CORRELATION OF DIFFERENT STRONG MOTION DURATION PARAMETERS AND DAMAGE INDICATORS OF REINFORCED CONCRETE STRUCTURES

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ABSTRACT:

Strong motion duration of an earthquake is an important and widely used seismic parameter. However, several definitions for strong motion durations exist that provide significantly different values for a given seismic excitation. This study examines the interdependency between several strong motion duration definitions and the overall building damage. In addition, peak ground acceleration and Arias intensity are considered as well. The overall damage indices after Park/Ang and after DiPasquale/Çakmak are used to express the post-seismic damage status, while the interdependency between the seismic parameters and the damage indicators have been evaluated by a correlation study. The investigation has been applied on a six story reinforced concrete building using as seismic excitation, a set of 450 different synthetic accelerograms. The results have shown that the peak ground acceleration and the Arias intensity provide medium and high correlation with the examined damage indices, respectively, while on the other hand, the correlation grade between the damage indices and the strong motion duration varies according to the definition used. Thus, the "absolute" definition group of bracketed durations provided better correlation with the damage indices than those of the "relative" one.

KEYWORDS: strong motion duration, damage indicators, reinforced concrete, seismic parameters

1. INTRODUCTION

It is well known that earthquake accelerograms possess inherent information that can be extracted in form of seismic parameters by a computer supported analysis. One important category of seismic parameters is that of the strong motion duration (SMD). Observations of structural and non-structural damages on buildings after severe earthquakes exhibit interdependency between the seismic parameters and the structural response. Numerical elaboration of structural systems quantified the interrelation degree between building damages and seismic parameters (Elenas, 2000).

This paper provides a study that quantifies the interrelationship between the SMD and several damage indices (DI). First, a computer supported elaboration of 450 synthetic time-acceleration histories supplies general and strong motion duration seismic parameters. As general parameters the peak ground acceleration (PGA) and the Arias intensity (AI) are used. Two groups of SMD parameters have been considered divided in merit of the way they are calculated. The “absolute” and “relative” groups according to whether the values are being directly or not extracted from the accelerograms’ PGA values. The next step was the use of nonlinear dynamic analysis in order to calculate the structural response for the given set of seismic excitations. Since a single number is used in order to express the aforementioned seismic parameters, the overall structural damage indices (OSDI) after Park/Ang and DiPasquale/Çakmak has been selected to represent the building’s structural response. Finally, a correlation study has been performed in order to express the degree of interdependency between the aforementioned strong motion parameters and overall structural building damage. The proposed methodology uses a six story reinforced concrete frame building and 450 strong motion seismic acceleration records. The aim is to quantify the interdependency degree between SMD parameters and OSDI in form of correlation coefficients and to compare them with the correlation coefficients provided by other traditionally used seismic parameters.

2. METHODOLOGY DESCRIPTION

2.1 Synthetic accelerograms and seismic parameters

The seismic excitations used for the dynamic analyses in this study are based on artificial accelerograms created to be compatible with the design spectra of the current Greek antiseismic code (2004). The reason for choosing this approach rather than relying on natural accelerograms was dictated by the need to have a sufficiently large database for statistical reasons. For the creation of the aforementioned artificial accelerograms the program SIMQKE [Gasparini and Vanmarcke, 1976] has been utilized. As artificial accelerogram creation parameters the peak ground acceleration (PGA), the total duration (TD) and the design spectra for all three Greek seismic regions (nominal PGA equal to 0.16g, 0.24g and 0.36g) have been used. All for subsoil category B, as described in Eurocode 8 [CEN, 1998] and the Greek Antiseismic Code (2004). In order to cover most types of Greek region seismic activity, an artificial accelerogram creation procedure has been devised comprising the creation of 10 random artificial accelerograms for each of the 5 preselected PGA values that were assigned for the three different Greek seismic regions and the 3 different total seismic durations selected (20 s, 30 s and 40 s). Thus, 450 different synthetic accelerograms have been compiled, which ensures that the overall structural damages of the examined structure will cover all the possible damage grades, from low to severe, in order to cover statistical demands as well.

For all created synthetic accelerograms, the following parameters, whose definitions can be found in the literature, have been evaluated by computer supported analyses: the peak ground acceleration (PGA) that is a very simple and a common seismic intensity measure, the Arias intensity (AI) [Arias, 1970] that is a measure of the total energy content of seismic excitation, the strong motion durations according Trifunac/Brady (SMD_{TB}) [Trifunac and Brady, 1975], according Trifunac/Novikova (SMD_{TN}) [Trifunac and Novikova, 1994], the SMD after McCann (SMD_{MC}) [McCann and Shah, 1979] and the bracketed duration, which is defined as the time elapsed between the first and last excursions beyond a specified threshold acceleration [Bolt, 1973]. In this study the 0.03g ($SMD_{B.03}$), the 0.05g ($SMD_{B.05}$) and the 0.1g ($SMD_{B.1}$) thresholds have been used. The SMD after Trifunac/Brady, after Trifunac/Novikova and after McCann (SMD_{MC}) belong to the so called "relative" SMD definition group, while on the other hand the bracketed durations belonging to the "absolute" SMD definition group.

2.2 Dynamic analyses of a frame structure

The reinforced concrete frame structure shown in Figure 1 has been detailed without antiseismic design, according to the codes of practice that were used before the introduction of the first Greek antiseismic code (1959). Thus, the six story reinforced concrete frame building represent the Greek suburban building stock designed before 1959. A consequence of detailing without antiseismic design is that medium and high damage degrees can be achieved without unrealistic strong seismic excitations. The cross-sections of the beams are considered as T-beams with 30 cm width, 20 cm slab thickness, 60 cm total beam height and 1.45 m effective slab width. The distances between each frame of the structure is equal to 6 m while the ground floor has a 4 m height and all subsequent floors 3 m. Furthermore, the subsoil was of type B (deep deposits of medium dense sand or over-consolidated clay at least 70 m thick). This procedure, apart from the self-weight, has taken into account the snow, the wind and the live loads. The eigenperiod of the frame was 1.0 s.

After the design procedure of the reinforced concrete frame structure, a nonlinear dynamic analysis evaluates the structural seismic response, using the computer program IDARC [Reinhorn et al., 1996]. A three-parameter Park model specifies the hysteretic behavior of beams and columns at both ends of each member. This hysteretic model incorporates stiffness degradation, strength deterioration, slip-lock and a trilinear monotonic envelope. Experimental results of cyclic force-deformation characteristics of typical components of the studied structure, specifies the parameter values of the above degrading parameters. This study uses the nominal parameter for stiffness degradation.

Among the several response parameters, the focus is on the overall structural damage indices (OSDI). This is due to the fact, that these parameters summarizes all the existing damages on columns and beams in a single value, which can be easily correlated to single value seismic parameters. In this study the modified damage index after Park/Ang [Park and Ang, 1985] and the maximum softening damage index after DiPasquale/Çakmak [DiPasquale and Çakmak, 1987] have been used. The damage indices have been evaluated for all the 450 created synthetic accelerograms.

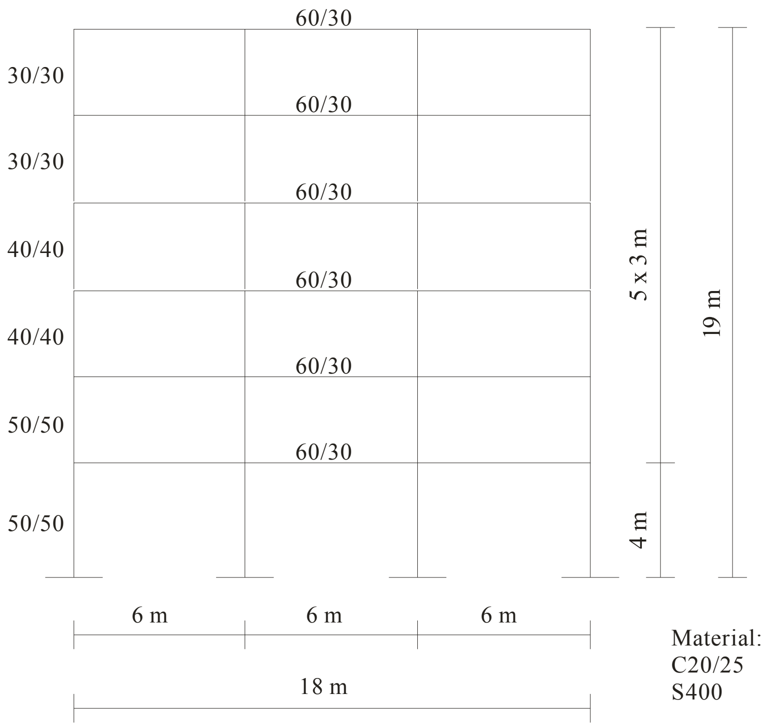

Figure 1. Reinforced concrete frame structure

2.3 Damage Indices

As explained previously, attention is focused on damage indicators that consolidate all member damage into one single value that can be easily and accurately be used for the statistical exploration of the interrelation with the also single-value seismic parameters in question. Thus, in the OSDI model after Park/Ang [Park and Ang, 1985] the global damage is obtained as a weighted average of the local damage at the ends of each element. The local damage index is a linear combination of the damage caused by excessive deformation and that contributed by the repeated cyclic loading effect that occurs during seismic excitation. Thus, the local DI is given by the following relation:

$$DI_L = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_T \qquad (2.1)$$

where, DI_L is the local damage index, θ_m the maximum rotation attained during the load history, θ_u the ultimate rotation capacity of the section, θ_r the recoverable rotation at unloading, β a strength degrading parameter, M_y the yield moment of the section and E_T the dissipated hysteretic energy. The Park/Ang damage index is a linear combination of the maximum ductility and the hysteretic energy dissipation demand imposed by the earthquake on the structure.

The global DI after Park/Ang [Park and Ang, 1985] is given by the following relation:

$$DI_G = \frac{\sum_{i=1}^{n} DI_L E_i}{\sum_{i=1}^{n} E_i} \qquad (2.2)$$

where, DI_G is the global damage index, DI_L the local damage index after Park/Ang, E_i the energy dissipated at location i and n the number of locations at which the local damage is computed.

The maximum softening index after DiPasquale/Çakmak [DiPasquale and Çakmak, 1987] has been selected as the second OSDI, which is based on the eigenperiods of the structures. Here, the change in the fundamental period of the structure is used as a measure of the change in the stiffness caused by the earthquake. The DI after DiPasquale/Çakmak is given by the expression:

$$\delta_M = 1 - \frac{T_0}{T_{max}} \qquad (2.3)$$

where, δ_M is the maximum softening, T_0 the initial natural period and T_{max} the maximum natural period of an equivalent linear system. For the evaluation of T_{max} a sliding window of 2.5 s has been used for the smoothness of the time-eigenperiod curve, as proposed by DiPasquale/Çakmak.

3. RESULTS

The first step was the creation of the aforementioned set of 450 synthetic accelerograms using the SIMQKE program. This program generates baseline corrected acceleration-time histories. The next step was a computer supported evaluation of the seismic parameters providing the PGA, AI, SMD_{TB}, SMD_{TN}, SMD_{MC}, $SMD_{B.03}$, $SMD_{B.05}$ and $SMD_{B.1}$, for each case. Nonlinear dynamic analyses has been performed for the reinforced concrete frame building under question, including all artificial acceleration-time histories, in order to obtain the structural damage indices after Park/Ang and DiPasquale/Çakmak. They express the overall post-seismic damage status of the examined structure. For this purpose the IDARC program has been utilized. Appropriate statistical procedures has been applied to provide the rank correlation coefficients after Spearman [Ryan, 2007], between all the evaluated seismic parameters and damage indices. The Spearman correlation shows how close are the examined data to monotone ranking. Table 1 summarizes the results of the correlation study.

Table 1. Spearman's correlation coefficients between the seismic parameters and the OSDI

	Rank correlation coefficient after Spearman for 450 cases							
OSDI	PGA	Arias	SMD_{TB}	SMD_{TN}	SMD_{MC}	$SMD_{B.03}$	$SMD_{B.05}$	$SMD_{B.1}$
Park/Ang	0.490	0.769	0.300	0.346	0.313	0.470	0.477	0.478
DiPasquale/Çakmak	0.589	0.857	0.246	0.296	0.251	0.444	0.450	0.452

The results show medium Spearman rank correlation between PGA and the considered OSDI. On the other hand, a high rank correlation between the Arias intensity and the considered OSDI is observed. It is noteworthy that the SMD has not a unique correlation grade with the OSDI. It is spreading from low (SMD_{TB}) to medium (bracketed duration). Thus, the "absolute" definition group of bracketed SMD ($SMD_{B.03}$, $SMD_{B.05}$ and $SMD_{B.1}$) shows better correlation with the OSDI than its "relative" definition group counterpart (SMD_{TB}, SMD_{MC}, SMD_{TN}). The above results indicate that SMD definitions, which are not directly interrelated with an intensity measure of accelerograms (e.g. PGA in the case of bracketed durations), are not appropriate descriptors for the damage potential of an earthquake.

Table 2. Spearman's correlation coefficients between the seismic parameters

	PGA	Arias	SMD_{TB}	SMD_{TN}	SMD_{MC}	$SMD_{B.03}$	$SMD_{B.05}$	$SMD_{B.1}$
PGA	1	0.590	-0.049	-0.116	-0.112	0.123	0.156	0.145
Arias	0.590	1	0.371	0.463	0.303	0.588	0.606	0.607
SMD_{TB}	-0.049	0.371	1	0.934	0.741	0.913	0.915	0.926
SMD_{TN}	-0.116	0.463	0.934	1	0.787	0.949	0.945	0.950
SMD_{MC}	-0.112	0.303	0.741	0.787	1	0.752	0.748	0.757
$SMD_{B.03}$	0.123	0.588	0.913	0.949	0.752	1	0.979	0.978
$SMD_{B.05}$	0.156	0.606	0.915	0.945	0.748	0.979	1	0.983
$SMD_{B.1}$	0.145	0.607	0.926	0.950	0.757	0.978	0.983	1

Table 2 shows the symmetric Spearman correlation coefficient matrix between all the examined seismic parameters. Thus, very high correlation is observed between the bracketed durations themselves, low correlation between them and the PGA and medium correlation with the Arias intensity, respectively. High correlation can be noticed between SMD_{TB} and SMD_{TN}. This can be explained by their similar definitions based on the Husid diagram (Husid, 1969). On the other hand, low correlation is observed between the "relative" definition group of SMD (SMD_{TB}, SMD_{MC}, SMD_{TN}) and the PGA and AI. Finally, the Spearman rank correlation between the overall structural damage indicators after Park/Ang and DiPasquale/Çakmak is high (0.942).

4. CONCLUSIONS

This study presented a methodology for the estimation of the interdependence between seismic acceleration parameters and damage indices, taking into consideration several seismic parameters. The focus was on the strong motion duration parameters. The latter were used in two alternative groups of definition ("absolute" and "relative"). On the other hand, structural damages are considered using the modified Park/Ang and the DiPasquale/Çakmak overall structural damage indicators. The numerical analysis used a six story reinforced concrete frame structure and 450 spectrum compatible baseline corrected synthetic accelerograms. Spearman rank correlation coefficients expressed the degree of interrelationship between seismic parameters and damage indices.

As the numerical results revealed, medium rank correlation between PGA and the OSDI has been observed. In addition, Arias intensity provided high correlation with the OSDI. Among the several definitions of SMD considered, the bracketed durations ($SMD_{B.03}$, $SMD_{B.05}$ and $SMD_{B.1}$) provided better correlation with the OSDI, in comparison with the other SMD definition group used (SMD_{TB}, SMD_{MC}, SMD_{TN}). The lowest correlation value can be tracked to SMD after Trifunac/Brady, which leads to pinpoint the worst interrelation between the OSDI and all the examined seismic parameters. In addition, low correlation is observed between the "absolute" definition group of SMD with PGA and medium with AI, while the "relative" definition group of SMD provides low correlation with the same parameters. Thus, strong motion duration definitions that are not direct enclosing an accelerogram intensity measure, are inappropriate seismic damage potential descriptors. Finally, high correlation is observed between the used overall damage indicators (Park/Ang and DiPasquale/Çakmak).

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