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Effects of Far- and Near-Field Multiple Earthquakes on the RC Single Degree of Freedom Fragility Curves Using Different First Shock Scaling Methods

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ABSTRACT

Typically, to study the effects of consecutive earthquakes, it is necessary to consider definite intensity levels of the first shock. Methods commonly used to define intensity involve scaling the first shock to a specified maximum interstorey drift. In this study the structure's predefined elastic spectral acceleration caused by the first shock is also considered for scaling. This study aims to investigate the effects of consecutive far-field (FF) and near-field (NF) ground motions on the exceedance probability of different performance levels of a reinforced concrete single degree of freedom system considering the aforementioned first shock scaling methods. Eight groups of simulations are defined with each considering a combination of FF and NF ground motions. By elastic spectral acceleration as the scaling method, it is found that the exceedance probability of the second shock performance levels, especially in pulse-like records, greatly depends on the order of far/near field ground motions and the level of damage caused by the first shock. It could be inferred that although first shock scaling method to maximum drift ratio is the commonly used method, the effects of record type multiple earthquakes are more revealed using elastic spectral acceleration as the first shock scaling criteria.

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1. INTRODUCTION

Buildings located in seismic regions are prone to experience several earthquakes during their lifetimes. Once an earthquake impacts a building, strength and stiffness degradation may occur depending on the intensity of the earthquake. As a result, the degraded structural system will respond differently to subsequent earthquakes. In many seismic design codes, seismic resistant buildings are designed considering a single earthquake known as the "design earthquake". In fact, damage accumulation caused by consecutive earthquakes is not explicitly considered in the traditional seismic design of the buildings.

During the last two decades, the impact of consecutive earthquakes on structural systems has been the subject of several research studies. Many researchers [1-7] studied the response of different structural systems to multiple earthquakes. They have shown that damage to structural systems subjected to multiple earthquakes is significantly higher than damage to those subjected to a single event. The results showed that the deformation demands of the system increase with exposure to repeated earthquakes. Consequently, they proposed some parameters, such as ductility demand spectra and reduced behavior factor, to be considered when designing structures susceptible to multiple earthquakes.

Abdelnaby [8], Abdelnaby and Elnashai [9] have studied on the effects of stiffness and strength degradation on the final deformations of RC frames subjected to multiple earthquakes. Hosseinpour and Abdelnaby [10] also analyzed the response of regular and irregular RC structures to the Christchurch 2010-2011 earthquake sequence. They found that aftershock polarity could affect the irregular structures more than the regular structures.

It is now well known that the seismic ground motions recorded within the near-fault (NF) region of an earthquake are quite different from those in the far-field

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(FF) region [11-14]. In a seismic region, the mainshock and its aftershocks are not necessarily located in the same place. Near-field seismic ground motions are mainly characterized by intense velocity and displacement pulses of relatively long periods [15]. Hatzigeorgiou [16] found that near-field and far-field earthquakes impose different ductility demands on structural systems. Yue et al. [17] investigated two cases of seismic sequences, FF main-shocks followed by FF aftershocks and FF main-shocks followed by NF aftershocks, to evaluate the collapse fragility for one steel frame structure. They concluded that although the mean structural collapse capacity for near-fault after shocks is smaller than that of far-fault after shocks, the collapse capacity appears to be more sensitive to FF after shocks when a building is severely damaged. Ruiz-Garcia and Mariquez [18] studied steel frames subjected to as-recorded FF and NF multiple earthquakes. They concluded that when NF earthquakes occur, the inter-storey drift ratio is larger than during FF earthquakes. Although several FF and NF combinations of multiple actual earthquakes have been studied, a comprehensive investigation of all possible ranges of NF and FF combinations has not yet to be carried out.

Luco and co-workers [19-21] have studied different damage indicators to quantify structural damage resulting from main-shocks. Their results show that drift measures are more effective indicators than other measures, such as the number of failed beams and columns, to predict capacity reduction.

Incremental Dynamic Analysis (IDA) curves are commonly used to present the results of multiple earthquakes. Each record is scaled to several levels of seismic intensity to force the structure through the entire range of behavior, from elastic to inelastic and finally to global dynamic instability when the structure essentially experiences collapse. Alternative simplified methods have also been proposed for seismic collapse analysis of structures [22]. However, in this study IDA is preferred since other performance levels in addition to collapse point was also of special interest. IDA curves are typically represented by a scalar Intensity Measure (IM) versus the structural response as measured by an engineering demand parameter (EDP), [23]. Structural capacities are assumed to have a lognormal distribution and the cumulative distribution function (CDF) is fitted to generate the fragility curves using S_a as a random variable, [24].

In seismic research and practice the scaling of ground motions for time history analyses is a common and important task. It is still one of the most challenging issues and involves considerable uncertainties. One of the earliest approaches was to match a target value of peak ground acceleration (PGA). The method does not take into account any structural characteristics and results in engineering demand values with large dispersion [25-28]. Including a vibration property of the structure has led to improved scaling methods, e.g., scaling records to a target value of the elastic spectral acceleration, $S_a(T_1)$ from the code-based design spectrum at the fundamental vibration period of the structure (T1), provides improved results for structures whose response is dominated by their first-mode [28]. An alternative of this method considering the important range of periods for the structure is now used in several seismic design codes. With regards to multiple earthquakes it has to be noted that the issue is somewhat different and there is no standardized method yet.

Depending on the purpose of the study most of previous studies have considered real (as recorded) [3, 6, 8-10, 18] or generated [1-5, 7-10, 16, 17, 19-29] sequences of earthquakes to apply a real or an estimated distribution of multiple earthquake characteristics to the structure. However to study a broader ranges of the possible scenarios it is important to take into account various intensity levels for the first and second shock. More specifically in multiple earthquake studies it is often necessary to apply a certain intensity of the first shock so that to assess the effects of the second shock. Recently Hosseinpour and Abdelnaby [10] and Raghunandan et al. [21] in studying multiple earthquakes and aftershock fragilities for RC structures have used interstorey drift criteria to quantify the various levels of mainshock damage. In this study, two scaling methods are used to evaluate the first shock seismic response of a RC single degree of freedom (SDOF) system. For the first scaling method, a specified maximum inter-storey drift corresponding to a predefined performance level is used. The second scaling method uses the commonly adapted intensity measure in IDA analysis, the predefined elastic spectral acceleration at the fundamental period of the structure under the first shock. To quantify the effect of first shock scaling methods using different scenarios of FF and NF record sets, second shock seismic fragility curves are developed. The performance evaluation is carried out for various first shock damage/intensity levels and second shock target performance levels.

2. STRUCTURAL MODEL

The structural system used for this research study is a cantilever beam-column with a lumped mass at its free end. The characteristics of the system are the same as the one used in an experimental test by Saatcioglu and Grira, [30]. OpenSEES [31] is used to develop the analytical model and calculate the response of the SDOF system. Based on the details of the experimental specimen, the system has a period of T = 0.53 seconds. The specimen dimensions and section details are presented in Figure 1a.

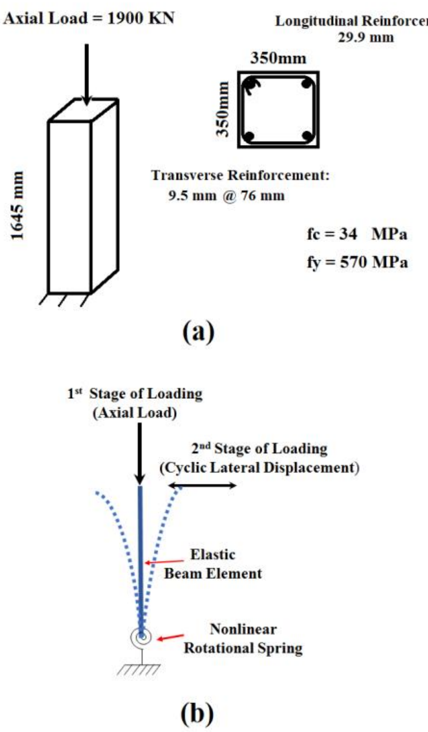

Figure 1. Main characteristics of SDOF system (a) Overview of tested model (b) Schematic numerical idealization

Since no shear damage was reported by the experimenter, the nominal column failure mode was classified as flexure-critical.

To simulate the test situation in the numerical modeling, the axial load of 1900KN is first applied, and then lateral cyclic displacement is imposed at the free end of the column. It also includes an elastic beam connected by a nonlinear rotational spring to the fixed base, see Figure 1b. Spring properties are assigned as suggested by Lignos and Krawinkler [32]. Their proposed model can include basic strength deterioration, post-capping strength deterioration, unloading stiffness deterioration, and accelerated reloading stiffness deterioration in the response. Additionally, the model includes P-Delta effects to consider the geometric nonlinearity.

For validation purposes, the model is subjected to cyclic lateral load, and the results are compared with those in the experimental study. Figure 2 shows the results of the validation study where the analytical results are compared with the experimental in terms of shear-force versus drift value. As it can be seen, the analytical results are in a good agreement with the experimental work. This model is used in this study to evaluate the response of SDOF systems under multiple seismic ground motions.

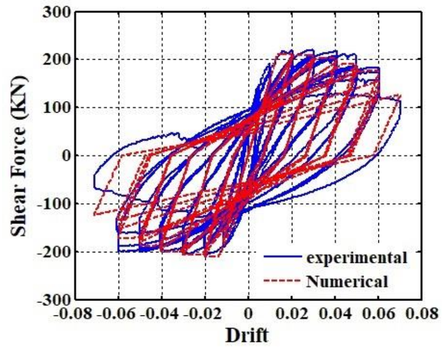

Figure 2. Validation of the numerical model: cyclic response comparison with BG-6 [30] experimental results

3. FIRST SHOCK SCALING METHODS

The effects of multiple earthquakes become engineering concerns when the first shock intensity is strong enough to create remarkable nonlinear deformations. Therefore, it is important to consider a range of damage levels from the first shock to study the seismic behavior of the system in resisting the second shock.

For this study, two scaling methods are used to evaluate the second shock seismic response of a RC SDOF system. Normally, the first shock is scaled so that to cause a specified maximum drift ratio in the structure. Another scaling method uses the predefined elastic spectral acceleration generated in the structure by the first shock. In order to determine equivalent intensity for the first scaling method, thirteen damage levels are considered which represent maximum drift range between 0.5 and 9.0%. In the second method, nine elastic spectral accelerations from 0.1 to 0.9 g are considered as first shock intensities. Related record scaling factors could be easily calculated from the elastic spectral acceleration.

4. DIFFERENT SCENARIOS EVALUATION

In this research, 22 far-field and 28 near-field records are used as recommended by FEMA P695 [33]. The records are downloaded from the strong ground motion database of the Pacific Earthquake Engineering Research Center [34]. This sufficient number of records can cover a range of frequency content, duration, and amplitude. In analysis 20 seconds time buffer between the first and second earthquakes is assigned to allow the motion of the system to go back to rest due to damping.

In this part, the influence of the record's type (FF or NF) in consecutive earthquakes is identified by the two aforementioned first shock scaling methods. The following sections presents the results in terms of second shock fragility curves for five performance levels (drift ratios of 1, 2.5, 5, 7 and 10%) for all the scenarios.

Eight groups of artificially generated seismic sequences are examined with each considering a combination of near-field and far-field ground motions. Near-field ground motions include both pulse-like and no-pulse motions so that the pulse effects can also be investigated. Table 1 displays all scenarios by their relevant first shock and second shocks with the total number of performed analyses. Two alternatives are considered: scenarios with FF as second shock and scenarios with NF as second shock.

The combination of both near- and far-field ground motions is included in a simplified manner using far-field and near-field records of one event (Cape Mendocino earthquake) as the first shock. In the following figures, the curves are provided as a function of second shock ground shaking intensity (S_a). It is not possible to present the fragility curve of all performance levels, hence in the following two cases of initial scaling for first shock are considered. The results can be expanded to other performance levels. Maximum drift ratios of 1 and 3.5% as well as two elastic spectral acceleration, S_a = 0.2 and 0.4g, are selected randomly from the thirteen and nine damage levels of performed analysis. Subsequently, the influence of the initial damage on the exceedance probability of considered performance levels during the second shock is evaluated to identify which scaling method is more appropriate to reveal the effects of the record type on the consequences of multiple earthquakes.

4. 1. Scenarios with FF as Second Shock

In this section, scenarios with far-field records as second shocks are considered with different first shocks in terms of near-field or far-field. The results are obtained using two scaling methods of the first shock.

It is worth noting that when the target performance level is lower than the first shock's residual drift, then no fragility curve is reported for multiple earthquakes.

TABLE 1. Different scenarios of FF and NF records and number of analyses for each scenario

Simulation Scenario			First shock	Second shock	Total No. of Analysis
Multiple	1	FFFF	FF	FF	1320
	2	NFFF	NF	FF	1320
	3	FFNF	FF	NF	
	4	FFNF-P	FF	NF-P	2520
	5	FFNF-NP	FF	NF-NP	
	6	NFNF	NF	NF	
	7	NFNF-P	NF	NF-P	2520
	8	NFNF-NP	NF	NF-NP	

To illustrate this, the residual drift values under single earthquakes are reported in Tables 2 and 3. Here, two FF and NF records of one seismic event are considered and the results are reported considering various maximum transient drifts for scaling the first shock. For example when maximum transient drift is 3.5% the corresponding residual drift for FF and NF records are 2.88 and 2.56% (see Table 2), respectively.

As a result the fragility curves for performance levels with 1 and 2.5% maximum transient drifts in Figure 3 coincide with vertical axis, i.e. showing 100% probability of exceedance for all intensity levels. Similar observation could be made for the other scaling method where the performance levels are lower than experienced residual drift ratios, (see Figure 4 and Table 3).

TABLE 2. Drift values in two different records of one event as first shock scaled to Maximum drift ratio

Max. Transient drift values for scaling the first shock (%)	Far-Field	Near-Field
	Max. Residual Drift (%)	Max. Residual Drift (%)
1.0	0.18	0.36
1.5	0.62	0.80
2.0	1.27	1.28
2.5	1.84	1.74
3.0	2.39	1.90
3.5	2.88	2.56
4.0	3.35	3.43
5.0	4.36	4.20
6.0	5.34	5.28
7.0	6.29	6.27
8.0	7.42	7.39
9.0	8.01	8.43

TABLE 3. Drift values in two different records of one event as first shock scaled to S_a

S_a for scaling the first shock	Far-Field		Near-Field	
	Transient (%)	Residual (%)	Transient (%)	Residual (%)
0.1g	0.30	0.00	0.42	0.00
0.2g	0.59	0.03	0.99	0.36
0.3g	1.19	0.33	1.79	1.06
0.4g	1.89	1.16	2.63	1.87
0.5g	2.60	1.91	2.91	1.93
0.6g	3.32	2.47	3.75	2.66
0.7g	4.17	3.53	5.63	4.92
0.8g	5.05	4.41	7.28	6.60
0.9g	5.90	5.24	10.38	10.03

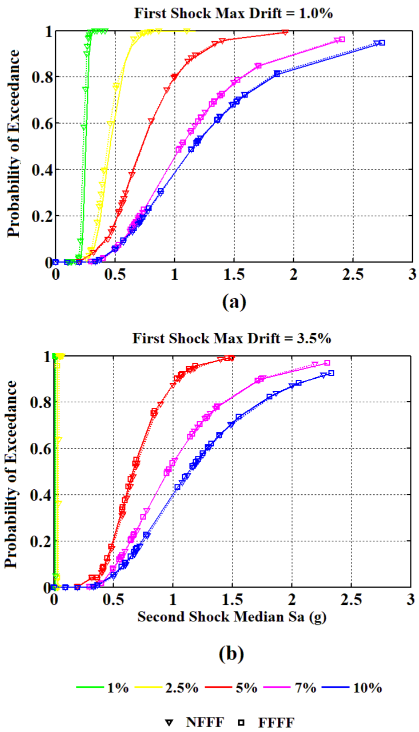

Figure 3. Fragilities under FFFF and NFFF scenarios where the first shock is scaled to specified maximum drift ratio (1 and 3.5%)

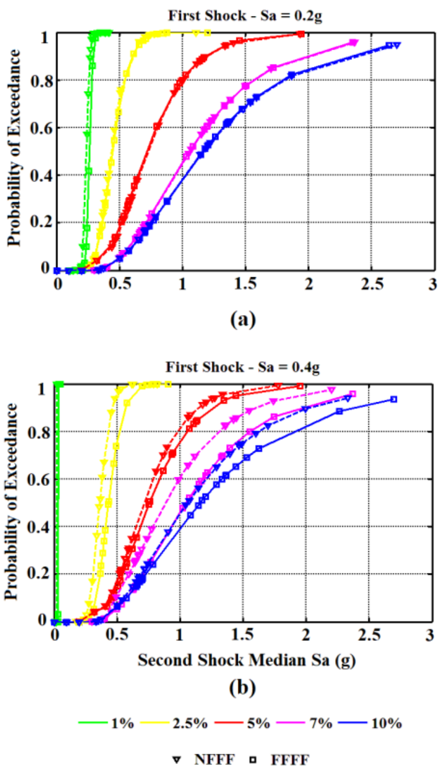

Figure 4. Fragilities under FFFF and NFFF where the first shock is scaled to have specified elastic spectral acceleration (0.2 and 0.4g)

Figure 3 presents probability of exceedance for scenarios of FFFF and NFFF where the first shock is scaled to maximum drift ratio of 1 and 3.5%. As depicted, no substantial difference is observed between the FFFF and NFFF scenarios. Since for these analyses the same target drift values under the first shock are used, it is generally expected that the structure will suffer the same initial damage level irrespective of which record has caused the damage. This indicates that the effect of the frequency contents of the first shock on various performance fragilities is negligible, when the first shocks are assumed to cause similar damage.

Figure 4 presents the effects of FFFF and NFFF scenarios where the first shock is scaled to a specified elastic spectral acceleration (S_a = 0.2g and 0.4g).

There are no significant differences between the intended scenarios in the lower first shock damaged level (Figure 4a) which can be disregarded.

These differences in the probability of exceedance become considerable at higher first shock intensity levels (see Figure 4b). As an example, probabilities of exceeding maximum drift = 2.5% in second shock (yellow curve) at intensities of 0.3 g, are 5, 20%, for FFFF and NFFF, respectively. This means that a system subjected to multiple earthquakes is more sensitive to record orders at higher damage conditions when the first shock is scaled to have specified S_a value.

According to Figure 4b, NFFF scenario results in higher probabilities of exceedance for all intended performance levels as comparing with FFFF scenario. This means that when NF is subjected as the first shock where the second shock is FF, there is a higher probability of exceedance. According to Table 3 this is explained by the higher residual drift values and different polarities caused by NF records when compared to FF records.

These observations indicate that although different records are scaled to similar spectral acceleration values, the resulted structural damage can be different when they are applied to the structure. Consequently, when the system is subjected to NF as the first shock, probability of exceedance for all the second shock performance levels are higher than that of FF as the first shock.

4. 2. Scenarios with the Second Shock Considering Pulse Effects

In this section pulse effects are studied by scenarios with NF records as the second shock. Figures 5 to 7 present fragility curves for the two aforementioned first shock scaling methods. Comparing the results for pulse versus no-pulse records (a vs. b or d vs. e in Figures 5 and 6) it can be seen that all relevant fragility curves for pulse records are indicative of a more fragile condition. This is obvious from higher steepness and leftward shift of fragility curves for pulse records. The same results are observed for all initial damage/intensity levels and all five intended second shock performance levels, see Figure 7. In addition, when both pulse and no-pulse records are included (see Figures 5, 6c and 6f), the probability of exceedance shows average values.

In general, since the probability of exceedance in pulse-like records is higher that of no-pulse records, excluding the pulse-like records in the response evaluation can underestimate the fragilities.

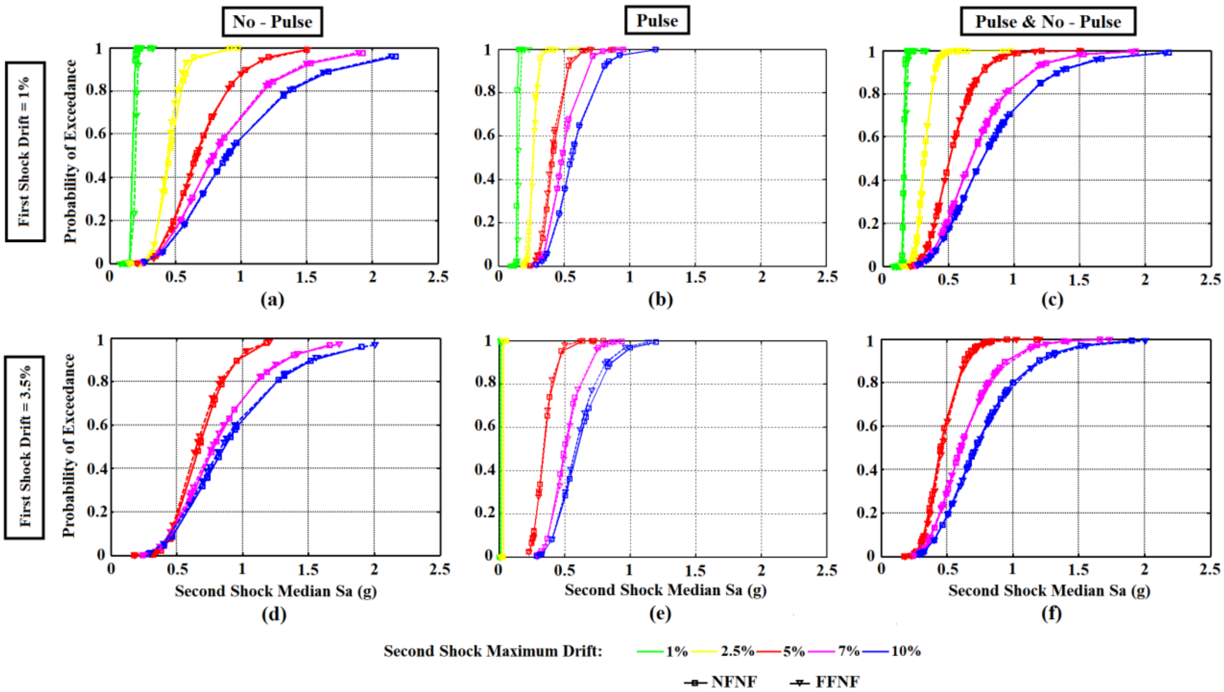

Figure 5. Pulse effect evaluation under different scenarios (FFNF and NFNF) where the first shock is scaled to specified maximum drift ratio (1 and 3.5%)

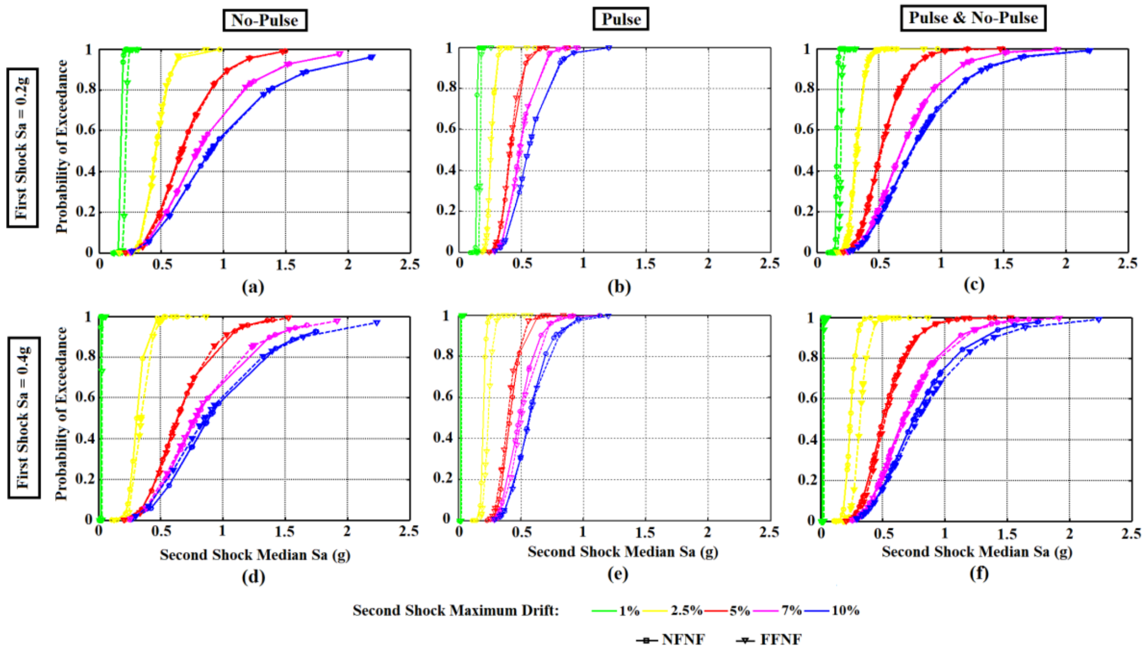

Figure 6. Pulse effect evaluation under different scenarios (FFNF and NFNF) where the first shock is scaled to have specified elastic spectral acceleration (0.2 and 0.4g)

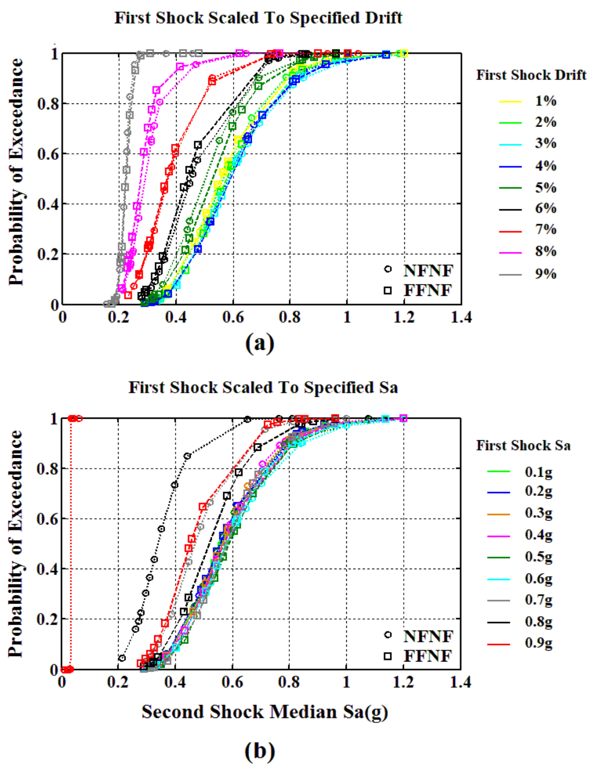

Figure 7. Second shock probability of exceedance for performance level of corresponding to drift vale = 10% considering pulse effect\under different scenarios (FFNF and NFNF) with two scaling method

In the case of record orders effects considering FF and NF as the first shock, there is no tangible difference between the FFNF and NFNF (Figures 5c and 5f) scenarios even in pulse-like records cases (Figures 5b and 5e) where the first shock is scaled to maximum drift ratio of 1 and 3.5%.

Figure 6 shows analysis results for the system to have elastic spectral acceleration of 0.2 and 0.4 g under the first shock. For the first shock intensity level of S_a = 0.2 g, there are negligible differences between FFNF and NFNF scenarios, except for performance level corresponding to 1 % drift value. As the initial intensity level increases, NFNF relevant fragility curves become more distinct from FFNF ones. This means that record order effects become more obvious in higher damage conditions where the first shock scaling criteria is elastic spectral acceleration.

For S_a = 0.4 g, the highest differences between two scenarios are seen for the performance level comparing to 2.5% drift value. This is more evident for pulse-like records for higher drift values the record type effects are reduced. As an example, when the second shock median intensity level is 0.2 g for pulse-like records (Figure 6 e), in performance corresponding level of 2.5%, probabilities of exceedance are 40 and 10% for the FFNF and NFNF, respectively. Corresponding probabilities of exceedance are approximately 20% for both scenarios under no-pulse records in Figure 6d.

Since the probability of exceedance for intended scenarios are more different in the case of pulse-like records, it is also concluded that scenarios with pulse-like records are more sensitive to the first shock record types than those in which the second shock is no pulse-like.

Figure 7 presents relevant fragilities for the second shocks in two intended first shock scaling methods. For brevity the curves are shown just for performance level with maximum drift of 10%. Figures 7a and 7b show probability of exceedance in nine damage/intensity levels under the first shock. For example, as it can be seen in Figure 7b when the first shock intensity is at S_a=0.8 g (black lines), the probabilities of exceedance at second shock intensity of about Sa=0.5g are 40% and 91% for FFNF and NFNF scenarios, respectively. For lower first shock intensity levels this difference reduces as the transient and residual drift values decrease, (see Tables 2 and 3).

5.CONCLUSION

The study investigates the probability of exceedance for a reinforced concrete single degree of freedom system when subjected to multiple earthquakes consisting of near-field and far-field records. This research focused on two scaling methods for the first shock and compares the results to determine which one shows the differences of consecutive record orders best. Therefore, the first shock scaling methods are defined by two terms: the maximum drift ratio experienced by the system subjected to the first shock and the peak elastic spectral acceleration (S_a).

In the method which uses the S_a parameter as the scaling measure, fragility analysis suggests that the exceedance probability of second shock performance levels are significantly dependent on the order of FF and NF. In this case, damage levels experienced by SDOF systems under the first shock play an important role in the fragility of the structural system.

In addition, pulse-like records in near-field cases under earthquake sequences have been incorporated in the research. In general, it appears that using S_a as the scaling measure for the first shock is more effective in revealing the effects of parameters such as record type (in terms of NF or FF) and pulse characteristics. For each performance level findings show that excluding pulse-like ground motions underestimate the system's fragilities.

In the case of S_a as a scaling method, comparing the family of fragility curves reveals that by increasing the intensity level, the probability of exceedance for the performance level increases. Furthermore, the order of imposing earthquake sequences in higher damage levels shows more influence on fragilities. Consequently, scenarios with NF as the first shock record show higher probability of exceedance than scenarios with FF as the first shock.

It has to be noticed that each aforementioned scaling methods could to be chosen according to the purpose of the study. However drift criteria is prevalent method to be used as the indicator of initial damage level. But as it is concluded from this research, where the record types have to be evaluated, it seems that S_a as the first shock scaling criteria is more appropriate.

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Effects of Far- and Near-Field Multiple Earthquakes on the RC Single Degree of Freedom Fragility Curves Using Different First Shock Scaling Methods

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چکیده

معمولا در مطالعه زلزله‌های متوالی لازم است زلزله اول به سطوح مشخصی از شدت مقیاس شود. یکی از روش‌های معمول برای مقیاس زلزله اول، حداکثر دریفت به عنوان معیاری از شدت زلزله اول محسوب می‌شود. روش دیگر استفاده شده در این مقاله شتاب طیف الاستیک به عنوان روشی برای تعیین ضریب مقیاس زلزله اول می‌باشد. در این مطالعه، احتمال فراگذشت سطوح عملکردی مختلف سیستم سازه‌ای بتن آرمه یک درجه آزادی تحت زلزله‌های متوالی با ترکیبات مختلفی از رکوردهای دور از گسل و نزدیک گسل برای هر دو معیار مقیاس مورد بررسی قرار گرفته است. اثرات توالی‌های مختلفی از زلزله‌های دور از گسل و نزدیک گسل برای ۸ سناریو شبیه‌سازی شده است. با استفاده از روش مقیاس به شتاب طیف الاستیک احتمال فراگذشت از سطح عملکرد زلزله دوم خصوصاً در حالتی که زلزله‌های پالس‌دار وارد شوند، به سطح خرابی سیستم در زلزله اول و ترتیب توالی رکوردهای دور از گسل و نزدیک گسل وابستگی بیشتری دارد. با اینکه روش مقیاس زلزله اول به دریفت حداکثر روش معمول‌تری به شمار می‌آید، اما اثرات نوع رکوردهای زلزله‌های متوالی در روش مقیاس به شتاب طیف الاستیک مشخص‌تر است.

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