

SIGNIFICANCE OF ROTATING GROUND MOTIONS ON NONLINEAR BEHAVIOR OF SYMMETRIC AND ASYMMETRIC BUILDINGS IN NEAR FAULT SITES

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Abstract: Building codes in the U.S. require 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 (when FN and then FP are aligned with transverse direction of the structural axes). 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. This assumption is examined here using 3D computer models of a single-story structure having symmetric (that is, torsionally-stiff) and asymmetric (that is, torsionally flexible) layouts subjected to an ensemble of bi-directional near-fault strong ground motions with and without apparent velocity pulses. In this parametric study, the elastic vibration period of the structures is varied from 0.2 to 5 seconds, and yield strength reduction factors R is varied from a value that leads to linear-elastic design to 3 and 5. The influence that the rotation angle of the ground motion has on several engineering demand parameters (EDPs) is examined in linear-elastic and nonlinear-inelastic domains to form a benchmark for evaluating the use of the FN/FP directions as well as the maximum-direction (MD) ground motion, a new definition of horizontal ground motions for use in the seismic design of structures according to the 2009 NEHRP Provisions and Commentary.

1. INTRODUCTION

In United States, both the California Building Code (ICBO, 2010) and International Building Code (ICBO, 2009) refer to ASCE/SEI-7 Chapter 16 (ASCE, 2010) when RHA is required for design verification of building structures. According to the ASCE/SEI-7 provisions, at least two horizontal ground motion components should be considered for three-dimensional (3D) response history analysis (RHA) of structures.

As input for RHAs, strong motion networks provide users with ground accelerations recorded in three orthogonal directions—two horizontal and one vertical. The sensors recording horizontal accelerations are often oriented in North-South and East-West directions, although for some stations, sensors are oriented perpendicularly not coinciding with the cardinal system. These records with station-specific orientations are referred to as the “as-recorded” ground motions.

Although the as-recorded pair of ground motion may be applied to the structural axes, there is no reason why the pair should not be applied to any other axes rotated about the structural vertical axis. Which angle, then, should one select for RHA remains a question for practitioners.

This notion of rotating ground motion pairs has been studied previously in various contexts. According to earlier work of Penzien and Watabe (1975), the principal axis of a

pair of ground motions is the angle or axis at which the two horizontal ground motion acceleration components are uncorrelated. Using this idea of principal axis, the effects of rotation angle, defined as the angle between the principal axes of the pair and the structural axes, on structural response was investigated (Franklin and Volker 1982; Fernandez-Davilla et al. 2000; MacRae and Matteis 2000; Tezcan and Alhan 2001; Khoshnoudian and Poursha 2004; Rigato and Medina 2007). A formula for estimating the angle that yields to peak responses over all possible non-redundant angles, called $\theta_{critical}$, was derived by Wilson (1995). Other researchers have improved upon 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 Tores, 1997; Lopez et al., 2000). The Wilson (1995) formula is, however, based on concepts from response spectrum analysis—an approximate procedure to estimate structural responses. Focusing on linear-elastic structures, Athanatopoulou (2004) investigated the effect of the rotation angle on structural response using RHAs, and provided formulas for determining the response at any rotation angle, given the response histories for two orthogonal orientations. Athanatopoulou (2004) also concluded that the critical angle corresponding to peak response over all angles varies not only with the ground motion pair under consideration, but with the response quantity, as well. However, no explanation was provided for

the latter observation.

According to the Section 1615A.1.25 of the California Building Code (ICBO, 2010), at sites within 3 miles (5 km) of the active fault that dominates the hazard, each pair of ground motion components shall be rotated to the fault-normal and fault-parallel (FN/FP) directions (also called as strike-normal and strike-parallel directions) for 3D RHAs. It is assumed that this approach will lead to two sets of responses that envelope the range of possible responses over all non-redundant angles of rotation. This assumption is examined here in a parametric study utilizing 3D computer models of single-story structures having either symmetric (torsionally-stiff) or asymmetric (torsionally flexible) layouts subjected to bi-directional near-fault strong ground motions with and without apparent velocity pulses.

The single-story structures selected represents symmetric- and asymmetric-plan buildings with elastic vibration period ranging from 0.2 to 5 seconds. The influence that the rotation angle (on horizontal plane) of the ground motion has on several engineering demand parameters (EDPs) is examined to form a benchmark for evaluating the use of the FN/FP directions. Also investigated are the rotation angle of an apparent velocity-pulse and its correlation with the FN/FP direction, as well as with the rotation angle of ground motion corresponding to peak structural response quantities.

For comparison purposes, responses due to ground motions oriented in the so-called maximum direction (MD) (that is, the direction of rotated ground motion pair resulting in peak linear-elastic response quantity of a single lumped mass oscillator) are also included. The maximum-direction (MD) ground motion is a new definition of horizontal ground motions for use in the seismic design of structures according to the 2009 NEHRP Provisions and Commentary (BSSC 2009). It is argued that the proposed new ground motion definition introduces overconservative bias to design ground motions; the bias is toward overestimation of ground motion by amounts ranging from 10 to 30% depending on period (Stewart et al 2011).

2. SELECTED NEAR-FAULT GROUND MOTIONS

The thirty near-fault strong motion records selected for this investigation were recorded from nine shallow crustal earthquakes compatible with the following scenario:

- Moment magnitude: $M_w=6.7\pm 0.2$
- Closest distance: $R_{closest}<15$ km
- Record highest usable period ≥ 6 sec

Details of these ground motions including style of faulting information are given in Reyes and Kalkan (2012). These ground motions were rotated to the fault-normal (FN) and fault-parallel (FP) orientations using the following transformation equations:

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

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

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. Shown in Figure 2 are the 5-percent-damped geometric-mean (termed “median” here after) response spectra for the FN and FP components of the unscaled ground motions. As expected, the ordinates of median spectra of FN components are larger than those of FP components, because the FN components of near-fault ground motions are generally stronger. The geometric-mean spectrum of thirty FN records is taken as the design spectrum for purposes of this investigation.

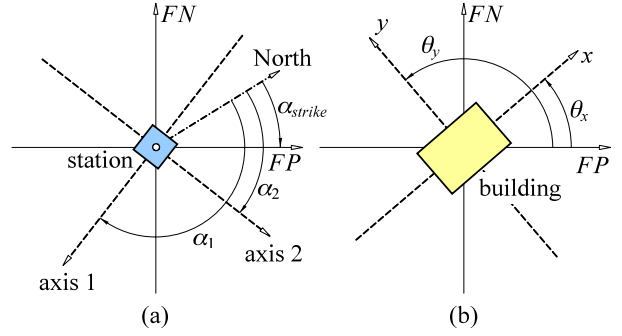


Figure 1 (a) Reference axes for the fault and the instrument with relevant angles noted. (b) Reference axes for the building.

The ground motions were additionally rotated θ_x° away from the FP axis as shown in Figure 1b. The angle θ_x varies from 5° to 360° every 5° . 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 axes as well as the angles θ_x and θ_y are shown in Figure 1b.

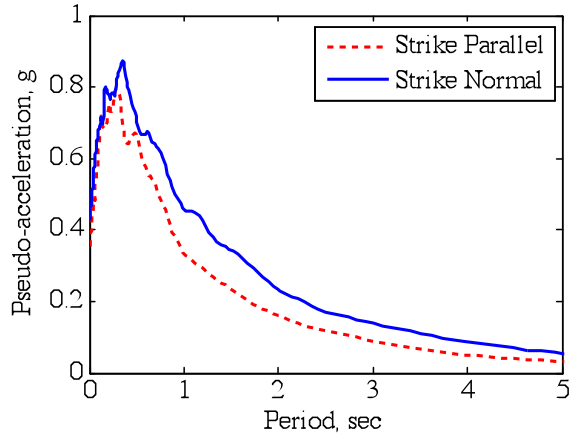


Figure 2 Geometric-mean of thirty response spectra of the selected near-fault ground-motions. Damping ratio 5-percent.

Figure 3 shows the response of a two-degree-of-freedom system with equal stiffness and damping ratio in the x and y directions subjected to the FN-FP components of a ground motion (i.e. $\theta_x=0$). 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). In the literature, the two perpendicular axes rotated θ_m from the FP axis are commonly called major (MA) and minor (MI) axes or simply principal axes.

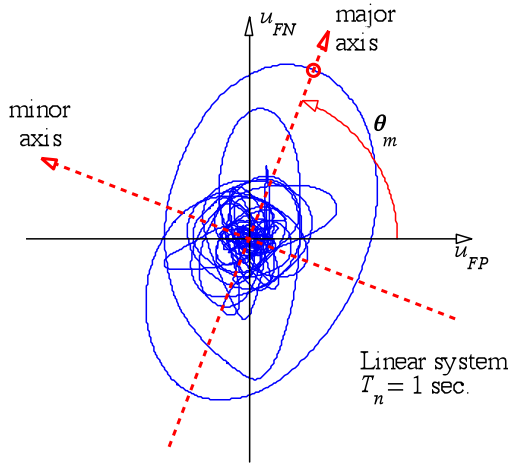


Figure 3 Trace of deformation orbit of a two-degree-of-freedom system with direction-independent stiffness and damping subjected to the FN-FP components of a ground motion; the maximum deformation occurs at θ_m .

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 (e.g., forward directivity), as well as the possible static deformation of the ground surface associated with fling-step effects (Kalkan and Kunnath 2006). These near-source effects cause most of the seismic energy from the rupture to arrive in a single coherent long-period pulse of motion (Kalkan and Kunnath 2007, 2008). Ground motions having such a distinct pulse-like character arise in general at the beginning of the seismogram, and their effects tend to increase the pseudo-acceleration in the long-period portion of the spectrum (Goesorkhi and Gouchon 2002). Baker (2007) developed a numerical procedure to identify and characterize velocity pulses for ground motion records. We use this procedure to identify velocity pulses in rotated motions whose rotation angle is varied from 5° to 360° at an interval of 5° . Results of these analyses are presented in Reyes and Kalkan (2012).

3. STRUCTURAL SYSTEMS SELECTED

The structures considered are 30 single-story buildings with three-degrees of freedom, 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 lead 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, while plan B is asymmetric about both x and y axes. The design spectrum was taken as the geometric-mean of the 5-percent damped pseudo-acceleration response spectra of the FN-components of the 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 .

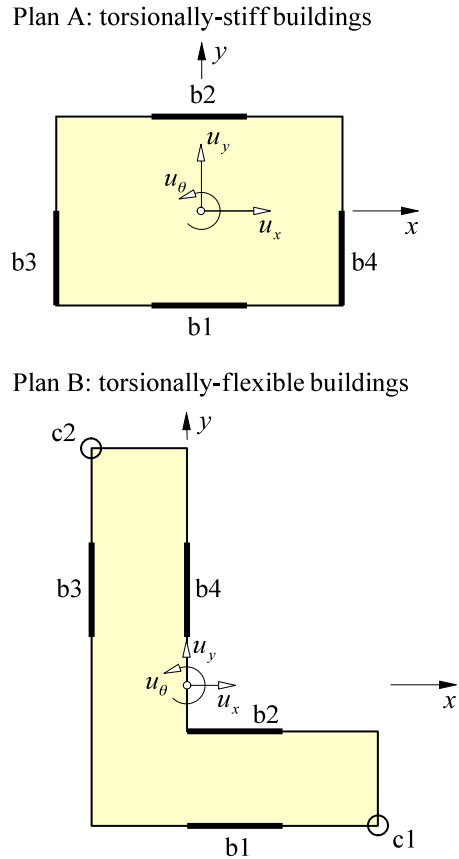


Figure 4 Schematic plan views of the selected structural systems with degrees of freedom noted; buckling-restrained braced frames are highlighted.

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 (Merrit et al. 2003). k and q_y are equal 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 buildings in modes 1 and 2 whereas torsion dominates motion in the third mode, indicating weak coupling between lateral and torsional components of motion. Additionally, the period of the dominantly-torsional mode is much shorter than the periods 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 buildings, whereas lateral displacements dominate motion in the

second mode. According to the ASCE/SEI-7, plan B presents an extreme torsional irregularity; (3) The higher-mode contributions to response are expected to be significant for the B-type buildings because the effective mass of the first lateral modes is less than 40% of the total mass.

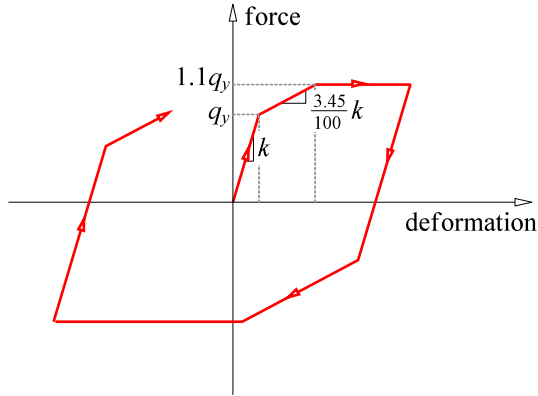


Figure 5 Constitutive model used for the buckling-restrained braces (BRBs).

4. EVALUATION METHODOLOGY

The following steps were implemented for evaluating the significance of the ground motion incidence angle on nonlinear behavior of buildings in near fault sites:

1. For each of the thirty records selected for this investigation, calculate rotated ground motion components by varying θ_x from 0° to 360° every 5° (Fig. 2b). The motions for $\theta_x=0^\circ$ 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 $\theta_x=\theta_m+90^\circ$. For estimating θ_m , use periods equal to 0.2, 1, 2, 3, and 5 sec.
2. Calculate the 5-percent 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 systems described previously using the geometric-mean spectrum of 30 FN components of Step 2 as the design spectrum. At the end of this step, values for k and q_y are obtained for each BRB. Recall that the 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 lead to linear-elastic design.

4. Conduct nonlinear RHAs of the 30 buildings subjected to bi-directional rotated components of ground motion obtained in Step 1. For each RHA, obtain floor displacements, floor accelerations, BRB plastic deformations, and BRB forces. This Step involves more than 34,000 nonlinear RHAs.

5. RESULTS

Nonlinear RHA was implemented for the systems of this investigation subjected to two horizontal components of ground motion following the procedure of Section 4. Figure 6 shows displacement u_x at the center of mass (red line) as a function of the incidence angle θ_x for symmetric-plan buildings 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 (FP) and fault-normal (FN) axes, respectively. Displacements u_x at corner c2 (Figure 4) as a function of the incidence angle θ_x for asymmetric-plan buildings are shown in Figure 7. More comprehensive results including other response quantities (that is EDPs) are presented in Reyes and Kalkan (2012).

Figures 6 and 7 permit the following observations: (1) Velocity-pulses may appear in directions different than the FN-direction; (2) The maximum displacement u_x over all non-redundant orientations seems to be 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-elastic system leading maximum displacement u_x also occur in the direction in which apparent velocity-pulse with period close to T_n is not observed (white areas); this is attributed to period elongation due to inelastic action; (3) Displacements in the x -direction may be underestimated by more than 50% if a building is subjected to only the FN/FP components of a pulse-like ground motion; (4) There is no optimum orientation for a given structure; the incidence angle that leads to maximum displacement u_x varies not only with the ground motion pair selected but also with the R value used in the design process of the building.

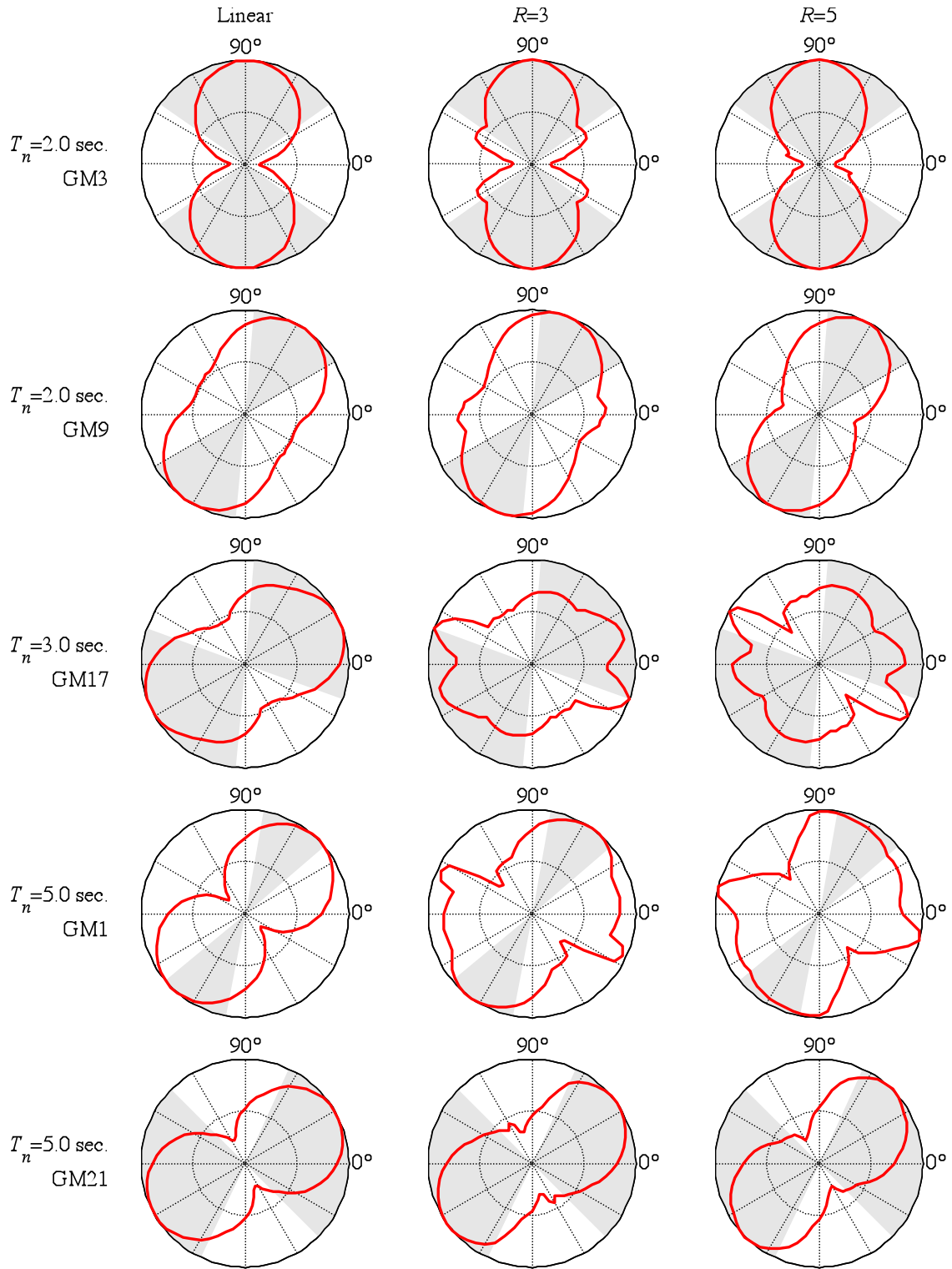


Figure 6 Displacement u_x (red) at the center of mass as a function of the incidence angle θ_x for symmetric-plan buildings with $T_n=2, 3$ and 5 sec. and with $R=3, 5$ and a value that lead to linear-elastic design. Each building is subjected to ground motions with velocity-pulse period close to T_n . The filled gray area shows values of θ_x in which velocity pulses are identified for each rotated ground motion pair. Angles $\theta_x=0^\circ$ and 90° correspond to the fault-parallel and fault-normal axes, respectively.

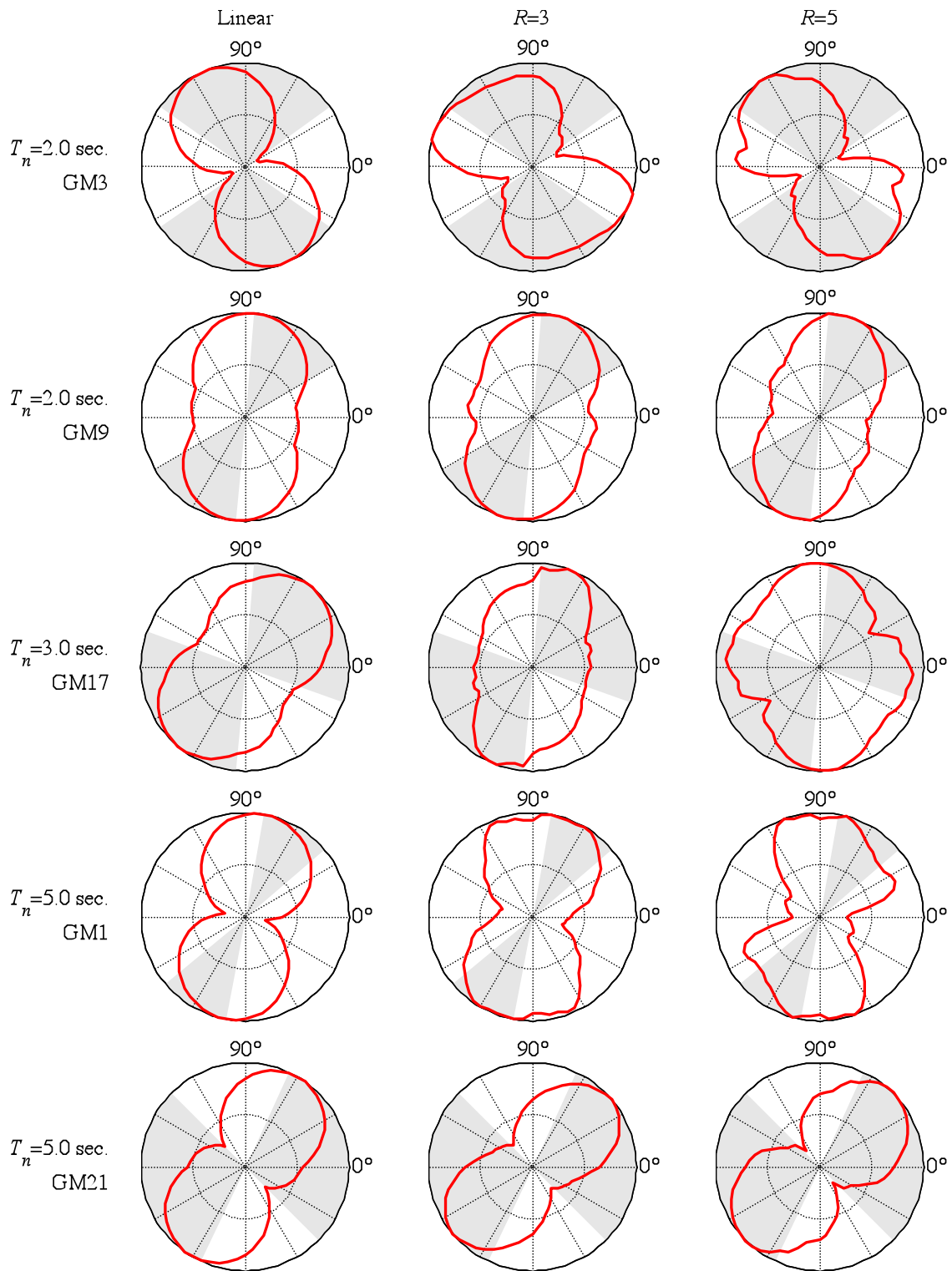


Figure 7 Displacement u_x (red) at corner c2 identified in Figure 4 as a function of the incidence angle θ_x for asymmetric-plan buildings with $T_n=2.0, 3.0$ and 5.0 sec. and with $R=3, 5$ and a value that lead to linear-elastic design Each building is subjected to ground motions with velocity-pulse period close to T_n . The filled gray area shows values of θ_x in which velocity pulses are identified for each rotated ground motion pair. Angles $\theta_x=0^\circ$ and 90° correspond to the fault-parallel and fault-normal axes, respectively.

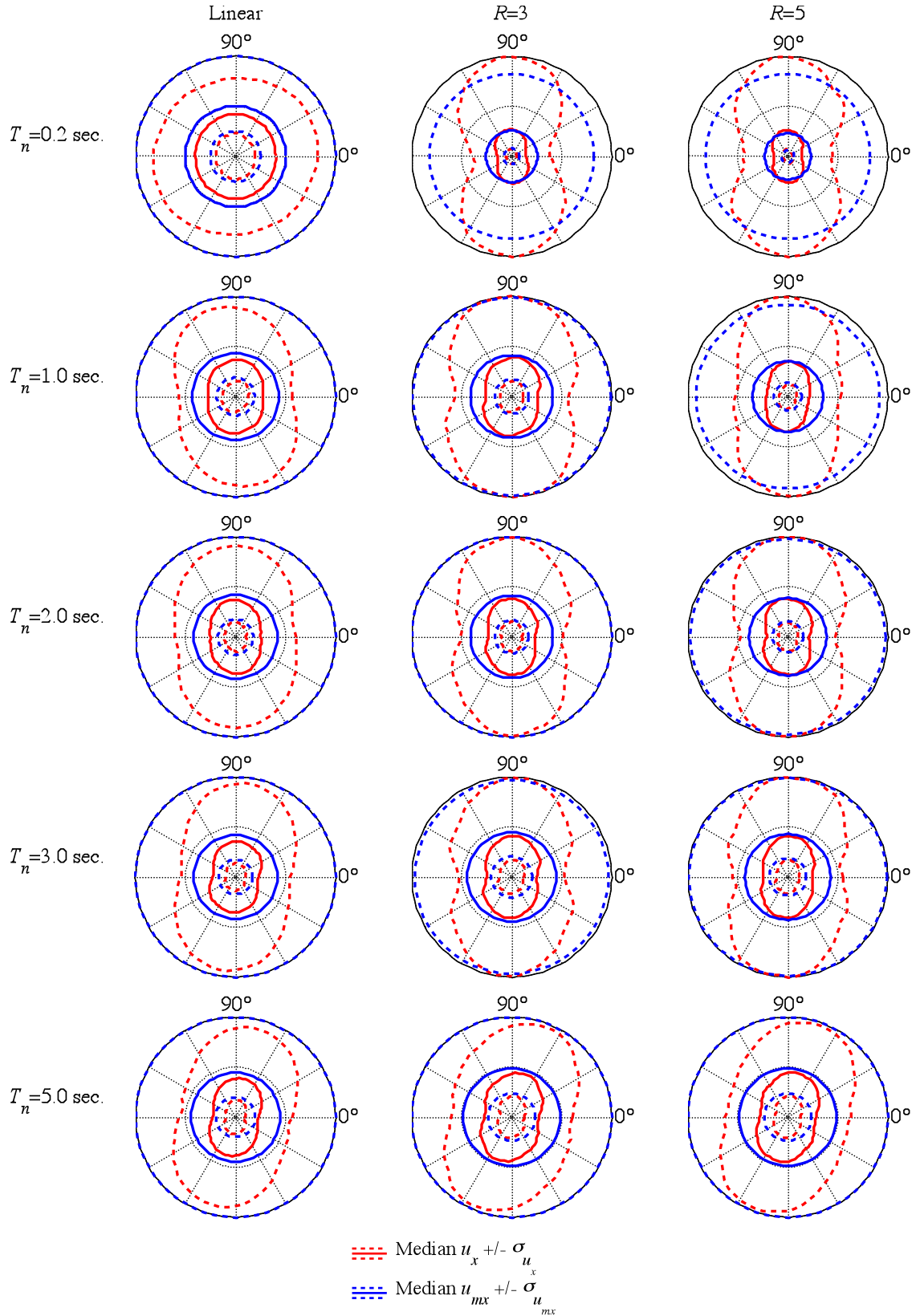


Figure 8 Median displacements u_x at the center of mass as a function of the incidence angle θ_x for symmetric-plan buildings with $T_n=0.2, 1, 2, 3,$ and 5 sec and with $R=3, 5$ and a value that lead to linear-elastic design subjected to 30 bi-directional motions. The red lines represent the median displacement $u_x \pm$ one standard deviation. The blue circles represent the median MD-displacement $u_{mx} \pm$ one standard deviation for the systems subjected to bi-directional ground motions in the principal axes (MD stands for maximum direction).

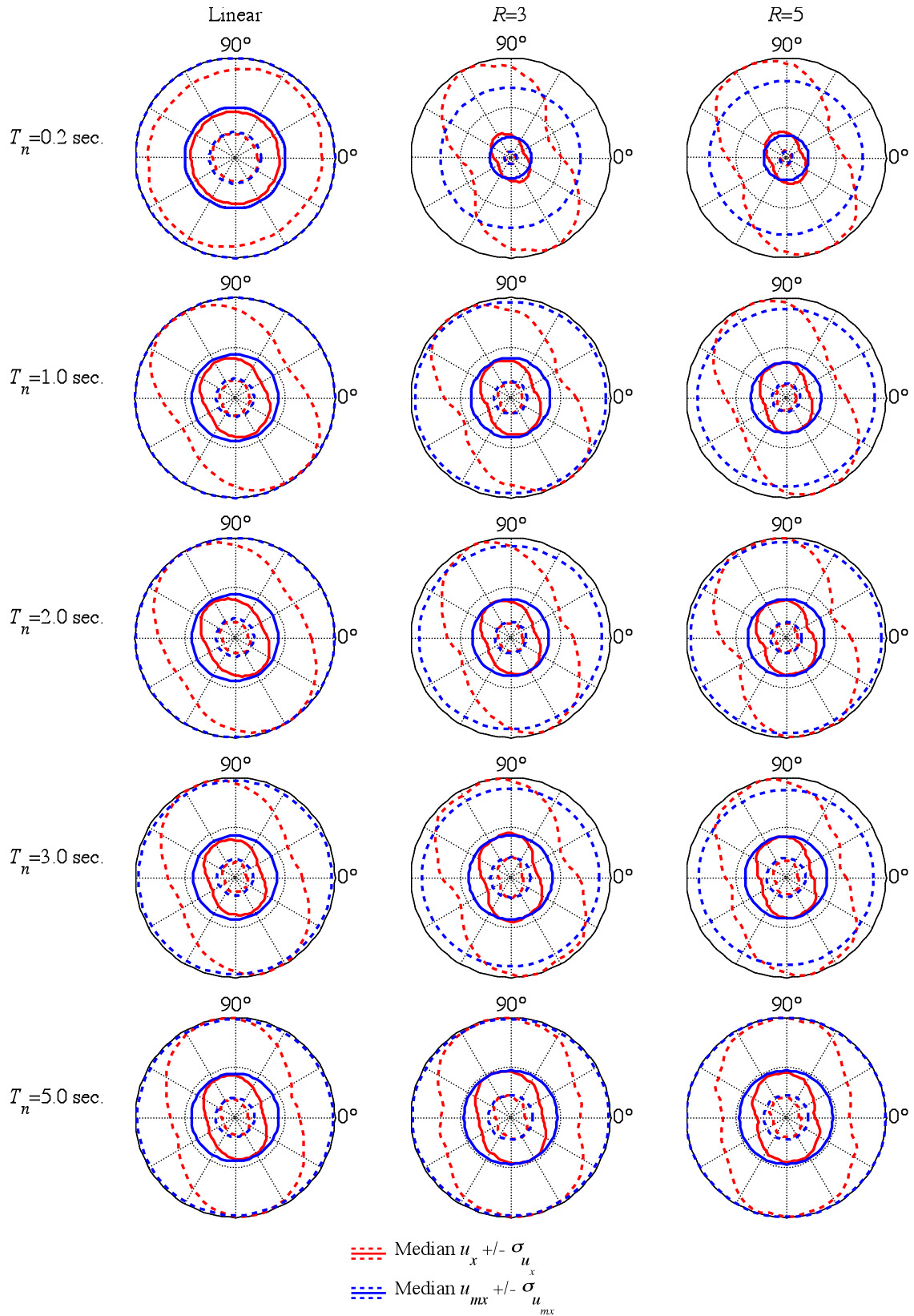


Figure 9 Median displacements u_x at corner c2 identified in Figure 4 as a function of the incidence angle θ_x for asymmetric-plan buildings with $T_n=0.2, 1, 2, 3,$ and 5 sec and with $R=3, 5$ and a value that lead to linear-elastic design subjected to bi-directional motions. The red lines represent the median displacement $u_x \pm$ one standard deviation. The blue circles represent the median MD-displacement $u_{mx} \pm$ one standard deviation for the systems subjected to bi-directional ground motions in the principal axes (MD stands for maximum direction).

For a selected earthquake scenario, it is commonly assumed that EDPs are lognormally 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 lognormal distribution are the same, we decided to employ the term “median” instead of geometric mean, as is commonly done. Figure 8 shows median displacements u_x at the center of mass as a function of the incidence 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 lead to linear-elastic design subjected to thirty bi-directional ground motions. The red lines represent the median displacement $u_x \pm$ one standard deviation σ computed based on peak response values due to each ground motion pair at each non-redundant incidence angle. In these figures, the blue circles represent the median MD-displacement $u_{mx} \pm \sigma$ (that is, $u_{mx} \exp(\pm\sigma)$) for the systems subjected to ground motions only in the principal axes. Recall that MD stands for maximum direction (that is, the specific directions of rotated ground motion pair resulting in peak linear-elastic response quantity of a single lumped mass oscillator as shown in Fig. 4). Note that for a given ground motion pair, principal axes (maximum direction) changes with period. In Figure 8, although the median 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 , which is a function of the incidence angle.

Median displacements at corner c2 (Fig. 5) for asymmetric-plan buildings are shown in Figure 9. Median values for other EDPs are presented in Reyes and Kalkan (2012).

For linear-elastic symmetric- and asymmetric-plan buildings with short periods, Figures 8 and 9 demonstrate very important information. The maximum median-displacement in the x -direction is almost independent of the incidence angle of the ground motion (Watson-Lamprey and Boore 2007). However, for R values of 3 and 5, the effect of the incidence angle is remarkable. 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. For linear-elastic systems, maximum median-displacements are smaller than median MD-displacements (Huang et al. 2008), but for nonlinear-inelastic systems, maximum median-displacements may be equal or larger than MD-displacements. For asymmetric-plan buildings (Fig. 10), maximum median-displacements $+ \sigma$ may be larger than MD-displacements $+ \sigma$ even for linear-elastic systems. These results clearly demonstrate that use of MD direction ground motions does NOT necessarily provide overconservative (or unrealistic) EDPs for systems responding in nonlinear-inelastic range in particular for asymmetric structures.

From Figures 8 and 9, 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 buildings are subjected to only the FN/FP components of a large set of ground motions. Similar observations are valid for other EDPs investigated (Reyes and Kalkan 2012). These observations and findings are also in agreement with those reported in Kalkan and Kwong (2012), where the influence that the angle of incidence angle of the ground motion pair has on several EDPs has been examined based on a linear-elastic computer model of a six-story instrumented building.

6. CONCLUSIONS

The current state-of-practice in U.S. is to rotate the as-recorded pair of ground motions to the fault-normal and fault-parallel (FN/FP) directions before they are used as input for three-dimensional nonlinear response history analyses (RHAs) of structures. 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 of rotation. Thus, it is considered to be a conservative approach appropriate for design verification of new structures and performance evaluation of existing structures. Based on a suite of symmetric and asymmetric single-story buildings having three-degree of freedom, the influence that the angle of incidence of the ground motion has on several engineering demand parameters (EDPs) has been examined here comprehensively. This investigation has led to the following conclusions:

1. Velocity-pulses may appear in directions different than the FN/FP directions.
2. For linear-elastic systems, the maximum displacement occurs in the direction in which apparent velocity-pulse with period close to the fundamental period of the structure is observed. This strong polarization vanishes for nonlinear-inelastic systems due to period elongation, which leads the maximum displacement occurs NOT in the direction in which apparent velocity-pulse with period close to the fundamental period of the structure.
3. Displacements may be underestimated by more than 50% if a building is subjected to only the FN/FP components of a single pulse-like ground motion.
4. If a building is subjected to a single near-fault ground motion, the incidence angle that leads to maximum displacement varies with the R value used in the design process of the building.
5. There is no optimum orientation for a given structure; the incidence angle that leads to maximum displacement varies with the ground motion pair selected.
6. For symmetric- and asymmetric-plan buildings with short periods that remain within the linear-elastic range, the maximum median-displacement is independent of the incidence angle of the ground motion. However, for R values of 3 and 5, the effect of the incidence angle is remarkable; maximum median-displacement occurs in the directions of FN/FP components.

7. Conducting nonlinear RHA for ground motions oriented in the principal axes (that is, maximum direction) does NOT always lead to the maximum engineering demand parameters (EDPs) overall orientations for systems responding in nonlinear-inelastic range in particular for asymmetric structures.
8. Conducting nonlinear RHA for ground motions oriented in the FN/FP axes does NOT always lead to the peak value of median-displacement overall orientations. However, displacements are not underestimated substantially (less than 20%) if the buildings are subjected to only the FN/FP components of a large set of ground motions. If only few ground motions are used, underestimations may be larger than 50%.

Although these observations and findings are primarily applicable to buildings and ground motions with characteristics similar to those utilized in this study, they are in close agreement with those reported in Kalkan and Kwong (2012), where the influence of rotation angle on several EDPs has been examined using a computer model of six-story instrumented building.

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