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Seismic risk of base isolated non-ductile reinforced concrete buildings considering uncertainties and mainshock–aftershock sequences

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ABSTRACT

Base isolation is a promising approach to retrofit seismically vulnerable buildings, but the supporting body of research on seismic risk mitigation through base isolation, particularly considering the associated uncertainties and mainshock–aftershock sequences, is deficient. Therefore, in this study seismic risk analysis was performed for an old non-ductile RC frame building before and after retrofit with base isolation. Various sources of uncertainty such as structural uncertainties, ground motions uncertainties and modeling uncertainties are discussed and propagated in the analysis procedure. A sensitivity study was also conducted to determine which structural parameters have the most significant impact on both the seismic demands of the un-retrofitted and base isolated building. A suite of recorded mainshock and aftershock ground motions was utilized to investigate the influence of considering aftershocks on the performance of these types of buildings. The study revealed that base isolation can greatly reduce the seismic risk for higher damage levels, as one would expect. More importantly, the results also indicated that neglecting aftershocks can cause considerable underestimation of the seismic risk.

1. Introduction

The seismic design of reinforced concrete (RC) frame buildings has evolved to a sophisticated level over the last few decades, making them ductile in order to perform well in moderate to severe earthquakes. However, many buildings that were constructed prior to the implementation of modern building codes are vulnerable to earthquakes. The design deficiencies that make these structures vulnerable are minimal shear reinforcement, insufficient development length for longitudinal reinforcement and strong beam-weak column, essentially resulting in a lack of ductility capacity [1,2]. These buildings includes typical RC frame buildings built in the Western United States (WUS) before the mid-1970s [1] and the typical RC frames built in Central and Eastern United States (CEUS) prior to 2000 [2]. Seismic rehabilitation for these non-ductile buildings is important in order to minimize extensive loss and casualties during possible earthquakes.

Among various seismic retrofit methods, base isolation is being increasingly used to "isolate" the superstructure from the earthquake ground motion, which has unique advantages in greatly reducing both the deformation and acceleration of the superstructure. When applied to retrofit an existing building, the parts connecting the superstructure and the footings are generally removed and replaced by the base isolation system, whereas the superstructure needs little structural retrofit work [3,4]. This will induce minimal interruption for the superstructure occupancy and operation, which may also be an important advantage for stakeholders who must decide which retrofit method to select.

Many comparative studies have revealed that the responses of the isolated structure are significantly smaller than the fixed base structure [4–9]. Most of these studies compared the seismic demands (e.g. inter story drift, floor acceleration and base shear) for the two types of building structures, but only a limited number of studies investigated the seismic risk of isolated structures based on probabilistic methods to incorporate the seismic demands, structural capacity, and seismic hazard. Karim and Yamazaki [7] studied the seismic fragility of 30 isolated highway bridges that were designed to conform to Japanese seismic code. They found that when the pier height is low, the isolated highway bridges have a lower level of fragility than their fix-based counterparts; but when the pier height is high, the isolated highway bridges are more vulnerable than the fixed-base bridges. Zhang and Huo [8] investigated which parameters are the most important for optimum design of isolated highway bridges to achieve a minimum fragility. Their research indicated that the design parameters of isolation devices affect the fragilities of highway bridges most, and the optimal

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parameters are functions of the structural properties and damage states. The results also suggested that well designed isolated highway bridges have a lower vulnerability than fixed base bridges. Huang et al. [9] evaluated the performance of both a conventional and a base isolated nuclear power plant under seismic and blast loading and found that the isolation system can effectively reduce the probability of unacceptable performance for nuclear power plants. However, little investigation has been conducted for the seismic risk of building structures, which have dissimilar characteristics to those of highway bridges and nuclear plants.

Performance based earthquake engineering (PBEE) is a design philosophy that allows building stakeholders to work with the engineering team and decide what level of performance best suits their needs and budget constraints. Thus, with the target performance level of rehabilitation for a building essentially decided by its stakeholders, there may be interest in seismic risk rather than a single response quantity, if properly informed. Therefore, it is necessary to evaluate the performance of the un-retrofitted and base isolated building using probabilistic seismic risk assessment. However, due to the inherent uncertainty of earthquakes ground motions and structural systems, all sources of uncertainties must be carefully identified and incorporated into the procedure. The two categories of uncertainties, namely aleatoric and epistemic uncertainties, are both considered in this paper.

In addition to the more conventional earthquake uncertainties, such as magnitude, epicenter, spectral content and amplitude [10,11], the fact that earthquake aftershocks also introduce uncertainty into the seismic demand has been a recent focus [12–15]. The mainshock is usually followed by a number of aftershocks which may be severe and generally cause further damage to buildings [16,17], and can increase the seismic demand (deformation or acceleration) for a structure. Therefore, 32 recorded mainshock–aftershock (MS–AS) sequences are utilized in this paper to consider the effect of aftershocks. The traditional seismic risk evaluation using only mainshock records is also presented for comparison. Record-to-record uncertainty is also discussed.

Uncertainties in various fix-based structural systems have been extensively investigated. For example, Yin and Li [11] examined the effect of ten hysteresis parameters on the dispersion of collapse capacity of light-frame wood buildings. Vamvatsikos and Fragiadakis [18] conducted sensitivity research on steel structures to identify which parameters have the most significant impact on structural performance. Celik and Ellingwood [19] studied the influence of uncertainties in material properties, damping and beam–column joint model parameters on the seismic fragility of RC frame buildings. Uncertainties of isolated bridges have also been studied. For instance, Padgett and DesRoches [20] investigated the parameter sensitivity of structural response for a class of bridges with elastomeric isolators. Zhang and Huo [8] examined the influence of design parameters on system fragility and developed an optimal design method.

Nonetheless, there is a dearth of insightful investigations related to the uncertainties of isolated building systems. There have been several research studies that have made progress. For example, Taflanidis and Jia [21] proposed a framework for risk assessment and sensitivity analysis of base isolated buildings. However, the analysis was based on a simplified mathematical model to explain the framework, and the detailed structural properties and nonlinear behavior of the superstructure was not included in their procedure. In addition, factors such as temperature and ageing have considerable impact on the properties of isolation devices (elastomeric or slide bearing) [22,23] and consequently need to be carefully treated in the assessment.

In this paper, a typical mid-rise non-ductile RC frame building in Los Angeles, CA was selected and hypothetically retrofitted using base isolation with lead-rubber bearings (LRB). The un-retrofitted building and the base isolated building were then used in a comparative seismic risk analysis. Both aleatoric and epistemic uncertainties in demand and capacity were propagated through the full analyses. The differences in risk assessment from using MS–AS sequences and mainshocks alone are also discussed. The results found herein can provide insight into seismic risk assessment of base isolated buildings considering various sources of uncertainty, and offers risk-informed decision making tools for structural rehabilitation.

2. Structural models

2.1. The un-retrofitted building

The Van Nuys Holiday Inn [24,25] in Los Angeles, CA (34.22°N, 118.47°W), which is a 7-story concrete moment frame building, was selected for investigation in this study. The building was designed in 1965 per Los Angeles Building Code 64 and constructed in 1966, with design details associated with typical non-ductile older-type RC frame buildings. The site condition is site class D. A 3-bay frame in the transverse direction at the east end was extracted as a 2-dimensional structural model. The elevation, plan, and member cross-sectional views are presented in Fig. 1. The thickness of the slabs are 10 in. (254 mm) at the 2nd floor, 8.5 in. (216 mm) for the 3rd to 7th floor, and 8 in. (203 mm) for the roof. The cross-sectional dimensions of beams and columns are also presented in Fig. 1. The design yield stress of reinforcements in columns and beams are 60 ksi (414 MPa) and 40 ksi (276 MPa) respectively, whereas the nominal compressive strengths of concrete are 5 ksi (34.5 MPa) for columns at the 1st floor, 4 ksi (27.6 MPa) for columns and beams at the 2nd floor, and 3 ksi (20.7 MPa) for all other members. Details of the reinforcement layout can be found in existing literature [24,25].

The two-dimensional finite element model of the un-retrofitted frame was developed in OpenSees [26] which can consider the nonlinearities in both geometry and material. Using a two-dimensional model cannot account for out-of-plane behavior or torsional effects caused by earthquakes, but such a model is much less time consuming for analysis. In addition, for a regular RC frame building, adopting a two-dimensional model can yield sufficiently accurate results for both the un-retrofitted frame [1,2] and the isolated frame [5,39]. Furthermore, results of a 2-D model can be used to draw conclusion without interference from torsional action or bi-axial interaction. The beam–column joint model was simulated using the joint model proposed by Park and Mosalam for seismically vulnerable beam–column joints [25], with rigid beams and columns end within the panel zone and a nonlinear rotational spring. Fig. 2(a) shows the detailed joint model and the relationship between the normalized panel zone shear force (horizontal joint shear force over nominal joint shear strength V_{jh}/V_n) and the joint rotation. The beams and columns were modeled as Beam-With-Hinges elements [27], each of which consists of two fiber-sectioned plastic hinge zones at the ends of the element and a linear elastic zone in the middle of the element. The length of plastic hinge zone was estimated using the equation proposed by Panagiotakos and Fardis [28]. A stiffness reduction factor was applied on the elastic zones to account for the stiffness decrease due to cracking. The fundamental period of the model was estimated using the median values of the structural parameters and was 1.67 s, the same as the fundamental period of the model adopted by Park and Mosalam [25] for the same prototype building using the identical modeling method for beams, columns and joints.

At the fiber sections of the plastic hinge zones, the increase in compressive strength and ultimate strain of the confined concrete were calculated based on the results of the study by Saatcioglu and