Significance of Rotating Ground Motions on Behavior of Symmetric- and Asymmetric-plan Structures: Part I. Parametric Study

Juan C. Reyes,[a] **and Erol Kalkan,**[b] **M.EERI**

The 2010 California Building Code requires at least two horizontal ground motion components for three-dimensional (3D) response history analysis (RHA) of structures. For sites within 5 km of an active fault, 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 envelope the range of possible responses over all non-redundant rotation angles. This assumption is examined using 3D computer models of single-story systems having symmetric- and asymmetric-plan subjected to a suite of bi-directional near-fault ground motions. The influence that the rotation angle of the ground motion has on several engineering demand parameters is examined in linear-elastic and nonlinear-inelastic domains to form benchmarks for evaluating the use of the FN/FP directions and also the maximum-direction—a new definition of horizontal ground motions for use in site-specific ground motion procedures for seismic design.

INTRODUCTION

In United States, both the International Building Code (ICBO, 2009) and the California Building Code (ICBO, 2010) refer to American Society of Civil Engineers/Seismic Engineering Institute ASCE/SEI 7-05 chapter 16 (ASCE, 2006) when response history analysis (RHA) is required for design verification of building structures. These guidelines require at least two horizontal ground motion components for 3D RHA. According to section 1615A.1.25 of the California Building Code (CBC2010), 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 (also called the

[a] Universidad de los Andes, Bogota, Colombia; jureyes@uniandes.edu.co
[b] United States Geological Survey, Menlo Park, California; ekalkan@usgs.gov (corresponding author)

strike-normal and strike-parallel directions) for 3D 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, as well as 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 in the CBC2010 is absent in the ASCE/SEI 7-05 guidelines. However, this modification is now included in the most recent ASCE/SEI 7-10 (ASCE, 2010) standards, which have additional proposed changes to be 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, results in peak linear-elastic 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 whose 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. 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 in fact not new; it has been studied previously in various contexts. Penzien and Watabe (1975) 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 and others, 2000; MacRae and Matteis, 2000; Tezcan and Alhan, 2001; Khoshnoudian and Poursha, 2004; Rigato and Medina, 2007; Lagaros, 2010; 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 $\theta_{critical}$ (or θ_{cr}) depends on the seismic excitation level and character of shaking. A formula for deriving θ_{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 and others, 2000). However, the Wilson (1995) formula is based on concepts from response spectrum analysis—an approximate procedure used to estimate structural response in the linear-elastic domain. Focusing on linear-elastic multi-degree-of-freedom symmetric- and asymmetric-plan structures, Athanatopoulou (2005) investigated the effect of the rotation angle on structural response using linear-elastic RHAs, and provided formulas for determining the maximum response over all rotation angles given the linear-elastic response histories for two orthogonal orientations. The analysis results have shown that, for the records used, the critical value of an 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 (2012a,b) where the impacts of ground motion rotation angle including those corresponding to the FN/FP directions on several different EDPs have been examined using a linear-elastic 3D computer model of a multi-story building.

The previous studies investigated response behavior of either linear-elastic multi-degree-of-freedom buildings or nonlinear-inelastic response of single-degree-of-freedom systems. Because there is still a lack of research addressing bi-directional nonlinear response of realistic multi-degrees-of-freedom 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, 3D 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 recommendations towards the use of MD and FN/FP directions to rotate ground motion records for RHA of building structures. The companion paper includes further validations using 3D nonlinear computer models of 9-story structures having symmetric and asymmetric layouts subjected to the same ground motion set.

GROUND MOTIONS SELECTED

30 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±0.2
- Closest fault distance from a site to co-seismic rupture plane: 0.1 to 15 km
- National Earthquake Hazards Reduction Program (NEHRP) soil type: C or D
- Highest usable period† ≥ 6 sec

These ground motions were rotated to fault-normal (FN) and fault-parallel (FP) orientations using the following transformation equations:

$$\ddot{u}_{FP} = \ddot{u}_1 \cos(\beta_1) + \ddot{u}_2 \cos(\beta_2) \quad (1)$$

* The term, conservative, is used here either peak or close to peak EDP values

† 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 5 sec.

$$\ddot{u}_{FN} = \ddot{u}_1 \sin(\beta_1) + \ddot{u}_2 \sin(\beta_2) \quad (2)$$

where $\beta_1 = \alpha_{strike} - \alpha_1$, $\beta_2 = \alpha_{strike} - \alpha_2$, α_{strike} is the strike of the fault, α_1 and α_2 are the azimuths of the instrument axes as shown in Figure 1a. The geometric mean or median spectrum[‡] of 30 FN records is taken as the target spectrum for design of single-story symmetric and asymmetric structures to be used in a parametric study. The ground motions (acceleration time series) were additionally rotated θ_x^{o} away from the FP axis as shown in Figure 1b. The angle θ_x varies from 5^{o} to 360° every 5° in the clockwise direction. These rotations were conducted using equations (1) and (2) with the following modifications: (a) α_1 and α_2 were changed by θ_x and θ_y, respectively; (b) β_1 and β_2 were redefined as $\beta_1 = \alpha_{strike} - \alpha_1 - \theta_x$ and $\beta_2 = \alpha_{strike} - \alpha_2 - \theta_y$. The *x*- and *y*-axis as well as the angles θ_x and θ_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 (that is, $\theta_x = 0$). The maximum deformation of this system occurs at an angle θ_m away from the FP axis. This new orientation for the response quantity of interest will be called in this research maximum-direction (MD).

For 30 near-fault ground motion pairs, Figure 3 shows the polar plots of spectral acceleration values as a function of the rotation angle θ_x for elastic single-degree-of-freedom (SDF) systems with vibration period (T_n) equal to 0.2, 1, 2, 3, and 5 sec. In this figure, the red lines represent the median spectral acceleration value ± one standard deviation (σ_n), and the blue points correspond to pairs of MD angle θ_m and spectral acceleration values A_m. The blue circles represent the median spectral acceleration value ± one standard deviation (σ_m) in the MD. Except for short period system (T_n = 0.2 sec), median spectral acceleration values A_n (red lines) tend to be polarized with the fault-normal ($\theta_x = 90°$) direction.

Studies of ground motion directionality have shown that the azimuth of the MD ground motion is arbitrary for fault distances (R_{rup}) larger than approximately 3–5 km (Campbell and Bozorgnia 2007, Watson-Lamprey and Boore 2007). At closer fault distances (R_{rup} < 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, θ_m (blue circles) in Figure 3 shows large scattering with no visible correlation with the FN

‡ Because we assume that the data is log-normally distributed, the geometric mean and the median are the same.

direction. Spectral acceleration values A_m corresponding to the maximum-direction angle θ_m are generally higher than median spectral acceleration value A_n.

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, 1, 2, 3, and 5 sec. The yield strength reduction factors R are equal to 3, 5, and a value that leads to linear-elastic design. The lateral resisting system of the buildings consists of buckling-restrained braced frames with non-moment-resisting beam-column connections. The plan shapes and bracing layouts are shown in Figure 4. 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 (RSA) of the building with the design spectrum reduced by a response modification factor R. The constitutive model used for the buckling-restrained braces (BRBs) is the simplified trilinear model shown in Figure 5. This model was obtained based on experimental results (Merritt et al., 2003). The parameters, k and q_y, are 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 resisting systems located along the perimeter of the plan; (2) Coupled lateral-torsional motions occur in the first and third modes of the B-plan (asymmetric-plan) buildings, whereas lateral displacements dominate motion in the second mode. According to the ASCE/SEI 7-05 (ASCE, 2005), plan B presents an extreme torsional irregularity; (3) The higher-mode contributions to response are expected to be significant for the B-plan 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-elastic and nonlinear-inelastic response behavior of single-story buildings with symmetric- and asymmetric-plan located in near fault sites:

(1) For each of the 30 ground motion records selected, calculate rotated ground motion components by varying θ_x from 0° to 360° at every 5° in the clockwise direction (Figure 1b). The motions for θ_x = 0° and 90° correspond to the FP and FN components of the record, respectively. In addition, calculate rotated ground motion components for $\theta_x = \theta_m$ and $\theta_x = \theta_m + 90°$. For estimating maximum-direction angle θ_m, use periods equal to 0.2, 1, 2, 3, and 5 sec.

(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 to 6 sec.

(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, 1, 2, 3, and 5 sec, and yield strength reduction factors R equal to 3, 5, and a value that leads to linear-elastic 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 floor total acceleration $\ddot{u}_{tx}$ at the center of mass, member force and plastic deformation of selected BRBs. Baker (2007) developed a numerical procedure to identify and characterize velocity pulses for ground motion records. As mentioned in Reyes and Kalkan (2012), this procedure was used to identify velocity pulses in rotated motions whose rotation angle is varied from 5° to 360°

at an interval of 5° in the clockwise direction. Figure 6 shows roof displacement u_x (red line) as a function of the rotation angle θ_x for symmetric-plan buildings with T_n = 2, 3 and 5 sec subjected to ground motions from Table 1. with velocity-pulse-period close to T_n. The filled gray area shows values of θ_x in which the velocity pulses are identified for each record. Note that angles θ_x = 0° and 90° correspond to the FP and FN axes, respectively. For asymmetric-plan systems, roof displacements u_x at the corner c2 (Figure 4) as a function of the rotation angle θ_x are shown in Figure 7. Similar figures for other EDPs are shown in Reyes and Kalkan (2012). These figures permit the following observations: (1) Velocity-pulses may appear in directions different than the FN or FP-direction. (2) For symmetric-plan systems, the maximum displacement u_x and floor total acceleration $\ddot{u}^t_x$ (shown in Reyes and Kalkan, 2012) 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-elastic systems, it vanishes for nonlinear-inelastic systems, leading maximum displacement u_x also occurs in the direction different from that of the velocity-pulse (white areas in Figure 6 and 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 u_x and the velocity-pulse direction even for linear-elastic case. (3) Only for linear-elastic symmetric-plan systems, the maximum force in selected BRBs is polarized in the direction in which the pulse is identified. Whereas for all nonlinear-inelastic systems, BRB reaches its ultimate capacity quickly without being influenced by the rotation angle (corresponding results for BRBs are shown in Reyes and Kalkan, 2012). (4) For symmetric-plan systems, maximum values of EDPs almost always occur in the direction at which the velocity pulse is identified. For the asymmetric-plan systems, however, maximum values of EDPs also take place in directions without the velocity-pulse. (5) 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. (6) 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 8 shows the median displacements u_x at the center of mass as a function of the rotation angle θ_x for symmetric-plan buildings with T_n = 0.2, 1, 2, 3, and 5 sec, and with R=3, 5 and a value that leads to linear-elastic design subjected to 30 bi-directional ground motions. The red lines represent the median displacement u_x ± one standard deviation (σ) 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_{mx} ± σ)[§] 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 8, although the MD-displacement $u_{mx} \pm \sigma$ 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 function of the rotation angle θ_x. For the asymmetric-plan systems, plots for displacements at corner c2 (Figure 4) are depicted in Figure 9. Median values of other EDPs are shown in Reyes and Kalkan (2012). These figures provide an overall statistical examination to generalize the observations previously made based on individual records in Figures 6 and 7. These general observations are: (1) For short period (T_n = 0.2 sec) linear-elastic symmetric- and asymmetric-plan systems, maximum median-displacement values (red lines) are independent of the ground motion rotation angle. At longer periods, however, maximum median-displacements 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-elastic and nonlinear-elastic 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-displacement over all non-redundant orientations. Maximum values of EDPs for linear-elastic systems are usually smaller than median MD-EDPs—a conclusion drawn by Huang et al., (2008). However, for nonlinear-inelastic systems, maximum median-EDPs may be equal or larger than MD-EDPs.

[§] 14th and 86th percentile values of u_{mx} are compute as $u_{mx}\, e^{\pm\sigma}$

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-inelastic range in particular for asymmetric structures.

It is evident that conducting nonlinear RHA for ground motions oriented in the FN/FP directions does not always lead to the peak value of median-displacement over all non-redundant rotation angles. However, displacements are not underestimated substantially (less than 20%) if the system is subjected to only the FN/FP components of a large set of ground motions. The underestimation could be as much as 50% if a single record is used.

CONCLUSIONS

Current seismic design practice in U.S. requires as-recorded pair of ground motions to be rotated to fault-normal and fault-parallel (FN/FP) directions before they are used as input for three-dimensional (3D) response history analyses (RHAs) of building structures to be located within 5 km of the active fault. It is assumed that this approach will lead to two sets of responses that envelope the range of possible responses over all non-redundant rotation angles. Thus, it is considered to be a conservative method appropriate for design verification of new structures. Additionally, the site-specific ground motion procedure according to the ASCE/SEI 7-10 requires that the ground motion to be rotated to the maximum-direction (MD) (that is, direction of rotated ground motion pair resulting in peak linear-elastic response quantity of a single lumped mass oscillator) when site-response analysis is performed; this new approach has been found to be controversial (Stewart et al., 2011). Currently, there is a lack of research addressing bi-directional nonlinear response of structures considering ground motion directionality effects. In this study, the influence that the rotation angle of the ground motion has on several engineering demand parameters (EDPs) has been examined systematically in linear-elastic and nonlinear-inelastic domains using a suite of 3D computer models of symmetric- and asymmetric-plan single-story buildings subjected to 30 bi-directional near-fault ground motion records. This investigation has led to the following conclusions:

- For linear-elastic systems, the maximum displacement occurs when 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-inelastic systems due to period elongation. For other EDPs (for example, member forces), their linear and nonlinear peak values are generally independent of the ground motion rotation angle. These observations are valid for both symmetric- and asymmetric-plan single-story buildings investigated.

- There is no optimum orientation for a given structure maximizing all EDPs simultaneously; maximum EDP can happen in any direction different than the direction of the velocity pulse. The critical angle θ_{cr} corresponding to the largest response over all possible rotation angles varies with the ground motion pair selected, *R* value used in the design process and the response quantity (EDP) of interest. Therefore, it is difficult to determine an "optimal" building orientation that maximizes demands for all EDPs before conducting RHAs.
- 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-elastic 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 use of MD or FN/FP directions applied along the principal directions of the building almost never 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 will simultaneously 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 all of the record pairs and response quantities considered. Therefore, compared to no rotation at all, use of the larger response of the two values corresponding to the MD or FN/FP directions is still warranted.

The results presented herein and also those in the companion paper (Kalkan and Reyes, 2012) have important implications for current earthquake engineering practice, suggesting that ground motions rotated to MD or FN/FP directions do not necessarily provide conservative estimates of EDPs in nonlinear-inelastic range. For a given record, rotation angle leading to maximum elastic response is different than that for maximum inelastic response, thus any conclusions drawn based on linear-elastic systems will not be applicable for nonlinear-inelastic systems.

ACKNOWLEDGEMENTS

We would like to thank C.B. Crouse, Dave Boore, Charlie Kircher and Katsuichiro Goda for their critical review on the material presented herein and offering their constructive comments and suggestions, which helped improving the technical quality of this paper.

REFERENCES

American Society of Civil Engineers, 2010. *Minimum Design Loads for Buildings and Other Structures*, *ASCE/SEI 7-10*, Reston, VA.

American Society of Civil Engineers, 2006. *Minimum Design Loads for Buildings and Other Structures*, *ASCE/SEI 7-05*, Reston, VA.

Athanatopoulou, A. M., 2005. Critical orientation of three correlated seismic components, *Engineering Structures* **27**, 301–312.

Baker, J. W., 2007. Quantitative classification of near-fault ground motions using wavelet analysis, *Bulletin of the Seismological Society of America* **97**(5), 1486–1501.

Bray, J. D., Rodriguez-Marek, A., 2004. Characterization of forward-directivity ground motions in the near-fault region, *Soil Dynamics and Earthquake Engineering* **24**(11), 815–828.

Campbell, K. W. and Bozorgnia, Y., 2007. *Campbell-Bozorgnia NGA Ground motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground motion Parameters*, *PEER Report No. 2007-02*, University of California, Berkeley.

Cornell, C. A., Jalayer, F., Hamburger, R. O. and Foutch, D. A., 2002. Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines: *ASCE Journal of Structural Engineering* **128**(4), 526–533.

Fernandez-Davila, I., Comeinetti, S. and Cruz, E. F., 2000. Considering the bi-directional effects and the seismic angle variations in building design, in *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland, New Zealand.

Goda, K., 2012. Comparison of peak ductility demand of inelastic sdof systems in maximum elastic response and major principal directions, *Earthquake Spectra* **28**, 385–399.

Hong, H. P. and Goda, K., 2010. Characteristics of horizontal ground motion measures along principal directions, *Earthquake Engineering and Engineering Vibration* **9**, 9–22.

Huang, Y., Whittaker, A. S. and Luco, N., 2008. Maximum spectral demands in the near-fault region, *Earthquake Spectra* **24**(1), 319–34.

International Conference of Building Officials (ICBO), 2009. *International Building Code*, Whittier, CA.

International Conference of Building Officials (ICBO), 2010. *California Building Code*, Whittier, CA.

Kalkan, E. and Kunnath, S. K., 2006. Effects of fling-step and forward directivity on the seismic response of buildings, *Earthquake Spectra* **22**(2), 367–390.

Kalkan, E. and Kunnath, S. K., 2007. Effective cyclic energy as a measure of seismic demand, *Journal of Earthquake Engineering* **11**(5), 725–751.

Kalkan, E. and Kunnath, S. K., 2008. Relevance of absolute and relative energy content in seismic evaluation of structures, *Advances in Structural Engineering* **11**(1), 17–34.

Kalkan, E. and Kwong, N.S., 2012a, *Evaluation of Fault-normal/Fault-parallel Directions Rotated Ground motions for Response History Analysis of An Instrumented Six-story Building, U.S. Geological Survey Open-File Report 2012–1058* (available at http://pubs.usgs.gov/of/2012/1058/).

Kalkan, E. and Kwong, N.S., 2012b, Pros and cons of rotating ground motion records to fault-normal/parallel directions for response history analysis of buildings. *ASCE Journal of Structural Engineering*, (in-press).

Kalkan, E. and Reyes, J.C., 2012, Significance of Rotating Ground Motions on Behavior of Symmetric- and Asymmetric-plan Structures: Part 2. Case Studies: Earthquake Spectra (Submitted for publication).

Khoshnoudian, F. and Poursha, M., 2004. Responses of three dimensional buildings under bi-directional and unidirectional seismic excitations, in *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

Lagaros, N. D., 2010. Multicomponent incremental dynamic analysis considering variable incident angle, *Structure and Infrastructure Engineering* **6**, 77–94.

Lopez, O. A. and Torres, R., 1997. The critical angle of seismic rotation and structural response. *Earthquake Engineering and Structural Dynamics* **26**, 881–894.

Lopez, O. A., Chopra, A. K. and Hernandez, J. J., 2000. Critical response of structures to multicomponent earthquake excitation, *Earthquake Engineering and Structural Dynamics* **29**, 1759–1778.

MacRae, G. A. and Mattheis, J., 2000. Three-dimensional steel building response to near-fault motions. *ASCE Journal of Structural Engineering* **126**(1), 117–126.

Mavroeidis, G. P. and A. S. Papageorgiou, 2003. A mathematical representation of near-fault ground motions, *Bulletin of the Seismological Society of America* **93**(3), 1099-1131.

Merritt S., Uang, C. M. and Benzoni, G., 2003. *Subassemblage Testing of Star Seismic Buckling Restrained Braces: Report No. TR-2003/04, Final Report to Star Seismic, LLC,* University of California, San Diego, CA.

Penzien, J. and Watabe, M., 1975, Characteristics of 3-dimensional earthquake ground motions, *Earthquake Engineering and Structural Dynamics* **3**, 365–373.

Reyes, J.C. and Kalkan, E., 2012, Should Ground motion Records be Rotated to Fault-Normal/Parallel or Maximum Direction for Response History Analysis of Buildings: U.S. Geological Survey Open-File Report 2012, 79 p. (available online at http://nsmp.wr.usgs.gov/ekalkan/PDFs/A90_Reyes_Kalkan.pdf)

Rigato, A. and Medina, R. A., 2007. Influence of angle of rotation on the seismic demands for inelastic single-storey structures subjected to bi-directional ground motions, *Engineering Structures* **29**(10), 2593–2601.

Singh, J. P., Porter L. D. and Zafir, Z., 2011. A practitioner's perspective of ASCE/SEI 7-10 maximum-direction ground motions, in *Proceedings of the Annual Convention of Structural Engineers Association of California*.

Stewart, J. P., Abrahamson, N. A., Atkinson, G. M., Baker, J., Boore, D. M., Bozorgnia, Y., Campbell, K. W., Comartin, C. D., Idriss, I. M., Lew, M., Mehrain, M., Moehle, J. P., Naeim, F., and Sabol, T. A., 2011. Representation of bi-directional ground motions for design spectra in building codes. *Earthquake Spectra* **27**(3), 927–937.

Tezcan, S. S. and Alhan, C., 2001. Parametric analysis of irregular structures under seismic loading according to the new turkish earthquake code, *Engineering Structures* **23**, 600–609.

Watson-Lamprey, J. and Boore, D. M., 2007, Beyond SaGMRotI: conversion to SaArb, SaSN, and SaMaxRot, *Bulletin of the Seismological Society of America* **97**, 1511–1524.

Wilson, E. L. and Suharwardy, I., 1995. A clarification of the orthogonal effects in a three-dimensional seismic analysis, *Earthquake Spectra* **11**(4), 659–666.

Table 1. Selected near-fault ground motion records

Record sequence number	Earthquake name	Year	Station name	Earthquake magnitude (M_w)	Style of Faulting	Closest fault distance (km)
1	Gazli, USSR	1976	Karakyr	6.8	Thrust	5.5
2	Imperial Valley-06	1979	Aeropuerto Mexicali	6.5	Strike-slip	0.3
3	Imperial Valley-06	1979	Agrarias	6.5	Strike-slip	0.7
4	Imperial Valley-06	1979	Bonds Corner	6.5	Strike-slip	2.7
5	Imperial Valley-06	1979	EC Meloland Overpass FF	6.5	Strike-slip	0.1
6	Imperial Valley-06	1979	El Centro Array #6	6.5	Strike-slip	1.4
7	Imperial Valley-06	1979	El Centro Array #7	6.5	Strike-slip	0.6
8	Irpinia, Italy-01	1980	Auletta	6.9	Normal	9.6
9	Irpinia, Italy-01	1980	Bagnoli Irpinio	6.9	Normal	8.2
10	Irpinia, Italy-01	1980	Sturno	6.9	Normal	10.8
11	Nahanni, Canada	1985	Site 1	6.8	Thrust	9.6
12	Nahanni, Canada	1985	Site 2	6.8	Thrust	4.9
13	Nahanni, Canada	1985	Site 3	6.8	Thrust	5.3
14	Superstition Hills-02	1987	Parachute Test Site	6.5	Strike-slip	1.0
15	Superstition Hills-02	1987	Westmorland Fire Sta	6.5	Strike-slip	13.0
16	Loma Prieta	1989	BRAN	6.9	Reverse	10.7
17	Loma Prieta	1989	Gilroy Array #3	6.9	Reverse	12.8
18	Loma Prieta	1989	LGPC	6.9	Reverse	3.9
19	Loma Prieta	1989	San Jose – St. Teresa Hills	6.9	Reverse	14.7
20	Loma Prieta	1989	Saratoga - Aloha Ave	6.9	Reverse	8.5
21	Loma Prieta	1989	Saratoga - W Valley Coll.	6.9	Reverse	9.3
22	Erzincan, Turkey	1992	Erzincan	6.7	Strike-slip	4.4
23	Northridge-01	1994	Jensen Filter Plant Gen.	6.7	Reverse	5.4
24	Northridge-01	1994	Newhall - Fire Sta	6.7	Reverse	5.9
25	Northridge-01	1994	Newhall - W Pico Can. Rd.	6.7	Reverse	5.5
26	Northridge-01	1994	Pacoima Dam (downstr)	6.7	Reverse	7.0
27	Northridge-01	1994	Rinaldi Receiving Sta	6.7	Reverse	6.5
28	Northridge-01	1994	Sylmar - Olive V. Med FF	6.7	Reverse	5.3
29	Kobe, Japan	1995	KJMA	6.9	Reverse	1.0
30	Kobe, Japan	1995	Nishi-Akashi	6.9	Reverse	7.1

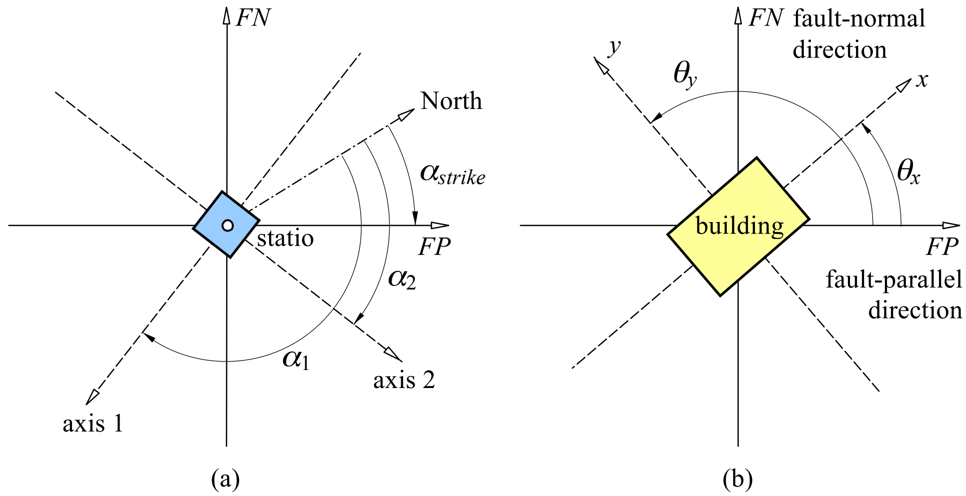

Figure 1. (a) Reference axes for the fault and the instrument with relevant angles noted. (b) Reference axis for the building.

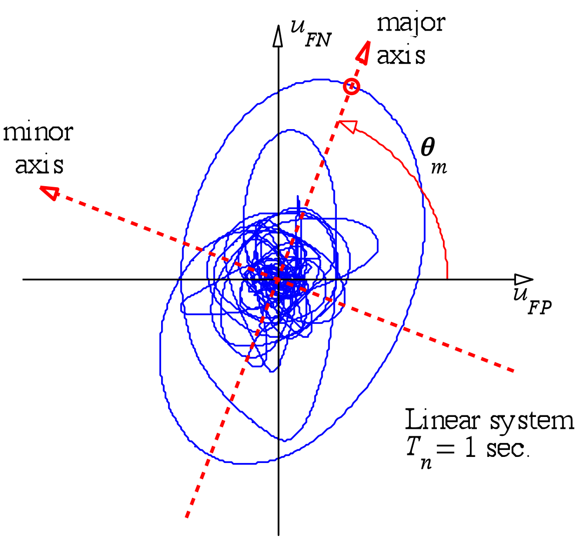

Figure 2. Trace of deformation orbit of a two-degrees-of-freedom system with direction-independent stiffness and damping subjected to the FN/FP components of a ground motion.

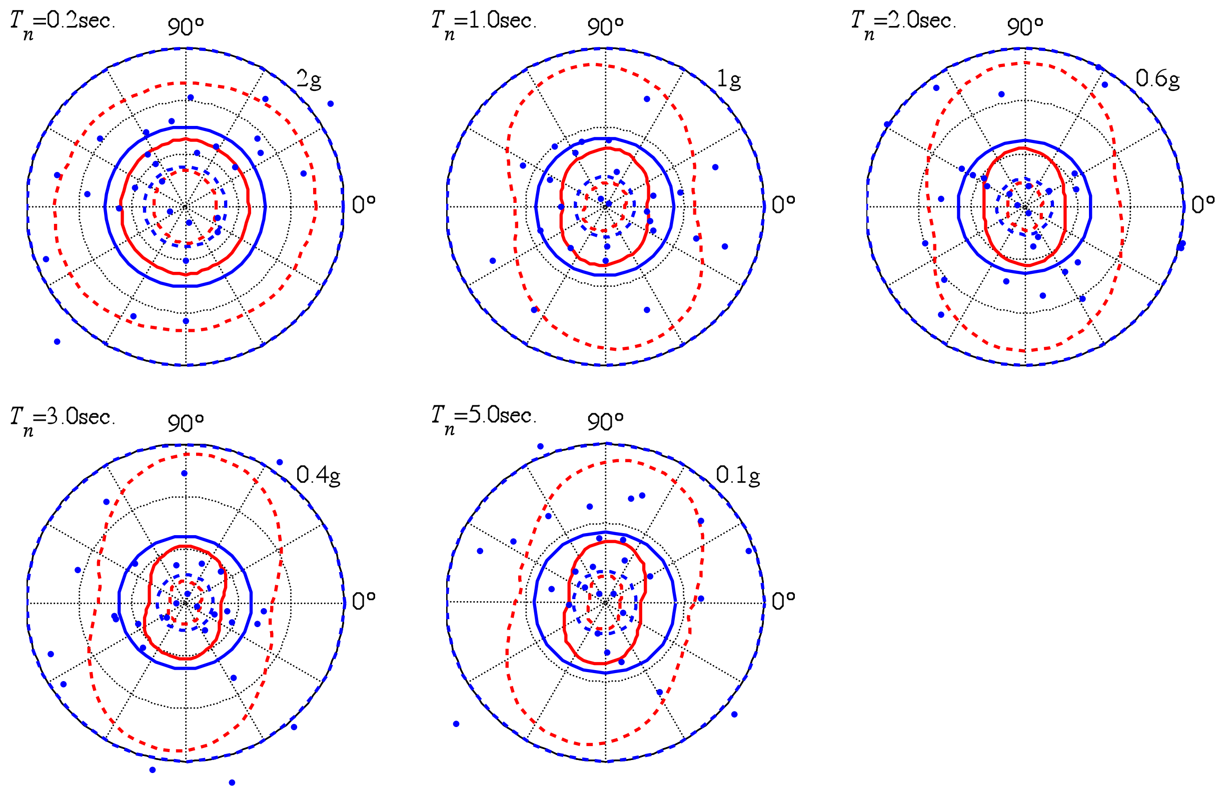

Figure 3. For 30 near-fault ground motion pairs, polar plots of spectral accelerations as a function of the rotation angle θ_x are shown for linear-elastic single-degree-of-freedom (SDF) systems with vibration period (T_n) equal to 0.2, 1, 2, 3, and 5 sec (damping ratio 5%). The red lines represent the median spectral acceleration value (A_n) ± σ_n. The blue points correspond to pairs of maximum-direction angle θ_m and spectral acceleration values A_m. The blue circles represent the median spectral acceleration value ± σ_m in the maximum-direction. Note that except for short period SDF system (T_n = 0.2 sec), A_n values are generally polarized with fault-normal (90°) direction; on the contrary, θ_m shows large scattering with no correlation with fault-normal (90°) direction.

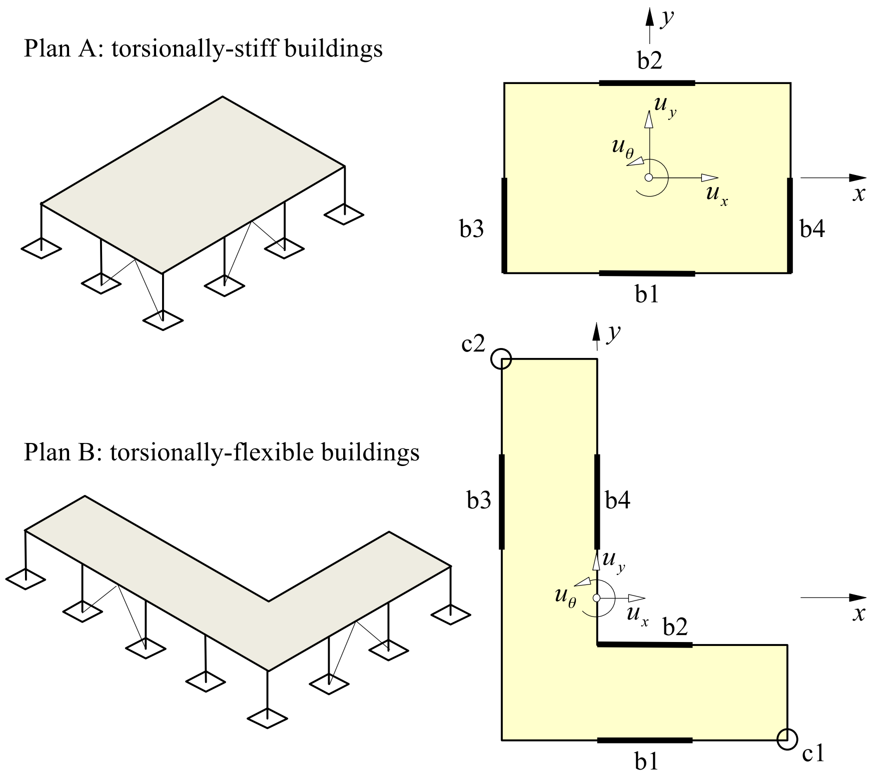

Figure 4. Schematic isometric and plan views of the selected single-story structural systems with three-degrees-of-freedom noted; buckling-restrained braced frames are highlighted.

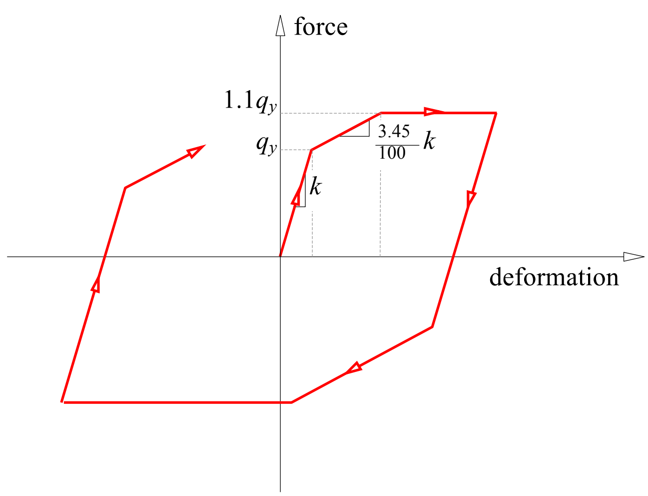

Figure 5. Constitutive model used for the buckling-restrained braces (BRBs).

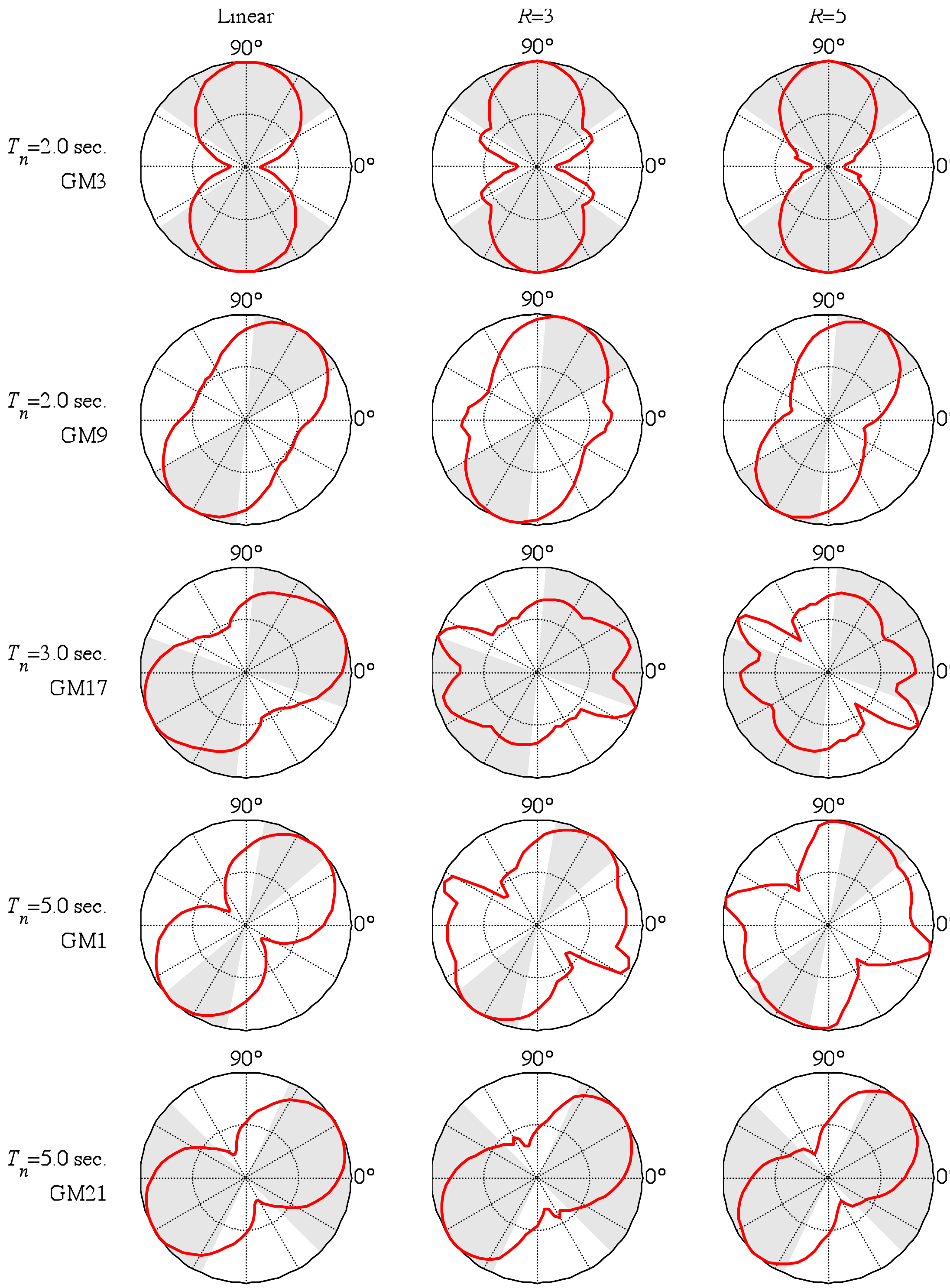

Figure 6. Displacement u_x at the center of mass (red line) as a function of the rotation angle θ_x for single-story symmetric-plan systems with $T_n = 2$, 3 and 5 sec subjected to ground motions with velocity-pulse-period close to T_n. The filled gray area shows values of θ_x in which velocity pulses are identified. Angles $\theta_x = 0^o$ and 90^o correspond to the fault-parallel and fault-normal directions, respectively.

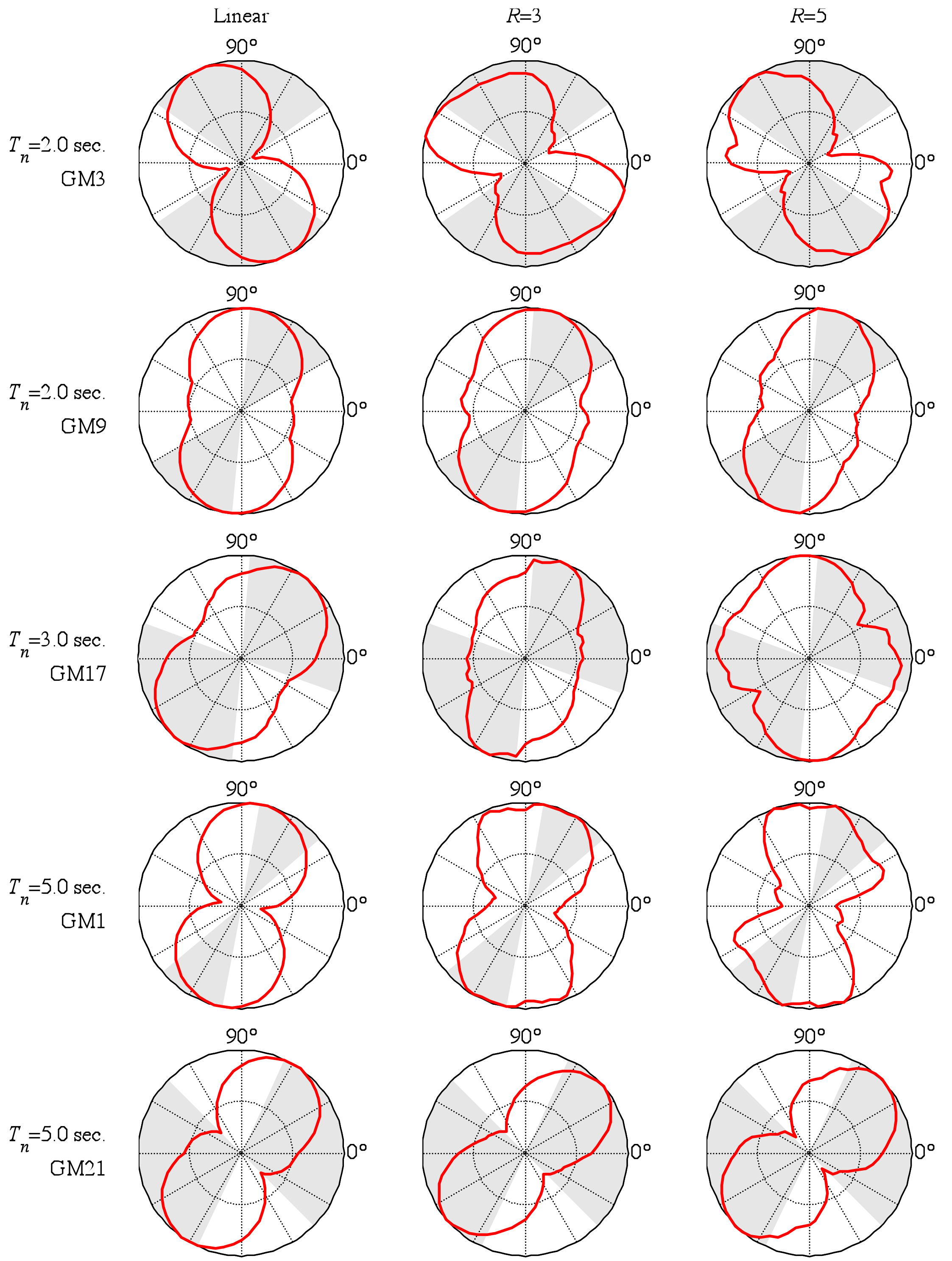

Figure 7. Displacement u_x at corner c2 (red line) as a function of the rotation angle θ_x for single-story asymmetric-plan systems with T_n = 2, 3 and 5 sec subjected to ground motions with velocity-pulse-period close to T_n. The filled gray area shows values of θ_x in which velocity pulses are identified for each record. Angles $\theta_x = 0^\circ$ and 90° correspond to the fault-parallel and fault-normal directions, respectively.

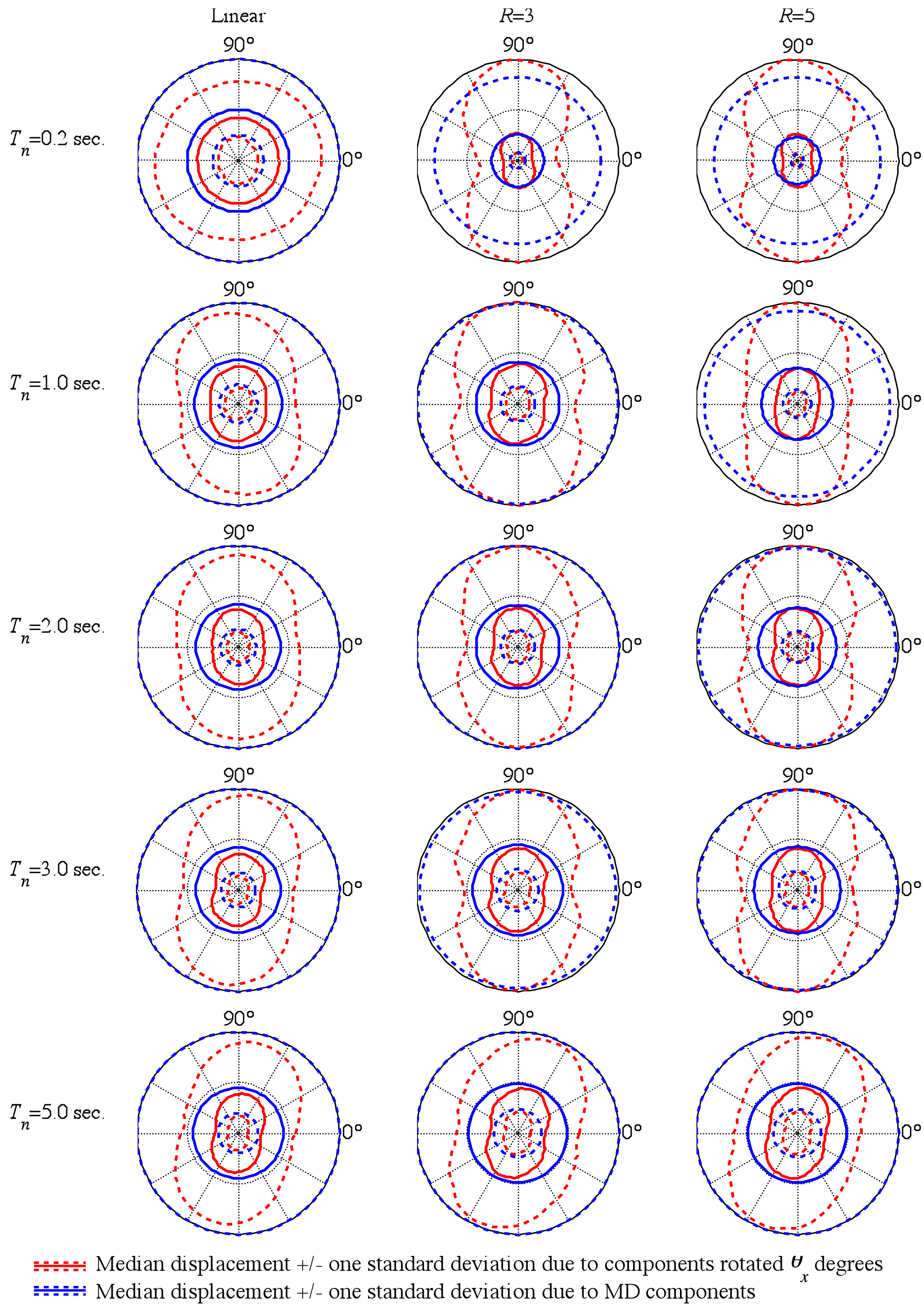

Figure 8. Median displacements u_x at the center of mass as a function of the rotation angle θ_x for single-story symmetric-plan systems with $T_n = 0.2$, 1, 2, 3, and 5 sec subjected to bi-directional loading. The red lines represent the median displacement $u_x \pm \sigma$. The blue circles represent the median displacement $u_{xm} \pm \sigma$ for the systems subjected to bi-directional ground motions in the maximum-direction.

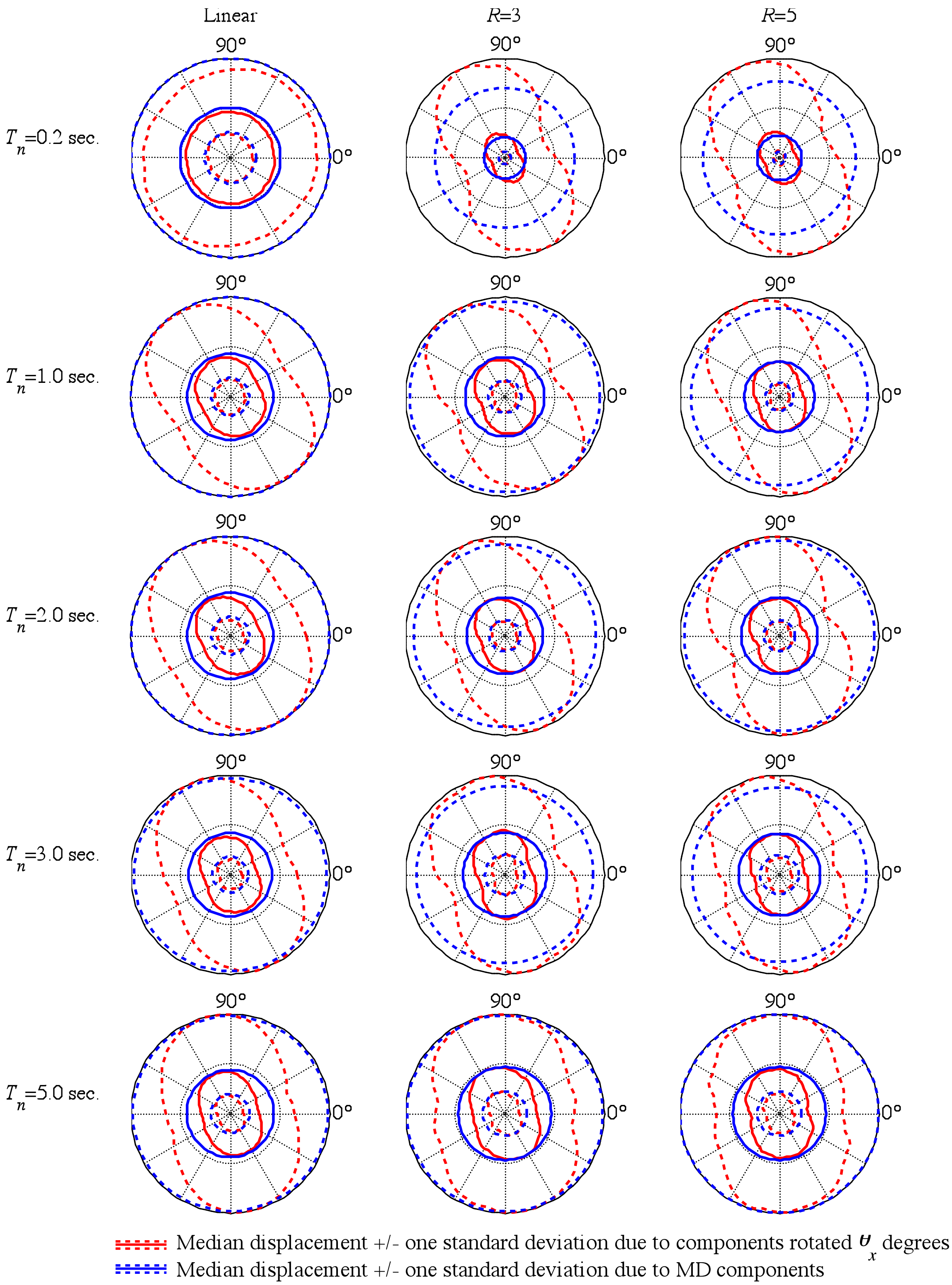

Figure 9. Median displacements u_x at corner p2 as a function of the rotation angle θ_x for single-story asymmetric-plan systems with T_n = 0.2, 1, 2, 3, and 5 sec subjected to bi-directional loading. The red lines represent the median displacement $u_x \pm \sigma$. The blue circles represent the median displacement $u_{xm} \pm \sigma$ for the systems subjected to bi-directional ground motions in the maximum-direction.