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INFLUENCE OF GROUND MOTION PARAMETERES ON SEISMIC RESPONSE

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Abstract

In order to establish a connection with structural vulnerability, ground motions generate intricate datasets that are distinguished by a variety of properties. The objective of the investigation is to evaluate the impact of specific seismic record characteristics on the nonlinear structural response of buildings, with the ultimate goal of determining the characteristics that have the most significant impact on structural vulnerability. An experimental model, the ICONS, was employed to calibrate a numerical nonlinear model for the study. This model depicts existing buildings that were constructed without regard for seismic regulations. These buildings are prevalent in cities such as Zagreb and Dubrovnik, which are located in highly seismically precarious regions of Croatia. The analysis comprised 30 seismic records that were selected based on parameters such as peak ground acceleration (PGA), magnitude (M), and distance from the epicentre (R), following the disaggregation and uniform hazard spectrum results for city of Zagreb. Storey displacement data was generated from the records through dynamic time-history analysis, which allowed for the calculation of maximum interstorey drift ratios (IDR) as a metric for structural damage. A substantial correlation between structural damage and seismic record characteristics was discovered during the analysis. Peak ground velocity (PGV), specific energy density (SED), and Housner intensity (HI) were identified as the most significant factors influencing structural vulnerability. Consequently, they should be prioritised when selecting seismic records for structural damage assessments.

Keywords: ground motion parameters, time history analysis, maximum inter-story drifts, peak ground velocity.

1. Introduction

Prediction of the response of structures to seismic forces is, therefore, the cornerstone of earthquake engineering; earthquakes have resulted in devastation and loss of life very many times. Numerical modeling and the availability of more detailed seismic data have greatly enhanced our ability to assess structural vulnerabilities due to seismic loading [1][2]. This development is particularly helpful for those regions where seismic activities are higher, and any reasonable accurate assessment will reduce risks of disasters.Nonlinear dynamic analysis is the primary tool for simulating complex inelastic behavior of structures during seismic events [3]. Different from the linear model, these methods consider geometric nonlinearities and material properties, hence providing a realistic representation of the structural behavior under extreme loads [4]. Nonlinear modeling is uniquely suited to capture major seismic events inducing cracking, plastic deformation, and collapse phenomena [3][5]. This capability is of particular importance for older structures built before the implementation of modern seismic codes [6].The complexity of seismic response modeling depends on structural type, soil-structure interaction, and characteristics of ground motion inputs. Selection of representative ground motion records is the most critical task for dynamic analysis. Many research studies emphasize developing region-specific seismic data based on local tectonic features and ground motion characteristics [5][7]. Traditional intensity measures include PGA, PGV, and SA that are in common use but very often result in poor correlation for nonlinear responses with structural damage [8].

In this direction, research for improving seismic analysis has put greater emphasis on energy-based and velocity-sensitive measures such as cumulative absolute velocity, spectral shape parameters, which present stronger correlation with structural damage in systems with moderate to low seismic resistance

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[9]. These metrics are especially relevant for the assessment of the performance of older structures, since their performance tends to deviate from that of modern code-compliant designs [6].
The interplay between ground motion characteristics and architectural properties is another key area of investigation. For reinforced concrete (RC) buildings, seismic performance depends on material properties, construction practices, and geometric configurations [3]. Advanced numerical simulations, validated through experimental data, improve our ability to predict the seismic performance of such structures [10]. Calibration against empirical observations enhances predictive accuracy, facilitating more reliable assessments of seismic vulnerability [4][10].
Despite these advances, some important gaps remain. Most studies focus on traditional parameters such as PGA and do not consider the increasing energy-based and frequency-dependent metrics that are really essential to understand damage potential [8]. Very few studies have investigated pre-code structures-buildings designed before modern seismic code provisions-even though their vulnerabilities and damage often differ substantially [6].
This research will complement these studies through the analysis of nonlinear seismic behaviour of older reinforced-concrete buildings focusing on energy-based ground motion parameters by using calibrated numerical models, which represent experimental data. It basically determines which seismic parameters give the most insight into structural damage.

2. Ground motion parameters

Earthquake records are highly complex data sets that require numerous parameters to describe them adequately. The definition of earthquake records outlines the intensity of seismic excitation and connects seismic hazard with the structural data needed to address engineering problems. The most significant characteristics of earthquake records from the perspective of earthquake engineering are amplitude, frequency content, and record duration. Some intensity measures are associated with one or more of these three characteristics.

Intensity measures that relate to more than one characteristic of earthquake records are more reliable for describing ground motion and reflecting the potential damage ground motion can cause to structural systems [11]. The characteristics of earthquake records explored in this study include: peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), specific energy density (SED), Housner intensity (HI), magnitude (M), and distance from epicenter (R).

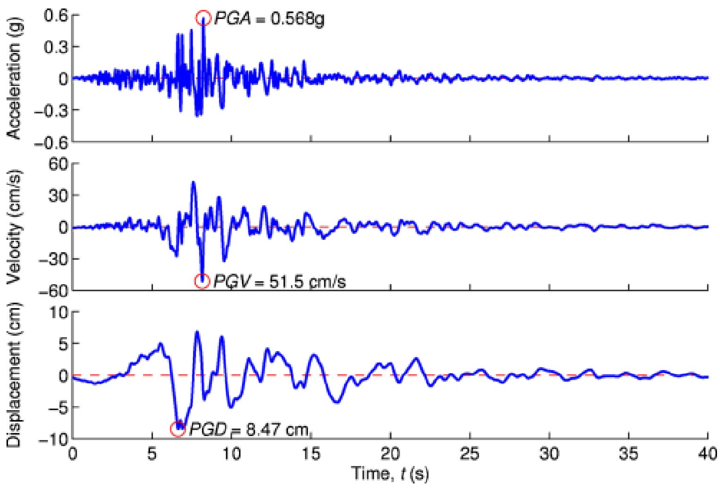

Figure 1. Overview of Peak Ground Acceleration, Velocity, and Displacement for the Horizontal Component of the 1994 Northridge Earthquake [12]

Peak ground acceleration (PGA) is a critical parameter in earthquake engineering, representing the maximum ground acceleration recorded during an earthquake. It serves as a measure of the amplitude of ground shaking intensity at a specific location. PGA is determined from the accelerogram, a time-history record of ground acceleration during seismic events. Unlike measures such as the Richter scale,

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which describe the total magnitude of an earthquake, PGA focuses solely on the local intensity of ground motion.

The horizontal peak ground acceleration (PHA) is widely utilized in construction and is expressed in terms of gravitational acceleration ($g = 9.81$ m/s²). This parameter is instrumental in the development of seismic hazard maps and is a key input in structural design codes aimed at improving the resilience of buildings and infrastructure to seismic forces.

Peak ground velocity (PGV) is another important measure of seismic amplitude, indicating the maximum velocity of ground motion during an earthquake. Like PGA, PGV is derived from the accelerogram but provides additional insight into the dynamic characteristics of seismic waves (Figure 1).

Peak ground displacement (PGD) represents the maximum displacement of the ground during an earthquake. It is also derived from the accelerogram and provides a measure of the total movement experienced at a specific location.

Specific Energy Density (SED) is defined as the integral of the square of velocity (Equation 1) [13]. It represents a measure of the total energy of an earthquake record. A higher SED value indicates greater earthquake energy and consequently greater expected damage potential.

$$SED = \int_0^{t_{ror}} [v(t)]^2 dt \quad (1)$$

Housner intensity (HI) is a measure of ground motion intensity during an earthquake [14], defined as:

$$HI(\xi) = \int_{0.1}^{2.5} Sv(\xi, T) dt \quad (2)$$

Magnitude (M) is a measure of the size or energy released by an earthquake. It is typically quantified using the Richter scale or moment magnitude scale (Mw). The magnitude reflects the amplitude of seismic waves recorded by seismographs, with higher magnitudes indicating more powerful earthquakes. A higher magnitude generally corresponds to more significant damage and a greater potential for ground shaking.

Epicenter distance (R) refers to the horizontal distance between the location where the earthquake is being observed and the epicenter, which is the point on the Earth's surface directly above the earthquake's focus (the point of origin). The closer the epicenter distance is to the observation point, the stronger the shaking is typically experienced, as seismic waves weaken with distance from the epicenter.

3. Earthquake record selection

The primary goal of design processes is to achieve predictable and reliable levels of safety across various seismic activity scenarios. Despite advancements in structural analysis, the reliability of these analyses and subsequent evaluations depends heavily on input data related to ground motion during earthquakes.

To address this need, numerous computational methods have been developed to select seismic records from databases of historically recorded earthquakes or to artificially generate and modify ground motion records to match desired earthquake characteristics.

The process of selecting earthquake records for this study involved the use of the Uniform Hazard Spectrum (UHS) and site-specific disaggregation based on magnitude (M) and epicentral distance (R) for city of Zagreb, as shown in Figure 2. These values guide the selection of earthquake records from [16].

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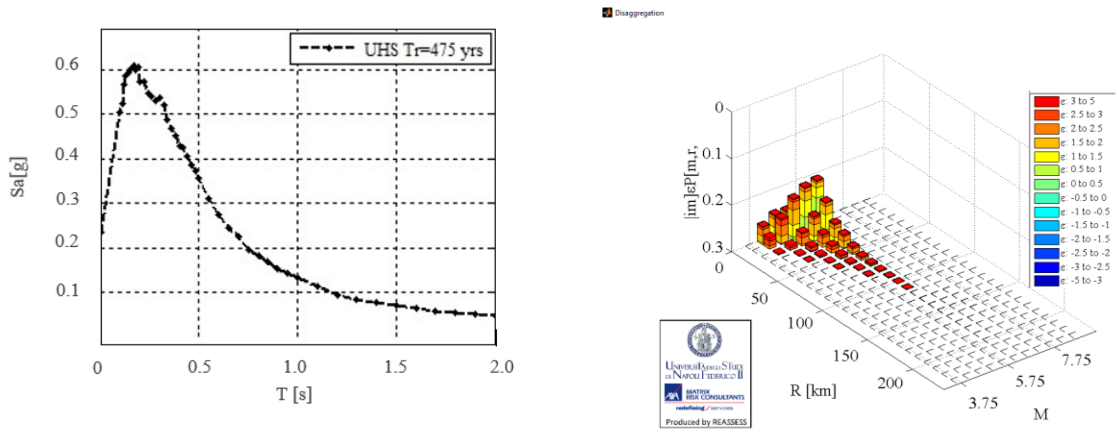

Figure 2. Uniform Hazard Spectrum (UHS) and site-specific disaggregation for city of Zagreb [15]

Based on the defined ranges of magnitude (M) and distance from the epicenter (R) for the Zagreb region, 30 earthquake records were selected to simulate potential seismic hazards for the area. The magnitude and epicentral distance values serve as boundaries. The selected earthquakes are characterized by their magnitude and distance values, illustrated in Figure 3.a). The figure shows that most epicentral distances (R) are within 25 km, while the majority of earthquake magnitudes fall between 4.5 and 6.0, with two outlier values.

Figure 3.a) presents the average ground acceleration for the 30 selected records, which is 2.60 m/s². This value corresponds to the observed peak ground acceleration (PGA) of 0.26g, and confirms the consistency between the initial and final selected parameters used to define the seismic scenario for Zagreb.

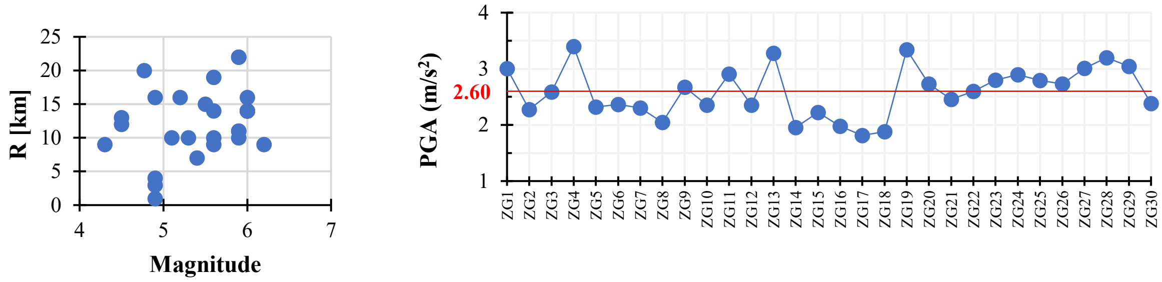

Figure 3. a) Relationship between magnitudes and epicentral distances for 30 selected earthquakes for Zagreb; b) Peak ground accelerations (PGA) for all earthquake records in scenario for Zagreb

Table 1. Ranges of characteristic values of selected earthquake records for the city of Zagreb

	PGA (m/s²)	PGV (cm/s)	PGD (cm)	SED (cm²/s)	HI (cm)	M	R (km)
Minimum value	1,81	30,70	5,28	285,59	41,59	4,3	1
Maximum value	3,40	315,94	90,16	63314,56	1132,44	6,2	22
Mean value	2,6	139,99	27,40	11387,50	361,93	5,48	12,43
Standard deviation	0,44	74,40	24,21	15487,99	272,29	0,54	4,93
Coefficient of variation (%)	17,16	53,15	88,36	136,01	75,23	9,88	39,66

For further analysis, seven earthquake record characteristics influencing the nonlinear structural response, along with their ranges, average values, and variability, are detailed in Table 1.

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4. Validation of nonlinear numerical model for dynamic analysis

Since the earthquake scenarios were developed for the city of Zagreb, where there is a large number of buildings that were not constructed according to the seismic standards that required mandatory implementation of seismic regulations for defining the behavior of structures under earthquake loading, a structure was selected that corresponds to the group of existing buildings.

The ICONS model, shown in Figure 4, presented in detail in [17] is a four-story reinforced concrete frame representing a structure designed without seismic regulations, intended only for vertical loads, which was common practice in construction about 40 years ago in much of Europe. The ICONS model was dimensioned by LNEC (National Laboratory for Civil Engineering) in Lisbon, Portugal, then constructed at full scale and tested in a moderate-strength earthquake at the ELSA laboratory (European Laboratory for Structural Assessment) in Ispra, Italy, for the purpose of assessing the seismic vulnerability of the frame. The model was subjected to earthquake loading with peak ground acceleration of 0.22g and a return period of 475 years. Numerical model for analysis is made in Seismostruct [18].

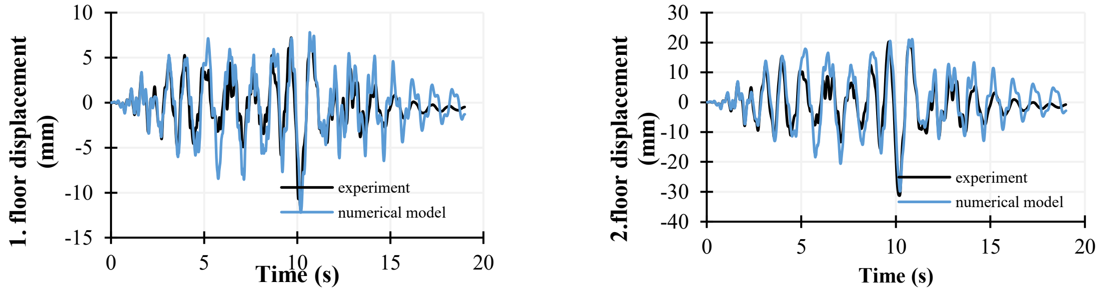
Figure 4. a) ICONS experimental model [17], numerical model of ICONS frame [18]

By comparing the fundamental dynamic characteristics of the experiment and the numerical model after the modal analysis, the first match between the models was confirmed (Table 2).

Table 2. Comparison of natural periods for numerical model evaluation

Mode	experiment	numerical model	error (%)
1	0,68	0,672	1,2
2	0,231	0,226	2,2
3	0,142	0,135	5

The results obtained from the numerical analysis correlate excellently with the experimental results. By comparing the floor displacements, it can be concluded that the numerical model fully replicates the behavior of the model during the experiment (Figures 5.14 and 5.15), which reflects the stiffness and load-bearing capacity of the structure.



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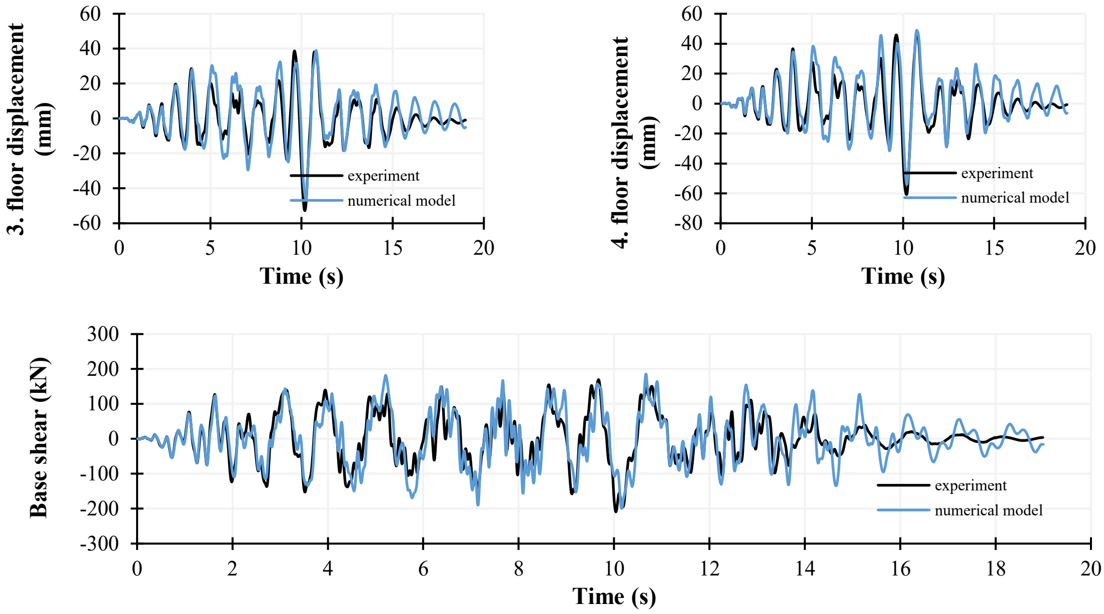

Figure 5. Comparison of displacements at all floors and base shear between the experiment and numerical model.

It is evident that the nonlinear model achieves excellent results with minimal deviations from the experimental test results. The maximum average relative error and deviation from full correlation are 12% for displacements. Based on this, it can be concluded that the model can reliably predict the system's behavior, and it can directly be applied to analyze the impact of earthquake record characteristics on the system's response.

5. Analysis of the impact of earthquake record parameters on seismic response

The previously calibrated numerical model ICONS was used to analyze the structure under time-history earthquake records. The analysis involves applying the selected earthquake records to the model and calculating the structural response by defining maximum interstory drift ratios.
According to [19] it is possible to define structural performance levels for different structural systems, which describe the state of the structure after an earthquake, as shown in Table 3. In Table 4, the maximum values of interstory displacements are marked, and based on Table 3, the behavior areas are defined to draw conclusions about the performance of such types of buildings in the observed seismic area.
It is evident that the model's condition is most critical under the action of earthquakes ZG9 and ZG11, with the maximum interstory displacements occurring on the 2nd and 3rd floors of the structure.
This indicates that the building experiences significant displacement on the higher floors under seismic loading, which may imply potential structural concerns. These results can guide further analysis, focusing on improving the building's ability to withstand seismic forces, particularly in the most affected areas of the structure (the 2nd and 3rd floors).

Table 3. Comparison of IDR (%) according to performance levels and structural type [19]

Structural performance level	Infilled frames	RC walls	RC frames
Slight damage	<0,10	<0,20	<0,20
Moderate damage	<0,40	<0, 80	<1,0
Extensive damage	>0,40	>0,80	>1,0
Near collapse	>0,80	>2,5	>3

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Table 4. Values of interstory drifts for 30 earthquake records

floor	ZG1	ZG2	ZG3	ZG4	ZG5	ZG6	ZG7	ZG8	ZG9	ZG10	ZG11	ZG12	ZG13	ZG14	ZG15
4	0,36	0,23	0,13	0,26	0,20	**0,29**	0,16	**0,09**	0,62	0,49	0,75	0,53	0,69	0,18	0,17
3	**0,52**	**0,38**	**0,17**	**0,46**	0,40	**0,29**	0,26	0,08	**1,32**	0,83	**1,96**	**0,74**	**1,19**	**0,27**	**0,19**
2	0,38	0,23	0,14	0,33	**0,43**	0,20	**0,28**	0,07	1,02	**0,92**	1,60	0,65	0,78	0,19	0,14
1	0,20	0,14	0,09	0,19	0,29	0,15	0,20	0,07	0,58	0,71	1,27	0,48	0,43	0,14	0,08

floor	ZG16	ZG17	ZG18	ZG19	ZG20	ZG21	ZG22	ZG23	ZG24	ZG25	ZG26	ZG27	ZG28	ZG29	ZG30
4	0,17	0,04	0,18	0,16	0,18	0,14	0,57	0,16	0,12	0,12	0,11	0,20	0,41	0,45	0,34
3	**0,18**	**0,05**	0,37	**0,26**	**0,27**	**0,16**	0,86	**0,20**	**0,11**	0,09	**0,12**	0,37	**0,57**	**0,47**	**0,44**
2	0,13	**0,05**	**0,39**	0,25	0,24	0,13	**0,89**	0,17	**0,11**	**0,12**	0,11	**0,39**	0,46	0,30	0,40
1	0,07	0,03	0,24	0,15	0,16	0,09	0,68	0,10	0,08	0,08	0,09	0,26	0,31	0,22	0,23

▢	Slight damage	IDR<0,20%
▢	Moderate damage	0,20% ≤ IDR<1,0%
▢	Extensive damage	1,0% ≤ IDR<3,0%
■	Near collapse	IDR ≥ 3,0%

Figures 6-7 illustrate the relationships between various characteristics of the earthquake records and the maximum interstory displacements. The aim is to identify the characteristics of earthquake records that have the most significant impact on the values of interstory displacements.

In analyzing the graphs comparing the curves of earthquake record characteristics and maximum interstory drifts, the objective is to find a curve trajectory that is as similar as possible. More specifically, the goal is for the trajectory of the earthquake record characteristic curve to closely follow the trajectory of the maximum interstory drift curve. Additionally, the jumps and dips in both curves should occur at the same points, indicating a strong correlation between certain characteristics of the earthquake records and the resulting structural response.

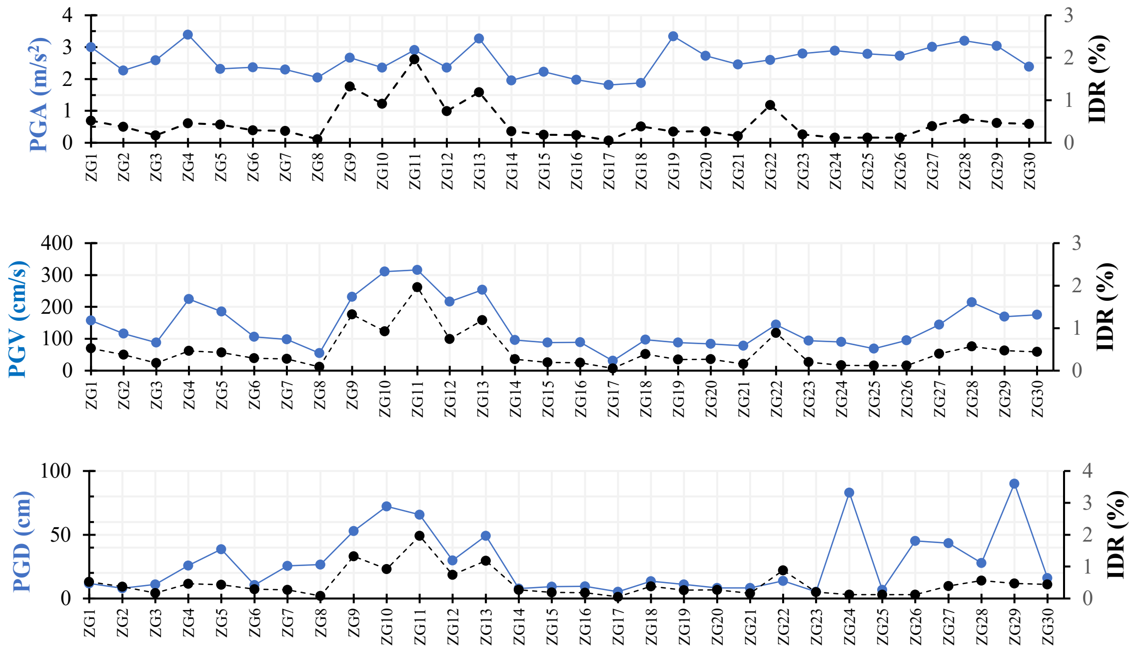

Figure 6. Comparison of peak ground acceleration, velocity and displacement curves and maximum inter-story drifts for all earthquakes for the city of Zagreb

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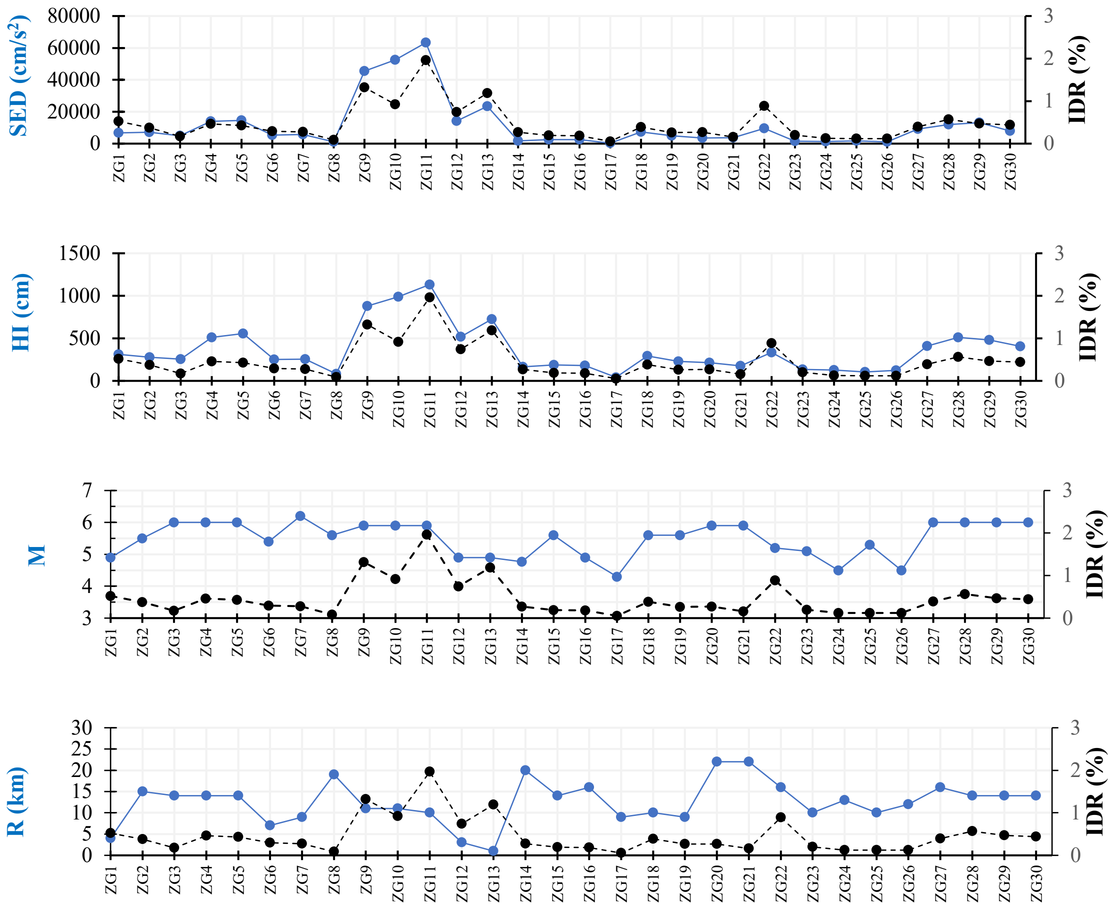

Figure 7. Comparison of specific energy density (SED), Housner intensity (HI), magnitude and epicenter distance and maximum inter-story drifts for all earthquakes for the city of Zagreb

6. Results of the analysis and selection of the most important earthquake record parameters

Based on the results of the comparisons, it can be concluded that there is a significant correlation between certain characteristics of earthquake records and the maximum inter-story drift as a measure of damage. This is because the trends of the PGV, SED, and HI characteristic curves align closely with the trend of the maximum inter-story drift curve. However, to ensure the comparison is measurable, given the differing units of measurement, all earthquake record characteristics and inter-story drift values were normalized to a range of 0–1. Correlation analysis was then used to determine the strength of influence and the degree of alignment corresponding to the changes in the observed parameters.

The correlation results for both observed earthquake areas are presented in Table 5, demonstrating that the characteristics PGV, SED, and HI have the greatest impact on the nonlinear response of the structure. This is evidenced by the fact that the correlations of the normalized values of these three characteristics reach approximately 90%, distinguishing them from other earthquake record characteristics.

Table 5. Comparison of corellation for normalized values

	PGA	**PGV**	**PGD**	**SED**	**HI**	**M**	**R**
	(g)	**(cm/s)**	**(cm)**	**(cm²/s)**	**(cm)**		(km)
Zagreb	0,30	**0,86**	0,47	**0,90**	**0,91**	0,21	0,34

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The analysis of 30 earthquake records revealed that peak ground velocity (PGV), as a characteristic of amplitude-based intensity measures, has a significant impact on the nonlinear response of structures and their vulnerability. As PGV values increase, the maximum inter-story drift values also rise. These two variables show a high percentage of correlation, as illustrated in Figure 7. According to the analysis specific energy density (SED), which captures the instantaneous values of kinetic energy generated during the earthquake, exhibits an exceptional correlation with maximum inter-story drift values and, consequently, with structural vulnerability. Specifically, higher energy levels correspond to greater structural vulnerability.

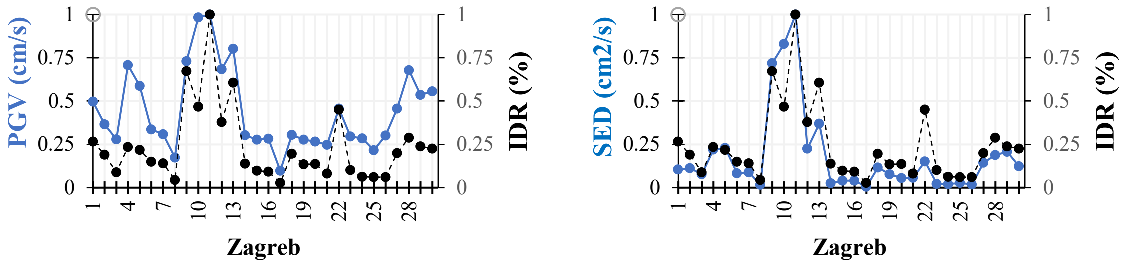

Figure 7. Comparison of normalized values of opeak ground acceleration and specific energy density (SED)and maximum inter-story drifts for all earthquakes for the city of Zagreb

As shown in Figure 8, the analysis of 30 earthquake records confirmed the statement that Housner intensity is the most effective parameter for correlating the severity of seismic events with structural vulnerability. Housner intensity exhibits an exceptional correlation with maximum inter-story drift values as a measure of structural vulnerability. This means that changes in HI values correspond to changes in maximum inter-story drift values (IDR) as a measure of vulnerability.

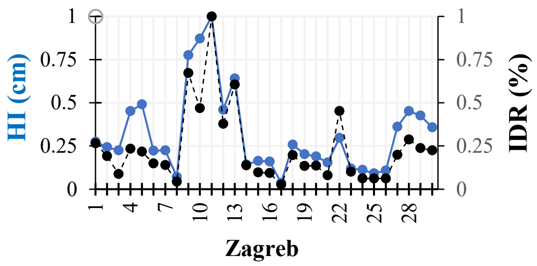

Figure 8. Comparison of normalized values of Housner intensity (HI) and maximum inter-story drifts for all earthquakes for the city of Zagreb

7. Conclusion

Seismic activity is an unexpected and sudden event and is considered one of the greatest global disasters, as it leads to a significant number of casualties and substantial property losses. During an earthquake, there is a sudden release of energy, causing the ground to shake, which is recorded by various devices. This creates complex datasets described by numerous characteristics, with the aim of linking them to the damage to structures. With the increasing frequency of earthquakes due to numerous climate changes, the number of seismic analyses has also risen, driven by the desire to reduce their consequences.

The objective of this analysis was to investigate the impact of specific seismic record characteristics on the nonlinear response of buildings and to define the characteristics with the most significant influence on structural damage. The analysis was carried out using a previously calibrated nonlinear model based on the experimental ICONS model, representing "existing buildings" designed without earthquake regulations approximately 40 years ago.

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The analysis involved the process of selecting seismic records based on magnitude (M) and epicentral distance (R), which are the results of the disaggregation, as well as peak ground acceleration (PGA). For each of the observed areas, 30 seismic records were chosen.
For each seismic record, an analysis of 7 seismic characteristics was performed. By analyzing seismic records in time on a nonlinear numerical model of a four-story building, the displacements of the floors were obtained, from which curves comparing the maximum interstory displacements were calculated as measures of structural damage.
The comparison of the maximum interstory displacements of the building and individual seismic characteristics led to the conclusion that there is a significant correlation with certain characteristics of the seismic records. Peak ground velocity (PGV), specific energy density (SED), and Housner intensity (HI) were the seismic characteristics that proved to be the most influential on the damage to the structures and, therefore, these characteristics are the most reliable for assessing structural damage.
Similarly, the characteristics used in the selection of seismic records (PGA, M, and R) were not sufficiently reliable for detailed seismic calculations of earthquake-induced damage, as they did not show a good correlation in the analysis. When selecting critical seismic records, it is essential to assess the peak ground velocity (PGV) based on the primary characteristics, as this would yield more realistic results for the observed areas.

References

[1] Krawinkler, H. (1996): Cyclic Loading Histories for Seismic Experimentation on Structural Components. *Earthquake Spectra*, **12**(1), 1-12. doi: https://doi.org/10.1193/1.1585

[2] Moehle, J. P. (2015): *Seismic Design of Reinforced Concrete Buildings*. McGraw-Hill Education, USA.

[3] Chopra, A. K. (2017). Dynamics of Structures: Theory and Applications to Earthquake Engineering. Prentice Hall, USA

[4] Luco, N., Ellingwood, B. R., Hamburger, R. O., Hooper, J. D., Kimball, J. K., & Kircher, C. A. (2007): Risk-Targeted versus Current Seismic Design Maps for the Conterminous United States. Structural Engineering International, 17(2), 157-161.

[5] Atkinson, G. M., & Boore, D. M. (2006). Earthquake ground-motion prediction equations for eastern North America. *Bulletin of the seismological society of America*, **96** (6), 2181-2205. doi: https://doi.org/10.1785/0120050245

[6] Bommer, J. J., & Acevedo, A. B. (2004). The Use of Real Earthquake Accelerograms as Input to Dynamic Analysis. *Journal of Earthquake Engineering*, **8**, 43-91. doi: https://doi.org/10.1080/13632460409350521

[7] Kalkan, E., & Kunnath, S. K. (2006). Effects of Fling Step and Forward Directivity on Seismic Response of Buildings. *Earthquake Spectra*, **22**(4), 803-825. doi: https://doi.org/10.1193/1.2192560

[8] Pampanin, S. (2012). Reality-Check and Renewed Challenges in Earthquake Engineering: Implementing Low-Damage Structural Systems – From Theory to Practice. *Bulletin of the New Zealand Society for Earthquake Engineering*, **45**(4), 137-160. doi: https://doi.org/10.5459/bnzsee.45.4.137-160

[9] Bento R, Simões A. (2021): Seismic Performance Assessment of Buildings. *Buildings*. **11**(10):440. doi: https://doi.org/10.3390/buildings11100440

[10] Iervolino, I., Galasso, C. & Cosenza, E. (2010) REXEL: Computer aided record selection for code-based seismic structural analysis. *Bull Earthquake Eng* **8**, 339–362 doi:https://doi.org/10.1007/s10518-009-9146-1

[11] Grubišić, M.(2016) Models for Strengthening Assessment of Reinforced Concrete Frames by Adding the Infills for Earthquake Action. Ph.D. Thesis, Faculty of Civil Engineering Osijek, University of Osijek, Osijek, Croatia.

[12] Malhotra p.K. (2003). Strong-Motion Records for Site-Specific Analysis*, Earthquake Spectra,* **19**, 3. 557–578. doi: https://doi.org/10.1193/1.1598439

[13] Kramer, S. L. (1996). Geotechnical Earthquake Engineering. Prentice Hall, USA.

[14] Housner, G.W., 1959. Behavior of Structures during earthquakes, Journal of the Engineering Mechanics Division, ASCE, Vol. 85., N° EM14, 109-129.

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.128

[15] Chioccarelli, E., Cito, P., Iervolino, I. et al. (2019) REASSESS V2.0: software for single- and multi-site probabilistic seismic hazard analysis. *Bull Earthquake Eng 17*, 1769–1793. doi: https://doi.org/10.1007/s10518-018-00531-x

[16] Luzi L., Lanzano G., Felicetta C., D'Amico M. C., Russo E., Sgobba S., Pacor, F., & ORFEUS Working Group 5 (2020). Engineering Strong Motion Database (ESM) (Version 2.0). Istituto Nazionale di Geofisica e Vulcanologia (INGV).doi: https://doi.org/10.13127/ESM.2

[17] Pinto A, Verzeletti G, Molina J, Varum H, Pinho R, Coelho E. (2002)Pseudo-Dynamic Tests on Non-Seismic Resisting RC Frames (Bare and Selective Retrofit). EUR 20244 EN. 2002 JRC23144

[18] SeismoStruct—A Computer Program for Static and Dynamic Nonlinear Analysis of Framed Structures. Available online: www.seismosoft.com

[19] Ghobarah A (2004). On Drift Limits Associated with Different Damage Levels, International Workshop on Performance-Based Seismic Design, Department of Civil Engineering, McMaster University, Ontario,Canada,June 28 - July 1.