Relationship between Seismic Redundancy and Failure Likelihood for Mass-eccentric Reinforced Concrete Frame Structures

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ABSTRACT

Any change in structure's occupancy or use can significantly impact the plan and elevation mass distributions, turning even regular structures into mass-eccentric structures with in-plan or vertical irregularities. Generally, irregular structures are more vulnerable to earthquake hazards because of the torsional effect, which causes non-uniform deformation demands. Existing design practices propose that irregular structures should be subjected to stringent design criteria. This research investigates how the use of a structure can affect its seismic vulnerability and tries to find how seismic demand (response) and supply (capacity) are related to failure probabilities. A series of reinforced concrete moment frames structures with varying in-plan and vertical irregularities are studied. Their 3D detailed analytical models are employed for numerical simulations. In fragility analysis, a relationship between the limit state function (seismic supply minus demand) and failure probability is derived. Previous research efforts mainly focus on investing seismic supply and demand for various structures by conducting vulnerability analysis. However, this study aims to derive how the seismic redundancy expressed by a limit state function relates to the structural failure likelihood.

Introduction

One of the deadliest natural calamities is earthquakes. Earthquakes killed about 800,000 people worldwide between 2000 and 2015 [1-3]. Furthermore, they frequently result in significant financial loss. A recent study shows that earthquakes in the United States cause a 4.4-billion-dollar loss per year [4] and be using new approaches for projects delivery, the risk of such loss can be improved [5]. Based on post-earthquake damage investigations, buildings with structural irregularities suffer the most. On the other hand, irregular building structures make up a considerable portion of the modern metropolitan infrastructure. Irregularities in structures are caused by unequal mass, stiffness, or strength distributions. Thus, the uneven use of the building space can significantly affect the overall seismic vulnerability of the structure. This study investigates the seismic response of reinforced concrete moment frame structures with varying vertical and in-plan irregularities due to building use changes. Various mass distributions in plan and elevation, associated with different live load scenarios, are assumed to create 3D structural models. A new method [6,7], which makes it possible to calculate structural failure probabilities with high accuracy and low computational cost, is used to overcome the computational challenge in seismic fragility analysis using 3D analytical models. The calculated failure probabilities are compared with the seismic redundancy or margin of safety (difference between seismic supply and demand) to find their correlation.

Many studies have used fragility curves to analyze the effect of vertical irregularity on the seismic performance of building structures. In most previous studies, structures were represented as 2D frames, and seismic fragility curves were calculated analytically. Hanan Al-Nimry used simple 3D analytical models to study building systems with vertical stiffness abnormalities [8]. In the vulnerability study, the analytical function-based method was used. N. Achaean and colleagues investigated vertically uneven buildings at various heights with soft stories [9]. The fragility curves were obtained analytically from the limit state functions using 2D simplified models. Regular and irregular moment-resisting concrete and steel 2D frames with various imperfections were compared by Nari et al. [10]. The failure probability was calculated using an analytical function-based method.

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Seismic Fragility Analysis

The studied structures are ordinary, three-story reinforced concrete and ordinary moment-resisting structures with three bays and three frames. The target structures are mainly intended for gravity loads. They are not earthquake-prepared, but they represent a significant fraction of office buildings in the United States. 3D analytical models are produced in the nonlinear structural analysis software ZEUS-NL for earthquake simulations. There are 48 reinforced concrete columns, each with a 12-inch square cross-section. Beams are modeled using a reinforced concrete T section with an 18-inch depth and a 6-inch slab thickness. The total mass of the structure is assumed to remain constant, while the live load distribution can be altered. A live load of 50 pounds per square foot (psf) for office buildings is assumed according to the ASCE 7-16 design code.

This study considers twenty-one different live load scenarios, categorized into three groups. The first group contains seven vertically irregular mass-eccentric models with uniformly distributed live loads on each floor plan (VIMEU). The second group includes the other seven models, which are vertically irregular mass-eccentric models with concentrated live loads on half of each floor plan (referred to as VIMEH). These models have the same vertical load distribution cases as those in the first group. Still, they also have unidirectional plan irregularities due to the eccentric live load distribution. The final group contains the remaining seven vertically irregular mass-eccentric models with concentrated live loads on the quarter of each floor plan (referred to as VIMEQ). The main difference with group 2 is that group 3 models have bi-directional plan irregularities. The twenty-one cases can cover various scenarios of the structure use (or live loads). Figure 1 depicts the seven vertical live load distribution scenarios. All loads are applied as concentrated forces determined from the two-way slab tributary method.

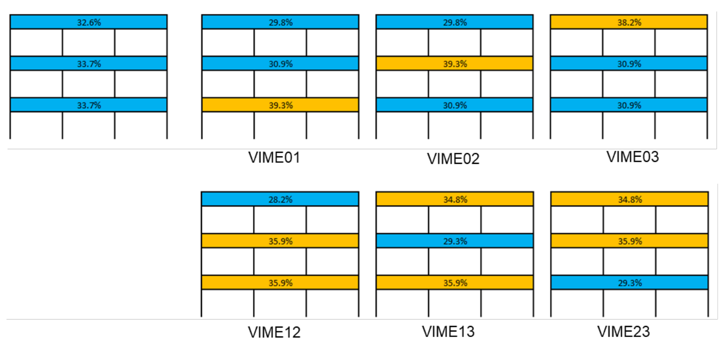


Figure 1. Vertical live load distribution

A series of dynamic response history analyses are performed in ZEUS-NL for seismic vulnerability analysis. Structural analysis results are forwarded to the reliability analysis software FERUM to determine failure probabilities. Several studies have been conducted in the subject of civil engineering simulation, such as [11], which simulates the construction of linear projects. Eight damage limit states are utilized based on the permissible drift ratio values of 0.25%, 0.50%, 0.75%, 1.00%, 1.25%, 1.50%, 1.75%, and 2.00%. The preset damage condition is assumed to be met when a structure reaches the predefined drift ratio. Ten earthquake ground motions are employed to conduct the seismic fragility analysis. With ten earthquake records and eight limit state criteria, twenty-one 3D frame models are analyzed in this study. This brings the overall number of instances to 1680. The fragility curves are derived with the calculated probability data, and smooth analytical fragility curves are determined after the regression analysis assuming a log-normal cumulative distribution, as shown in figure 2.

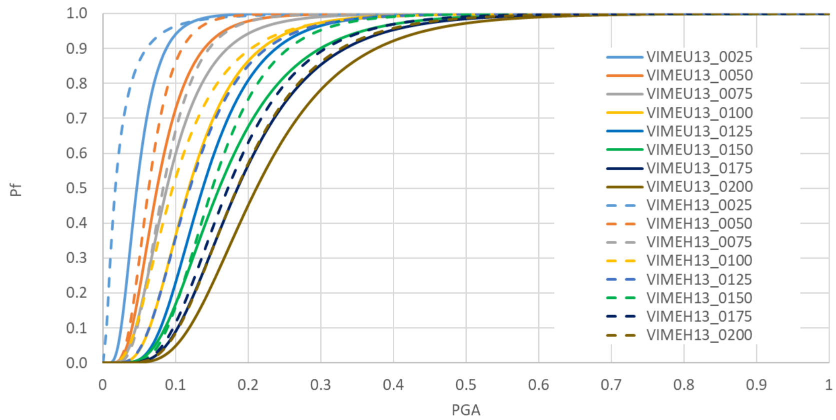


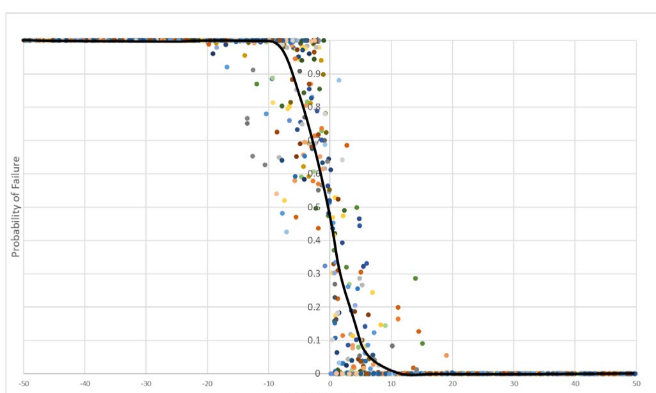
Figure 2. Fragility curves for VIMEU and VIMEH models

Seismic Redundancy and Failure Likelihood

The seismic redundancy or margin of safety can be quantified mathematically using the limit state function. The limit state function is defined as the structural supply (or capacity) minus seismic demand (or response). The limit state function value will be significantly larger than zero when there is enough seismic capacity than the predicted seismic demand (i.e., the supply is much larger than the demand). The failure probability corresponding to such a case will be extremely low, and structures will not fail. Thus, the failure probability is closely related to the value of the limit state function.

To find how the limit state function (or seismic redundancy) and failure likelihood are correlated, the failure probability versus the limit state function value for studied models is presented. Figure 3 shows the relationship between failure probabilities and values of the limit state function for three analyzed groups, which are vertically irregular mass-eccentric models with uniformly distributed live loads on each floor plan (VIMEU), vertically irregular mass-eccentric models with concentrated live loads on the half of each floor plan (VIMEH) and vertically irregular mass-eccentric models with concentrated live loads on the quarter of each floor plan (VIMEQ). The failure probability increases as the limit state function decrease, demonstrating the link between the seismic safety margin and failure probability. Note that the computational cost can be significantly reduced by limiting the fragility analysis to the range of the trend line and assuming failure probability as either 0 or 1 outside of this range.

VIMEU



VIMEH VIMEQ

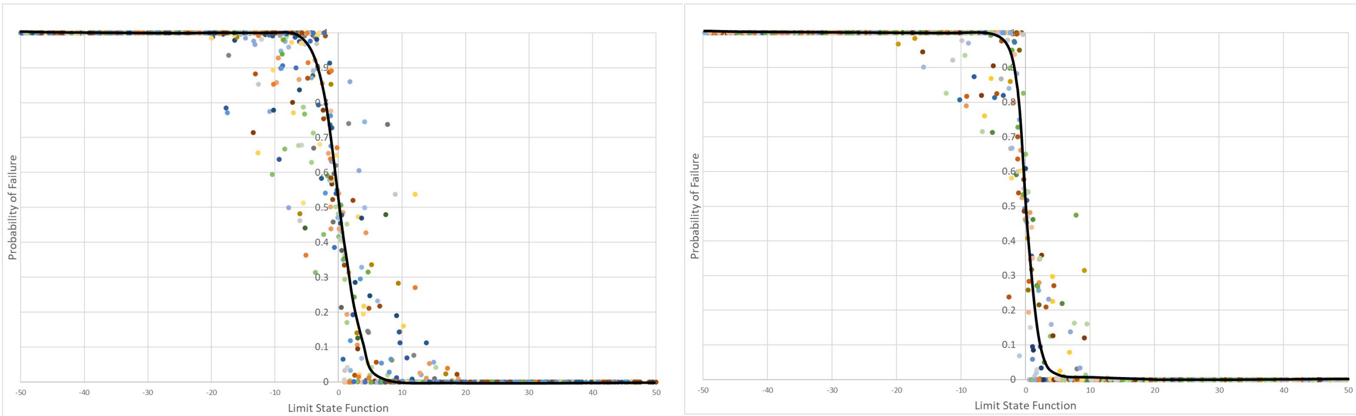


Figure 3. Failure probability vs. limit state function value

The plots in figure 3 clearly show the difference in trend lines from three distinct groups. The slope of the curve gets steeper from the uniformly loaded case to the half-loaded case and then to the quarter-loaded case. This is because the structure's seismic supply (or capacity) decreases with the increase of the degree of plan irregularity while the demand remains constant. The structure is more vulnerable and exposed to failure as the irregularity in the structural system increases. Figure 4 compares curves obtained from three groups. The black, blue, and orange lines refer to the VIMEU, VIMEH, and VIMEQ cases. The slope of the trend lines in the transition range between failure probabilities of 0 and 1 increases as the irregularity of the structure increases. Note that the transition lengths where the failure probability changes from 1 to 0 are different, decreasing as the structural irregularity increases.

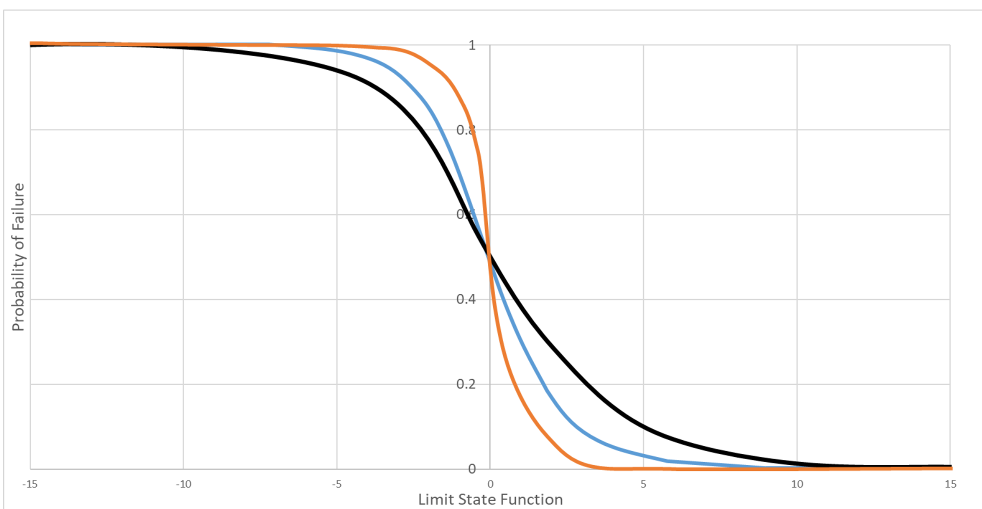


Figure 4. Comparison of seismic redundancy and failure likelihood curves

Conclusions

This research aims to study how the seismic performance of reinforced concrete frame structures can be affected by the vertical and in-plan irregularities caused by the change in the structure and to find out how the seismic redundancy is related to the structural failure likelihood. Twenty-one different irregular analytical models are generated. A new method was adapted for fragility analysis to handle computationally expensive 3D models. Fragility curves are successfully derived, and the resulting fragility curves confirm the direct impacts of vertical and in-plan irregularities on seismic performance. The limit state function values are compared with failure probabilities to study the relation between seismic safety margin and failure likelihood. As expected, a strong correlation between them is observed. This research presents a new approach for determining the probability of failure of a structure from its seismic capacity and the expected seismic demand with minimum computational cost.

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