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Seismic risk for Croatia: overview of research activities and present assessments with guidelines for the future

Authors:

Assoc.Prof. Josip Atalić, PhD. CE
University of Zagreb
Faculty of Civil Engineering
Department of Engineering Mechanics
atalic@grad.hr

Assist.Prof. Marta Šavor Novak, PhD. CE
University of Zagreb
Faculty of Civil Engineering
Department of Engineering Mechanics
msavor@grad.hr

Assist.Prof. Mario Uroš, PhD. CE
University of Zagreb
Faculty of Civil Engineering
Department of Engineering Mechanics
uros@grad.hr

Subject review

Josip Atalić, Marta Šavor Novak, Mario Uroš

Seismic risk for Croatia: overview of research activities and present assessments with guidelines for the future

An overview of numerous methodologically different risk assessments, including sporadic individual initiatives, is presented from the perspective of a leading expert for earthquake risk assessments for Croatia. The aim of the paper is to evaluate and discuss contributions of each of the assessments, but also to caution about their deficiencies i.e. limitations. A common methodology for estimating seismic risk is described by analysing each of its factors, by providing an overview of current research in Croatia and worldwide, and by offering guidelines for further strategic actions, as all existing results reveal that earthquake is an unacceptable risk for Croatia.

Key words:
seismic risk, seismic hazard, exposure, vulnerability, strategy, mitigation of effects

Pregledni rad

Josip Atalić, Marta Šavor Novak, Mario Uroš

Rizik od potresa za Hrvatsku: pregled istraživanja i postojećih procjena sa smjernicama za budućnost

Iz pozicije glavnog izvršitelja za procjene rizika od potresa za Hrvatsku, napravljen je pregled brojnih i metodološki različitih procjena rizika, uključujući nepovezane pojedinačne inicijative. Cilj rada je pozicionirati i osvrnuti se na doprinose svake od procjena, ali i upozoriti na manjkavosti odnosno ograničenja. Opisana je i uobičajena metodologija analizirajući svaki od faktora seizmičkog rizika, dajući pregled sadašnjeg stanja istraživanja u Hrvatskoj i u svijetu te nudeći smjernice za daljnje strateško djelovanje jer svi postojeći rezultati ističu potres kao neprihvatljiv rizik za Hrvatsku.

Ključne riječi:
rizik od potresa, seizmički hazard, izloženost, oštetljivost, strategija, umanjenje posljedica

Übersichtsarbeit

Josip Atalić, Marta Šavor Novak, Mario Uroš

Überblick über die Erdbebenrisikoforschung und -Bewertung für Kroatien mit Leitlinien für die Zukunft

Ausgehend von der Position des Hauptausführenden für Erdbebenrisikobewertungen für Kroatien wurde ein Überblick über zahlreiche und methodisch unterschiedliche Risikobewertungen einschließlich nicht verbundener Einzelinitiativen gegeben. Ziel der Arbeit ist es, die Beiträge der einzelnen Bewertungen zu positionieren und auf sie einzugehen, aber auch auf die Mängel und Einschränkungen hinzuweisen. Es wird die übliche Methodik beschrieben, indem die einzelnen seismischen Risikofaktoren analysiert werden, ein Überblick über den aktuellen Stand der Forschung in Kroatien und weltweit gegeben wird und Leitlinien für weitere strategische Maßnahmen bereitgestellt werden, da alle vorliegenden Ergebnisse das Erdbeben als inakzeptables Risiko für Kroatien betonen.

Schlüsselwörter:
Erdbebenrisiko, Erdbebengefahr, Exposition, Schadensempfindlichkeit, Strategie, Schadensminderung

1. Introduction

As a member state of the European Union, Croatia has adopted numerous obligations, including those related to the field of disaster risk management. In accordance with Article 6 of the Decision 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism, member countries were required to submit disaster risk assessment summaries to the European Commission (EC) by 22 December 2015. In 2014, Croatian Government issued the Decision to start the procedure for fulfilment of appropriate objectives by which all relevant institutions in Croatia were invited to take actions with respect to risks under their jurisdiction, and lead executives were selected for individual risks. The Faculty of Civil Engineering of the University of Zagreb took its responsibility and became the lead executive for preparation of the seismic risk assessment. The initial step was made in 2015 when a report entitled *Disaster risk assessment for the Republic of Croatia – Earthquake risk* [1] was prepared (described in Section 3.4). With this assessment, the seismic risk together with potential negative impacts from other two natural hazards: flood and fire risks, was rated as unacceptable for Croatia. In 2018, the ensuing risk management process continued with *Assessment of the risk management capability for the Republic of Croatia*, while the *Disaster risk assessment for the Republic of Croatia – earthquake risk* was updated and upgraded to high-level [2] (described in Section 3.8).

Although individual studies on earthquake risk assessment in Croatia had started long before the EC requirement, they were carried out periodically and unsystematically. Several risk assessments are currently available based on different methodological approaches and conducted by experts from various disciplines what can be confusing for the community. One of the aims of this paper is to provide a high-level overview of the available risk assessment studies in Croatia (Section 3), to analyse and critically evaluate each of them, and to put into perspective their contributions. In addition, the paper offers a wider perspective with regard to connected complementary activities, pointing out numerous challenges (problems) encountered in Croatia which pose a serious obstacle to a more reliable seismic risk assessment. Despite potential inconsistencies and shortcomings, all these risk assessment studies point to potentially disastrous consequences, which largely exceed current capacity in Croatia to deal with will them effectively. Similar conclusions were drawn during the 7th conference of Croatian Platform for Disaster Risk Reduction, where it was concluded that seismic hazard poses an unacceptable risk for Croatia [3].

Accurate prediction of the potential consequences relies first of all on the analyses of the observations from historic strong earthquakes, when such information is available. Earthquake epicentres are usually clustered in areas that have already been affected by seismic activity. Such are the two catastrophic earthquakes with intensity X° on the MCS scale (Mercalli-Cancani-Sieberg) recorded in Croatia. The earthquake on the island of Pag of year 361 AD, when the Roman settlement of Cissa actually collapsed into the sea, and the 1667 Dubrovnik earthquake with about 3,000 fatalities. Additional 21 earthquakes with IX° MCS intensity have also been recorded. Known earthquakes epicentres in Croatia from 373 BCE to 2015 together with magnitude scales are shown in Figure 1 [4]. The fact that earthquakes are not just historic occurrences is demonstrated by a total 36,733 recorded relatively low intensity earthquakes in Croatia and its surroundings in the period between 2006 and 2015, out of which 37 ranged from 4.0 to 4.9 in magnitude [5].

The most recent strong earthquake in Croatia was the 1996 Ston earthquake with a magnitude of M_L = 6.0 on the Richter scale [6], or MCS intensity of VIII°. Approximately 1900 houses were damaged in this small town and its surroundings within an area of 400 km^2 (Figures 2a and 2b). This earthquake clearly pointed to the numerous challenges Croatia could eventually face in case of an important disaster. This specifically refers: to the difficulties with the assessment of losses following the earthquake, despite the efficient response reaction of engineers [7]; to the emergency response; to the assistance and long-term accommodation provided to disaster victims; and to the long-term recovery process. Since the Ston earthquake occurred in the early post wartime, it failed to trigger increased awareness to the seismic vulnerability and to the lack of preventive measures with regard to future earthquakes, especially in some of the bigger urban centres such as Zagreb, Split, Rijeka or Dubrovnik [8]. The last destructive earthquake in a big city was the 1880 Zagreb earthquake with intensity of VIII° and epicentre in the area of Medvednica. The City of Zagreb was practically devastated by this event, with almost every building damaged to a some extent (damage to 1758 houses was officially reported), with about 13 % collapse rate (Figures 2c and 2d). At that time, Zagreb had less than 30,000 inhabitants and many of them left because of the lack of accommodation capacities and freezing winter [9].

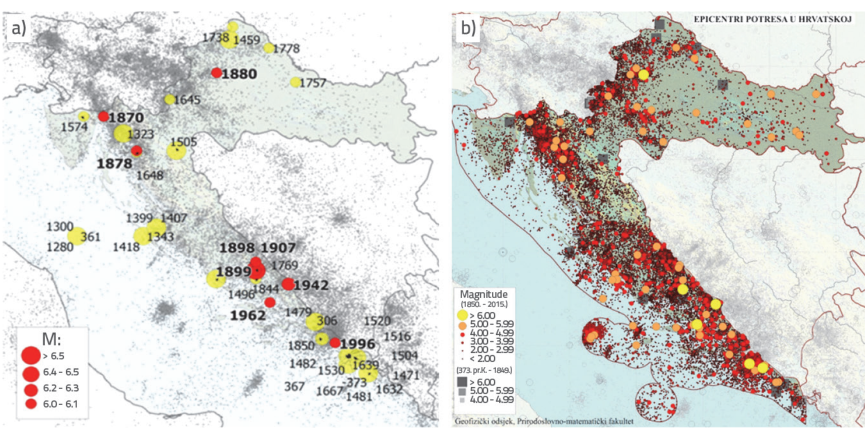


Figure 1. Epicentres of earthquakes in Croatia from 373 BCE to 2015 [4, 5]

As the current demographic crisis due to emigration is one of the most sensitive issues in Croatia, another catastrophic earthquake, involving considerable destruction to the building stock and workplace, could further encourage negative trends and impair the fragile economic, social and political stability of the country [10]. The actual readiness,

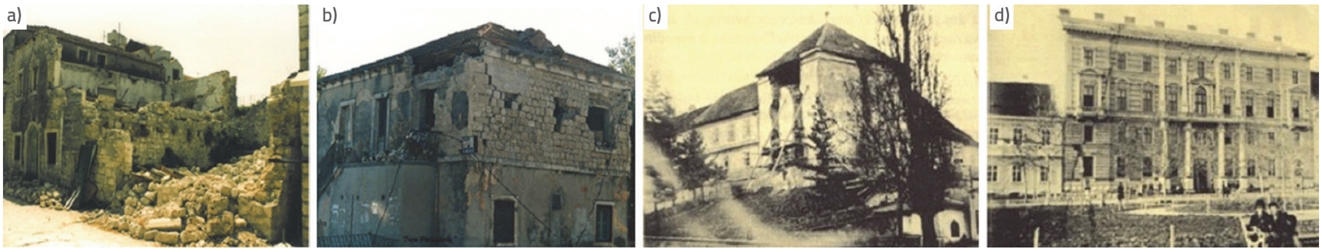


Figure 2. a) and b) Damage after Stone earthquake [6]; c) and d) Damage after Zagreb earthquake [9]

capability and capacity of the emergency response system to act in case an earthquake strikes one of Croatia's bigger cities (Zagreb, Split, Rijeka, or Dubrovnik) is questionable. It can, however, be inferred with general reasonings that, despite all the efforts and dedication, Croatia does not have sufficient capacities needed for rapid response after a disastrous earthquake (rescue and accommodation of people, damage assessment, recovery of the buildings etc.), although a general framework for the response system has been established. Setting up a system that would ensure efficient recovery of local communities has proven to be even more challenging, as demonstrated by the recent flooding disaster in eastern Slavonia (Gunja, 2014) and by reactions such as the *Law on remedy of disaster effects in Vukovar-Srijem county* (NN 77/14). Considerable damage was experienced during the flooding, yet it can be assumed as a relatively low when compared to damage that could be expected following a destructive earthquake. Such are the recent earthquakes in Italy (L'Aquila 2009 [11], Emilia Romagna 2012 [12], Central Apennines 2016 [13]), where the extent of economic losses was of the order of magnitude that could broadly be compared to Croatia's annual budget. Furthermore, studies prepared in various parts of the world point to potentially important problems that can be expected in countries similar to Croatia and, in that respect, a worldwide trend of increase in economic and societal losses due to natural disasters, mainly earthquakes, has been observed in recent decades [14, 15]. It is always useful to learn from the experience of countries leaders in the field of seismic risk mitigation, response and recovery strategies, e.g., Japan, New Zealand, Chile, USA, Italy, Greece, etc. Most of them acted *post factum* having suffered significant losses, e.g., through massive investments in reconstruction of lost assets [16]. Such examples exist in the Croatian neighbourhood as well, e.g., Skopje 1963, Banja Luka 1969 and Montenegro 1979 [17], but it seems that everything is being forgotten rather fast despite the fact that consequences were immense, and despite recent warnings form the neighbouring countries (Italy).

Unfortunately, all of the aforementioned seems to be insufficient to spur general awareness about earthquake hazard and vulnerability in Croatia. The general public interest after local seismic activity is reported in public media is usually relatively low and often reduced to a brief reaction, mainly in form of comments. Eventual improvement of the seismic resistance during ongoing projects such as energy renovation or maintenance of structures (such as bridges) is in most cases not even mentioned during public debates. Even the new national strategy (currently in preparation) fails to recognise the seismic risk as unacceptable. Therefore, for the time being, the burden of eventual mitigation efforts rests on certain individual initiatives and studies. Still, large damaging earthquakes have occurred in the past in Croatia and will occur again and, if not adequately addressed, the loss of life and property can be enormous. On the other hand, opportunities for strategic preventive actions are available and should be seized before Croatia is confronted with consequences of yet another destructive earthquake (we still have the time) [8].

2. Methodology

As an introduction to the overview of risk assessment activities in Croatia, some basic terms will briefly be defined and the standard state-of-the-art methodology will be described through a short overview of current situation in the country, including an overview of relevant research conducted worldwide. The term "earthquake risk" is used in a variety of settings and sometimes is differently defined by various institutions such as EERI (Earthquake Engineering Research Institute), UNISDR (United Nations Office for Disaster Risk Reduction), etc [18]. However, an earthquake risk is generally defined as a combination of the negative consequences and their likelihood of occurrence. The seismic risk assessment process, on the other hand, involves the convolution of three major input factor (parameters): seismic hazard, exposure, and vulnerability (Figure 3). Seismic hazard is generally defined by the intensity of the ground shaking in the study area; exposure by assets at risk, which in a dense urban environment consist predominantly of buildings with different occupancies (residential, commercial, etc.); and respective vulnerabilities that determine the likelihood of damage for a given level of seismic shaking intensity [19]. The assessment of negative consequences starts most often from the computation of expected damage to the building stock, based on which potential threat to human health and life as well as economic losses are calculated [20].

Figure 3. Earthquake risk factors (parameters) [20]

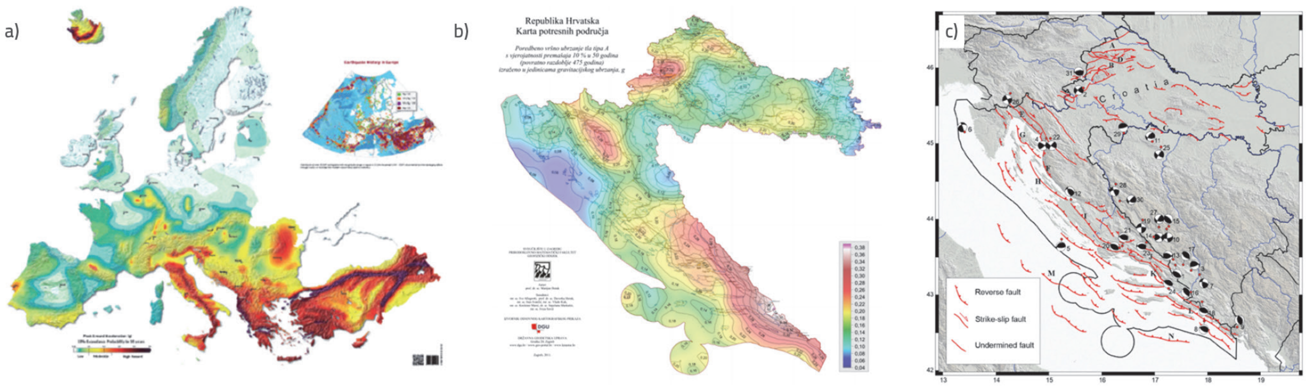


Figure 4. Expected horizontal peak ground accelerations for soil class A (hard rock) with return period of 475 years: a) for Europe [23], b) for Croatiaj [24]; c) spatial distribution of major linear faults in Croatia [5]

2.1. Seismic hazard

The seismic hazard covers the destructive effects of an earthquake mainly the transient ground motion (seismic shaking), but also permanent ground displacement due to liquefaction, landslide, settlement, etc. [21]. It is determined through an earthquake scenario with a given magnitude and distance, often referred to as event scenario, what-if scenario, or as an expected ground motion that may affect the study area over a given return period, probabilistic scenario. In both cases, the intensity of the seismic action is representative for a given probability of exceedance. Various earthquake intensity scales are commonly used to measure the size of the earthquake, e.g., the already mentioned MCS scale, Richter scale, etc. Building dynamic response and damage are, however, most often related to peak ground acceleration (PGA) especially since it is used by experts as design parameter (as it is related to lateral forces acting on a structure during an earthquake event; base shear).

The occurrence of earthquakes is most often related to the theory of tectonic plates, which in Croatia refers to the thrusting of the Adriatic micro-plate under the Dinarides. The thrusting process is a result of the relative movement of the African Plate with respect to the Eurasian Plate [22], which in turn creates the Mediterranean-Trans-Asian belt characterized by high seismic activity (Figure 4.a). Among the new generation regional probabilistic seismic hazard analyses (PSHA) worth mentioning are GSHAP (1999) and SESAME (2002), although several initiatives with similar objective were initiated even earlier (for more details, see Section 3.1). The European hazard map presented in Figure 4a is one of the outputs of the EU project SHARE (2013) the objective of which was to define the Euro-Mediterranean seismic hazard model (ESHM13) [23] based on historic earthquakes records and probabilistic analyses. Significant scientific contribution in the field was provided by a more recent project funded by NATO, Harmonization of Seismic Hazard Maps in the Western Balkans, BSHAP I-II (2007-2017). Currently, the regional research activities are concentrated in the ongoing SERA project (for more details, see Section 3.9).

In Croatia, individual seismic risk assessment initiatives are mainly conducted using seismic hazard maps [24] generated based on the observed seismicity in the territory of Croatia and neighbouring areas using available earthquake records (sparse written historic accounts, earthquake motions recorded by instruments) and data related to existing faulting systems. To prepare the Croatian probabilistic seismic hazard (PSHA) maps, complex seismic computations have been carried out by the Geophysical Department of the Faculty of Science – University of Zagreb, an educational and research institution constituting a centre of excellence for issues relating to seismic hazard. The last series of PSHA maps was published in 2011 (available at: http://seizkarta.gfz.hr) and inserted into Croatian National Annex of current European standards for the design of earthquake resistant structures (Eurocode 8, HRN EN 1998-1:2011/NA:2011). Figure 4b shows a PGA seismic hazard map for soil class A (hard rock) and for a return period of 475 years (corresponding to a probability of exceedance of 10 % in 50 years).

The PSHA maps of Figures 4a and 4b were obtained considering all known and inferred seismic sources (linear, aerial and volume) subdivided into sub-sources approximated as a point-sources (e.g., faults given in Figure 4c), respective magnitude vs. earthquake frequency relationships (activity rate), and spectral attenuation laws to estimate the shaking intensity at a location for a series of exceedance rates. On the other hand, event scenarios are generated taking into account one individual seismic source at the time together with respective parameters or as repeat of past strong earthquakes. Both PSHA maps and event scenario shake maps represent complementary earthquake prediction models and allow to assess the potential negative impacts. PSHA maps are mainly used for a high level assessment of potential damage (e.g. average annual losses - AAL) usually used are most often used for comparing various areas exposed to earthquake (e.g. regions) or for comparisons with other risks (e.g. floods) by analysing parameters of various losses [25]. The what-if scenario approach (deterministic), on the other hand, are related mostly to planning activities for emergency response, overall preparedness, recovery efforts, raising awareness etc.

Independently of the various existing approaches for hazard definition, it is of crucial importance to use all available data (multidisciplinarity) as the accuracy in the hazard assessment is closely related to the quality and reliability of the input data. It is therefore significant to anticipate and ensure at national level continuous and adequate investments in seismological, geological, geotechnical and seismotectonic research, so that the hazard can be defined as reliably as possible. For instance, increasing the density of stations of the national seismograph network may significantly increase the level of seismicity knowledge, while a more detailed faults map could enable identification of potentially active and inactive sources and evaluation of their seismotectonic potential. In addition, the seismic hazard maps presented in Figures 4a and 4b show the ground shaking intensity at the bedrock level. Since rock outcrops are generally rare in urban areas, soft surficial sediments are dominant at the ground surface (ranging from several meters to several hundred meters in thickness). The impedance contrast at the interface and decreasing shear wave velocities towards the ground surface modify the frequency and amplitude content of the incoming seismic waves, a phenomenon referred to as local site effect. Seismic microzonation, currently conducted at some localities [27] will help to determine the influence of surficial soil layers on the intensity of the seismic shaking and a better understanding of the seismic shaking potential on the ground surface. As a result, the quality of the ensuing risk assessment and eventual mitigation actions will be increased. It is international practice that the seismic hazard maps (Figures 4) are periodically revised and extended, usually every five years, based on acquisition of new information, which in other words means that these maps eventually become outdated. For instance, the development of the Croatian seismic hazard map (Figure 4b) involved the analyses of more than 40,000 earthquake records, whereas since 2011, in average more than 10,000 new records have been introduced each year in the Croatian earthquake catalogue [28]. An updated map of the seismic hazard based on this new knowledge would eventually contribute to the increase the reliability of the current PSHA. Numerous additional activities will have also to be considered, such as the selection or development of representative attenuation lows [26], preparation of seismicity models, etc., especially because all current research data clearly place Croatia among the most threatened countries in Europe. Nevertheless, it can still be confirmed that the level of the seismic hazard knowledge is relatively well defined compared to other seismic risk inputs (Figure 3) in the country.

2.2. Exposure of building stock

Exposure can be defined as the extent of human activity in the areas that are exposed to seismic hazard, e.g., presence of buildings and other man-made structures. The most important part of the exposure is the inventory of the existing buildings, which overwhelmingly contribute to the social and economic risk [29]. A building inventory usually consists of the following major attributes: location, year of construction, dimensions (height, number of stories, footprint), structural type, dominant construction material (wood, steel, concrete, masonry), lateral force resisting system (bearing wall, shear wall, frame, etc.), occupancy (residential, industrial, critical infrastructure, etc.), number of residents, replacement cost (basis for calculation of economic losses). Once those attributes are collected, a given building is assigned appropriate description code (taxonomy) within a standard classification scheme able to capture average properties among the different building types so that an unambiguous classification is made.

A literature review of research in this segment shows that most countries develop their own taxonomy based on specific typology representative of local construction practices, which is also often related to insurance policies. Among the first is the well known US FEMA HAZUS building classification scheme that set the world standard with 36 building types [30]. Among others are CAPRA in South America, RiskScape is present in New Zealand, ER2 in Canada [31], etc., while it would also be appropriate to mention here the World Housing Encyclopedia (WHE) [32]. For Europe are important the RISK-UE project [33] and, in particular, the GEM (Global Earthquake Model) initiative that is developing a worldwide scheme (GEM Basic Building Taxonomy) [34]. This classification is based on 13 major attributes and an application has been created to facilitate the input of the parameters during the buildings survey. The objective of the GEM platform is the global applicability and continuous work on all seismic risk components (to be discussed in more detail below), but also on some other risks (floods, hurricanes, fires, etc.). Unfortunately, most of these global initiatives often lack the necessary support at local level supposed to provide basic information.

The definition of the building stock in Europe was also the objective of the NERA project (network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation), which covers Croatia as well [35]. Most of the available data were collected in

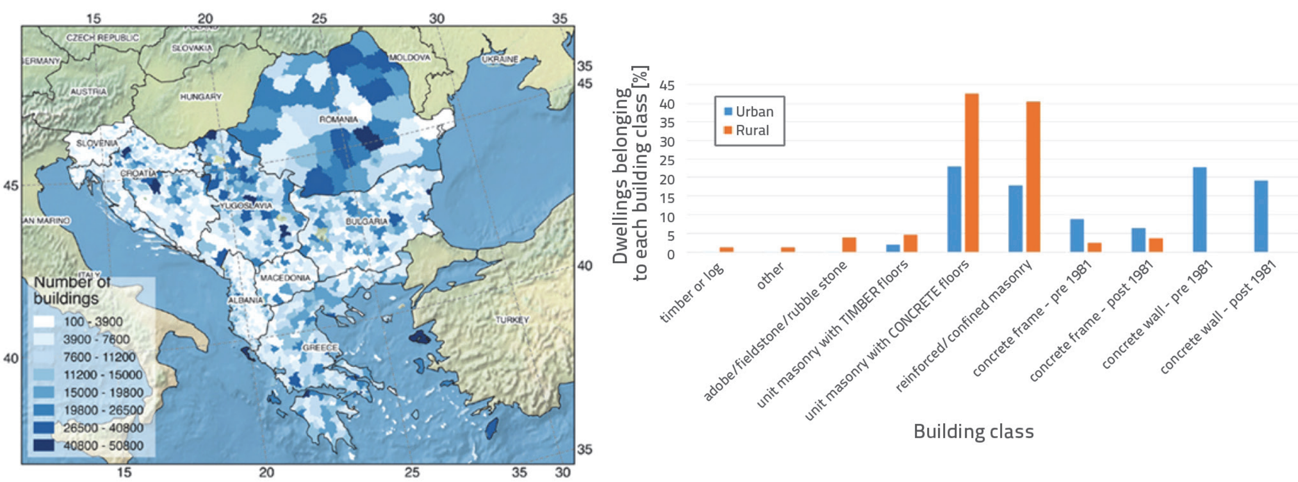


Figure 5. NERA project: a) number of residential buildings defined according to national statistical data, b) percentage of residential units per building type in Croatia, according to expert estimates [35]

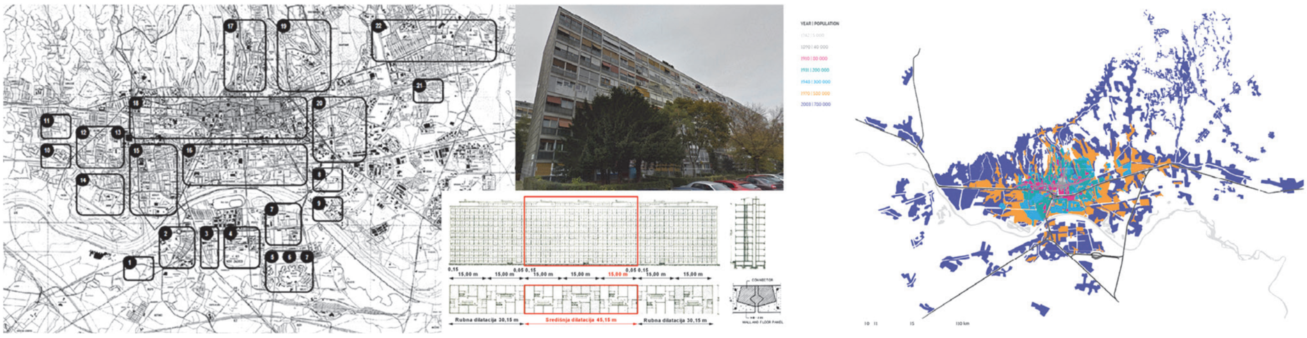


Figure 6. a) Areas with characteristic building types in the city of Zagreb, with a typical building [8]; b) b) Zagreb expansion diagram [39]

the scope of this project (e.g., data on dwellings, cadastre data, financial reports, etc.). It was, however, concluded that existing data for Croatia are inadequate or unavailable. Additional effort was devoted to identify representative building types via the Google Street application and based on questionnaires filled in by local civil engineers and experts in the domain (Figure 5). The final dataset was systematized and presented in a standardized manner through the Global Exposure Database [36, 37] with the GEM taxonomy. The initiative for acquisition of a representative building database for Croatia continued in the scope of the more extensive SERA project, where yet again Croatian experts (including authors of this paper) are invited to take part (as described in more detail in Section 3.9).

It can generally be concluded that exposure is a very poorly defined parameter in the risk assessment process in Croatia, since there is a chronic lack of ready to use information or databases on properties of the existing building stock. Furthermore, efforts on acquisition of necessary building attributes have been almost completely neglected. The exception are certain individual initiatives such as those for Zagreb (Section 3.5) and Osijek (Section 3.6), where research work and classification of the building stock is conducted in collaboration with universities and their faculties of civil engineering. An example output is shown in Figure 6.a, where the existing building stock in Zagreb is roughly categorised with respect to typical structural types (load-bearing structures), construction method, period of construction, etc. (Figure 6.b) [38]. This type of data is significant as construction methods underwent changes depending on the development of structure-related technologies, knowledge on soil properties, space planning, need for construction space, etc. In the scope of this rough categorisation of city development, a more detailed classification was made according to typical building types (such as Jugomont JU-60 – Figure 6a, buildings constructed using tunnel formwork, building aggregates, etc.) during the *Updated risk assessment* (more details are given in Section 3.8). Fourteen most frequent building types were defined during this assessment, while a detailed categorisation involving 42 types was made within the *Study for the earthquake risk reduction* (Section 3.5). In addition, the categorisation of the existing buildings for the City of Osijek was made into 15 types (cf. Section 3.6), while a very rough classification with up to 5 types is made in disaster risk assessments specified in regulations (cf. Section 3.3).

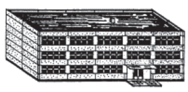
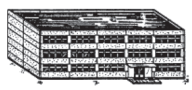
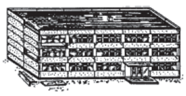
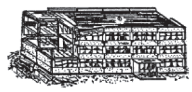
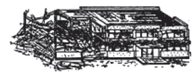
These individual efforts can hardly compensate the fact that some of the necessary building information, which could otherwise be relatively easily collected, is not included in the past and the next 2021 statistical questionnaires. Even the currently available general data (year of construction, number of storeys, floor area, etc.) is related to dwellings rather than to individual buildings. In addition, some Croatian construction particularities have to be considered such as the poorly documented renovations, although they can impact the seismic behaviour of structures (e.g., reduction or removal of ground floor walls). A high number of illegally built or renovated buildings, which is not a typical situation in the EU, make the problem even worse (over 900,000 requests for legalisation have been received in Croatia).

There are currently several ongoing project proposals that are expected to initiate considerable improvements (cf. Section 4). Perhaps the most significant initiative is related to the classification of existing buildings for the city of Zagreb, a pilot project that could be extended across the whole country. All these initiatives have the same underlying goal: to systematically create a high-quality inventory containing representative attributes of the existing building stock. For the time being, the critical infrastructure facilities have been systematically ignored in these initiatives due to their particularities and are currently occasionally dealt with in the scope of individual analyses. It can be concluded that the lack of reliable data about the building stock is probably the biggest challenges as such data constitute the key element for accurate seismic risk assessment [8, 10].

2.3. Physical vulnerability

Physical vulnerability can be defined as the susceptibility of the buildings to seismic damage. The goal of the risk assessment is to determine the probability of occurrence of a certain level of damage in a certain type of buildings as a result of the seismic action. The capacity for damage quantification has been recognised as significant for the determination of respective economic and societal losses due to future earthquakes [19]. In modern risk assessments, the level of physical vulnerability of buildings is most often described through vulnerability curves that are usually defined as the probability of loss given a level of ground shaking, and/or through fragility curves representing the probability of exceeding a specified limit state, e.g., percentage physical damage given a level of ground shaking. Vulnerability functions can be derived from fragility functions using consequence functions, which describe the probability of loss, conditional on the damage state. The methods that have been developed over time for the assessment of physical

Table 1. Damage classification according to EMS98 scale [42]

Categorization	I	II	III	IV	V
	Slight damage	**Moderate damage**	**Heavy damage**	**Very heavy damage**	**Destruction**
RC					
Masonry					
Description	Negligible structural damage and slight non-structural damage	Slight structural damage and moderate non-structural damage	Moderate structural damage and heavy non-structural damage	Heavy structural damage and very heavy non-structural damage	Very heavy structural damage

vulnerability can broadly be classified into empirical, analytical and experts judgement methods, where two or all three approaches can also be combined as hybrid methods. All vulnerability methods quantify potential damage according to some discrete damage scale, usually consisting of three to six categories [40, 41]. The most often used EMS98 scale [42] features damage categories from I to V (Table 1). These categories very roughly determine damage to structural and non-structural elements as well as safety hazards to occupants (descriptions of damage given in the table below have been abbreviated).

Damage scales (tables, matrices, etc.) based on post-earthquake damage statistics are often used in empirical procedures. Gradual development of empirical methods involved, for instance, damage probability matrices (Figure 7a) [43, 44], vulnerability indices [45, 46], and continuous vulnerability curves based on damage data [47, 48] and screening [49]. Figure 7a shows an example of a qualitative description of a number of damaged structures (few, many, most) for five levels of damage (1 – 5) depending on earthquake intensity (V – XII) which is, according to EMS-98 scale, associated with vulnerability category C (these can for instance be unreinforced masonry buildings with walls that are adequately connected with a RC slab (usually A represents the highest and F the lowest level of vulnerability).

In analytical procedures, the damage scale is related to limit-state mechanical properties of the buildings (e.g., interstorey drift), using numerical models for simulation of dynamic response of structures to an increased levels of ground motion. Such approaches involve analytically derived vulnerability curves and damage probability matrices [50, 51], collapse mechanism-based methods [52], capacity spectrum-based methods [43], and fully displacement-based methods [53]. Figure 7b shows an example of a set of fragility curves for four damage states including the damage histogram for shaking intensity measure (IM). Damage states are defined as follows: ds_0=no damage, ds_1=slight damage, ds_2=moderate damage, ds_3=extensive damage, ds_4=complete damage [54]. Each curve defines probability of achieving a specified damage level depending on observed IM. In the example presented for the selected IM (grey line), there is about 7 % probability that will be no damage (blue column), about 42 % probability of slight damage (green column), about 34 % probability of moderate damage (yellow column), about 8 % probability of extensive damage (orange column) and about 9 % probability of complete damage (red column) – distance between two neighbouring curves.

It should be noted that the earthquake action can be described by means of a variety of intensity measures (IMs), such as PGA, spectral accelerations (SA), peak ground velocity (PGV), peak ground displacement (PGD), depending on which one correlates best to the expected response of a given structure. Curves are generally described by the lognormal probability distribution, although it has been recognized that this distribution is not necessarily the most appropriate for all cases. Detailed guidelines for the development of fragility curves and vulnerability curves based on analytical approach can be found in [54], while the systematization and critical review of derivation of curves is presented in [55, 56].

a)

Class C					
Damage Level / Intensity	1	2	3	4	5
V					
VI	Few				
VII		Few			
VIII		Many	Few		
IX			Many	Few	
X				Many	Few
XI					Many
XII					Most

b)

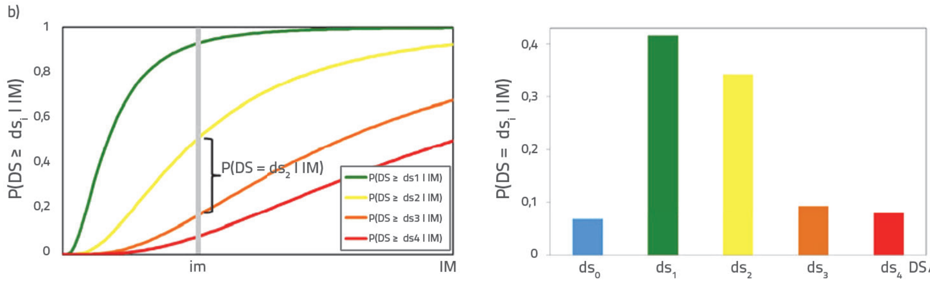


Figure 7. a) Example of damage matrix [1], b) Example of fragility curve for various categories of damage [54]

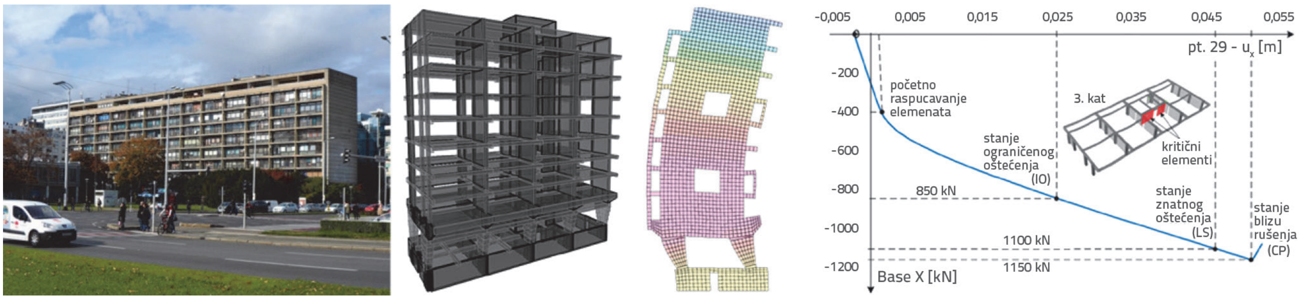


Figure 8. Example of detailed analysis of a typical building [64]

The above discussion indicates that there are several approaches for the assessment of physical vulnerability of buildings. It is therefore important to consider specific conditions in the study area (town, region, country) for which the risk model is being established, taking into account the local building stock, construction practices, the most recent information about the seismic hazard and existing data about past earthquakes. The advantage of the analytical approach for vulnerability assessment is that it is independent of the availability of post-earthquake damage data, although model calibration against damage observations is always recommended. Considering that in Croatia, despite a relatively high seismicity, post-earthquake damage observations are relatively scarce; the use of modern analytical procedures for estimating vulnerability seems to be appropriate and efficient choice for seismic risk research and for assessment of earthquake losses [1].

It is significant to note that the sets of fragility curves are always applied to a particular building typology representing a group of building with similar properties, where the categorisation is mostly based on materials (e.g. unreinforced masonry, reinforced concrete, steel, etc.), structural system (e.g. wall, frame, dual, etc.), number of storeys (e.g. 1 storey, 2 storeys, 3-5 storeys, more than 6 storeys, etc.) and, depending on the availability of data, the categorisation can also be more detailed (e.g. soft first storey). An example of the building classification for the city of Zagreb with 42 distinct building types was considered in the previous section, while examples of fragility curves for selected types of load-bearing systems are presented in Section 3.8. Establishment of a pertinent vulnerability curves database (for individual countries) is of crucial significance for a more reliable risk assessment. It is therefore significant to place emphasis on those initiatives that involve systematization of vulnerability curves in the form of applicable databases such as those in HAZUS, GEM, ER2, etc. (including guidelines for their development). The use of these datasets is, however, valid only for regions for which they were developed according to the local building tradition and practices. Data required for the development of vulnerability curves strongly depend on local characteristics of a particular country or region, i.e., on construction methods historically applied in the area (quality of construction, specific structures, etc.), change of regulations and building codes, available materials, local soil conditions, etc. It is obvious that, in Croatia, the abovementioned challenges with the inventory of the building stock are directly linked with problems respective to vulnerability assessment of the existing building stock, or in other words, it is difficult to evaluate the expected behaviour of structures if input data is unreliable.

As to developments in Europe, the SYNER-G project [57] is significant as it systemized research effort focusing on advancements in the development of databases and vulnerability assessment methodologies, including the building stock, critical infrastructure, transportation facilities, etc. Vulnerability curves were studied already in former Yugoslavia [58], and are currently investigated at the universities in Osijek and Zagreb. Considering similarities of national building stocks in a wider region, results from studies conducted in the neighbouring countries can also be used, such as in Italy, Slovenia, Bosnia and Herzegovina, North Macedonia, Bulgaria, etc. [59-63]. Creating a comprehensive database of vulnerability curves is a long-lasting and continuous process for each region/country, and it must be approached integrally, taking into account and establishing the interconnections with other components of seismic risk.

It should be repeated that it would be very difficult to include critical (infrastructure) structures in the above data acquisition procedure, first of all since these engineering structures exhibit dynamic behaviour that greatly differs when compared from one to another structure. As such, these specific structures cannot be easily regrouped into different categories with similar properties and a set of vulnerability curves, but rather require individual approach adjusted to particular parameters and needs (e.g., the need to maintain full post-earthquake functionality following seismic action). In addition, although this is not specially emphasized, the standard vulnerability curve definition process is most often reduced to analyses of an idealised of systems with a single degree of freedom which can, from the engineering standpoint, hardly be applied to complex structural systems. This has recently been confirmed by the results of detailed experimental and numerical analyses for selected typical buildings in the city of Zagreb [64, 65]. In fact, these results point to frequent deviations with respect to the preliminary assessments with simplified methods/models. Detailed analyses usually include complex spatial models and geometrical and material nonlinearities, which can be applied to detect gradual structural failure mechanisms (limit states of structures) and to identify the weakest component(s) in the structure (Figure 8). Obviously, a detailed approach to the analysis of buildings would not be appropriate for the analysis of the entire building stock (it would be very time-consuming). However, results for typical buildings can be applied in many ways, such as for the development of vulnerability curves, for the analysis of complex structural systems (e.g. critical infrastructure), for definition of typical seismic reinforcement for individual structural types, and for numerous tangential uses such as for cooperation with civil protection teams (cf. Section 3.5).

The ultimate objective behind the seismic risk assessment process is to identify and quantify the negative impacts, i.e., to determine losses, both societal and economic, and to subsequently use this information for strategic actions (as a trigger). Determination of potential losses is linked to the physical damage (of exposed structures), the main cause of the loss of human lives is the partial or full collapse of buildings. In the past century, approximately 75 % of the earthquake fatalities could be linked to the dynamic response of buildings, where most of the fatalities are related to the collapse state in masonry buildings [66], which contribute important part of the existing building stock in Croatia. Statistical data, however, also point to an increase in the number of fatalities in reinforced concrete structures, which have, in recent times, often been the preferred choice of load-bearing system of buildings. Thus, in case of collapse, they can often cause even higher consequences when compared to masonry structures [20]. The problem appears to be mainly connected to the deviation from modern seismic design principles, e.g., the ductility issues, soft first storeys, plan-view asymmetry, inadequate renovations, etc., which all apply to the current conditions in Croatia. The link between the number of human casualties and the number of heavily damaged structures can be established through observations from a number of historic earthquakes [66] or based on various models that cover a series of parameters depending on the type of structure, such as the total number of occupants, percentage of indoors people at the moment of earthquake action, percentage of people that remain trapped in the structure, spatial distribution of injuries in case of building collapse, percentage of fatalities after collapse, etc. [67-69].

The economic losses related to building reconstruction are assumed as directly dependent on its damage state. They are obtained as the ratio of the reconstruction cost for each damage state to the total replacement cost of the building, usually determined as a percentage of the building construction value and not of its market value. Valuable information in this field has been generated from observations of damage to building stock in Turkey [70]. The standardised methodology HAZUS also proposes percentage respective costs for each damage state and building type [30]. The evaluation of the total economic loss should also include a study of indirect losses (such as debris removal, shelter needs, business loss, transportations costs, etc.), requiring highly complex economic analyses [71] involving a variety of empirical parameters. These analyses are however beyond the scope of this study.

Croatia is certainly faced with numerous challenges with respect to the individual components of the risk assessment components including the vulnerability assessment, which is why it is crucial to initiate these activities on a broader scale as soon as possible. The City of Zagreb can serve as warning example since about one third of its building stock was built prior to 1964, the time when lateral seismic forces were not considered into account in the building design. More than a half of the building stock was built in the period from 1964 to 2013 and designed with seismic forces a few times lower than those specified in the current building codes. It is evident that the City of Zagreb and other urban centres in Croatia are highly vulnerable to seismic action. Hence the need for a reliable assessments of potential losses due to strong earthquakes, which is the basis for preparation and implementation of adequate risk mitigation strategies and of particular significance for national authorities, but also for practical engineers and a wider social community [8].

3. Overview of existing seismic risk assessments in Croatia

Following the above review of the state of the art approaches in the seismic risk assessment, this chapter provides a chronological overview of activities related to the existing seismic risk assessment studies in Croatia. The basic objective is to document the current situation, to place emphasis on valuable contributions, make comparisons, outline current deficiencies and propose suggestions for future risk assessments. So far, comprehensive and integrated seismic risk assessment studies were not among high priorities in Croatia, but rather restricted to certain individual efforts. A variety of respective documents are currently available, each of them using a different approach to assess the negative impacts and to present final results, such that it may be quite confusing for the wider public safety community. In order to obtain an overall picture of the current situation in Croatia, overview includes all individual initiatives considering the risk assessment issues (various aspects) and efforts from several EU seismic risk assessment projects. As it would be impossible to present herein all these studies in detail, the example of the City of Zagreb will mainly be referred to since it has been the subject of most of the studies because of its importance as Croatia's capital (for the social, economic and political stability of the country), the highest population and construction densities combined with the relatively high seismic hazard [8].

3.1. Seismic risk activities prior to 1990

Every historic overview related to seismic risk in Croatia have to start with the mention of Andrija Mohorovičić who, in the early twentieth century, provided a number of technical instructions aimed at increasing seismic resistance of buildings. He noticed the necessity to link seismology with the construction practice and, in that respect, we are currently witnessing the continuation of that association. In former Yugoslavia, just like in many other countries, strong earthquakes and their destructive consequences such as those in Skopje (1963), Banja Luka (1969) and coastal area of Montenegro (1979) [14], were the triggering factor that activated the comprehensive effort by the government, experts and researchers to focus on the mitigation of negative impacts. The first significant step was the 1964 update of the building design code [72], in which the seismic action was for the first time explicitly taken into account, although the knowledge on seismic behaviour of structures was quite limited at the time.

In the following years, the frequency of strong earthquakes in the Mediterranean countries contributed to the increase of research activities in the field of earthquake engineering accompanied with improvements in the seismic hazard assessment and dynamic calculation procedures (e.g., introduction of ductility in regulations) [73]. Projects such as the *Survey of the Seismicity of the Balkan Region* (UNESCO/UNDP) achieved in the 1970s, *Seismic Risk Reduction in*

Figure 9. Monograph [77]: a) Seismic hazard map, b) Old urban core microzoning, c) Geotechnical zoning, d) Categorisation of building damage

the Balkan Region (UNDP/UNESCO) implemented in the 1980s and *Building Construction under Seismic Conditions in the Balkan Region* (UNDP/UNIDO) conducted in collaboration with the US National Science Foundation from 1979 to 1985, resulted in publication of numerous outputs (books, manuals, scientific papers) [74, 75 which summarized the experience gained during their implementation. Local experts also initiated numerous studies and guidelines, such as instructions for post-earthquake inspection of structures [76], and through the *European Association for Earthquake Engineering (EAEE)* organized the first conference on earthquake engineering in Skopje in 1964 and the sixth one in Dubrovnik in 1978. It can generally be stated that, at the time, experts from this region were among the leading experts in the field of earthquake risk in Europe, where members of the Institute for Earthquake Engineering and Seismology (IZIIS) were among the most active ones.

Another positive example of their activity is the 1988 monograph entitled *Rehabilitation, seismic retrofitting and structural repair of cultural monuments in the old urban core of Dubrovnik,* published at the request of the Institute for Restoration of Dubrovnik with the aim of systematization of the modern scientific advances relating to seismic issues [77]. Encouraged by the experience gained after the Montenegro destructive earthquake, the authors systematized the work on determination of the seismic risk, seismic microzonation, structural investigations, seismic resistance analysis, retrofitting, etc. The monograph is an example of excellence analysing all risk components from hazard to exposure including detailed analyses of vulnerability of buildings (Figure 9). Two years later, the first scientific book on the seismic resistance of buildings in Croatia (1963-1990) was published [78].

The situation in Croatia changed considerably with the outbreak of the 1991-1995 Homeland War. Quite understandably, the seismic risk was not the priority and the existing studies seemed to be forgotten. Croatia did not follow the traditions set by the Former Yugoslavia institutions which would have led and coordinated activities related to earthquake risk (e.g. iZIIS). The 1996 Ston earthquake could have represented a triggering factor for increasing seismic awareness and community resilience, however, due to destructive effects of the war, the government was unable to react in that direction. Today, other Mediterranean countries such as Italy, Turkey and Greece, have assumed the leading role in the scientific research – although the trigger seems to be repeating – they previously suffered disastrous earthquakes. The question that arises here is the following: do we really have to live once again through catastrophic consequences of a destructive earthquake before we as a society decide to take stronger stance in addressing the seismic risk and its mitigation.

3.2. Assessment of building stock damage and fatalities in a possible future earthquake in Zagreb

The first published research in Croatia is the 1992 earthquake risk assessment for the City of Zagreb [79], although most of the research had been conducted already in 1983 but was not published for confidentiality reasons. The aim was to assess potential damage to building stock and the number of casualties, intended for the organisation of the public safety system, level of preparation and definition of respective strategies. The comprehensive initial part of the research is dedicated to the description of a situation following a hypothetical destructive earthquake with explanation of the way in which accurate risk assessment could assist in the organisation of the response. An overview of the existing information (including seismic microzonation) is given, and suggestions for the future actions are defined (most of which have not yet been implement). The developed 1987 seismic hazard map for a 500 year return period was approved by relevant ordinance in 1990. The respective damage assessment for the city (ten regional centres) with approximately 700,000 residents was conducted for an earthquake scenario with the intensity of VIII° on the MSK-64 scale with a maximum acceleration of 2.0 m/s2 (≈0.2 g) imposed uniformly over the study area, strong motion duration of 15 seconds and uniform soil conditions, etc. The city was divided into 45 zones (Figure 10) each with specific age and number of buildings, number of storeys, structural system, and population density.

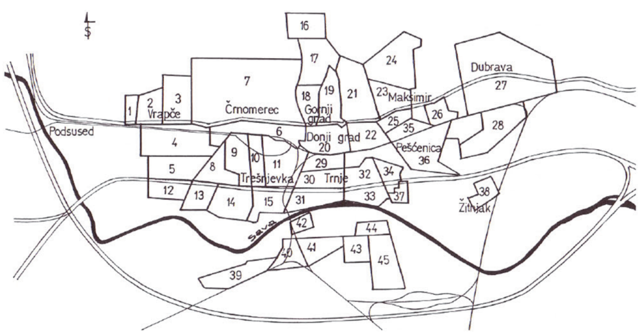


Figure 10. Division of Zagreb into 45 zones [79]

Depending on the time and method of construction, buildings were classified into different categories: masonry buildings, confined masonry buildings, reinforced-concrete frame buildings, reinforced-concrete buildings with load-bearing walls, and reinforced-concrete frame buildings with reinforced-concrete load-bearing walls. The percentage of buildings belonging to a particular structural system was estimated based on experience, as data was not available at the time (today the problems are the same). The damage to buildings was assessed using vulnerability matrices with six damage levels corresponding to each of the assumed building types, and each type was attributed a percentage of damage with regard to the total number of buildings. For comparison with other assessments, some 80,000 dwellings were estimated to suffer a certain degree damage, which when were converted via correction factors into damaged individual buildings this represents about 11 % of the building stock. For an average 60 sq. m. apartment, and the construction cost of 1,000 DM/m^2, the economic loss was estimated to 1,440,000,000 DM. Assuming that a dwelling is on an average occupied by 3.1 persons it was estimated that there could be 13,500 injuries, 2,000 fatalities and about 130,000 inhabitants would be left without basic living conditions. The results of this study, although the described analysis represents only a first-hand rough estimate (noted in conclusion of the research), are still used as the basis for estimating disaster risk by counties and towns (cf. next section). This leads us the general conclusion that the assessment was based on state-of-the-art scientific research at that time and objective was to be used as a good basis and encouragement for future research. In addition to the above seismic risk assessment to the building stock, it is also appropriate to mention the study of the seismic risk assessments of bridges in Croatia [80, 81] .

3.3. Risk assessment of population, material and cultural assets and environment exposed to disasters and large-scale accidents from 2008 to the present day

It is specified in the *Law on Protection and Rescue* (NN 174/04, 79/07, 38/09 and 127/10) and in the *Ordinance on the methodology of development of vulnerability assessments and plans of protection and rescue* (NN 38/08) that assessments of negative impacts from disasters including earthquakes must be made for Croatia, individual counties, cities and districts. Accordingly, these assessments could only be made by experts authorized by the *National Protection and Rescue Directorate*. The new *Ordinance on guidelines for preparation of risk assessments to natural disasters and large accidents for the Republic of Croatia and local and regional administrative units* (NN 65/16) represents a step toward harmonisation with the EC guidelines. A brief overview of the existing risk assessments indicates that earthquakes are considered very roughly together with the analysis of a number of other risks selected for the areas under study. The methodology described in section 3.2 is most often used ignoring new trends and research initiatives, and the level of expertise is quite uneven involving experts from different domains. Nevertheless, we should bear in mind the criteria and purposes for which these assessments are made (e.g. protection and rescue plans).

The assessment work conducted by the *Office of Emergency Management of the City of Zagreb* and the risk assessment for the city of Dubrovnik (mentioned in Section 3.6 as one of the most endangered cities) will be presented herein as examples and for comparison with other results. In all of the assessments and according to the Ordinance from 2008, seismic hazard is commonly defined based on available maps similar to those given in Figure 11. The official 2011 map indicating seismic zones (Figure 4b) is used in some more recent assessments, although the maps accepted in the 1990 Ordinance are still used quite frequently (for instance, the map shown in Figure 11a is used in the assessment made in 2016 for the City of Dubrovnik). The influence of different surficial soil conditions is usually not taken into account, with the exception of the 2016 assessment for the City of Zagreb, where the potential amplification was considered according to the valid regulations. Most assessments, however, contain the necessary chronological overview of the past earthquakes recorded in the surrounding area and general data about seismicity of the area study, such as the epicentral area, expected earthquake intensity, and soil properties, what is valuable data.

The building inventory is usually conducted by groping the number of dwellings into approximate periods of construction according to the specific building codes (available statistical data – Figure 12a) and in this way a characteristic building typology is related to a particular period. For example, most of the masonry buildings had been built before 1964. The categorisation is also made according to the presence of structural types within a given administrative unit (district, urban zone, municipality, city, etc.) giving an estimate of the percentage of specific typology to the total building stock

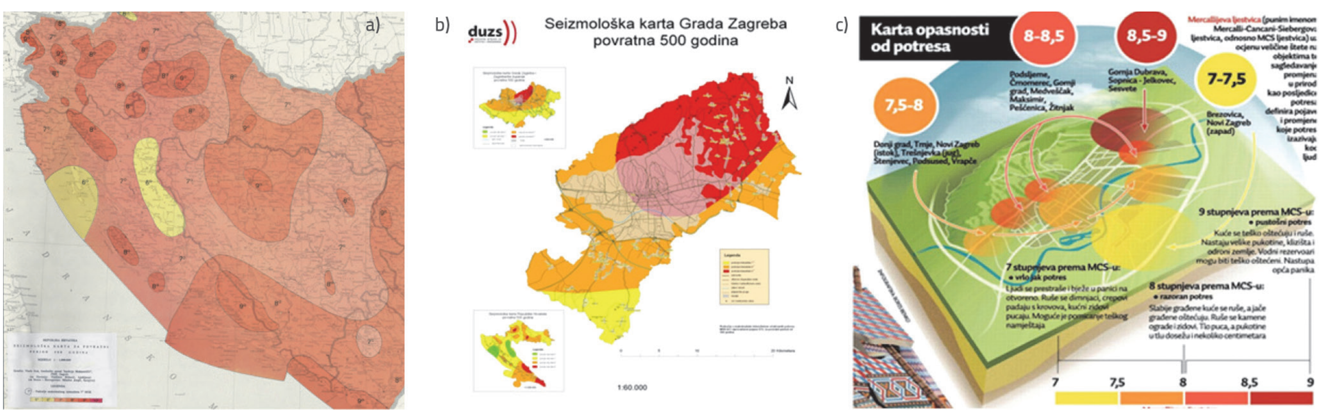


Figure 11. a) Seismological map approved by the 1990 Ordinance, b) Seismological map of the City of Zagreb (DUZS, 2010) c) Earthquake hazard map (technical services of the City of Zagreb)

(using urban spatial plans). In the assessments conducted for the City of Dubrovnik in 2011 and 2016, five building types (described in previous section) were considered in three zones of this city. In 2011, the classification was made by districts (17 in total) for the City of Zagreb. According to the new assessment made in 2016, the city was initially divided into three areas of different vulnerability, where the district of Podsljeme was defined as the area of highest vulnerability while the lowest vulnerability status was attributed to Brezovica. The remaining fifteen districts were roughly divided according to structural system (Figure 12b): masonry buildings with 1-2 storeys (B1), masonry buildings with 3 storeys (B2), reinforced-concrete buildings with 1-12 storeys (C1), reinforced concrete buildings with 13-25 storeys (C2) and various types of buildings (A). The different percentages for the individual building types were determined according to expert estimate and prior experience.

Damage probability matrices related to earthquake intensity and structural system have almost always been used in the damage assessment, as shown in the example given in previous section [79] or example from the assessment made for the City of Zagreb in 2016 (Figure 12b). The following parameters are used in these matrices: damage categories according to EMS scale (column 1-3), damage index DI in percentage (ranges shown in column 4), and previously described structural systems A, B1, C1 and C2 (damage percentages per level of damage and structural systems are shown in columns 5, 6 and 7), all this for the horizontal ground acceleration of 0.3 g (in previous section, this assessment was made for 0.2 g). It should be noted that the methodology used is very often not mentioned in assessments (such as in the assessment made in 2011 for the City of Zagreb).

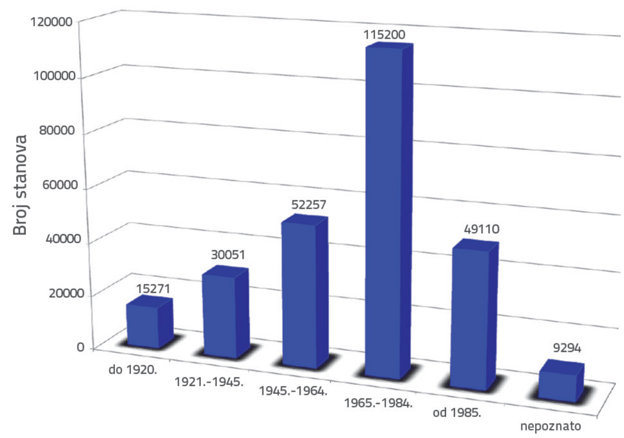


Figure 12. a) Number of dwellings per period of construction [82]

The results obtained differ in the level of detail depending on the local administrative unit considered. For instance, for the seismic risk assessment in Croatia (2013), it can roughly be estimated that more than 30 % of the area, i.e. about 60 % of population, is exposed to stronger earthquakes where significant consequences may be expected [1]. This assessment was obtained by dividing counties into seismic zones (Figure 11.a), and by classifying the number of dwellings and residents by periods in which specific regulations were used. The roughness of the results is confirmed by the fact that in county-level assessments, the results are presented at the city/municipality scale, while in assessments for cities the results are presented at district scale or for selected zones.

Table 2. Damage probability matrix [82]

1	2	3	4	5	6		7	
Level of damage	**Colour**	**Brief description of damage**	**Range and average vulnerability index (DI) [%]**	**Load-bearing system**	**Load-bearing system**		**Load-bearing system**	
		Designation		A	B1	B2	C1	C2
		Number of storeys		do 2	1-2	3-6	1-12	13-25
				Proportion in the total number of dwellings of a particular load-bearing system (UU)				
1	Green	No or slight	0-5 (2)	5	20	10	15	10
2	Green	Moderate Building is usable	6-25 (15)	15	40	35	25	50
3	Yellow	Heavy, Building not usable but can be repaired	26-50 (40)	20	30	30	30	20
4	Red	Partial collapse, Building unusable and irreparable	51-85 (65)	50	5	15	15	10
5	Red	Collapse	81-100 (90)	10	5	10	15	10
			Total:	**100**	**100**	**100**	**100**	**100**

To get an impression about the level of risk and for eventual comparison with other risk assessments, the results of the assessment conducted in 2011 for the City of Zagreb indicate 2,127 dwellings in the collapse state (category V according to EMS scale) and 4,379 dwellings with very heavy damage (category IV). A total of 51,865 dwellings (about 16.5 % of the building stock) would be unfit for immediate occupancy and the number of fatalities would amount to about 3,000. The assessment from 2016, predicts an increased number of irreparable dwellings to 63,743 which represents 21 % of the building stock, whereas the number of partially damaged (reparable) dwellings would be 39,888 or 13 % of the building stock. According to the results, temporary housing should be provided for approximately 168,000 people for the period until the replacement of demolished buildings, while shelters should be provided for additional 103,000 persons. With an average area of 70 m^2/ dwelling and the construction price of 1000 €/m^2 (the value estimated at the time), the economic loss to building stock is estimated at € 9,035,250,000. The methodology used for estimating the number of fatalities takes into account the total number of dwellings with a particular load-bearing system, proportion in the total number of dwellings of a particular load-bearing system, damage index for a particular level of damage, estimated number of fatalities per dwelling, and an average number of 2.58 people per dwelling. The expected number of fatalities is 5,626, the number of injuries 11,539, whereas the number of people trapped under rubble amounts to as much as 10,632.

Structures belonging to the category of critical infrastructure facilities are almost always mentioned in the assessments, but are most often not analysed or are referred to a more detailed analyses. A preliminary assessment from the project proposal [83] (described in Section 4) is used in the assessment conducted for the City of Zagreb in 2016. According to this assessment, a high-intensity earthquake could cause considerable damage to gas and electrical lines, telecommunication facilities, transport infrastructure (roads, bridges, viaducts, overpasses), water

It can generally be concluded that the applied analyses are very rough and highly dependent on certain assumed values that rely first of all on expert's opinion and approximate engineering estimates. The insufficient knowledge and coarse data about the exposure and structural types represent the main challenge (approached differently by experts), and quite often conclusions indicate that for accurate assessment more extensive research has to be conducted. In this respect, a positive example is the City of Zagreb that invests in research work, so that the assessments are becoming increasingly detailed and accurate. For instance, the seismic risk assessment conducted in 2018 (not discussed as an example in this section) comprises all the existing research work. Some results from this assessment will be presented in the following sections of this paper.

3.4. Disaster risk assessment for the Republic of Croatia – earthquake (2015)

This assessment was made in the scope of preparation of the *Disaster Risk Assessment for the Republic of Croatia* based on *Guidelines for the Preparation of National Disaster Risk Assessment for the Republic of Croatia* issued by the National Protection and Rescue Directorate (2014) in accordance with the *Risk Assessment and Mapping Guidelines for Disaster Management SEC (2010) 1626,* and HRN ISO 31000 *Risk Management.* One of objectives of the guidelines was to ensure comparability of individual risk assessments, both on the national level and on the EU level.

The assessment was made by the Faculty of Civil Engineering – University of Zagreb as the lead executive, in collaboration with other executives (Faculty of Science – Zagreb in particular). The worst-case scenario was selected as the *Ground shaking in the City of Zagreb caused by an earthquake with return period harmonized with regulations for the design of seismic resistance.* The assessment contains an extensive description of the considered scenario itself with a general overview of situation regarding current research in Croatia and worldwide. In addition, the state-of-the-art methodology is described in detail, and a theoretical approach was presented for each earthquake-risk component, including analysis of data available for each component, with an emphasis on deficiencies that prevent more reliable (accurate) assessment. Considering the numerous unknowns, one of the objectives was to set the basis and directions for future seismic risk assessments. In this context, certain parts of the assessment were used for the 2018 Risk Assessment of the City of Zagreb. The analyses from the studied scenario were also used for a rough earthquake risk assessment at the level of individual counties (Figure 13.a).

Special forms were prepared in an attempt to overcome the key deficiency related the building inventories (database of buildings/structures).

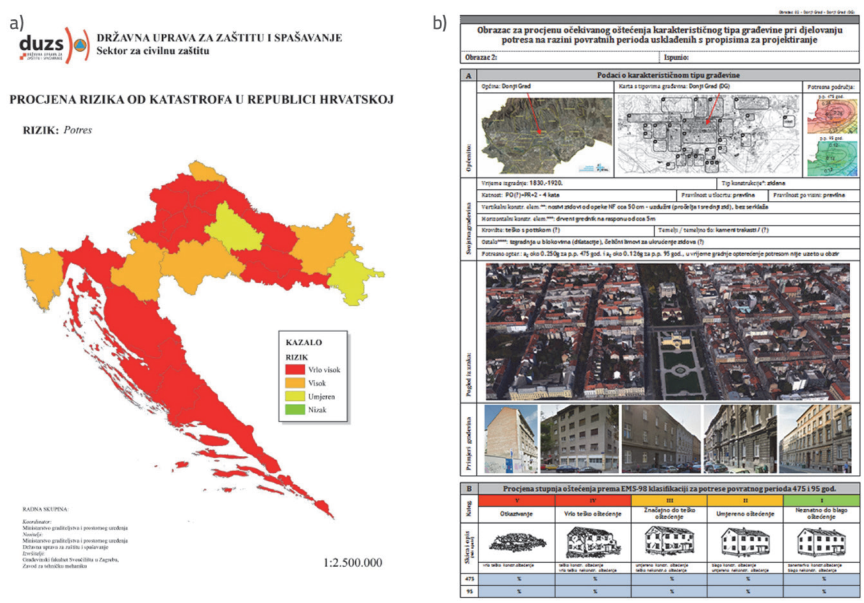


Figure 13. a) Rough risk assessment for counties, b) Forms for the damage assessment of characteristic building types at the level of return periods harmonized with design regulations [1]

These *Forms for damage assessment of characteristic building types at the level of return periods harmonized with design regulations* (Figure 13.b), were used to systematize all available data, including available statistical data from 2011. The forms [1] include the analysis of characteristic construction types by city districts or municipalities with regard to the type of structure, time of construction, intensity of earthquake loading (reference load and design load), height (number of storeys), horizontal and vertical regularity, load bearing elements for horizontal and vertical load, type of foundations, soil type, etc. The map of earthquake-prone areas in Croatia (Figure 4b), not including additional influence of soil, was used in the definition of hazard.

The analyses were made by preparing initial assessments according to EMS-98 classification procedure complemented with experts estimates based on knowledge of the design of such and similar structures and, especially, based on the knowledge of specific "local" conditions in particular (including, for instance, great number of illegally built structures, faults, landslides, quality of construction, specific construction typology, etc.) which is otherwise not covered in EMS-98. As an example, it would be appropriate to single out the results for the city district of Podsljeme (mentioned in Section 3.3) where for the total of 8,834 dwellings the following results may be expected: 2-10 % in category V (collapse), 10-20 % in category IV (very heavy damage), 15-25 % in category III (heavy damage), 20-30 % in category II (moderate damage) and 30-40 % in category I (no damage). The estimate of expected 8,126 fatalities and economic loss of € 1,706,363,505 was made according to results that were obtained for all city districts combined [69]. The values were adjusted to previously defined criteria (minimum values were used) and are not representative of real costs which depend on many parameters (such as the age of the building, type of material, etc.) nor do they cover specific structures (such as bridges, critical-infrastructure facilities, etc.).

It can generally be concluded that the described analysis is still rather rough as it takes into account only several types of structures per city district, but it represents nevertheless a step forward in building vulnerability analyses as it uses more detailed data about the structure (load-bearing system). In conclusion, it can be stated that the described assessments have proven to be satisfactory considering the predefined criteria (category of consequences), although they constitute only an initial step toward state-of-the-art risk assessment methods.

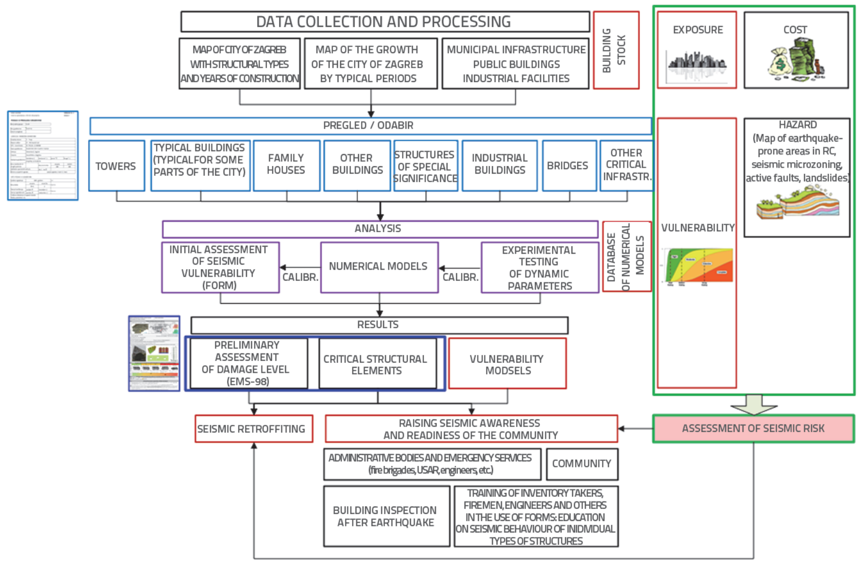


Figure 14. Activities undertaken in the scope of the Study [84, 85]

3.5. Study on earthquake risk reduction in the City of Zagreb (2013-2019)

The study on earthquake risk reduction in the City of Zagreb [38], as one of the individual initiatives, is related to the realisation of the Project No. 11 of the City Office of Emergency Management. The objectives were to create real preconditions for mitigation and recovery of earthquake effects, since a strong earthquake event represents potentially the most important disaster that could strike the City of Zagreb. This study is being conducted in the scope of the development strategy of the City of Zagreb in accordance with prevailing regulations, and in collaboration with the Faculty of Civil Engineering – University of Zagreb. The work in the scope of this study has been in progress since 2013. It was initially conceived as a support to a larger-scale project [83] within which the seismic risk assessment for the City of Zagreb was planned to be conducted (as presented in more detail in Section 4).

While awaiting realisation of the project, a number themes relating to activities prior to and after the earthquake have been treated by numerous experts during the six years of work in the scope of this study. These activities include: creation of a high-quality database on existing structures (definition of methodology, forms, key attributes, organisation of city into characteristic parts – map preparation (Figure 6.a), training of surveyors, etc.), development of methodology for rapid initial assessment of seismic vulnerability (identification of key parameters, creation of respective forms, etc.), detailed assessment of seismic resistance of buildings based on experimental and numerical analysis with identification of critical spots, seismic retrofitting, organisation of inspection of earthquake-damaged structures (preparation of inspection forms, organisation of system, education, participation in field exercises, etc.) and other side activities (Figure 14). All these themes are focused on earthquake risk reduction, and most of them can be used in other areas in Croatia [84].

Among the numerous considered issues, the efforts aimed at creation of building inventory database are described in Section 2.2. In the following, particular focus is placed on detailed experimental and numeric analyses of selected buildings, since the generated results can be extremely useful for a number of purposes. During the selection process of candidate buildings, attempts were made to include characteristic building types based on the period of construction, materials used, height, applied design code, as well as buildings

Figure 15. Selected examples of buildings analysed in detail in the Study

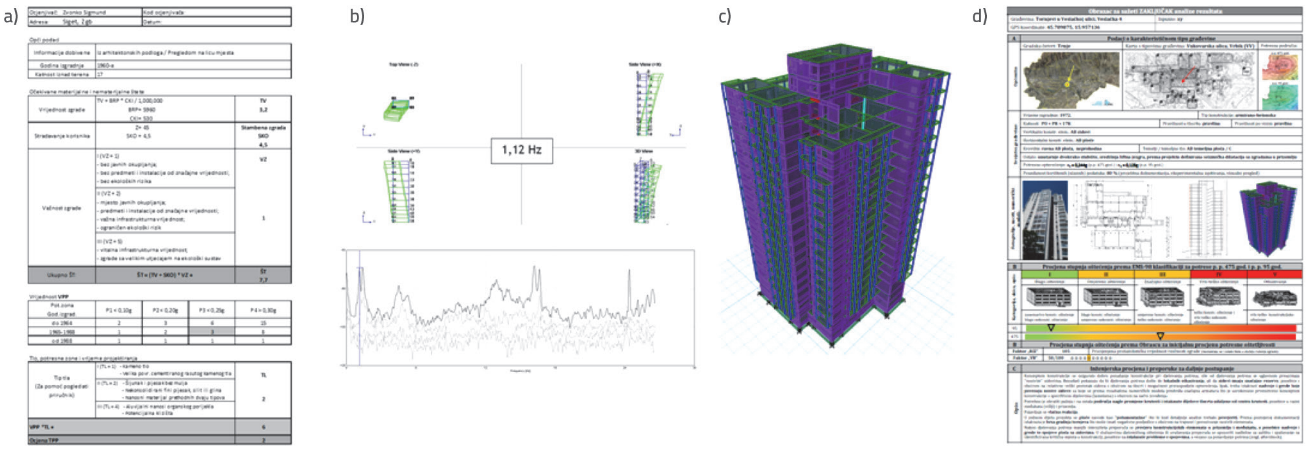


Figure 16. Approach to detailed analysis of existing structure based on data collected for that purpose: a) form for initial rapid assessment of seismic vulnerability; b) experimental study of dynamic parameters; c) numerical model; d) form with summary of results obtained by analysis [83]

with specific local features (such as can-shaped buildings, buildings constructed using tunnelling methods, etc.), towers, significant and essential buildings (historic buildings, fire stations, hospitals, industrial buildings, student dormitories, concert halls, theatres, schools, other public buildings, etc.) and other elements of critical infrastructure (Figure 15).

Selected buildings were analysed through experimental study of dynamic parameters using state-of-the-art methods [86], followed by establishment of complex numerical models. It should be noted that visual inspection often revealed that the actual conditions are not necessarily identical to the available documentation, i.e., that buildings were often modified either during the construction or use, and these changes were not subsequently documented. Considering these and other potential unknowns regarding structural details, it was concluded that the experimental determination of dynamic parameters (Figure 16.b) was extremely useful for calibration of numerical models.

The results from the numerical analyses (Figure 16.c) were used to provide a general assessment of the expected behaviour of the considered buildings when subjected to seismic action with a return period of 95 and 475 years (according to EMS-98 scale). The results of the detailed analyses can also be extrapolated to a number of buildings of the same or similar structural type and, by their linking with a city district and the number of people residing in each building, useful information can be obtained contributing to a more accurate assessment of risk. In addition, a significant contribution is that critical spots were noted for each analysed building, which is especially significant during possible removal of debris, search and rescue of victims buried under the debris, or inspection following a lower intensity earthquake (timely reaction is possible in case of damage, and especially in cases of earthquake aftershocks). The data can also be used when formulating proposals for seismic retrofitting, for developing monitoring and maintenance plans and for limiting interventions within the building, which would ultimately contribute to higher safety, and would also extend the service life of buildings [84].

One of the special issues involved systematization of the existing bridges over the Sava River flowing through Zagreb, as they are of utmost significance for ensuring emergency response following a strong earthquake, and especially for determination of evacuation routes, for instance, for maintaining an uninterrupted traffic flow between the old and new parts of Zagreb. The other issue was the detailed analysis of the existing hospital buildings: Sv. Duh (Holy Spirit Hospital) (Figure 15), University Hospital Centre Sestre milosrdnice (Sisters of Mercy) and University Hospital for Infectious Diseases Fran Mihaljević. In conclusion, numerous activities were conducted in the scope of this study in order to deal efficiently with the multitude of issues relating to potential earthquake impacts.

3.6. Rapid assessment of seismic risk in Croatia (2016)

It is important to place emphasis herein on the long-standing research in the field of seismic risk conducted at the University of Osijek, where the tradition of study of risk assessment issues

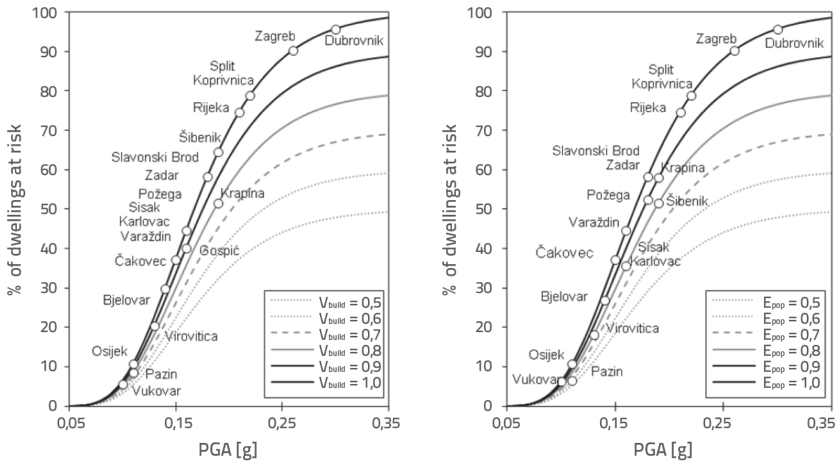
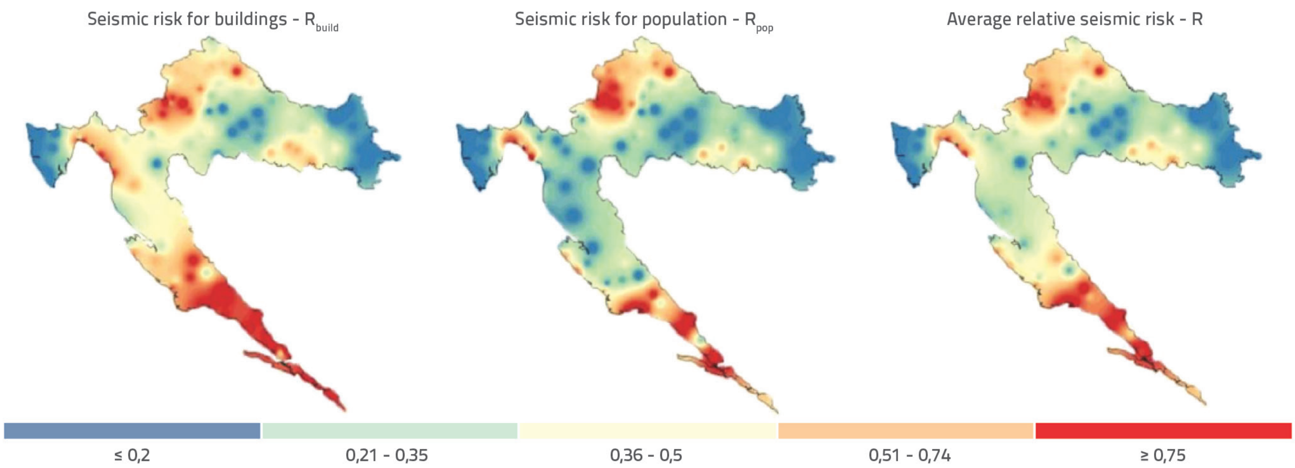


Figure 17. Models for predicting earthquake risk in Croatia [87]

has remained unabated despite the fact that the awareness about the earthquake risk in Croatia has been declining for decades now. Some of the activities have already been mentioned in Section 2 and, relating to the objective of this paper, we will consider in this section the rapid assessment of the seismic risk in urban areas in Croatia as a potential first step in the identification of highly endangered areas and urban centres. The use was made of a simulation model for acquisition and interpretation of, despite the scarcity of statistical data, the available information in Croatia (e.g., data on dwellings and population density). In the second phase, this information was analysed with respect to a probable seismic event (Figure 17 and Figure 18). The results show relative correlation among the urban centres at risk and identify areas in which additional activities have to be encouraged including preparation of detailed seismic risk assessments of the most endangered municipalities [87, 88].

As to other existing activities in this field, worth mentioning is the preparation of the building database for the City of Osijek (fourth-biggest city in Croatia with about 110,000 inhabitants). More than 1500 buildings have so far been included in this database [89]. The analysed buildings/structures were divided into fifteen distinct typologies and include schools, kindergartens, suburban buildings, old city core buildings [88]. For some of these building specific vulnerability curves were also developed [46].



Slika 18. Risk assessment for Croatia using relative RAPID method [88]

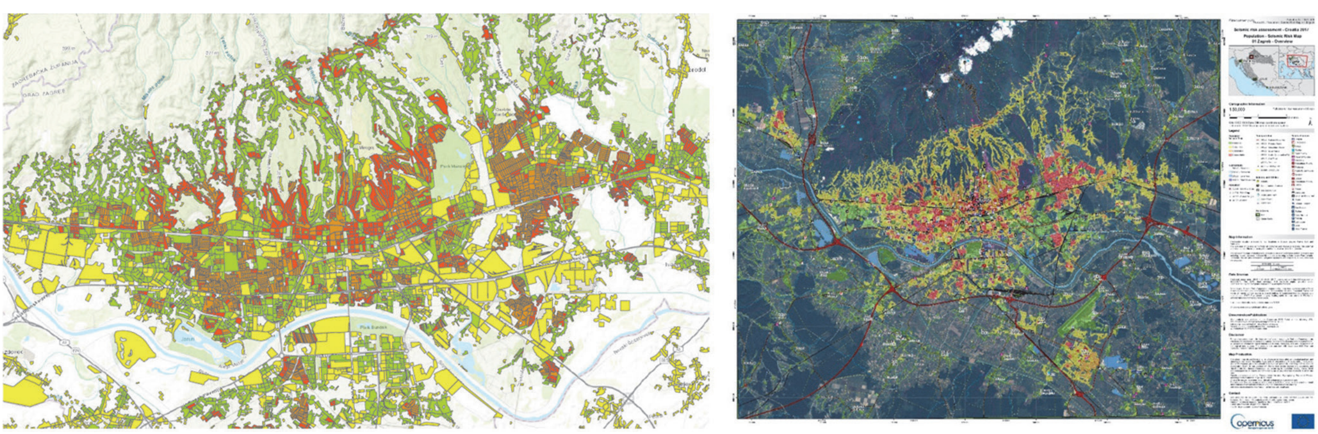


Figure 19. Classification of inhabitants into categories and seismic risk map for population [92]

In addition, the use of various assessment methods for the analysis of earthquake vulnerability, such as macroseismic methods can be mentioned herein. A special attention was drawn to the method proposed by the Faculty of Civil Engineering, University of Osijek, based on the vulnerability index, and whose application is described in full detail on the example of the City of Osijek [18]. Finally, the university textbook related to assessment of vulnerability of buildings also deserves to be mentioned [89].

3.7. Risk assessment in Croatia – EMSN-039 (2017)

Following the initiative of the Croatian Crisis Management Association (HUKM), an assessment was made for four cities: Zagreb, Split, Rijeka, and Dubrovnik, by activation of the Risk and Recovery Mapping component of the Copernicus Emergency Management Service [29]. The assessment was conducted by Indra Sistemas S.A. based in Madrid, Spain. Public announcement of results in local newspapers and portals spurred professional debate in Croatia and so, finally, following the observation of deficiencies were noted, the assessment was withdrawn from the official sources. In the context of overview of the existing assessments, and to enable proper positioning and better understanding of the earthquake risk, some facts have to be stated with respect to this study. The basic idea behind this assessment was to make use of data obtained primarily via satellite imagery combined with the support of other available services, e.g., OpenStreetMap. The seismic hazard was defined based on the existing *Map of earthquake-prone areas* in Croatia (Figure 4.b) and data from the 2011 census were used to create the exposure layer of information. The geostatic raster layer with 100 m accuracy was used for visualisation of input and output parameters. Available building data were categorised according to height, type and material. Appropriate weighting factors were used (ALARP principle) and, finally, the level of vulnerability at city block level was obtained overlapping different maps and by means of risk matrices. The results obtained in this way provide only a relative vulnerability relationship, which is a very rough estimate and cannot be used to quantify the negative impacts, something that was noted in the conclusion of the final report).

According to available information, the authors of the study plan to rectify present deficiencies and to additionally adjust the results to the emergency response planning requirements (e.g., evacuation routes). In this way, the company plans to move away from the seismic risk assessment domain due to problems raised by critical reviews from professional community). Still, this assessment is even today among the first choices of the internet search engines for the term "earthquake risk in Croatia", which shows how important it is to clearly position the existing investigations and their results in order to increase the awareness of citizens and of the experts of their own exposure and vulnerability to earthquakes, which is one of basic objectives of this paper.

3.8. Updated disaster risk assessment for the Republic of Croatia – Earthquake (2018)

The updated risk assessment is the most recent risk assessment work for Croatia, and prepared applying state-of-the-art research methodologies it represents a significant step toward more accurate estimation of disaster risks. According to the Law on civil protection system (NN 82/15 and 118/18), assessments must be updated every three years or more often when necessary. This assessment is based on the risk assessment study conducted in 2015 (Section 3.4). However, the aim of this updated assessment was to rectify the previously observed deficiencies, especially those related to the exposure and respective vulnerabilities as well as to include all available data from all existing risk assessments (described earlier). Following the initiative by the National Protection and Rescue Directorate and the Ministry of Construction and Physical Planning, this updated assessment was carried out by the Faculty of Civil Engineering as the main executive in collaboration with the Faculty of Science, both with the University of Zagreb. The scenario *Ground shaking in the City of Zagreb caused by the earthquake at the level of return period*

Figure 20. a) Map of Zagreb with boundaries of local boards, b) types of structures marked on the map

harmonized with regulations for the design of seismic resistance, used in assessment made in 2015, was used in this assessment as well due to the exceptional significance of the City of Zagreb. The improvements to seismic risk assessment are briefly described below through each of the steps. Seismic hazard was defined in accordance with the mentioned *Map of earthquake-prone areas* in the Republic of Croatia (Figure 4b) for horizontal peak ground acceleration with return periods of 475 and 95 years and evaluated at the centroid of each local board of the City of Zagreb. The influence of local soil conditions was not taken into account as the detailed microzonation activity is still in progress. In addition, one deterministic scenario was also analysed to account for the 1880 M6.3 Zagreb earthquake, but this scenario was not included in the official report.

The inventory of the building stock was conducted over a more detailed administrative classification of the city, involving 218 local boards, was used in this updated assessment (while classification involving 17 city districts was used in Section 3.4). The biggest step forward of this assessment represents the focus on the identification of specific data about structural systems of buildings. Thus structural systems most frequently encountered in this city were first clearly identified (14 typologies), and then the proportion of each type in the total number of residential occupancy buildings was defined. The procedure included selection of each building or group of buildings with similar properties and assignment of the corresponding load-bearing system, which was a particularly time consuming activity. At the level of individual local districts, each type of structural system was associated with the respective number of residents so that the number of casualties could be estimated on the expected number of heavily damaged and collapsed buildings. Figure 20 shows the spatial distribution of structural systems for some local districts, developed in a GIS system using the most recent ortophotographic chart of the city (prepared in 2018). For instance, the structural system URM represents unreinforced masonry buildings, RC2 denotes buildings with reinforced-concrete walls, etc., while the height of buildings was described using the extension L, M, and H. Despite the fact that important advancement was made toward a more accurate building inventory, it was observed that there were still many more distinct structural systems in the field. Therefore, in the second phase of the study a building categorisation scheme with 42 typologies was introduced.

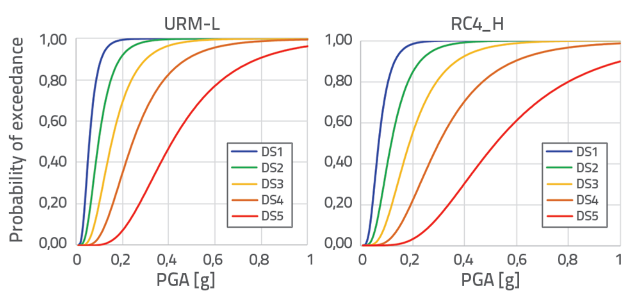


Figure 21. Examples of fragility curves for building types URM_L and RC4_H

The vulnerability analyses of the exposed buildings and evaluation of the respective economic losses were carried out using fragility and vulnerability curves (described in detail in Section 2.3, Figure 21.). A set of curves was associated with each individual structural type and the procedure was conducted according to the macroseismic method in accordance with the RISK-UE project [93]. The classification of damage was conducted according to the EMS-98 scale with five damage states and the vulnerability of buildings was communicated by means of vulnerability index [94].

Damage factors (DF) were then assumed in order to correlate the economic losses to the expected structural damage. DFs associate the cost of repair for each damage state to the total replacement cost of the building. Thus, vulnerability curves for each building type were obtained by convolving building fragility curves with the cumulative cost of a given damage state [95]. These vulnerability curves for characteristic building types represented the basis for estimation of economic losses and fatalities for seismic scenarios in Zagreb. Total economic losses due to the earthquake scenarios were calculated for each local board with respect to the structural systems and the number buildings. The estimate of fatalities was also made for each local board and was determined depending on the number of people residing in the collapsed buildings during the earthquake action. Recommendations from relevant literature were used in this process [66, 67]. According to the model predictions, almost 6,000 buildings (about 5 % of the inventoried building stock) would collapse, while 21,087 (about 17 %) would be heavily damaged. The direct economic loss was estimated at approximately € 15.6 billion and, to gain a better insight into the situation, its spatial distribution is presented in GIS (Figure 22).

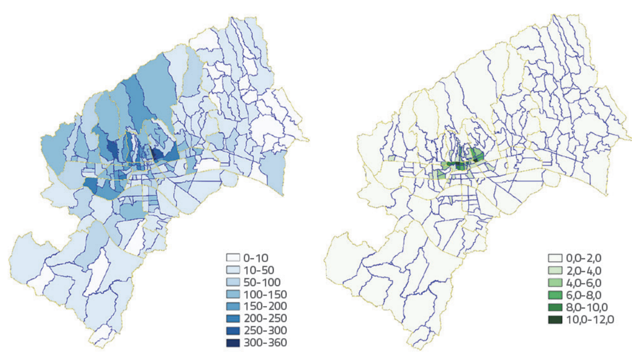


Figure 22. Economic loss in millions of euros per local board (left) and per hectare (right)

It can generally be concluded that the presented methodology represents a considerable step forward when compared to the other existing assessments. Important advancements have been made toward identification of the number of buildings and their classification according to structural systems, which was the basic problem in earlier risk assessments. Nevertheless, it is important to bear in mind that more reliable risk assessments have to be prepared only after a continuous detailed investigation of each of the seismic risk factor (inputs).

3.9. SERA project (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe), 2018-2020

The SERA project focused on the harmonisation of data and creation of the unified seismic risk model for the entire Europe [96], represents a continuation of large-scale European projects already mentioned in Section 2, such as the SHARE project (analysis of seismic hazard), NERA project (analysis of building exposure) and Syner-G project (analysis of vulnerability curves). The focus of the project is on buildings inventories at the European level, but also on additional analysis of each risk component with reference to the existing data from previous projects and to the newly acquired data. Project partners, cooperate with the wider scientific and engineering community through internet applications, workshops, and individual meetings - including active contribution authors of this paper (experts for Croatia). Socioeconomic indicators, average annual losses, maximum losses, etc., will be analysed at the concluding stage of the project with the uniform risk assessment at the level of the entire Europe and creation of the European risk map as main objectives (to be issued in April 2020). The outputs of these analyses will be accessible through the GEM platform [97] and will be publicly available. Continuous development and updates of the model are expected in future with the aim being to further develop risk mitigation strategies.

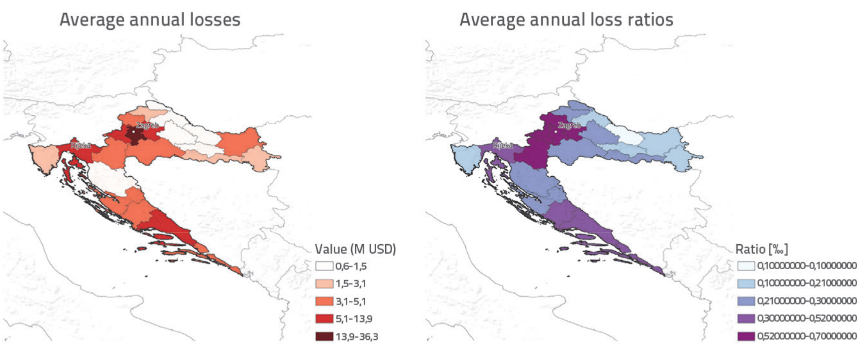


Figure 23. Predicted average annual losses and average annual loss ratios caused by earthquakes in Croatia [97]

An overview of available inventory databases for Croatia was made within the SERA project, however, due to frequent deficiencies, databases had to be completed with additional information obtained via questionnaires sent to Croatian experts to provide missing parameters needed in the analyses (based on their experience). The following attributed were collected and analysed: period of application of design regulations (related to analysis of building ductility), proportion of building types classified according to GEM taxonomy (e.g. reinforced-concrete buildings, masonry buildings, confined masonry buildings, steel structures, etc.), types of lateral load bearing systems (mainly bearing walls, frame structures, dual systems, etc.), location, occupancy, and other relevant data. At that, residential buildings in urban and rural areas, as well as industrial and commercial buildings, were analysed. Based on the collected data, the monetary value of the building stock was calculated by type of structures. For instance, the total replacement cost of the building stock in the City of Zagreb was estimated at €36 billion and, according to new GEM risk map, the City of Zagreb is presented as the urban centre of maximum seismic risk with €35 million expected annual losses. The average annual losses were calculated as the ratio of the total economic loss and the return period expressed in years for which this loss was evaluated (in the presented case the return period is 200 years, which means that it is assumed that these losses will be realized or exceeded at least once in every 200 years). Only the direct damage to residential, commercial and industrial buildings was considered due to the intensity of the ground shaking. The average annual loss ratio was then calculated as the average annual loss normalized by the total asset replacement cost.

It can be concluded that the approach applied in SERA is directly linked to the accuracy of the collected input data, which is not always the case. On the positive side is the continuous development of the considered state-of-the-art risk assessment methods and of the inventory databases used in the analyses. The final outputs will be extremely useful as representative analyses based on the current knowledge and for comparisons among the EU countries.

4. Insight into future strategies

The discussed existing seismic risk assessment initiatives undoubtedly show that, despite the associated challenges, various approaches (differences) and rough outputs, a future destructive earthquake in Croatia could generate unacceptable level of risk for the country (catastrophic consequences). Since earthquakes cannot be prevented, it is important to rapidly undertake mitigating measures and prepare the wider public safety community for such an eventuality. These measures are usually smoothly directed toward new update of the building codes to assure the construction of earthquake-resistant structures but, what is more important since new large-scale construction effort is not expected in near future, to make the existing building stock less vulnerable to seismic loads. The seismic risk assessment process, which measures the negative impacts from earthquakes, e.g., structural damage, economic and social losses and their likelihood, is the prerequisite to any strategic action aimed at seismic retrofitting of existing structures, or for increasing the level of preparedness of the first responders. This points to the need to ensure continuous and accountable work on the earthquake risk issues and, in this respect, some of the crucial steps have already been emphasized in Section 2 through the analysis of each factor of risk seismic risk analyses.

An additional encouragement could be the Sendai Framework for Disaster Risk Reduction 2015-2030 (UN document published in 2015) in which seven global targets and four priorities for action have been defined for preventing new and reducing existing disaster risks. The basic objectives include reduction of: human casualties, direct economic losses, and damage to critical infrastructure due to natural disasters. The report also encourages further activity of the scientific community aimed at quantifying disaster risk parameters and scenarios with a special emphasis on regional, national and local applications [98]. Increasing the disaster resilience is emphasized as one of key aspects for sustainable development and, in this respect, EU institutions give this principle central place and ensure funds for future activities. Although Sendai Framework conclusions are rather general, they address almost all of the above mentioned challenges for Croatia, so that the remaining question is our capacity for adjustment.

One of the key projects that could encompass most of these issues has been proposed by the Office of Emergency Management of the City of Zagreb and by the Croatian Academy of Engineering [83] The project was first proposed in 2014, but has been adjusted afterwards on several occasions so that it can now become a pilot project for Croatia. It involves a detailed analysis of the earthquake impacts for the City of Zagreb including definition of methodology for a more accurate assessment of impacts to buildings, engineering structures, and population [81]. It also includes additional investigations related the seismic hazard (including the existing microzonation research), preparation of a detailed inventory database (building by building) with basic properties, vulnerability assessment and determination of the impacts to residents and their property. Some preliminary parts of the project were used in the disaster risk assessments for the City of Zagreb conducted in 2016 and 2018. The generated knowledge will be used by relevant services of the City of Zagreb to inform their decisions making on measures to be taken in order to reduce to a minimum human casualties and economic losses. The new scientific and technical knowledge will be communicated to relevant organisations and services of the City of Zagreb, which includes recommendations given by the UN Office for Disaster Risk Reduction, widely influencing activities of the society as a whole. The project will also provide a detailed historic overview with an emphasis on changes to society caused by potential destructive earthquakes. Furthermore, the project will provide a review of : building codes and regulations and their evolution with time, development of worldwide research activities, seismic risk assessments, while a special focus will be on representative professional and scientific literature that useful for experts involved in earthquake risk studies. It is expected that the outputs of this project will represent a turning point for the risk analyses in Croatia, i.e., it is only after the project completion that it will be possible to undertake standardised accurate earthquake risk assessment activities. Certainly, this project will not instantaneously solve the numerous challenges in Croatia, although it will represent important step forward in increasing the awareness of the population and relevant institutions about the need to take stronger action in dealing with this issue.

The realisation of the project of such a significance can best be enriched through appropriate platform such as the *Croatian disaster risk reduction platform*, which efficiently connects together the seismic risk experts with competent organizations and services at national level. Such initiatives have resulted in excellent scientific contributions in the field of risk assessment (Sections 3.4 and 3.8) and in the realization of several projects whose outputs are already implemented in the system. A good example is the "Matilda project" (MultinATional modulLe on Damage Assessment and CounTermeasures) conducted as part of a larger-scale program funded by the European Commission (Civil Protection Preparatory Action on an EU Rapid Response Capability) realized in 2014-2016. The objective was to develop proper capabilities for international emergency situations that are, as needed, activated in the scope of the EU Civil Protection Mechanism, and to achieve the best possible coordination of civil protection activities in case of a disaster. A significant element of the project was the involvement of civil engineers in the processes of building post-earthquake damage assessment and the encouragement of their collaboration with the civil protection teams. The cooperation that links together different types of knowledge and expertise to enable optimum response following destructive earthquakes was realized by gathering together researchers from the Faculty of Civil Engineering – Zagreb, professionals and civil protection members. The outputs from this project are being gradually implemented into Croatian civil protection systems through field exercises (Istra 2017, ZG POTRES 2018, Cascade'19), workshops and integration of civil engineering experts in MUSAR teams [99].

In addition, the Civil Protection Office of the Ministry of the Interior is currently implementing the project entitled *On the path to disaster risk reduction* aimed at educating school children and increasing awareness among the population about the potential threats in the Republic of Croatia. One of the elements of this project is to acquire an earthquake simulator so that the children and larger public can get in touch with the destructive power of earthquake shaking and to build a model of a building resistant to seismic action. Such activities are significant for raising general awareness as a key step toward integrated solutions of the earthquake risk issues.

Furthermore, the project "*Preventing, Managing and Overcoming Natural-Hazards Risks to mitiGATE economic and social impact*" (PMO-GATE) was initiated in 2019 in the scope of the Interreg Italy-Croatia 2014-2020 Program in which Croatia participates through the Faculty of Civil Engineering, Architecture and Geodesy of the University of Split (Nikolić et al.). The general objective is to involve joint development of an innovative methodology for prevention, management and control of natural hazards and increase the protection level and resilience to natural disasters specific to the participating regions, such as river and sea flooding, meteorological tsunamis and earthquakes. The proposed approach is based on the integration of risk assessment with subsequent prevention, preparedness, and response to considered natural disasters. It brings together three main parameters: capitalisation of existing knowledge of participating regions in the field of natural disaster management, definition of possible scenarios including a detailed analysis of territorial vulnerability in accordance with regulations of the authority managing strategic assessment of environmental impacts, and efficient communication strategy raising awareness and changing perception of population and public agencies through communication between the participating regions and affected members of the community.

The project entitled "Resilience Enhancement of Adriatic basiN from firE and SeiSmic hazards – READINESS", which focuses on the analysis of buildings of special (strategic) significance, such as schools and hospitals, in three counties, is also currently in progress [100]. The project is carried out by the Faculty of Science and the Faculty of Civil Engineering of the University of Zagreb, and a special emphasis is placed on the extremely complex and detailed analysis of the General Hospital building in Dubrovnik that involves the state-of-the-art testing of dynamic parameters and numeric calculations at several levels including nonlinear static pushover method and nonlinear dynamic time step analysis. Such projects focused on analysis of the seismic resistance of existing buildings are of crucial importance as Croatian critical infrastructure and essential facilities generally over fifty years old, their usual service life. No need to mention that such structures are crucial for functioning and rapid recovery following strong earthquake and they have to be given priority for seismic retrofitting [101].

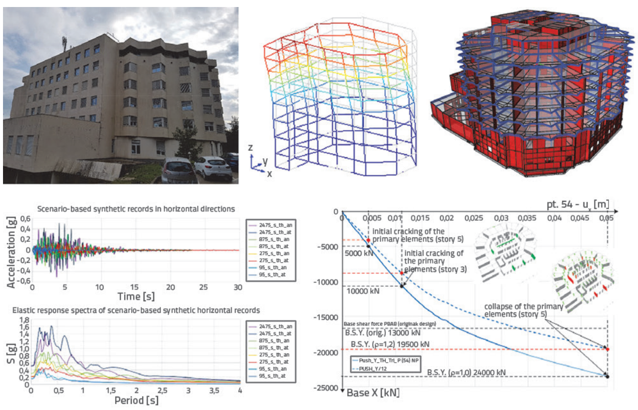


Figure 24. Detailed analysis of the General Hospital building in Dubrovnik: a) Photos of analysed structure, b) Results of experimental measurements of ambient vibrations, c) Numerical model, d) Time-series acceleration records, e) Building pushover curve [101]

Unfortunately, the opportunity to link the ongoing activities related to energy renovation and certification of buildings with the seismic retrofitting effort was not seized in Croatia. In addition to the lack of funding, the problem is in the insufficient awareness about the earthquake risk in a way that structural properties of buildings are not collected during energy renovation activities. The opportunity to encourage seismic retrofitting of buildings is still there since, in 2018, the EU Council revised the Directive relating to energy renovation (Directive 2018/844) and emphasized the need to improve buildings' resistance in earthquake-prone areas. Buildings that have to undergo significant renovation are already specified and Croatia is required to implement the directive by March 2020. These activities are directly related to challenges for providing regular funding necessary for maintenance of the building stock, which would be a separate topic.

Additional opportunity that should not be missed is the use of modern technologies for acquisition of significant data needed for risk assessment. This includes high-resolution satellite imagery, LiDAR, drones, Google Street View, etc., that can all be used to obtain building footprints, height, number of storeys, etc. These data, however, is not sufficient since they have first to be processed by experts (problems described in Section 3.7), but also complemented with supplementary information also important for vulnerability assessment, e.g., data on structural system, occupancy, people indoors, etc.

Numerous countries in seismically active regions face challenges with risk assessments similar to those encountered in Croatia. It is therefore important to take advantage of the extensive research efforts that are conducted at regional level to further develop seismic risk assessment methodologies that could also be applied in Croatia. The Global Earthquake Model (GEM) initiative, which develops most-advanced and widely applicable databases, including program packages/tools for seismic risk assessment, has already been mentioned as an example of such efforts. Existing databases and models should be continuously updated based on exchange of experience and collaboration between users including participation of Croatian experts.

All of the above mentioned individual pieces require a systemic and comprehensive integration which can be enabled through a specialized platform currently in place in most of the countries exposed to relatively high seismic risk. Such a platform has to be included among the strategic priorities of Croatia and would help timely recognition of the previously mentioned challenges (Section 2) related to seismic risk parameters that will once again be briefly emphasized herein. For a better definition of the seismic hazard, it is essential to ensure seismological, geological, geotechnical and seismotectonic research activities, increase the density of stations of the national seismograph network, create detailed maps of active faults, conduct microzonation studies, continuously update existing seismic hazard maps, etc. The effort for development of a comprehensive inventory database should focus on integration of all available databases and attributes such as statistical data, archived data, data from scientific and technical projects (described in Section 2.2) that could assist in the estimation of all hazards risks including seismic risk. This ("ultimate") database is valuable as it can also be used for integration of numerous attributes that can be associated with various needs, e.g., emergency services in situations following destructive earthquakes. Follows integration of the information relative to the vulnerability of man-made structures that should involve respective research results in Croatia and worldwide, study of local specific buildings, critical and essential infrastructure (hospitals, schools, bridges) and all other parameters that are needed for a more accurate assessment of physical damage. All databases must be continuously developed and extended, as well as adjusted to various needs [102]. The above mentioned clearly points to the need for linking together the experts in various related domains (integration of knowledge) and institutions (from national to local government units) through an appropriate platform (centre with legitimacy, such as IZIIS). Within this platform, all collected data would be interpreted, analysed and harmonized with modern scientific achievements and, in this way, prepared for various uses (e.g., increasing awareness, preparation of various instructions/guidelines, building insurances, seismic retrofitting, etc.). It is of author's opinion that these efforts will lead, step by step, to the reduction of consequences of seismic action.

5. Conclusion

The Republic of Croatia is among the most earthquake-prone countries in Europe, yet the current activities related to assessment of potential earthquake risk and its reduction in particular can be characterized as individual and insufficient. For instance, there are currently several existing and ongoing disaster risk assessments in Croatia (conducted by various authors that apply different approaches) and few isolated individual initiatives what is confusing for general public and makes the activities aimed at reducing negative impacts aggravating. That is why the analysis of existing seismic risk assessments for Croatia, presented in Section 3, has been carried out from the perspective of the lead executive for earthquake risk with the objective to provide a clearer overview and better understanding of the overall situation in Croatia and worldwide. Each of these studies (assessments) was considered individually discussing the used method, most significant results together with study contributions and deficiencies to enable their comparison, integration and mutual position within the bigger seismic risk reduction picture. Continuous advancement and integration within the international state-of-the-art research is evident (such as those presented in Section 3.8), however, the encountered numerous challenges that hinder generation of accurate results should also be emphasized. These challenges are identified through description of the usual seismic risk assessment approach (Section 2), where each of the input parameters (factors) is separately analysed through an overview of current research in Croatia and worldwide. Inadequate building inventories are recognized as the main obstacle in reliable seismic risk assessment in Croatia. The situation is additionally complicated by characteristic problems such as widespread illegal construction, undocumented reconstructions and renovations and the lack of some critical attributes such as those related to specific local construction practices, age of the building stock and critical infrastructure facilities, poor system organisation, lack of funding, etc.

Despite the often overlooked approach deficiencies and incompatibility of the results, existing all hazard risk assessment studies clearly point to earthquake as one of the biggest risks for the Republic of Croatia, with possible catastrophic consequences. It is emphasized that a destructive earthquake that would destroy a part of the building stock and/or workplaces could further impair the fragile economic stability of the country, additionally boost current migration trends and, finally, put in jeopardy the social and political fabric of the country [19]. In cases where potential earthquake consequences exceed financial capacity, seismic risk assessments as the first step toward mitigation should be of special interest to national authorities as they are the basis for the implementation of policies (estimation of capabilities, capacities, implementation of strategies, etc.).

According to vision of the future activities (Section 4), concluded that the earthquake risk assessments ultimately have to be conducted within a systematic (standardized) and integrated framework based on state-of-the-art scientific achievements combined through a single platform. Regrouping the available knowledge and expertise under a centralised leadership and management body (devoted to earthquake risk) would facilitate challenges and enable systematic work on both seismic risk assessments and mitigation of consequences. Suggested approach would avoid missing opportunities to work together on activities such as the energy renovation efforts or introduction of structural property attributes when creating various databases (population census, building register, etc.).

It can be concluded that the present level of awareness about our own exposure and vulnerability to earthquakes in Croatia is not sufficiently developed to serve as a basis for compelling efforts to foster institutionalised seismic risk assessment, mitigation and preparedness activities. In fact, it seems that the relatively low probability of occurrence of strong earthquakes, when compared to natural and other disaster hazards, contributes to a pervasive ignorance of the fact that earthquakes constitute an unacceptable risk. It is therefore essential to act without delay as, unlike some other countries, we still have time to react before another potentially disastrous earthquake strikes in Croatia.

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