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Performance limits of seismically isolated buildings under near-field earthquakes

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ABSTRACT

The mission of seismic isolation is two folds: (i) protecting the integrity and (ii) protecting the contents of a structure by reducing floor accelerations to target limits and concurrently keeping base displacements below practical and economical limits. To this end, while seismic isolation has proven to be successful under far-field earthquakes, its success in case of near-field earthquakes is being questioned for over a decade now; the main reason being the threat of excessive base displacements due to the presence of long period large velocity pulses. Lowering isolation period and increasing isolation damping aiming to reduce base displacements unfortunately may result in a reduced seismic performance in terms of floor accelerations particularly under far-field earthquakes. And the success level of such a precaution under near-field earthquakes depends both on the fault-distance and the pulse period to the isolation period ratio. Thus, the aim of this study is to evaluate the performance limits of buildings equipped with seismic isolation systems of different characteristics when subjected to near-field ground motions at different fault distances with different velocity pulse periods. Accordingly, a methodology for assessing the performance limit of a seismic isolation system design that explicitly considers the seismic actions on the contents of the superstructure in the near-field region is introduced. Benchmark buildings with base isolation systems of different isolation periods and characteristic force ratios are subjected to synthetically developed near-field earthquake records at different fault-distances with different velocity pulse periods and their seismic performances are reported.

1. Introduction

Major earthquakes can lead to loss of lives due to collapse of buildings resulting from lack of proper earthquake-resistant design. Loss of lives may be prevented in case the buildings are designed following the classical earthquake-resistant design methodology which primarily depends on ductile behavior mobilized during a major earthquake. This, however, inadvertently means that there may be structural damage due to the plastic hinge formations in structural members in addition to the non-structural damage in walls/windows due to the excessive interstory displacements. Even if an attempt is made to protect the integrity of the building by increasing the stiffness, this unfortunately may lead to the increase of floor accelerations which may successively result in damaging of the contents of the building. This may be a much bigger problem in mission-critical buildings such as hospitals, financial centers, and industrial facilities that house vibration-sensitive contents which play a vital role in sustaining daily life without disruption [1].

Seismic isolation has emerged as an alternative earthquake-resistant design method that has the potential of offering both the protection of the structural and non-structural components and the protection of the contents of a building. Thus, the goal of seismic isolation is set as reducing floor accelerations to target limits while keeping base displacements below practical and economical limits. This goal is achieved by (i) elongating the natural period of the building via use of laterally flexible isolation elements, (this reduces spectral accelerations and thus the effective seismic forces), (ii) allowing the superstructure to move flexibly on the isolation system (this provides rigid-body-motion that minimizes interstory drift ratios), and (iii) providing damping through the isolation elements (this helps dissipating the energy input from the earthquake and is particularly essential in limiting the base displacements).

Numerous research studies on seismic isolation have been conducted in the last several decades [2–16]. But there is an incontrovertible fact: A properly designed seismic isolation system

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effectively reduces floor accelerations and interstory drift ratios to acceptable levels without causing unacceptably large base displacements in case of *far field* earthquakes. The observed performances of seismically isolated buildings under real earthquakes further support this result: The roof acceleration and the peak story drift of the USC hospital building under the 1994 Northridge Earthquake were reduced to 50 and 30%, respectively [8]. The West Japan Postal Computer Center survived the 1995 Kobe earthquake without any damage [17].

Unlike the glorious success of seismically isolated buildings under far-field earthquakes, its success level in case of near-field pulse-like earthquakes is still being questioned. These earthquakes contain large-amplitude long-period velocity pulses whose periods may be close to or sometimes even coincident with those of seismically isolated buildings. Heaton et al. [18] pointed out to the possibility of excessive deformations to occur in the isolators of base isolated buildings if they were exposed to near-field earthquakes. Then, researchers reported other problems related to the same issue. In a probabilistic study, Alhan and Gavin [19] assessed the reliability of floor isolation systems for the protection of vibration sensitive equipment. They showed that it may not be able to offer a full protection for those housed in buildings which are located in the close vicinity of the fault. Later, it was shown by various researchers [14,20,21] that in addition to base displacement, floor accelerations may also increase in case seismically isolated structures are exposed to near-field earthquakes with pulse periods close to their isolation period. Excessive base displacements in case of a near-field earthquake may lead to the pounding of a seismically isolated building if the isolation system displacement exceeds the seismic gap left around it. And, Matsagar and Jangid [22] showed that such a pounding may cause significant increases in floor accelerations. Similarly, Taflanidis and Jia [23] performed the risk assessment of base isolated structures equipped with lead rubber bearings via a proposed simulation-based framework. They proved that the seismic risk is increased due to the possibility of excessive deformation of bearings exceeding the isolation gap depending on the pulse property of the near-field earthquake. Just recently, Mazza and Vulcano [24] and Mazza et al. [25] pointed out that the isolators may even undergo tensile loads when vertical components of near-field ground motions with high peak values are in question along with a possible failure of isolation system owing to high seismic displacement demands. Finally, Lu et al. [26] have evaluated sliding isolation systems experimentally and confirmed that when the isolation period is close to pulse period, it may cause resonance-like behavior.

On the solution side of the aforementioned problem, researchers turned to the use of high damping at the isolation system to reduce excessive base displacements. But, the proposed solution itself had the potential to cause other problems. Using a two degree of freedom model, Kelly [27] showed that use of additional damping would effectively reduce such excessive base displacements, but at the expense of possible increases in interstory drifts and floor accelerations. Later, Jangid and Kelly [28] reported a similar finding: although floor accelerations may be reduced using higher isolation damping up to a certain point, further increases in isolation damping may transmit higher accelerations into the superstructure in case of near-field earthquakes. More recently, Providakis [29] assessed the effects of near-field ground motions on the base-isolated buildings that are equipped with lead-rubber and friction pendulum bearings along with supplemental damping. It was shown that although use of supplemental damping reduces base displacement and limits floor accelerations up to a certain point in case of near-field earthquakes, it may result in increases of both inter-story drifts and floor accelerations specifically in case of far-field earthquakes. Mazza and Vulcano [14] confirmed that although supplemental damping is necessary for controlling the base displacements of seismically isolated buildings, it may not guarantee a better performance in terms of the structural and non-structural damage under near-field earthquakes. Furthermore, it may even produce unfavorable results for relatively short pulse periods. Alhan and Şahin [30] investigated the role of isolator characteristics in reducing the floor accelerations of seismically isolated buildings with flexible superstructures under near-field earthquakes. It is reported that higher isolation damping (i.e. characteristic force ratios) would reduce floor accelerations up to a certain point but further increases in isolation damping may result in higher floor accelerations.

These studies make it clear that an unlimited use of isolation damping is not feasible. And, it was shown by Hall [31] that use of an "optimum" amount of additional damping had the potential of reducing base displacements without increasing floor accelerations or interstory drifts. Later, in the context of a realistic 8-story benchmark building, Alhan and Gavin [32] confirmed that there exists an optimum combination of isolation stiffness and damping for reducing base displacements without significantly increasing floor accelerations, but only to certain levels. In another analytical study, Jangid [33] has investigated the seismic response of shear type multi-story buildings equipped with lead-rubber bearings under near-field effects and showed that there exist optimum characteristic force ratios (i.e. isolation damping) for the minimization of both the top floor accelerations and the base displacements under historical near-field ground motions. Most recently, Niğdeli et al. [34] proposed a harmony search optimization methodology for determining optimum isolation period and damping ratio for linear isolation systems to obtain the best seismic performance.

The studies cited above revealed that the seismically isolated buildings under near-field earthquakes may face large base displacements especially if the isolation period is close to the pulse period. They have shown that while use of high damping decreases base displacements, it may decrease floor accelerations only up to a certain point and any further increases in isolation damping may cause increases in the floor accelerations depending on the earthquake characteristics. However, a quantification of the performance limits of these structures at varying fault-distances in the near-field region by taking the demands and limitations concurrently into account is essential. Base displacement and floor acceleration *demands* would vary depending on the ratio of the isolation period to the pulse period of the earthquake, the isolation damping (i.e. the characteristic force ratios), and the amplitude of the velocity pulse which is related to the closest distance to the fault. On the other hand, these demands may not always be met as there exists practical and economical *limitations*. In order to examine this two-sided problem along with its all influencing parameters, in this study, a benchmark building equipped with seismic isolation systems of different isolation periods and characteristic force ratios are subjected to synthetically developed near-field earthquake records at different fault-distances with different velocity pulse periods and their seismic performance limits subject to different limitations on peak base displacements and peak floor accelerations are identified. Thereby, a methodology for assessing the performance limit of a seismic isolation system design that explicitly considers the seismic actions on the contents of the superstructure in the near-field region is introduced.

2. Structural model

In this study, 5-story seismically isolated benchmark buildings equipped with 12 different isolation systems are modeled [35]. The structural model, which is shown schematically in Fig. 1, consists of a shear-building type superstructure supported on a