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Probabilistic two-hazard risk assessment of near-fault and far-fault earthquakes in a structure subjected to earthquake-induced gas explosion

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ABSTRACT

Over the past decades, several studies have compared damage induced by near-fault and far-fault earthquakes in a deterministic approach. Following a probabilistic approach and generating several scenarios, the present study was aimed at assessing the probabilistic two-hazard risk of a structure concurrently subjected to earthquake and earthquake-induced blast. The two critical events (earthquake and blast explosion) were considered as compatible and dependent events, such that the blast would occur simultaneously with the earthquake and as the result of it. The probabilistic two-hazard risk was evaluated in two separate phases: one was characterized by near-fault earthquakes with blast; and the other phase was defined by far-fault earthquakes with blast. Comparing the probabilistic risk for the two phases revealed that the probabilistic risk of the near-field earthquake, though with a long return period, is substantially greater than that of the far-fault earthquake.

1. Introduction

A structure could be subject to multiple critical events, such as earthquake, wind, blast or fire, during its service life. Ordinary building structures are typically designed to resist earthquakes or, in certain cases, wind loads. Critical loads like blast or fire are rarely considered in design of ordinary buildings. Progressive collapse is a consequence of such critical loads. Progressive collapse describes the spread an initial local failure in a structure element that leads to total collapse of a structure [1–3].

Nowadays, different guidelines have incorporated provisions to address the problem of progressive collapse in structures. In 2006, National Institute of Standards and Technology (NIST) [4] drew up codes of practice to reduce the potential for progressive collapse in buildings subjected to abnormal loadings. National Building Code of Canada (1996) [5] laid down requirements for design of major elements and ways of providing load transfer paths. The Eurocode 1. (2002) [6] proposed a design standard for selecting plan types as to prevent progressive collapse. The American Concrete Institute (ACI 318, 2002) [7] required structural integrity so that partial damage by abnormal load does not lead to total collapse. The United States Department of Defense (DoD) [8], the General Service Administration (GSA) [9], and also the Unified Facilities Criteria (UFC) [10] have presented a design method of structures to resist progressive collapse.

There are two approaches to risk analysis in structures: deterministic and probabilistic. To date, deterministic risk assessment has been extensively researched both analytically and experimentally to estimate progressive collapse [11–14]. As for probabilistic risk assessment, the stability of a structure is evaluated in different scenarios based on the probability of progressive collapse. Such probabilistic risk can be considered in association with the occurrence of only one critical event (such as earthquake, blast, etc.) or even multiple critical events. In case where probabilistic risk assessment is associated with multiple critical events, compatibility or incompatibility and dependence or independence of events are of great importance. Considering earthquake and blast hazards as mutually exclusive, Asprone et al. [15] evaluated the probability of failure following a two-hazard approach. By subjecting a reinforced concrete (RC) framed structure to blast loads, Parisi and Augenti [16] considered several blast scenarios defined by the quantity of explosive and location of blast center. They further performed global pushdown analysis to assess robustness. The study aimed at assessing probabilistic risk, considering compatibility and dependence of critical events, such that due to gas release in case of earthquake an explosion occurs in the structure. The gas explosion can occur either simultaneous with the occurrence of earthquake or shortly after the earthquake though before repairing the structure back to its intact state (compatibility of the two critical events). Also, the gas explosion occurs due to the earthquake (dependence of the two critical events). The study is also noteworthy for its probabilistic risk assessment of near-fault and far-fault earthquakes.

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Cavaco et al. [17] suggested a new method of evaluating robustness index, based on structure performance for a reinforced concrete structure. According to Gao and Liu [18], one of the most important indices of maintaining structure safety is in considering specific loading in form of human damage activities; they also suggested a weighted structure graph for robustness analysis.

Guedri et al. [19] defined two kinds of uncertainty in materials and geometrical features (i.e. Epistemic and Aleatory uncertainty), showing their importance and characteristics, and evaluating robustness based on uncertainty analysis of the structure. Lu et al. [20] presented a robustness index against structures' progressive collapse, using Pushdown Analysis, and in their evaluation of robustness eliminated structural elements index. Brett and Lu [21], comprehensively studied the current status of the researches about structures' robustness, focusing on the amounts and methods of robustness evaluation in the structures. They did not discuss ascertaining methods, required by robustness, only talking about some related conceptions such as redundancy, ductility, etc.

In Yang and Xi-La's [22] opinion the reason development of damage is lack of robustness when a local damage occurs in the structure, concluding that the safety of such structures is not guaranteed by traditional methods such as trustworthy analysis tools and building management methods. This research presents a quantitative method to evaluate structure robustness in topologic terms. Kwag and Ok [23] suggested a robust approach for optimum design of separating system of the bridges against uncertainty parameters in these systems, like bridge model parameters and isolation bearing.

Zhong et al. [24] investigated the performance of different stiffness connections against progressive collapse by the static loading tests and numerical analysis. They studied three different stiffness connections based on double full-span assemblies and discussed and analyzed failure modes, load-deformation responses, and mechanical behaviors of specimens. Also, they assessed the influence of peripheral components' constraint on the anti-collapse performance of the assembly.

Research has targeted major parameters in risk analysis and studied their effect in near-fault and far-fault earthquake accelerograms [25–27]. For near-fault earthquakes, it can be argued that considering the faulting, location of the site and its distance from the seismic source, the probability that a structure during its lifetime is subjected to near-fault earthquakes is considerably low, and that structures are generally subjected to far-fault earthquakes. That is, for a given structure the annual rate of occurrence of near-fault earthquakes is significantly less than that of far-fault earthquakes. Yet, the fragility and destruction of a structure subjected to near-fault earthquake is much greater than far-fault earthquake. As such, assessing probabilistic two-hazard risk of near-fault and far-fault earthquakes merits investigation and the results of which can be compared.

2. Probabilistic two-hazard risk

If E is the occurrence of earthquake, B is the occurrence of blast and C is the structural collapse, assuming that E and B are incompatible and mutually exclusive, that is:

$$P(B \cup E) = P(B) + P(E) \tag{1}$$

$$P(B \mid E) = 0 \tag{2}$$

Then, the probabilistic two-hazard risk ($P(C)_i$) can be expressed as:

$$P(C)_i = P(C \mid (B \cup E)) = \frac{P(C \mid B).\ P(B) + P(C \mid E).\ P(E)}{P(B \cup E)} \tag{3}$$

Finally, by reformulating Eq. (3), the probabilistic two-hazard risk ($P(C)_i$), where the events are incompatible and mutually exclusive, can be written as:

$$P(C)_i = P(C \mid B).\ P(B) + P(C \mid E).\ P(E) \tag{4}$$

where $P(C \mid B)$ stands for blast fragility, *P(B)* is the annual rates of occurrence of blast, $P(C \mid E)$ is the seismic fragility, and $P(E)$ is the annual rates of occurrence of earthquake. Such probabilistic risk assessment has been the target of different studies [15,28].

Assuming only one critical event, the probabilistic risk $P(C)_A$ can be derived from following:

$$P(C)_A = P(C \mid A).\ P(A) \tag{5}$$

Where $P(C \mid A)$ and $P(A)$ represent the fragility of the critical event and the annual rates of occurrence of the critical event, respectively.

In this study, we intend to consider seismic load along with blast loads, and as a result, these two events are considered compatible (they can occur simultaneously) and codependent (blast occurs if earthquake occurs). In such a way that during or immediately after an earthquake, a blast occurs due to the failure of thermal/mechanical installations and consequent gas leak in the building, without any chance for recuperation or reparation of the structure. Finally, it is manifested that under the proposed condition, the time of the blast would influence the uncertainty of the blast load.

On the other side, one can observe that in most strong or medium earthquakes along with critical earthquake load, gas explosive can increase the damages subjected to a structure due to mechanical and thermal failure of the installation. This factor highlights the significance of performing the current study so that one can evaluate the collapse rate of the structure with an appropriate method under such condition and also obtain an acceptable and correct assessment of structures subjected to these two critical loads.

So, in this study, earthquake and blast hazards are assumed dependent and compatible as following:

$$P(B \cup E) = P(B) + P(E) - P(B \cap E) \quad \text{(Law of the community of two events)} \tag{6}$$

$$P(B \mid E) = \frac{P(B \cap E)}{P(E)} \text{(Conditional equation of two events)} \tag{7}$$

Therefore, the probabilistic two-hazard risk ($P(C)_C$) can be calculated as follows:

$$P(C)_C = P(C \mid (B \cap E)).\ P(B \cap E) \tag{8}$$

Considering Eq. (7), Eq. (8) can be reformulated as [1,3,29]:

$$P(C)_C = P(C \mid (B \cap E)).P(B \mid E).\ P(E) \tag{9}$$

where $P(C \mid (B \cap E))$ is the concurrent blast and seismic fragility, $P(B \mid E)$ is the probability of blast induced by earthquake, and $P(E)$ is the annual rates of occurrence of earthquake. The present study aims to evaluate the probabilistic two-hazard risk $P(C)_C$ in two states, namely near-fault and far-fault earthquakes. For do this, a region of the highest seismicity has been considered, then effect on two-hazard risk have been assessed in tow different phases for "near-field" and "far-field" earthquakes. Estimating major parameters in the risk of interest, the study is further concerned with comparing the results of the two states.

3. Assessing seismic-blast fragility

In this study, based on uncertain parameters in blast induced by gas release and also uncertainty in selecting records of near-fault and far-fault earthquakes, several scenarios were generated. Then, considering the occurrence of progressive collapse in each scenario, the fragility of interest was evaluated. Therefore, for the sake of simplicity in assessing the fragility of interest, discrete sample space was used for scenario generation, considering uncertain blast and earthquake parameters. In this case:

$$P(C \mid (B \cap E)) = \frac{\sum_{i=1}^{N_{sim}} I_C}{N_{sim}} \tag{10}$$