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Probability distribution of the seismic damage cost over the life cycle of structures

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ABSTRACT

In the life-cycle analysis, the total cost of damage caused by earthquakes is a significant but highly uncertain component. In the current literature, the seismic risk analysis is largely limited to the evaluation of the average cost of damage, which is not informative about the full extent of variability in the cost. The paper presents a systematic development of the stochastic modeling of seismic risk analysis problem and reformulates the damage cost analysis as a superposition of compound Poisson processes. An explicit analytical solution for the distribution of damage cost is derived in form of a recursive equation. The proposed approach extends the capability of the existing framework of seismic risk analysis, which can be used to optimize initial design and retrofitting of structures.

1. Introduction

1.1. Background

With the advent of probabilistic modeling of structural safety problems in 1960s and 70s, the risk-based calibration and optimization of design codes became an important area of research in structural engineering. Comprehensive studies by Whitman et al. [1] and Whitman and Cornell [2] laid the foundation of the seismic risk analysis and design of structures that are likely to face multiple seismic events during the service life. This framework, which still serves as a basis for modern code development [3], embodies the following key ideas:

- The two most basic goals of seismic design were recognized as minimizing the likelihood of costly repairs and avoiding the loss of life [4, p. 18].
- Stochastic modeling of earthquake occurrences as the homogeneous Poisson process accompanied by a random variable representing the ground motion intensity [5].
- The probability distribution of annual maximum of the ground motion intensity as a basis to evaluate structural reliability. This is to meet the objective of life safety.
- The expected cost of losses caused by seismic events as a measure of seismic risk, which in turn relates to the economic efficiency of a design.
- Optimization of seismic resistance by balancing the initial cost premium for improving the resistance against the future expected cost of damage. This guiding principle serves as a basis for code development.

In recent years, the move towards the performance-based design has prompted the development of more and more refined models for life cycle cost analysis in which the seismic damage cost is an important but fairly uncertain element. Note that he term *damage cost* includes all the losses that could incur due to loss of services, damage to contents and cost of repairing and restoring the damaged structure.

In the current literature, the life cycle analysis is almost exclusively focussed on the evaluation of expected (or average) cost of seismic damage. The expected cost is not informative about the extent of losses, given that a large variance is associated with the damage cost [6]. It means that an exclusive reliance on the expected cost for optimizing a design would not yield a realistic result due to large variability potentially associated with an outcome. Instead, an upper percentile of the cost would be a more meaningful bound of the risk, such as the Value at Risk (VaR) used in the financial literature. In spite of this limitation of the expected cost measure, the evaluation of probability distribution of damage

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Nomenclature

SMRF	steel moment resisting frame	PDF	probability density function
DCPP	Diablo Canyon power plant	PMF	probability mass function
PSHA	probabilistic seismic hazard analysis	F	cdf function
RV	random variable	*iid*	independent and identically distributed
CDF	cumulative distribution function	HPP	homogeneous Poisson process
POE	probability of exceedance	δ	unit cost of damage

cost has not been tackled in the seismic literature. It could well be a result of a presumption that the simulation-based method is the only way to determine the cost distribution, and that the computational burden associated with simulation makes it impractical tool foe seismic risk analysis.

Thus, the primary goal of this study is to present a clear exposition of the stochastic modeling of seismic risk analysis that leads to an analytical expression for the probability distribution of total cost of seismic damage. This distribution can be used to evaluate a probabilistic bound on risk, which could serve as a basis to optimize design and retrofitting options for structures.

The approach taken in this paper is to draw a parallel between the seismic risk analysis and the theory of stochastic renewal process. This understanding provides new interpretations and insights which are necessary to derive the full distribution of the damage cost.

1.2. A motivating example

The analytical formulations presented in this paper are aimed to analyze practical examples like the seismic damage cost for a 20-storey steel moment resisting frame (SMRF) building, as shown in Fig. 1. The building was designed as a standard office building sitting on stiff soil. It has a fundamental period of 4.0 s. Other structural details can be found elsewhere [7].

The building is (hypothetically) situated at a site of the Diablo Canyon power plant (DCPP) in California. This site is in the proximity of the Hosgri, Los Osos, San Luis Range, and Shoreline faults, as

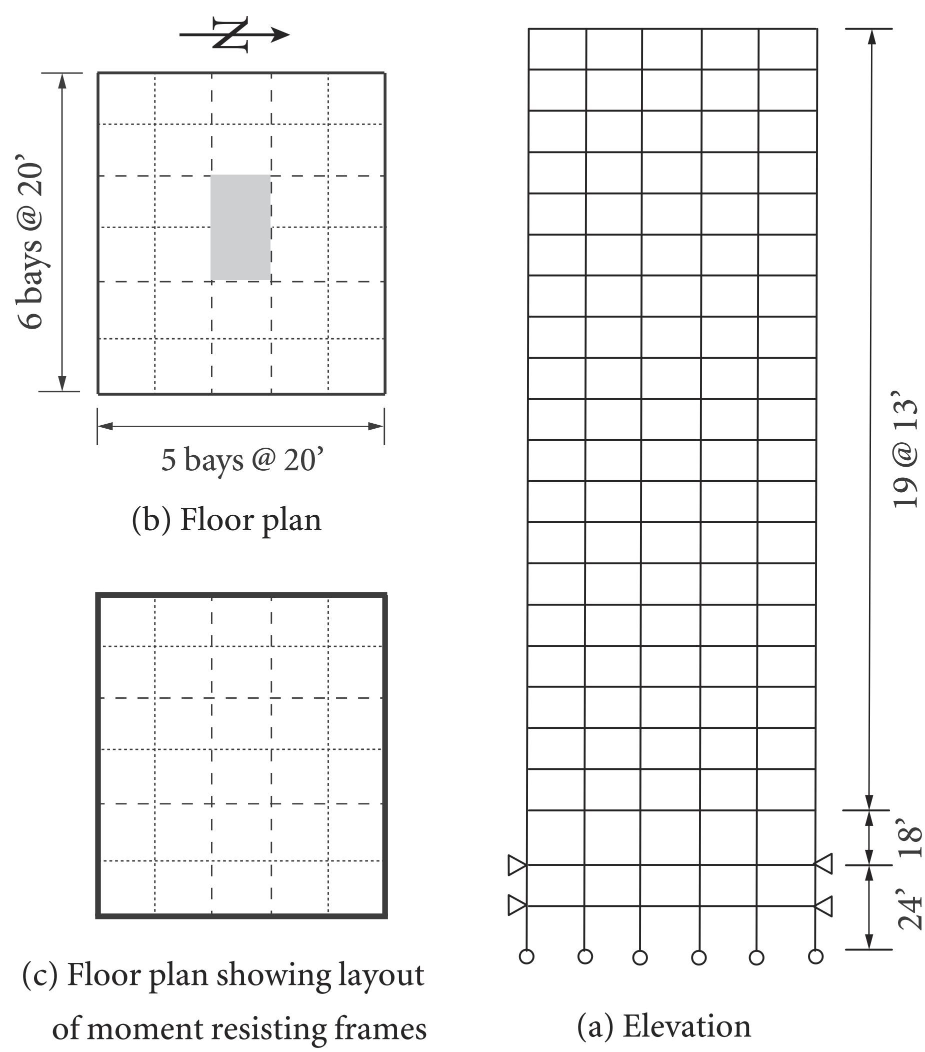

Fig. 1. Example building for seismic risk analysis.