Significance of Rotating Ground Motions on Behavior of Symmetric- and Asymmetric-Plan Structures: Part I. Single-Story Structures

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The California Building Code requires at least two ground motion components for the three-dimensional (3-D) response history analysis (RHA) of structures. For near-fault sites, these records should be rotated to fault-normal/fault-parallel (FN/FP) directions, and two RHA analyses should be performed separately. This approach is assumed to lead to two sets of responses that envelop the range of possible responses over all non-redundant rotation angles. This assumption is examined here using 3-D computer models of single-story structures having symmetric and asymmetric plans subjected to a suite of bi-directional earthquake ground motions. The influence that the rotation angle has on several engineering demand parameters is investigated in linear and non-linear domains to evaluate the use of the FN/FP directions, and the maximum direction (MD). The statistical evaluation suggests that RHAs should be conducted by rotating a set of records to the MD and FN/FP directions, and taking the maximum response values from these analyses as design values. [DOI: 10.1193/072012EQS241M]

INTRODUCTION

In the United States, both the International Building Code (ICBO 2015) and the California Building Code, CBC2013 (ICBO 2013), refer to ASCE/SEI 7-10 Chapter 16 (ASCE 2010) when response history analysis (RHA) is used for design validation of building structures. These guidelines require at least two horizontal ground motion components for three-dimensional (3-D) RHA. According to section 1615A.1.25 of the CBC2013, at sites within 5 km (3.1 miles) of the active fault that dominates the earthquake hazard, each pair of ground motion components shall be rotated to the fault-normal and fault-parallel (FN/FP) directions for 3-D RHAs. It is believed that the angle corresponding to the FN/FP directions will lead to the most critical structural response. This assumption is based on the fact that in the proximity of an active fault system, ground motions are significantly affected by the faulting mechanism, direction of rupture propagation relative to the site, and the possible static deformation of the ground surface associated with fling-step effects (Bray and Rodriguez-Marek 2004, Kalkan and Kunnath 2006), and these near-source effects cause most of the seismic energy from the rupture to arrive in a single coherent long-period
pulse of motion in the FN/FP directions (Mavroeidis and Papageorgiou 2003; Kalkan and Kunnath 2007, 2008). Thus, rotating ground motion pairs to FN/FP directions is assumed to be a conservative approach, appropriate for design verification of new building structures.

The provision for rotating ground motion records to FN/FP directions has been introduced in the most recent ASCE/SEI 7-10 (ASCE 2010) standards, which have additional changes incorporated in the new generation of the building codes. One of the changes is the use of maximum-direction (MD) ground motion, a revised definition of horizontal ground motions used for site-specific ground motion procedures for seismic design (Chapter 21 of ASCE/SEI 7-10). The MD, the direction of the rotated ground motion pair, leads to peak linear response quantity of a single lumped mass oscillator free to vibrate in both horizontal directions. The assumptions behind the MD ground motions are that the structural properties including stiffness and strength are identical in all directions, and the azimuth of the MD ground motion coincides with the structure’s principal axes (Singh et al. 2011). While the first assumption may be true for purely symmetric-plan structures (such as oil tanks, communication poles, elevated water tanks, guyed towers etc.), it may not be valid for other systems in which response is dominated by modes of vibration along specific axes. The second assumption, on the other hand, refers to ground motions with a lower probability of occurrence—it is very unlikely that ground motion incidence angle (angle of attack) with respect to the building’s transverse direction is same as the MD.

For linear single-degree-of-freedom (SDOF) systems, MD retains the characteristics of pulse-like motions and provides an upper bound (in the maximum direction) and a lower bound (in the minimum direction) spectral response (Zamora and Riddell 2011). In Chapter 21 of the ASCE/SEI 7-10, the concept of MD is used to develop a MD response spectrum to be used for seismic design. In the MD response spectrum, spectral ordinates at each period can be in a different orientation because the maximum motion varies with the period of the oscillator. Because of these issues, use of MD ground motions for seismic design is found to be controversial, and it is argued that it would result in 10% to 30% overestimation of design ground motion level (Stewart et al. 2011).

The idea of rotating ground motion pairs to certain axes, critical for response, is not new; it has been studied previously in various contexts. Penzien and Watabe (1974) defined the principal axis of a pair of ground motions as the angle or axis at which the two horizontal components are uncorrelated, and as being independent of the vibration period. It is also shown that the principal axis is not associated with the MD (Hong and Goda 2010). Using this idea of principal axes, the effects of seismic rotation angle—defined as the angle between the principal axes of the ground motion pair and the structural axes—have been comprehensively investigated (e.g., Fernandez-Davilla et al. 2000; MacRae and Matteis 2000; Tezcan and Alhan 2001; Khoshnoudian and Poursha 2004; Rigato and Medina 2007; Lagaros 2010; Zamora and Riddell 2011; Kalkan and Kwong 2012, 2014; Goda 2012). The previous studies demonstrate that the rotation angle of ground motions influences the structural response significantly and that the angle that yields the peak response over all possible non-redundant angles, called $\theta_{\text{critical}}$ (or $\theta_{\text{cr}}$), depends on the seismic excitation level and character of shaking.

A formula for deriving $\theta_{\text{cr}}$ was proposed by Wilson (1995). Other researchers have improved on the closed-form solution of Wilson (1995) by accounting for the statistical correlation of horizontal components of ground motion in an explicit way.
(Lopez and Torres 1997, Lopez et al. 2000). However, Wilson’s formula is based on concepts from response spectrum analysis—an approximate procedure used to estimate structural response in the linear domain. Focusing on linear multi-degree-of-freedom (MDOF) symmetric- and asymmetric-plan structures, Athanatopoulou (2005) investigated the effect of the rotation angle on structural response using RHAs, and provided formulas for determining the maximum response over all rotation angles given the linear response histories for two orthogonal orientations. The analysis results have shown that, for the records used, the critical value of an engineering-demand parameter (EDP) can be up to 80% larger than the usual response produced when the as-recorded ground motion components are applied along the structural axes. Athanatopoulou (2005) also concluded that the critical angle corresponding to peak response over all angles varies not only with the ground motion pair under consideration, but also with the response quantity of interest. These findings are confirmed in Kalkan and Kwong (2012, 2014) where the impacts of ground motion rotation angle including those corresponding to the FN/FP directions on several different EDPs are shown based on a linear 3-D computer model of a six-story instrumented building.

The previous studies investigated response behavior of either linear MDOF buildings or nonlinear response of single-degree-of-freedom (SDOF) systems subjected to two components of ground motion. Because there is still a lack of research addressing bi-directional nonlinear response of realistic MDOF systems considering ground motion directionality effects, this study systematically evaluates whether ground motions rotated to MD or FN/FP directions lead to conservative estimates of EDPs from RHAs. For this purpose, 3-D computer models of single-story structures having symmetric (torsionally stiff) and asymmetric (torsionally flexible) layouts are subjected to an ensemble of bi-directional near-fault ground motions with and without apparent velocity pulses. Also investigated are the rotation angle of an apparent velocity pulse, and its correlation with the MD and FN/FP directions. At the end, this study provides practical recommendations towards the use of MD and FN/FP directions to rotate ground motion records for RHA of building structures. The companion paper (Kalkan and Reyes 2015) presents further validations using 3-D computer models of nine-story structures having symmetric and asymmetric layouts subjected to the same ground motion set.

**GROUND MOTIONS SELECTED**

Thirty near-fault ground motion records selected for this investigation (listed in Table 1) were recorded from nine shallow crustal earthquakes compatible with the following hazard conditions:

- Moment magnitude: $M_w = 6.7 \pm 0.2$
- Closest fault distance from a site to co-seismic rupture plane: 0.1 km to 15 km
- National Earthquake Hazards Reduction Program (NEHRP) site class: C or D
- Highest usable period\(^\dagger\) $\geq 6$ s

\(^\dagger\)The term, conservative, is used here either peak or close to peak EDP values.

\(^\dagger\)Low-cut corner frequency of the Butterworth filter applied; because the highest usable period is greater than 6 sec, records in Table 1 have enough long period content to compute their spectra reliably up to 6 sec.
Because the number of ground motions recorded within 5 km of causative faults is limited
in ground motion databases, the distance limit is extended up to 15 km with the premise that
ground motions do not attenuate significantly within 15 km of rupture plane for the earth-
quake magnitude range considered (e.g., Campbell and Bozorgnia 2007, Segou and Kalkan
2011, Graizer and Kalkan 2015). These ground motions were rotated to fault-normal (FN)
and fault-parallel (FP) orientations using the following transformation equations:

\[ \vec{u}_{FP} = \vec{u}_1 \cos(\beta_1) + \vec{u}_2 \cos(\beta_2) \]  

\[ \vec{u}_{FN} = \vec{u}_1 \sin(\beta_1) + \vec{u}_2 \sin(\beta_2) \]

<table>
<thead>
<tr>
<th>Record sequence number</th>
<th>Earthquake name</th>
<th>Earthquake magnitude ((M_w))</th>
<th>Style of Faulting</th>
<th>Closest fault distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gazli, USSR</td>
<td>6.8</td>
<td>Thrust</td>
<td>5.5</td>
</tr>
<tr>
<td>2</td>
<td>Imperial Valley-06 1979 Aeropuerto Mexicali</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Imperial Valley-06 1979 Agrarias</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>0.7</td>
</tr>
<tr>
<td>4</td>
<td>Imperial Valley-06 1979 Bonds Corner</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>Imperial Valley-06 1979 EC Meloland Overpass FF</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>Imperial Valley-06 1979 El Centro Array #6</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>1.4</td>
</tr>
<tr>
<td>7</td>
<td>Imperial Valley-06 1979 El Centro Array #7</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>0.6</td>
</tr>
<tr>
<td>8</td>
<td>Irpinia, Italy-01 1980 Auletta</td>
<td>6.9</td>
<td>Normal</td>
<td>9.6</td>
</tr>
<tr>
<td>9</td>
<td>Irpinia, Italy-01 1980 Bagnoli Irpinio</td>
<td>6.9</td>
<td>Normal</td>
<td>8.2</td>
</tr>
<tr>
<td>10</td>
<td>Irpinia, Italy-01 1980 Sturro</td>
<td>6.9</td>
<td>Normal</td>
<td>10.8</td>
</tr>
<tr>
<td>11</td>
<td>Nahanni, Canada 1985 Site 1</td>
<td>6.8</td>
<td>Thrust</td>
<td>9.6</td>
</tr>
<tr>
<td>12</td>
<td>Nahanni, Canada 1985 Site 2</td>
<td>6.8</td>
<td>Thrust</td>
<td>4.9</td>
</tr>
<tr>
<td>13</td>
<td>Nahanni, Canada 1985 Site 3</td>
<td>6.8</td>
<td>Thrust</td>
<td>5.3</td>
</tr>
<tr>
<td>14</td>
<td>Superstition Hills-02 1987 Parachute Test Site</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>1.0</td>
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<tr>
<td>15</td>
<td>Superstition Hills-02 1987 Westmorland Fire Sta</td>
<td>6.5</td>
<td>Strike-slip</td>
<td>13.0</td>
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<tr>
<td>16</td>
<td>Loma Prieta 1989 BRAN</td>
<td>6.9</td>
<td>Reverse</td>
<td>10.7</td>
</tr>
<tr>
<td>17</td>
<td>Loma Prieta 1989 Gilroy Array #3</td>
<td>6.9</td>
<td>Reverse</td>
<td>12.8</td>
</tr>
<tr>
<td>18</td>
<td>Loma Prieta 1989 LGPC</td>
<td>6.9</td>
<td>Reverse</td>
<td>3.9</td>
</tr>
<tr>
<td>19</td>
<td>Loma Prieta 1989 San Jose – St. Teresa Hills</td>
<td>6.9</td>
<td>Reverse</td>
<td>14.7</td>
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<td>20</td>
<td>Loma Prieta 1989 Saratoga – Aloha Ave</td>
<td>6.9</td>
<td>Reverse</td>
<td>8.5</td>
</tr>
<tr>
<td>21</td>
<td>Loma Prieta 1989 Saratoga – W Valley Coll.</td>
<td>6.9</td>
<td>Reverse</td>
<td>9.3</td>
</tr>
<tr>
<td>22</td>
<td>Erzincan, Turkey 1992 Erzincan</td>
<td>6.7</td>
<td>Strike-slip</td>
<td>4.4</td>
</tr>
<tr>
<td>23</td>
<td>Northridge-01 1994 Jensen Filter Plant Gen.</td>
<td>6.7</td>
<td>Reverse</td>
<td>5.4</td>
</tr>
<tr>
<td>24</td>
<td>Northridge-01 1994 Newhall – Fire Sta</td>
<td>6.7</td>
<td>Reverse</td>
<td>5.9</td>
</tr>
<tr>
<td>26</td>
<td>Northridge-01 1994 Pacoima Dam (downstr)</td>
<td>6.7</td>
<td>Reverse</td>
<td>7.0</td>
</tr>
<tr>
<td>27</td>
<td>Northridge-01 1994 Rinaldi Receiving Sta</td>
<td>6.7</td>
<td>Reverse</td>
<td>6.5</td>
</tr>
<tr>
<td>28</td>
<td>Northridge-01 1994 Sylmar – Olive V. Med FF</td>
<td>6.7</td>
<td>Reverse</td>
<td>5.3</td>
</tr>
<tr>
<td>29</td>
<td>Kobe, Japan 1995 KIMA</td>
<td>6.9</td>
<td>Reverse</td>
<td>1.0</td>
</tr>
<tr>
<td>30</td>
<td>Kobe, Japan 1995 Nishi-Akashi</td>
<td>6.9</td>
<td>Reverse</td>
<td>7.1</td>
</tr>
</tbody>
</table>
where $\beta_1 = \alpha_{\text{strike}} - \alpha_1, \beta_2 = \alpha_{\text{strike}} - \alpha_2, \alpha_{\text{strike}}$ is the strike of the fault, and $\alpha_1$ and $\alpha_2$ are the azimuths of the instrument axes, as shown in Figure 1a. The geometric mean or median\(^\dagger\) of 30 FN records is taken as the target spectrum for the design of single-story symmetric and asymmetric structures to be used in a parametric study. The ground motions (acceleration time series) were additionally rotated $\theta_x$ away from the FP axis, as shown in Figure 1b. The angle $\theta_x$ varies from 5° to 360° at every 5° in the counterclockwise direction. These rotations were conducted using Equations 1 and 2, with $\beta_1$ and $\beta_2$ redefined as $\beta_1 = \alpha_{\text{strike}} - \alpha_1 - \theta_x$ and $\beta_2 = \alpha_{\text{strike}} - \alpha_2 - \theta_y$. The x- and y-axes, as well as the angles $\theta_x$ and $\theta_y$, are shown in Figure 1b.

Figure 2 shows the response of a two-degrees-of-freedom system with equal stiffness and damping ratio in the x- and y-axes subjected to the FN/FP components of a ground motion ($\theta_x = 0$). The maximum deformation of this system occurs at an angle $\theta_m$ rotated counterclockwise from the FP axis. As mentioned above, this orientation is called maximum-direction. The maximum radial deformation in Figure 2 could also be obtained by analyzing a SDOF system subjected to only the MD rotated ground motion.

For 30 near-fault ground motion pairs, Figure 3 shows the polar plots of spectral acceleration values as a function of the rotation angle $\theta_x$, for elastic SDOF systems with vibration period ($T_n$) equal to 0.2 s, 1 s, 2 s, 3 s, and 5 s. Each dot (color coded according to distance from fault rupture) indicates $\theta_m$ of the MD ground motion pair and corresponding linear response of the SDOF system ($A_m$). In each polar plot, there are 30 dots (purple, black, and green). We took the median of the response values from 30 MD ground motion

\(^\dagger\)Because we assume that the data is log-normally distributed, the geometric mean and the median are the same.
pairs; this median value is the radius of the blue circle and blue dashed circles representing the 16th and 84th percentile. Similarly, the red curves represent the median spectral acceleration value ± one standard deviation (\( \sigma_n \)). Spectral accelerations are scaled to the number labeled on the upper-right corner of each plot; this number is the radius of the largest circle. Except for short period system (\( T_n = 0.2 \) s), median spectral acceleration values (red curves) tend to be polarized with the fault-normal (\( \theta_x = 90^\circ \)) direction.

Studies of ground motion directionality have shown that the azimuth of the MD ground motion is arbitrary for fault distances larger than approximately 3–5 km (Campbell and Bozorgnia 2007, Watson-Lamprey and Boore 2007). At closer fault distances (closer than 3–5 km), however, the azimuth of the maximum-direction motion tends to align with the strike-normal direction (Watson-Lamprey and Boore 2007, Huang et al. 2008). In contrast, \( \theta_m \) (purple dots corresponding to those MD records within 5 km of fault rupture) in Figure 3 clearly shows large scattering with no visible correlation with the FN direction.

It should be also noted that spectral acceleration values, \( A_m \), corresponding to the maximum-direction angle, \( \theta_m \), are generally higher than the median spectral acceleration value \( A_n \).

**POLARIZATION OF VELOCITY PULSES WITH FAULT-NORMAL/FAULT-PARALLEL AND MAXIMUM DIRECTIONS**

Baker (2007) developed a numerical procedure to identify and characterize velocity pulses for ground motion records. This procedure was used here to identify velocity pulses in rotated motions at each rotation angle \( \theta_x \). Figure 4 shows polar plots of identified velocity-pulse periods and spectral accelerations as a function of \( \theta_x \) for the records that contain velocity pulses. In these plots, the red dots indicate pulse periods scaled in polar coordinates and
the directions in which the velocity pulses are identified. The filled gray area shows ranges of
θx with velocity pulses. The dashed blue curves show spectral accelerations computed for a
SDOF system with Tn equal to the maximum pulse period of the ground motion (GM) at a
5% damping ratio (e.g., dashed blue curves for GM1 correspond to spectral accelerations
computed for a SDOF system with Tn = 4.9 s). The blue line identifies the maximum-
direction angle θm. The numerical values for maximum pulse periods and maximum spectral
accelerations are presented in the upper right corner of each sub-plot. This figure presents
important findings. For example, polar plot for the GM1 (left upper corner in Figure 4)
indicates that the apparent velocity pulses are identified for θx in between 40°–80° and
130°–170°, and the pulse disappears at other angles including 90° (fault-normal direction).
For this record, the maximum-direction angle, θm, is computed at 45° and 135° in which the
velocity pulse is also identified. Lastly, a maximum spectral acceleration of 0.2 g is observed.

Figure 3. For 30 near-fault ground motion pairs, polar plots of spectral accelerations as a func-
tion of the rotation angle θx are shown for linear SDOF systems with vibration period (Tn) equal
to 0.2 s, 1 s, 2 s, 3 s, and 5 s (damping ratio 5%). The red curves represent the median spectral
acceleration value (An) ± σn (solid line is for median, and dash lines are for 16th and 84th per-
centile; log-normal distribution is used). The purple, black and green points (color distinguished
based on closest fault distance) correspond to pairs of maximum-direction angle θm and spectral
acceleration values Am. The blue circles represent the median spectral acceleration value ±σm in
the maximum direction. Note that except for short period SDOF system (Tn = 0.2 s), An values
are generally polarized with fault-normal (90°) direction; on the contrary, θm shows large scatter-
ing with no correlation with fault-normal (90°) direction.

<table>
<thead>
<tr>
<th>Tn (s)</th>
<th>Median An ± σn</th>
<th>Median Am ± σm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2g</td>
<td>0.2g</td>
</tr>
<tr>
<td>1</td>
<td>1.0g</td>
<td>0.6g</td>
</tr>
<tr>
<td>2</td>
<td>0.4g</td>
<td>0.1g</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
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</tr>
</tbody>
</table>

Note: Except for short period SDOF system (Tn = 0.2 s), Am values are generally polarized with fault-normal (90°) direction; on the contrary, θm shows large scattering with no correlation with fault-normal (90°) direction.
Figure 4. Polar plots of identified velocity-pulse periods and spectral accelerations (damping ratio 5%) as a function of the rotation angle $\theta_x$ for 22 ground motion (GM) pairs. The red dots show the directions in which velocity pulses are identified with their corresponding pulse periods. The filled gray area shows range of $\theta_x$ with velocity pulses. The dashed blue curves show spectral acceleration values for the maximum identified pulse period. The blue solid line identifies the maximum direction. Numerical values for maximum pulse periods and maximum spectral accelerations are presented in the upper right corner of each sub-plot.
at $\theta_m$. In the FN direction, the maximum spectral acceleration is decreased by 30% and equals 0.14 g. Examinations of polar plots of all records permit the following observations:

1. The velocity pulses are identified for 22 out of 30 records (approximately 75% of the complete set of records). Seven records with velocity pulses identified at some rotation angles have no pulses in the FN direction (within $\pm 2.5^\circ$ of 90°), indicating that the FN direction does not always have an apparent velocity pulse, as also demonstrated by Zamora and Riddell (2011).

2. For almost all ground motion pairs, the maximum-direction angle, $\theta_m$, is in the range of directions that the velocity pulses are identified. This strong correlation shows that the maximum spectral acceleration almost always occurs in the direction at which the velocity pulse is observed.

3. FN direction and MD angle $\theta_m$ coincide (within $\pm 5^\circ$) for 9 records out of 22 records having velocity pulses (approximately 40% of records with velocity pulses), indicating that approximately 60% of the time, maximum spectral acceleration takes place in directions other than the FN direction for those records with apparent velocity pulses.

4. For a given ground motion pair, the rotation angle $\theta_x$ may alter the maximum pulse period significantly (for example GM6), showing that the pulse period of rotated components varies with $\theta_x$.

**DESCRIPTION OF STRUCTURAL SYSTEMS AND COMPUTER MODELS**

The structural systems selected for this investigation are 30 single-story buildings with three-degrees-of-freedom. Their vibration periods $T_n$ are equal to 0.2 s, 1 s, 2 s, 3 s, and 5 s. The yield strength reduction factors $R$ are equal to 3, 5, and a value that leads to linear design (i.e., $R = 1.0$ for the strongest ground motion in the dataset; $R < 1.0$ for rest of the records).

The lateral load–resisting system of the buildings consists of buckling-restrained braces (BRBs) with non-moment-resisting beam-column connections. The plan shapes and bracing layouts are shown in Figure 5. The buildings are identified by the letters A and B depending on the plan shape; plan A is rectangular with two axes of symmetry (torsionally stiff), while plan B is asymmetric (torsionally flexible) about both $x$- and $y$-axes. The design spectrum was taken as the geometric mean (median) of the 5% damped spectral acceleration response spectra of the FN components of the 30 records. The earthquake design forces were determined by bi-directional linear response spectrum analysis of the building, with the design spectrum reduced by a response modification factor $R$. The constitutive model used for the BRBs is the simplified trilinear model shown in Figure 6. This model was obtained based on experimental results (Merritt et al. 2003). The parameters, $k$ and $q_y$, are the same for all BRBs of a building. Plots of mode shapes and effective modal masses presented in Reyes and Kalkan (2012) permit the following observations: (1) Lateral displacements dominate motion of the A-plan (symmetric-plan) buildings in modes 1 and 2, whereas torsion dominates motion in the third mode. This indicates weak coupling between lateral and torsional components of motion. Additionally, the period of the dominantly torsional mode is much shorter than the period of the dominantly lateral modes, a property representative of buildings with lateral load–resisting systems located along the perimeter of the plan. (2) Coupled lateral-torsional motions occur in the first and third modes of the plan B (asymmetric-plan) buildings, whereas
Plan A: torsionally-stiff buildings

Plan B: torsionally-flexible buildings

**Figure 5.** Schematic isometric and plan views of the selected single-story structural systems with three-degrees-of-freedom noted; BRBs are highlighted as b1…4.

**Figure 6.** Constitutive model used for BRBs.
lateral displacements dominate motion in the second mode; according to the ASCE/SEI 7-10 (ASCE 2010), plan B presents an extreme torsional irregularity. (3) The higher-mode contributions to response are expected to be significant for the plan B buildings because the effective mass of the first lateral modes is less than 40% of the total mass.

EVALUATION METHODOLOGY

The following steps were implemented for evaluating the significance of the ground motion rotation angle on linear and nonlinear response behavior of single-story buildings with symmetric and asymmetric plans located in near-fault sites:

1. For each of the 30 ground motion records selected, calculate rotated ground motion components by varying $\theta_x$ from 0° to 360° at every 5° in the clockwise direction (Figure 1b). In addition, calculate rotated ground motion components for $\theta_x = \theta_m$ and $\theta_x = \theta_m + 90°$ as explained earlier.
2. Calculate the 5% damped response spectrum $A(T)$ for the FN component of the 30 records at 300 logarithmically spaced periods $T$ over the period range from 0.001 s to 6 s.
3. Implement an iterative procedure for designing the 30 single-story systems described previously using the median spectrum of 30 FN components of Step 2, as the design spectrum. At the end of this step, values for parameters $k$ and $q_y$ are obtained for each BRB. Recall that the single-story systems have vibration periods $T_n$ equal to 0.2 s, 1 s, 2 s, 3 s, and 5 s, and yield strength reduction factors $R$ equal to 3, 5, and a value that leads to linear design.
4. Conduct linear and nonlinear RHAs of the 30 single-story symmetric- and asymmetric-plan systems subjected to bi-directional rotated components of ground motions obtained in step 1. For each RHA, obtain floor displacements, floor total accelerations, BRB plastic deformations, and BRB forces. This step involves more than 34,000 RHAs.

RESULTS

Selected EDPs for single-story systems are displacement, $u_x$ and $u_y$; floor total acceleration, $\ddot{u}_x$ and $\ddot{u}_y$, at the center of mass; member forces; and plastic deformation of selected BRBs. Figure 7 shows floor total accelerations, $\ddot{u}_x$, at the center of mass (red curve) as a function of the rotation angle, $\theta_x$, for symmetric-plan buildings with $T_n = 2$ s, 3 s, and 5 s subjected to ground motions with velocity-pulse period close to $T_n$. The filled gray area shows values of $\theta_x$ in which the velocity pulses are identified for each record. Note that angles $\theta_x = 0°$ and 90° correspond to the FP and FN axes, respectively. For asymmetric-plan systems, roof displacements $u_y$ at the center of mass and member forces at bracing b3 (Figure 5) as a function of the rotation angle $\theta_x$ are shown in Figure 8 and Figure 9, respectively. Similar figures for other EDPs along the x- and y-axes are shown in Reyes and Kalkan (2012). In these figures, the EDPs are normalized by their peak values in each polar plot. These figures permit the following observations: (1) For symmetric-plan systems, the maximum floor total acceleration, $\ddot{u}_x$, over all non-redundant orientations are generally polarized in the direction in which apparent velocity pulse with period close to $T_n$ is observed; while this polarization is almost perfect for linear systems, it vanishes for nonlinear systems,
Figure 7. Floor total accelerations, $u^2_x$, at the center of mass (red curve) as a function of rotation angle $\theta_x$ for single-story symmetric-plan systems with $T_n = 2\,s$, 3\,s, and 5\,s subjected to ground motions with velocity-pulse-period close to $T_n$. The filled gray area shows values of $\theta_x$ in which velocity pulses are identified. Angles $\theta_x = 0^\circ$ and $90^\circ$ correspond to the fault-parallel and fault-normal directions, respectively. Floor total accelerations are normalized by peak values in each polar plot.
Figure 8. Displacement $u_x$ at center of mass (red curve) as a function of rotation angle $\theta_x$ for single-story asymmetric-plan systems with $T_n = 2$ s, 3 s, and 5 s subjected to ground motions with velocity-pulse period close to $T_n$. The filled gray area shows values of $\theta_x$ in which velocity pulses are identified for each record. Angles $\theta_x = 0^\circ$ and $90^\circ$ correspond to the fault-parallel and fault-normal directions, respectively. Displacements are normalized by peak values in each polar plot.
Figure 9. Force in bracing b3 (red curve) as a function of rotation angle, \( \theta_x \), for single-story asymmetric-plan systems with elastic first-mode vibration period \( T_n = 2 \text{ s}, 3 \text{ s}, \) and \( 5 \text{ s} \) subjected to ground motions (GM) with velocity-pulse period close to \( T_n \). The filled gray area shows values of \( \theta_x \) in which velocity pulses are identified for each record. Angles \( \theta_x = 0^\circ \) and \( 90^\circ \) correspond to the fault-parallel and fault-normal directions, respectively. Forces are normalized by peak values in each polar plot.
leading the maximum floor total acceleration $u_\text{max}$ to also occur in the direction different from
that of the velocity pulse (white areas in Figure 7); this is attributed to period elongation due
to inelastic action. For asymmetric-plan systems, however, no strong correlation is observed
between the orientation leading to maximum displacement $u_x$ and the velocity-pulse direction
even for linear case. (2) Only for linear systems, the maximum force in selected BRBs is
polarized in the direction in which the pulse is identified (Figure 9), whereas for all nonlinear
systems, BRB reaches its ultimate capacity quickly without being influenced by the rotation
angle. (3) EDPs may be underestimated by more than 50% if a building is subjected to only
FN/FP components of a pulse-like ground motion; this observation is valid for both
symmetric- and asymmetric-plan systems (for example, last row in Figure 7 and Figure 8).
(4) There is no optimum orientation for a given structure; the rotation angle that leads to
maximum EDPs varies not only with the ground motion pair selected, but also with the period
and $R$ value used in the design process of the building.

For a selected earthquake scenario, it is commonly assumed that EDPs are log-normally
distributed (Cornell et al. 2002). For this reason, it is more appropriate to represent the
“mean” structural response by the median; a conclusion that is widely accepted. Because
the geometric mean and median of a random variable having a log-normal distribution
are the same, we decided to employ the term “median” instead of geometric mean, as is
commonly done. Figure 10 shows the median displacements, $u_x$ (normalized by their
peak values), at the center of mass as a function of the rotation angle, $\theta_x$, for symmetric-
plan buildings with $T_n = 0.2$ s, 1 s, 2 s, 3 s, and 5 s, and with $R = 3, 5$ and a value that
leads to linear design subjected to 30 bi-directional ground motions. The red curves represent
the median displacement $u_x \pm$ one standard deviation ($\sigma$) computed based on peak response
values due to each ground motion pair at each non-redundant rotation angle. In these figures,
the blue circles represent the median MD displacement ($u_{\text{MD}} \pm \sigma$)\(^\dagger\) for the systems subjected
to ground motions only in the MD. Recall that MD stands for maximum direction. Note that
for a given ground motion pair, MD changes with period. In Figure 10, although the MD
displacement $u_{\text{MD}} \pm \sigma$ values correspond to a single value for each system, it is visualized as a
full circle to facilitate direct comparisons with median displacements $u_x \pm \sigma$, which is a func-
tion of the rotation angle $\theta_x$. For the asymmetric-plan systems, plots for displacements at
corner c2 (Figure 5) are depicted in Figure 11. Median values of other EDPs are shown
in Reyes and Kalkan (2012). These figures provide an overall statistical examination to gen-
eralize the observations previously made based on individual records in Figures 7 thru 9.

These general observations are: (1) For short period ($T_n = 0.2$ s) linear symmetric- and asym-
metric-plan systems, maximum median-displacement values (red curves) are independent of
the ground motion rotation angle $\theta_c$. At longer periods, however, maximum median displace-
ments are influenced by the rotation angle, and they are generally polarized with the FN
direction; this is more pronounced for symmetric-plan systems. For $R$ values of 3 and 5, the
effect of the rotation angle on displacement is significant for all systems. (2) Median values of
floor total accelerations and member forces are generally not influenced by the ground
motion rotation angle in both linear and nonlinear range for both symmetric- and asymmetric-
plan buildings. (3) For all systems, it is clear that the $R$ value used in the design process
affects the difference between the median MD displacement and the maximum median

\[^{\dagger}\]16th and 84th percentile values of $u_{\text{MD}}$ are computed as $u_{\text{MD}} e^{\pm \sigma}$
Figure 10. Median displacements $u_x$ at the center of mass as a function of rotation angle $\theta_x$ for single-story symmetric-plan systems with $T_n = 0.2, 1, 2, 3, 5$ s subjected to bi-directional loading. The red curves represent the median displacement $u_x \pm \sigma$. The blue circles represent the median displacement $u_{cm} \pm \sigma$ for the systems subjected to bi-directional ground motions in the maximum direction. Displacements are normalized by peak values in each polar plot.
Median displacement +/- one standard deviation due to components rotated $\theta_x$ degrees

Median displacement +/- one standard deviation due to MD components

**Figure 11.** Median displacements $u_x$ at corner c2 as a function of rotation angle $\theta_x$ for single-story asymmetric-plan systems with $T_n = 0.2$ s, 1 s, 2 s, 3 s, and 5 s subjected to bi-directional loading. The red curves represent the median displacement $u_x \pm \sigma$. The blue circles represent the median displacement $u_{m,x} \pm \sigma$ for the systems subjected to bi-directional ground motions in the maximum direction. Displacements are normalized by peak values in each polar plot.
displacement over all non-redundant orientations. Maximum values of EDPs for linear systems are usually smaller than median MD EDPs—a conclusion also drawn by Huang et al. (2008). However, for nonlinear systems, maximum median EDPs may be equal or larger than MD EDPs. This is an important finding since it demonstrates that use of MD ground motions does not necessarily provide over-conservative (or unrealistic) EDPs for systems responding in nonlinear range in particular for asymmetric-plan structures.

Next, median percent error in estimation of peak median response over all rotation angles due to MD or FN/FP directions rotated ground motions are computed as:

\[
\text{Error}(\%) = \frac{\max(\hat{x}_{FN/FP}, \hat{x}_{MD}) - \hat{x}_{\text{max}}}{\hat{x}_{\text{max}}} \times 100 \tag{3}
\]

where \(\hat{x}_{\text{max}}\) is the peak median EDP over all rotation angles. \(\hat{x}_{MD}\) and \(\hat{x}_{FN/FP}\) are the peak median EDP due to MD or FN/FP directions rotated ground motions, respectively. The positive error means overestimation, and negative is the underestimation of peak median EDPs from 30 ground motion pairs. Using Equation 3, the error values are computed for nonlinear symmetric- and asymmetric-plan buildings and for EDPs shown in Figure 10 and Figure 11 along x- and y-axes; these results are tabulated in Table 2. The maximum value of underestimation and overestimation of peak median response when either MD or FN/FP directions rotated ground motions are used are 9% and 8%, respectively. It is evident that conducting nonlinear RHA for ground motions oriented in the FN/FP and MD directions does not always lead to the peak value of median displacement over all non-redundant rotation angles. However, displacements are not underestimated or overestimated substantially (less than 10%) if the system is subjected to MD and FN/FP directions of a large set of ground motions, and the maximum response values from these analyses are taken as design values. The underestimation could be as much as 50% if a single record is used.

Table 2. Percent error in estimation of peak median displacements over all rotation angles using equation (3); positive error means overestimation, and negative underestimation (shown with bold numbers).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Structural period (s)</th>
<th>x-direction</th>
<th>y-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Linear R = 3</td>
<td>R = 5</td>
</tr>
<tr>
<td>Symmetric-plan</td>
<td>0.2</td>
<td>19%</td>
<td>-1%</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>17%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>14%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>17%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>14%</td>
<td>8%</td>
</tr>
<tr>
<td>Asymmetric-plan</td>
<td>9.0</td>
<td>-14%</td>
<td>-9%</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>-2%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>7.8</td>
<td>-1%</td>
<td>-1%</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>-1%</td>
<td>5%</td>
</tr>
</tbody>
</table>
CONCLUSIONS

In this study, the influence that the rotation angle of the ground motion has on several engineering demand parameters has been examined systematically in linear and nonlinear domains using a suite of 3-D computer models of symmetric- and asymmetric-plan single-story buildings subjected to 30 bi-directional near-fault ground motion records. The results presented herein suggest that:

- Velocity pulses in near-fault records may appear in directions different from the maximum-direction (MD) or fault-normal and fault-parallel (FN/FP) directions. For the near-fault records examined, MD shows large scattering with no visible correlation with the FN/FP directions. This observation is valid even for motions recorded within 5 km of the fault.

- For linear systems, the maximum displacement occurs in the direction in which apparent velocity pulse with a period close to the fundamental period of the structure is observed. This strong polarization vanishes for nonlinear systems due to period elongation. These observations are valid for both symmetric- and asymmetric-plan single-story buildings investigated.

- For a given ground motion pair, rotation angle leading to maximum elastic response is different than that for maximum inelastic response; thus, any conclusions drawn based on linear systems will not be applicable for nonlinear systems.

- For a given ground motion pair, the use of FN/FP directions applied along the principal directions of the building not always guarantees that the maximum response over all possible angles will be obtained. Even though this approach may lead to a maximum for one EDP, it may be non-conservative for other EDPs.

- Treating the as-recorded direction as a randomly chosen direction, it is observed that there is more than a 50% chance for the larger response among the FN and FP values to exceed the response corresponding to an arbitrary orientation. The latter observation is valid for most, but not for all, of the record pairs and response quantities considered.

- For a given ground motion pair, MD is not unique; it changes with period and $R$ value of the system, as a result, the MD response spectrum becomes an envelope of the maximum response spectral accelerations of the ground motion pair at all possible rotation angles and periods. It is therefore argued that the use of MD ground motion for design is an overly conservative approach. While it can be true for linear systems, conducting nonlinear RHA for ground motions oriented in the MD does not always lead to maximum EDPs over all orientations in particular for asymmetric-plan buildings.

- The conclusions drawn above are for a given ground motion pair. The statistical evaluation based on the large set of ground motion pairs suggest that, for
practical applications in near-fault sites, RHAs should be conducted by rotating a
set of records to the MD (computed at building’s first-mode period) and FN/FP
directions, and taking the maximum response values from these analyses as
design values. The results presented in our companion paper also support this
recommendation.

- We also recommend rotating ground motions to MD and FN/FP direction for sites
within 15 km of the fault instead of 5 km; the rational for this recommendation is
that propagating waves do not show notable attenuation within 15 km of the cau-
sative fault; thus their intensity and frequency content do not alter for events with
high seismic energy (moment magnitude $> 7.0$).

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