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Investigation of Correlations between Seismic Parameters and Damage Indices for Earthquakes of Iran Region

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ABSTRACT

Seismic record of an earthquake contains important and significant data about characteristics of a ground motion. In this study, interdependencies between important seismic parameters and three overall structural damage indices including the Bracci index, the modified flexural damage ratio (MFDR) index and the drift index were determined for several records of earthquakes occurred in Iran. Calculations were done for medium rise concrete frame structures. In next step, seismic parameters that had strongest and weakest interdependencies with three mentioned damage indices were determined by the Spearman and Pearson correlation coefficients. As the final value of damage indices cannot show the process of member degradation, time variations in the Powell and Allahabadi model were calculated to give a good insight into the behavior of structural members during earthquake.

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1. INTRODUCTION

One of the most important parameters that affects on seismic vulnerability of structures is the earthquake accelerogram. Seismic parameters of an earthquake record can be extracted from the acceleration time history. These parameters include Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD), Root-Mean-Square (RMS) of acceleration, RMS of velocity, RMS of displacement, Arias Intensity (AI), Housner Intensity (HI),Characteristic Intensity (CI), Cumulative Absolute Velocity (CAV), Velocity Spectrum Intensity (VSI), Specific Energy Density (SED), Sustained Maximum Acceleration (SMA), Sustained Maximum Velocity (SMV) and Effective Design Acceleration (EDA). The above seismic parameters have been presented in literature [1-6].

Damage indices are utilized for determining performance of structure during and after an earthquake. There are two classifications based on the approach used in the definition of damage indices. One of them is the demand imposed by earthquake with respect to structural characteristics that is related to the corresponding capacity of the member. Other classifications include the degradation of a certain seismic variable such as strength, stiffness and energy dissipation. The degraded values are compared with a predetermined critical value that is expressed as a percentage of the initial value at undamaged state. For example, the Bracci model is based on capacity/demand approach and MFDR model is based on the approach of degraded variables.

Story and overall structural damage can be calculated by weighting factor based on dissipated energy at members. Weighting factor relation is presented by following formula:

$$\lambda i = \frac{Ei}{\sum_{i=1}^{N} Ei} \quad i= 1,\ldots,N \text{ (number of members)} \tag{1}$$

where, λi is weighting factor and Ei is dissipated energy at members.

Elenas and Meskuris [7] have shown that the peak ground motion parameters have fair correlation with the modified Park-Ang overall structural damage index (OSDI). On the other hand, spectral and energy parameters have strong correlation with OSDI. Also, the

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central period and the strong motion duration after Trifunac/Brady provide a poor correlation with OSDI.

Elenas [8] has presented that the spectral pseudo-acceleration and the spectral absolute seismic input energy have the best correlation with OSDI including the modified Park-Ang model and the maximum softening index after Dipasquale/Cakmak. Also, PGA, central period and the SMD defined after Trifunac /Brady provide the fair correlation with OSDI.

Nanos et al. [9] investigated correlation between several strong motion duration definitions and the overall building damage indices including the Park-Ang model and Dipasquale/Cakmak model.

Elenas [10] has evaluated the correlation between the seismic intensity parameters and the structural damage indices. He used the Park-Ang model and the drift model as damage index. He concluded that the spectral and energy parameters provide strong correlation to the damage indices. They showed that strong motion duration definitions that are not direct enclosing an accelerogram intensity measure, are inappropriate seismic damage potential descriptors.

The collapse of the structure can be determined by overall structural damage indices. Although, the overall structural damage index has less accuracy than local damage index, it is useful to find out the behavior of the whole structure. Generally, local structural damage can be utilized for determining damages at each member.

This paper has two parts. The determination of interdependencies between important seismic parameters and three overall structural damage indices including the Bracci index, the MFDR index and the drift index are contained at the first part of this paper. Time-variation of the member's degradation is presented at second part of this paper. It is useful to perceive the behavior of members during earthquake and after that.

2. ANALYTICAL FORMULATIONS

2. 1. Damage Index Models The quantitative form of seismic performance can be determined by damage indices. Also, failure corresponding to the maximum degree of damage can be estimated by these indices. Estekanchi and Arjomandi [11] investigated correlation between numerical values of damage indices which are based on deformation, energy, modal parameters and low cycle fatigue behavior. Bracci et al. [12] presented a damage index based on the relationship between three parameters including damage potential, strength damage and deformation damage. The total capacity of the member is defined as an area between the monotonic load-deformation curve and the fatigue failure envelope. The damage demand includes strength loss and deformation related to damage. Strength loss is defined as the loss of a member ability to tolerate damage because of strength degradation, dissipated hysteric energy and deformation damage that is related to irrecoverable permanent deformations. Consequently, the Bracci model is assumed according to the following equation:

$$D = \frac{D_s + D_d}{D_p} = \frac{\Delta M(\phi_u - \phi_y) + (M_y - \Delta M)(\phi_{max} - \phi_y)}{M_y(\phi_u - \phi_y)} \quad (2)$$

$$\Delta M = \frac{Sd \int dE}{\phi_y} \quad (3)$$

where, ϕ_u, ϕ_y and ϕ_{max} are ultimate curvature, yielding curvature and existing curvature respectively. Also, D_s, D_d and D_p are strength damage, deformation damage and damage potential respectively. M_y is yielding moment at member. S_d is the strength deterioration factor and $\int dE$ is dissipated energy in the member.

Some of the damage indices cannot consider the effects of repeated loading. The degradation of stiffness and strength determine the ability of members and structures to suffer an earthquake. A model that is based on the reduction of secant stiffness is proposed by the Roufaiel and Meyer [13]. Although the cumulative damage cannot be accounted for by the Roufaiel and Meyer model, this model is an improvement on the displacement ductility and considers the strength and stiffness degradation during an earthquake loading. The maximum modified flexural damage ratio (MFDR) for positive or negative loading is considered by the Roufaiel and Meyer model. The following formula presents the MFRD equation:

$$MFDR = \frac{(\phi_m / M_{max} - \phi_y / M_y)}{(\phi_u / M_u - \phi_y / M_y)} \quad (4)$$

where, ϕ_{max}, ϕ_u and ϕ_y are maximum curvature, ultimate curvature and yielding curvature at members, respectively. Also, M_{max}, M_y and M_U are maximum moment, ultimate moment and yielding moment at members, respectively. The easiest method that characterizes the seismic behavior of a story is the use of the relative inter-story drift. Erduran and Yakut [14] used interstory drift ratio as damage function to investigate effects of their material and geometrical properties on the behavior of the structural members. The inter story drift is presented by the Sozan according to following equation [15]:

$$\frac{\Delta x_i}{h_i} = \left(\frac{x_i - x_{i-1}}{h_i}\right) \quad (5)$$

where, x_i and x_{i-1} are the horizontal displacements of two adjacent floors and h_i is the corresponding story height.

Powell and Allahabadi [16] have presented a damage index that is based on plastic deformation. This model is known as general damage function. This model has an equation according to following formula:

$$\boldsymbol{D} = \left(\frac{\delta_{max} - \delta_y}{\delta_u - \delta_y}\right)^{\boldsymbol{m}} \quad (6)$$

where, δ_{max} is defined as damage parameter and δ_y and δ_u are the yield and maximum damage parameter, respectively. Also, variable m utilizes a more complex relationship between damage variables. In this study we have assumed that the value of m is equal to one.

2. 2. Correlation Coefficients In statistics, interdependencies between two variables are measured by correlation coefficient. Its value varies between -1 to 1. 1 means the strongest positive correlation and -1 means the strongest negative correlation between two variables. Also, absence of correlation is indicated by zero value.

The Pearson correlation and the Spearman correlation are two outstanding correlation coefficients. The Pearson correlation is commonly used in linear regression [17]. The Pearson correlation coefficient between two variables X and Y is measured by the following equation:

$$\rho_{pearson} = \frac{\sum_{i}^{n}(Xi-mean(X))(Yi-mean(Y))}{\sqrt{\sum_{I=1}^{N}(Xi-mean(X))}\sqrt{\sum_{I=1}^{N}(Yi-mean(Y))}} \quad (7)$$

where, N is the number of the pairs of values (Xi, Yi) and mean(X) and mean(Y) are mean values of Xi and Yi respectively.

The Spearman correlation coefficient is utilized for a nonparametric measure of statistical dependence between two variables [17]. The Spearman correlation coefficient between two variables X and Y is presented by following equation:

$$\rho_{Spearman} = 1 - \frac{6\sum D^2}{N(N^2-1)} \quad (8)$$

where, D is differences between ranks of corresponding values of Xi and Yi. Also, N is the number of pairs of values (X, Y) in data.

3. PARAMETRIC ANALYSES

3. 1. Nonlinear Dynamic Analyses The reinforced concrete frame used in this paper is shown in Figure 1. This frame is designed according to rules of the recent ACI for concrete structures. The cross section of columns and beams are shown in Figure 1. Dimensions of columns are shown at the left side of the Figure 1 for each story of frame. Also, the dimensions of beams are shown at the center of Figure1 for each story of frame.

The distance between each frame of the structure is 600 cm and the height of each story is 320 cm. All of the necessary loads such as dead load, self-weight load and live load have been calculated for analyzing the frame. The values of dead and live loads were 650 kgf/m^2 and 150 kgf/m^2, respectively.

Also sway special is considered for element types and the type of C is selected for the seismic design category. After design process of the frame structure was done, a dynamic analysis has been performed by the computer program IDARC 7.0. Based on experimental results of cyclic force-deformation characteristics for beams and columns, stiffness degrading parameter, ductility-based strength decay parameter and hysteretic energy-based strength decay parameter have been considered for hysteretic modeling rules. Also, no pinching has been taken into account. Rayleigh proportional damping was considered as structural damping.

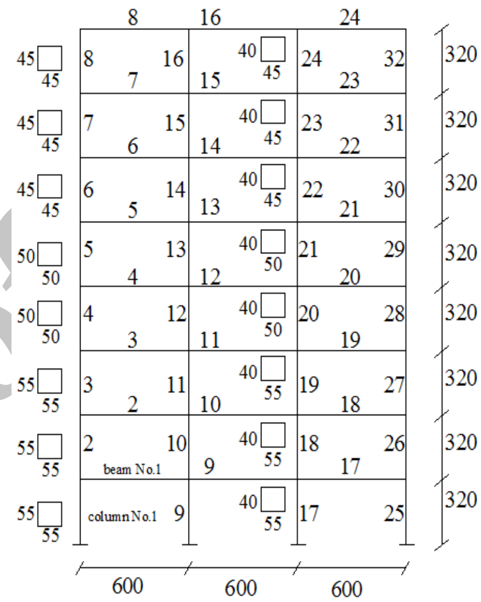


Figure 1. Concrete frame structure

TABLE 1. Earthquakes events

Earthquake	Station	Component	Date
Ardakul	Baghestan	L138 T228	1997/05/10
Avaj	Avaj	L119 T209	2002/06/22
Varzaqan	Varzaqan	L240 T330	2012/08/11
Bam	Bam	L278 T8	2003/12/26
Garmkhan	Rezvan	L345 T75	1997/02/04
Golbaf	Abaragh	L72 T162	1998/03/14
Manjil	Abhar	Transvers	1990/06/20
Karebas	Balaadeh	L120 T210	1999/05/06
Sarein	Kariq	L60 T150	1997/02/28
Tabas	Tabas	Transverse	1978/09/16
Zarand	Zarand	L34 T124	2005/02/22

TABLE 2. Values of the seismic parameters

Earthquake	PGA (g)	PGV (cm/s)	PGD(m)	V_{max}/a_{max} (s)	ARMS (g)	VRMS (cm/s)	DRMS (m)	AI (m/s)	CI	SED (cm^2/s)	CAV (cm/sec)	VSI(cm)	HI (m)	SMA (g)	SMV (cm/s)	EDA (g)
Ardakul	0.009	2.7	0.048	0.313	0.002	0.747	0.028	0.015	0.002	102.07	311.2	10.83	11.3	0.008	2.47	0.01
Avaj	0.482	69.8	0.26	0.148	0.047	8.83	0.039	7.07	0.147	16193.57	3443.7	397.95	384.07	0.375	66.87	0.475
Bam	0.78	115.3	0.29	0.14	0.088	10.74	0.033	7.9	0.212	7672.26	2246.7	397.02	389.02	0.63	40.83	0.68
Varzaqan	0.471	105.6	0.4	0.22	0.038	10.57	0.047	4.92	0.11	24839.8	2848.08	447.08	444.21	0.314	77.9	0.47
Garmkhan	0.009	2.16	0.006	0.23	0.002	0.57	0.002	0.006	0.001	25.5	123.29	10.49	10.48	0.008	1.84	0.009
Golbaf	0.011	1.29	0.004	0.122	0.003	0.34	0.001	0.01	0.001	10.47	180.92	7.84	7.36	0.009	1.235	0.028
Karebas	0.052	4.33	0.016	0.085	0.006	0.708	0.002	0.059	0.005	58.74	343.68	22.92	21.53	0.042	3.63	0.052
Manjil	0.22	27.22	0.13	0.12	0.055	10.81	0.053	1.36	0.069	3462.58	1197.94	91.7	91.4	0.209	24.52	0.216
Sarein	0.52	52.44	0.071	0.101	0.049	4.17	0.006	7.82	0.158	3635.6	3467.8	210.84	168.16	0.38	30.66	0.482
Tabas	1.01	58.24	0.18	0.058	0.138	13.39	0.043	10.83	0.311	6642.06	2915.5	290.5	271.6	0.633	47.85	0.912
Zarand	0.256	42.61	0.11	0.17	0.025	4.91	0.019	2.79	0.068	6872.67	3146.4	196.43	182.9	0.22	28.18	0.26

3. 2. Earthquake Input Parameters In this paper, 11 records of earthquakes have been selected throughout the country of Iran. Stations, components and dates of these earthquakes are shown in Table 1. Also, seismic parameters of these earthquakes are presented in Table 2.

After analyzing frame structure, the end curvatures of members were extracted for calculating damage indices. In the next step, the Bracci and the MFDR models were calculated according to above equations.

The interstory drift was calculated by maximum displacements of two adjacent floors. Finally, overall structural damages were determined by weighting factors. Values of overall structural damages are shown in Table 3.

TABLE 3. Values of damage models

Earthquake	Bracci model	MFRD model	Drift Model (%)
Ardakul	0.00509	0.014	0.273
Avaj	0.465	0.557	1.37
Bam	0.841	0.843	8.23
Varzaqan	0.447	0.677	1.06
Garmkhan	0.00	0.00	0.132
Golbaf	0.00	0.00	0.201
Karebas	0.624	0.804	1.09
Manjil	0.608	0.992	0.524
Sarein	0.0999	0.217	0.411
Tabas	0.200	0.384	0.571
Zarand	0.597	0.699	1.04

TABLE 4. Values of the Spearman correlation coefficient

Seismic Parameter	Bracci model	MFDR model	Drift model
PGA	0.445	0.4	0.613
PGV	0.568	0.531	0.790
PGD	0.55	0.577	0.727
V_{max}/a_{max}	-0.259	-0.240	-0.20
Acceleration RMS	0.545	0.572	0.531
Velocity RMS	0.540	0.622	0.527
Displacement RMS	0.445	0.572	0.440
ARIAS Intensity	0.45	0.404	0.627
CI	0.463	0.436	0.604
SED	0.486	0.477	0.736
CAV	0.331	0.304	0.509
VSI	0.486	0.468	0.754
HI	0.559	0.540	0.790
SMA	0.445	0.4	0.613
SMV	0.431	0.422	0.709
EDA	0.440	0.395	0.618

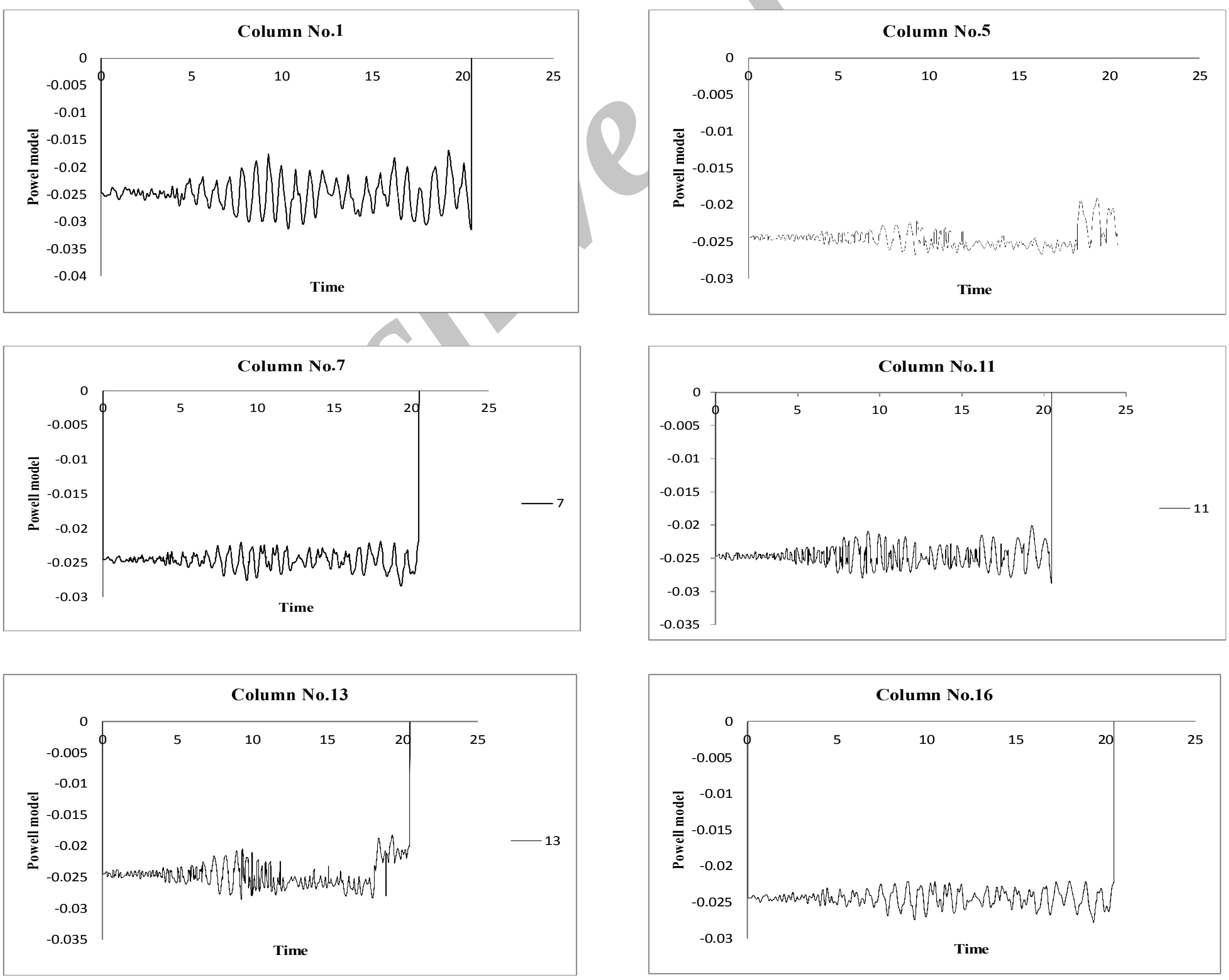
TABLE 5. Values of the Pearson correlation coefficient

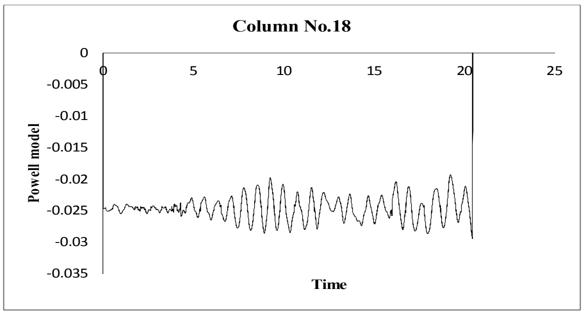
Seismic Parameter	Bracci model	MFDR model	Drift model
PGA	0.287	0.288	0.394
PGV	0.131	0.099	-0.09
PGD	-0.115	-0.124	-0.39
V_{max}/a_{max}	-0.181	-0.208	-0.40
Acceleration RMS	0.258	0.304	0.277
Velocity RMS	0.026	0.040	-0.28
Displacement RMS	-0.115	-0.124	-0.39
ARIAS Intensity	0.082	0.072	0.025
CI	0.174	0.182	0.184
SED	-0.089	-0.097	-0.38
CAV	0.117	0.120	-0.18
VSI	0.424	0.388	0.346
HI	0.432	0.393	0.333
SMA	0.384	0.362	0.462
SMV	0.059	0.068	-0.25
EDA	0.229	0.234	0.212

3. 3. Damage Index Calculation After values of the overall structural damages had been estimated, interdependencies between seismic parameters and overall structural damages were determined by the Pearson and the Spearman correlation coefficient. Results of interdependencies between seismic parameters and overall structural damages are presented in Table 4 and Table 5.

3. 4. Discussion Among values of the Spearman correlation coefficient, it is observed that two parameters including PGV and the Housner Intensity have the strongest interdependencies with the Bracci model. On the other hand, V_{max}/a_{max} and CAV have shown the weakest interdependencies with the Bracci model.

For the MFDR model, the strongest interdependencies are observed between PGD and velocity RMS with this model. Also, the weakest interdependencies are observed by CAV and V_{max}/A_{max} with this model. Two parameters that have the best correlation with the drift index include PGV and the Housner intensity. Inversely, two parameters that have the weakest correlations with the drift index include V_{max}/a_{max} and CAV. Using the Pearson correlation coefficient, the Housner intensity and VSI have shown the best interdependencies with the Bracci model at middle range. On the other hand, velocity RMS and SMV have shown the weakest interdependencies with the Bracci model. As it is shown in Table 5, VSI and the Housner intensity have the best interdependencies with MFDR model at middle range. Also, velocity RMS and SMV have shown the weakest interdependencies with MFDR model. Finally, the best correlations are determined between the PGA and SMV with the drift index and the weak correlations are determined between the Arias intensity and PGV with the drift index. The Housner intensity that shows the best correlation with most of damage indices is classified as spectral parameter. On the hand, energy parameters including the Arias intensity, specific energy density and characteristics intensity did not show strong correlations with damage indices. Often, final values of local damage indices have been presented in most researches. In these cases where the final values of local damage indices are reported, the process of member degradation cannot be determined during and after an earthquake. For this reason, the time-variation of the Powell and Allahabadi model that provides general and basic form has been used for the members. These curves are determined for the scenario of Manjil earthquake. The curves that show the time-variation of the Powell model are presented for sample columns and beams in Figure 2. The curves showed that all of the columns had elastic behaviors during the Manjil earthquake. On the other hand, one part of the beams showed elastic behavior and other part of them showed inelastic behaviors during the Manjil earthquake. Consequently, in this paper, it is confirmed that the time variation of damage indices have consistency with the rules of building codes. Based on rules of building codes, columns have the more important task than beams. On the first onset, damage should be lead to beams to attain safe condition during earthquake and after that. Damage curves that are presented in Figure 2 confirm the safe condition that is considered in rules of building codes.

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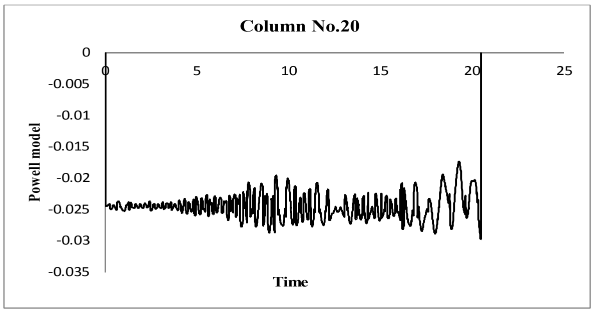
Powell model
Time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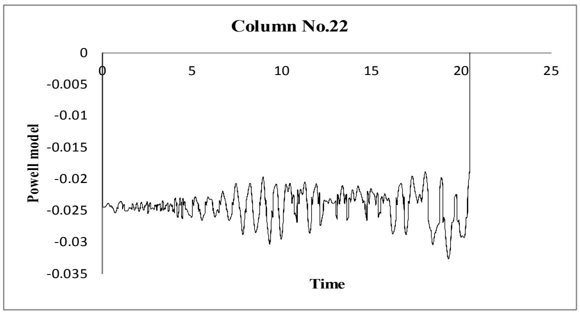
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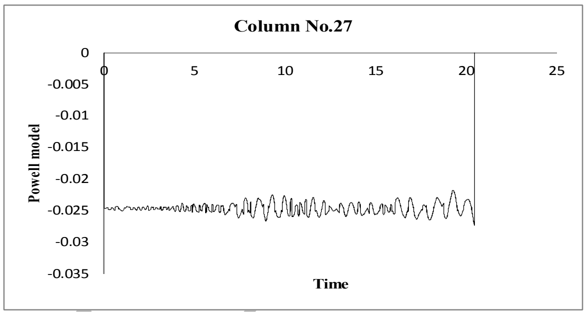
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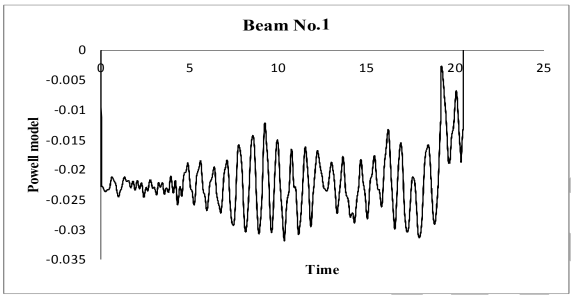
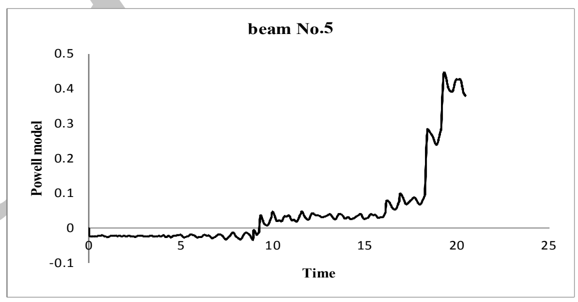

Beam No.1
Powell model
Time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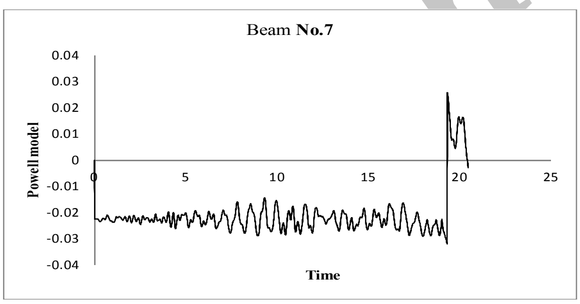
Powell model
Time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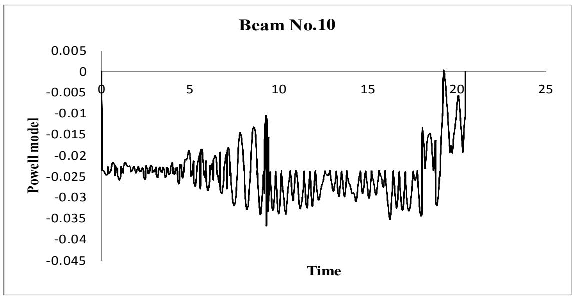
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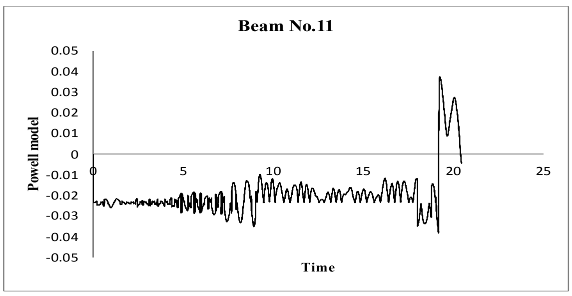
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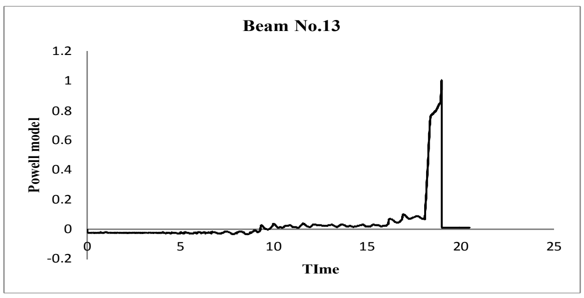
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TIme

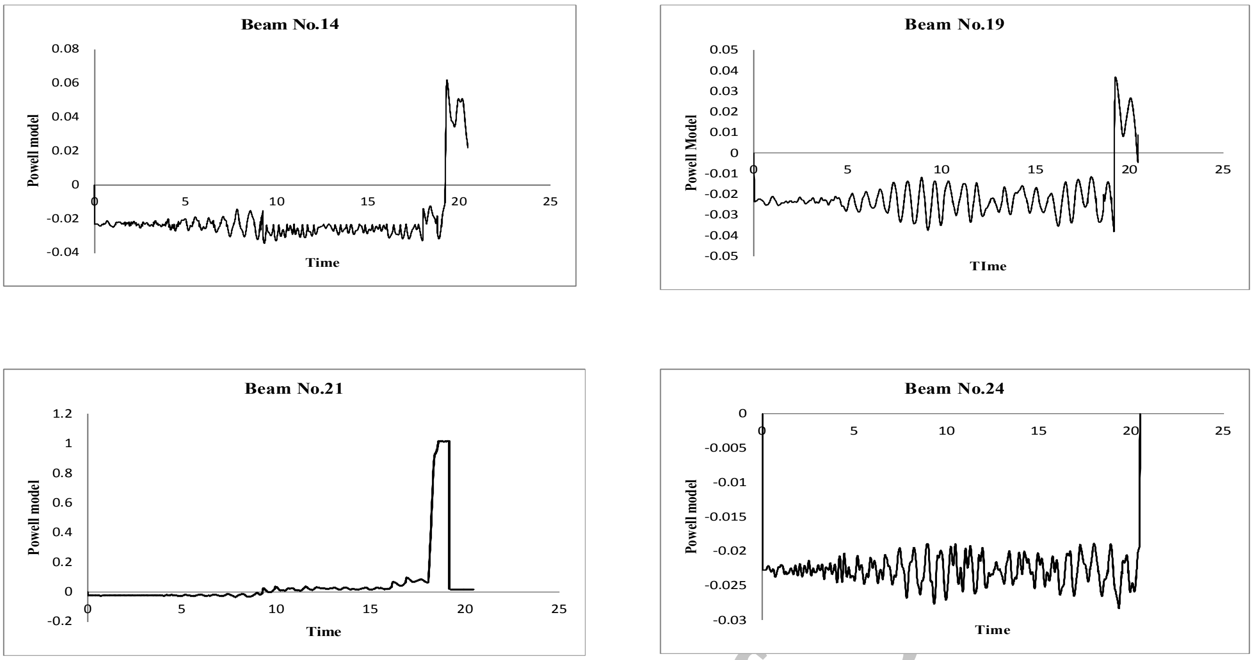

Figure 2. Time variation of the Powell and Allahabadi model

4. COMMENTS AND CONCLUSIONS

This paper has two parts. One part comprises the determination of correlations between important seismic parameters and overall structural damage indices including the Bracci, the drift and the MFDR model. All of the earthquake records are selected from earthquakes that happened in Iran.

Interdependencies between seismic parameters and damage indices that are mentioned above are calculated by the Spearman and the Pearson correlation coefficient. Results of the Spearman correlation coefficient show that the best correlation is determined by PGV and the Housner Intensity with the Bracci model.

On the other hand, the weakest interdependencies are shown between V_{max}/a_{ma} and CAV with the Bracci model. Two parameters that have the best correlations with the MFDR model include PGD and Velocity RMS. Inversely, the parameters that have the weakest correlations with the MFDR model include CAV and V_{max}/A_{max}. Also, these results show that PGV and the Housner intensity with the drift index have best correlations and V_{max}/A_{max} and CAV with the drift index have the weakest correlations.

For the Pearson correlation coefficient, the best interdependencies are observed between the Housner intensity and VSI with the Bracci model. On the other hand, the weakest interdependencies were observed between velocity RMS and SMV with the Bracci model.

5. ACKNOWLEDGEMENT

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Investigation of Correlations between Seismic Parameters and Damage Indices for Earthquakes of Iran Region

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چکیده

رکوردهای لرزه‌ای یک زلزله حاوی داده‌های مهم و موثری درخصوص مشخصات جنبش زمین می‌باشد. در این مطالعه همبستگی‌های میان پارامترهای لرزه‌ای مهم و سه شاخص خرابی کلی سازه‌ای شامل شاخص برراسی (Brraci)، شاخص نسبت آسیب خمشی اصلاح شده (Modified flexural damage ratio) و شاخص دریفت (Drift) برای چندین رکورد لرزه‌ای حادث شده در ایران تعیین شده بود. محاسبات برای قابهای بتنی با ارتفاع متوسط انجام شده بود. در قدم بعدی پارامترهای لرزه‌ای که قویترین و ضعیفترین همبستگی‌ها را با سه شاخص خرابی ذکر شده دارا بود بوسیله ضرایب همبستگی پیرسون (Pearson) و اسپیرمن (Spearman) تعیین شده بود. چون مقادیر نهایی شاخص های خرابی نمی تواند فرآیند تنزل عضو را نشان دهد، تغییرات زمانی مدل خرابی پاول (Powell) برای ارائه دادن یک بینش خوب در خصوص رفتار اعضای سازه‌ای در طی زلزله محاسبه شده بود.

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