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AN EFFICIENT RECORD-TRUNCATION SCHEME FOR PULSE-LIKE RECORDS USING A WAVELET-BASED APPROACH

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Abstract

The paper shows, that especially for pulse-like ground motions, it is possible to truncate pulse-like signals using a novel wavelet-based definition that identifies the duration of the predominant velocity pulse. The truncated time history can efficiently reproduce the increased seismic demand that near-field records typically produce. Substituting the original ground motion with the truncated signal, significantly accelerates structural analysis and design. The truncated signal is the part of the original accelerogram that coincides with the duration of the predominant pulse, which is identified using a wavelet-based procedure, previously proposed by the authors.

Keywords: Record truncation, effective duration, predominant pulse, pulse-like, pulse index, near-field.

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1 INTRODUCTION

Replacing an acceleration time history with an equivalent, "truncated", signal has many benefits in terms of accelerating the seismic performance assessment and for understanding structural response. Although this is a very appealing approach, experience has shown that there is no silver bullet to the problem. It is practically impossible to have a record truncation algorithm that is efficient and accurate for all ground motions and all structural systems possible. However, if the problem is narrowed down to the case of pulse-like ground motions, it is possible to achieve an efficient truncation using a novel wavelet-based definition for the record effective duration. The effective duration is calculated first fitting a wavelet on the ground motion and then truncating the record to the time interval that corresponds to the fitted wavelet.

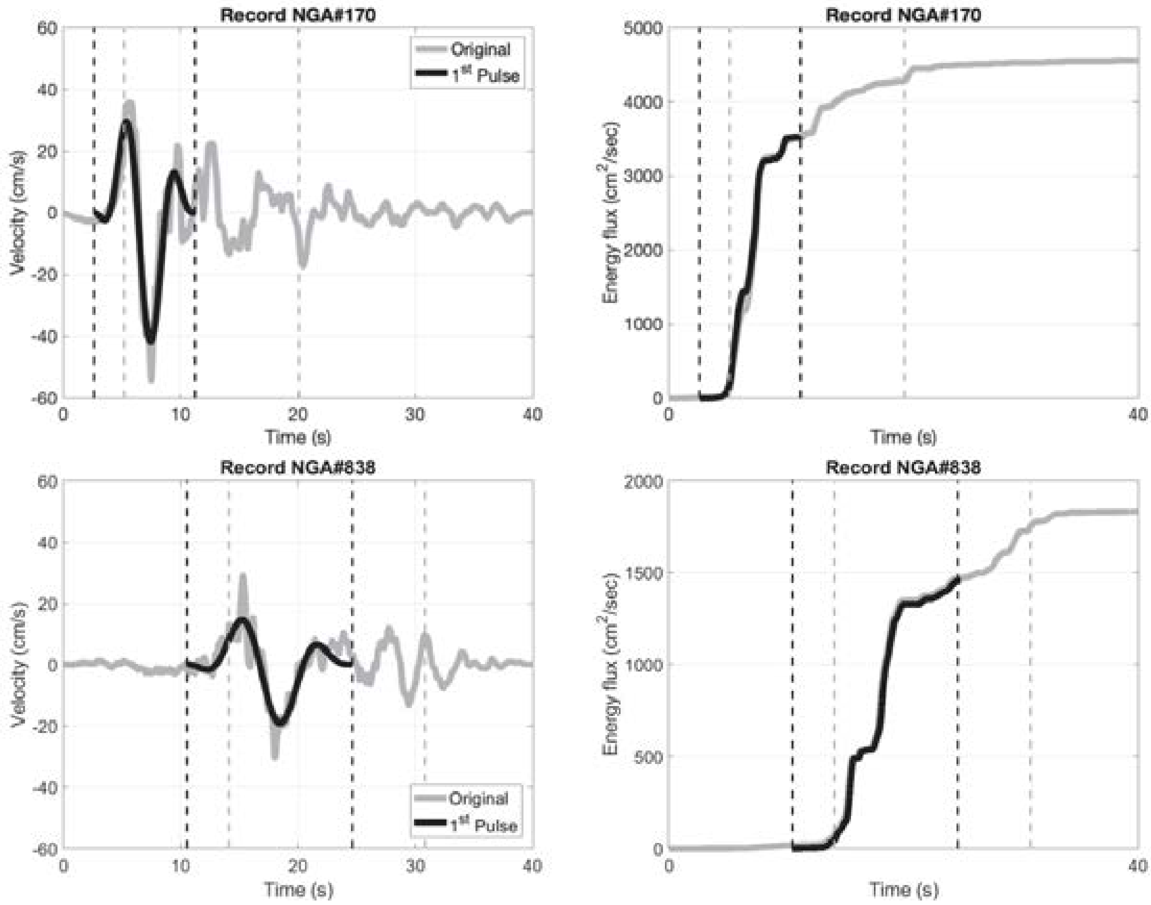
One of the early efforts for record truncation was that of Srivastav and Nau [1] who studied the influence of truncated earthquake records on the response of long-period structures. They recommend truncating the earthquake record at a small value of acceleration in order to reduce the error. However, most efforts are based on Arias intensity [2]. For example, Jin et al. [3] proposed the use of Arias intensity in order to study arch dams, while artificial intelligence approaches have been also proposed [4].

The scope of this study is to adopt the wavelet-based duration definition proposed by Repapis et al. [5] in order to truncate the acceleration time history and obtain a simpler and shorter signal. The paper shows that this practice can efficiently accelerate the simulation time with minor loss of accuracy. The efficiency of the proposed truncation approach depends on the pulse content of the record, which can be quantified with the aid of a pulse index. The approach proposed is quite efficient in the case of pulse-like records, such as those recorded in the case of near-field ground motions with forward directivity. These signals are characterized by strong, coherent, long period pulses that are found mainly in the strike normal direction. The effect of significant velocity pulse on the structural response has been highlighted by several studies, e.g. [6], [7], [8].

2 METHODOLOGY

Figure 1 shows two characteristic pulse-like ground motion records and the corresponding significant pulses. The pulses have been identified using the methodology proposed by Mimoglou et al. [9], i.e., appropriately fitting a wavelet on the signal. The plot on the right shows the cumulative energy flux and the time limits that correspond to the proposed "wavelet-based duration" (black dashed lines). The plots also show the 5% and the 95% of the record energy flux (dashed grey lines), which was proposed by Trifunac and Bray [10] as a measure of the record "significant duration". Clearly, the two definitions of record duration differ considerably (Figure 1a).

In order to calculate the record duration, we first extract the predominant pulse. According to [9] the extraction is based on optimally fitting the Mavroeidis and Papageorgiou wavelet [11] on the signal. This is a versatile wavelet, suitable to represent different duration levels, since it includes a parameter that is explicitly associated with the number of pulse cycles. A further advantage of this wavelet is that it is defined as the product of a sinusoidal periodic function and a bell-shaped envelope.



(a) (b)

Figure 1: (a) Velocity time history showing the total, the proposed wavelet-based and the significant duration definition, (b) Energy flux (records NGA #170 and NGA #838).

The Mavroeidis and Papageorgiou wavelet [11] depends on four parameters that control the frequency (T_p), the amplitude (A), the number of cycles (γ) and the polarity (φ) of the signal. The frequency is obtained as the period value that the product of velocity and displacement spectra becomes maximum. An exhaustive search algorithm is then adopted in order to identify the other three parameters; the search is narrowed to two parameters since the amplitude and the number of cycles are related by the expression proposed by Taflampas *et al*. [12]:

$$CAD = \frac{\gamma A T_p}{\pi} \qquad (1)$$

where CAD is the cumulative absolute displacement, obtained as the integral of the absolute value of ground velocity. The wavelet parameters that have the best cross-correlation value with the original signal define the most suitable wavelet model of the record predominant pulse. Once the wavelet is fitted on the ground motion, e.g., see Figure 1a, the wavelet-based effective duration of the signal is defined by the time boundaries of the fitted pulse.

The truncated signal is the part of the original record contained in the time boundaries of the wavelet that represents the predominant pulse (Figure 1a black vertical lines). Therefore, the truncated signal contains all the information, including the high frequency information, of the original ground motion. Moreover, according to Figure 1b, the ends of the proposed duration definition appear at points where the graph of the energy flux shows a horizontal step with zero first gradient. Therefore, there is no significant baseline offset at the beginning and the end of the truncated duration. This is not the case with other duration definitions, e.g. the “significant duration" definition that use the arbitrary limits of 5 to 95% of the total energy flux in order to truncate the ground motion.

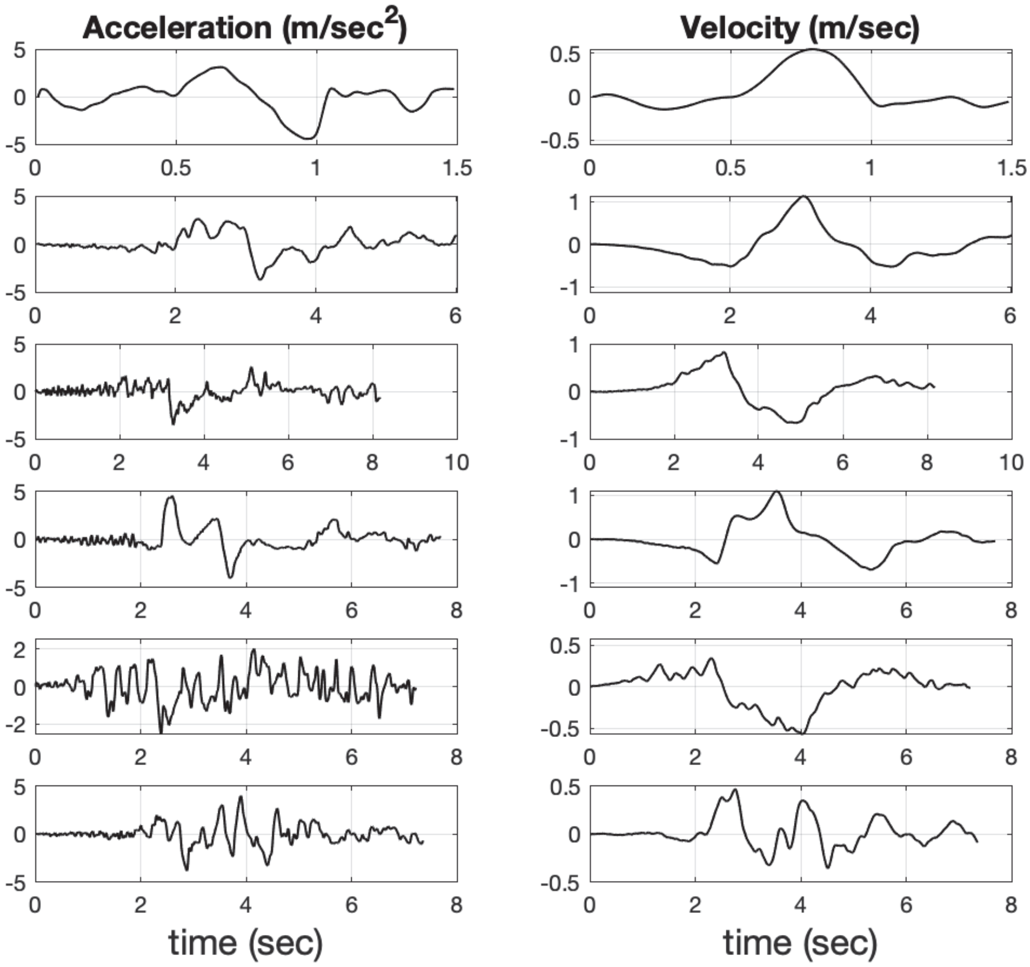


Figure 2: Acceleration and velocity time histories of truncated signals.

Thanks to the proposed wavelet fitting, the time boundaries identified, ensure that the truncated signal starts and ends at an acceleration value close to zero, similarly to the case of recorded acceleration time histories. Therefore, the limits of the envelope can be considered as boundary tapers that attenuate the harmonic function and smooth the baseline of the cut-off instants. This can be better understood looking at Figure 2, where the acceleration and velocity of six truncated signals are shown. The time histories smoothly converge to zero acceleration and velocity line which allows to use them for structural response history simulations without the need for further processing.

3 GROUND MOTION RECORDS

A set of 48 pulse-like ground motion records, included in the PEER-NGA2-West database [13], have been selected for our work. The excitations were recorded on different soil types and distances from the rupture plane and have different values of predominant pulse periods. Moreover, the selected ground motion sample contains records with strong directivity, mainly in the fault-normal direction (e.g., Loma Prieta), or records where both the fault-normal and the fault-parallel components show prominent directivity effects (e.g., Erzincan-Turkey).

4 NUMERICAL INVESTIGATION

The efficiency of the proposed record truncation approach is studied using a nine-storey steel moment-resisting frame. The well-know LA9 frame is used as a testbed multi-degree-of-freedom (MDOF) structure. The building consists of five bays and a hinge-storey basement. The gravity loads and the mass of the internal gravity-resisting frames are placed on a leaning column, which does not contribute to the lateral stiffness. The fundamental period of the frame was found equal to T_1=2.35 sec and the mass modal participation of the first mode amounts to 84% of the total mass. Thus, the frame is essentially dominated by the first mode, while higher modes may also contribute to the response. The cross-sections and more details about the building design can be found in [14]. A centreline model is adopted using the OpenSees platform [15]. The model account explicitly for the geometric nonlinearities in the form of $P{-}\Delta$ effects. The columns are assumed linear-elastic, while a quadrilinear model is adopted for the beam-column connections. More specifically, the moment-rotation relationship of all beam-column connections have degrading properties equal to: a_h=10%, a_c=-50%, μ_c=3 and r=50%.

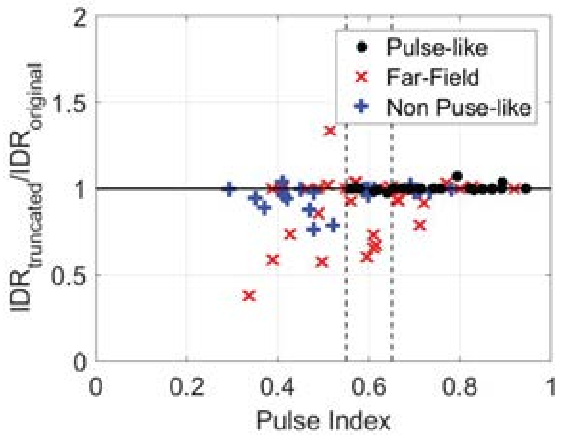
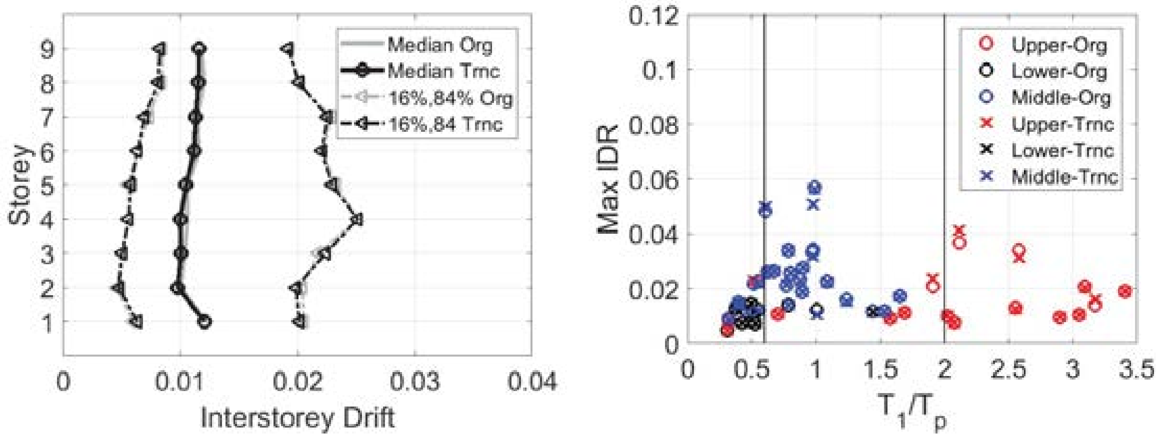


Figure 3: Ratio of the maximum interstorey drift for the 9-storey steel moment frame versus the calculated cross correlation.

Primarily, the correlation with a pulse index is studied. Since the proposed wavelet-based truncation, in principle, applies to pulse-like ground motions, the seismic demand obtained with the truncated and the original ground motions is expected to be close. However, often the proposed approach gives sufficiently accurate results also for records that have been a priori classified as non pulse-like. It is, therefore, very useful to have a metric that can be used to determine, prior analysis, if the proposed truncation can be used to substitute the original signal. An obvious metric suitable for this purpose is a “pulse index” such as the one proposed by Kardoutsou *et al*. [16], which is defined as the cross-correlation of the original signal and the extracted wavelet and adopted in our work. This study is also based on fitting the Mavroeidis and Papageorgiou wavelet, as discussed in [9]. The authors recommend that records with *PI* less than 0.55 are non-pulse like, while when $PI>0.65$ the record is definitely pulse-like. Records with intermediate values, i.e., $0.55<PI<0.65$, are characterized as ambiguous.

Figure 3 compares the ratio of peak interstorey drift of the original and the wavelet-based truncated time-history versus the Pulse Index (*PI*). The comparison is based on the record set of FEMA P-695 [17]. A different and well-known record database is adopted in order to use ground motions that are completely different from those used in their previous studies of the authors, [9], [16]. Moreover, the ground motion set of [17] consists of 44 far-field records, 28 near-field records characterized as “pulse-type” and 26 near-field records characterized as “non pulse-type”. The far-field set includes earthquakes of large magnitude (M_w>6.5), recorded on soil types C and D according to the NEHRP classification. The pulse-type set contains records, with varying pulse periods, corresponding to events of magnitude between 6.5 and 7.6. These records present strong directivity effects in the fault-normal/and or the fault parallel direction.

According to Figure 3, the difference in the maximum peak interstorey drift demand between the original and the truncated records is small for ground motions with a pulse indicator *PI* above the 0.65 threshold. This observation holds even for records that belong to the far-field set. The largest differences are again found for the far-field records (red crosses), but even for *PI*<0.55 the differences do not seem to exceed on average 18%. Overall, for the building examined, the scatter in the computed drift values is significantly decreased as *PI* increases, regardless of the classification of the ground motion record. This indicates the efficiency of the proposed wavelet-based approach for truncating a ground motion record and also the potential on the proposed pulse index *PI* metric to quickly assess using the efficiency of the proposed wavelet-based truncation.



(a) (b)

Figure 4: (a) Profile of the median and the 16 and 84% percentiles drift demand for the 48 pulse-type ground motions; (b) Maximum interstorey drift obtained using the original and the truncated records versus the T_1/T_p ratio.

In the following, the LA9 steel frame is subjected to the 48 near-field ground motions with forward directivity. Figure 4a presents the median peak interstorey drift demand and the corresponding 16% and 84% percentile curves of the interstorey drift demand. Excellent agreement for all the stories has been achieved along the height of the frame. Furthermore, the effect of record-to-record variability on the maximum interstorey drift demand is studied in Figure 4b. Although minor differences are seen for individual records, for the majority of ground motions the drift estimates of the original and the truncated signal practically coincide. Figure 4b deserves further attention. A different marker colour has been adopted depending on the storey that the maximum interstorey drift occurred. Overall, the seismic response computed for the truncated signals, follows the same pattern observed for the original records while for most cases the maximum drift demand occurs at the same level. Since the structure studied is sensitive to the first mode, the larger demand is due to records with T1/Tp≤1. Furthermore, for these records, the peak drift appears at the middle stories (stories 4, 5 and 6).

Our findings are in agreement with Baker and Cornel [18] who discuss the effect of pulse period on the seismic behaviour of MDOF systems. They investigated the effect of the pulse on the higher modes of excitation through MDOF structures sensitive to second mode excitation and suggested that the ratio T1/Tp is indicative of the level at which the peak displacement occurs; short period records excite higher modes, while for records with long period pulses the maximum response is expected at the low stories, indicating that first mode response governs the peak displacements of the building. They proposed the thresholds, T1/Tp<0.5 and T1/Tp>2 that are also shown as vertical dashed lines in Figure 4b. According to Figure 4, for records with short period pulses, T1/Tp>2 the higher modes of vibration are excited and the maximum interstorey drift is located at the upper stories (stories 7, 8 and 9). On the other hand, for records with T1/Tp<1, the maximum drift demand is observed at lower stories, indicating that the response is first mode dominated.

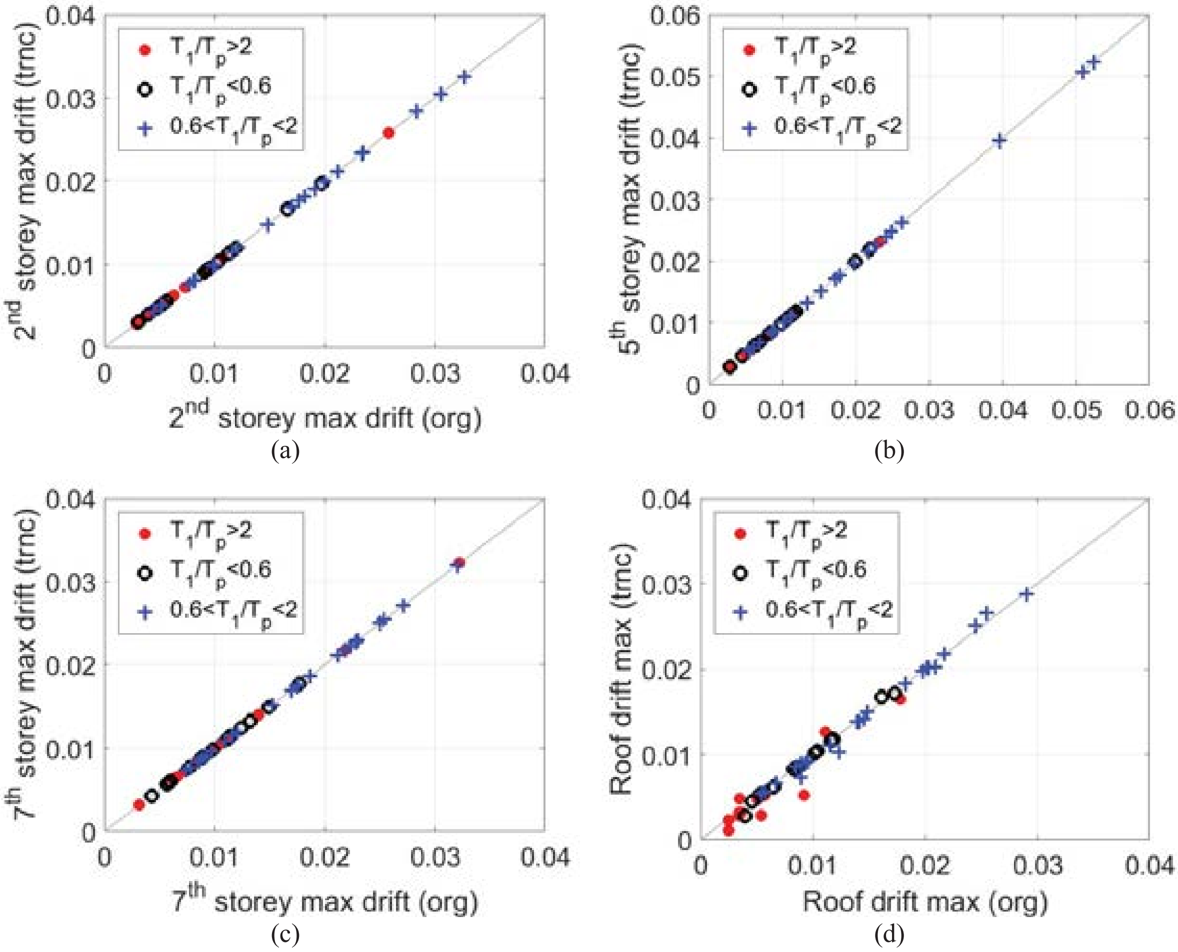
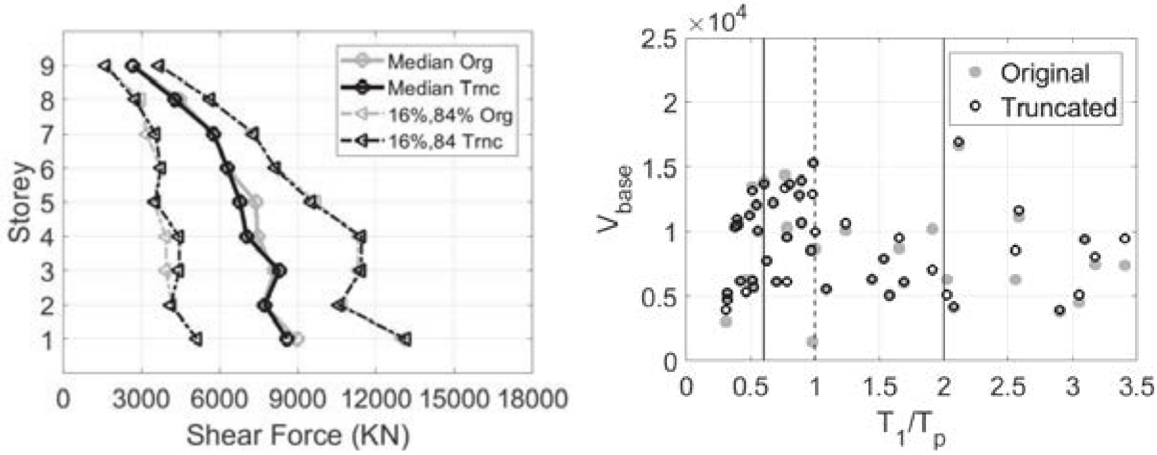


Figure 5: Maximum interstorey drift at different stories of the building, (a) 2nd storey, (b) 5th storey, (c) 7th storey and (d) 9th storey (roof).

Figure 5 shows the maximum drift demand for the 2nd, the 5th, the 7th and the 9th (top) storey. The agreement is practically perfect for all stories with the exception of the top storey where some minor errors appear for ground motions with $T_1/T_p>2$. The maximum interstorey drifts occur mainly for records with T_1/T_p between 0.6 and 2, and in some cases for $T_1/T_p>2$, while for the structure considered, the peak values appear at the middle stories of the building. Figure 6a shows the profiles of the median shear forces along the height of the building and the corresponding 16% and 84% percentiles. Very good agreement is again obtained, since the damage patterns are very close. Some minor differences are observed with respect to the demand in stories 3, 4 and 5. Furthermore, Figure 6b compares the base shear demand for the original and the truncated signal. It should be pointed out that the maximum values of the base shear are computed in the period range $0.5<T_1/T_p<1$, while (although not shown) most differences appear at the 1st and 5th storey, as also applies for the interstorey drifts (Figure 5).



(a) (b)

Figure 6: (a) Profiles of the maximum median storey shear force along with the standard deviation of storey shears. (b) Dispersion of the maximum base shear for original and truncated records versus T_1/T_p.

5 CONCLUSIONS

A novel record truncation approach has been presented. The proposed approach simplifies the input signal and accelerates the seismic performance assessment, especially in the case of pulse-like ground motions. The truncation does not require baseline correction and thus it can be integrated to give truncated realistic velocity and displacement time histories. The proposed approach has been validated through the study of a nine-storey steel building. Almost in all cases, the seismic demand, measured in terms of displacement, drift and shear forces, obtained using the truncated signal will produce close estimates. The computational process is performed within a fraction of the CPU time required when the original complete record is used, since the duration reduction lies on average around 80%.

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