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Nonstructural performance of seismically isolated structures in the near fault region

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Abstract. Seismic isolation is used worldwide to protect a myriad of structures from traditional use to industrial applications. Its success evolves from the use of rigid body motion reducing the demand on the structure especially in terms of drifts. Nonstructural damage refers to the loss of content of a structure including equipment and machinery that can be deemed necessary for facility operation. In many cases, this content is acceleration sensitive especially for machinery with fundamental frequencies above 2 Hz. Most work to date has focused on either nonstructural damage or isolated buildings with little known about the relationship between them. With this in mind, the study herein explores the performance of nonstructural content in seismically isolated structures in the near-fault region with vertical excitation. Using floor level time histories and response spectra, the presence of high frequency content is observed along with areas of decreased performance for the seismic isolation system. The results reinforce the complex relationship between the performance of nonstructural content, seismically isolated structures, and near-fault excitations.

Keywords: floor response spectra; near-field; seismic isolation

1. Introduction

Seismic risk associated with seismic isolation (base isolation) and nonstructural damage in essential facilities is a major concern for resilient seismic designs. Seismic isolation is one of the most important concepts in earthquake engineering to prevent and/or minimize damage to buildings during an earthquake. With a worldwide increase in seismically isolated essential facilities, it is necessary to assess and optimize nonstructural performance of such facilities, particularly since most work to date focused either on nonstructural damage or on isolated buildings. However, little is known about the relationship between them. Earthquake-based nonstructural damage refers to the loss of content of a structure, i.e., everything housed in the structure, including mechanical, electrical, and plumbing (MEP) systems as well as equipment and machinery used by the occupants. Essential facilities include hospitals, schools, air traffic control centers, and database centers to name only a few structures that rely heavily on their nonstructural content to meet post-earthquake performance needs.

The loss of nonstructural content is profound for a number of reasons: (i) Its economic impacts is substantial as it constitutes nearly 50-70% of the overall construction costs of new structures (Taghavi and Miranda 2003). (ii) It is one of the greatest threats to the resilience or recovery of a community. In fact, the economic loss of nonstructural content spans all three decision variables (DVs) associated with PBD (a.k.a. 3Ds): death, dollars, and downtime (Gunay and Mosalam 2012). Most nonstructural content, including equipment in essential facilities, is vibration-sensitive (Gordon 1991, Inaudi and Kelly 1993, Alhan and Gavin 2005, Gavin and Saicenco 2007, Ungar 2007, Ismail *et al*. 2009, Alhan and Sahin 2011). Vibrations arising from floor accelerations caused by earthquakes must be restricted to a specific level to ensure the continued operation of all equipment in an essential building (EQE 1994, Taghavi and Miranda 2003, Whittaker and Soong 2003, FEMA 2006, FEMA 2012, Filiatrault and Sullivan 2014). However, basic research on floor level response is sparse, and the available codes and guidelines are, for the most part, based on past experiences, and on judgment and intuition of engineers rather than on objective experimental and analytical results.

The objective of this research was to conduct dynamic analyses on a representative seismically isolated three story building for a distribution of near-fault motions to evaluate the performance of nonstructural content using floor level accelerations. Additionally, as the vertical component of motion is many times underrepresented in dynamic studies, this work emphasized the inclusion of this component of motion and the effect its presence on the floor level response. This study begins to close a critical gap in relating seismic hazard in the near-fault to seismic risks associated with nonstructural damage.

2. Background

2.1 Seismic isolation

Seismic isolation is one of the most popular means of

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protecting a structure against earthquake forces and has been used for over a century with the greatest progress made in the past 50 years. Seismic isolation relies on the introduction of a highly flexible layer between the structure and the ground increasing its fundamental period producing rigid body motion. Isolators integrate performance objectives into their design by restricting the response to ensure structural integrity (Kelly 1986, Buckle 1990, Naeim and Kelly 1999, Constantinou 2008, Sanchez *et al*. 2012, Warn and Ryan 2012, EPRI 2013, Wong 2014, Serror *et al*. 2015). However, although isolation reduces structural drift or the relative displacement of a structure's floors (Kelly 1996, Naeim and Kelly 1999), floor accelerations are still a topic of extensive debate as many studies do not address the vertical component of motion (Khechfe *et al*. 2002, Ismail *et al*. 2009, Kang *et al*. 2009). In addition, the use of supplemental damping through viscous damping has been the discussion of various studies including Wolff *et al*. (2014). This study explored the use of linear and nonlinear viscous dampers on a friction pendulum isolated structure via experimental testing. Although, damping is generally considered detrimental to a seismically isolated structure, this study did show that linear viscous damping could be implemented to reduce the drifts and forces. Wolff *et al*. did note that in their comparison of SAP2000 computational models, there were discrepancies in the predicted floor accelerations. Given this, this study explores the floor accelerations of an isolated system with elastomeric bearings without supplemental damping to create a baseline set of results from which comparisons could be drawn from for a damped system.

Recent studies reveal that the inclusion of vertical excitation is necessary to fully capture a structure's expected seismic risk. Ryan et. al. conducted a critically important study on a full-scale isolated structure on the E-Defense Shake Table in Japan (Ryan *et al*. 2012). Nonstructural damage and content disruption was clearly observed when a strong vertical motion was included. This study raised significant concern in industry as isolation was always believed to be the answer to increasing not only structural, but also nonstructural integrity. Based on this experimental work, seismic fragility curves were developed for unanchored nonstructural components (Pujols 2016). These fragility curves provide initial information on the ability to evaluate seismic risk demonstrating that a structure is sensitive to Peak Ground Velocity (PGV). However, these curves are limited to spectrally matched motions and do not fully explore the near-fault. Pujols and Ryan (2018) explored the vertical excitation of slabs in a hybrid isolated system that used cross-linked bearings along with traditional elastomeric bearings. In this experimental study, they observed increased slab amplifications over the building height with coupling of the horizontal and vertical response. This emphasizes the need to further explore the floor level response for isolated systems as is done in this study for the near-fault. In addition, Milanchian *et al*. (2017) evaluated various vertical seismic isolation systems in which one major conclusion was that a stiffer substructure was preferable. This has motivated this study to evaluate a relatively stiff isolation system.

Ryan's experimental study and the subsequent work identified serious gaps in the current knowledge on nonstructural damage, which form the strong basis for this work including limited availability of computational models and evaluation of results including vertical excitation. This paper begins to address these issues by utilizing a suite of real motions to develop isolation models producing an extensive amount and variation of data while addressing the impacts on the sensitivity of the design to the floor level responses.

2.2 Nonstructural content

Nonstructural content refers to everything housed in a structure, including mechanical, electrical, and plumbing (MEP) systems as well as equipment and machinery used by the occupants. The reports of the Federal Emergency Management Agency FEMA highlight the significant risks associated with earthquake damage to nonstructural components and the detrimental impacts to the structure's operation (FEMA 2006, 2012). The aftermath of recent earthquakes demonstrate that a facility may be structurally sound, but that the loss of nonstructural components may make it inoperable compromising its integrity. Records of nonstructural damage are extensive: the 1994 Northridge earthquake resulted in the loss of HVAC equipment in many buildings (EQE 1994) and nonstructural damage amounted to nearly $18.5 billion dollars, which accounted for nearly 50% of the economic loss from this event (Whittaker and Soong 2003). In the 1995 Hyogoken-Nanbu earthquake equipment from 44 different industries and plants was lost (Iwatsubo 1998). The 2008 Sichuan Earthquake severely damaged scientific equipment at the Southwest University of Science and Technology (Stone 2008). The Chilean earthquake in 2010 resulted in minimal structural damage, but the nonstructural damage was extensive and forced the closure of many facilities, which negatively affected the resilience and recovery efforts of the community (EERI 2010). In other seismic events, Foo and Lau (2004) noted that the delays in nonstructural damage led to challenges in the accessibility of buildings leading to an increase in casualties. Failure of nonstructural components has serious consequences: It threatens life safety, and causes property loss and interruption or loss of essential functions (Filitrault and Sullivan 2014). It may also result in direct and indirect injury or loss as a consequence of the components' failure.

Current U.S. codes present major challenges for engineers due to the simplified approach on the design of nonstructural components relying on designers to conduct independent advanced analyses without much guidance. As a result, some designers opt to increase stiffness or other structural parameters without closely examining the overall response. A major challenge is the simplification of nonstructural forces. Per ASCE 7, Section 13, Equation 13.3-1 (ASCE 2017), the horizontal seismic force is directly proportional to the height of the nonstructural component in the structure. This assumption is inherently wrong for isolated structures, as the story force is not linearly proportional to height due to rigid body motion. As a result, this code provision does not provide an accurate estimation by underestimating the lower story level forces. Even in the most recent update in the ASCE 7 [2017], this idealization is still present. In fact, this simplification of the story forces raises concerns even for fixed based structures as discussed by both researchers and practicing engineers (Singh *et al*. 1993, Villaverde 1996, Searer and Freeman 2002).

Current U.S. codes simplified major details in the design process potentially affecting the isolation performance. In ASCE 7, vertical motion is included through the use of a scalar multiplier. As discussed by Ahmad and Wong (2017), the code in many cases underestimates the response of an isolated system taking vertical motion into account. Although ASCE 7 does not provide guidance on isolation design, its previous version is still used by many entities requiring extensive peer review decreasing the attractiveness of the design for most clients. In the new version, ASCE 7-16, this requirement has changed. The amount of peer review required is reduced, which has advantages and disadvantages. Although it makes the system more attractive, it also reduces the amount of outside design advice an engineer will receive. However, such advice is crucial given the little guidance provided by standard provisions.

Kitayama and Constantinou (2019) examined the probability of damage for various structures isolated using triple friction pendulum bearings considering a design approach as prescribed by ASCE 7-16 (code minimum) as well as an enhanced criterion. This study concluded that the isolated structures still present a far lower probability of structural or non-structural damage even with the use of the new code minimum design approach compared to a non-isolated structure. These conclusions were drawn using various engineering design parameters including drift and peak floor accelerations. As this study established a strong analytical approach to this discussion, the study herein builds upon their work by expanding this research to elastomeric bearings, vertical excitations and the consideration of near-fault motions.

Codes such AASHTO (2014) provide a Simplified Method for isolation design. However, it has some limitations that are related to rigid body idealizations (Escalona and Wong 2018). With the reduction in the external review requirement, engineers will need reliable performance metrics to address a structure's needs and to meet clients' expectations for performance.

2.3 Near-fault motions

Near-fault motions are those in the region of 10 km or less from a fault. They are considered for this work for the following reasons: They are characterized by pulse-like excitations with long period motion and high ratios of peak ground velocity (PGV) to peak ground acceleration (PGA) and present a significant risk to long period structures, such as seismically isolated buildings (Berton *et al*. 2008, Cichowicz 2010, Archila *et al*. 2017). The PGA and PGV near 1 g and 1 m/s respectively for earthquake magnitudes greater than 7.0 (Johansen 2017) and pose a significant displacement demand on a structure, especially the foundation, causing great concern (Hall 1995).

Various studies of isolated structures in the near-fault region have been conducted. Jangid (2007) explored lead-rubber bearing performance and showed an ability to optimize the isolation system for near-fault performance. The study only discussed restricting performance to the isolation displacement, top floor accelerations, and using only the normal component of six near-fault motions in a numerical study. However, it set a precedence that horizontal floor acceleration optimization is possible through isolation system alterations. A follow-up study by Berton *et al*. (2008), took a step forward by using bi-direction near-fault ground motions, which however, reduced the structural system to a lumped mass atop the isolator. More recent studies included isolated structures in the near-fault region, but focused predominantly on isolator displacement (Ismail *et al*. 2013). Tajammolian *et al*. (2014) evaluated the use of friction pendulum bearings in the near-field with addition to high PGVs which emphasized their improved performance in longer period and higher PGV scenarios. Pavlidou and Komodromos (2020) studied the peak seismic response for near and far fault excitations with varying incident angles. Their study concluded that peak seismic responses in the near fault were higher. Prior studies mainly focused on the displacement of the isolated structure and did not closely examine the influence of the vertical component of motion or its impact on floor level responses (displacement, velocity, and acceleration). Understanding the relationship of elastomeric isolators and near field motions is imperative as the impact on nonstructural content needs to be better characterized. Through identifying the ways in which isolation influences these floor level responses for these isolators, engineers can better optimize designs and layouts to ensure continued performance of essential equipment/machinery. These considerations were taken into account in this study and are crucial for quantifying the risk to nonstructural components.

3. Model description

A representative 2D three-story, four-bay moment frame structure was used for the main structure of interest as shown in Fig. 1 (McCallen and Larsen 2003). The structure was designed to carry standard dead loads with a tributary weight of approximately 8452kN. The model was built and analyzed in OpenSees (McKenna and Fenves 2000). The structural system itself was designed to remain elastic with any nonlinearity to occur only in the isolation system. The structure or superstructure as it will be termed from here on had a fundamental period of 0.9 s with elemental loading applied versus lumped mass. The structure was assumed to have 5% damping assigned using Rayleigh damping anchored at the first and third modes.

The isolation system is comprised of five high damping elastomeric bearings, one under each column, modeled using OpenSee's elastomeric bearing element. These bearings were designed for a period of 3s elongating the superstructure's period by three times. The bearings had a lateral stiffness of 755 kN/m and vertical stiffness of 525 kN/mm providing a vertical fundamental frequency of 5 Hz

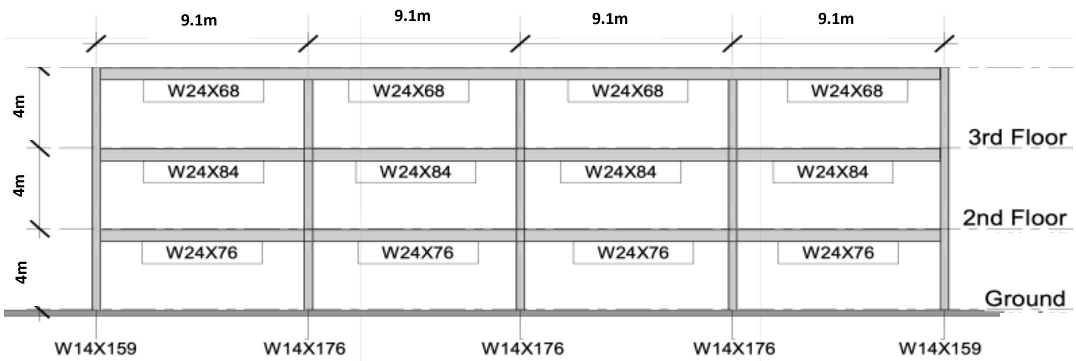

Fig. 1 Three-story steel moment frame

Table 1 Ground motions

Event	Station	Direction	PGA (g)	PGV (cm/s)	PGV/PGA (s)	PGD (cm)	Dist (Rjb) (km)
Chi-Chi	TCU068	FP	0.51	250	0.5	297	0
		FN	0.37	264	0.73	422	0
		V	0.53	213	0.41	223	0
Chi-Chi-	TCU075	FP	0.33	110	0.34	110	0.89
		FN	0.26	36	0.14	223	0.89
		V	0.23	51	0.23	223	0.89
Imperial Valley	El Centro Array #7	FP	0.34	52	0.16	28	0.56
		FN	0.47	113	0.25	47	0.56
		V	0.58	27	0.05	10	0.56
Kobe	Takatori	FP	0.62	121	0.2	40	1.46
		FN	0.67	123	0.19	30	1.46
		V	0.28	16	0.06	4.4	1.46
Kobe	KJMA	FP	0.83	91	0.11	21	0.94
		FN	0.63	76	0.12	18	0.94
		V	0.34	40	0.12	14	0.94
Northridge	Sylmar	FP	0.62	116	0.19	39	0
		FN	0.92	88	0.1	22	0
		V	0.61	26	0.04	8	0
Northridge	Rinaldi	FP	0.87	148	0.17	42	0
		FN	0.47	75	0.16	23	0
		V	0.96	42	0.04	3.7	0

(0.2 s). These bearings were designed for a maximum displacement of 18 inches. To avoid artificial viscous damping in the isolators, the OpenSee's element does not contribute to the Rayleigh damping automatically. As a result, 10% Rayleigh damping was applied again anchored to the isolated structure's first and third modes.

A suite of near-fault ground motions were used from the PEER database (Ancheta *et al*. 2013). Components of motion in the fault parallel (FP) and fault normal (FN) directions were used with the essential information shown in Table 1. This table provides pertinent information including peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD).

Using OpenSees, two types of analyses were conducted on the fixed base and isolated systems: 1) horizontal only (uniaxial) and 2) horizontal plus vertical motion (biaxial). The fixed base structures are used to create a basis for comparison. Additionally, the two components of horizontal motion are considered separately as traditional practice has predominantly used the fault normal component of motion only. The use of a 2D structure is a simplification to the larger dynamic problem. However, using this simplified system will allow for a systematic approach and provide foundational insight into the general changes and impact on response due to these near-fault motions and the inclusion of vertical excitation.

4. Results

The following sections summarize the results related to the uniaxial and biaxial results from two perspectives: time histories and floor response spectra (FRS). All of these results are taken at the floor level to provide the best insight into the potential hazard to nonstructural content. The time histories are initially presented to provide a basis for which we can understand how the changes in motion influence the results across the time series. The response spectra then give insight into the potential distribution in response for equipment. As their fundamental periods vary across a wide expanse, generally above 2 Hz, this response must be examined from a broader viewpoint.

Table 2 Peak horizontal floor accelerations (units: g) for fixed base structure - Uniaxial

Ground Motion	Parallel			Normal		
	1	2	3	1	2	3
Chi-Chi (68)	0.67	0.92	1.12	0.45	0.57	0.93
Chi-Chi (75)	0.40	0.37	0.61	0.24	0.26	0.36
El Centro	0.49	0.68	0.99	0.47	0.94	1.21
Kobe KJMA	1.09	1.68	2.51	0.75	1.43	2.41
Kobe Takatori	0.81	1.18	1.71	0.96	1.40	1.70
Northridge Rinaldi	1.17	2.07	2.77	0.89	1.05	1.35
Northridge Sylmar	0.93	1.47	2.34	1.19	1.35	2.16

Table 3 Peak horizontal floor accelerations (units: g) for isolated base structure - Uniaxial (Note: Floor 0 is the ground floor above the isolation system.)

Ground Motion	Parallel				Normal			
	0	1	2	3	0	1	2	3
Chi-Chi (68)	0.41	0.47	0.45	0.48	0.27	0.26	0.25	0.27
Chi-Chi (75)	0.26	0.30	0.32	0.33	0.16	0.15	0.14	0.16
El Centro	0.12	0.13	0.13	0.14	0.32	0.36	0.37	0.38
Kobe KJMA	0.45	0.21	0.14	0.30	0.26	0.17	0.15	0.21
Kobe Takatori	0.25	0.24	0.23	0.26	0.28	0.26	0.26	0.32
Northridge Rinaldi	0.28	0.19	0.19	0.28	0.19	0.16	0.16	0.20
Northridge Sylmar	0.30	0.37	0.38	0.40	0.22	0.12	0.15	0.21

4.1 Time histories - Uniaxial

Initially examining the fault parallel and normal results in Figs. 2 and 3, there is the clear presence of long period motion with the introduction of an isolated base. The isolation system is able to de-emphasize the presence of any pulse like behavior that the fixed base system would exhibit. However, the magnitude of the reduction of horizontal accelerations tends to be larger for higher PGA motions such as Northridge (Rinaldi and Sylmar) and Kobe (Takatori and KJMA) as can be observed in comparing Tables 2 and 3. These motions observe nearly a 75% decrease in accelerations for the isolated structure at the second floor compared to Chi-Chi (65, 78). Even though there is this minimal variation in response between the motions, the peak floor accelerations do not exceed 0.5 g which still presents a favorable condition for nonstructural content. The direction of the motion (fault normal versus parallel) did not play a significant role in presenting any sensitivities to the horizontal response of the structure.

From Figs. 4 and 5 as well as Tables 2 and 3, the differences in accelerations through the height of the structure are observed. As the results for fault normal and fault perpendicular have shown negligible difference, fault normal results are used for discussion. Two motions are selected for this section, Chi-Chi (75) and Northridge Sylmar, as they present two ends of the sphere of PGA, PGV and PGD for the motions considered. In the case of the fixed based system, there is the expected increase in floor accelerations as one moves up the structure with the increase nearly 100% with each floor for all motions. For the isolated system, there are some interesting results. For Chi-Chi, there is a nearly uniform set of accelerations observed through the entire height of the structure indicative of the rigid body behavior. The difference between the floor accelerations from one floor to next is less than a 25% increase. The accelerations are not significantly reduced compared to the fixed base case as mentioned previously. For Sylmar, the reduction in overall floor level accelerations is significant with the rigid body response producing negligible difference between the floors similar to Chi-Chi. However, the biggest difference between the uniaxial and biaxial results is the increased presence of high frequency content. This content is especially prevalent near the segments of the time series with significant excitation. For Chi-Chi this is between 5 s and 15 s while Sylmar's is between 5 s and 10 s. This pertubations in the time series seem to be minimal in relation to the overall behavior but this will be discussed in more detail in the FRS section. However, to get a more complete idea of the situation we must move into the discussion of biaxial motion. (Note, in terms of the vertical response, the uniaxial excitation produces zero vertical acceleration in the floors.)

4.2 Time histories - Biaxial

Although the use of Fault Normal motions is the common practice, it is important to consider how the presence of the vertical component of motion will influence the horizontal response. Figs. 6 and 7 present a very different horizontal response with the inclusion of the vertical component of motion. One of the most poignant differences between the uniaxial and biaxial results is the fact that the high frequency content in the isolated results is more prominent. In the Chi-Chi (65, 78) uniaxial results, this content was slightly noticeable in the time range of 5 to 15 seconds. With the vertical component added, very high frequency motion is introduced into the response of all the motions used. This high frequency content is visible not only in the areas of high excitation but throughout the entire time series. In addition, the benefit of the isolation layer has been diminished in many cases as can be observed in Tables

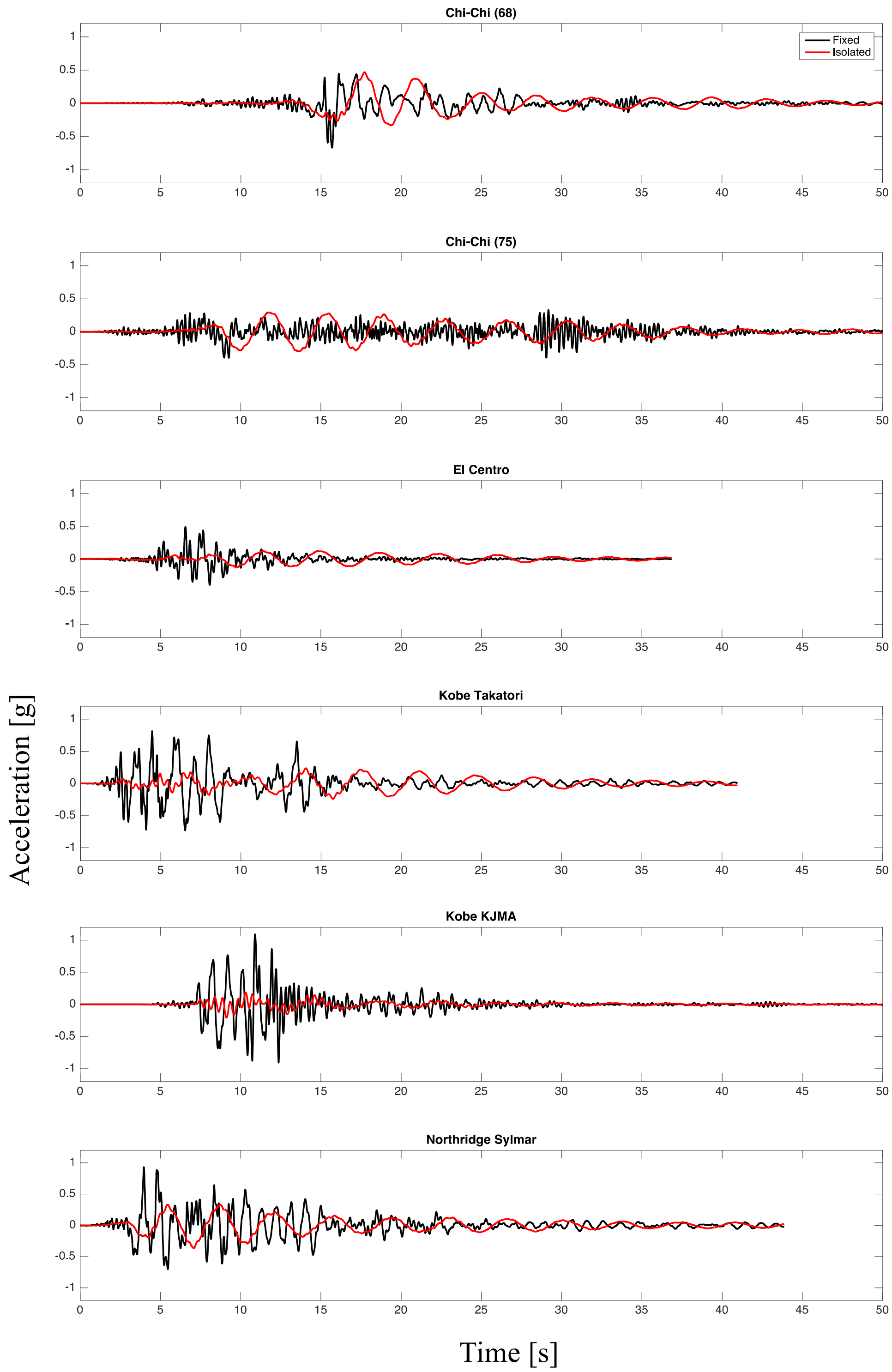

Fig. 2 Horizontal absolute acceleration time histories for fault parallel uniaxial ground motions at the 2nd floor

4 and 5. The general observed decrease in floor acceleration response through the building's height is no longer present with the inclusion of vertical motion. Certain floors observe increases while others have decreasing accelerations. Notably, the motions that fall in between the extremes of the motion characteristics still yield improvement in the floor performance.

Based on Figs. 8 and 9, the difference through the height of the structure can be observed. In the fixed based system, the accelerations increase 100% from the 2nd to 3rd floor with the increase to the 4th floor being far less substantial at around a 50% increase. In transitioning to the isolated system, the rigid body response is present given that the increase in floor acceleration between one floor to the next

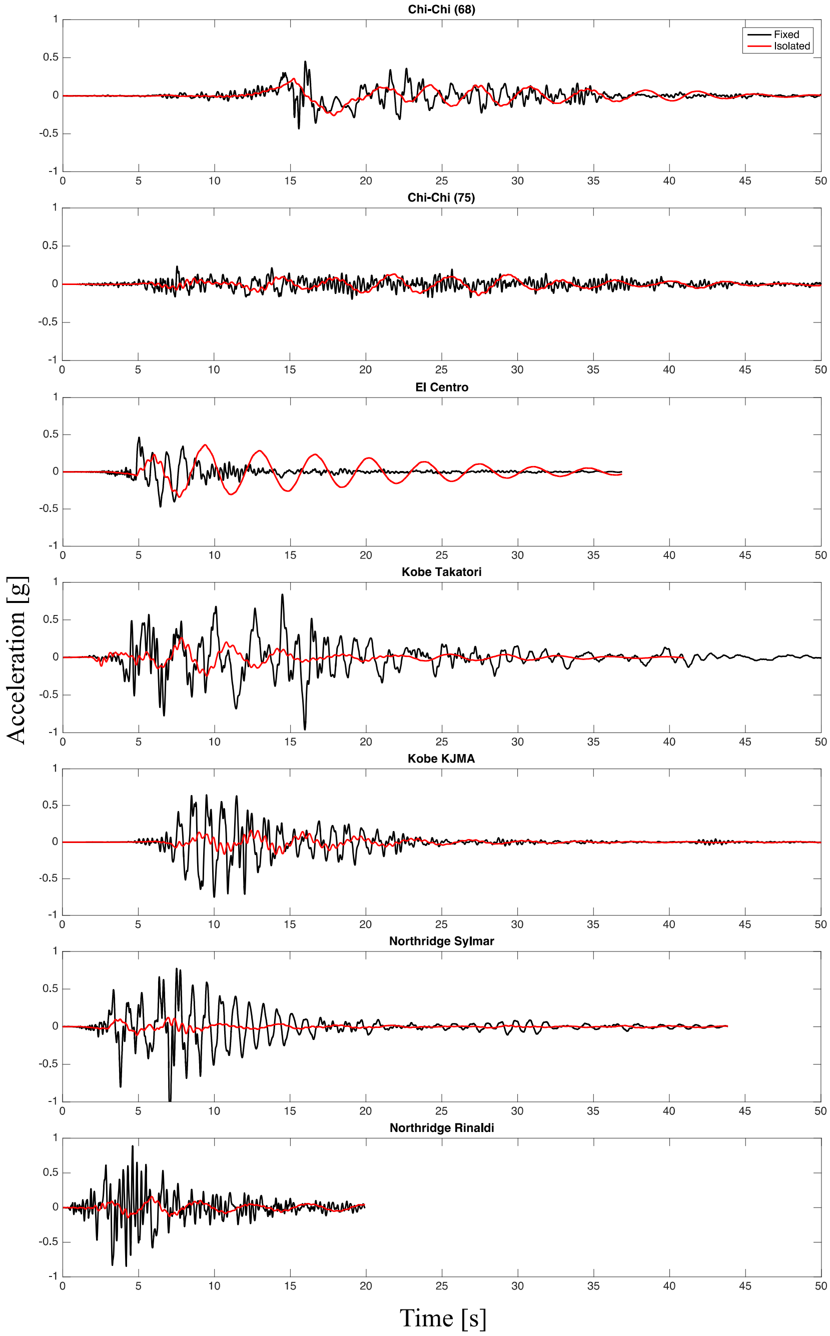

Fig. 3 Horizontal absolute acceleration time histories for fault normal uniaxial ground motions at the 2nd floor

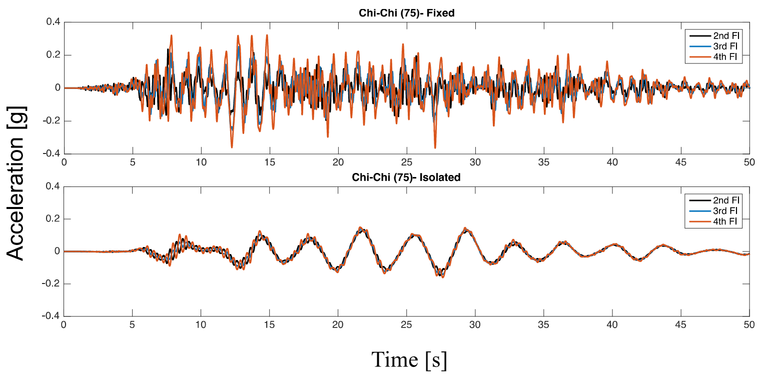

Fig. 4 Horizontal absolute acceleration time histories for Chi-Chi (75) fault normal uniaxial ground motions at all floors for the fixed (top) and isolated

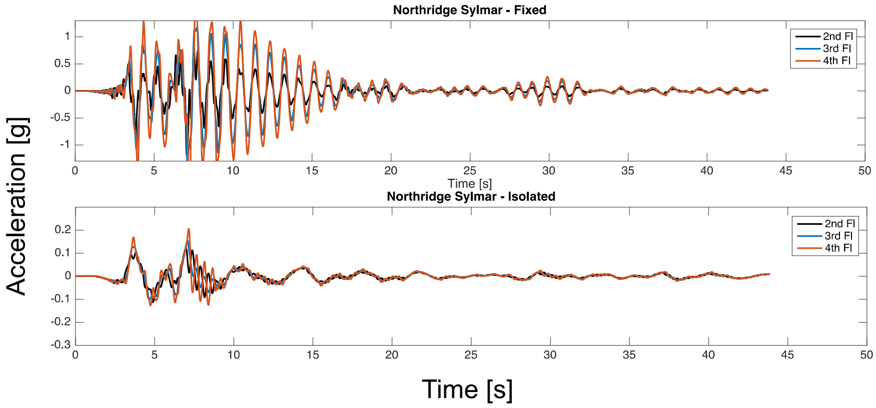

Fig. 5 Horizontal absolute acceleration time histories for northridge sylmar fault normal uniaxial ground motions at all floors for the fixed (top) and isolated

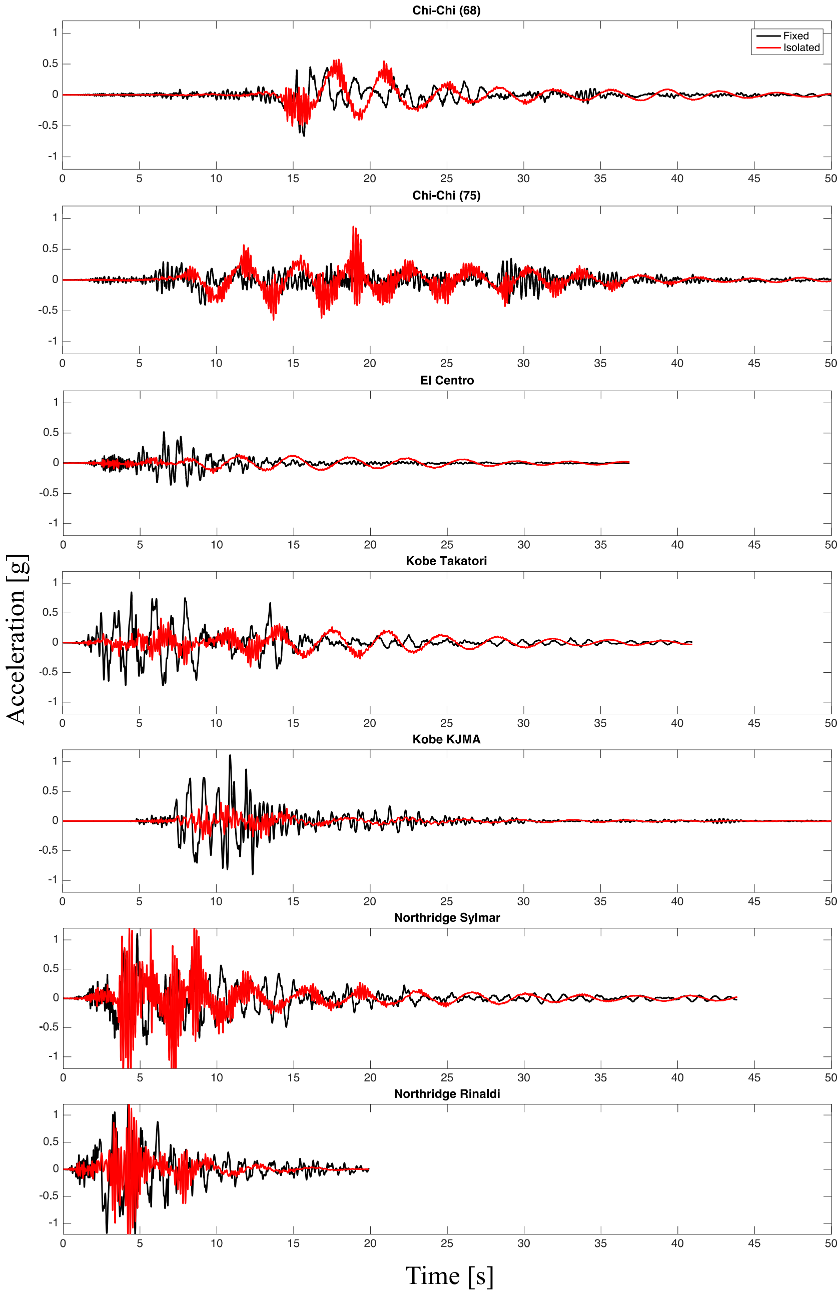

Fig. 6 Horizontal absolute acceleration time histories for fault parallel biaxial ground motions at the 2nd floor

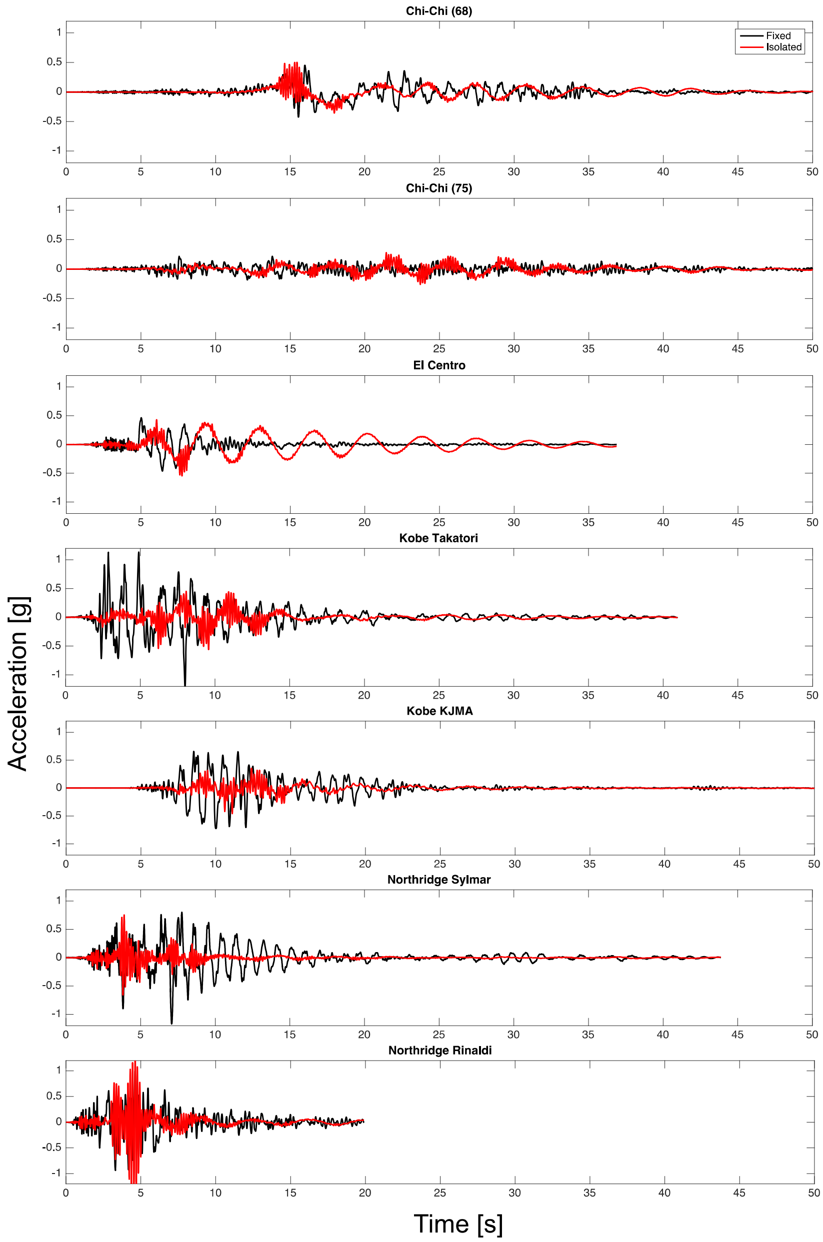

Fig. 7 Horizontal absolute acceleration time histories for fault normal biaxial ground motions at the 2nd floor

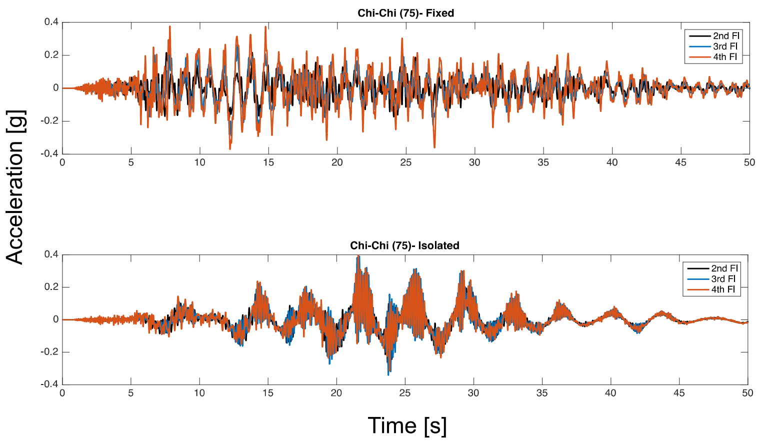

Fig. 8 Horizontal absolute acceleration time histories for Chi-Chi (75) fault normal biaxial ground motions at all floors for the fixed (top) and isolated

Table 4 Peak horizontal floor accelerations (units: g) for fixed base structure - Biaxial

Ground Motion	Parallel			Normal		
	1	2	3	1	2	3
Chi-Chi (68)	0.66	0.92	1.14	0.45	0.57	0.93
Chi-Chi (75)	0.41	0.36	0.63	0.22	0.29	0.38
El Centro	0.52	0.69	1.05	0.46	0.93	1.20
Kobe KJMA	1.11	1.80	2.48	0.73	1.47	2.30
Kobe Takatori	0.85	1.20	1.73	1.24	1.50	1.96
Northridge Rinaldi	1.21	2.04	2.87	1.00	1.10	1.77
Northridge Sylmar	1.10	1.65	2.77	1.17	1.39	2.30

Table 5 Peak horizontal floor accelerations (units: g) for isolated structure - Biaxial (Note: Floor 0 is the ground floor above the isolation system.)

Ground Motion	Parallel				Normal			
	0	1	2	3	0	1	2	3
Chi-Chi (68)	1.03	0.58	0.67	0.65	1.02	0.50	0.75	0.73
Chi-Chi (75)	1.53	0.87	1.41	1.31	0.58	0.28	0.39	0.41
El Centro	0.38	0.17	0.17	0.19	0.86	0.55	0.59	0.70
Kobe KJMA	0.79	0.31	0.36	0.50	1.06	0.46	0.61	0.65
Kobe Takatori	0.93	0.41	0.55	0.57	1.44	0.56	0.76	0.86
Northridge Rinaldi	3.50	1.40	1.51	1.22	4.26	1.37	1.96	1.66
Northridge Sylmar	3.96	1.59	2.21	2.08	1.92	0.76	1.31	1.19

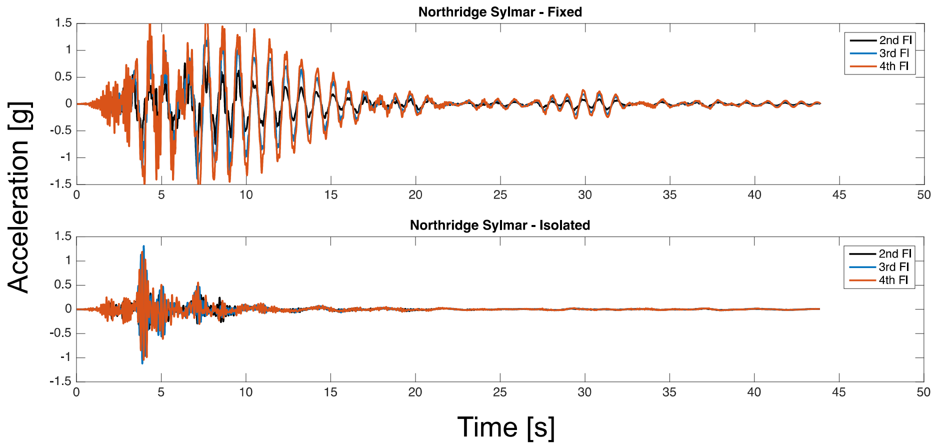

Fig. 9 Horizontal absolute acceleration time histories for northridge sylmar fault normal biaxial ground motions at all floors for the fixed (top) and isolated

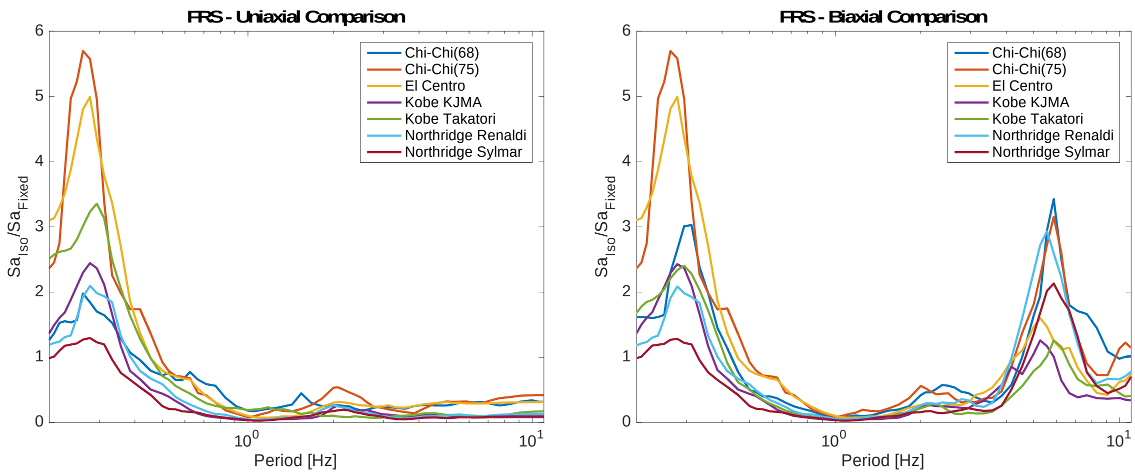

Fig. 10 Ratios of isolated to fixed based horizontal floor response spectra for uniaxial (left) and biaxial (right) fault normal motions at the roof level

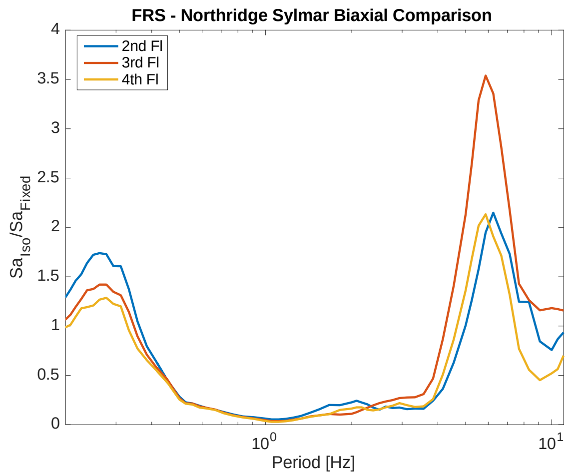

Fig. 11 Ratios of isolated to fixed based horizontal floor response spectra for northridge sylmar biaxial (right) fault normal motions at all levels

is incremental at most. With this respect, the isolation has effectively reduced the complexity of the response. Sylmar also exhibits a similar trend with the uniaxial concentrating the high frequency content around the early part of the time series where the excitation was strongest. In terms of the peak floor responses for the system, it was acknowledged that the lower PGA motions did not yield as significant of a decrease throughout the story height. However, looking at the Sylmar results, Fig. 8 presents a case where the significant decrease that was once observed in the uniaxial results no longer holds true. In this case, we have the isolated system seeing a significant peak near the 4s mark with the accelerations in the 4th floor (or roof) being reduced by only 20%. In addition to the changes in the magnitude of the motion and the frequency, there is a difference in the long period waveforms observed. Notably, Chi-Chi still presents longer period waveforms compared to the fixed base case. However, the Sylmar motion appears to nearly produce a more pulse like response with the excitation concentrated between 3 s and 10 s.

All of the trends observed in the time histories present interesting complexities to the typical isolation response. Changes alone in the peak floor acceleration cannot fully present the basis for the nonstructural performance. To understand how these nuances observed in these time histories will manifest in the performance of the nonstructural content, the next section will examine the floor level response spectra.

4.3 Floor response spectra

Fig. 10 presents the spectral results for the uniaxial and biaxial motions at the 4th floor or roof level. This level was selected as the accelerations tend to increase with height and typically house key equipment essential to HVAC systems as well as other machinery required for facility performance. In this Figure, the area in green (ratios less than one) represents the spectral accelerations from the isolated system that fall below the fixed based case. For the uniaxial plot, we have a large portion of the frequency range in the green. The spectral responses for all the motions tend to move into this increased performance for systems of a fundamental frequency greater than 0.3 Hz. Given that most equipment are in the frequency range above 2 Hz, this provides very promising results. When the vertical excitation is used, the spectra change. As seen in the right Figure, in the frequency range of 4.5 Hz to 6 Hz, the isolation system now experiences a segment of frequencies in which the isolation system does not provide improvement over the fixed base system. This can be attributed to resonance with the vertical mode's period of 5 Hz. Instead, there appears to be an optimal segment of frequencies for which the nonstructural content will experience the best performance.

Additionally, the distribution of the results in the areas performing below expectations (those outside the green regions) have significant distribution even though all these motions are generally characterized as near-fault. However, there is no clear trend in terms of any motion characteristic that corresponds to the level of acceleration observed in the FRS ratios. In the biaxial results, the secondary peak that occurs in the high frequency range do follow a slight trend of having higher ratios as the distance to the fault decreases. However, there is one outlier which is the Chi-Chi (75) motion which originates further away from other motions in the set. For this reason, no definitive relationship can yet be identified for means of optimizing or reducing down these ratios.

Although the biaxial spectra yield this secondary peak in response, the plateaued area suggests the ability to optimize the performance of the system. By identifying the fundamental frequencies of the nonstructural content, there is the opportunity to identify equipment suitable for this level. From Fig. 11, the variation in response through the height of the structure can be observed.

The response exhibits the presence of two peaks for all three levels of the structure. Thus, this feature is not characteristic of only a single floor. In examining the curvatures closes, the larger peak ratios occur for the higher frequency range rather than the lower frequency range. This suggests that potentially certain motions will result in reduced performance in either the low or high frequency zones. Additionally, the third floor presents the largest ratios while the second and fourth floors have nearly identical curvatures.

5. Conclusions

Seismically isolated structures in the near-fault region present a significant challenge to designers. With the focus mainly been on the need for displacement capacity, the subject of floor level response has typically been de-emphasized not only for the near-fault region but in general. Additionally, there is the secondary issue of the level of importance that vertical excitation is given in these analyses. With the lack of computational simulations exploring these topics, this study presents a foundation of work examining how near-fault motions considering vertical excitation can influence the performance of nonstructural content in seismically isolated structures.

From the time histories, several conclusions could be drawn. Firstly, the use of purely uniaxial motions does not provide the full depth of response in the horizontal direction for isolated systems. The vertical component of motion does influence the horizontal response in the form of increased frequency content. Additionally, the improvement in performance of the isolation system is reduced when the vertical component is included. The use of fault normal over fault parallel motions is confirmed as the results show negligible difference in the observed trends.

From the floor response spectra, the results reinforce the need to include the vertical component of motion. Using ratios of the spectral accelerations taken at the roof level, an area of improved performance was identified. This was the area in which the isolated results reduce the floor level accelerations below the fixed based response. In doing so, the uniaxial response only provided one overall peak in the floor level response. This occurred in the lower frequency range outside the concern for nonstructural content such as machinery. In the frequency range of interest, there was a positive result having the accelerations significantly decreased for all the input motions. However, this result then changed when we introduced the vertical component of motion. In this scenario, the overall maximum ratios did not change but it did introduce a secondary peak. In doing so, equipment that has fundamental frequencies between 4.5 Hz to 6 Hz would have mispredicted their performance if only a simple uniaxial study was conducted. The plateauing of the biaxial curve and the shift in peak from the low to high frequency range present a case for which optimization is possible. This type of information can help direct designers and clients to place essential equipment on floors that will accommodate their seismic demands.

Overall, there are several key conclusions to take away from this study. Firstly, the presence of vertical excitations do impact the horizontal response by introducing high frequency content into the response. The level of impact does vary depending upon the characteristics of the input motion with the most significant difference coming from increased PGAs. Secondly, to appropriately predict the response of nonstructural content in a seismically isolated structure, one must account for the vertical excitation. Without this component of motion, there is the possibility of underestimating the potential damage to that component given the inability of uniaxial motions to capture the full behavior of the system. Even with the use of currently available near-fault motions in the PEER database, there is a clear distribution in the response of the seismically isolated structure. The motions used in this study fall into the parameters of near-fault excitations but there are numerous variabilities accounting for PGA, PGV, PGD and the ratio PGV to PGA. Considering all of these components, there still did not present a strong relationship to the distribution observed in the floor response spectra ratios. Nevertheless, it did reinforce the fact that more information is needed to understand the potential differences outside of these key parameters influencing the floor level responses. This study effectively approached the topic of near-fault motions and explored the use of uniaxial/biaxial motions to better understand and evolve our understanding of nonstructural content.

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