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# Comparison of Ground Motion Pulse Models for the Drift Response of Seismically Isolated Buildings


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# Comparison of Ground Motion Pulse Models for the Drift Response of Seismically Isolated Buildings

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## Abstract

Seismic isolation offers an improved protection to buildings by significantly reducing inter-story drifts, which is proven by the observed behaviors of seismically isolated buildings in the past earthquakes. On the other hand, with increasing database of earthquake records, researchers have come to realize that there exist ground motion records with near-fault effects characterized by long-period large-amplitude velocity pulses which threaten seismically isolated buildings with long natural periods of vibration. Therefore, drift responses of seismically isolated buildings under pulse-like near-fault earthquakes has been an important topic of discussion. As the number of recorded near-fault ground motions is scarce, researchers turn to use of artificially developed earthquakes. Makris (1997) and Agrawal and He (2002) developed ground motion pulse models that can be used in representing near-fault ground motions, which were used as excitation input in the investigations of the behavior of seismically isolated buildings previously. Therefore, investigation of the capability of these models in representing the effects of pulse-like ground motions on inter-story drift responses of seismically isolated buildings is essential. In order to examine this issue, the comparison of the inter-story drift responses of a prototype seismically isolated building with different seismic isolation systems under two historical earthquakes and their approximate counterpart Makris (1997) and Agrawal and He (2002) pulse models is presented here. Results show that the accuracy of the pulse models in representing near-fault earthquakes in terms of inter-story drift responses of seismically isolated buildings vary with respect to the earthquake and isolation system characteristics.

**Keywords:** Drift response, earthquake engineering, seismic isolation, near-fault earthquake, ground motion pulse model.

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## Introduction

Seismic isolation systems can protect the structural systems from the detrimental effects of high frequency excitations by shifting the predominant frequency of the those systems out of the frequency range that may be dangerous in terms of the possibility of a resonance (Komodromos, 2000). However, in the case of rapid and long-period motions such as near-fault ground motions, seismic isolation systems may strengthen the effects of the ground motion on the structure by amplifying the structural response parameters (Makris, 1997). Of the structural response parameters, inter-story drift response is very important in terms of the integrity and the safety of the super-structure. There are quite a few investigations about this issue in the literature (Kelly, 1999; Hall, 1999; Gavin and Alhan, 2002; Alhan and Gavin, 2004; Providakis, 2008; Alhan and Göktas, 2009). However, these studies generally make use of the earthquake record databases to retrieve near-fault earthquake ground motions. But, as the number of recorded near-fault ground motions is scarce, researchers are in need of artificially developed earthquakes, particularly to carry out parametric studies.

Near-fault ground motions include long-period pulses with high peak ground velocities (He and Agrawal, 2008), and can be simulated using equivalent pulse models (Sehhati et al., 2011). They may also be used in lieu of recorded ground motions to investigate the effects of near-fault ground motions on structural response parameters. In the literature, there are several analytical pulse models, proposed by various researchers (Hall et al., 1995; Makris, 1997; Makris and Chang, 2000; Alavi and Krawinkler, 1999; Agrawal and He, 2002; Menun and Fu, 2002; Mavroeidis and Papageorgiou, 2003; He and Agrawal, 2008) to simulate the pulse-like ground motions.

The ground displacement pulses in near-fault ground motions were classified into two main groups as A and B by Hall et al (1995). They denoted the pulses which have a forward only displacement as A, and the pulses which have a forward and backward displacement as B. To model the displacement pulses of both groups, they made use of the quadratic functions, based on the pulse period and the maximum value of the velocity pulse. Similarly, Makris (1997) denoted the half-cycle forward velocity pulses as Type A and the full-cycle forward-backward velocity pulses as Type B. In another study, Makris and Chang (2000) extended this classification, and denoted a ground motion pulse, exhibiting n main pulses in its displacement history, as Type $C_n$ pulse by providing the necessary trigonometric functions for these types of pulses. Alavi and Krawinkler (1999) proposed three linear velocity pulse models with piecewise linear functions, which have a half, a full, and two-and-half cycles, and denoted these pulses as P1, P2 and P3, respectively. Agrawal and He (2002) modeled the velocity pulses in near-fault ground motions with forward rupture directivity effect by using decaying sinusoids. Depending upon the five parameters such as velocity pulse, pulse period, time at which the pulse starts, and shape parameters, Menun and Fu (2002) proposed a mathematical model for the fault-normal component of the near-fault ground motions, to be used in lieu of ground motions. The velocity function, that they presented, was a piecewise-function, valid for specific time intervals as in Hall et al. (1995), Makris (1997), Alavi and Krawinkler (1999), and Makris and Chang (2000). Next, Mavroeidis and Papageorgiou (2003) proposed a single function to model the ground motion pulses analytically using Gabor wavelet. Thereafter, He and Agrawal (2008) presented the improved case of the pulse model, which they proposed in Agrawal and He (2002). Unlike the pulse model proposed in Mavroeidis and Papageorgiou (2003), both the special and improved case pulse models proposed by Agrawal and He (2002, 2008) are based on the Belarge wavelet. However, all of the models, presented in Mavroeidis and Papageorgiou (2003) and Agrawal and He (2002, 2008), are single functions and were verified using a large number of recorded ground motions (Dicleli and Buddaram, 2007).

The comparison of the inter-story drift responses of a prototype seismically isolated building with different seismic isolation systems under two historical earthquakes and their approximate counterpart Makris (1997) and Agrawal and He (2002) pulse models is presented in this study; while the comparison of the acceleration response part of the problem is presented in a companion paper by Öncü-Davas et. al, 2013.

## Synthetic Pulse Models

This section addresses the pulse models which were used to generate the synthetic earthquake records representing actual near-fault ground motions considered in this study. Because of its significant advantages arising from its simpler time domain expression, we made use of Agrawal and He (2002) pulse model, to simulate the recorded earthquakes. The proposed closed-form approximations of Agrawal and He (2002), for displacement, velocity, and acceleration time histories of the ground motions using circular frequency ($\omega_p$), initial amplitude of the velocity pulse (s) and damping factor for the decaying sinusoid ($\zeta_p$) are given in Eqs. 1-3, respectively.

$$d(t) = \left[ s e^{\alpha t} \left[ \alpha \sin(\beta t) - \beta \cos(\beta t) \right] + s\beta \right] / \omega_p^{2} \quad (1)$$

$$v(t) = s e^{\alpha t} \sin(\beta t) \quad (2)$$

$$a(t) = s e^{\alpha t} \left[ \alpha \sin(\beta t) + \beta \cos(\beta t) \right], \qquad \alpha = -\zeta_p \omega_p \,, \;\; \beta = \omega_p \sqrt{1 - \zeta_p^{\,2}} \quad (3)$$

In their study, Agrawal and He (2002) made comparisons to another pulse model which was developed by Makris (1997). Therefore, in our study we also include the pulse model proposed by Makris (1997) which is basically formed of trigonometric functions: The displacement, velocity, and acceleration time histories for a Type A pulse are given by

$$d_A(t) = (V_p/2)t - (V_p/2\omega_p)\sin(\omega_p t) \quad (4)$$

$$v_A(t) = (V_p/2) - (V_p/2)\cos(\omega_p t) \quad (5)$$

$$a_A(t) = \omega_p (V_p/2)\sin(\omega_p t) \quad (6)$$

and for a Type B pulse are given by

$$d_B(t) = (V_p/\omega_p) - (V_p/\omega_p)\sin(\omega_p t + \pi/2) \quad (7)$$

$$v_B(t) = -V_p \cos(\omega_p t + \pi/2) \quad (8)$$

$$a_B(t) = \omega_p V_p \sin(\omega_p t + \pi/2) \quad (9)$$

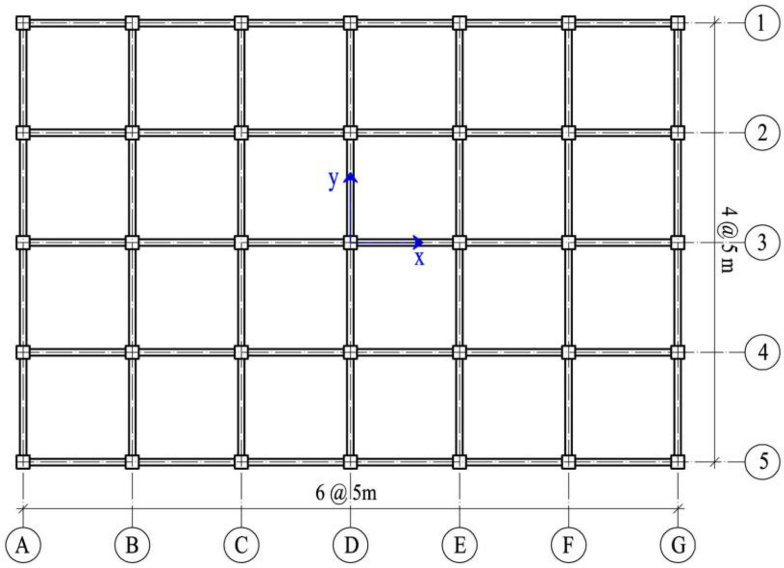
In Eqs. 4-9, where the functions are valid for the time interval $0 \leq t \leq T_p$, $V_p$, $T_p$, and $\omega_p$ are the amplitude, duration, and circular frequency of the main velocity pulse, respectively. The relation between $T_p$ and $\omega_p$ is obtained from the expressions in Makris (1997) as follows: $T_p = 2\pi/\omega_p$.

## Structural Model

The superstructure of the seismically isolated building, considered in this study, have 5 floors, consisting of moment resisting reinforced concrete frames. The typical floor plan and the typical section of the building are given Figure 1 and Figure 2, respectively. The typical bay width is 5m in each direction, and the typical story height is 3m. All frames of the superstructure consist of rectangular beams and square columns which have 30×50 cm×cm and 45×45 cm×cm cross-sections, respectively. The concrete class is considered to be C30 with an elastic modulus of 32000 MPa for all members.

Each floor of the superstructure has 650 $kNs^2/m$ translational mass, which is assumed to be lumped at the center of gravity of the corresponding floor level. All floors are modeled as rigid diaphragms, having three degrees of freedom at the center of mass of each floor: translational X, translational Y, and a rotational degree of freedom. The natural translational period of the building, obtained from modal analyses, conducted in SAP2000 (CSI, 2011) for fixed-base condition, is 0.65s.

**Figure 1.** *Typical floor plan of the seismically isolated building*



Four different isolation systems (Table 1) each of which consists of 35 isolators, exhibiting bi-linear behavior and placed centrally underneath each column, are considered in this study. To connect the isolators, a rigid base floor with a mass equal to the masses of other floors is also added between the isolators and the columns. As seen in Table 1, two different levels of isolation period ($T_0$=3.0 s and $T_0$=5.0 s) and two different levels of characteristic strength ratio (Q/W=5% and Q/W=10%) are considered to set up the isolation systems. The pre-yield stiffness ($K_1$), the post-yield stiffness ($K_2$), and the yield displacement ($D_y$) of the isolators are also listed in Table 1.

**Figure 2.** *Typical section of the seismically isolated building*


**Table 1.** *Isolation systems and their characteristic parameters*

| Isolation System | T (s) | Q/W (%) | Q (kN) | $K_1$ (kN) | $K_2$ (kN) | $D_y$ (m) |
|---|---|---|---|---|---|---|
| **T03QW5** | 3 | 5 | 53.14 | 1803.72 | 475.22 | 0.04 |
| **T03QW10** | 3 | 10 | 106.28 | 3132.21 | 475.22 | 0.04 |
| **T05QW5** | 5 | 5 | 53.14 | 1499.57 | 171.08 | 0.04 |
| **T05QW10** | 5 | 10 | 106.28 | 2828.07 | 171.08 | 0.00 |

**Near-fault Ground Motions**

In this study, we have simulated two components of two recorded near-fault ground motions (Table 2), and generated synthetic time history counterparts for these records. We used pulse models Type A and B, presented in Makris (1997), and the pulse model presented in Agrawal and He (2002). Generation of the synthetic time histories have been completed using Eqs. 1-9.

**Table 2.** *Near-fault ground motion components*

| Component | Earthquake | Date | Station | PGA (g) | PGV (cm/s) | PGD (cm) |
|---|---|---|---|---|---|---|
| **RRS228** | Northridge | 1/17/1994 | 77 Rin. Rec. Sta. | 0.838 | 166.100 | 28.780 |
| **N90** | Landers | 6/28/1992 | Lucerne Valley | 0.731 | 145.45 | 259.39 |

The time histories of the recorded ground motions RRS228 (obtained from PEER, 2005) and N90 (obtained from COSMOS, 2013) and the corresponding synthetic time histories, generated for these ground motions using Type A, Type B and Agrawal & He pulse models, are shown in Figures 3 and 4, respectively. The parameters used for modeling each synthetic pulse model are listed in Table 3. $T_p$ and $V_p$ values of Type A and B pulses corresponding to RRS228 record, are obtained from Makris and Chang (2000); whereas those for N90 record are obtained from Makris (1997). The parameters for Agrawal & He pulses are obtained from Agrawal and He (2002).

**Table 3.** *Synthetic pulse parameters defining RRS228 and N90*

| Pulse Model | RRS228 | | | N90 | | |
|---|---|---|---|---|---|---|
| | $T_p$ (s) | $V_p$ (m/s) | s (m/s) | $T_p$ (s) | $V_p$ (m/s) | s (m/s) |
| **Makris - A** | 0.800 | 1.750 | - | 3.100 | 1.153 | - |
| **Makris - B** | 1.300 | 1.300 | - | 4.870 | 1.153 | - |
| **Agrawal & He** | 1.030 | - | 2.000 | 4.620 | - | 1.740 |

**Figure 3.** *Recorded and generated time histories of RRS228*

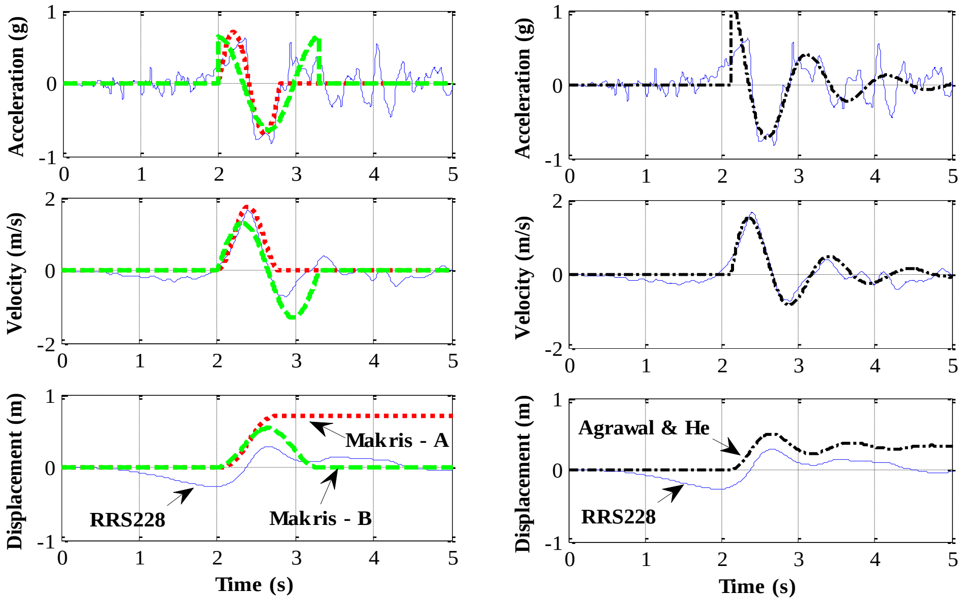
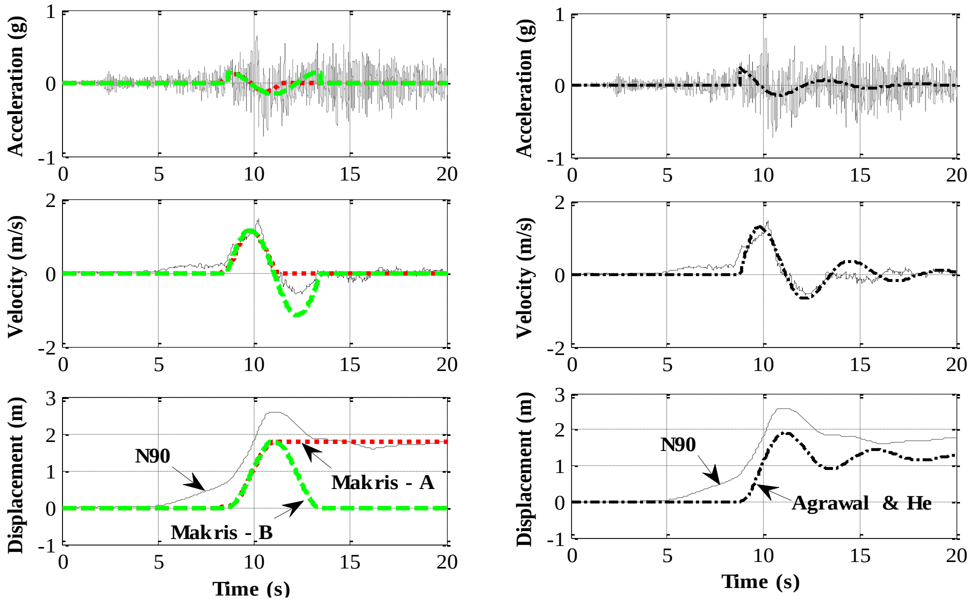



**Figure 4.** *Recorded and generated time histories of N90*



## Results and Conclusions

The results of the full three dimensional nonlinear dynamic analyses conducted in 3D-Basis (Nagarajaiah et al., 1990) for the structural model described in Section 3 when subjected to the acceleration records of RRS228 and N90 and their generated counterparts are presented in this section. The peak (absolute maximum) inter-story drift ratios, which have been obtained for RRS228, N90, and generated ground motion pulses, are presented in Table 4 for all floor levels.

For a better comparison of the ground motion pulses in terms of drift responses, error ratios of the pulse models are presented in Figure 5. These ratios are calculated by dividing the drift ratios obtained for a generated ground motion data by the drift ratios obtained for the corresponding recorded ground motion data (**Error ratio = Drift ratio$_{\textbf{generated}}$/ Drift ratio$_{\textbf{recorded}}$**).

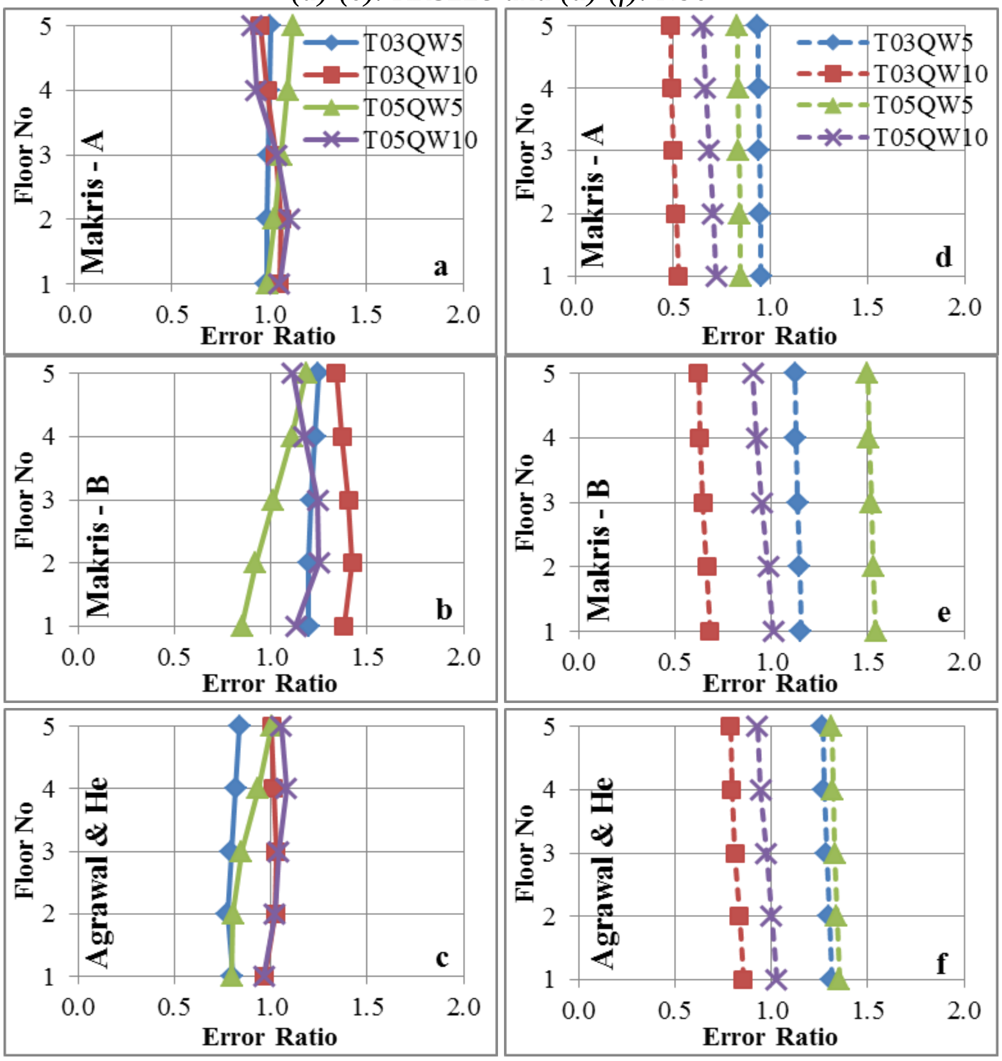
**Table 4.** *Peak inter-story drift ratios*

| EQ | Floor No | T03 QW5 | T03 QW10 | T05 QW5 | T05 QW10 | EQ | Floor No | T03 QW5 | T03 QW10 | T05 QW5 | T05 QW10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RRS228 Recorded | 1 | 0.00285 | 0.00293 | 0.00151 | 0.00183 | N90 Recorded | 1 | 0.00280 | 0.00303 | 0.00205 | 0.00200 |
| | 2 | 0.00348 | 0.00359 | 0.00182 | 0.00222 | | 2 | 0.00335 | 0.00369 | 0.00245 | 0.00245 |
| | 3 | 0.00281 | 0.00307 | 0.00145 | 0.00200 | | 3 | 0.00266 | 0.00298 | 0.00194 | 0.00198 |
| | 4 | 0.00196 | 0.00229 | 0.00100 | 0.00162 | | 4 | 0.00182 | 0.00207 | 0.00132 | 0.00139 |
| | 5 | 0.00106 | 0.00130 | 0.00054 | 0.00103 | | 5 | 0.00097 | 0.00112 | 0.00071 | 0.00075 |
| RRS228 Makris - A | 1 | 0.00281 | 0.00309 | 0.00150 | 0.00193 | N90 Makris - A | 1 | 0.00266 | 0.00159 | 0.00173 | 0.00144 |
| | 2 | 0.00344 | 0.00382 | 0.00187 | 0.00244 | | 2 | 0.00318 | 0.00189 | 0.00206 | 0.00172 |
| | 3 | 0.00280 | 0.00317 | 0.00154 | 0.00208 | | 3 | 0.00250 | 0.00149 | 0.00162 | 0.00136 |
| | 4 | 0.00196 | 0.00227 | 0.00110 | 0.00152 | | 4 | 0.00170 | 0.00102 | 0.00110 | 0.00092 |
| | 5 | 0.00107 | 0.00124 | 0.00060 | 0.00095 | | 5 | 0.00091 | 0.00054 | 0.00059 | 0.00049 |
| RRS228 Makris - B | 1 | 0.00340 | 0.00405 | 0.00129 | 0.00207 | N90 Makris - B | 1 | 0.00323 | 0.00206 | 0.00315 | 0.00202 |
| | 2 | 0.00416 | 0.00510 | 0.00168 | 0.00277 | | 2 | 0.00384 | 0.00245 | 0.00374 | 0.00240 |
| | 3 | 0.00340 | 0.00432 | 0.00147 | 0.00249 | | 3 | 0.00302 | 0.00192 | 0.00294 | 0.00189 |
| | 4 | 0.00241 | 0.00313 | 0.00111 | 0.00191 | | 4 | 0.00205 | 0.00131 | 0.00200 | 0.00128 |
| | 5 | 0.00132 | 0.00174 | 0.00063 | 0.00115 | | 5 | 0.00109 | 0.00069 | 0.00106 | 0.00068 |
| RRS228 Agrawal & He | 1 | 0.00228 | 0.00284 | 0.00121 | 0.00176 | N90 Agrawal & He | 1 | 0.00368 | 0.00259 | 0.00277 | 0.00206 |
| | 2 | 0.00270 | 0.00368 | 0.00146 | 0.00226 | | 2 | 0.00436 | 0.00307 | 0.00328 | 0.00245 |
| | 3 | 0.00224 | 0.00316 | 0.00123 | 0.00209 | | 3 | 0.00341 | 0.00242 | 0.00257 | 0.00193 |
| | 4 | 0.00160 | 0.00232 | 0.00093 | 0.00175 | | 4 | 0.00231 | 0.00165 | 0.00175 | 0.00131 |
| | 5 | 0.00089 | 0.00131 | 0.00054 | 0.00109 | | 5 | 0.00123 | 0.00088 | 0.00093 | 0.00070 |

As seen in Table 4, Makris - A pulse model results match the results for the actual RRS228 record for all isolation systems the best. Error ratio for this model varies between 0.92 and 1.12 (Figure 5a). The next good match is observed for Agrawal & He model (Figure 5c) with error ratios varying from 0.78 to 1.08. Makris - B pulse model seems to provide results that are relatively off (Table 4) with error ratios varying from 0.85 to 1.42 (Figure 5b). When the results for N90 is examined, it is seen that pulse models in general do a poorer job compared to RRS228 case (Table 4). For example, the error ratios of Makris - A pulse model go down to 0.5 for T03QW10 case as seen in Figure

5d; the error ratios of Makris - B pulse model change in a wide range, between 0.5 and 1.5, as seen in Figure 5e; and the error ratios of the Agrawal & He model change in the range of 0.79 ~ 1.35 as seen in Figure 5f. However, there still exist cases where pulse models accurately represent N90 record. For example, T03QW5 and T05QW5 cases with Makris - A model (Figure 5d), T03QW5 and T05QW10 cases with Makris - B model (Figure 5e), and T03QW10 and T05QW10cases with Agrawal & He model (Figure 5f) work well. Therefore, it is clear that the accuracy of the pulse models in representing near-fault earthquakes in terms of inter-story drift responses of seismically isolated buildings vary with respect to the earthquake and isolation system characteristics.

**Figure 5.** *Error ratios of peak inter-story drift ratios (a)-(c): RRS228 and (d)-(f): N90*




In order to present a visual comparison of the ground motion pulse models and the actual earthquake records in terms of the generated drift responses, the time history plots of the first story and the fifth story drift ratios for all isolation systems are given in Figures 6 and 7 for RRS228 and N90, respectively. It is observed from Figures 6 and 7 that although none of the drift ratio time histories corresponding to the synthetic pulse models exactly fits the drift ratio time histories corresponding to the actual recorded ground motions, there still exists a general compliance between the time histories. For the shown example plots, Makris - A and Agrawal & He follow the responses corresponding to the actual earthquake records very closely, in particular during the main-shock time bracket.

**Figure 6.** *First story drift ratio histories, RRS228*

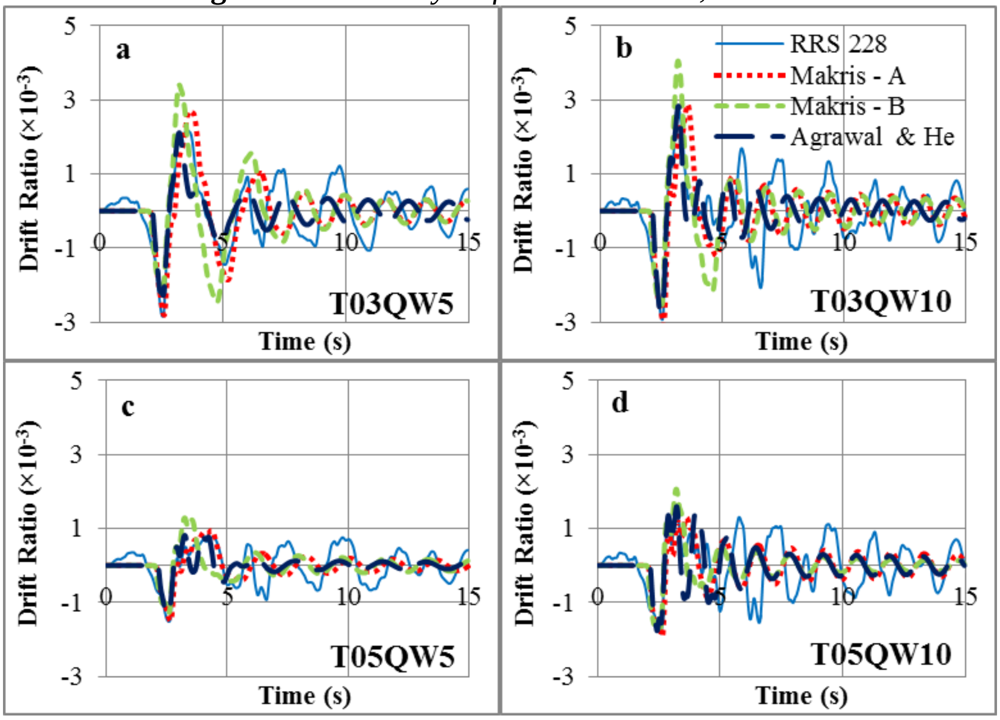
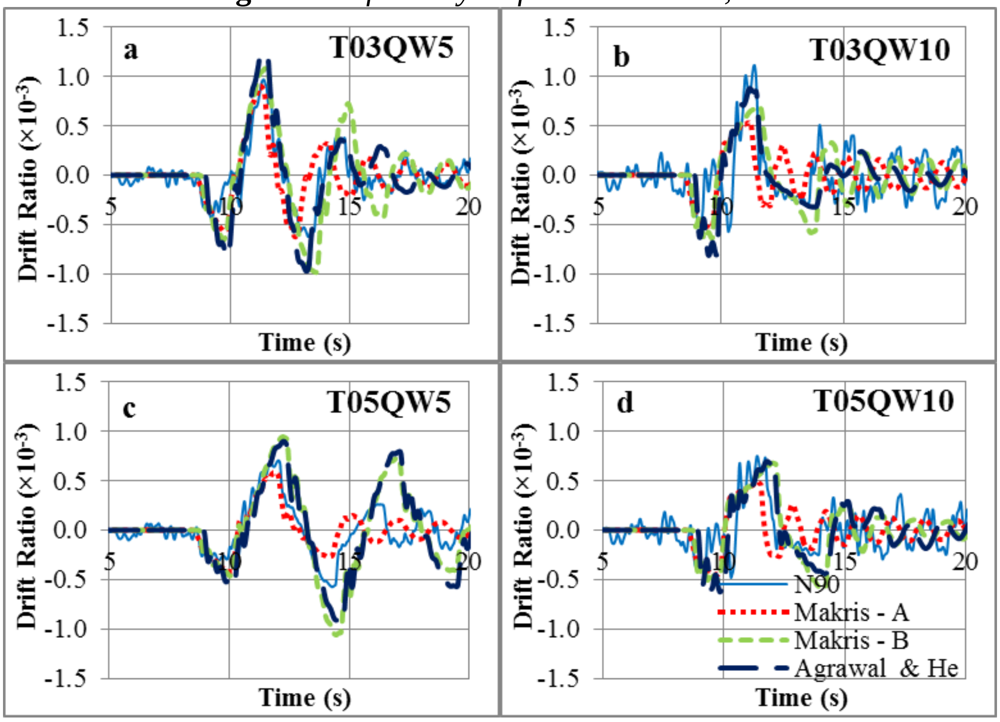



**Figure 7.** *Fifth story drift ratio histories, N90*



So far, we have compared the peak inter-story drift ratios. In addition to the peak value of a structural response parameter, the root mean square (RMS) values are also important for structural design. RMS values better indicate the general compliance of the inter-story drift time histories corresponding to the synthetic pulses and the actual records throughout the whole time history. Thus, we present the RMS values of the inter-story drift ratios, calculated for all isolation systems in Figures 8 and 9 for RRS228 and N90, respectively. It's seen in Figure 8 that, while Makris - A and B provide good estimates for short period cases ($T_0$ = 3 s), Agrawal & He model approximations are generally off. As for the N90 record (Figure 9), Makris - A generally underestimates the drift ratios; whereas Makris - B and Agrawal & He models generally overestimates these ratios.

Based on the parametric analyses conducted and discussed above, it is finally concluded here that the accuracy of the pulse models in representing near-fault earthquakes in terms of inter-story drift responses of seismically isolated buildings vary with respect to the earthquake and isolation system characteristics. In general, the pulse models provide better approximations in terms of peak values compared to RMS values, since inter-story drift ratio time histories corresponding to the actual earthquake records are best matched during the main-shock time bracket by the inter-story drift ratio time histories corresponding to the synthetic pulses.

**Figure 8.** *Root mean square inter-story drift ratios, RRS228*

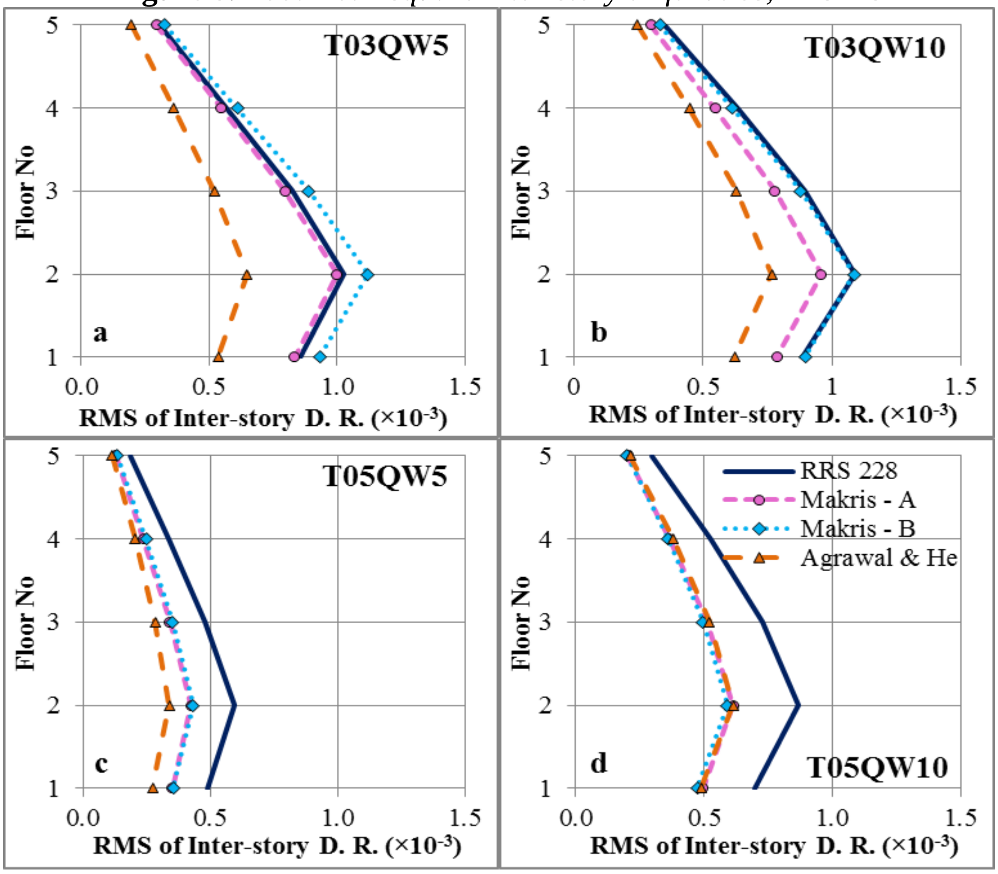
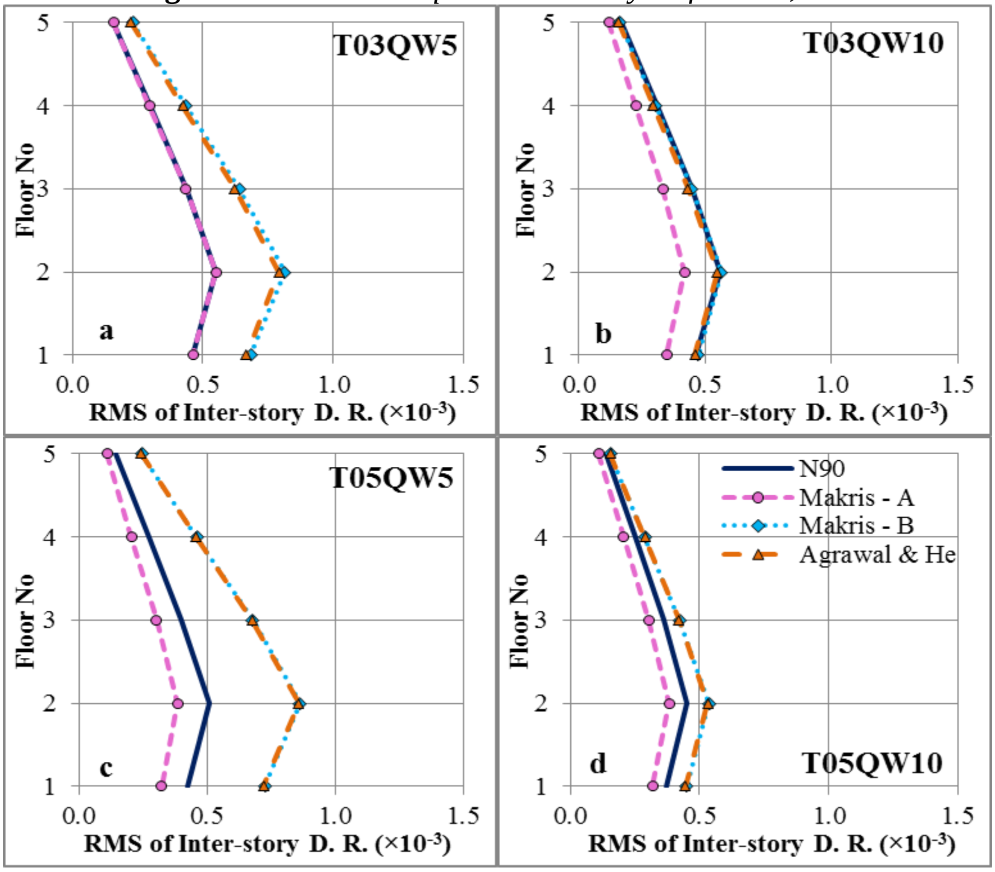


**Figure 9.** *Root mean square inter-story drift ratios, N90*

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