COMPDYN 2011
III ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis, V. Plevris (eds.)
Corfu, Greece, 25–28 May 2011

INTENSITY PARAMETERS AS DAMAGE POTENTIAL DESCRIPTORS OF EARTHQUAKES

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Keywords: Seismic Parameters, Damage Indices, Seismic Ground Motion, Damage Potential, Reinforced Concrete.

Abstract. *This paper provides a methodology to quantify the interrelationship between the seismic intensity parameters and the structural damage. First, a computer-supported elaboration of the accelerograms provides several peak, spectral and energy seismic parameters. After that, nonlinear dynamic analyses are carried out to provide the structural response for a set of seismic excitations. Among the several response characteristics, the overall structure damage indices after Park/Ang and the maximum inter-story drift ratio are selected to represent the structural response. Correlation coefficients are evaluated to express the grade of interrelation between seismic acceleration parameters and the structural damage. The presented methodology is applied to a six-story reinforced concrete frame building. According to the first step of the methodology sixteen seismic parameters are evaluated: PGA, PGV, PGA/PGV, spectral acceleration (SA), spectral velocity (SV), spectral displacement (SD), central period (CP), absolute seismic input energy (E_{inp}), Arias intensity (I_A), strong motion duration after Trifunac/Brady (SMD_{TB}), seismic power ($P_{0.90}$), root mean square acceleration (RMS_a), intensity after Fajfar/Vidic/Fischinger (I_{FVF}), spectral intensities after Housner (SI_H), after Kappos (SI_K) and after Martinez (SI_M). The frame structure has been designed according to the rules of the recent Eurocodes. Then, a nonlinear dynamic analysis has been carried out for the evaluation of the seismic response. Among the several response parameters, the focus is on the overall structure damage indices. This is due to the fact, that this parameter summarizes statistically all the existing damages on columns and beams in a single value, which can be easily correlated to single value seismic parameters. As seismic input for the nonlinear dynamic analysis, a set of spectrum-compatible synthetic accelerograms has been used. To emphasize the grade of interrelation between seismic acceleration parameters and the overall structure damage indices, the correlation coefficient after Pearson and the rank correlation coefficient after Spearman have been calculated. As the numerical results have shown, the spectral and energy parameters provide strong correlation to the damage indices. On the opposite, the CP, SMD_{TB} and the term PGA/PGV delivered poor correlation with the damage indices. Due to this reason, spectral and energy related parameters are better qualified to be used for the characterization of the seismic damage potential.*

1 INTRODUCTION

It is well-known that seismic accelerograms are ground acceleration time-histories that cannot be described analytically. Several seismic parameters have been presented in the literature during the last decades. These can be used to express the intensity of the seismic excitations and to simplify its description. Post-seismic field observations and numerical investigations have indicated the interdependency between the seismic parameters and the damage status of buildings after earthquakes [1, 2]. The latter can be expressed by proper damage indices, while the interdependency between the considered quantities can be quantified numerically by appropriate correlation coefficients. Their values deliver the correlation grade (low, medium or high) between the examined quantities.

This paper provides a method for quantifying the interrelationship between the seismic parameters and global damage indices. First, a computer analysis of the accelerograms provided several peak ground motion, spectral and energy seismic parameters. After that, nonlinear dynamic analyses were carried out to provide the structural response for a set of seismic excitations and a given reinforced concrete frame structure. Keeping in mind that most of the seismic loading parameters are characterized by a single numerical value, single-value damage indicators have also been selected to represent the structural response. Thus, the overall structural damage index (OSDI) after Park/Ang ($DI_{G,PA}$) and the maximum inter-story drift ratio (MISDR) are selected to represent the structural response. Finally, correlation coefficients are evaluated to express the grade of interdependency between seismic acceleration parameters and the used damage indices. The presented methodology is applied to a six-story reinforced concrete frame building subjected to several artificial accelerograms.

2 SEISMIC INTENSITY PARAMETERS

In general, the intensity parameters can be classified with peak, spectral and energy parameters. In this work the following parameters have been selected to represent the seismic intensity: peak ground acceleration PGA, peak ground velocity PGV, the term PGA/PGV, spectral acceleration (SA), spectral velocity (SV), spectral displacement (SD), central period (CP), absolute seismic input energy (E_{inp}), Arias intensity (I_A), strong motion duration after Trifunac/Brady (SMD_{TB}), seismic power ($P_{0.90}$), root mean square acceleration (RMS_a), intensity after Fajfar/Vidic/Fischinger (I_{FVF}), spectral intensities after Housner (SI_H), after Kappos (SI_K) and after Martinez-Rueda (SI_{MR}). They have been chosen from all three of the seismic parameter categories. Table 1 provides an overview of the used parameters and their literature references, respectively. The definition of each parameter is presented in the mentioned literature.

No	Seismic parameters	Reference	No	Seismic parameters	Reference
1	PGA	[3]	9	I_A	[7]
2	PGV	[3]	10	SMD_{TB}	[8]
3	PGA/PGV	[3]	11	$P_{0.90}$	[9]
4	SA	[4]	12	RMS_a	[3]
5	SV	[4]	13	I_{FVF}	[10]
6	SD	[4]	14	SI_H	[11]
7	CP	[5]	15	SI_K	[12]
8	E_{inp}	[6]	16	SI_{MR}	[13]

Table 1: Seismic parameters.

3 SEISMIC ACCELERATION TIME HISTORIES

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 [14] has been utilized. As artificial accelerogram creation parameters the 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 created for subsoil category B, as described in Eurocode 8 (EC8) [15] and the Greek Antiseismic Code [16]. This subsoil category belongs to deep deposits of medium dense sand or over-consolidated clay at least 70 m thick. In order to cover most types of Greek region seismic activity, an artificial accelerogram creation procedure has been devised comprising the creation of 5 random artificial accelerograms for each of the 15 preselected PGA values that were assigned for the three different Greek seismic regions. Thus, 75 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.

4 GLOBAL 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 [17] 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:

$$DI_{L,PA} = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_T \tag{1}$$

where, $DI_{L,PA}$ 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 damage index after Park/Ang [17] takes into account the local damages of all elements of the examined structure (e.g. beams and columns of a frame). Thus, it depends both, the distribution and the severity of the localized damage and is given by the following relation:

$$DI_{G,PA} = \frac{\sum_{i=1}^{n} DI_{L,PA} E_i}{\sum_{i=1}^{n} E_i} \tag{2}$$

where, $DI_{G,PA}$ is the global damage index, $DI_{L,PA}$ 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 MISDR [18, 19] is a simple OSDI that describes satisfactorily various forms of damages after an earthquake. The post-seismic damage degree can be classified according to this index. Equation (3) defines the maximum inter-storey drift ratio (MISDR) as the ratio of the maximum absolute inter-story drift $|u|_{max}$ to the inter-storey height h:

$$\mathrm{MISDR} = \frac{|u|_{max}}{h} 100\ [\%] \tag{3}$$

5 APPLICATION

The reinforced concrete frame structure shown in Figure 1 has been detailed is in agreement with the rules of the recent Eurocodes for structural concrete and aseismic structures, EC2 and EC8 [20, 15]. According to the EC8 Eurocode, the structure shown in Figure 1, has been considered as an "importance class II, ductility class M"-structure with a subsoil category B. 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. The subsoil was of type B (deep deposits of medium dense sand or over-consolidated clay at least 70 m thick). The eigenperiod of the frame was 1.0 s.

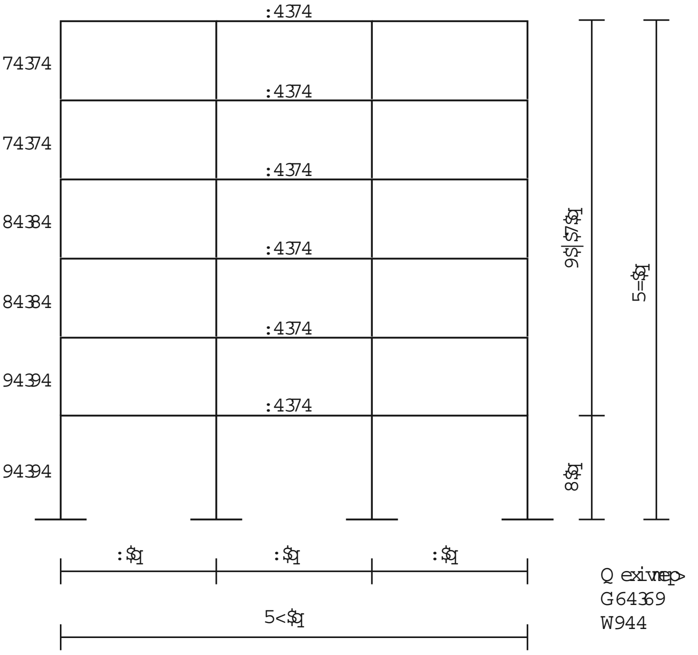

Figure 1: Reinforced concrete frame structure.

After the design procedure of the reinforced concrete frame structure, a nonlinear dynamic analysis evaluates the structural seismic response, using the computer program IDARC [21]. 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 tri-linear 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) described in the previous section.

6 RESULTS

The first step was the creation of the aforementioned set of 75 synthetic accelerograms using the SIMQKE program. This program generates baseline corrected acceleration-time histories. The next step was a computer supported evaluation of 16 seismic parameters as presented in Table 1. 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 the MISDR. Statistical procedures provide the correlation coefficients after Pearson and Spearman [22], between all the evaluated seismic parameters and damage indices. The Pearson correlation shows how well the data fit a linear relationship, while the Spearman correlation shows how close the examined data are to monotone ranking. The latter coefficient is more important in the present study. Table 2 summarizes the results of the correlation study.

Seismic parameters	Pearson correlation		Spearaman rank correlation	
	$DI_{G,PA}$	MISDR	$DI_{G,PA}$	MISDR
PGA	0.568	0.523	0.635	0.631
PGV	0.657	0.659	0.788	0.795
PGA/PGV	-0.355	-0.367	-0.393	-0.394
SA	0.711	0.678	0.803	0.806
SV	0.724	0.696	0.804	0.804
SD	0.738	0.706	0.849	0.845
CP	-0.342	-0.326	-0.351	-0.332
E_{inp}	0.668	0.667	0.812	0.821
I_A	0.682	0.659	0.824	0.821
SMD_{TB}	0.103	0.086	0.155	0.145
$P_{0.90}$	0.685	0.662	0.823	0.820
RMS_a	0.713	0.677	0.824	0.821
I_{FVF}	0.655	0.656	0.789	0.796
SI_H	0.703	0.664	0.796	0.795
SI_K	0.702	0.670	0.802	0.806
SI_{MR}	0.614	0.558	0.725	0.725

Table 2: Correlation coefficients between the seismic parameters and the OSDIs.

It is supposed that correlation coefficients up to 0.5 means low correlation, coefficients between 0.5 and 0.8 means medium correlations, while coefficients greater than 0.8 means strong correlation between the two variables. Table 2 presents the correlation coefficients after Pearson and the rank correlation coefficients after Spearman among all the examined seismic parameters presented and the examined the damage indices. Thus, the results show low Pearson and Spearman correlation between the term PGA/PGV, CP, SMD_{TB} and the examined damage indices. All the remaining seismic parameters provided medium Pearson correlation with the damage indices. On the other hand, high rank correlation is observed between SA, SV, SD, E_{inp}, I_A, $P_{0.90}$, RMS_a, SI_K and the damage indices. In addition, medium rank correlation is observed between PGA, PGV, I_{FVF}, SI_H, SI_{MR} and the damage indices.

Finally, the seismic parameters show the same correlation grade with $DI_{G,PA}$ with MISDR in all the cases. All the seismic parameters show the same correlation grade for both, Pearson and Spearman correlation, with exception the cases with high rank correlation. There, the Pearson correlation grade is medium.

7 CONCLUSIONS

- In this paper a methodology for the value estimation of the interdependence between seismic acceleration intensity parameters and damage indices has been presented. Peak, spectral and energy parameters have been considered. The global damage index after Park/Ang and the MISDR represented the post-seismic structural damage status. The degree of the interrelationship between seismic parameters and damage indices has been expressed by the Pearson correlation coefficient and by the Spearman rank correlation coefficient.
- The results show low Pearson and Spearman correlation between the term PGA/PGV, CP, SMD_{TB} and the examined damage indices.
- Medium correlation is observed between PGA, PGV, I_{FVF}, SI_H, SI_{MR} and the damage indices, in all the cases.
- High rank correlation is observed between SA, SV, SD, E_{inp}, I_A, $P_{0.90}$, RMS_a, SI_K and the damage indices. In all these cases, the corresponding Pearson correlation grade was medium.
- The seismic parameters show the same correlation grade with $DI_{G,PA}$ with MISDR in all the cases
- All these results lead to conclude that the spectral and energy seismic parameters are reliable descriptors of the seismic damage potential and to recommend them as appropriate descriptors of the seismic damage potential.

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