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A Comparative Study of the Effects of Earthquakes in Different Countries on Target Displacement in Mid-Rise Regular RC Structures

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Abstract: Data from past earthquakes is an important tool to reveal the impact of future earthquakes on engineering structures, especially in earthquake-prone regions. These data are important indicators for revealing the seismic loading effects that structures will be exposed to in future earthquakes. Five different earthquakes from six countries with high seismic risk were selected and were within the scope of this study. The measured peak ground acceleration (PGA) for each earthquake was compared with the suggested PGA for the respective region. Structural analyzes were performed for a reinforced-concrete (RC) building model with four different variables, including the number of storeys, local soil types, building importance class and concrete class. Target displacements specified in the Eurocode-8 were obtained for both the suggested and measured PGA values for each earthquake. The main goal of this study is to reveal whether the proposed and measured PGA values are adequately represented in different countries. We tried to reveal whether the seismic risk was taken into account at a sufficient level. In addition, target displacements have been obtained separately in order to demonstrate whether the measured and suggested PGA values for these countries are adequately represented in structural analysis and evaluations. It was concluded that both seismic risk and target displacements were adequately represented for some earthquakes, while not adequately represented for others. Comments were made about the existing building stock of the countries considering the obtained results.

Keywords: target displacement; earthquake; peak ground acceleration; reinforced-concrete; pushover

1. Introduction

Significant loss of life and property after earthquakes increases the consequence of efforts to reduce the effects of earthquakes. The studies on structural and seismic risk analyzes are carried out on both pre-earthquake and post-earthquake in order to prevent and minimize earthquake damages [1–9]. Such studies have special importance in regions with high seismic risk [10]. Ground motion parameters are needed to determine and evaluate the effects of earthquakes in a particular region [11–13]. These parameters are important in terms of both revealing earthquake characteristics and analyzing the behavior of structures under the influence of earthquakes [14–16]. Fault geometry, seismic waves, and earthquake characteristics should be known while the determination of the ground motion parameters by considering local ground conditions. The amplitude parameter is one of the engineering aspects of ground motion parameters. The ground velocity, acceleration and displacement values are known as amplitude parameters [17,18]. Knowing that the earthquake ground motions measurements as a function of time or frequency constitutes an important database for engineering applications and scientific studies for earthquake-resistant structure design [19–21]. In this context, many different programs are used to predict earthquake threats. Openquake Engine [22], Earthquake Loss Estimation Routine (ELER) [23], HAZUS [24], Ez-Frisk [25], PSHRisk-Tool [26], FRISK [27], CRISIS2007 [28], SEISRISK III [29] and OpenSHA [30] are some of the software that are commonly used programs for predicting earthquake threat.

The obtained ground acceleration records from strong ground motion measurements can be used to both determine seismic risk and to monitor the performance of structures during earthquakes. Acceleration records can also be used for the design of earthquake-resistant structures and for the development of attenuation relationships. In addition, the expected damage estimation and intensity distribution in the settlements at different distances from the station can be determined by using attenuation relationships. Earthquake ground motions can be quite complex from this perspective. It is possible to define earthquake motion with three components of linear motion [31,32]. The Peak Ground Acceleration (PGA) is the most common measure used to determine the amplitude of strong ground motion. Any accelerometer used for acceleration records has two horizontal (EW and NS) components and one vertical component. The maximum horizontal ground acceleration is either the geometric mean of the maximum values of the component in both directions or the largest one of them regardless of direction [33–35]. Therefore, obtained PGA values from any earthquake are used to determine seismic and structural risks. Different types of analyzes can be used to decide the performance levels of structures in performance-based design [36–38].

Pushover analysis is a widely used nonlinear analysis technique to estimate the dynamic demands imposed on a structure under earthquake impact. The maximum roof displacements, known as target displacement, are one of the results obtained from this analysis [39–42]. The earthquake performances and damage estimation of the structures can be predicted using the target displacements [43–46]. It is then required to decide the structural performance by comparing the demand values to the deformation capacity for the expected performance levels [47]. Adequate demand displacement values will better reflect real values for the damage estimation of structures and building earthquake performance [48].

In this study, seismic risk and target displacements were compared, taking into account the measured and suggested PGA values for different earthquakes in different countries. Six countries with different seismicity were selected, including as Bosnia and Herzegovina, Albania, Croatia, Iran, Türkiye, and Serbia, and these were within the scope of this study. Two different country groups were selected in this study. In the first group, neighboring Bosnia and Herzegovina, Serbia, Croatia, and Albania were taken into account, while in the second group, neighboring Türkiye and Iran were taken into account. Bulgaria, Macedonia, and Greece are located between these two groups of countries. Earthquakes that occur in both groups of countries also affect other countries within the group. Therefore, seismic and structural parameters were obtained for two different country groups. For this purpose, five different earthquakes were selected for each country. The earthquakes whose data can be accessed were taken into account in the selection of these earthquakes. First, the measured and suggested PGA values were compared for selected earthquakes. Information is provided about the seismicity and the selected earthquakes for each country, respectively. Structural analyzes were made for a sample reinforced concrete (RC) structure to reveal the effect of PGA values. In order to make the structural results more understandable, the RC building has been taken into account with three different numbers of stories, including four, six, and eight-storeys. In order to reveal the effect of different structural conditions, four different variables, namely: the number of storeys, local soil class, building importance class and concrete class were selected. Within the scope of this study, regular mid-rise RC building models were taken into account. In addition, the natural fundamental periods obtained with the empirical formulas used in the earthquake regulations for each country were compared with the period values obtained from the structural analysis. The target displacement values used to determine the performance level and damage estimation of the structures were obtained separately for each number of storeys and each earthquake. In addition, information is given about the building stocks of these countries at the point of the earthquake-structure relationship. The main purpose of this study is to reveal if the suggested PGA values for the building design in seismic design codes and earthquake hazard maps meet the measured PGA values. The novelty of the study is the detailed comparison of both seismic parameters and structural analysis results for six different countries. This study will contribute to the development of seismic hazard maps and seismic design codes for the selected countries. This study will make important contributions to this and similar studies in many different countries and earthquakes.

2. Seismicity of the Selected Countries

Within the scope of this study, six different countries with different seismic characteristics, including Albania, Bosnia and Herzegovina, Croatia, Serbia, Türkiye, and Iran were selected. Comparisons were made by considering the suggested and measured peak acceleration values for the five different earthquakes in each country. In addition to the information about the selected earthquakes, brief information about the seismicity of these countries is given in this section. The locations of selected countries in the active tectonic map were shown in Figure 1.

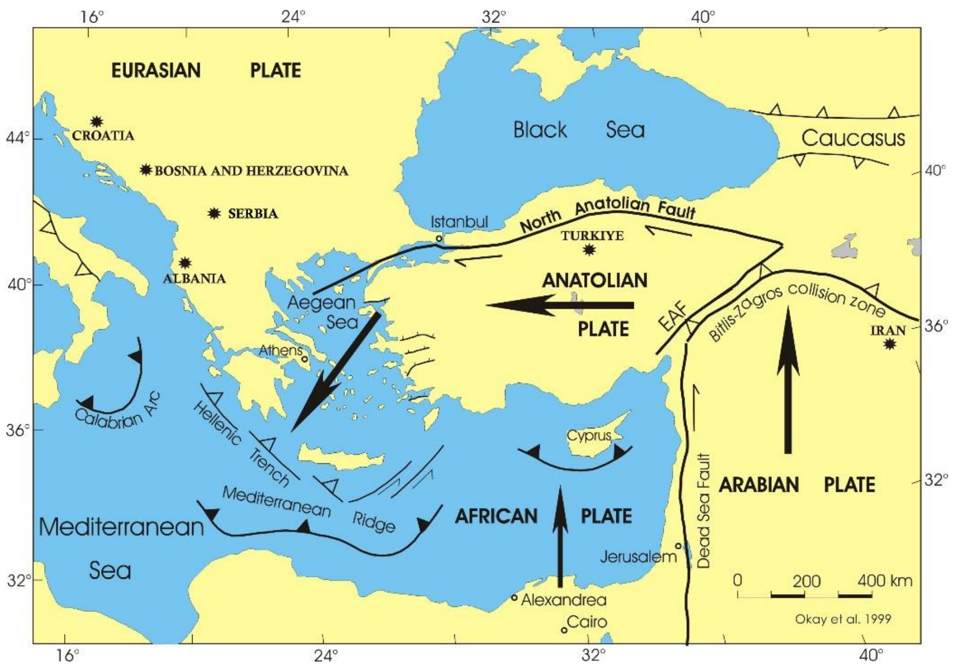

Figure 1. Location of selected countries in the active tectonic map (adopted from [49,50]).

2.1. Albania

Albania is a country with moderate seismicity in the Western Balkans. Located on the Alpine-Mediterranean plate, this region has historically been affected by high-intensity earthquakes. Albanian seismic activity is characterized by intense seismic microactivity (3.0 > M > 1.0) by lots of small earthquakes (5.0 > M > 3.0), few mid-sized earthquakes (7.0 > M > 5.0) and very rarely by large earthquakes (M > 7.0). The most important tremors in the last century are given in Table 1.

Table 1. Major earthquakes in Albania [51].

Date	Area affected	M_w	Depth (km)	Causalities	
				Dead	Injured
26.11.2019	Durres	6.4	20	52	3000+
21.09.2019	Durres	5.6	10	-	108
09.01.1988	Tirana	5.4	24	-	-
16.11.1982	Fier	5.6	22	1	12
15.04.1979	Shkoder	6.9	10	136	1000+
30.11.1967	Diber	6.6	20	12	174
18.03.1962	Fier	6.0	-	5	77
26.05.1960	Korce	6.4	-	7	127
01.09.1959	Fier	6.2	20	2	-
27.08.1942	Diber	6.0	33	43	110
21.11.1930	Vlore	6.0	35	30	100
26.11.1920	Tepelene	6.4	-	36	102
06.01.1905	Shkoder	6.6	-	200	500

Albania and its neighborhood are in a rather complicated seismotectonic region and are prone to earthquakes. A high frequency of earthquakes has been experienced, resulting in loss of life and property destruction in the region (Table 1). According to available records, this region sits in a high rate of seismicity, ranging from moderate to a high seismic risk level. It is characterized by noticeable micro-seismicity (a high number of small earthquakes), sparse mid-sized earthquakes, and very rare large earthquakes. Considering the recorded earthquakes from the accessible data, the earthquakes given in Table 1 were selected by the authors [51].

The first seismic zone intensity map of Albania dates back to 1952. Since then, it has been updated many times until 1979, which is at the moment that the map for seismic evaluation is enforced by the law. The KTP-1963 and KTP-1978 seismic guides were based on the pre-1979s map, which had lower seismic load requirements than the updated values due to a lack of information at the time. Few authors have studied this issue [52]. The largest earthquake in Albania occurred on June 1, 1905, in the North-Western part of Albania with a magnitude of Ms = 6.6. The duration of the tremor was 10–12 s and caused extensive damage to the built environment. In Shkodra alone, around 1500 residential buildings were completely destroyed and all other buildings were severely damaged. In addition, the walls of the historical Shkodra fortress were damaged and partially destroyed. The 15.04.1979 earthquake is one of the strongest earthquakes to occur in the Balkan Peninsula with a moment magnitude of 6.9. The epicenter of this tremor was the coastal area near Petrovac/Montenegro. Several tremors occurred about two weeks before the main shock, and aftershocks lasted for more than nine months. A strong aftershock of Ms = 6.3 occurred on May 24 [53]. This earthquake was one of the main reasons that led to amendments to the earthquake code and seismic zoning maps. Today's seismic zonation map is still based on regions of maximum intensity, not peak ground acceleration. Another strong earthquake occurred in Durrës on November 26, 2019, with a magnitude of M_s = 6.4 [14]. The fact that the epicenter of the earthquake was so close to Albania's most populated and urban area increased the loss of life and injuries. In particular, the old masonry structures in the region were severely damaged and some of them were completely demolished. In this study, this earthquake and its losses will be examined and the results of all analyzes will be compared with the actual damage to the buildings.

The seismic source zones of Albania, characterized by active faults and tectonic regimes, are the essential primary inputs for the estimation of seismic hazards [53]. The following nine earthquake zones have been defined in and around Albania:

1. Zone of Lezha-Ulqin
2. Zone of Peri-Adriatic Lowland
3. Zone of Ionian Coast
4. Zone of Korca-Ohrid
5. Zone of Elbasan-Diber/Tetova
6. Zone of Kukes-Peshkopi
7. Zone of Shkodra-Tropoja
8. Zone of Peja-Prizren
9. Zone of Skopje

The compiled Albania earthquake catalog comprises earthquakes of magnitude Ms > 4.5 that struck the territory between 39.0° N and 43.0° N and between 18.5° E and 21.5° E spanning a timeline 1958–2005 [53]. The best assessments of maximum magnitude are done by taking into account the biggest seismic activity identified and observed in similar tectonic locations. All this data input is processed by utilizing a probabilistic methodology and appropriate attenuation relationships to develop the Probabilistic Hazard Map of Albania.

The seismic zonation map of Albania is based on the intensity values [54], whereas new modern seismic guidelines like Eurocode 8 use probabilistic seismic hazard maps utilizing the peak ground acceleration values derived by probabilistic approaches with different return periods. In many modern codes, Damage Limitation (DL) is expected to be satisfied for an earthquake with peak ground acceleration for a return period of 95 years. Meanwhile, for an earthquake with PGA within the return period of 475 years, buildings should perform as per the limit state of Significant Damage (SD). Seismic hazard maps for maximum horizontal ground acceleration with recurrence periods of 95 and 475 years, respectively, are given for hard rock conditions (Figure 2).

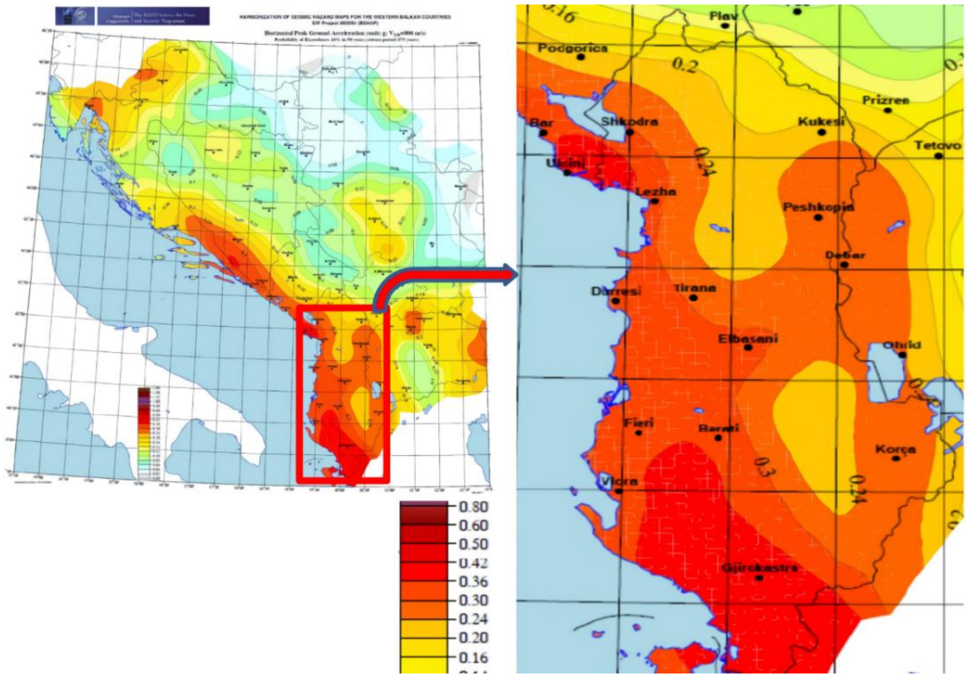

Figure 2. Horizontal peak ground acceleration values for a return period of 475 years (probabilistic seismic hazard map of Albania [55].

As shown in Figures 2 and 4, in many cities with dense masonry structures, such as Durrës, Shkodra, Elbasan, Tirane, and Vlora, the expected PGA for an earthquake with a recurrence period of 95 years is around 0.20 g, whereas this value is around 0.30–0.40 g with a recurrence period of 475 years. If these values are compared to the recordings of the 26 November 2019 shakings, in most of the regions these values are near the values of a 95 year return period. The data for the selected earthquakes in Albania is shown in Table 2.

Table 2. Data of selected earthquakes in Albania.

No	Date	Lat.	Lon.	Magnitude			Loss of Life	Damaged Buildings	Loss of Life/Damaged Buildings	Location
				Mb	Ms	Mw				
1	26/11/2019	41.51°	19.52°			6.4	52	~90,000	0.0006	Durrës/Albania
2	26/11/2019	41.51°	19.52°			6.4	52	~90,000	0.0006	Durrës/Albania
3	21/09/2019	41.43°	19.71°			5.6	-	120	-	Durrës/Albania
4	09/01/1988	41.20°	19.80°			5.9	-	188	-	Tirana/Albania
5	15/04/1979	42.096°	19.209°			6.9	136	~1000	0.14	Shkoder/Albania

A comparison of the measured and suggested PGA values of the selected earthquakes for Albania are given in Table 3.

Table 3. Comparison of the measured and suggested PGA values of the selected earthquakes for Albania.

No	Earthquake Location	Station Name	Year	Earthquake Magnitude (Mw)	PGA(g)	Seismic Risk Zone	A(g)
						Seismic Risk Zone (As Per KTP-N.2-89)	(A(g) (Expected Design Base Acceleration) (from the Probabilistic Map of Albania)
1	Albania	Tirana	2019	6.4	0.11	High	0.30
2	Albania	Durrës	2019	6.4	0.12	High	0.28–030
3	Albania	Tirana	2019	5.6	0.18	High	0.32–0.36
4	Albania	Tirana	1988	5.4	0.40	High	0.28–0.30
5	Albania	Shkoder	1979	6.9	0.46	High	0.30

While the number of damaged buildings in the first two earthquakes considered for Albania was quite high, the loss of life was quite low. In addition, the highest loss of life/damaged buildings ratio for this country was obtained for the fifth earthquake, and this ratio was 0.14. The measured PGA values in these earthquakes that have occurred in these regions with high earthquake risk were considerably lower than the suggested PGA values for the first three earthquakes. However, the measured PGA values for the third and fourth earthquakes are considerably higher than the recommended PGA values. For this country, the seismic risk can be expressed adequately by considering the earthquake ground motion levels for different probabilities of exceedance.

2.2. Bosnia and Herzegovina

Bosnia and Herzegovina is located in the central part of the Dinaridic Mountain System [56]. The location of Mediterranean is characterized by various types of faults that have been identified in this region. The Adriatic coast and the Dinarides are specific for reverse faults, while normal faults are mainly identified in the Apennine Peninsula. The fault plane solution for major earthquakes in Adria has been presented by Slejko et al. [57], while obtaining data from various sources; Gasparini et al. [58], Herak et al. [59], Louvari et al. [60], Sulstarova et al. [61], and Harvard [62].

As stated in the article in [63], quote: "It is evident that with the increase of population in seismically prone areas, urban areas are becoming more vulnerable to seismic risk. Record losses were registered in 2011 [64] after earthquakes that hit Japan and New Zealand, for developed countries with a high degree of earthquake disaster awareness and preparedness. In absolute terms, the costliest disasters happen in the most developed countries, however, with respect to their GDP, it was limited to a few percentage points [65]. The analysis showed that countries of middle income in the last two decades were at a higher risk in comparison to the countries with low and high GDP. From the available data [65], Bosnia and Herzegovina falls into lower-middle-income."

Taking into account the high density of the population, high level of vulnerability of buildings, and moderate to high in some locations PGA results in a high risk of earthquakes in Bosnia and Herzegovina. After the Zagreb 2020 earthquakes, the engineering community awakened regarding the potential risk and level of devastation to the existing building stock in Bosnia and Herzegovina. It should be mentioned that the last devastating earthquake that hit Zagreb was in 1880. Then, 140 years later, the Zagreb 2020 earthquake and Petrinja earthquake occurred and had a major effect on the building and clearly showed the high vulnerability of the existing stock. It is important to state that the Pokupsko- Petrinja Fault is oriented in the NW-SE direction within the Eurasian plate. This is the strongest earthquake that occurred since the 1880 Great Zagreb earthquake (magnitude of 6.3). The seismicity of this region (Croatia and the upper part of Bosnia and Herzegovina-Banja Luka region) is given in Figure 4. Looking at the map, it is believed that the Petrinja fault is the same as the Banja Luka fault, as indicated in Figure 3 and indicated as PKBL = Pokuplje-Kostajnica-Banja Luka right-lateral fault.

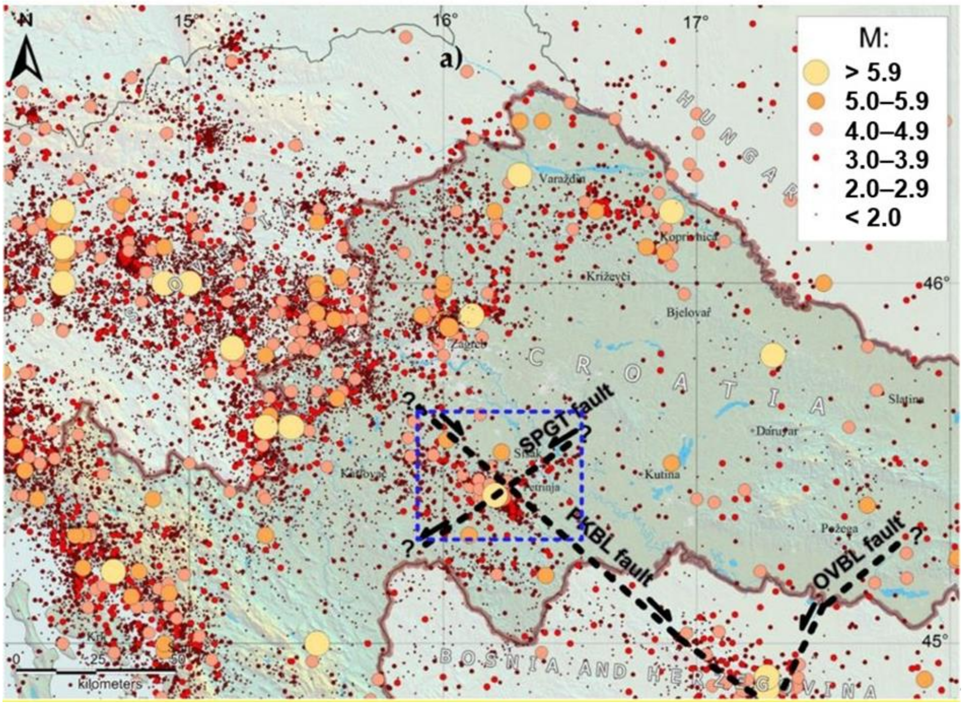

Figure 3. The spatial distribution of earthquakes in Croatia (373 BC–2019, according to the Croatian Earthquake Catalogue (CEC), of which an updated version was first described in [67], with the Pokupsko-Petrinja epicentral area indicated (blue rectangle). Thick, black-dashed lines mark regional active faults: PKBL = Pokuplje-Kostajnica-Banja Luka right-lateral fault, SPGT = Sisak-Petrinja-Glina-Topusko left-lateral fault, and OVBL = Orljava-Vrbas-Banja Luka left-lateral fault.

After the Petrinja earthquake, a quick field inspection revealed that fresh fault planes in the outcrops on the Hrastovička gora appeared mostly along the longitudinal NW–SE-striking Pokupsko–Kostajnica–Banja Luka Fault and showed clear dextral coseismic strike-slip displacements and a 20 km long section of the Pokupsko Fault was (re)activated. It is assumed by Markušić et al. [68] that the creeping sinistral Sisak–Petrinja–Glina–Topusko Fault is locking the dextral Pokupsko–Kostajnica–Banja Luka Fault and a similar complex fault mechanism is also proposed for the Banja Luka area. According to Markušić et al. [68], the dextral Pokupsko–Banja Luka Fault could be one of the main inherited active faults between the crustal segments of Adria.

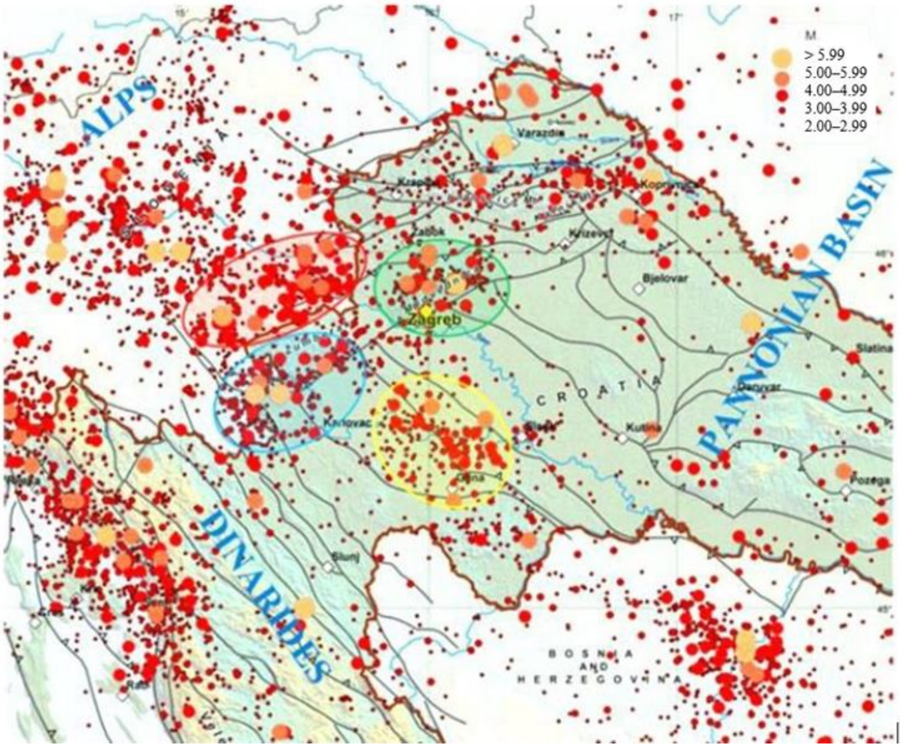

Figure 4. Map of earthquake epicenters in Croatia and part of Bosnia and Herzegovina in the period from BC to 2015 according to the Catalog of Earthquakes in Croatia and the neighboring areas [66–71].

Taking this all into account, it is of the utmost importance to take Bosnia and Herzegovina into account regarding the effects of earthquakes on target displacement in RC structures and other structures as well. Other than the Peak Ground Acceleration, it is necessary to take into account the vulnerability of structures and the exposure of the population during the assessment of the seismic risk. After the Petrinja earthquake, the seismic community in Bosnia and Herzegovina discussions started, and at the moment, there are initiatives for a revision of the interactive seismic map of Bosnia and Herzegovina.

Papeš [72] gave the most comprehensive picture of the tectonic structure in Bosnia and Herzegovina. The longest fault is the Sarajevo Fault, which spreads in the direction of NW-SW, followed by the Banja Luka fault and Konjic Fault. Sarajevo fault with a low to moderate seismic activity level is under-passed by all the transversal deep faults, where the highest seismic motions are noted. Ademović et al. [73] presented that 64% of all earthquakes have a focal depth of up to 10 km and that this is one of the causes of the damaging impact on the structures. Bosnia and Herzegovina in the last 50 years was hit by more than a few medium-sized earthquakes of magnitude M_w up to 6.1 [74]. The earthquake, which had the most devastating impact on the structures, was the 1969 Banja Luka earthquake. According to the MSK-64, the Banja Luka earthquake was marked as a VIII intensity scale [75]. The aftermath of this earthquake was 15 fatalities, 1117 injured people, and over $300 million in damage [74,76].

The second-largest earthquake that should be mentioned is the 1962 Treskavica earthquake with a magnitude Mw= 5.9, and a focal depth of 15 km. As the epicenter of the earthquake was in an abandoned area of Mount Treskavica, there were no major casualties, nor significant damage to the buildings due to the low level of population and construction in this region at that time [77]. Several structures have been damaged in Sarajevo by this earthquake activity (Building of the Executive Council, the Main Post Office, Faculty of Medicine) [73]. The damage caused by this earthquake in the financial means was equal to 396 million dinars [78]. Looking at the period from 306 to 2015, 66.9% of all earthquakes had a magnitude between 3.6–4.5, while 20.5% of the earthquakes had a magnitude in the range of 4.6 to 6. This region was not often hit (4.2% of all earthquakes) by an earthquake of larger magnitudes, while only 8.5% of all earthquakes that hit this region had a magnitude between 3.1 to 3.5 [73].

Figure 5 shows epicentres of regional north-western Balkan earthquakes observed between 1900 and April 2021 with Mw $\geq$ 3.0 [79], as well as the boundaries of Croatia, Bosnia and Herzegovina, and Serbia. It also shows epicentres of the earthquakes from which PGA values have been recorded on rock, as well as the recording sites. In 2018, new seismic hazard maps were compiled for Bosnia and Herzegovina and incorporated into the National Annex to Eurocode 8 [80]. It should be noted that the reference PGA values in these maps are given for ground type A, i.e., for the rock sites. Recently, in all three countries (Croatia, Bosnia and Herzegovina, and Serbia), current official seismic hazard maps are part of the respective National Annexes to Eurocode 8 and the PGA values for rock sites (ground type A) are used to express the hazard. Hence, in Table 5, we have presented only the PGA values recorded on rock (i.e., sites with shear wave velocity in the top 30 m of the soil larger than or equal to 800 m/s). This has unfortunately posed a challenge, since for some devastating historical earthquakes there were very few accelerograph stations on rock sites, while for others we could not find any available data.

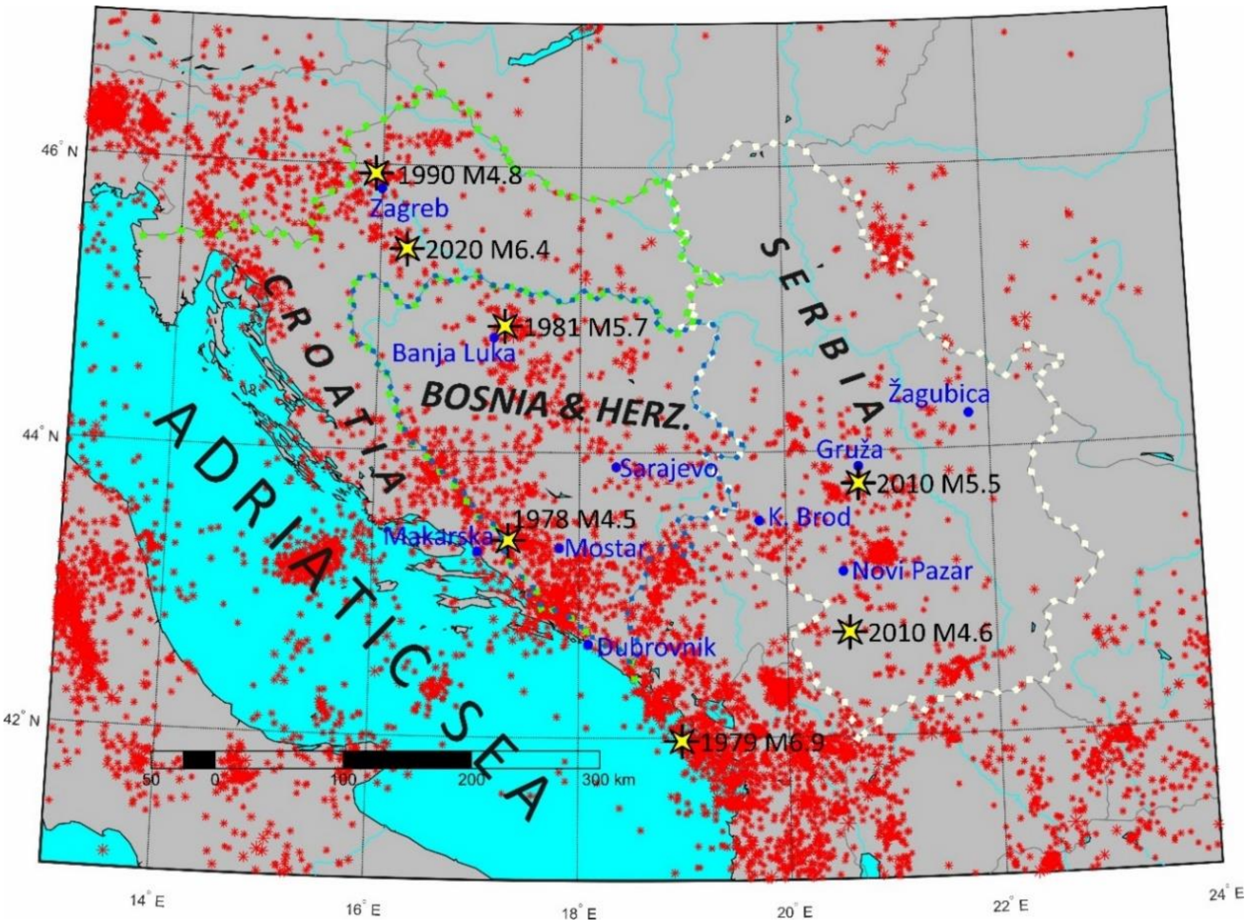

Figure 5. Epicentres of the north-western Balkan earthquakes observed between 1900 and 2021 [79], including the epicentres of the earthquakes that were recorded in Croatia, Bosnia and Herzegovina, and Serbia on rock (blue circles show locations of the corresponding recording stations).

During the analysis, we have chosen the countries of the Balkan as two years ago several earthquakes hit Croatia, which, even though not of "extreme" magnitude, had a major impact on the building stock and community as a whole. The data on the 1981 Banja Luka earthquake are shown in Table 4.

Table 4. Data of the selected earthquake in Bosnia and Herzegovina [81,82].

No	Date	Lat.	Lon.	Magnitude			Loss of Life	Damaged Buildings	Loss of Life/ Damaged Buildings	Location
				Mb	Ms	Mw				
1	13.08.1981	44.82	17.26	5.3	5.5	5.7	-	-	-	Banja Luka (Bosnia and Herzegovina)

The comparison of the PGA values for selected earthquakes in Bosnia and Herzegovina is shown in Table 5. In Table 5, all PGA values were taken from the EQINFOS database [83]. All given PGA values were recorded at rock sites (corresponding to ground type A according to Eurocode 8).

Table 5. Comparison of the measured and suggested PGA values of selected earthquakes for Bosnia and Herzegovina [83].

No	Earthquake Location	Station Name	Year	Earthquake Magnitude (Mw)	Distance to Epicentre to Station (km)	PGA(g)	Seismic Risk Zone	A(g)
							Seismic Risk Zone	(A(g) (Expected Design Base Acceleration) (from the Probabilistic Map of B&H)
1	Banja Luka, B&H	Banja Luka	1981	5.7	7.1	0.29	High	0.17
2	Banja Luka, B&H	Banja Luka	1981	5.7	7.4	0.36	High	0.17
3	Banja Luka, B&H	Banja Luka	1981	5.7	6.5	0.43	High	0.17
4	Montenegro	Sarajevo	1979	6.9	215	0.01	High	0.18
5	Montenegro	Mostar	1979	6.9	177	0.04	High	0.26

For Bosnia and Herzegovina, the loss of life/damaged buildings ratio for the first earthquake, whose data can be accessed, was 0.09. The measured PGA values for the three earthquakes were considerably higher than the predicted PGA values, however, it should be noted that these values were recorded at very short epicentral distances—7.1, 7.4, and 6.5 km, respectively—while the hypocentral depth was only 10 km. Smaller measured PGA values are recorded at large distances of 215 and 177 km, respectively.

2.3. Croatia

As part of the Mediterranean–Trans-Asian belt, the territory of the Republic of Croatia is located in a seismically active area. The territory of Croatia consists of several tectonic units: The Pannonian basin in the north, the eastern part of the Alps in the northwest, the Dinarides, the transition zone between the Dinarides and the Adriatic plate, and the Adriatic plate [84,85]. Structural-geological data on recently active faults, combined with data on seismic activity, form the basis for the interpretation of seismotectonic activity, seismic hazard, and risk in seismically active areas.

The majority of earthquakes in Croatia occur around the Adriatic coast due to the interaction (collision) of the Adriatic Platform and the Dinarides (see Figure 6). However, the north-east parts of Croatia are located in an intraplate low to moderate seismicity region of the Pannonian Basin [85]. Moho depths in Croatia range from 25 km beneath the Pannonian Basin to 45 km beneath the Dinarides [86,87]. Since 2011, current official seismic hazard maps (for a return period of 95 and 475 years) for Croatia are part of the Croatian National Annex to Eurocode 8 [88]. Hazard maps for the return period of 475 years for Croatia are presented in Figure 6. In Table 6, data on selected earthquakes in Croatia are given. All given PGA values were recorded at rock sites (corresponding to ground type A according to Eurocode 8). The ratio of loss of life/damaged buildings was 0.01 for the first earthquake and 0.09 for the third earthquake. Here, the first earthquake is the 6.4 Mw earthquake that devastated the village of Petrinja on 29 December 2020, with the epicentre 40 km south of the capital of Croatia, Zagreb [89]. The focal depth of the earthquake was around 10 km. Another earthquake that should be mentioned here, and which caused damages in Bosnia and Herzegovina as well as in Croatia and even Albania, is the 1979 Montenegro earthquake, which was the strongest earthquake recorded in the area of the former Yugoslavia, with the epicentre offshore in the Adriatic Sea (see Figure 5). While this earthquake was felt up to 900 km from the epicentre, it had destructive consequences only in a 100 km coastal zone and a 25 km stretch from the shore to the mountains [90]. Montenegro suffered 101 and Albania 35 fatalities as a result of the earthquake [90]. This earthquake contributed to the last two PGA values in Table 5, and the third and fourth PGA values in Table 6.

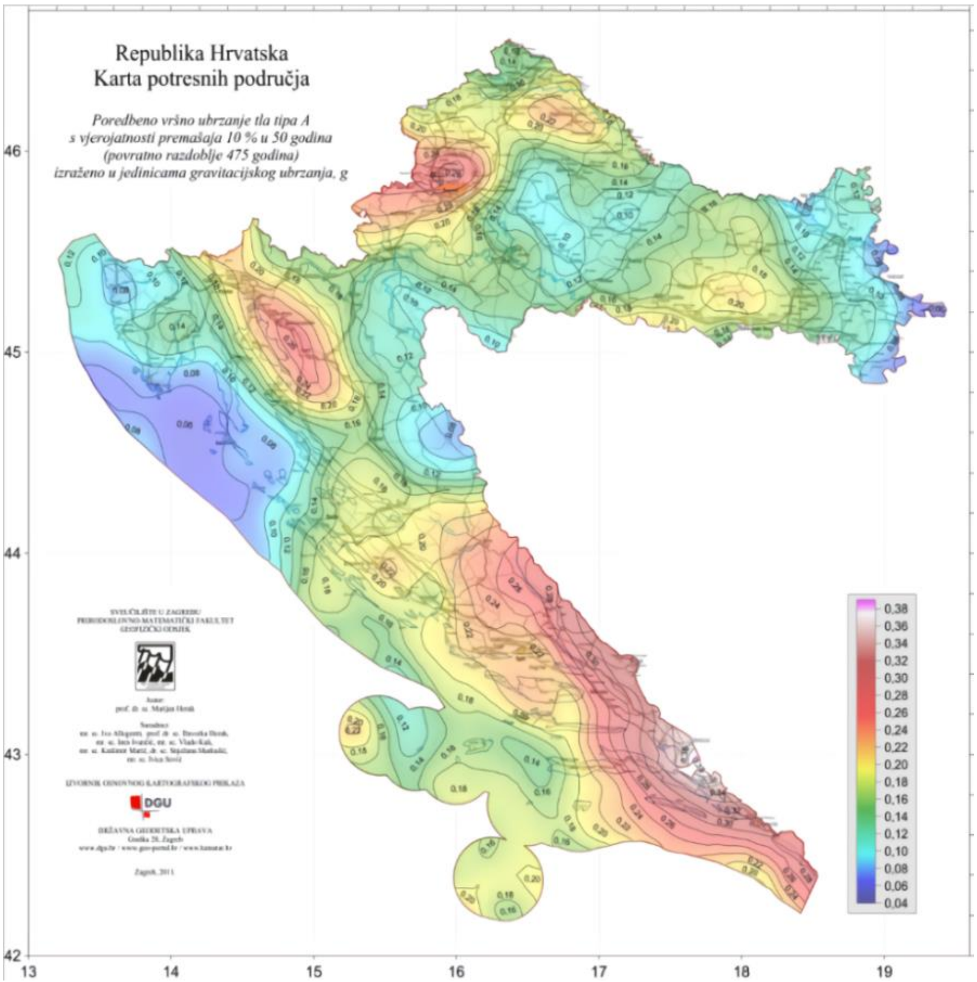

Figure 6. Seismic hazard maps for Croatia for a return period of 475 years (http://seizkarta.gfz.hr/karta.php, accessed 30 August 2022) [91].

Table 6. Data of selected earthquakes in Croatia [79,82,83].

No	Date	Lat.	Lon.	Magnitude			Loss of Life	Damaged Buildings	Loss of Life/ Damaged Buildings	Location
				Mb	Ms	Mw				
1	29.12.2020	45.40	16.22	6.0		6.4	7	8300*	0.01	Petrinja, Croatia
2	03.09.1990	45.92	15.92	4.8	4.7	4.9	-	-	-	Kraljev Vrh, Croatia
3	17.12.1978	43.38	17.29	4.5	3.7	4.7	-	-	-	Imotski, Croatia

* UNICEF Country Office for Croatia, Earthquake Situation Report #5, 3 February 2021 [92].

The comparison of measured and suggested PGA of the selected earthquakes for Croatia is given in Table 7.

Table 7. Comparison of the measured and suggested PGA values of the selected earthquakes for Croatia [82,83,93,94].

No	Earthquake Location	Station Name	Year	Earthquake Magnitude (Mw)	Distance to Epicentre to Station (km)	PGA(g)	Seismic Risk Zone	A(g)
								(A(g) (Expected Design Base Acceleration) (from the Probabilistic Map of Croatia)
1	Petrinja, Croatia	Zagreb-Puntijarka	2020	6.4	60	0.04	High	0.279
2	Kraljev Vrh, Croatia	Zagreb	1990	4.9	12	0.06	High	0.259
3	Montenegro	Dubrovnik	1979	6.9	105	0.08	High	0.305
4	Montenegro	Makarska	1979	6.9	208	0.04	High	0.276
5	Imotski, Croatia	Makarska	1978	4.7	24	0.03	High	0.276

Table 7 shows all the PGA values recorded on rock sites in Croatia that could be found at the moment. The first PGA value corresponds to the 2020 Petrinja earthquake [94]. The second PGA value was taken from the ISESD database [81,83]. The last three PGA values were taken from the EQINFOS database [82]. It is interesting to see from Table 5 that, although there were no casualties in Croatia, the PGA values recorded from this earthquake on rock sites at distances of 105 and 218 km are very similar to those recorded in Croatia at much smaller distances, but during moderate size events. From what can be seen from Table 7, the presented PGA values are very, very low compared to the corresponding PGA values given in the Croatian hazard map. However, it should be noted that some of these values were recorded at relatively large epicentral distances. For example, the first value was recorded at a distance of 60 km, while the third and fourth PGA values were recorded at distances of 105 and 218 km, respectively (the hypocentral depth was 12 km). The second value was recorded at the epicentral distance of 12 km while the epicentral depth was 13 km. The fifth value was recorded at the epicentral distance of 24 km, while the epicentral depth was 10 km.

2.4. Serbia

The major part of Serbia is located in intraplate low to moderate seismicity regions. To the north, Serbia comprises the Pannonian Basin's southern part, with a rare occurrence of larger earthquakes [95]. To the southwest, Serbia is surrounded by Dinaric Alps and borders the Mediterranean-Trans-Asian belt, known for its frequent occurrence of stronger earthquakes. To the northeast, Serbia is surrounded by the Carpathian Mountains, and to the southeast by the Balkan Mountains and Rhodopes. The range of the Moho depths is similar to that in Croatia (shallowest beneath the Pannonian Basin and deepest beneath the Dinarides) [86,87]. Normal faults are, however, more common in Serbia than thrusts and strike-slip faults, which do account for practically all occurrences in the External Dinarides.

A series of earthquakes struck central Serbia in the twentieth century, causing largely rural devastation, such as the 1922 M6.0 Lazarevac, 1927 M = 5.9 Rudnik, 1980 M = 5.8 Kopaonik, and 1998 M = 5.7 Mionica earthquakes. The most recent devastating earthquake in Serbia was the M = 5.5 Kraljevo Earthquake, which occurred on 3 November 2010, with an epicentral intensity of VII-VIII °MCS. Two individuals died, 180 people were injured, and numerous buildings were damaged [96].

Data of selected earthquakes that are available for Serbia [97] is given in Table 8 and the comparison of PGA's is given in Table 10. All given PGA values were recorded at rock sites (corresponding to ground type A according to Eurocode 8).

Table 8. Data of selected earthquakes in Serbia [97].

No	Date	Lat.	Lon.	Magnitude			Loss of Life	Damaged Buildings	Loss of Life/ Damaged Buildings	Location
				Mb	Ms	Mw				
1	03.11.2010	43.76	20.73	5.3	5.0	5.5	2	1689	0.01	Kraljevo, Serbia
2	10.03.2010	42.77	20.56	5.0	4.0	4.6	-	-	-	Peć

In 2018, new seismic hazard maps were compiled for Serbia and incorporated into the National Annex to Eurocode 8. Similar to Croatia and Bosnia and Herzegovina, for Serbia, it was also a challenge to find PGA records on rock sites, especially because Serbia did not experience an event with Mw larger than 5.9 in the past 100 years. The values presented in Table 9 are the only ones we could find for the rock sites, and which were recorded by the Seismological Survey of Serbia's (2021) [98] accelerograph network in Serbia.

Table 9. Comparison of the measured and suggested PGA values of the selected earthquakes for Serbia [98].

No	Earthquake Location	Station Name	Year	Earthquake Magnitude (Mw)	Distance to Epicentre to Station (km)	PGA(g)	Seismic Risk Zone	A(g)
								(A(g) (Expected Design Base Acceleration) (from the Probabilistic Map of Serbia)
1	Kraljevo, Serbia	Gruža	2010	5.5	13	0.06	High	0.20
2	Kraljevo, Serbia	Novi Pazar	2010	5.5	69	0.01	High	0.20
3	Kraljevo, Serbia	Radoinja, Kokin Brod	2010	5.5	83	0.01	Medium	0.15
4	Kraljevo, Serbia	Žagubica	2010	5.5	102	0.01	Medium	0.15
5	Peć	Novi Pazar	2010	4.6	46	0.01	High	0.20

Data of selected earthquakes that are available for Serbia is given in Table 8 and the comparison of PGA's is given in Table 9. All given PGA values were recorded at rock sites (corresponding to ground type A according to Eurocode 8).

For Serbia, the ratio of loss of life to damaged buildings was 0.01 for the first earthquake. The recorded PGA values considered for Serbia are very, very low compared to the corresponding PGA values given in the Serbian official seismic hazard map. However, most of these values shown here were also recorded at relatively large epicentral distances. The epicentral distances for the last four PGA values were 69, 83, 102, and 46 km, respectively, while for the first value the distance was 13 km (the hypocentral depth was 13 km for the first four records and 12 km for the last record).

2.5. Türkiye

Türkiye is situated within the Alpine-Himalayan orogenic belt and is among the most seismically active areas in the world [99,100]. The distribution of seismicity is focused on high-strain regions, many of which are major strike-slip faults, such as the North Anatolian Fault Zone (NAFZ), the East Anatolian Fault Zone (EAFZ), and the Western Anatolian Graben Zones (WAGZ). The NAFZ is a 1200 km long strike-slip fault zone that connects the East Anatolian convergent zone to the Hellenic subduction zone [101–103]. The distribution of earthquakes that dominate the seismic pattern of the northern part of Türkiye is mostly parallel to the NAFZ [104–106]. The NAFZ is a continuous and narrow fault system that cuts the Anatolian Peninsula in an E-W direction from Karlıova in the east to the northern Aegean in the west. The NAFZ, which is the northern plate boundary of the Anatolian Plate with the N-S extensional regime of the Aegean region, spreads as a complex fault system in the eastern part of the Marmara region, in contrast to the simple structure of the NAFZ (Figure 7).

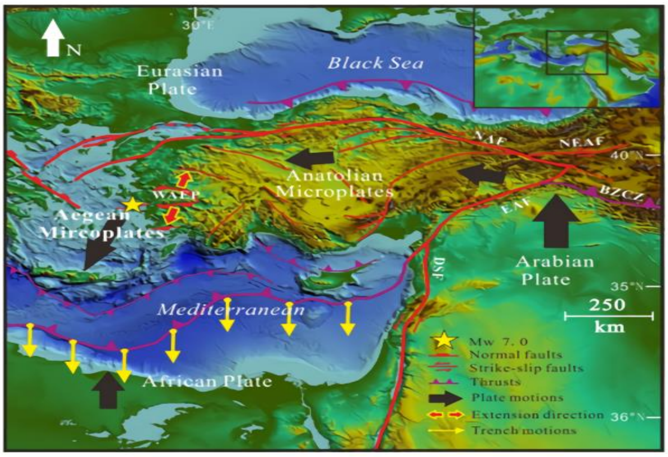

Figure 7. Main tectonics elements for Türkiye [107].

Distribution of the epicenters (M ≥ 3.0) and main fault zones in Türkiye was given in Figure 8.

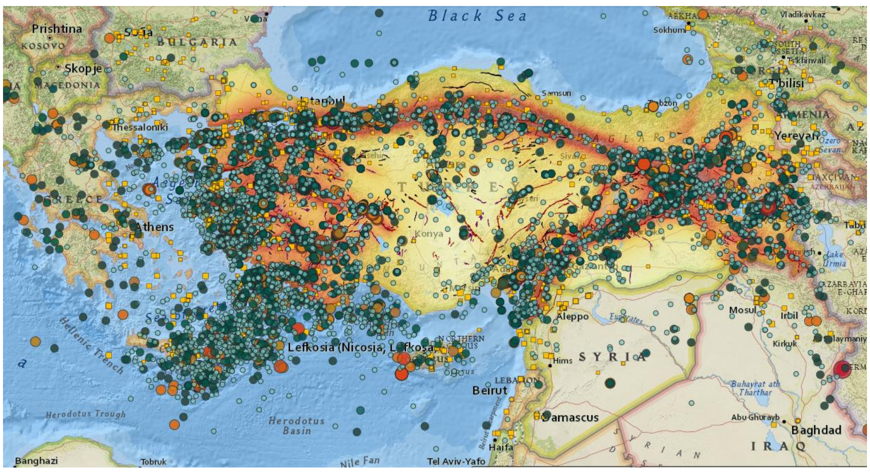

Figure 8. Distribution of epicenters (M ≥ 3.0) and main fault zones in Türkiye.

The earthquakes taken into account for Türkiye are the 1992 Erzincan, 1999 Kocaeli, 1999 Düzce, 2003 Bingöl, and 2011 Van. The 1992 Erzincan earthquake occurred in the eastern half of the Erzincan basin, and two days after this earthquake, the largest aftershock occurred in Pülümür [108]. After this 6.8 magnitude earthquake, many engineering structures were damaged [109]. The 1999 Gölcük (Kocaeli) earthquake, which was felt in and around the Marmara region, caused different levels of structural damage in these settlements. This earthquake, which occurred on the northern branch of the North Anatolian Fault Zone (NAFZ), is associated with a 145 km long surface rupture extending from the southwest of Düzce in the east to the west of the Hersek delta in the west [110]. The 1999 Düzce earthquake, which took place three months after the 1999 Gölcük earthquake, was felt in many different settlements and caused huge structural damage [111]. The surface rupture of this earthquake, which occurred on the Düzce Fault, which is an extension of the North Anatolian Fault Zone in the Bolu Basin, was 40 km long and the maximum right lateral deviation was measured as 500 ± 5 cm [112]. The 2003 earthquake that occurred in Bingöl, one of Türkiye's provinces with high seismicity, occurred approximately 60 km southwest of the triple junction near Karlıova, where the North Anatolian Fault Zone (NAFZ) and the East Anatolian Fault Zone (EAFZ) intersect [113]. The earthquake-causing fault is a right-lateral strike-slip fault and it is stated that the earthquake depth is in the range of 5–15 km [114]. The last earthquake considered in the study is the 2011 Van earthquake that happened in the Lake Van Basin. The epicentral depth of this earthquake, which was centered in Tabanlı village between Van and Erçiş, was measured as 5 km [115]. The large aftershock of 9.11. 2011 ($M_W = 5.7$) was caused by additional damage, especially in the city center of Van, and more than 40 fatalities [116,117]. The settlements where the epicentres of these five different earthquakes, which are considered for Türkiye, have high seismic risk.

The loss of life and property of a total of selected earthquakes and their locations are shown in Table 10. Data on these earthquakes were obtained from the databases of two main institutions that record instrumental earthquakes in Türkiye such as the Republic of Türkiye Prime Ministry Disaster and Emergency Management Presidency (DEMP) and the Kandilli Observatory Earthquake Research Institute of Bogaziçi University (KOERI) and [118,119].

Table 10. Data of selected earthquakes in Türkiye [118,119].

No	Date	Lat.	Lon.	Magnitude			Loss of Life	Damaged Buildings	Loss of Life/ Damaged Buildings	Location
				Mb	Ms	Mw				
1	13.03.1992	39.72	39.63	6.1	6.8		653	8057	0.08	Erzincan
2	17.08.1999	40.76	29.96	6.1	7.4		17,480	73,342	0.24	Gölcük (Kocaeli)
3	12.11.1999	40.81	31.19	6.2	7.2		763	35,519	0.02	Düzce
4	01.05.2003	39.00	40.46	5.7	6.3		176	6000	0.03	Bingöl
5	23.10.2011	38.76	43.36			7.2	644	17,005	0.04	Van

Among the selected earthquakes in this study, the greatest damage occurred in the 1999 Kocaeli (Gölcük) earthquake. The loss of life per building was obtained as 0.24 for this earthquake. The lowest loss of life per building occurred in the 1999 Düzce earthquake. These five different earthquakes caused a total of 19,716 deaths in a total of 139,923 damaged buildings. This data is sufficient to clearly demonstrate Türkiye's earthquake hazard. The loss of life per building for five earthquakes was calculated as 0.14. The measured and recommended PGA values for these earthquakes are given in Table 11. The standard design earthquake ground motion level was selected to determine the suggested PGA values. This level is opposed to probabilities of exceedance of 10% in 50 years, which has a 475-year repetition period.

Table 11. Comparison of the measured and suggested PGA values of the selected earthquakes for Türkiye.

No	Earthquake Location	Station Name	Year	Earthquake Magnitude	Magnitude Type	PGA(g)	Seismic Risk Zone As Per TSDC-2007	PGA(g) As Per TBEC-2018
1	Türkiye	Van	2011	7.2	Mw	0.182	High	0.399
2	Türkiye	Bingöl	2003	6.3	Ms	0.511	Very High	0.633
3	Türkiye	Düzce	1999	7.2	Ms	0.823	Very High	0.588
4	Türkiye	Erzincan	1992	6.8	Ms	0.485	Very High	0.432
5	Türkiye	Kocaeli	1999	7.4	Ms	0.399	Very High	0.690

Except for the third and fourth Düzce earthquakes, the recommended PGA values for the design earthquake were not exceeded for the other three earthquakes. For Türkiye, the recommended PGA values for the first, second and fifth earthquake locations are lower than the predicted PGA values, and the seismic risk for these locations has been adequately taken into account. All earthquake hazard maps used in Türkiye until 2018 were prepared on a regional basis. However, the earthquake hazard is specified specifically for the geographical location with the map currently used after this date. In addition, while there was only one earthquake ground motion level in the previous seismic design code, four different exceedance probabilities are taken into account with the updated code. With the earthquake hazard specific to the geographical location, the expected target displacements from the structures under the effect of the earthquake could be obtained more realistically. Considering the earthquake ground motion levels for different probabilities of exceedance, it is possible for the structures to provide the desired performance levels under the influence of larger earthquakes.

2.6. Iran

The Iranian plateau is located on the Alpine–Himalayan seismic belt, which is considered to be one of the most seismic zones of the world [120,121] and the source of major and destructive earthquakes that occurred in this country throughout history. Some of the most catastrophic earthquakes recorded in the seismic history of Iran include 1960 Lar (Ms = 6.5), 1962 Buin-Zahra (Ms = 7.2), 1978 Tabas (Mw = 7.35), 1990 Manjil (Mw = 7.37), and 2003 Bam (Mw = 6.6) [122]. One of the first elaborate attempts at research on the tectonics and seismicity of Iran was conducted by Ambraseys and Melville (1982) [123]. Berberian (1994) [124] published the first earthquake catalogue of Iran. Updated earthquake catalogues and seismic zoning maps of Iran are regularly published by the seismic zoning sub-committee of the Iranian Seismic Code's permanent committee and are provided by the Iranian Strong Motion Network (ISMN) as the major source of seismology and earthquake engineering in Iran [125]. Figure 9 shows the epicenter of earthquakes that occurred in Iran in 2017 recorded by ISMN (ISMN, 2017) [126], while Figure 10 represents records of large earthquakes that occurred in Iran and adjacent countries from 1900 up to recent years [127]. This figure shows 17 earthquakes with $M_w > 7$, 103 earthquakes with $6 < M_w < 7$, and more than 1700 earthquakes with $M_w > 5$ that have occurred in the recorded seismic history of Iran [125]. It is also demonstrated from Figure 10 that the Zagros zone in the western and southwestern part of Iran is the most seismically active zone which also confirms the major seismic zone categorization proposed by Shoja-Taheri and Niazi (1981) [128]. Based on Figures 11 and 12, as well as the earthquake zonation map of Iran, most of the provinces with large populations are located within high or very high seismic zone areas. As mentioned in the study by Izadkhah and Amini [129], more than 70 percent of cities in Iran are in the vicinity or within the route of active faults, which poses a great risk of seismic hazards to such cities.

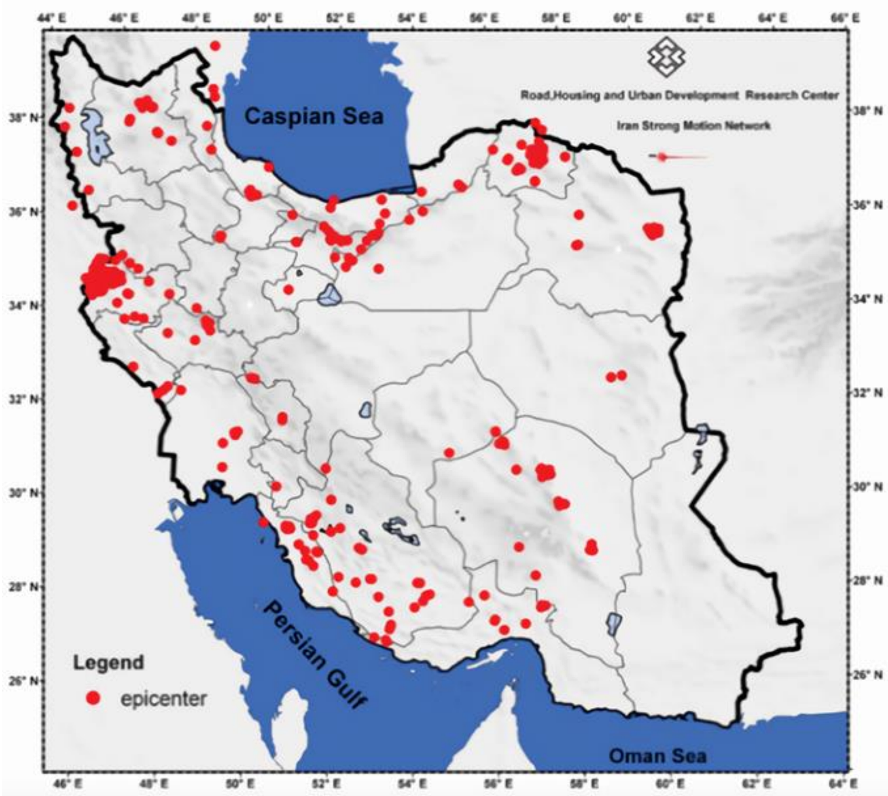

Figure 9. Epicentre of earthquakes occurred in Iran in 2017, recorded by ISMN [126].

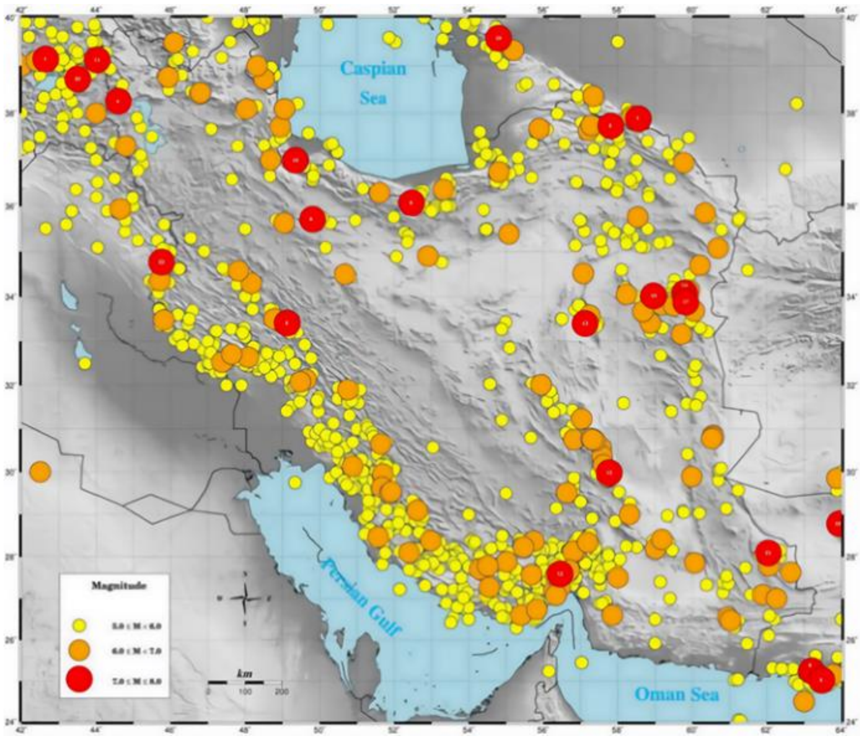

Figure 10. Large earthquakes in Iran and adjacent countries (1900–2019) [126].

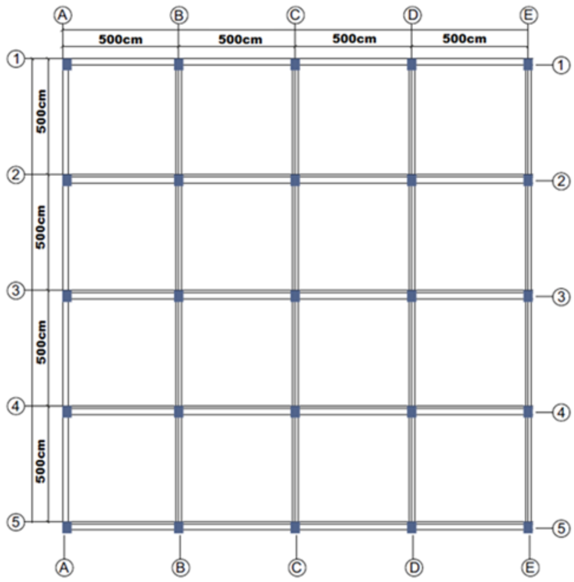

Figure 11. The blueprint of the sample RC building.

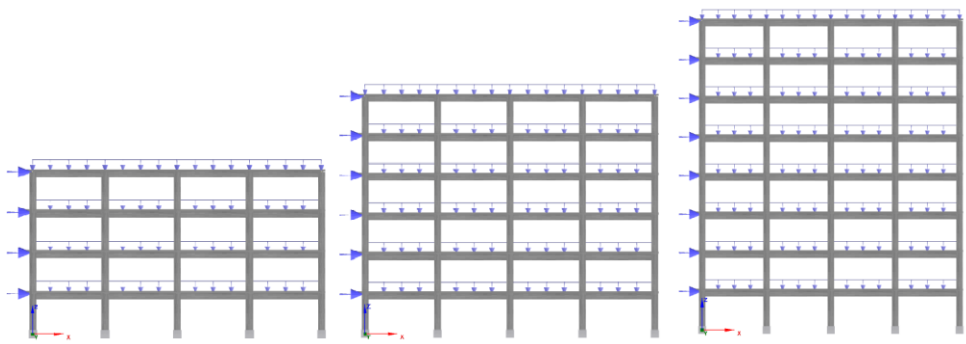

Figure 12. 2D models of the sample RC building for different numbers of stories.

Epicentre locations, loss of life and properties, and magnitudes for some of the most destructive earthquakes that occurred in the seismic history of Iran have been presented in Table 12. Major sources of these data include USGS, ISMN, IIEES, and IRIS.

Table 12. Data of the selected earthquakes in Iran [130–135].

No	Date	Lat.	Lon.	Magnitude			Loss of Life	Damaged Buildings	Loss of Life/ Damaged Buildings	Location
				Mb	Ms	Mw				
1	2003/12/26	29.04	58.33	-	-	6.6	35,000	85%	-	Bam, Iran
2	1990/06/20	36.96	49.41	6.4	7.7	-	40,000–50,000	Nearly all buildings	-	Manjil-Rudbar, Iran
3	1978/09/16	33.37	57.44	6.4	7.4	-	11,000–13,000	>15,000	-	Tabas, Iran
4	1968/08/31	34.02	58.96	-	-	7.2	15,000	>12,000	-	Dasht-e Bayaz, South Khorasan, Iran

Table 13 shows magnitudes, PGA values, and Design Base Accelerations (A(g)) for the calculation of base shear for building structures recommended by the Iranian Code of Practice for Earthquake Resistant Design of Buildings, Standard 2800 [136] for some of the most destructive earthquakes and corresponding seismic zones of Iran.

Table 13. Measured magnitude, PGA values, seismic risk zones, and recommended design base acceleration of selected earthquakes for Iran [126,130–135].

No	Earthquake Location	Station Name	Year	Earthquake Magnitude	Magnitude Type	PGA(g)	Seismic Risk Zone	A(g)
							(As Per IS-2800)	(Design Base Acceleration) (As Per IS-2800)
1	Manjil, Iran	Qazvin	1990	7.37	Mw	0.130	Very High	0.35
2	Manjil, Iran	Rudsar	1990	7.37	Mw	0.086	Very High	0.35
3	Manjil, Iran	Rudsar	1990	7.37	Mw	0.538	Very High	0.35
4	Tabas, Iran	Tabas	1978	7.35	Mw	0.641	Very High	0.35
5	Bam, Iran	Bam	2003	6.60	Mw	0.970	High	0.30

The measured PGA values for the first two recorded earthquakes in the considered stations for Iran are considerably lower than the recommended PGA values, and it can be said that the seismic risk for these locations represents a sufficient level. However, the measured PGA values for the last three earthquakes exceeded the recommended PGA values considerably. This clearly reveals Iran's high potential for seismic risk, taking into account the high population of the selected cities.

3. RC Building Models for Numerical Analysis

Earthquake-resistant rules aim to construct buildings that do not experience damage under an expected ground motion level. Structural analyses for a total of five earthquake locations from each country, whose PGA values can be reached. The Seismostruct software was used for numerical analysis [137]. Pushover analyses were used in these analyses for the sample RC building models with four-storey, six-storey, and eight-storey using obtained data. The story plan was taken in the same way in all analyzed buildings and is shown in Figure 11.

The infrmFBPH (force-based plastic hinge frame elements) were used for structural elements such as beams and columns while creating all building models. These elements model force-based extensional flexibility and limit plasticity to only a finite length. The ideal number of fibers in the section should be sufficient to model the stress-strain distribution in the section [138]. A total of 100 fiber elements are defined for the selected sections. This value is sufficient for such partitions. Plastic-hinge length (Lp/L) was selected as 16.67%. The boundary conditions of the column were set in accordance with the cantilever boundary conditions, which resulted in a fully fixed column footing and a free top end. The boundary condition of the footings was fixed on the ground.

The storey height in all building models is considered as 3 m. The sample RC building was chosen symmetrically in the X and Y directions, and each of this span is 5 m in each direction was considered. The applied loads and 2D and 3D building models are shown for four-storey, six-storey, and eight-storey in Figures 12 and 13, respectively.

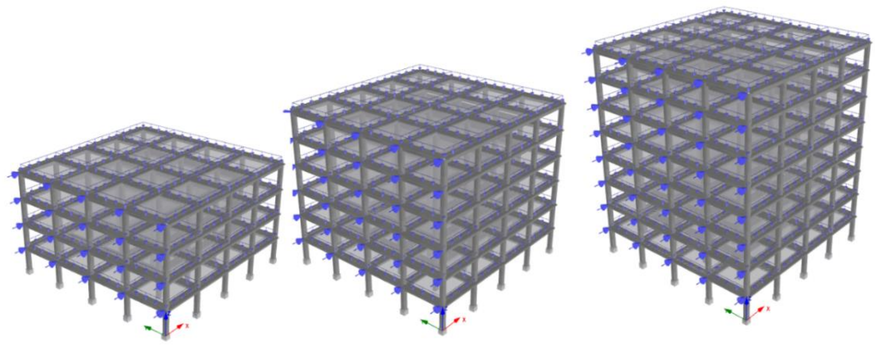

Figure 13. 3D models of the RC building for different numbers of stories.

The structural properties of the RC building model are shown in Table 14.

Table 14. Analysis of input data for the structural models.

Parameter		Value
Concrete Grade		C20
Reinforcement Grade		S420
Beams		250 × 600 mm
Floor height		120 mm
Cover thickness		25 mm
Columns		400 × 500 mm
Longitudinal reinforcement	Corners	4Φ20
	Top bottom side	4Φ16
	Left right side	4Φ16
Transverse reinforcement		Φ10/100
Material model (steel)		Menegotto-Pinto [139]
Material model (Concrete)		Mander et al. nonlinear [140]
Constraint type		Rigid diaphragm
Local soil class		ZD
Incremental loads		5.0 kN
Permanent loads		5.0 kN/m
Target-displacement (4-storey)		0.24 m
Target-displacement (6-storey)		0.36 m
Target-displacement (8-storey)		0.48 m
Importance class		IV
Damping ratio		5%

In performance-based earthquake engineering, it is critical to estimate target displacements for damage estimation when certain performance limits of structural members are reached. The limit states envisaged in Eurocode 8 (Part 3) [141,142] were taken into account for damage estimation in this study. The target displacements are presented in Figure 14 and the description of these states are shown in Table 15.

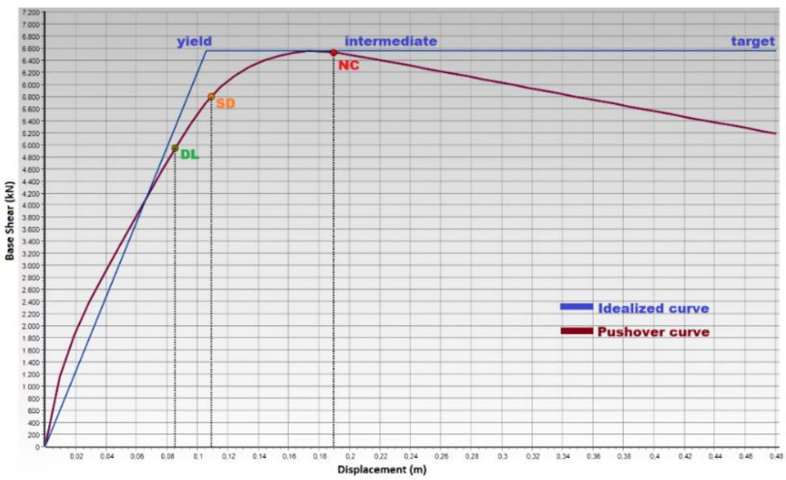

Figure 14. Target displacements on idealized curves/typical pushover.

Table 15. Suggested limit states in Eurocode 8 (Part 3) [141,142].

Limit State	Description	Return Period (Year)	Probability of Exceedance (in 50 Years)
Damage Limitation (DL)	Only lightly damaged, damage to non-structural components is economically repairable	225	0.20
Significant Damage (SD)	Uneconomic to repair, significantly damaged, some residual strength and stiffness, non-structural components damaged,	475	0.10
Near collapse (NC)	Very low residual strength and stiffness, large permanent drift but still standing, heavily damaged	2475	0.02

4. Structural Analyses Results

Within the scope of this study, firstly, the natural fundamental periods for the sample building models were obtained from the eigenvalue analysis. The target displacements and base shear forces for all the structural models were obtained for each country, respectively.

4.1. Comparison of Natural Fundamental Periods

In this part, the period values obtained according to the eigenvalue analyses were compared with the empirical ones predicted for each country. The time required for the undamped system to complete one vibration cycle is called the natural vibration period of the system. The more rigid one of the same mass with a single degree of freedom system will have a shorter natural period and a higher natural frequency. Similarly, of two structures of the same stiffness, the heavier (greater mass) has a lower natural frequency and a longer natural period. This value can be obtained both with approximate formulas and as a result of numerical analysis [143–146]. The empirical relations and explanations stipulated in the corresponding design code for each country are given in Table 16. The comparison of these periods with the ones obtained from structural analyses is shown in Table 16. The empirical formulas used in Table 16 are directly taken from the seismic design codes currently used by countries.

Table 16. Comparison of the natural fundamental periods for selected countries.

Country	Number of Storey	Empirical Formula	Empirical Period (s)	Structural Analyses Period (s)	Description
Albania	4 6 8	$T_1 = (0.09.h)/b^{1/2}$	0.242 0.362 0.483	0.402 0.597 0.796	h—the height of the structure (in meters). b—dimension of the building in parallel to the applied forces (in meters).
Bosnia and Herzegovina	4 6 8	$T = C_t \cdot H^{3/4}$	0.484 0.655 0.813	0.402 0.597 0.796	C_t is 0.075 for RC frame structures and H is the total height of the building
Croatia	4 6 8	$T = C_t \cdot H^{3/4}$	0.484 0.655 0.813	0.402 0.597 0.796	C_t is 0.075 for RC frame structures and H is the total building height
Iran	4 6 8	$T = 0.05H^{0.9}$	0.468 0.674 0.873	0.402 0.597 0.796	H is the total building height
Serbia	4 6 8	$T = C_t \cdot H^{3/4}$	0.484 0.655 0.813	0.402 0.597 0.796	C_t is 0.075 for RC frame structures and H is the total building height
Türkiye	4 6 8	$T_{PA} = C_t.\ H_N^{3/4}$	0.645 0.874 1.084	0.402 0.597 0.796	H_N is the building's total height; C_t is the correction coefficient. C_t = 0.1 for RC building frames that built only beams and columns

The fundamental periods obtained from the structural analyses for all countries were constant since the structural characteristics of the sample RC buildings models did not change. Empirically, the smallest period values were obtained for Albania, while the highest periods were obtained for Türkiye. The empirical periods suggested for Albania were lower than the periods obtained from the structural analysis. For the other five countries, the empirically suggested period values were higher than the period values obtained from the structural analyses.

4.2. Comparisons of Limit States

In this study, the target displacement values for the different number of storeys were obtained from the structural analyses for each country, considering the limit states in Eurocode 8 for six different countries. The comparison of target displacements of sample RC models for Albania is given in Table 17.

Table 17. The obtained target displacements of sample RC models for Albania.

No	Date	Location	Number of Storeys	Code Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	26 November 2019	Tirana	4	0.115	0.157	0.295	0.035	0.045	0.088
			6	0.203	0.262	0.459	0.071	0.092	0.164
			8	0.272	0.348	0.604	0.099	0.128	0.221
2	26 November 2019	Durres	4	0.115	0.157	0.295	0.039	0.049	0.099
			6	0.203	0.262	0.459	0.078	0.101	0.179
			8	0.272	0.348	0.604	0.109	0.139	0.242
3	21 September 2019	Tirana	4	0.135	0.182	0.338	0.058	0.082	0.164
			6	0.231	0.298	0.521	0.119	0.155	0.272
			8	0.308	0.395	0.685	0.163	0.209	0.362
4	9 January 1998	Tirana	4	0.115	0.157	0.295	0.164	0.219	0.403
			6	0.203	0.262	0.459	0.273	0.351	0.614
			8	0.272	0.348	0.604	0.362	0.465	0.805
5	15 April 1979	Shkoder	4	0.115	0.157	0.295	0.193	0.257	0.468
			6	0.203	0.262	0.459	0.314	0.405	0.707
			8	0.272	0.348	0.604	0.416	0.534	0.926

The target displacements suggested by the seismic design code for the first three earthquakes in Albania provide target displacements in which the acceleration values measured in earthquakes are taken into account. However, the target displacements predicted for the structure for the last two earthquakes and the target displacements obtained under the effect of the earthquake were exceeded. This suggests that the target displacements are adequately represented for some earthquakes, while it is not sufficient for others.

The comparison of target displacements of sample RC models for Bosnia and Herzegovina is given in Table 18.

Table 18. The obtained target displacements of sample RC models for Bosnia and Herzegovina.

No	Date	Location	Number of Storeys	Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	1969	Bosnia and Herzegovina	4	0.055	0.076	0.154	0.111	0.151	0.284
			6	0.112	0.146	0.257	0.196	0.253	0.443
			8	0.154	0.197	0.342	0.263	0.337	0.584
2	1962	Bosnia and Herzegovina	4	0.055	0.076	0.154	0.145	0.194	0.360
			6	0.112	0.146	0.257	0.245	0.316	0.552
			8	0.154	0.197	0.342	0.326	0.418	0.725
3	1981	Bosnia and Herzegovina	4	0.055	0.076	0.154	0.179	0.237	0.436
			6	0.112	0.146	0.257	0.293	0.378	0.661
			8	0.154	0.197	0.342	0.389	0.499	0.866
4	1969	Bosnia and Herzegovina	4	0.058	0.082	0.164	0.003	0.004	0.007
			6	0.119	0.155	0.272	0.006	0.008	0.014
			8	0.163	0.209	0.362	0.009	0.012	0.020
5	2019	Bosnia and Herzegovina	4	0.096	0.132	0.251	0.013	0.016	0.029
			6	0.175	0.226	0.397	0.026	0.033	0.058
			8	0.235	0.302	0.524	0.036	0.046	0.081

The target displacements suggested by the seismic design code for the first three earthquakes in Bosnia and Herzegovina do not provide target displacements in which the acceleration values measured in earthquakes are taken into account. However, the target displacements predicted for the structure for the last two earthquakes and the target displacements obtained under the effect of the earthquake were not exceeded. This suggests that the target displacements are adequately represented for some earthquakes, while it is not sufficient for others.

The comparison of target displacements of sample RC models for Croatia is given in Table 19.

Table 19. The comparison of target displacements of sample RC models for Croatia.

No	Date	Location	Number of Storeys	Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	2020	Petrinja	4	0.105	0.144	0.272	0.013	0.016	0.029
			6	0.188	0.243	0.426	0.026	0.033	0.058
			8	0.253	0.324	0.562	0.036	0.046	0.081
2	1990	Kraljev Vrh	4	0.095	0.131	0.250	0.019	0.025	0.043
			6	0.174	0.225	0.395	0.039	0.050	0.087
			8	0.234	0.301	0.522	0.054	0.070	0.121
3	1979	Montenegro	4	0.112	0.160	0.300	0.026	0.033	0.057
			6	0.206	0.266	0.467	0.052	0.067	0.118
			8	0.276	0.352	0.614	0.072	0.093	0.161
4	1979	Montenegro	4	0.104	0.142	0.269	0.013	0.016	0.029
			6	0.186	0.241	0.422	0.026	0.033	0.058
			8	0.250	0.321	0.556	0.036	0.046	0.081
5	1978	Imotsk	4	0.104	0.142	0.269	0.010	0.012	0.021
			6	0.186	0.241	0.422	0.019	0.025	0.043
			8	0.250	0.321	0.556	0.027	0.035	0.060

The target displacements suggested by the seismic design code for all earthquakes in Croatia provide target displacements in which the acceleration values measured in earthquakes are taken into account. It shows that the seismic hazard is adequately taken into account in the structural analysis for all the selected earthquakes.

The comparison of target displacements of sample RC models for Serbia is given in Table 20.

The target displacements suggested by the seismic design code for all earthquakes in Serbia provide target displacements in which the acceleration values measured in earthquakes are taken into account. It shows that the seismic hazard is adequately taken into account in the structural analysis for all selected earthquakes.

The comparison of target displacements of sample RC models for Türkiye is given in Table 21. As seen in Table 21, the target displacements suggested by the seismic design code for the first, second, and fifth earthquakes for Türkiye provide target displacements in which the acceleration values measured in earthquakes are taken into account. However, the target displacements predicted for the other earthquakes for these structures were exceeded. This suggests that the target displacements are adequately represented for some earthquakes, while it is not sufficient for others.

Table 20. The obtained target displacements of sample RC models for Serbia.

No	Date	Location	Number of Storeys	Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	2010	Gruža	4	0.067	0.094	0.186	0.019	0.025	0.043
			6	0.133	0.173	0.304	0.039	0.050	0.087
			8	0.181	0.232	0.403	0.054	0.070	0.121
2	2010	Novi Pazar	4	0.067	0.094	0.186	0.003	0.004	0.007
			6	0.133	0.173	0.304	0.006	0.008	0.014
			8	0.181	0.232	0.403	0.009	0.012	0.020
3	2010	Kokin Brod	4	0.048	0.063	0.132	0.003	0.004	0.007
			6	0.098	0.128	0.226	0.006	0.008	0.014
			8	0.136	0.174	0.302	0.009	0.012	0.020
4	2010	Žagubica	4	0.048	0.063	0.132	0.003	0.004	0.007
			6	0.098	0.128	0.226	0.006	0.008	0.014
			8	0.136	0.174	0.302	0.009	0.012	0.020
5	1990	Novi Pazar	4	0.067	0.094	0.186	0.003	0.004	0.007
			6	0.133	0.173	0.304	0.006	0.008	0.014
			8	0.181	0.232	0.403	0.009	0.012	0.020

Table 21. The obtained target displacements of sample RC models for Türkiye.

No	Date	Location	Number of Storeys	TBEC-2018, Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	23 Octorber 2011	Van	4	0.164	0.219	0.402	0.058	0.083	0.167
			6	0.272	0.351	0.612	0.121	0.156	0.276
			8	0.361	0.463	0.803	0.165	0.211	0.366
2	1 May 2003	Bingöl	4	0.278	0.365	0.656	0.218	0.289	0.524
			6	0.435	0.560	0.975	0.350	0.451	0.786
			8	0.573	0.735	1.275	0.463	0.594	1.029
3	12 November 1999	Düzce	4	0.256	0.337	0.607	0.371	0.484	0.862
			6	0.404	0.520	0.906	0.568	0.730	1.270
			8	0.532	0.683	1.184	0.745	0.956	1.657
4	13 March 1992	Erzincan	4	0.180	0.239	0.439	0.206	0.273	0.495
			6	0.295	0.380	0.664	0.332	0.428	0.746
			8	0.391	0.502	0.870	0.439	0.563	0.977
5	17 Augst 1999	Kocaeli	4	0.306	0.401	0.718	0.164	0.219	0.402
			6	0.475	0.611	1.064	0.272	0.351	0.612
			8	0.625	0.801	1.389	0.361	0.463	0.803

The comparison of target displacements of sample RC models for Iran is shown in Table 22.

The target displacements suggested by the seismic design code for the first two earthquakes for Iran provide target displacements in which the acceleration values measured in earthquakes are taken into account. However, the target displacements predicted for the structure for the last three earthquakes and the target displacements obtained under the effect of the earthquake were exceeded. This suggests that the target displacements are adequately represented for some earthquakes, while it is not sufficient for others.

In addition to the structural analysis according to the number of stories, the local soil class change was taken into account. The structural analyzes were carried out only for the four-storey RC building model since it is aimed to reveal the soil class effects. In the previous structural analyses, the ZD soil class envisaged in Eurocode-8 was taken into account. In this section, structural analyzes were made separately for each earthquake by choosing the ZA class in the same code. The recommended properties in the code for these two soil types are given in Table 23. The target displacements for selected earthquakes for each country for the ZA soil class type were given in Table 24.

Table 22. The obtained target displacements of sample RC models for Iran.

No	Date	Location	Number of Storeys	IS-2800 (Suggested)			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	1990	Qazvin	4 6 8	0.140 0.238 0.317	0.188 0.307 0.407	0.349 0.536 0.705	0.031 0.062 0.086	0.039 0.079 0.110	0.072 0.141 0.191
2	1990	Rudsar	4 6 8	0.140 0.238 0.317	0.188 0.307 0.407	0.349 0.536 0.705	0.028 0.056 0.078	0.035 0.072 0.100	0.062 0.127 0.173
3	1990	Rudsar	4 6 8	0.140 0.238 0.317	0.188 0.307 0.407	0.349 0.536 0.705	0.231 0.369 0.487	0.306 0.475 0.625	0.553 0.828 1.083
4	1978	Tabas	4 6 8	0.140 0.238 0.317	0.188 0.307 0.407	0.349 0.536 0.705	0.282 0.441 0.580	0.370 0.567 0.745	0.665 0.988 1.291
5	2003	Bam	4 6 8	0.115 0.203 0.272	0.157 0.262 0.348	0.294 0.459 0.604	0.442 0.670 0.878	0.576 0.861 1.127	1.022 1.498 1.953

Table 23. The characteristics of local soil types considered in this study [147].

Ground-Type	Description of Stratigraphic Profile	Parameters		
		$V_{s,30}$ (m/s)	N_{SPT} (Blows/30 cm)	C_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	>800	—	—
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	<180	<15	<70

Table 24. Comparison of target displacements for the ZA soil class type.

Earthquake No	Country	Location	Number of Storeys	Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1 2 3 4 5	Albania	Tirana Durres Tirana Tirana Shkoder	4 4 4 4 4	0.054 0.054 0.061 0.054 0.054	0.070 0.070 0.079 0.070 0.070	0.121 0.121 0.137 0.121 0.121	0.020 0.022 0.033 0.072 0.083	0.025 0.028 0.042 0.093 0.107	0.044 0.048 0.072 0.161 0.185
1 2 3 4 5	Bosnia and Herzegovina	Banja Luka, Banja Luka Banja Luka, Montenegro Montenegro	4 4 4 4 4	0.030 0.030 0.030 0.033 0.047	0.040 0.040 0.040 0.042 0.060	0.068 0.068 0.068 0.072 0.104	0.052 0.065 0.078 0.002 0.007	0.067 0.083 0.100 0.002 0.009	0.117 0.145 0.173 0.004 0.016
1 2 3 4 5	Croatia	Petrinja Kraljev Vrh Montenegro Montenegro Imotsk	4 4 4 4 4	0.050 0.047 0.055 0.050 0.050	0.065 0.060 0.071 0.064 0.064	0.112 0.104 0.123 0.111 0.111	0.007 0.011 0.014 0.007 0.005	0.009 0.014 0.019 0.009 0.007	0.016 0.024 0.032 0.016 0.012
1 2 3 4 5	Serbia	Gruža Novi Pazar Kokin Brod Žagubica Novi Pazar	4 4 4 4 4	0.036 0.036 0.027 0.027 0.036	0.046 0.046 0.035 0.035 0.046	0.080 0.080 0.060 0.060 0.080	0.011 0.002 0.002 0.002 0.002	0.014 0.002 0.002 0.002 0.002	0.024 0.004 0.004 0.004 0.004
1 2 3 4 5	Türkiye	Van Bingöl Düzce Erzincan Kocaeli	4 4 4 4 4	0.072 0.114 0.106 0.078 0.125	0.092 0.147 0.136 0.100 0.160	0.160 0.254 0.236 0.174 0.277	0.033 0.092 0.149 0.087 0.072	0.042 0.118 0.191 0.112 0.092	0.073 0.205 0.331 0.195 0.160
1 2 3 4 5	Iran	Qazvin Rudsar Rudsar Tabas Bam	4 4 4 4 4	0.063 0.063 0.063 0.063 0.054	0.081 0.081 0.081 0.081 0.070	0.141 0.141 0.141 0.141 0.121	0.023 0.016 0.097 0.116 0.175	0.030 0.020 0.125 0.149 0.225	0.052 0.035 0.216 0.258 0.390

Another parameter chosen in order to put the effect of different structural conditions in common was the importance class of the structure. While the IV class was selected in the previous analysis, it was considered as the II class in the new analysis. The only difference in the initial analysis is the building importance class, all other features remained the same. Selected building importance class characteristics are given in Table 25. The target displacements for selected earthquakes for each country for the II class were given in Table 26.

Table 25. Selected importance classes for buildings [147].

Importance Class	Buildings
II	Ordinary buildings, not belonging to the other categories.
IV	Buildings whose integrity during earthquakes is of vital importancefor civil protection, e.g., hospitals, fire stations, power plants, etc

Table 26. Comparison of target displacements for building important class II.

Earthquake No	Country	Location	Number of Storeys	Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	Albania	Tirana	4	0.074	0.103	0.202	0.025	0.032	0.056
2		Durres	4	0.074	0.103	0.202	0.027	0.035	0.062
3		Tirana	4	0.088	0.121	0.233	0.041	0.053	0.109
4		Tirana	4	0.074	0.103	0.202	0.109	0.147	0.279
5		Shkoder	4	0.074	0.103	0.202	0.129	0.175	0.326
1	Bosnia and Herzegovina	Banja Luka,	4	0.039	0.05	0.101	0.07	0.099	0.194
2		Banja Luka	4	0.039	0.05	0.101	0.094	0.130	0.248
3		Banja Luka,	4	0.039	0.05	0.101	0.119	0.161	0.302
4		Montenegro	4	0.041	0.053	0.109	0.002	0.003	0.005
5		Montenegro	4	0.06	0.085	0.171	0.009	0.011	0.02
1	Croatia	Petrinja	4	0.066	0.094	0.185	0.009	0.011	0.02
2		Kraljev Vrh	4	0.059	0.085	0.170	0.014	0.018	0.031
3		Montenegro	4	0.075	0.105	0.205	0.018	0.024	0.041
4		Montenegro	4	0.065	0.093	0.183	0.009	0.011	0.02
5		Imotsk	4	0.065	0.093	0.183	0.007	0.009	0.015
1	Serbia	Gruža	4	0.046	0.059	0.124	0.014	0.018	0.031
2		Novi Pazar	4	0.046	0.059	0.124	0.002	0.003	0.005
3		Kokin Brod	4	0.034	0.044	0.085	0.002	0.003	0.005
4		Žagubica	4	0.034	0.044	0.085	0.002	0.003	0.005
5		Novi Pazar	4	0.046	0.059	0.124	0.002	0.003	0.005
1	Türkiye	Van	4	0.108	0.147	0.278	0.042	0.054	0.11
2		Bingöl	4	0.190	0.252	0.46	0.147	0.198	0.365
3		Düzce	4	0.174	0.232	0.425	0.256	0.337	0.607
4		Erzincan	4	0.12	0.162	0.304	0.138	0.186	0.345
5		Kocaeli	4	0.21	0.278	0.504	0.108	0.147	0.278
1	Iran	Qazvin	4	0.091	0.126	0.240	0.030	0.038	0.700
2		Rudsar	4	0.091	0.126	0.240	0.020	0.025	0.044
3		Rudsar	4	0.091	0.126	0.24	0.157	0.21	0.386
4		Tabas	4	0.091	0.126	0.240	0.192	0.256	0.466
5		Bam	4	0.074	0.103	0.202	0.307	0.403	0.721

In addition to all these different structural conditions, the concrete class is also considered as a variable. While previous analyzes were performed for the C20 concrete class, new structural analyzes considered the C12 concrete class with lower properties for all load-bearing elements. The target displacements for selected earthquakes for each country for the C12 concrete class were given in Table 27.

Table 27. Comparison of target displacements for the C12 concrete class.

Earthquake No	Country	Location	Number of Storeys	Suggested			Measured		
				DL (m)	SD (m)	NC (m)	DL (m)	SD (m)	NC (m)
1	Albania	Tirana	4	0.124	0.167	0.311	0.038	0.049	0.096
2		Durres	4	0.124	0.167	0.311	0.042	0.054	0.107
3		Tirana	4	0.144	0.193	0.356	0.063	0.089	0.175
4		Tirana	4	0.124	0.167	0.311	0.175	0.232	0.424
5		Shkoder	4	0.124	0.167	0.311	0.205	0.272	0.492
1	Bosnia and Herzegovina	Banja Luka,	4	0.059	0.082	0.164	0.119	0.161	0.3
2		Banja Luka	4	0.059	0.082	0.164	0.154	0.206	0.379
3		Banja Luka,	4	0.059	0.082	0.164	0.19	0.252	0.458
4		Montenegro	4	0.063	0.088	0.175	0.004	0.005	0.008
5		Montenegro	4	0.104	0.141	0.266	0.014	0.018	0.031
1	Croatia	Petrinja	4	0.113	0.153	0.287	0.014	0.018	0.031
2		Kraljev Vrh	4	0.103	0.14	0.264	0.021	0.027	0.047
3		Montenegro	4	0.126	0.17	0.316	0.028	0.036	0.062
4		Montenegro	4	0.112	0.151	0.284	0.014	0.018	0.031
5		Imotsk	4	0.112	0.151	0.284	0.01	0.013	0.023
1	Serbia	Gruža	4	0.073	0.102	0.198	0.021	0.027	0.047
2		Novi Pazar	4	0.073	0.102	0.198	0.004	0.005	0.008
3		Kokin Brod	4	0.052	0.069	0.141	0.004	0.005	0.008
4		Žagubica	4	0.052	0.069	0.141	0.004	0.005	0.008
5		Novi Pazar	4	0.073	0.102	0.198	0.004	0.005	0.008
1	Turkey	Van	4	0.174	0.232	0.423	0.064	0.09	0.177
2		Bingöl	4	0.293	0.385	0.688	0.231	0.305	0.55
3		Düzce	4	0.271	0.355	0.637	0.39	0.509	0.903
4		Erzincan	4	0.191	0.253	0.46	0.218	0.288	0.52
5		Kocaeli	4	0.322	0.422	0.752	0.174	0.232	0.423
1	Iran	Qazvin	4	0.149	0.2	0.367	0.045	0.058	0.118
2		Rudsar	4	0.149	0.2	0.367	0.03	0.039	0.069
3		Rudsar	4	0.149	0.2	0.367	0.245	0.323	0.58
4		Tabas	4	0.149	0.2	0.367	0.297	0.389	0.697
5		Bam	4	0.124	0.167	0.311	0.465	0.605	1.069

4.3. Evaluation of Existing Building Stocks

4.3.1. Albania

According to the Albanian Institute of Statistics (INSTAT) 2001, the Albanian building stock primarily consists of four typologies, namely brick and stone, prefabricated, wood, and other building materials. However, when referring to the recent census of 2011 (INSTAT), information on building materials is not included and houses are classified based on their heights and construction period. Table 28 presents a summary of the Albanian building stock based on existing information (INSTAT 2001) [148]. Accordingly, the 'RC and masonry' type represents the biggest part of the current building stock.

Table 28. Albanian building stock [147].

Material Type	<1945	1945–1960	1961–1980	1981–1990	1991–1995
RC and masonry structures	37416	63870	141170	102198	43324
Prefabricated concrete	-	-	4601	5993	4575
Wooden	462	-	1821	1273	743
Other types	2560	3393	7105	6263	4238

According to the Albanian Institute of Statistics (INSTAT) 2011, one-storey buildings account for 85% of the total building stock corresponding to the accommodation of the half population of the country. They were mostly built with unreinforced masonry and reinforced concrete frames with infill walls. However, the total number of multi-storey houses in Albania is significantly lower compared to one-storey houses, but they shelter the remaining half of the population. During the recent earthquake sequences in 2019, multi-storey buildings were significantly affected, resulting in higher damage in the stricken areas. While the available data given in Table 24 is outdated, they highlight an important indicator (design code) on the construction year of the housings. An important portion of the current building stock was built before 1990 showing a lack of adequacy to the modern code requirements [17]. Therefore, it is likely that there were deficiencies affecting the seismic performance of buildings constructed in this time period.

4.3.2. Bosnia and Herzegovina

According to the available data for Bosnia and Herzegovina (CBS 2013) [149], it is noted that, from the total of 1,078,156 buildings, 60.72% are structures made of brick, stone, and concrete, 35.08% of reinforced concrete and steel frames and only 4.20% of wood and light material [73]. The majority of the structures are either confined masonry buildings or RC buildings constructed according to the regulations from 1981 (35%), considering age distribution from 1981–1990. Since 1991 Prestandards (ENV) have been applied and this accounts for 18.9% of all buildings being either RC buildings or confined masonry buildings. The application of Eurocode 8 started after 2006 accounting for 2.0% of all buildings (as well as RC buildings or confined masonry buildings). Masonry structures with rigid floors were mainly constructed in the period from 1971 to 1980, amounting to 33.6% of all structures built in Bosnia and Herzegovina. Brick masonry structures with rigid RC slabs were built in the period from 1946 to 1970, amounting to 6.6% of all the structures built in Bosnia and Herzegovina. The remaining 4% is devoted to stone masonry buildings with wooden floors constructed before 1945. Seismic vulnerability assessment of structures in Bosnia and Herzegovina is mainly done by individual researchers [150–153]. At the moment, Bosnia and Herzegovina does not have a well-organized and efficient database of structures and building's typologies. Several studies were conducted to determine the vulnerability of buildings in several cities of Bosnia and Herzegovina, like Banja Luka and Sarajevo [74]), Visoko [154], and Tuzla [155]. For the first time, the specific site and its influence on the vulnerability were taken into consideration in the Tuzla region [155]. Currently, 700 structures in the city of Sarajevo are being examined and a database is being created [156]. Based on all this preliminary analysis, it is clear that most of the existing building stock in Bosnia and Herzegovina does not possess sufficient resistance to ground motions that may be expected in this region. It is necessary to construct a detailed database taking into account all the data required to conduct adequate seismic assessments and perform a seismic risk assessment. Without this database and conducted calculations, it is not possible to construct an effective disaster management plan.

4.3.3. Croatia

According to the 2011 Census, the total number of dwellings in Croatia by year of construction was 1,496,558. Of that, 13.2% were built before 1945, which means that they did not follow any building codes. Building design and construction in Croatia did not follow earthquake-resistant building rules until 1948 [157].

Masonry houses used timber floor constructions until 1920. Most of these structures were constructed between 1860 and 1920 and are now part of Croatia's historic town centers, most of which are categorized as historical heritage. These structures were not intended to withstand significant horizontal ground motions (e.g., earthquakes). After 1930, the first semi-prefabricated RC floors were installed, followed by monolithic RC floors in 1964. After the Skopje earthquake in 1963, the first seismic building codes were developed and later modified. In addition, following the earthquake in Skopje in 1963, masonry structures throughout the former Yugoslavia were erected systematically using horizontal tie-beams and vertical tie-columns to achieve confined masonry. The load-bearing system in reinforced concrete structures (RC frames and RC shear walls) was built in accordance with the seismic regulations enacted in 1964 (following the 1963 Skopje earthquake) and 1981 (following the 1979 Montenegro (coast) earthquake). Eurocodes were gradually adopted as voluntary structural design norms between 1992 and 1998. Due to the challenges associated with the harmonization of new standards with old national legislation at the time, they kept a pre-standards status (ENV label). The final version was introduced in 1998, with the European standard (EN label), but the ultimate implementation began in 2005 with the adoption of the technical standards for concrete buildings (NN 101/05). Eurocodes were ultimately made a requirement in official usage in 2011, however, pre-standards were still used until the end of 2012 [147].

Predominant structural systems for the buildings in one of the Croatian cities (Osijek) can be summarized as follows [147]: Unreinforced masonry buildings made of old bricks with flexible floors, unreinforced masonry structures with rigid floors, confined masonry structures, RC frame structures, RC shear walls, and RC dual structures. For RC structures, the level of earthquake resistance design should be taken into account.

On December 29, 2020, an earthquake of magnitude 6.4 MW hit Sisak-Moslavina county with an epicentre 3 km southwest of the Croatian city of Petrinja. In the preliminary report on the consequences of the earthquake, a detailed description of the damage to residential low-rise and multi-family residential buildings is presented [158]. The following are the primary sources of damage and failure in low-rise residential buildings: Excessive lateral displacements of flexible timber flooring caused out-of-plane damage or failure of exterior masonry walls at the upper/top levels of older URM structures (built before World War II). Recent masonry structures have rigid floors, but they also suffered damage owing to the lack of vertical reinforcement at the bottom floor level. Due to the extremely high seismic demand, the in-plane damage pattern took the form of diagonal tension cracks in the walls. The major tensile stresses in the walls created by the earthquake surpassed the masonry tensile strength, resulting in the formation of inclined cracks (diagonal tension cracks). In certain situations, the quality of masonry materials and construction appeared to be poor, which was also a source of damage. The primary sources of damage and failure in multi-family residential buildings can be summarized as follows: Excessive lateral displacements of flexible timber flooring caused out-of-plane damage or failure of exterior masonry walls at the upper/top levels of older URM structures (built before World War II). In general, the failure process in low-rise and mid-rise structures is relatively similar.

Many older URM buildings were not properly maintained, and as a result, their condition was poor before the earthquake [159]. The level of damage is thought to have been impacted by the degradation of building materials and components (such as wooden floors and roofing) as well as the use of weak mortar.

Due to extremely high seismic demand, masonry structures with rigid floors built in the 1960s developed in-plane shear cracking at the building's base. The major tensile stresses in the walls created by the earthquake surpassed the masonry tensile strength, resulting in the formation of inclined cracks (diagonal tension cracks). The earthquake caused no structural damage to RC structures; nevertheless, minor damage to non-structural components such as chimneys occurred in several buildings.

4.3.4. Serbia

According to the 2011 Serbian Census of population, household, and dwellings, 85% of all dwellings in Serbia were constructed after 1945, i.e., in the period when there were at least some seismic design codes. Before 2019, the seismic design codes created and implemented in the former Yugoslavia were used. The first seismic design code was published in 1948, but it lacked detailed detailing guidelines for RC and masonry construction. The disastrous earthquakes that struck Skopje in 1963 and Montenegro in 1979 served as turning points in the creation of Yugoslavian seismic design codes. Following the 1963 Skopje Earthquake, the first complete seismic design code was published in 1964. Two years after the 1979 Montenegro earthquake, a new, much more advanced code was published. The seismic design of new structures in Serbia must comply with Eurocode 8—Part 1 [147] as of 2019 [160]. However, although most buildings were constructed after 1945, a recent moderate-size Mw = 5.5 2010 Kraljevo earthquake revealed the vulnerability of the Serbian building stock. It should be noted that reinforced-concrete structures accounted for only 10% of the building stock in the affected area. As expected, buildings with unreinforced brick masonry walls and flexible diaphragms sustained notable damages while properly constructed modern confined masonry buildings remained undamaged. However, numerous one- or two-storey masonry buildings with rigid RC floors and horizontal ring beams suffered severe damage and/or partial collapse due to the inadequate design and construction and/or low-quality building materials and many multi-storey masonry buildings were damaged due to poorly planned and executed renovations and extensions [161]. These findings call for increased efforts toward a more realistic estimation of the vulnerability of the existing building stock in Serbia if one would like to obtain a realistic estimate of the seismic risk.

4.3.5. Türkiye

Most of the existing building stock in Türkiye does not have sufficient resistance to earthquakes. This is clearly seen from the observed damage caused by the recent earthquakes in Türkiye. Earthquake regulations are renewed over time and put into effect, especially after the large-scale loss of life and property [162–164]. Insufficient structural features of the existing building stock play an active role in losses in earthquakes. For this reason, these uninspected buildings, which constitute the majority of the building stock, should be examined, some of them should be strengthened and others should be evaluated within an urban transformation project. The need for low-cost housing as a result of unplanned urbanization due to population growth and migration to big cities in Türkiye has caused both the shift from residential areas to areas with high earthquake hazards and the growth of building stock with weak earthquake safety. Knowing the characteristics of both new buildings and relatively old buildings with weak earthquake safety is of great importance in order to make accurate earthquake risk and loss calculations of settlements. To reduce the damage caused by earthquakes and for effective disaster management, the earthquake risks of existing structures should be calculated realistically. In this context, it is of great importance to know the properties of the building stock that affect the earthquake behavior well, to make the risk and loss calculations correctly. In this respect, examining the Turkish building stock in terms of time and space is of great importance in earthquake risk calculations.

4.3.6. Iran

After the 1990 Manjil mega-earthquake, one of the biggest and most fatal incidents in the seismic history of Iran that claimed the lives of more than 40,000 people, several investigations were initiated by many researchers on the analysis of the damages and vulnerability of the building stocks in the similar earthquake-stricken areas. The catastrophe caused a turning point in the analysis and design approaches of buildings and several modifications to the Iranian Code of Practice for Earthquake Resistant Design of Buildings, Standard 2800, and the definition of many research programs [165]. A study was conducted on three earthquakes in Iran, including the 2003 Bam earthquake, the 2005 Zarand earthquake, and the 2006 Silakhor earthquake by Mahdi and Mahdi [166]. The Bam earthquake has been the biggest earthquake with the highest rate of fatalities in the country after the 1990 Manjil earthquake, in which more than 53,000 buildings were destroyed while the remaining structures were severely damaged [167]. Damage analysis of buildings after the 2003 Bam earthquake by Mostafaei and Kabeyasawa [168] showed that building stock in this city at the time of the earthquake was comprised of adobe, masonry (reinforced and unreinforced), steel, and concrete buildings. As shown in this study, the major building system type has been unreinforced masonry (for around 68% of the buildings), and only 24% of the buildings in the city had been designed seismic-resistant, having a structural system as per the Iranian seismic design code of practice. This is while even the remaining steel or reinforced concrete (RC) damaged buildings suffered from inappropriate structural design, low-quality construction practices, and insufficient implementation controls. Buildings that have been destroyed or heavily damaged in the other two earthquakes have been mostly adobe or unreinforced masonry buildings, while inadequate seismic-resistant structural systems or unsuitable construction practices were recognized as the main reason for damages. According to the 2016 national census conducted by the Statistical Centre of Iran (SCI) on the residential building stock and different building types, it is understood that the five main types of building systems, i.e., concrete, steel, masonry, adobe, and wooden, could be recognized in Iran. The census shows that masonry, steel, and concrete structures contain 39%, 30%, and 27% of the building stock, respectively. The remaining building types were either wooden or adobe, with 0.14% and 4%, respectively, while the remaining 0.26% had no recognizable system [169]. The study by Bastami et al. [169] which proposes new seismic vulnerability models for building stocks in Iran, shows a considerable change in newer versions of the Iranian Code of Practice for Earthquake Resistant Design of Buildings, Standard 2800, in terms of response factor for calculating base shear in the equivalent static method. These revisions as well as other stricter regulations and modifications for the design and construction of seismic-resistant buildings are in line with the above-mentioned started programs and initiatives for more protection of structures in Iran.

5. Results and Conclusions

Both the seismic parameters and the expected target displacements from the structures have been obtained by considering five earthquakes that occurred in six different countries with different seismic risks within the scope of the study. The highest PGA value for all considered earthquakes was obtained in the 2003 Bam (Iran) earthquake and is 0.970 g. The lowest measured PGA was obtained as 0.01 g for the Serbian earthquakes. While the measured PGA's for Croatia and Serbia provided the recommended PGA's, the recommended PGA values for Türkiye, Bosnia and Herzegovina, Iran and Albania were exceeded. PGA values were compared, considering the standard design earthquake with a 10% exceedance of probability in 50 years (repetition period of 475 years). Therefore, it is possible that these values can be met with the consideration of earthquakes with a larger repetition period. Considering the largest earthquake data as the ground motion level in regions with high seismicity risk means that the seismicity risk can be adequately represented.

The selected earthquake range in Albania is between 5.4–6.9. Medium-sized earthquakes are mostly in the range of 0.1–0.2 g. However, the acceleration of the 5.4 magnitude earthquake that occurred in Tirana in 1988 was recorded as very high (0.4 g), exceeding the expected acceleration value (0.28–0.3 g). Two earthquakes, one moderate (5.7) and the other large (6.9) were selected in Bosnia and Herzegovina. The first selected earthquake exceeded the expected acceleration value (0.17 g) at nearby stations and took values in the range of 0.29–0.43 g. However, the 6.9 magnitude earthquake created an acceleration value (0.01–0.4 g) far below the expected acceleration value (0.18–0.26 g) at stations approximately 200 km away. In three different earthquakes selected in Croatia, a small (4.9) earthquake, however, close to the recording station (6.4 km) created an acceleration of 0.0 g. The acceleration value created by the 6.4 magnitude earthquake 60 km away from the station was 0.04 g. The 6.9 magnitude earthquake that occurred in Montenegro in 1979 had an acceleration of 0.08 g in Dubrovnik, 105 km away, and 0.04 g in Makarska, 208 km away. All of the recorded accelerations are considerably lower than the expected acceleration values. The earthquakes considered in Serbia are medium-sized, and the distances of the earthquakes to the acceleration stations are also high. Moreover, the places where the stations are located are rocky. For this reason, the acceleration values formed were quite low. The lowest of the five earthquakes selected that occurred in Türkiye is 6.3 and the highest is 7.4. It is quite interesting that three earthquakes greater than 7 produce very different accelerations from each other. The lowest acceleration was recorded in Van (M_w= 7.2) with 0.182 g and Düzce (M_w = 7.2) with 0.823 g. However, very high accelerations were observed in Erzincan (M_w = 6.8) earthquakes in 1992 and Bingöl (M_w = 6.3) earthquakes in 2003 (Bingöl 0.511 g and Erzincan 0.485 g). One of the main factors in recording very high acceleration values is the proximity of the recording station to the earthquake focus and the other is ground conditions. It is seen that very high acceleration values were recorded in three different earthquakes in Iran. The 7.37 magnitude earthquake that occurred in Manjil in 1990 was recorded differently at different stations. Accordingly, the acceleration value of 0.13 g in Qazvin, 0.086 g in Rudsar, and 0.538 g at the other station in Rudsar show how different geological conditions affect the acceleration value. The acceleration of the 7.35 magnitude earthquake that occurred in Tabas in 1978 was recorded as 0.64 g, and the acceleration of the 6.6 magnitude earthquake that occurred in Bam in 2003 was recorded as an extraordinarily large 0.97 g. It is clear that the very loose soil structure of the city of Bam played the most important role in such magnification of the acceleration value.

The highest loss of life/damaged buildings ratio was found as 0.24 for 17.08.1999 Türkiye (İzmit) and the lowest value was determined as 0.0006 for 26.11.2019 Albania (Durrës). While the highest loss of life among all earthquakes was 17,480 in the 17.08.1999 Türkiye (İzmit) earthquake, the most building damage occurred in the Albania (Durrës) earthquake of 26.11.2019 with ~90000 buildings.

In order to reveal the effect of different structural conditions within the scope of this study, the number of storeys, local soil class, building importance class, and concrete class were chosen as variables. There is complete agreement between the target displacements obtained for all variables. The target displacements increased for three different limit conditions as the number of storeys in the building increased. In the case of weak local soil properties, the target displacements were obtained larger. The values obtained for ZA are lower than the values obtained for ZD. At the same time, target displacements were found to be larger in buildings that were required to be used after the earthquake. The displacements obtained for the building importance class IV are larger than those obtained for the II. class. As the strength of the concrete decreased, the target displacements expected from the structure increased. This once again reveals that buildings with weak earthquake vulnerability require larger displacements.

However, it was examined whether the seismic risks taken into account for different countries are adequately represented. In this context, since the seismicity elements of each country differ, the losses resulting from the earthquakes vary. Therefore, it is obvious that the realistic determination of the seismic risk will result in a more realistic result with the performance levels expected from the structures. In this respect, the building stock characteristics and local ground conditions also directly affect the losses. The vulnerability of the existing building stock increases the structural damage.

Earthquakes occur in fragile parts of the earth's crust due to their formation mechanism. Loose layers near the surface cannot be a source of earthquakes in this sense. However, since such areas are areas of weakness, they allow the incoming tremor to reach the surface easily and stand out because they are geologically highly impacted areas. In this study, it is observed that the earthquakes selected in countries other than Bosnia and Herzegovina and Croatia occur under the influence of geological conditions. Selected earthquakes in Albania are mostly in Durres, Shkoder, and Tirana. The depression areas formed with the neotectonic uplift that started in the Pliocene period in Albania led to the formation of Quaternary lakes and plains. In these grabens, the thickness of which reaches 200 m, unstable soil formations at the swamp level cause earthquakes to be more effective [170]. In Serbia, mainly earthquakes occurred in Kraljevo. This area is in the current alluvial and Tertiary flysch structure. The second important earthquake zone is the Pec zone, which is also the flysch zone. Therefore, it can be said that earthquakes occurring in these regions are based on weak geological conditions. Almost all the earthquakes selected in Türkiye have occurred in the current alluvial areas (Erzincan, Kocaeli, Düzce, Bingöl, Van). Plain regime areas created by very thick alluvial structures and active tectonism continue to be sources of earthquakes. The Bam and Manjil earthquakes, which were selected from the earthquakes that occurred in Iran, were effective in the current alluvial basin-type areas.

The reason for the occurrence of earthquakes in these areas can be considered as specific geological conditions.

Buildings constructed in loose and unstable ground conditions are the most vulnerable to earthquakes. For this purpose, it is necessary to choose the soil-building interaction correctly. Almost all the earthquakes selected in this article, which are considered important in the country where they occurred due to the damage caused, have resulted in severe damage due to incompatibility. One of the main purposes of this study is to show that the damages caused by earthquakes without borders are based on similar faults.

It is important to construct buildings in accordance with earthquake-resistant building design guidelines in earthquake-prone regions against the possibility of the recurrence of earthquakes that cause significant damage. This depends on the correct application of earthquake-resistant building design principles during the design and construction stages. The application of earthquake-resistant building design principles together with adequate supervision can be seen as the first step in minimizing the problems, both during the project and construction phases. In addition, the existing building stock should be determined quickly and reliably, and then strengthening and demolition procedures should be decided in buildings that do not have sufficient earthquake performance. At this point, the number of weak buildings under the effect of earthquakes should be minimized by utilizing urban transformation.

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