ASSESSMENT OF SYNTHETIC GROUND MOTION RECORDS OBTAINED FROM ALTERNATIVE SIMULATION TECHNIQUES IN NONLINEAR TIME HISTORY ANALYSES OF MULTI-STOREY FRAME BUILDINGS: A CASE STUDY

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ABSTRACT:

In regions with sparse ground motion data, simulations provide alternative acceleration time series for evaluation of the dynamic response of structures. Different ground motion simulation methods provide varying levels of goodness of fit between real and synthetic data. Before using the seismologically acceptable synthetic records for engineering purposes, it is critical to investigate the efficiency of synthetics in predicting real seismic responses of structures. For this purpose, in this study, we present nonlinear time history analyses of multi-story reinforced concrete frames under real and synthetic records of a particular earthquake. Synthetic records of 6 April 2009 L'Aquila (Italy) earthquake (Mw=6.3) are simulated using both the Hybrid Integral-Composite method and the Stochastic Finite-Fault method. Results of the analyses from real and alternative synthetic records are compared in terms of maximum displacement of each story level. Our results indicate that the match between the Fourier Amplitude Spectrum of the real and synthetic record around the frequencies that correspond to the fundamental period of the structure governs the misfit between the real and synthetic nonlinear response. We also show that even for cases where nonlinear behavior is more likely, period dependent SDOF indicators of goodness of fit between a particular real and corresponding synthetic record (such as 5% damped response spectrum) represents the difference in MDOF behavior of frame structures due these records. Finally, simulation of realistic amplitudes over the entire broadband frequency range of interest is found to be critical while using the synthetics for earthquake engineering purpose.

KEYWORDS: Nonlinear time history analysis, synthetic ground motions, l'aquila, hybrid integral-composite method, stochastic finite-fault method.

1. INTRODUCTION

For seismic design purposes and dynamic response analyses of building structures, it is essential to estimate the hazard to which the structures will be exposed during their lifetimes. Nonlinear time-history analysis, which requires full time series of ground acceleration, is one of the alternative techniques to assess the dynamic response of a structure. Most structures are expected to deform nonlinearly when exposed to severe ground motion excitation; thus nonlinear time history analysis to evaluate post-elastic dynamic response of structures is employed commonly. In regions of sparse strong ground motion data, common practice is to use a set of records from other regions with similar seismotectonics and to estimate an average dynamic response of the structure. Based on the modeling assumptions and solution techniques, strong ground motion simulation methods can be divided into three main groups: deterministic, stochastic and hybrid simulations.

Deterministic approach employs numerical solutions of the wave equation and requires well-defined seismic sources and wave velocity models (e.g.: Frankel *et al*. 1993; Olsen *et al.* 1996; Komatitsch *et al*., 2004). Despite its accuracy, it is practical for relatively lower frequencies due to the computational and physical constraints related to the minimum wavelength. Stochastic method combines the deterministic far field S-wave spectrum with random phases (Boore, 1983). It has inherent limitations due to lack of full wave propagation effects, yet it is employed effectively for several seismic regions in the world for both point-source and finite-fault modeling (e.g.: Beresnev and Atkinson, 1997; Roumelioti et al., 2004; Motazedian and Atkinson, 2005; Ugurhan and Askan, 2010). Hybrid methods are developed for generating broadband ground motions by combining deterministic and stochastic approaches for the simulation of low and high frequency components, respectively (e.g.: Kamae *et al*., 1998; Pitarka *et al*., 2000; Mai *et al*., 2010).

A significant research problem is to further validate the simulated motions from engineering point of view by investigating the dynamic response of structures due to synthetics records. Majority of the past studies used either SDOF systems to model building structures or employed ground motion records generated for scenario events. A topic that remains to be studied is the dynamic response of typical Multi-degree-of-freedom (MDOF) structures to synthetic records of a particular earthquake generated with different simulation techniques in comparison with the response due to the real records of the same event. For this purpose, in this study, we compute the dynamic response of the typical reinforced concrete frame structures under synthetic data generated for the same actual earthquake based on two alternative simulation methods. The earthquake we consider is the 6 April 2009 L'Aquila event (Mw=6.3) that caused heavy damage in the epicentral area and yielded a large number of near-field ground motions. We use synthetic records generated for this event in two recently-published work conducted independently by the two authors of this manuscript. The first method is the Hybrid Integral Composite method (introduced by Gallovič and Brokešová, 2007) and the simulations for the 2009 L'Aquila event with this method are presented in Ameri *et al*. (2012). The second method is the Stochastic Finite-Fault method (based on the approach by Motazedian and Atkinson, 2005) and the corresponding synthetic records for 2009 L'Aquila earthquake are presented in Ugurhan *et al*. (2012).

In this study, we consider the horizontal components of the records at 7 selected stations within about 50 km from the epicenter, and the corresponding synthetics for nonlinear analyses. We employ three typical two-dimensional frames for modeling low, mid and high rise buildings and compare the maximum story displacement due to 7 sets of real and synthetic records at the selected stations.

The fundamental purpose of this study is to provide insights into the nonlinear dynamic behavior of typical frame structures to real records of a particular event versus the corresponding synthetic records. The key question here is whether the seismologically "acceptable" synthetic ground motion records can be used for earthquake engineering purposes without any prior scaling or modification of the records. We also investigate if the misfits in terms of seismological measures (such as Fourier Amplitude Spectrum) between the real and simulated records correspond to consistent differences in engineering demand parameters.

2. CASE STUDY: REAL AND SYNTHETIC GROUND MOTION RECORDS OF 6 APRIL 2009 L'AQUILA EARTHQUAKE (MW=6.3)

In this study, real and simulated acceleration records of 2009 L'Aquila earthquake (Mw=6.3) are employed for the nonlinear dynamic analyses of buildings. This event occurred in central Italy, very close to town L'Aquila, on a NW–SE trending normal fault (Cirella et al., 2009; Gallovic and Zahradník, 2012). Despite its moderate size, 6 April 2009 L'Aquila earthquake caused significant structural damage in the near-fault area. The mainshock was recorded at 14 strong motion stations within 50 km epicentral distance. Most of the near-fault stations were located on sites with class A according to EC08, however at some stations on softer soils, local site effects were pronounced.

In this study, for use in nonlinear time history analyses of the buildings, we employ records from 7 selected stations from the near-fault area. Figure 1 displays the map of the meizoseismal region with the epicenter, fault plane and the locations of the selected stations. Also, table 1 lists information regarding the locations and site classes of these stations.

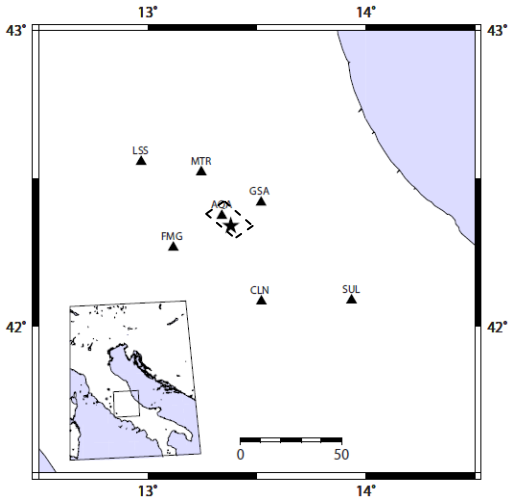

Figure 1. the fault plane and epicenter of 2009 L'Aquila earthquake with the locations of the selected stations

Table 1. Information on the strong motion stations that recorded the 2009 L'Aquila earthquake

Station Code	Station Name	Site Class (EC08)	Repi (km)	RJB (km)	PGA (cm/s^2)
AQA	V. Aterno-F. Aterno	B	4.6	0	435.39
CLN	Celano	A	31.64	11.69	88.47
FMG	Fiamignano	A	19.32	17.07	26.32
GSA	Gran Sasso	B	18.05	7.86	146.62
LSS	Leonessa	A	39.02	33.68	9.61
MTR	Montereale	A	22.35	14.48	61.37
SUL	Sulmona	C	56.53	32.23	33.61

In two recent papers by the authors of this draft (Ameri et al., 2012 and Ugurhan et al., 2012), the horizontal records at these stations are simulated using two different simulation techniques: Hybrid Integral Composite method (Gallovič and Brokešová, 2007) and Stochastic Finite-Fault method (Motazedian and Atkinson, 2005). Next, the techniques used for simulating the L'Aquila earthquake of the mentioned studies are summarized.

2.1. Synthetic Records from the Hybrid Integral Composite Method

Ameri et al. (2012) employed a broadband Hybrid Integral Composite (HIC) method to simulate the near fault records of the 2009 L'Aquila earthquake. Introduced by Gallovič and Brokešová (2007), HIC method relies on the representation theorem with a k-squared slip distribution over the fault plane in the low-frequency band where source parameters are constrained by a detailed source inversion (Gallovic and Zahradník, 2012). For the high frequencies, the method uses a composite application of Brune's source time functions with proper seismic moment and corner frequency defined by the sizes of the subsources.

From this point onward, in this paper we name the synthetic ground motions obtained from this technique as SYN1 records. There will be two horizontal SYN1 components at each site as the method can effectively simulate EW and NS components of the ground motion.

2.2. Synthetic Records from the Stochastic Finite-fault Method

Ugurhan et al. (2012) used the Stochastic Finite-Fault method based on a dynamic corner frequency approach (Motazedian and Atkinson, 2005) to simulate the 2009 L'Aquila earthquake. This technique is an extension of the stochastic point source model of Boore (1983) to finite-faults. The fault plane is discretized into smaller subfaults, and the contributions of the subfaults are summed in the time domain where every subfault is treated as a stochastic point source.

Recently, Ugurhan et al. (2012) used this method to test four different sets of models for alternative source, path and site effects to simulate the 2009 L'Aquila mainshock. The authors performed sensitivity analyses for source and path parameters by employing two finite-fault source models that take into account the source complexity of the event along with two alternative path models derived from regional weak and strong ground motion databases.

From this point onward, in this paper we name the synthetic ground motions obtained from this technique as SYN2 records. We note that there is only one SYN2 record per station as the stochastic method provides a single horizontal component at each simulation site.

2.3. Comparison of synthetic and real ground motions

Obtained from SYN1 and SYN2 record sets, at every station we have a total of 3 simulated and 2 real horizontal components which sum up to 35 records at 7 stations to use as input ground motions for dynamic analyses of the selected frames. We note that the synthetic and real records are filtered between 0.1 and 10 Hz. Figure 2 displays Fourier Amplitude Spectra of the acceleration time histories for both observed and simulated data from the two methods at each station.

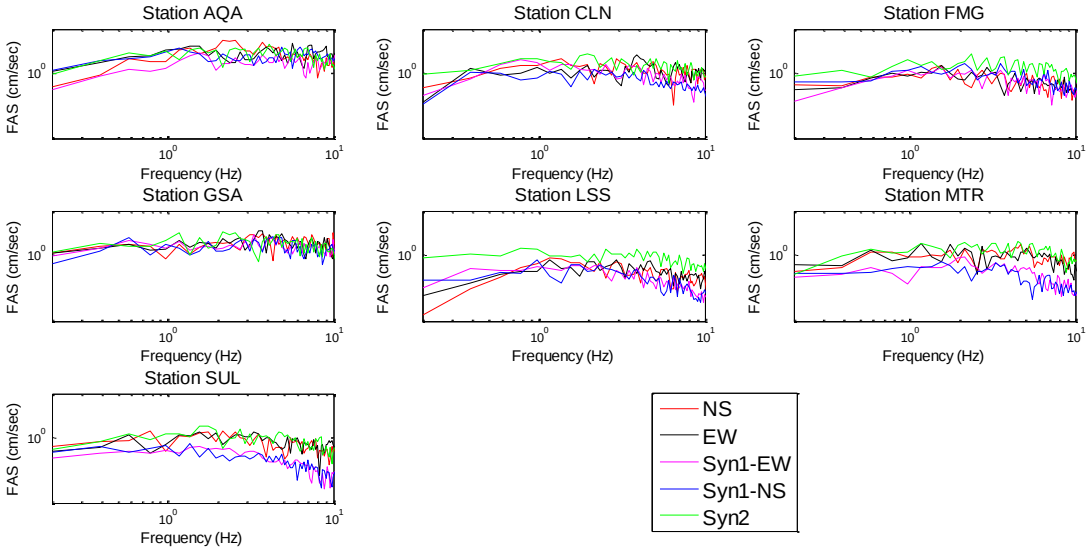

Figure 2. Fourier Amplitude Spectra for stations AQA, CLN, FMG, GSA, LSS, MTR, and SUL obtained for real (NS and EW) and simulated horizontal components (Syn1-EW, Syn1-NS, and Syn2)

It should be mentioned that the two alternative simulation methods are performed in two independent studies, which use different but consistent model parameters. Therefore, it might not seem valid or fair to compare these synthetics with each other; instead; we compare them against the real records.

Before we present nonlinear analyses, we check the differences between the real and synthetic records at the selected stations. We quantify the period dependent misfits for each frame between the synthetic and the real records in terms of the Fast Fourier Amplitude Spectra (FAS) and elastic response spectra with 5% damping (RS) as follows:

$$Misfit_{FAS} = \frac{1}{n_f}\sum_{f=1}^{n_f}\left|log\frac{FAS_{syn}(f)}{FAS_{obs}(f)}\right| \quad (1)$$

$$Misfit_{RS} = \frac{1}{n_T}\sum_{T=1}^{n_T}\left|log\frac{RS_{syn}(T)}{RS_{obs}(T)}\right| \quad (2)$$

Where for each frame n_f and n_T are the number of discrete frequencies and periods in the selected period band used in the FFT and response spectrum computations, respectively. Here, it should be mentioned that for each frame we have considered the corresponding period band separately with respect to the fundamental period of that frame while the lower value of the period band is selected with respect to the highest modal frequency of the considered frame (20 percent of the first fundamental period), and the upper period band is selected with respect to the nonlinearity effects in increasing of the period of each frame after dynamic analysis (120 percent of the first fundamental period). For each frame the geometric mean of the misfits in NS and EW directions are displayed in Tables 2-4.

Table 2. Misfits in terms of fast FAS and response spectra for real and synthetic data at the stations for frame F3S2B

Frame ID	**F3S2B**			
Station	**FAS(SYN1)**	**FAS(SYN2)**	**RS(SYN1)**	**RS(SYN2)**
AQA	0.957	0.6814	0.6488	0.3083
CLN	0.9125	0.9834	0.3915	0.6616
FMG	0.7353	1.5702	0.2444	1.0442
GSA	0.6978	0.8038	0.287	0.5257
LSS	0.9721	1.457	0.3586	1.2203
MTR	1.8451	0.9232	1.0101	0.3457
SUL	1.7999	0.6868	1.233	0.4506

Table 3. Misfits in terms of fast FAS and response spectra for real and synthetic data at the stations for frame F4S3B

Frame ID	**F4S3B**			
Station	**FAS(SYN1)**	**FAS(SYN2)**	**RS(SYN1)**	**RS(SYN2)**
AQA	0.8556	0.6981	0.6338	0.3903
CLN	1.2311	0.8743	0.4997	0.5744
FMG	0.7624	1.5254	0.2555	1.219
GSA	0.8013	0.8643	0.3239	0.3358
LSS	1.3474	1.3511	0.4387	1.2186
MTR	2.3009	0.843	0.9646	0.3842
SUL	2.1933	0.7923	1.3756	0.4387

Table 4. Misfits in terms of fast FAS and response spectra for real and synthetic data at the stations for frame F8S3B

Frame ID	**F8S3B**			
Station	**FAS(SYN1)**	**FAS(SYN2)**	**RS(SYN1)**	**RS(SYN2)**
AQA	0.9266	0.6353	0.5355	0.3703
CLN	0.7621	0.9964	0.3701	0.5888
FMG	0.7066	1.368	0.229	1.0879
GSA	0.6104	0.9216	0.3421	0.8234
LSS	0.729	1.364	0.3202	1.2107
MTR	1.3947	0.9423	0.9751	0.3087
SUL	1.6345	0.6396	0.8941	0.3507

Next, we assess the nonlinear response of typical frame buildings due to this ground motion set.

3. NONLINEAR TIME HISTORY ANALYSES

Nonlinear time history analysis (NLTHA) is a step by step analysis of the dynamic response of a structure under a loading that is a function of time, which in this case is a ground motion record. For this study, NLTHA involves the numerical solution to MDOF equation of motion under the two horizontal-components of the real and synthetic motions presented in the previous section.

We select three two-dimensional, regular and symmetric reinforced concrete (RC) frames to model building structures for NLTHA. Frame 1 (F3S2B) is a 3 story-2 bay frame with story height of 3 meters. Frame 2 (F4S3B) is a 4 story-3 bay frame with story height equal to 2.7 meters, and finally frame 3 (F8S3B) is a 8 story-3 bay frame with a 3.96 meters story height (Kadaş, 2008; Yılmaz 2007).

Materials used for modeling are Kent-Scott-park concrete with no tensile strength and steel with strain hardening ratio of 0.005. In these models, nonlinear fiber-based beam-column elements are used.

Assuming 100% dead load and 25% live load contributions to the total mass, the eigenvalue analyses yield fundamental periods listed in Table 5. Damping ratio of the first mode for all frames is assumed to be 5%.

Table 5. Modal properties of the frames

Frame ID	**Modal Properties (Period (sec))**							
F3S2B	T1=0.717		T2= 0.219		T3= 0.124			
F4S3B	T1=0.494		T2= 0.158		T3= 0.089		T4= 0.063	
F8S3B	T1=1.203	T2=0.481	T3=0.414	T4=0.281	T5=0.262	T6=0.252	T7=0.218	T8= 0.2

Numerical modeling of the frames is carried out by the use of OPENSEES software that employs finite elements for discretization and solution of the equation of motion. Two-dimensional modeling is preferred due to the symmetry of the frames. To compare the nonlinear dynamic response of the frames, for each record, maximum displacement of each story is computed.

4. RESULTS: COMPARISON OF DYNAMIC RESPONSES OF THE BUILDINGS TO REAL AND SYNTHETIC RECORDS

The main objective of this study is to investigate whether the nonlinear responses of building structures to synthetic records from alternative simulations are consistent with the "real" response. Another fundamental question of interest is whether the measured period dependent misfits in terms of FAS and SDOF response indicators (RS) correlate with differences between the real and synthetic nonlinear responses of the frames. For this purpose, we define a misfit measure for differences in nonlinear response (NR) under real and synthetic motions. The NR misfit is expressed in terms of average of maximum story displacements as follows:

$$Misfit_{NR} = \frac{1}{n_s}\sum_{s=1}^{n_s}\left|log\frac{NR_{syn}(s)}{NR_{obs}(s)}\right| \quad (3)$$

where n_s is the total number of stories in the frames.

Table 6 shows nonlinear response misfits calculated from real and two alternative synthetic ground motion records.

Table 6. Misfits in terms of nonlinear responses to real and synthetic data at the stations

Frame ID	F3S2B		F4S3B		F8S3B	
Station	$Misfit_{NR}(SYN1)$	$Misfit_{NR}(SYN2)$	$Misfit_{NR}(SYN1)$	$Misfit_{NR}(SYN2)$	$Misfit_{NR}(SYN1)$	$Misfit_{NR}(SYN2)$
AQA	0.1717	0.0854	0.5124	0.0419	0.1447	0.1049
CLN	0.0640	0.2508	0.0451	0.6621	0.2247	0.3185
FMG	0.1270	0.4119	0.0488	0.5638	0.0411	0.5964
GSA	0.0606	0.4072	0.2584	0.3469	0.3044	0.5854
LSS	0.0940	0.6969	0.2300	0.3593	0.1246	0.5625
MTR	0.6705	0.0658	0.1290	0.3258	0.4056	0.1270
SUL	0.5622	0.1542	0.4631	0.2220	0.1338	0.0939

To study the differences in seismic responses of reinforced concrete frame structures under the real and synthetic records, maximum displacements computed at each story level for all three frames are compared in Figures 3-5.

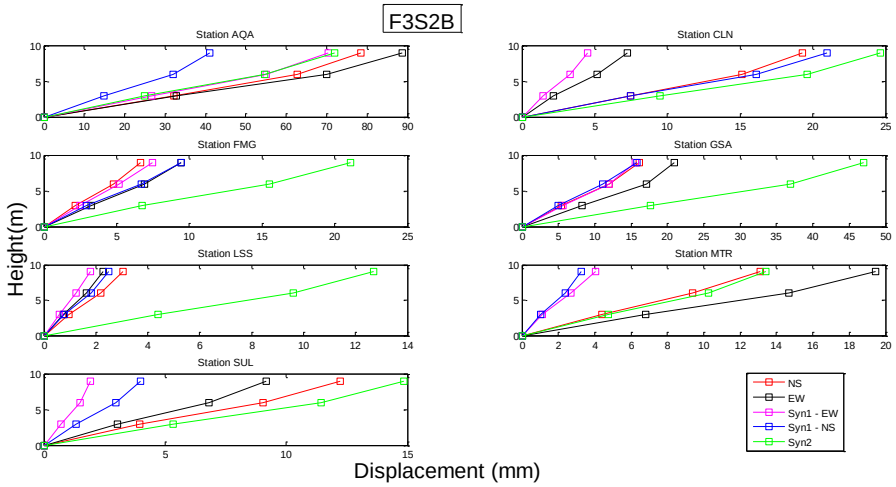

Figure 3. Distribution of maximum story displacements for Frame 1 (F3S2B) due to the real and synthetic records at the selected stations

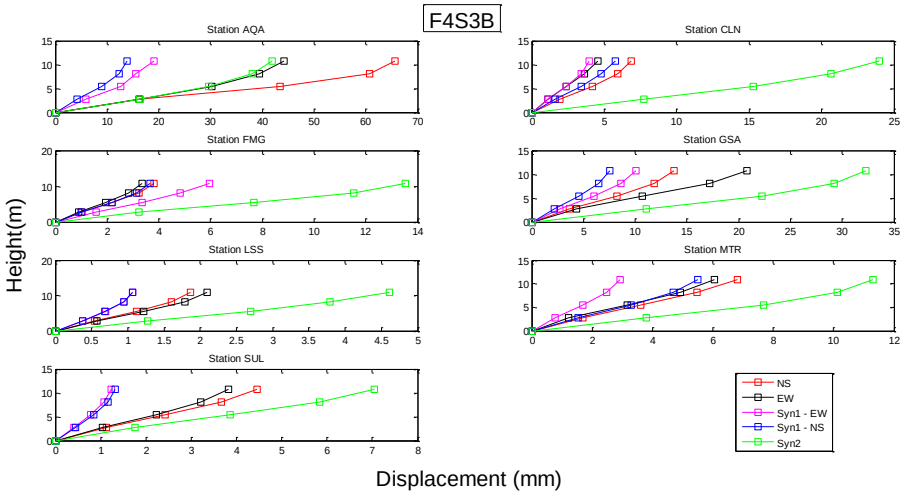

Figure 4. Distribution of maximum story displacements for Frame 2(F4S3B) due to the real and synthetic records at the selected stations

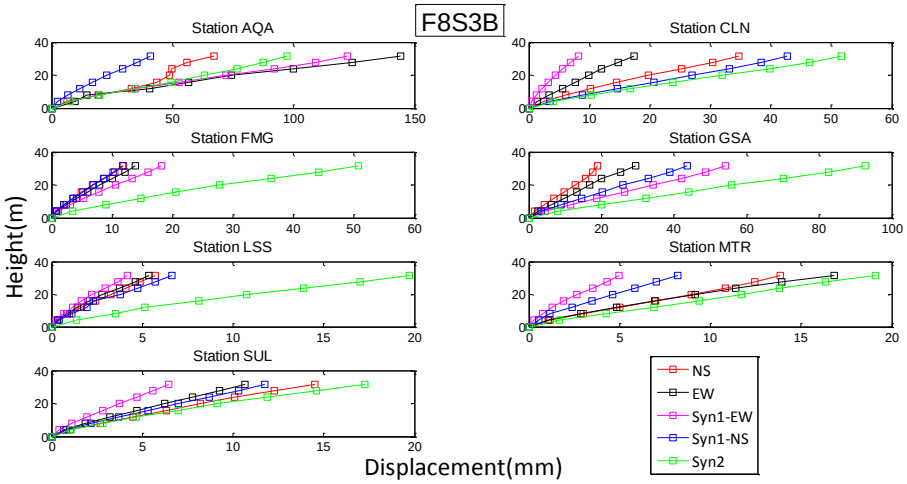

Figure 5. Distribution of maximum story displacements for Frame 3 (F8S3B) due to the real and synthetic records at the selected stations

Next, the results of the nonlinear dynamic analyses of the selected frames are presented.

4.1. Evaluation of Results for F3S2B

We observe that for F3S2B at station AQA, nonlinear dynamic responses are underestimated by both SYN1 and SYN2 records when compared to the real records; however SYN2 yields closer results for this frame. This is due to the bad fit of synthetic record of Hybrid Integral Composite obtained for the NS component at AQA, (Ameri, et al. 2012). At station CLN, the response to SYN1 records is closer to the real response than that of SYN2. On the other hand, nonlinear analyses with SYN2 records yield much more conservative (larger) results when compared to the real story displacements. At station FMG, we observe that both of the simulation techniques yield larger nonlinear responses than the real one except the EW component from the Hybrid Integral Composite method for this frame. The responses of the SYN2 records are overestimated when compared to the real response by a factor of about 2.5, while the results from SYN1 record is closer to the real response. NR misfits for station GSA shown in Table 6 indicate that synthetic records from HIC method perform better than those from the Stochastic Finite-Fault method at this station. At station LSS, response from SYN1 records are closer to the real response but underestimate the real response. On the other hand, Stochastic Finite-Fault method overestimates the real nonlinear response by a factor of almost 5. For MTR station, the nonlinear response due to records from Stochastic Finite-Fault method is much closer to the real response than the synthetic records obtained from HIC method as observed from Table 6; however; both synthetic records underestimate the real response. For this station, synthetic ground motions obtained from HIC method were not considered a good fit by the authors of the corresponding study (Ameri, et al. 2012). Therefore, when a bad fit is obtained from a seismological point of view, a similar observation is made for nonlinear response of the frame. Finally, for the station SUL, considering the NR misfits, Stochastic Finite-Fault method yields closer results to the real response. One critical observation at this station is that response to SYN1 underestimates the real maximum roof displacement by a factor of almost 5. This is mostly due to the fact that the higher frequencies of the record at this station are not well represented by the SYN1 records. In addition, SUL is a EC8 class C station (Table 1) and the station is characterized by significant site effects which lead to the bad fit of the HIC simulations due to not considering the particular site effects by the SYN1 method, (Ameri. et al. 2012). For this frame, when the misfits in Tables 3 and 4 are considered, we note that for all stations both FAS and also RS misfits are consistent with the NR misfits. However, RS misfit is more sensitive to the differences in nonlinear behavior due to SYN1 and SYN2.

4.2. Evaluation of Results for F4S3B

For frame 4S3B, the results of the two simulated methods are in agreement with the results of frame 3S2B at all stations except for the results of SYN2 records at station MTR. Unlike F3S2B, at this station Stochastic Finite-Fault method overestimates the NR by a factor of about 2. In addition, SYN1 records yield closer results to the real response when compared to those from the SYN2 records (Table 6). For this frame, for most of the stations both RS and FAS misfits are in agreement with the nonlinear response misfits. However, through a comparison of the results of Table 2 and Table 6 it is clear that for station CLN only RS misfit governs the accuracy of the nonlinear response. Another observation is that at station MTR, neither of the FAS nor RS misfits match with the NR misfit where NR misfits in Table 6 show that SYN1 performs closer to the real record.

4.3. Evaluation of Results for F8S3B

When frame 8S3B is considered it is seen that at station AQA, the results are similar to the other frames. At this station, SYN1 clearly underestimates the real response whereas SYN2 closely matches the real response. At station CLN and FMG, the results are similar to the results of F3S2B and F4S3B. The results at station FMG shows that both of the simulation techniques yield larger nonlinear responses than the real records. The roof displacement from SYN2 record is overestimated by a factor of 4 with respect to the real roof displacement. At station GSA both simulation methods result in an overestimation of the nonlinear response. However, from Table 6 it is noticeable that HIC method performs better than Stochastic Finite-Fault method. For the rest stations, the results based on SYN1 method are slightly underestimated. On the other hand, Stochastic Finite-Fault method overestimates the real response. Table 6 illustrates that for station LSS, NR misfits of SYN1 are less than SYN2 method, hence, SYN1 performs better than SYN2 method. In contrast, for the station MTR and SUL, it is vice versa. Yet, due to the higher number of stories (or the longer fundamental periods), response of HIC method approaches the real response. This could be explained with the fact that SYN1 matches closely with the low frequency content of the real record corresponding to longer fundamental periods (Figure 2). For this frame, both the RS and FAS misfits are in agreement with the NR misfits.

5. CONCLUSIONS

Following are the conclusions drawn from the numerical experiments conducted in this study:

- Among the two simulation methods used in this article, at the majority of the stations the Stochastic Finite-Fault model yields more conservative results due to overestimation of the nonlinear response. On the other hand, Hybrid Integral Composite method mostly provides accurate results as it covers the broadband frequency range. However, when a poor fit is obtained from a seismological point of view (e.g.,MTR and SUL for HIC model) a similar outcome is observed from the engineering point of view.
- Period dependent SDOF indicators of goodness of fit between the real and synthetic records match MDOF behavior of those real frame structures. Thus, in cases where synthetic records are to be used for frame structures, SDOF approximations that cover the lower and upper period band of the frames are sufficiently describing the response.
- The match between the Fourier Amplitude Spectrum of the real and synthetic record around the frequencies that correspond to the fundamental period of the structure governs the nonlinear response. Thus, it is important to simulate realistic amplitudes over the entire broadband frequency band.
- For this specific case, simulated records that seismologically satisfy a certain goodness of fit criterion yield nonlinear responses (story displacements) that are acceptable when compared to the real responses.
- Finally, synthetic records that overestimate the nonlinear response could be conservatively used for seismic design and assessment purposes. However, it is always better to accurately model the nonlinear response as close as possible with simulated records.

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