MAPPING DEMAND PARAMETERS IN HIGH-FRICTION SLIDING ISOLATED HOUSES TO IDENTIFY REGIONS FOR IMPLEMENTATION IN THE WESTERN US

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ABSTRACT

Light-frame houses are susceptible to costly damage and displacement of residents from moderate to strong intensity earthquakes. This paper compares earthquake-induced deformations and accelerations in houses in conventional fixed-base construction to seismically-isolated houses under DBE and MCE\(_R\) ground motion intensities throughout the western United States. The isolation systems include both conventional low-friction and high-friction dish isolators, which have interesting performance tradeoffs. Regional maps of deformation and acceleration highlight the near-fault locales where the isolation systems are particularly effective at reducing the earthquake damage. Results show that isolated houses have significantly reduced deformation and acceleration demands compared to fixed-base structures. The high-friction sliding isolation systems are particularly effective in the very high seismic regions, where they offer the benefit of reduced demands with moderate isolator sliding displacements.

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Light-frame houses are susceptible to costly damage and displacement of residents from moderate to strong intensity earthquakes. This paper compares earthquake-induced deformations and accelerations in houses in conventional fixed-base construction to seismically-isolated houses under DBE and MCE ground motion intensities throughout the western United States. The isolation systems include both conventional low-friction and high-friction dish isolators, which have interesting performance tradeoffs. Regional maps of deformation and acceleration highlight the near-fault locales where the isolation systems are particularly effective at reducing the earthquake damage. Results show that isolated houses have significantly reduced deformation and acceleration demands compared to fixed-base structures. The high-friction sliding isolation systems are particularly effective in the very high seismic regions, where they offer the benefit of reduced demands with moderate isolator sliding displacements.

Introduction

While considerable attention is often given to major structural failures and building collapse due to major earthquakes, the most significant economic losses and disruption are often the result of widespread damage to light-frame residential houses. One strategy to improve the seismic performance of residential buildings for seismic events is sliding isolation. Tests have confirmed the ability of friction sliding bearings to improve the seismic performance of all types of structures. Full-scale tests of a unibody house on low-cost base isolators made from off-the-shelf parts at UC San Diego by Jampole et al. indicate that sliding isolation reduces deformation demands to below 0.1% story drift (well below the 0.15% threshold for expected damage) when the isolated house was subjected to fourteen MCE-level earthquake ground motions [2] [3].

This study demonstrates the viability of various sliding isolation solutions for use in light-frame structures in the western United States. Results estimate response parameters for four alternatives: fixed-base, conventional low-friction sliding isolation with a small dish radius

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(µ=0.05, R_{curve}=100 \text{ cm}), high-friction sliding isolation with a shallow dish radius (µ=0.20, R_{curve}=200 \text{ cm}), and high-friction sliding isolation on a flat surface (µ=0.20). Based on the regional seismicity, the maps highlight locations where sliding isolation can provide a significant improvement in performance for light-frame structures, providing building owners and developers a reference for initial seismic resistance planning.

**Numerical Model**

A conventional two-story light-frame home is modeled using OpenSees, based on an idealized three-dimensional pancake model (represented below in Fig. 1) [4] [5] [6]. The weight is lumped at each level: 75 kN at the base, 110 kN in the second floor, and 120 kN in the roof level, for a 305-kN total weight. The story heights are 2.4 meters with 3% stiffness-proportional damping in the superstructure. The model is calibrated to have a 0.2-second fixed-base period, and the ratio between second- and first-story stiffness (k_2/k_1) is 1.75.

![Figure 1. Schematic diagram of the OpenSees model and isolator hysteresis.](image)

A nonlinear material model was calibrated to simulate strength and stiffness deterioration in the superstructure. The ultimate lateral strength of the structure is assumed to be 1.1 times its weight. Assuming that the ratio of the yield to ultimate strength typically falls between 0.3 to 0.5 [7] [8] [9] [10], a yield strength ratio of 0.4, the mass, and the assumed structure period were used to determine the initial strength and stiffness. The OpenSEES Pinching4 material is calibrated to cyclic test data to capture the hysteretic response of a 2.4-meter wide oriented strand board (OSB) specimen subjected to the CUREE loading protocol [11] [12]. The hysteretic parameters of the single wall are scaled to represent the approximate hysteretic properties for a full structure with the given masses and assumed period = 0.2s, which results in an equivalent total length of 17 meters of one-sided OSB shear wall in the first story.

The isolators are modeled using an exponential velocity-dependent friction model [13]. The high friction sliding systems, consist of glass-filled PTFE (polytetrafluoroethylene) sliders on galvanized steel, which is assumed to have a nominal dynamic sliding friction at high sliding velocities (µ_{max}) equal to 0.2. This friction coefficient is based on tribology tests conducted by the authors and others [5] [14]. The conventional low-friction sliding isolators are assumed to have µ_{max} equal to 0.05. In both types of isolators, the coefficient of friction for a sliding velocity, µ_{min}, is half of the maximum friction coefficient, and the transition rate is 0.4 s/cm. Dish-type isolators have a restoring stiffness equal to the weight divided by the dish radius [15].
Ground Motion Selection

The “PEER Transportation Set 1a” broadband ground motion set was used for conducting incremental dynamic analyses (IDA) of the fixed-base and isolated house models to determine demand parameters under increasing seismicity [16]. The IDA was performed at scale factors from 0 to 5, incremented at 0.1.

Scale factors for ground motion record sets were computed for each building site following procedures in ASCE7-16 [17]. Gridded map data for spectral accelerations for short periods and one-second periods as found in 2015 NEHRP provided the basis for scaling results for each specific site [18]. Site classes were based on USGS mapped data for $V_{s30}$ values based on topographic slope correlated to measurements [19] [20]. Based on this data, the target spectra for the design base event (DBE) and the risk-targeted maximum considered event (MCE$_R$) were constructed. Scale factors for a single site vary based on the friction coefficients and radii of curvature, which affect the period range over which the maximum direction response spectrum is to be scaled to the target spectrum. The maximum direction spectrum was used for scaling both the fixed-base and isolated models to maintain consistency. Scale factors for the fixed-base model were computed by matching the maximum direction spectral ordinate to the target spectral ordinate at the fixed-base period of 0.2 sec; and the ordinates for the isolated structures were scaled over period ranges of about 1.5 sec to 2.5 sec. Fig. 2 demonstrates the two scaling methods.

![Scaling Methods](image)

(a) Scaling for fixed-base structure  
(b) Scaling for isolated structure

Figure 2. Record scaling example for Stanford, CA (37.4,-122.15, Zip Code: 94305).

Intensity Dependent Results

The peak isolation displacement is determined as the peak relative displacement from the origin during simultaneous bi-directional application of the ground motion. The story drift ratio (SDR) and floor accelerations are the peak in an individual direction because the walls provide resistance in each direction of application. Cases in which the SDR exceeds 10.0% are considered to represent structural collapse. The collapse cases are reported separately from the non-collapse cases, and are not included in statistics for the displacement and acceleration demand parameters.
Fig. 3 shows the hysteretic responses of the superstructure for a fixed-base model and a high-friction dish-isolated model, subject to the unscaled KJM ground motion recording from the 1995 Kobe Earthquake. The hysteresis of the fixed-base house in Fig. 3a demonstrates the pinching behavior of the OSB walls at large deformations. In Fig. 3b, the friction base isolator maintains elastic behavior in the super-structure, resulting in a straight-line hysteresis. Fig. 4 shows the corresponding relative base displacement histories of the isolated models. As indicated by the red plot in Fig. 4, the higher friction dish isolators have much smaller isolation displacement than the low-friction dish isolators or the flat isolator [3][5]. The added restoring stiffness from the concave dish reduces residual displacement compared to the flat system.

![Figure 3. Hysteretic response of first story of the numerical models subjected to KJM000.](image)

![Figure 4. Isolator plane displacement history of isolated structures subjected to KJM000.](image)
Incremental Dynamic Analyses Results

Following the incremental dynamic analyses, the key engineering demand parameters are compared to the scale factor applied to the ground motion record set. The resulting plots compare the performance of the four systems considered under earthquakes with similar occurrence rates.

Fig. 5 shows the mean peak isolator displacement ($\Delta_{\text{max}}$) as a function of ground motion intensity. The high-friction systems have significantly reduced peak displacements compared to the low-friction system. The peak displacements of the high-friction flat slider and dish slider systems are similar at lower intensities because the contribution of the restoring stiffness to the response of the high-friction dish system is minimal at small relative displacements compared to the contribution of the high-friction element. At higher intensities, the restoring element is a significant portion of the lateral resistance of both the high-friction and low-friction dish sliding systems. Compared to the flat sliding isolator, the restoring forces in the dish systems induce much larger forces in the superstructure, which in turn causes larger superstructure deformations. In some cases, the superstructure drift exceeds 10.0% which is considered to represent superstructure collapse. As shown in the upper plot of Fig. 5 the risk of superstructure collapse beings at ground motions of 0.8 to 1.2 times the MCE ground motion. Once collapses begin to occur, the isolator demands exhibit discontinuities as the collapse data is excluded from the calculated isolator demands. From a practical design standpoint, the risk of collapse is low (almost negligible) for ground motion intensities below MCE.

![Figure 5. The mean peak relative isolation displacement during a ground motion averaged for the set of 40 ground motions as a function of intensity. At increasing intensities, the risk of superstructure collapse (SDR > 10%) are shown in the upper plots; and the collapse data points are excluded from the isolator demand plots.](image)

Damage to structural and nonstructural components is reflected by the SDRs, shown for the first story in Fig. 6 as a function of intensity for the fixed-base and isolated systems. Horizontal
lines represent various damage levels: (a) hairline cracks at corners of walls and openings at 0.1%; (b) popped screws at edge of sheathing at 0.3%; (c) popped screws at interior of sheathing at 0.5%; and (d) large cracks through sheathing at 1.0% [21]. All the isolation systems significantly reduce the SDR (and thus damage) compared to the fixed-base structure. The high-friction dish isolator effective prevent all significant damage up to about MCE level ground motions (provided there is adequate displacement capacity in the isolator itself). The low-friction isolators commonly have lower radii of curvature, resulting in a large restoring force at large isolation displacements. The larger base forces can induce larger SDR, which can result in damage for ground motions above about 0.5 times the MCE ground motion.

![Graph showing probability of collapse and mean maximum story drift ratio](image)

Figure 6. The probability of collapse (upper plots) and mean maximum story drift ratio from non-collapse ground motions (lower plots) as a function of intensity.

Damage to building contents (e.g., tipping of furniture or equipment) is related to peak floor accelerations. The isolators offer a substantial advantage in this respect as well, especially at higher ground motion intensities. Fig. 7 shows that the low-friction dish isolator has lower floor accelerations at lower intensities. At these low intensities, sliding has initiated in the low-friction system but not the high-friction systems. At higher intensities, the greater restoring force in the low-friction dish with the small radius of curvature produces higher demands in the structure. The two models with high-friction systems experience very similar floor acceleration demands. This is concurrent with the response observed during the full-scale shake table test of a unibody house on sliding isolators [6].
Results from the IDAs are used to create performance maps for the western United States to highlight the regions that will most benefit from seismic isolation.

Fig. 8 shows that throughout most of the western US, high-friction dish isolators have lower relative isolation displacements than conventional low-friction high-restoring dish isolators. Because the expected base displacement is lower for high-friction isolators, the dishes could be smaller, leading to a lower cost of the isolation system almost everywhere.

In regions where the isolators have zero base displacement or very low base displacement during the MCE event, isolation is not needed because the earthquake intensity is below the sliding intensity. In regions where there is very low displacement in the high friction system, lower friction systems can still potentially improve the performance of light-frame structures compared to equivalent fixed-base structures. Fig. 9 shows that the majority of fixed-base homes in Washington, Oregon, and California are expected to experience damage during a design-level earthquake. The extent of damage in densely-populated areas of California represents a significant risk and carries heavy implications for the personal financial losses, displacement of homeowners, and community resilience. In contrast, only minor damage is expected in dish-isolated homes anywhere in the US, illustrated in Fig. 9b. Even in the areas with the highest seismic activity, high-friction dish isolators can reduce the damage to only small cracks during the DBE event.
Low-cost high-friction base isolators show a significant potential to affordably reduce earthquake risk throughout the western US, illustrated in Fig. 10. “Substantial benefit” in structural performance is seen where fixed-base structures are expected to have story drift ratios over 0.5% at DBE intensity, which is associated with popped screws at the interior of sheathing – requiring a substantial investment to repair. A flat or dish high-friction isolator can eliminate this expected damage. There is “benefit” to implementing the isolation system over a larger area where fixed-base structures would have hairline cracks at corners of walls, doors, and windows (SDR=0.15%).
at DBE intensity, which wouldn’t be seen with a high-friction dish isolated structure. In small areas (highlighted in red) structures isolated with high-friction dish isolators would still be expected to experience minor damage; however, the isolators have an even greater benefit compared to fixed-base houses in these areas because these are the regions with highest seismicity.

Figure 10. Locations in the Western US where light-frame structures benefit from implementing high-friction sliding isolation.

Conclusions

Damage to light-frame structures during earthquakes has significant implications on capital loss and community resilience. This study provides a valuable resource to support the merit of high-friction seismic isolation for light-frame structures.

These maps can be used to identify where residential light-frame construction would benefit from base isolation. The incremental dynamic analysis can be used to conduct performance-based engineering analysis to determine the expected loss and quantify the value of the isolation systems. Finally, this study could become the basis for a simplified design method for sliding isolation of homes. For example, response history analysis may not be required in the future; rather, a builder might select from several standard sliding isolators based on a home’s location on a map created for homes of similar size and construction.

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