally, this methodology and the associated retrofit optimization algorithm are illustrated using a simplified hypothetical community in China that is composed of four building sectors exposed to scenario earthquake hazards.

2. Community functionality considering the functional interdependency among building sectors

To quantify community resilience, the measure of community functionality (performance) shown by the vertical axis of Fig. 1 must be defined [39,29,11,8,14]. Conceptually, the community resilience can be measured in terms of the probability of its "undesired outcome", the occurrence of which would adversely impact a community's ability to function normally, as suggested in Mieler et al. [27]. For instance, if the residential building sector is seriously damaged by an earthquake, the building occupants may be forced to relocate to temporary housing some distance away, which leads to a decline in retail customers and school students, affecting local business and the operation of the education system. Local businesses therefore lose both employees and customers and some businesses might close permanently or their owners might decide to relocate, taking additional employees with them [27]. Such effects can further ripple throughout a community and its economy [10,20,23,34,40]. As businesses and residents relocate, tax revenues decline, forcing cuts to essential public services and further layoffs, causing more residents to leave and making community recovery extremely difficult. [This, in fact, is what happened following Hurricane Katrina in 2005; see Girard and Peacock [16] for a comprehensive discussion.] Accordingly, *significant population outmigration* as one undesired outcome following a hazard event can be used as an overall community resilience metric, which is highly dependent on the damage to each community building sector and the interdependent functionalities among them. These interdependencies are highly complex in nature. Furthermore, what is "*significant*" is different from community to community; ultimately, it is up to a community to determine the goals that are most appropriate, and such goals ideally should be developed by a diverse group of community stakeholders in a transparent public process to properly address a potentially wide range of competing objectives and considerations (SPUR, 2009; [35,27].

Certain essential community functions must be maintained to prevent the occurrence of significant population outmigration [27]. The essential community functions considered in this conceptual study are housing, employment, education, and public services [37,38,33,12]; failure to maintain one or more of these functions may result in significant population outmigration following an earthquake (or other major natural hazard). The buildings supporting each of these four essential community functions are referred herein as residential building sector (RBS), business building sector (BBS), education building sector (EBS) and public service building sector (PBS), respectively.

For a community in which the building portfolio consists of the above-mentioned four building sectors, let $p_{o,i}$ denote the percentage of population outmigration (PO) conditional on the loss of only sector *i*. Similarly, $p_{o,ij}$, $p_{o,ijk}$ and $p_{o,ijkh}$ denote the percentage of PO, conditioned on the loss of two, three or four sectors simultaneously. Let P_i represent the probability of losing functionality of sector *i*. Since structural types and preparedness to hazards of

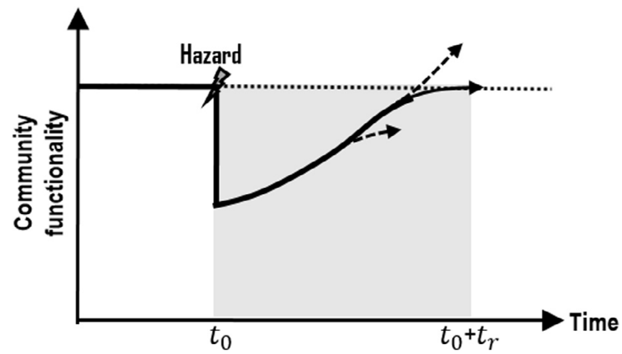

Fig. 1. Schematic representation of community resilience.

different sectors are generally different, losing the function of sector *i* and that of sector *j*, conditional on the same hazard event, are assumed statically independent. Then according to the theorem of total probability, the expected percentage of PO, P_{PO}, is:

$$P_{PO} = \sum_{i=0}^{4} p_{o,i} P_i \prod_{\substack{j=1 \\ j\neq i}}^{4} (1-P_j) + \sum_{\substack{i,j=1 \\ i\neq j}}^{4} p_{o,ij} P_i P_j \prod_{\substack{k=1 \\ k\neq i,j}}^{4} (1-P_k) + \sum_{\substack{i=1 \\ j,k,h\neq i}}^{4} p_{o,jkh} P_j P_k P_h (1-P_i) + p_{o,ijkh} P_i P_j P_k P_h \quad (1)$$

Considering that P_i typically is small for engineered building sectors, the last two higher order terms in Eq. (1) (representing the loss of three or four essential functions simultaneously) can be neglected, and Eq. (1) simplifies to:

$$P_{PO} = \sum_{i=0}^{4} p_{o,i} P_i \prod_{j\neq i}^{j=1^4} (1-P_j) + \sum_{i\neq j}^{i,j=1^4} p_{o,ij} P_i P_j \prod_{k\neq i,j}^{k=1^4} (1-P_k) \quad (2)$$

which can be expressed in matrix form:

$$P_{PO} = I_{1\times4} \begin{bmatrix} p_{o,1} & \frac{p_{o,12}-p_{o,1}-p_{o,2}}{2}P_1 & \frac{p_{o,13}-p_{o,1}-p_{o,3}}{2}P_1 & \frac{p_{o,14}-p_{o,1}-p_{o,4}}{2}P_1 \\ \frac{p_{o,12}-p_{o,1}-p_{o,2}}{2}P_2 & p_{o,2} & \frac{p_{o,23}-p_{o,2}-p_{o,3}}{2}P_2 & \frac{p_{o,24}-p_{o,2}-p_{o,4}}{2}P \\ \frac{p_{o,13}-p_{o,1}-p_{o,3}}{2}P_3 & \frac{p_{o,23}-p_{o,2}-p_{o,3}}{2}P & p_{o,3} & \frac{p_{o,34}-p_{o,3}-p_{o,4}}{2}P_3 \\ \frac{p_{o,14}-p_{o,1}-p_{o,4}}{2}P_4 & \frac{p_{o,24}-p_{o,2}-p_{o,4}}{2}P_4 & \frac{p_{o,34}-p_{o,3}-p_{o,4}}{2}P_4 & p_{o,4} \end{bmatrix} \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{Bmatrix} \quad (3)$$

The probability that building sector *i* is lost (P_i) can also be interpreted as the percentage of buildings in sector *i* that are lost (l_i). With this interpretation, we further define community functionality loss (L_C) and the residual post-disaster functionality level (F_C), measured herein by the percentage of PO for a considered scenario event, as:

$$1 - F_C = L_C = I_{1\times4}[\mathbf{DAM}]\{l\}_{1\times4} \quad (4)$$

in which F_C and L_C are the overall community functionality and loss, normalized on the interval from 0 to 1; $\{l\} = \{l_1, l_2, l_3, l_4\}^T$, in which l_i ranging from 0 to 1 reflects the fraction of functionality loss of the individual building sector *i*, and *i* = 1, 2, 3 and 4 denotes RBS, BBS, EBS and PBS, respectively. We define [**DAM**] as a **Damage Augmentation Matrix** (DAM), which accounts for the interdependencies among the essential functionalities provided by the four buildings sectors. According to Eq. (3), the [**DAM**] takes the form:

$$[DAM] = \begin{bmatrix} a_{11} & a_{12}l_1 & a_{13}l_1 & a_{14}l_1 \\ a_{21}l_2 & a_{22} & a_{23}l_2 & a_{24}l_2 \\ a_{31}l_3 & a_{32}l_3 & a_{33} & a_{43}l_3 \\ a_{41}l_4 & a_{42}l_4 & a_{43}l_4 & a_{44} \end{bmatrix} \quad (5)$$