Research Note

Estimation of Interdependencies between Seismic Parameters and Damage Indices Including the MFDR Model and the Modified Park-Ang Model

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ABSTRACT

Correlations between seismic acceleration parameters and damage indices can help to predict the value of the damage for an earthquake event. This paper has two parts. One part is the detection of the interdependency between important seismic acceleration parameters, and two damage models including the modified Park-Ang cumulative damage model and the maximum modified flexural damage ratio model (MFDR) by using of the Spearman correlation coefficient. For the first part, we have utilized 17 records of the earthquake from all over the world. Results showed sustained maximum acceleration and effective design acceleration have the best correlation with the Park-Ang model. Besides, the weakest interdependencies are related to displacement RMS and cumulative absolute velocity for the Park-Ang model. However, among selected seismic acceleration parameters, peak ground velocity and Housner Intensity have the best interdependencies with the MFDR model. On the other hand, cumulative absolute velocity and Vmax/Amax have shown the weakest interdependencies with the MFDR model. Other part includes the time variation of the MFDR model in duration of the Victoria earthquake. It can give a good sight about process of behavior members during earthquake. Moreover, time variation of the MFDR model can determine process degradation of each member.

Keywords:
Seismic acceleration parameter; Damage index; Spearman correlation coefficient; Interdependency

1. Introduction

The estimation of damage in reinforcement concrete frames is a necessary step for characterizing performance of the concrete members in duration of an earthquake and after that. The determination of damages can be very important to calculate the required cost for repairing or restructuring member and structure.

Accelerograms contain valuable information about characterizations of an earthquake. Seismic parameters that are important to describe accelerograms include Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD), Root-Mean-Square (RMS) of acceleration, Root-mean-square (RMS) of velocity, Root-mean-square (RMS) of displacement, Arias intensity (AI), Characteristic intensity (CI), Specific Energy Density (SED), Cumulative Absolute Velocity (CAV), Velocity Spectrum Intensity (VSI), Housner Intensity (HI), Sustained Maximum Acceleration (SMA), Sustained Maximum Velocity (SMV), and Effective

Design Acceleration (EDA).

Interrelationship between damage index and seismic parameters can give a good sight about important parameters which have prominent effect on damage index. Seismic parameters that are mentioned above are described in the literature [1-6].

Elenas and Meskouris [7] have investigated the interdependency between several seismic acceleration parameters and structural damage indices including the modified Park-Ang overall structural damage index, the maximum interstory drift and the maximum floor acceleration. Peak ground motion, spectral and energy parameters have been used by them. It has been showed that peak ground motion parameters provide poor or fair correlation with the modified Park-Ang overall structural damage index, whereas the spectral and energy parameters provide good correlation. Besides, it has been shown that the central period and the strong motion duration after Trifunac/Brady indicated poor correlation with the OSDI. As a result, spectral and energy related parameters are believed to be better suited for the characterization of the seismic damage potential.

Safi and Soleymani [8] have evaluated correlations between three global damage indices (the modified flexural damage index, the Bracci index and the drift index) and seismic parameters. Time-variations of the members' degradations were calculated and presented. It has been shown that the Housner intensity has the best interdependencies with the three damage indices (the modified flexural damage index, the Bracci index and the drift index).

Moreover, Elenas [9] has been shown the grade of the interrelation between seismic acceleration parameters and the overall structural damage index by the linear correlation coefficient after Pearson and the linear rank correlation coefficient after Spearman. He used the Park-Ang model and the Di Pasquale/Cakmak model. He concluded that spectral pseudo-acceleration and spectral absolute seismic input energy have the strongest correlation with the overall structural damage index. In most of the literatures, the final quantities of damage indices are reported by many researchers, but the process of the member degradation has not been determined during earthquake time and after that. Furthermore, specification of time variation for damage indices can be very useful. Estekanchi and Arjomandi [10] investigated correlation between numerical values of damage indices based on deformation, energy, modal parameters and low cycle fatigue behavior.

Elenas [11] has evaluated the interdependencies between the structural damage indices and the seismic intensity parameters. He utilized the modified Park-Ang damage index and drift model as damage index. He concluded that the spectral and energy parameters provide strong correlation to the damage indices.

In another research, Nanos et al. [12] have investigated interdependencies between several strong motion duration definitions and the important damage indices including the Park-Ang model and the Di Pasquale/Cakmak model. They have shown that strong motion duration definitions that are not direct enclosing an intensity measure of record, are inappropriate seismic damage potential descriptors.

This paper has two parts. One part contains determination of the interrelationship between seismic parameters and the damage index including the modified Park-Ang model and the modified flexural damage ratio (MFDR) model. For this purpose, we utilized the Spearman correlation coefficient. The other part includes time variation of the MFDR model at different member for attaining a good sight about process of member degradation.

2. Damage Models

One of the most important damage indices is the Park-Ang model [13], which combines hysteretic energy dissipation and maximum deformation. When inelastic behavior is restricted to plastic zone near the end of members, the relationship between member deformation and local plastic rotation can be presented by the modified Park-Ang model [14].

$$DI = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta}{M_y \theta_u} E_h \qquad (1)$$

Here, θ_m is maximum rotation related to loading history; θ_u is ultimate rotation capacity of the member; θ_r is recoverable rotation when member is unloading; M_y is yield moment and E_h is dissipated energy at the section. A damage model was proposed by the Roufaiel and Meyer [15] that was based on the reduction in secant stiffness. It should be mentioned that cumulative damage was not calculated by Roufaiel and Meyer model. Depends on the degradation stiffness and strength suffered during an earthquake, this model presents the ability of the structure to resist against an earthquake. The maximum modified flexural damage ratio (MFDR) presented by the Roufaiel and Meyer are utilized as an indicator of the member damage from negative or positive loading. The following formula presents MFDR relation:

$$MFGR = \frac{\left(\phi_m / M_m - \phi_y / M_y \right)}{\left(\phi_u / M_u - \phi_y / M_y \right)} \tag{2}$$

Here, ϕ_m is maximum curvature related to loading history; ϕ_u is ultimate curvature of the end member; M_y is yielding curvature of the end member, M_m, M_y and M_u are maximum moment, yielding moment and ultimate moment, respectively. These damage models can be utilized to count different damage indices including element, story and overall damage index. In this paper, we use overall damage indices by weighting factor that is based on dissipated energy at each member. The weighting factor is given by the following formula:

$$\lambda_i = \frac{E_i}{\sum_{i=1}^{N} E_i} \tag{3}$$

where E_i is dissipated energy by each member. When we utilized an overall damage index, we can attain a good indicator about collapse of the overall structure, whereas the local damage just determinates damage at the member.

3. The Spearman Correlation Coefficient

In statistics, there are many numerical measures that determine the extent of the statistical dependence between pairs of variables. A nonparametric measure of statistical dependence between two observations is calculated by the Spearman correlation coefficient. The Spearman correlation coefficient between two variables X and Y is given by the following formula:

$$\rho_{Spearman} = 1 - \frac{6\sum D^2}{N(N^2 - 1)} \tag{4}$$

Here, D is the difference between the ranks of corresponding values of X_i and Y_i. N is the number of pairs of values (X, Y) in the data. Besides, it is necessary to notice that the value of the Spearman correlation coefficient between 0 and 0.3 (0 and -0.3) indicate a weak positive (negative) interdependency, values between 0.3 and 0.7 (0.3 and -0.7) indicate a moderate positive (negative) interdependency, and values between 0.7 and 1.0 (-0.7 and -1.0) indicate a strong positive (negative) interdependency.

4. Analytical Procedure

According to the rules of ACI codes for structural concrete, the reinforced concrete frame structure that is shown in Figure (1) has been designed. Besides, numbers of columns and beams are presented in Figure (1).The cross sections of T-beams contain 15 cm plate thickness, 125 cm effective plate width, and 55 cm total beam height. The cross section of columns contain 60×60 cm for first, second and third levels, 55×55 cm for fourth, fifth, sixth and seventh levels and 50×50 cm for eigth, ninth and tenth levels. Distances selected between each frame are 600 cm. compressive strength of concrete element is equal to 240 kg/cm^2 and strain at maximum strength of concrete is equal to 0.2%. All of the necessary loads such as self-weight load, dead load and live load are considered in calculation.

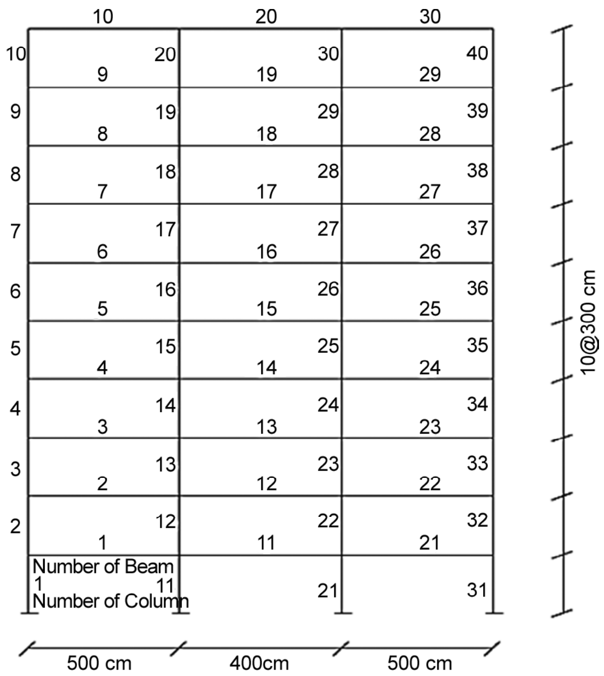

Figure 1. Reinforcement concrete frame.

Moreover, Iranian code of practice for seismic resistant design of building, standard No. 2800-05 was selected as seismic design codes and sway special was selected for element types. The eigenperiod of structure was 1.60 s.

When the design procedure of the frame structure was completed, an inelastic dynamic analysis has been done by the computer program IDARC 7.0.

For beams and columns; we used hysteresis models that include stiffness degradation, strength deterioration and slip parameter. For beams and columns, grades related to stiffness degrading parameters are equal to moderate degrading and mild degrading, respectively. In addition, for beams and columns, grades related to strength degrading parameters (energy controlled) are equal to moderate deterorating and mild deteriorating, respectively. Besides, no pinching was considered for members. In this paper, we used 17 accelerograms from the whole world that are presented in Table (1). The seismic parameters related to each accelerogram are shown in Table (2). The maximum modified flexural damage ratio (MFDR) and the modified Park-Ang model were calculated for each accelerogram, results of which are presented in Table (3). When quantities of the overall structural damage indices were determined, the interdependencies between the overall structural damage indices and seismic parameters were calculated by the Spearman rank correlation coefficient.

Quantities of the correlation coefficient are presented in Table (4). In second part of this paper, we estimated time variation of the MFDR at some of the beams and columns for the Victoria earthquake. The end curvatures of beams and columns are calculated by IDARC for MFDR model.

5. Discussion

The results of correlations coefficient between seismic parameters and damage models are prepared in Table (4). As it has been observed, sustained maximum acceleration and effective design acceleration have the best interdependencies with the modified Park-Ang model.

Furthermore, the weakest interdependencies are related to cumulative absolute velocity and displacement RMS for the modified Park-Ang model.

Table 1. Earthquakes events.

Earthquake	Station-Country	Component	Date
Cape Mendocino	Rio Dell Overpass-USA	270	1992/04/25
Coalinga	Pleasant Valley-USA	H-PVY045	1983/05/02
Manjil	Abhar-Iran	Transverse	1990/06/20
Chi-Chi	CHY006-Taiwan	CHY006-E	1999/09/20
Imperial Valley	Bonds Corner-USA	H-BCR140	1979/10/15
Gazli	Karakyr-Uzbakistan	GAZ000	1976/05/17
Northridge	Tarzana-USA	TAR360	1994/01/17
Kobe	Shin-Osaka-Japan	SHI000	1995/01/16
Victoria	Cerro Prieto-USA	CPE045	1980/06/09
Westmorland	West Fire Sta-USA	WSM180	1981/04/26
Avaj	Avaj-Iran	35 N 49E	2002/06/22
Duzce	Duzce-Turkey	DZC270	1999/11/12
San Fernando	Castaic old-USA	270	1971/02/09
Nahanni	Site 1-Canada	S1010	1985/12/23
Loma Prieta	Corralitos-USA	CLS000	1989/10/18
Kocaeli	Sakarya-Turkey	SKR090	1999/08/17
Whittier Narrows	SanGabriel-USA	DZC270	1999/11/12
Varzaqan	Varzaqan-Iran	N-E	2012/08/11
Erzincan	95 Erzincan- Turkey	ERZ-NS	1992/03/13
Landers	24 Lucerne-USA	LCN000	1992/06/28

Table 2. Values of the seismic parameters.

Earthquake	PGA (g)	PGV (cm/s)	PGD (m)	V_{max}/a_{max} (s)	A RMS (g)	V RMS (cm/s)	D RMS (m)	IA (m/s)	Ic	SED (cm^2/s)	CAV (cm/s)	VSI (cm)	HI (m)	SMA (g)	SMV (cm/s)	EDA (g)
Kobe	.262	40.0	0.07	0.156	.037	5.45	.018	.827	.045	1159.1	709.4	133.6	114.73	0.19	22.6	0.26
Victoria	.609	33.45	0.1	.056	.072	7.813	.033	1.948	.095	1492.5	982.2	159.3	141.22	.411	28.1	.465
Loma Prieta	.661	57.73	0.06	0.089	.073	6.515	.017	3.245	.124	1694.8	1252.	175.8	152.65	.472	26.6	.683
Northridge	.94	64.5	0.22	0.07	.165	14.0	.068	16.69	.422	7876.6	3516	305.9	262.17	.812	50.5	0.69
Kocaeli	.389	68.95	0.35	0.181	.043	9	.098	1.721	.069	4844.6	1041.	133.2	139.61	.308	30.7	0.31
San Fernando	.339	15.4	0.02	0.046	0.03	2.64	.005	0.683	.041	209.66	661.1	62.60	50.121	.194	10.4	.327
Whittier	.316	25.0	0.03	0.081	.042	3.87	.006	0.831	.048	449.27	557.3	105.6	89.801	.213	13.8	.289
Imperial Valley	.573	46.01	0.12	0.082	.105	10.40	.044	3.809	.161	2434.0	1270.	209.0	173.60	.517	34.27	0.56
Chi-Chi	.364	53.2	0.20	0.149	.053	9.83	.047	1.697	.076	3832.4	917.7	240.2	227.20	.295	46.7	.356
Gazli	.592	59.5	0.24	0.103	.134	17.8	.098	4.519	.198	5171.3	1342.	234.2	214.13	.564	51.2	.547
Westmorland	.363	39.64	0.09	0.111	.054	6.63	.029	1.744	.078	1740.4	942.1	195.3	178.95	.316	33.9	.363
Cape Mendocino	.357	39.57	0.11	0.113	.053	6.33	.035	1.52	.072	1426.8	1025.	151.6	139.97	.238	19.3	.363
Nahanni	.954	42.6	0.09	0.046	0.12	8.17	.029	4.412	.185	1337.0	1261	151.2	126.47	.856	26.7	.749
Manjil	.22	48.8	0.24	0.226	.064	20.7	.111	1.865	.088	12742	1440	99.86	121.00	.212	46.3	.226
Avaj	.496	77.33	0.29	0.159	.053	10.5	.046	7.9	.165	19981.	3728.	425.4	413.18	.389	71.2	.497
Coalinga	.638	57.0	0.08	0.091	.082	8.40	.018	4.142	.148	2821.3	1537	231.6	196.57	.575	36.7	.601
Duzce	.501	64.4	.451	.131	.118	30.3	.206	2.693	.144	11483	1031	255.1	259.11	.331	57.6	.482
Varzaqan	0.47	10.5	0.4	0.22	0.04	10.57	0.05	4.92	0.11	2483.9	284.8	447.8	144.20	0.31	77.90	0.47
Erzincan	0.51	83.90	0.27	0.16	0.07	17.65	0.07	1.50	0.08	6665.60	770.94	296.9	319.90	0.24	51.10	0.51
Landers	0.78	31.88	0.16	0.04	0.09	5.01	0.03	6.58	0.19	1244.4	2463.4	110.6	90.21	0.64	26.43	0.46

Table 3. Values of damage models.

Earthquake	Park-Ang Model	MFRD Model
Kobe	0.665	0.436
Victoria	0.265	0.534
Loma Prieta	0.008	0.072
Northridge	0.051	0.216
Kocaeli	0.024	0.073
San Fernando	0.016	0.005
Whittier	0.007	0.049
Imperial Valley	0.883	0.266
Chi-Chi	0.058	0.031
Gazli	0.074	0.083
Westmorland	0.057	0.175
Cape Mendocino	0.062	0.099
Nahanni	0.770	0.594
Manjil	0.149	0.096
Avaj	0.329	0.401
Coalinga	1.330	0.866
Duzce	0.047	0.026
Varzaqan	0.316	0.197
Erzincan	0.106	0.518
Landers	0.082	0.796

Table 4. Values of the Spearman correlation coefficient.

Seismic Parameter	Park-Ang Model	MFDR Model
PGA	0.497	0.428
PGV	0.411	0.647
PGD	0.363	0.576
V_{max}/A_{max}	0.372	-0.079
Acceleration RMS	0.418	0.605
Velocity RMS	0.521	0.638
Displacement RMS	0.317	0.524
AI	0.395	0.319
CI	0.414	0.448
SED	0.536	0.586
CAV	0.309	0.296
VSI	0.535	0.507
HI	0.392	0.712
SMA	0.561	0.441
SMV	0.452	0.485
EDA	0.637	0.349

In some cases, damage may require repeated cycles of high amplitude to develop. Sustained maximum acceleration includes five cycles as fifth highest (absolute) value of acceleration in the time history. Effective design acceleration is defined as the peak acceleration that remains after filtering out accelerations above 8-9 Hz. Cumulative absolute velocity (CAV) is defined as the integral of the absolute value of the acceleration time series. In fact, CAV includes the cumulative effects of ground motion duration. Displacement RMS is defined as a single parameter which includes the effect of amplitude and frequency content of displacement motion record. The ratio of PGV and PGA is considered to account the effects of both PGV and PGA. For MFDR model, peak ground velocity and the Housner intensity have the best interdependencies. On the other hand, the weakest interdependencies are related to cumulative absolute velocity and V_{max} / A_{max} with the MFDR model.

Housner intensity is defined as time integral that is referred to the area under the pseudo-velocity response spectrum over the period range of 0.1 to 2.5 s. It is obvious that all of the seismic parameters do not have the strongest interdependency with these damage models. Therefore, based on seismic parameters, the foreseen selection of the accelerogram that have the most important effect on the MFDR model cannot be an easy anticipation.

Overall structural damage indices can give a good sight about collapse of structure. Moreover, overall structural damage has less accuracy than local structural damage, determined at each member. Local structural damage indices are very useful for determining damage at each member. In most of the papers, the final values of damage indices are reported by researchers. Final values of damage indices cannot show process degradation of members. In this paper, process degradation of members has been shown for Modified Flexural Damage Ratio (MFDR). The curves that present time variation of the MFDR model are shown in Figure (2) for some of the beams and columns. When curves that are related to all of the members are considered, they show that most of the columns remained at the elastic range and few numbers of them have inelastic behavior. In other hand, all beams have inelastic behavior except for beams number 10 and 29. In fact, the results imply that the safe conditions of columns are more important than the safe conditions of beams at the rules of design codes during earthquake time.

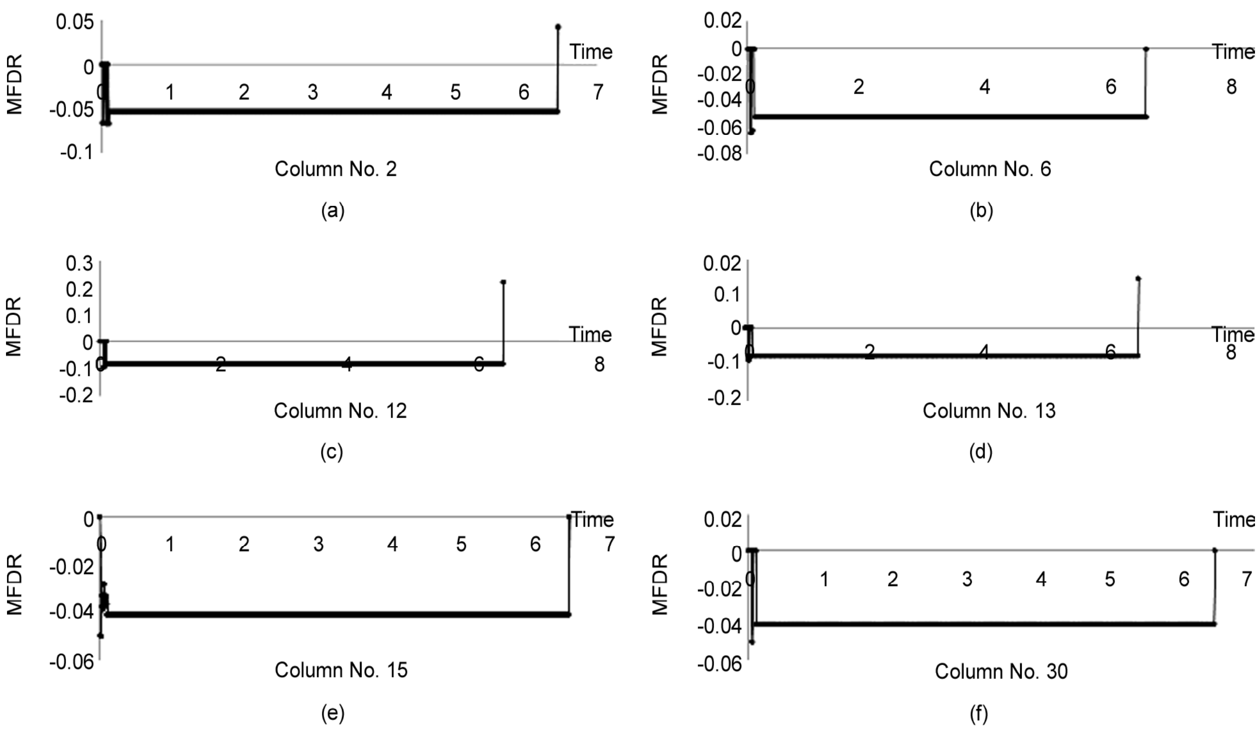

Figure 2. Time variations of the MFDR model.

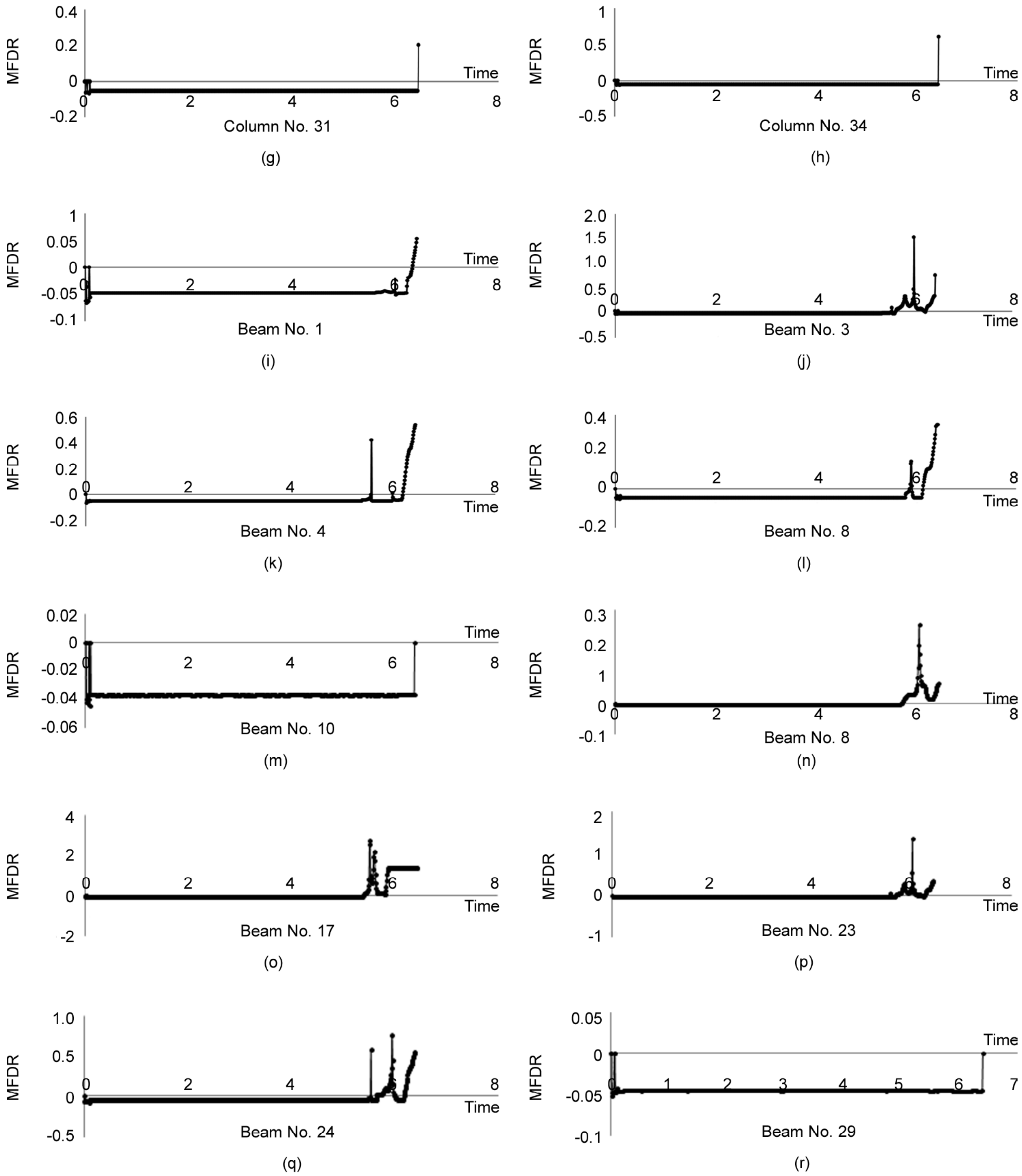

Figure 2. (Continue)

6. Conclusion

In this paper, the interdependencies between important seismic parameters and damage indices are investigated by the Spearman correlation coefficient. The results have been shown that sustained maximum acceleration and effective design acceleration have moderate interdependencies with the modified Park-Ang model, whereas the weakest interdependencies are related to cumulative absolute velocity and displacement RMS for the modified Park-Ang model. For MFDR model, peak ground velocity and Housner intensity have the best interdependencies. Besides, the weakest interdependencies are obtained for cumulative absolute velocity and V_{max} / A_{max} . Other part of this article that includes the time variation of the MFDR model presents the process of the degradation members during the time of the inelastic dynamic analysis. While the final values of damage indices are reported in the most of the paper, it is a useful procedure to recognize time variation of the member degradations.

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Underline

- Correlations between seismic acceleration parameters and damage indices can help to predict the value of the damage for an earthquake event.
- Sustained maximum acceleration and effective

design acceleration have the best correlation with the Park-Ang model.

- Cumulative absolute velocity and V_{max} / A_{max} have shown the weakest interdependencies with the Maximum flaxural damage ratio model.
- the time variation of the MFDR model in duration of the Victoria earthquake can give a good sight about process of degradation members.