Response of RC frames under pulse-like seismic ground motion: sensitivity analysis and relevance of the dominant pulse

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Keywords: Near-fault ground motion; RC frame; Pulse period; Nonlinear dynamic analysis; OpenSEES

ABSTRACT

The present study addresses the numerical simulation of the response of reinforced concrete (RC) frames subjected to near-fault pulse-like earthquakes. A 2D parametric model of a RC frame is first developed using the OpenSEES software package. This parametric model accounts for the non-linear behavior of the members through a fiber-based approach. Numerical investigations are performed on 2D RC frames with 4 and 10 floors (which correspond to fundamental period values equal to 0.49 s and 0.98 s, respectively). Several time histories of near-fault pulse-like earthquakes are then selected, from which the dominant pulse and the corresponding period are derived by means of a recent approach based on the Variational Mode Decomposition technique. The seismic time histories are characterized using some seismic Intensity Measures (IMs) whereas the structural response is reported in terms of different engineering demand parameters (EDPs). Finally, a discussion about the relationship between selected IMs and EDPs is provided, together with some comments on the relevance of the dominant pulse.

1 INTRODUCTION

Near-fault ground motions have significantly different characteristics compared to the ones observed in earthquakes recorded far away from the seismic source (Yang et al., 2019). In fact, compared with an ordinary (non-pulse-like) seismic ground motion, a pulse-like earthquake typically has large amplitudes at low frequencies, a higher energy level and a larger ratio of the peak ground velocity to peak ground acceleration. Previous studies about the seismic response of civil structures show that pulse-like earthquakes often induce an extremely high structural seismic demand (e.g., Mylonakis and Voyagaki, 2006).

The characterization of near-fault pulse-like earthquakes has been addressed within several studies. For instance, Baker (2007) implemented the Wavelet Decomposition Method for the analysis of pulse-like seismic ground motion records. Mukhopadhyay and Gupta (2013) have developed an algorithm to extract the pulses based on a repetitive smoothening technique. Amiri and Moghaddam (2014) have proposed a modified version of the S-transform for the decomposition of seismic signals to identify the pulse-like part of near-fault velocity records. Chang et al. (2016) have identified the dominant impulsive mode from the original record by minimizing the difference between a numerical pulse model and the velocity time history of the seismic ground motion. On the other hand, Mimoglou et al. (2017) have illustrated a direct method to estimate the pulse period: according to their approach, the pulse period corresponds to the period value for which the product of velocity and displacement elastic response spectra for 5% damping attains its maximum value. More recently, Quaranta and Mollaioli (2019) proposed an approach based on the use of the Variational Mode Decomposition technique for the analysis of pulse-like ground motion.

Near-fault pulse-like ground motions caused much of the damage in recent major earthquakes (e.g., Northridge 1994, Kobe 1995, Chi-Chi 1999). For such seismic loading condition, the response is sensitive to the pulse period value as compared to the fundamental period of the structure, as shown for the first time by Anderson and Bertero (1987) when studying the response of steel frames subjected to ground motions recorded during the 1979 Imperial Valley earthquake. Only a few recent studies have investigated the response of reinforced concrete (RC) frames under pulse-like seismic ground motion.

Within this framework, the present study attempts to shed a light into the seismic response of RC structures under pulse-like ground motion by examining a few simple frames and taking into account a quite large number of near-fault ground motion records. To this end, a 2D parametric model of a RC frame is first developed using the OpenSEES software package. The model accounts for the non-linear behavior of the members through a fiber-based approach. A numerical investigation is then performed for two frames having a different number of floors. Several time histories of near-fault pulse-like earthquakes are then considered in order to perform nonlinear dynamic analyses. The seismic time histories are characterized by using some seismic Intensity Measures (IMs). Different engineering demand parameters (EDPs) are also calculated. Finally, a discussion about the relationship between selected IMs and EDPs is provided.

2 MODEL DESCRIPTION AND DESIGN

To investigate the effects of the pulse-like seismic ground motion characteristics on buildings with different natural periods, two typical three-bay RC frames with 4 and 10 floors are designed in compliance with the Italian Building Code (NTC, 2018). The two frames are designed taking into account, both, gravity and seismic loads (assuming a design peak ground acceleration equal to 0.2g). In these two RC frames, the height is 4 m for the first-story and 3 m for the others, while the span width is taken equal to 6 m. Figure 1 illustrates the elevation view of the two RC frames together with the dimension of the cross-section of beams and columns. The seismic response of each frame is calculated by means of a 2D numerical model built within the OpenSEES (Version 2.4.6) framework (McKenna et al., 2013) and by invoking each analysis using Matlab©. Beams and columns are modeled using a force-based beam-column element and only the columns account for the P-Δ effect. The cross-section is subdivided into concrete layers as follows: 1 in the neutral axis direction and 80 in the perpendicular direction. The reinforcement bars are modeled as single fibers. The concrete is modeled using Concrete02 Material - Linear Tension Softening whereas the steel is modeled using Steel02 Material (McKenna et al., 2013). The compressive strength of concrete is 25 MPa whereas the yield strength of the steel is assumed equal to 400 MPa. Rayleigh damping with modal damping ratios 5% of critical damping in the first mode is considered. The natural period of the 4- and 10-story RC frames along the considered direction is 0.49 s and 0.98 s, respectively.

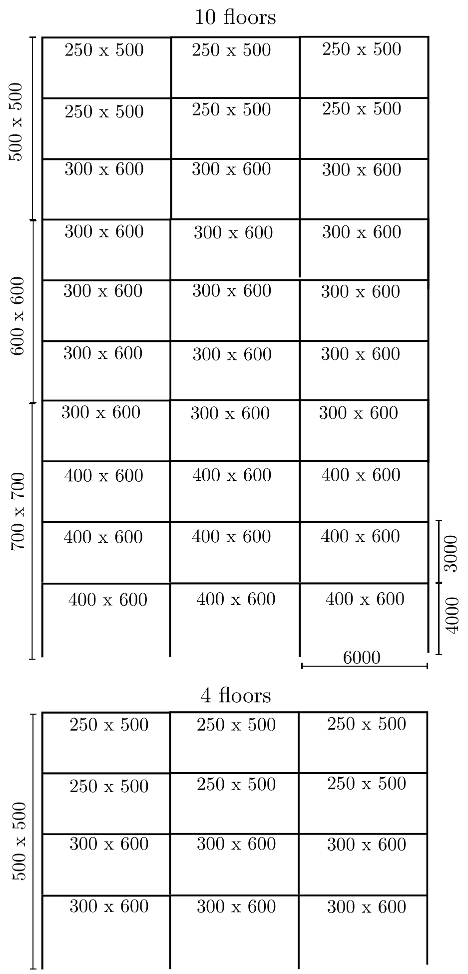

Figure 1. Elevation view of the two RC frames considered in the present study (4 and 10 floors). (Units: mm).

3 GROUND MOTION DATASET AND ANALYSIS

3.1 Pulse extraction via Variational Mode Decomposition technique

The pulse and the corresponding period have been identified according to the approach developed by Quaranta and Mollaioli (2019), which is based on the use of the Variational Mode Decomposition (VMD) method (Dragomiretskiy and Zosso, 2014). According to the VMD technique, the bandwidth of the mode is determined through the following procedure:

1. compute the analytical signal for each mode using the Hilbert transform in such a way to obtain a unilateral frequency spectrum;
2. shift the mode's frequency spectrum to baseband for each mode, by mixing with an exponential tuned to the respective estimated center frequency;
3. estimate the bandwidth using the H1 Gaussian smoothness of the demodulated signal (i.e., squared L2-norm of the gradient).

Formally, this requires the solution of the following constrained variational problem:

$$\min_{v_k(t),\omega_k} \left\{ \sum_{k=1}^{N} \left\| \partial_t \left[\left(\delta(t) + \frac{\mathrm{j}}{\pi t} \right) * v_k(t) \right] e^{-\mathrm{j}\omega_k t} \right\|_2^2 \right\}$$

$$\text{s.t.} \sum_{k=1}^{N} v_k(t) = v(t), \qquad (1)$$

where $v(t)$ is the signal to be decomposed (i.e., the ground motion velocity of the near-fault earthquake), $v_k(t)$ is the kth mode and ω_k the corresponding center pulsation ($k = 1, \cdots, N$, in which N is the number of modes), $\delta(\cdot)$ is the Dirac delta operator and $*$ is the convolution operator (t is the time variable).

This mathematical programming problem can be solved by means of different approaches. A convenient way is the one based on the use of Lagrangian multipliers and quadratic penalty term, in such a way to transform the original constrained optimization into an unconstrained one.

Once the signal modes $v_k(t)$ have been extracted through the VMD technique, they are fitted with a pulse-like numerical waveform, thereby obtaining $\hat{v}_k(t)$. In the present study, the waveform proposed by Mavroeidis and Papageorgiou (2003) is employed. In order to identify the dominant pulse (and the corresponding pulse period T_p) among the extracted modes $\hat{v}_k(t)$, the pulse indicator $0 < PI < 1$ proposed by Baker (2007) is computed, by assuming a threshold equal to 0.50. Only the records that contain a clear and dominant pulse in their velocity time series are considered. The obtained database consists of 143 strong-motion records and is briefly described in the following.

3.2 Database of seismic records and pulse characterization

Figure 2 illustrates the main seismological features of the considered dataset of horizontal near-fault pulse-like earthquakes.

Figure 3 shows a comparison between the estimates of the pulse period obtained according to several methodologies. Herein, it can be observed that a general good agreement exists among the different proposals available in the literature.

Finally, an example of pulse extraction and pulse period estimation according to the illustrated procedure is given in Figure 4.

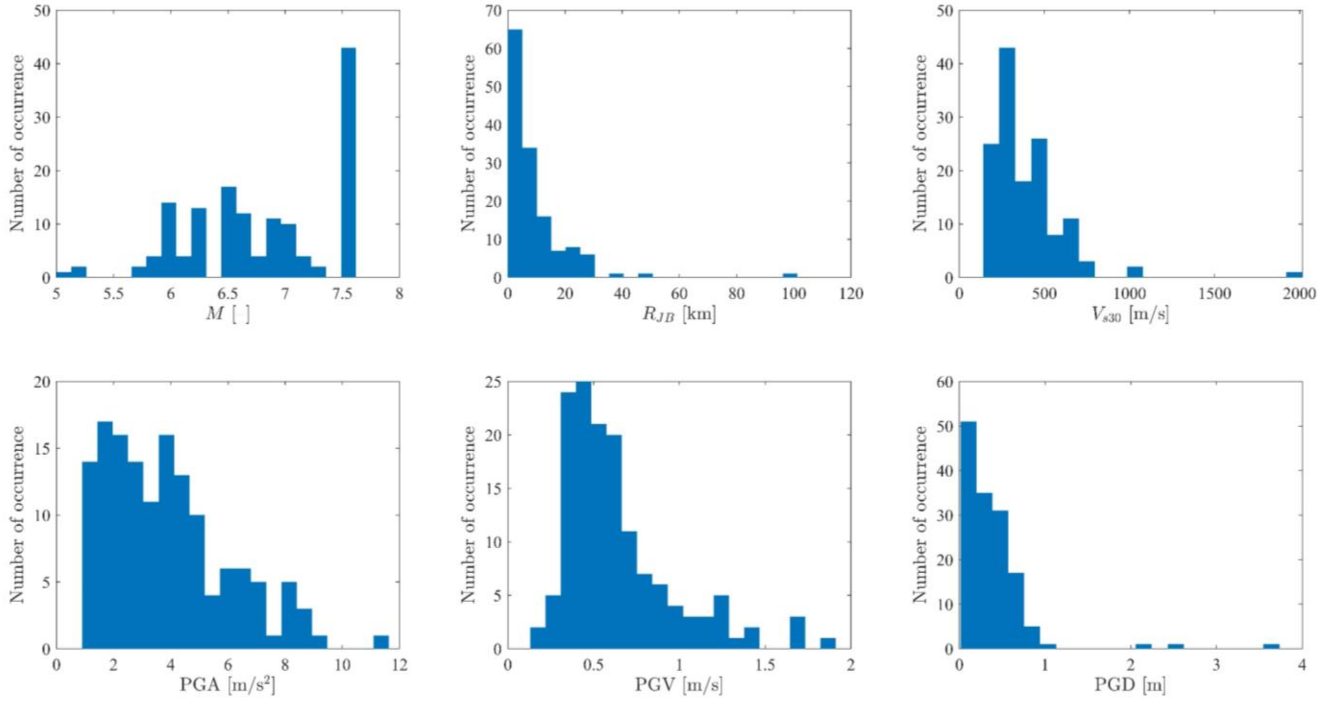

Figure 2. Variation of seismological parameters within the considered database of fault-normal horizontal seismic signal components: moment magnitude M, Joyner-Boore distance R_{JB}, preferred shear wave velocity in the upper 30 m of the site V_{s30}, peak ground acceleration PGA, peak ground velocity PGV and peak ground displacement PGD.

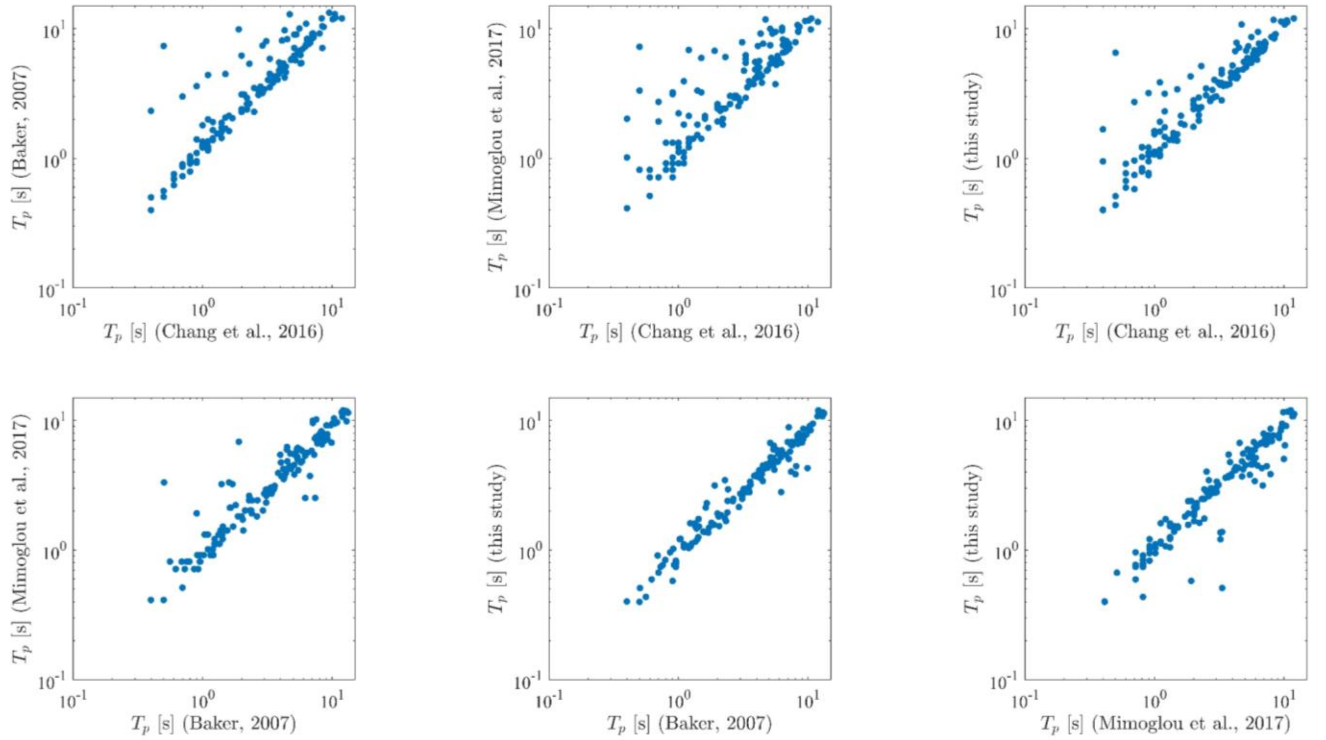

Figure 3. Comparison of pulse period estimates obtained by means of different methods.

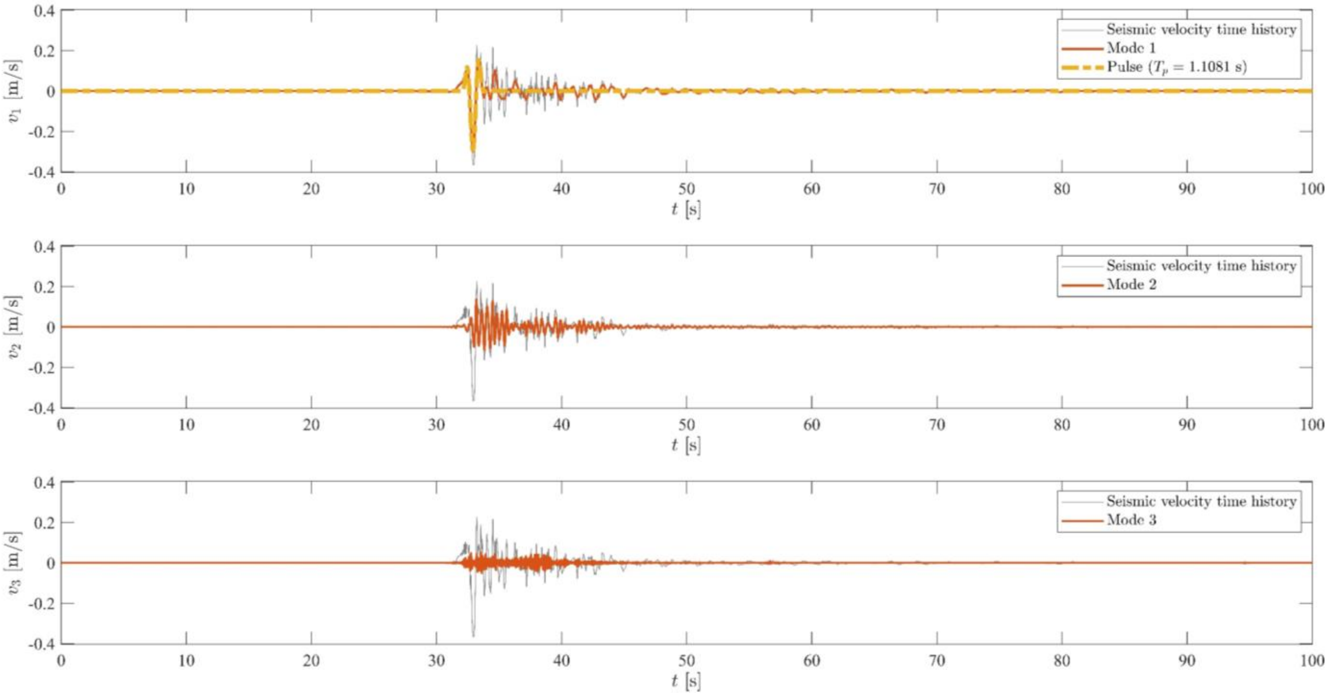

Figure 4. Pulse extraction and pulse period estimation for a seismic record of the L'Aquila earthquake (2009). The pulse period estimates carried out according to the methodologies proposed by Baker (2007), Chang et al. (2016) and Mimoglou et al. (2017) are 1.10 s, 0.90 s and 1.02 s, respectively.

4 STRUCTURAL RESPONSE

The analyses are carried out by considering, both, the recorded ground motion and the extracted dominant pulse. Figure 5 reports the maximum inter-story drift ratio values for the 4- and 10-story RC frame calculated using the whole seismic ground motion record and the extracted dominant pulse only. For the 4-story RC frame, these results highlight that a large difference exists in terms of inter-story drift ratio if the pulse only is considered instead of the whole seismic ground motion record. Particularly, the inter-story drift ratio is largely underestimated if the pulse only is considered. The difference is especially evident for higher values of the peak ground acceleration. On the other hand, for the 10-story RC frame, the difference is not so large even through, as expected, the use of the whole ground motion record leads to larger drift ratios than the ones estimated using the dominant pulse only.

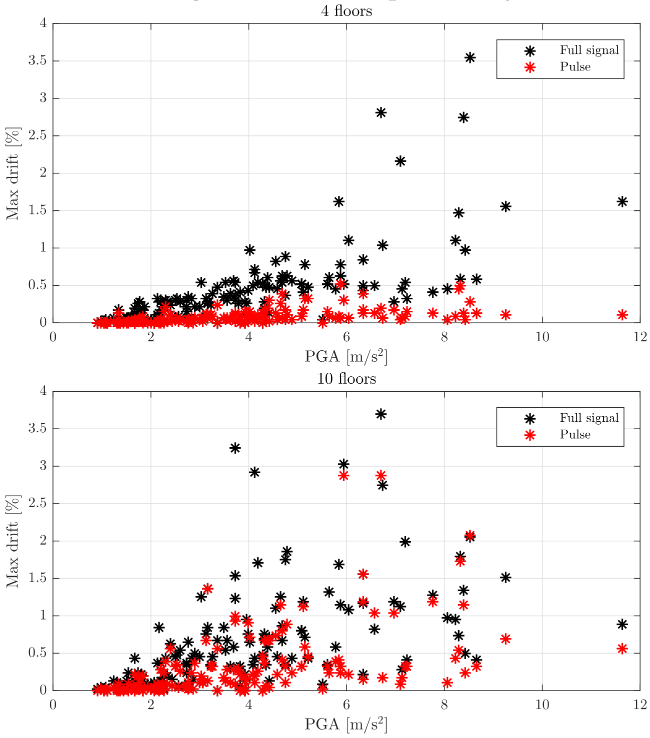

Figure 5. Inter-story drift ratio for 4- and 10-story RC frame calculated using the whole seismic ground motion record and the extracted dominant pulse only.

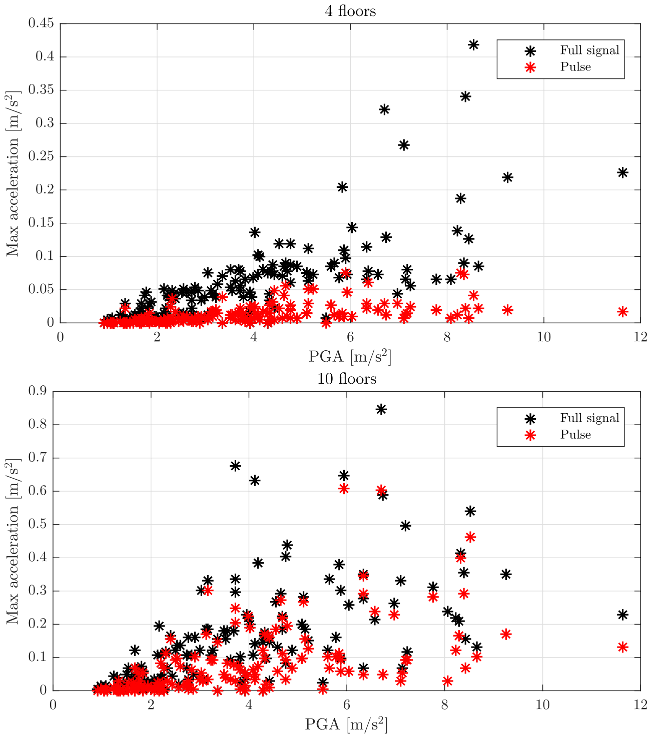

Figure 6. Peak floor acceleration for 4- and 10-story RC frame calculated using the whole seismic ground motion record and the extracted dominant pulse only.

Similarly, Figure 6 reports the peak floor acceleration for the 4- and 10-story RC frame calculated using the whole seismic ground motion record and the extracted dominant pulse only. The trend in this case is similar to that observed for the maximum inter-story drift ratio.

5 DISCUSSION

It can be useful to investigate to what extent the dominant pulse only is reliable for predicting the maximum inter-story drift ratio in structural systems under pulse-like seismic ground motion. The ability of the extracted dominant pulse to represent a ground motion in terms of inter-story drift is evaluated by computing an error term E defined according to Rupakhety and Sigbjörnsson (2011) as follows:

$$E = \frac{IDR_{th}}{IDR_p} \tag{2}$$

where IDR_{th} and IDR_p are the maximum inter-story drift ratio calculated using the whole seismic ground motion record and the extracted dominant pulse. The error is plotted against the normalized period T_1/T_p, i.e. the ratio between first mode period of the frame and pulse period of the seismic ground motion.

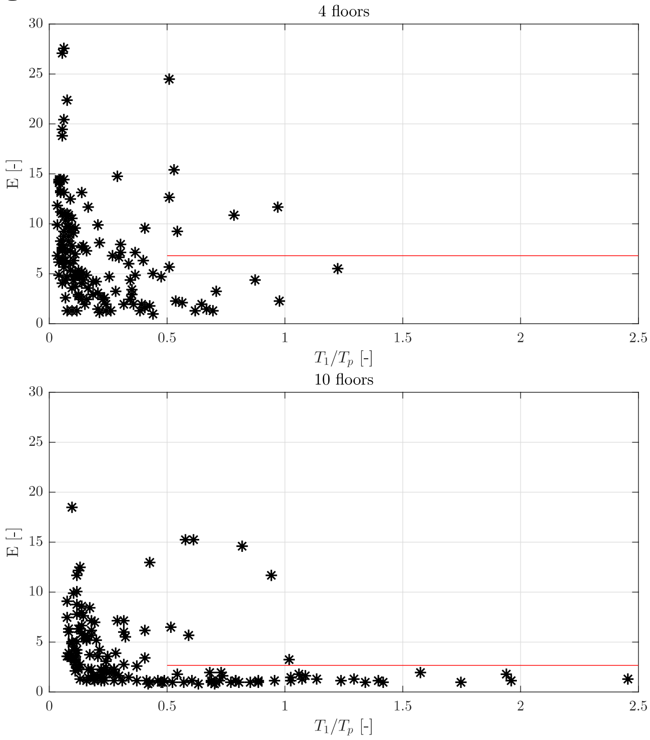

Figure 7. Errors in the computation of inter-story drift ratio for 4- and 10-story RC frame due to the use of the extracted dominant pulse only instead of a the whole seismic ground motion record. The mean error in the range 0.5-2.5 are indicated by a red horizontal line.

This normalized period is commonly considered a critical parameter to evaluate the severity of the structural response under pulse-like ground motion (Akkar et al. 2005; Champion and Liel 2012). Figure 7 shows that E decreases for increasing values of T_1/T_p. In particular, it can be inferred that the error is very large for low values of T_1/T_p. The mean error for T_1/T_p in the range 0.5-2.5 is indicated in Figure 7 with a horizontal red line. It is found that the mean error is equal to 6.8 and 2.7 for the 4- and 10-story RC frame, respectively. The conclusions that can be drawn from this discussion are somewhat in agreement with the ones reported in (Rupakhety and Sigbjörnsson 2011) for elastic frames. Overall, the obtained results lead to the conclusion that a simple pulse cannot provide a satisfactory prediction of the structural demands in RC frames subjected to pulse-like earthquakes, especially for low values of the ratio T_1/T_p.

6 CONCLUDING REMARKS

This study addressed the numerical assessment of the response of RC frames subjected to near-fault pulse-like earthquakes. A 2D parametric model of a RC frame has been first elaborated using the OpenSEES software package. Herein, the non-linear behavior of the members is modeled through a fiber-based approach. This model has been employed to perform nonlinear dynamic analyses taking into account a rather large dataset of near-fault pulse-like seismic records, from which the dominant pulse and the corresponding period are carried out by means of a recent methodology based on the Variational Mode Decomposition technique.

Preliminary results confirm that the maximum inter-story drift value strongly depends on the ratio between the fundamental period of vibration and the pulse period. Furthermore, it has been found that a simple pulse cannot represent adequately the effects of pulse-like earthquakes on RC frames, especially for low values of the ratio T_1/T_p.

AKNOLEDGEMENTS

The present work is framed within the ReLUIS 2019–2021 project. The first author acknowledge the Zhejiang University-University of Illinois at Urbana Champaign Institute (ZJUI) for the partial financial support given to the present research.

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