Resilience-based Performance Objectives for Residential Buildings Subject to Seismic Hazard

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ABSTRACT: The paradigm of performance-based engineering provides a framework for engineers and planners to achieve desired levels of performance of building clusters and civil infrastructure systems that are essential for community resilience and well-being. While it is recognized that the 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 to be achieved do not yet exist. In this study, we illustrate the feasibility of the proposed framework that de-aggregates the resilience goal of a community residential building cluster under portfolio design earthquake through an inverse optimization formulation. This de-aggregation yields the minimum building performance criteria, which can be utilized as the building performance objectives for new constructions and pre-event strengthening. The overarching aim of this framework is to bridge engineering design and retrofit practices to socio-economic expectations of a community as a whole and to provide a vehicle for risk-informed resilience-based decision-making in seismic hazards. Building performance objectives obtained in this manner will enable communities to achieve their portfolio resilience goal under the seismic hazard in a long-term through portfolio renewal process realized by new constructions and retrofit of existing buildings.

1. INTRODUCTION

Buildings are traditionally designed according to the minimum requirement from design codes, guidelines, and regulations. The grave outcome of recent earthquake events (e.g. Christchurch Earthquake in 2011), however, solicits the problematic design philosophy of current seismic design codes (e.g. ASCE 7 (2016)), which generally focus on ensuring life safety by limiting collapse in individual buildings scale under rare earthquakes. The unproportioned economic loss and social impact in recent earthquakes suggest that the engineering community need to shift their focus to community level resilience, i.e. community as a whole should preserve the key functionality and recover from the interruption in a prompt manner under natural or man-made hazards.

On the other hand, communities in the U.S. start to realize the importance of communities' resilience as a whole and urges to implement the community level, long-term resilience planning (e.g. San Francisco (SPUR, 2010)) to withstand unprecedented natural hazards and other man-made hazards under the context of continuously growing economy and population. NIST community resilience planning guideline (NIST, 2015) is the first comprehensive guideline that provides principles communities may follow on their own resilience planning. However, such large-scale resilience plans suffer from lacking quantitative measurement that links the gap (between current and target performance) and planned elevating strategies.

The resilience characteristics of a community under hazard events are collectively defined by its critical functionality sectors, e.g. residential, commercial, hospital, transportation etc., which is eventually defined by individual components. Reversely, it is possible to quantitatively relating performance requirement of the individual building from the community level resilience performance goal(s), i.e. via risk de-aggregation. Some studies have been done to lay the foundation of risk de-aggregation under the context of community resilience (Miller et al, 2010; Lin and Wang, 2015), and Wang et al (2018) employ de-aggregation to derive the minimum performance requirements for wood residential building under tornado hazard. However, little studies have been done regarding risk de-aggregation under seismic hazard.

The aim of this paper is to illustrate the feasibility of risk de-aggregation under seismic hazard, address the challenges in hazard characterization in community level, and explore the basic properties of de-aggregation for wood residential buildings located in typical communities in the U.S.

The rest of the paper begins with the introduction of (ii) resilience-based design and how to define the (iii) portfolio resilience goal, and portfolio design earthquake and part (iv) gives the mathematical formulation of the de-aggregation problem. The seismic risk de-aggregation framework is applied to a hypothetical community in part (v). Part (vi) gives the conclusion.

2. RESIELIENCE-BASED DESIGN

While it is recognized that the resilience of the community as a whole cannot be achieved without appropriate performance of its critical functional sectors (e.g. residential building portfolio), which is further guaranteed by corresponding resilient individual physical components (e.g. individual buildings), current building design codes (e.g. ASCE 7 (2016), IRC (ICC, 2012)) generally do not explicitly require the preserve of functionality in the building level nor portfolio level under hazards. Generations of seismic design codes in the U.S. were back -calibrated from previous design codes (e.g. Ellingwood, 1980), which were ultimately from the first edition of Uniform Building Code (ICOC, 1927). Further, the general public have high expectation on the performance of buildings and communities under hazards, buildings codes, however, do not fully reflect such expectation (Porter, 2015). This inconsistency urges to modify the codes according to communities' requirements rather than calibrating from previous codes and shifting the design philosophy from ensuring life-safety to preserving functionality and accelerating recovery.

In addition, current design codes do not explicitly state their performance objectives nor anticipated performance levels for non-structural components and contents, both of which are essential for preserving the functionality of buildings after seismic events, Further, there is lack of consideration on the performance objectives of the building portfolio as a whole under specific hazard levels.

By contrast, Resilience-based Design (RBD) is a design philosophy that considers Immediate Occupancy (IO) at portfolio level as the primary performance objective, which helps derive the performance requirement of individual buildings according to their occupancy type and importance in the community resilience performance.

Features of the Resilience-based Design (RBD)

1. Not Life Safety (LS), but Immediate Occupancy (IO) is considered as the major performance objective for buildings under specific hazard levels (illustrated in Figure 1).
2. The performance level of the individual building is derived from portfolio level resilience requirement (Low-level de-aggregation); Portfolio level resilience requirement is further derived from community resilience goals defined by community stakeholders (High-level de-aggregation) (Wang et al, 2018).
3. There is an explicit statement of the performance objective in structural and non-structural components under specific hazard level.
4. Can be conducted in traditional prescriptive form for practicing engineers, by calibrating the performance of buildings with the

design requirements derived from portfolio goals (Maloney et al, 2018).

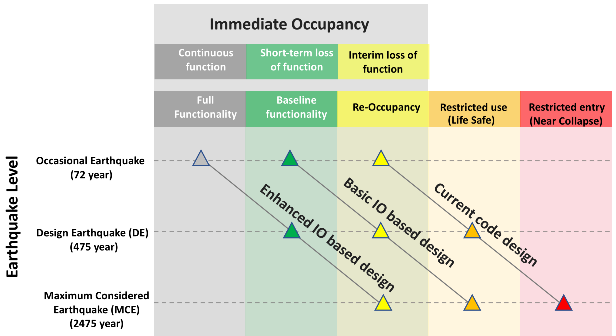

Figure 1 Example of Immediate Occupancy (IO)-based design and current code design

The comparison of current code design and two examples of IO-based design are illustrated in Figure 1, which gives the performance requirement of each design method under specific hazard level. In the context of RBD under seismic hazard, to be consistent with current seismic design codes (e.g. ASCE 7-16), we define the Design Earthquake (PDE) as one with a return period of 475 years, the details of PDE are discussed in Section 4.

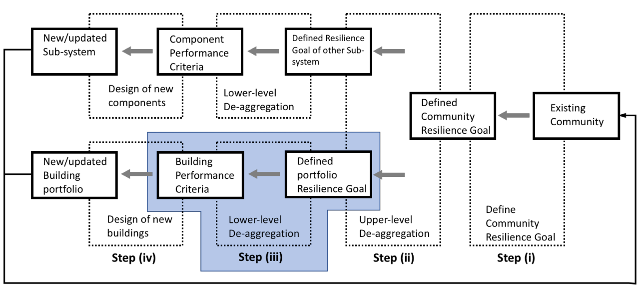

Figure 2. Proposed resilience-based design flowchart

3. PORTFOLIO RESILIENCE GOAL

Resilience goal on portfolio level is usually defined in terms of a resilience metric under a certain hazard level. In this study, the portfolio resilience goal is defined by the Immediate Occupancy (IO) of the portfolio under design earthquakes.

To support the portfolio-level performance goal, it is required that, for individual buildings, the damage to the structural system is controlled, limited, and repairable while buildings remain safe to occupy, and the damage to the non-structural system is minor to moderate. We define that an individual building fulfills ***Immediate Occupancy (IO)*** performance limit if it has up to minor damage in structural components and up to moderate damage in non-structural components as introduced in Lin and Wang (2017). In individual building level, we denote indicator $IO^i = 1$ as the IO is fulfilled and $IO^i = 0$ as the IO is unfulfilled in building i. For simplicity, we denote ST^i, NA^i, and ND^i as the damage state of structural, non-structural components acceleration-sensitive, and non-structural components drift-sensitive of building i. Thus, the probability of IO of building i under ground motion level $IM = x$, $P\left(IO^i = 1|x\right)$ can be obtained by

$$\begin{aligned} &P\left(IO^i = 1|x\right) \\ &= P\left(\left(ST^i \leq 1\right) \cap \left(NA^i \leq 2\right) \cap \left(ND^i \leq 2\right)|x\right) \\ &= P\left(ST^i \leq 1|x\right) \cdot P\left(NA^i \leq 2|x\right) \cdot P\left(ND^i \leq 2|x\right) \\ &= \left(1 - Fr^i_{SD|IM}(2|x)\right) \cdot \left(1 - Fr^i_{NA|IM}(3|x)\right) \\ &\qquad \cdot \left(1 - Fr^i_{ND|IM}(3|x)\right) \end{aligned} \tag{1}$$

where $P\left(ST^i \leq 1|x\right)$ denotes the probability of structural component being not exceeding damage state 1 under ground motion level x, similar definition could be given for $P\left(NA^i \leq 2|x\right)$ and $P\left(ND^i \leq 2|x\right)$; $Fr^i_{SD|IM}(2|x)$ denotes the probability of structural component of building i being in damage state *2* or higher, similar definition could be given for $Fr^i_{NA|IM}(3|x)$ and $Fr^i_{ND|IM}(3|x)$.The above equation implies that the failure probability of structural, non-structural acceleration-sensitive, and non-structural drift-sensitive components are independent. Further, the conditional joint probability of all component of all buildings $\boldsymbol{BDS} = \left(BDS^1, \dots, BDS^i, \dots, BDS^{I_N}\right), BDS^i = \left(ST^i, NA^i, ND^i\right)$ being in or exceeding damage state vector $\boldsymbol{ds} = [ds]_{I_N \times 3}, ds \in (0,1,2,3,4)$ for the portfolio under the hazard level $H = h$ is obtained by

$$P(\boldsymbol{BDS} \geq \boldsymbol{ds}|h) = \int Fr_{\boldsymbol{BDS}|\boldsymbol{IM}}(\boldsymbol{ds}|\boldsymbol{x}) f_{\boldsymbol{IM}|H}(x|h) d\boldsymbol{x} \quad (2)$$

where the bold-faced notations denote vector-valued variables. $Fr_{\boldsymbol{BDS}|\boldsymbol{IM}}(\boldsymbol{v}|\boldsymbol{u})$ denotes the joint cumulative distribution function (CDF) of $\boldsymbol{BDS}$ being $\boldsymbol{ds}$ or higher damage state given intensity measure $\boldsymbol{IM} = \boldsymbol{u}$, i.e. fragility function, with logarithmic parameter $\boldsymbol{\lambda_R}$ and $\boldsymbol{\varepsilon_R}$; $f_{\boldsymbol{IM}|H}(\boldsymbol{u}|h)$ denotes the joint probability distribution function (PDF) of $\boldsymbol{IM}$ in the community conditioned on hazard level h, which will be discussed in **Section 4**.

Generally, the portfolio resilience can be expressed in a probabilistic form due to uncertainties from hazard and portfolio performance (Wang et al, 2018). Specifically, for portfolio IO performance goal under design earthquake, the equation can be written as

$$R^{IO} = P(M_{IO} \geq G_{IO}|H = DE) = a\% \quad (3)$$

where M_{IO} represents the portfolio resilience metric IO evaluated under design earthquake (DE), and $M_{IO} = IO^P = \sum_{i=1}^{I} IO^i$, i.e. the number of buildings that fulfill IO within the portfolio; G_{IO} is the prescribed resilience goal corresponding to M_{IO} . An example of the probabilistic resilience goal statement would be $R^{IO} = P(M_{IO} \geq 80\%|DE) = 90\%$, which means "No less than 80% of the residential buildings are reached the IO performance limit under any design earthquake events with 90% probability". The hazard characterization and definition of design earthquake will be discussed in Section 4.

4. PORTFOLIO DESIGN EARTHQUAKE (PDE)

A major challenge in community-level resilience assessment and decision-making at seismic active regions lies in how to characterize the seismic hazard at the community level. Seismic hazard characterization refers to how the spatial and temporal characters of the ground motion are modeled and how the uncertainties involved in the earthquake source, path transmission, and local amplification are properly addressed. In this study, we focus on the definition of design earthquake in portfolio level and discuss how to obtain it for a specific portfolio with given geological location and seismic sources.

The intensity of natural hazards (e.g. earthquake, hurricane) is traditionally represented in the return period (e.g. 1000 year) for hazards themselves as well as specific sites. For civil engineering structures subjected to seismic hazard, ASCE-7 (ASCE, 2016) defines design earthquake intensity for individual buildings (in terms of PSA, with return period of about 475 years) as 2/3 of the intensity of risk-targeted maximum considered earthquake (MCE_R, with return period of about 2475 years) (Luco et al, 2007). Generally, earthquake intensities in different sites are different due to different site-to-epicenter distance, site soil amplification, and aleatory uncertainties, and are correlated due to location closeness and common construction practices. Hence, the portfolio design earthquake (PDE) is defined as the earthquakes that have an arithmetic mean PSA value over the portfolio with a return period of 475 years.

To derive the portfolio design earthquake (PDE), all possible seismic sources (S), magnitudes (M) and epicenter locations (L) are considered. The probability mass function (PMF) of S and PDF of M, and L can be represented by p_S, $f_{M|S}$, and $f_{L|S,M}$, the latter two PDF imply conditional probability. In theory, the PDF of $\boldsymbol{IM}$ can be written as $f_{\boldsymbol{IM}}(\boldsymbol{u})$

$$f_{\boldsymbol{IM}}(\boldsymbol{u}) = \int\int f_{\boldsymbol{IM}|M,L}(\boldsymbol{u}|y,z) f_{L|S,M}(z|x,y) f_{M|S}(y|x)\, dzdy \quad (4)$$

where $p_S(x)$ denotes the probability mass function (PMF) of the occurrence rate of S, i.e. annual occurrence rate of earthquake in that source; $f_{M|S}(y|x)$ is the PDF of M conditioned on certain S; $f_{L|S,M}(z|x,y)$ is the PDF of L conditioned on S and M; $f_{\boldsymbol{IM}|M,L}(\boldsymbol{u}|y,z)$ is the PDF of $\boldsymbol{IM}$ conditioned on M and L according to the ground motion attenuation model. The bold-faced notion in $\boldsymbol{IM}$ denotes vector-valued intensity measure.

Generally, the above equation cannot be solved in closed-form in most real applications. To evaluate the above multi-layer conditional probability problem, one may employ the multi-layer Monte Carlo Simulation (MCS). In this paper, we adopt the multi-layer importance sampling (IS) technique (Jayaram and Baker, 2010), where the seismic source and magnitude are sampled by IS, which reduces the number of MCS about 2 - 3 order of magnitudes.

5. ILLUSTRATION

We apply the risk de-aggregation framework to a hypothetical homogeneous portfolio of 20 by 20 km under seismic hazard. Suppose there is only one fault lies on the left side of the community, the length of the fault is 100 km. The distance *d* from the center of the community to fault is 50 km.

We consider the case of uniform design objectives throughout the portfolio, i.e. all buildings within the portfolio have same $\boldsymbol{\lambda_R}$, **specifically** $\lambda_{R_{ST,2}}$, $\lambda_{R_{NA,3}}$, $\lambda_{R_{ND,3}}$ corresponding to the $ds = 2$ for ST component and $ds = 3$ for NA and ND components. For given community layout and geological location, the relation between portfolio IO threshold, G_{IO} and $\lambda_{R_{ST,2}}$, $\lambda_{R_{NA,3}}$, $\lambda_{R_{ND,3}}$ is defined. As illustrated in Figure 3, the value of $\lambda_{R_{Item,ds}}$ derived from resilience goal are plotted in solid lines corresponding to $Item \in (ST, NA, ND)$ component. $\lambda_{R_{Item,ds}}$ increases monotonically when portfolio IO threshold, G_{IO} increases with fixed $R^{IO} = 90\%$. The value of $\lambda_{R_{Item0,ds}}$ from building type W1 (high code) in HAZUS is printed in dot line as the baseline and shows the gap between current and desired performance for each component. It is found that for high-code W1 building in HAZUS, it has very different performance level for ST, ND, and NA components. For instance, if $G_{IO} = 0.7$, NA components in high code W1 already fulfills the requirement from de-aggregation while ST and ND components need significant strengthen to reach the required performance level.

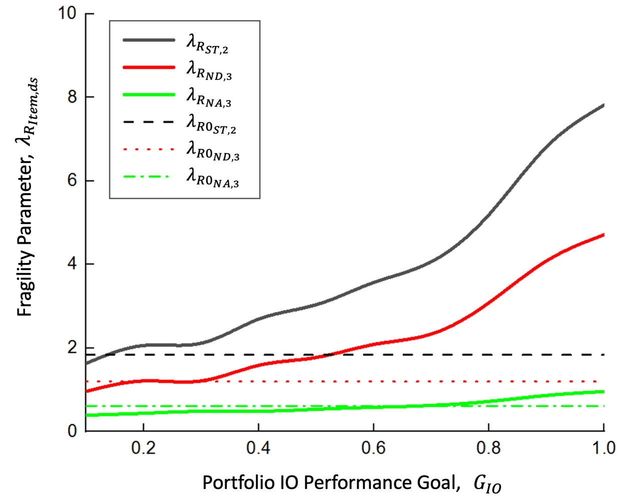

Figure 3. The relation between fragility parameter $\boldsymbol{\lambda_R}$ and portfolio IO performance goal, G_{IO}

6. CONCLUSION

In this paper, we propose a risk de-aggregation framework that can derive the performance requirement of individual buildings from the portfolio resilience goal under seismic hazard. Such a de-aggregation methodology is intended to explore the feasibility and serve as a basis for future resilience-based design (RBD), which is of great potential. More researches are needed in hazard characterization and investigating the correlation of performance between ST, ND, and NA component and their impact on de-aggregation results.

7. ACKNOWLEDGEMENT

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