PROŠLOST I NEKI AKTUELNI PROBLEMI ZAŠTITE GRADITELJSKOG NASLEĐA OD ZEMLJOTRESA

PAST AND SOME TOPICAL PROBLEMS OF BUILT HERITAGE PROTECTION FROM EARTHQUAKES

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1 UVOD

Tokom cele istorije graditeljstva, građevine su bile izložene brojnim devastacijama prouzrokovanim prirodnim i ljudskim faktorima. Savremeni teoretičari arhitekture često raspravljaju o tome kakve bi bile potencijalne mogućnosti graditeljskog razvoja da povremeno nije dolazilo do njegovog diskontinuiteta izazvanog nepogodama. Vremenske i prostorne praznine (cezure) u istoriji graditeljstva bile su, povremeno, izazvane upravo katastrofalnim zemljotresima, koji su prekidali razvojnu nit graditeljstva mnogih generacija. Velike prirodne nepogode često su bile uzrok razaranja, ne samo pojedinačnih građevina već i čitavih naselja. Među najrazornije sile koje deluju, nesumnjivo, ubrajaju se zemljotresi. Suočeni s tom opasnošću, ljudi su na tim područjima prvo i počeli da stvaraju oblike konstrukcija koje su bile najpogodnije da "prežive" ili bar ublaže posledice zemljotresa. Posle takvih nesreća, pojedina rešenja su usavršavana ili su stvarani potpuno novi graditeljski oblici, da bi se gubici ublažili. O tome postoji niz dokaza, a savremena proučavanja pronalaze stalno nove podatke o izboru materijala i tehnikama građenja. To je od posebnog značaja za do danas očuvano graditeljsko nasleđe.

Posle zemljotresnih dejstava i oštećenja koja ona izazivaju, društva su različito reagovala, opredeljujući se za uklanjanje svih građevina i to u celosti ili za njihovu obnovu u obliku koji su imale pre zemljotresa. Savremena

1 INTRODUCTION

Throughout the history of building, structures have been exposed to numerous devastations caused by natural and human factors. Contemporary theorists of architecture often discuss what the potential possibilities of architectural development would be if there were no occasional discontinuities caused by disasters. Temporal and spatial gaps (caesuras) in the history of construction were, occasionally, caused by catastrophic earthquakes, which interrupted the thread of construction development for many generations. Major natural disasters were often the cause of destruction, not only of individual buildings but also of entire settlements. Undoubtedly, earthquakes are among the most destructive forces at work. Faced with this danger, the people in these areas first began to create the forms of structures that were most suitable to "survive" or at least mitigate the effects of the earthquakes. After such accidents, certain designs were improved or completely new forms of construction were created, in order to mitigate the losses. There is a body of evidence about that, and contemporary research studies are constantly finding new data on the choice of materials and construction techniques. It is particularly important for the built heritage preserved to this day.

Human societies had different reactions after the earthquakes and the damage they caused, opting either for the complete removal of all buildings or for their reconstruction in the distinctive shape they had had

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praksa zaštite graditeljskog nasleđa predviđa blagovremeno ojačanje konstruktivnog sklopa, koji po svojim tehničkim rešenjima nije bio predviđen da izdrži jake seizmičke udare. S druge strane, nekoliko snažnih zemljotresa u našem okruženju opominje da treba ozbiljnije pristupiti istraživanju zemljotresa kroz istoriju područja i formiranju baze podataka za pojedinačne spomenike kulture. Tokom istraživačkih radova na građevinama nailazi se na starije intervencije, od kojih su se neke, verovatno, odnosile na ojačanja i popravke oštećenja izazvanih zemljotresom.

Na osnovu različitih statističkih podataka koji potiču iz zemalja Evropske unije, zemalja Azije, Južne i Severne Amerike, sačinjen je savremeni popis prirodnih katastrofa koje su rangirane prema relativnoj učestalosti i obimu štete koju nanose kulturnom nasleđu [4], [9], [15–18], [22], [49], [55], [59] i [66–67]. U tom popisu, prvo mesto dodeljeno je zemljotresima, a potom slede poplave, uragani, tajfuni i cikloni (koji se međusobno objedinjuju), dalje slede klizišta, oluje, tornada, cunamiji i, na kraju, erupcije vulkana [3] i [19]. Danas se ovi klasični obrasci prirodnih katastrofa u mnogim zemljama često dopunjavaju i klimatskim promenama, kao globalnim oblikom agresivnih prirodnih efekata.

Nepredvidljivost zemljotresa uticala je na to da su ljudi od najranijih vremena bili svesni da se, na neki način, treba obezbediti od stihije. Oblikovanje građevina koje je trebalo da budu što sigurnije bilo je tako, s jedne strane, povezano s mitovima, legendama i strahovima koje je zemljotres izazivao kod ljudi, a s druge strane intuitivno osiguravano, tako da se toj nesreći građevine odupru i da se izbegnu posledice razaranja. U borbi da se odbranimo od zemljotresa od posebnog je značaja proces postepenog uočavanja i razumevanja porekla zemljotresa i efekata koje on proizvodi. Teorija konstrukcija omogućila je formulisane matematičkih modela za predviđanje ponašanja različitih tipova konstrukcijskih elemenata i/ili sistema pod zemljotresima. Pre njihovog formiranja postojali su različiti načini za kodifikaciju iskustva koje se postepeno sticalo prilikom gradnje, a trebalo je da služi kao vodič za projektovanje i izvođenje sve kvalitetnijih i na zemljotres otpornijih građevina.

Da bi se razumeli naponi starih graditelja pri stvaranju seizmički otpornih građevina, treba imati na umu da se njihova polazišta znatno razlikuju od današnjih. Dok savremeni graditelji, na osnovu proračuna i modela, unapred tačno znaju šta na građevini treba da bude pojačano kako bi se prihvatila seizmička dejstva, stari graditelji su seizmički otpornu građevinu stvarali tako što su pravilno obrađivali svaki njen deo, od pripreme terena, izvođenja temelja, sve do oblikovanja svih detalja do krova. Promišljeno su birani i ugrađivani materijali na mesta uslovljena njihovim oblikom i strukturom da bi se obezbedila seizmička stabilnost. To je predmet zemljotresnog inženjerstva čiji tragovi se nalaze i u dalekoj prošlosti.

U celoj istoriji građenja mogu se izdvojiti tri potpuno različita pristupa pri stvaranju seizmički otpornih građevina [9] i [59]:

before the earthquake. The contemporary practice of protection of architectural heritage focuses on the timely strengthening of the structural systems, whose technical design solutions were not intended to withstand strong seismic shocks. On the other hand, several strong earthquakes in our close surroundings warn us that earthquake research through the history of the area and the formation of a database for individual cultural monuments should be approached more seriously. During the research works on the buildings, older interventions were encountered, some of which were probably related to the strengthening and repair of damage caused by the earthquake.

Based on various statistical data originating from the countries of the European Union, Asia, South and North America, a modern list of natural disasters has been made, ranked according to the relative frequency and extent of damage to cultural heritage [4], [9], [15–6]. [22], [49], [55], and [66–67]. In that list, the first place has been assigned to earthquakes, followed by floods, hurricanes, typhoons and cyclones (which unite with each other), followed by landslides, storms, tornadoes, tsunamis and, finally, volcanic eruptions [3] and [19]. Today, these classic patterns of natural disasters in many countries are often supplemented by the climate change, as a global form of aggressive natural effects.

The unpredictability of earthquakes made people from the earliest times become more aware of the need to protect themselves from the elements. The design of buildings that were supposed to be as safe as possible, was, on one hand, related to the myths, legends and fears caused by the earthquake in people, and on the other hand intuitive, in the sense that buildings could resist the disaster and avoid the destructive effects. In the struggle to tame the nature, the process of gradual observation and understanding of the earthquake origin and the effects it produces is of special importance. Structural theory has made it possible to formulate mathematical models for predicting the behaviour of different types of structural elements and/or systems in earthquakes. Prior to their emergence, there were various ways to codify the experience that was gradually gained during construction, and it was to serve as a guide for the design and construction of increasingly high-quality and earthquake-resistant buildings.

In order to understand the efforts of ancient builders in creating seismically resistant structures, it should be borne in mind that their starting points were significantly different from the present day ones. While modern builders, based on calculations and models, know in advance exactly what should be reinforced on a building so that it could resist seismic effects, builders in the past created a seismically resistant building by properly treating every part of it, from site preparation, construction of the foundations, to shaping all the details up to the roof. Materials were carefully selected and installed in place, depending on their shape and structure, and seismic stability was ensured. It is the subject of earthquake engineering, traces of which can be found in the distant past.

Throughout the history of construction, three completely different approaches to the creation of seismically resistant structures can be distinguished [9] and [59]:

- Najčešći pristup sastoji se u podizanju građevine s nosivošću koja omogućuje da podnese zemljotres bez značajnijih oštećenja. Ovaj način građenja primenjivao se na svim područjima za koja je od davnina poznato da su trusna.

- Drugi pristup zasniva se na sprečavanju čvrste veze između tla i građevine, jer je poznato da čvrsta veza između građevine i trusnog zemljišta, povećava efekte seizmičkih pokreta/dejstva na zgradi, a slabija veza ih smanjuje. Kod istorijskih građevina, slabljenje ove veze postizalo se različitim načinima, od nabacivanja slojeva peska u najstarijim vremenima, preko glinenih jastuka do utežućih pojaseva i drugih klizećih elemenata. Danas se ovaj način takođe primenjuje i mnogi ga nazivaju pasivnom zaštitom od zemljotresa.

- Treći pristup je upravo suprotan prethodnom, jer zahteva određena rešenja koja mogu promeniti dinamičke karakteristike građevine, da bi se izbeglo da uđe u rezonantno područje. Smatra se da je to i najstariji metod zaštite od zemljotresa, jer svaka građevina može izmeniti svoju krutost čime se modifikuje njena konstrukcija, a time i perioda njenih prirodnih vibracija. Pomerajući se izvan perioda vibracija očekivanog seizmičkog dejstva, građevina se izvlači iz tog opasnog stanja [59].

O značaju organizovane utemeljene zaštite graditeljskog nasleđa svedoči i formiranje istraživačkih projekata u Evropi, npr. NIKER [84] i PERPETUARE [70]. Opšti aspekti kulturnog nasleđa i prirodne nepogode analizirani su u [22] i [97] i uz analizu oštećenja nasleđa u seizmičkim područjima u [15–16], [27] i [116]. Iskustva seizmičke zaštite objekata kulturnog nasleđa nakon zemljotresa u Kraljevu prezentirana su u [42]. Ublaženje oštećenja razmatrano je u [114] i [116]. Zaštita u zemljama u razvoju razmatrana je u [58]. Seizmički rizik kulturnog nasleđa razmatran je u [93]. Analiza metoda primenjivanih u zemljotresnom inženjerstvu i mogućnosti njihove zaštite prikazani su u [34]. Metode pregleda objekata kulturnog nasleđa u Italiji prikazane su u [1], u Novom Zelandu [3], u Brazilu [13], u Kini [116] i u Rumuniji [81]. Procena kamenih istorijskih zgrada prikazana je u [105]. Procena i povredljivost predmet su radova [10], [17], [28], [86], [108], [111] i [112], a postupci dijagnoze stanja predmet su rada [10]. Procena i pojačavanje razmatrani su u [2] i [41] u Švajcarskoj [40], a prilagodljivost kulturnog nasleđa u [24]. Povredljivost zidanih istorijskih objekata razmatrana je u [4], [6] i [91], a monumentalnih zgrada u Švajcarskoj u [28]. Informacije za vlasnike tretirane su u [31]. Integritet je razmatran u [71]. Značajan doprinos eksperimentalnim ispitivanjima graditeljskog nasleđa dali su istraživači Instituta za zemljotresno inženjerstvo i inženjersku seizmologiju (IZIIS) iz Skoplja, na vibro-plattformi [60]. Projektovanje seizmički otpornih zgrada razmatrano je u [82] i [98], sanacija i pojačavanja u [99], a *retrofitting* u [87]. Procena rizika kulturnog nasleđa tretirana je u [100]. Seizmičke performanse istorijskih i monumentalnih građevina razmatrane su u [103].

- The most common approach is to erect a building with a load-bearing capacity that allows it to withstand an earthquake without significant damage. This method of construction was implemented in all areas that had been known as seismic since the ancient times.

- The second approach is based on preventing a strong connection between the ground and the building, because it is known that a strong connection between the building and seismic ground increases the effects of seismic movements/actions on the building, and a weaker connection reduces them. In historical buildings, the weakening of this connection was achieved in various ways, throwing layers of sand in the earliest times, through clay beds to weighting belts and other sliding elements. Nowadays, this method is also used and it is called by many the passive earthquake protection.

- The third approach is exactly the opposite of the previous one, because it requires certain designs that can change the dynamic characteristics of the building, in order to avoid entering the resonant area. It is considered to be the oldest method of earthquake protection, because each building can change its rigidity, which modifies its structure, and thus the period of its natural vibrations. By displacing outside the vibration periods of the expected seismic action, the building is pulled out of that dangerous state [59].

The importance of organized protection of architectural heritage is evidenced by the formation of research projects in Europe NIKER [84] and PERPETUARE [70]. General aspects of cultural heritage and natural disasters were analyzed in [22] and [97] and with the analysis of heritage damage in seismic areas in [15–16], [27] and [116]. Experiences of seismic protection of cultural heritage buildings after the earthquake in Kraljevo are presented in [42]. Damage mitigation was discussed in [114] and [116]. Protection in developing countries is discussed in [58]. The seismic risk of cultural heritage is discussed in [93]. An analysis of the methods applied in earthquake engineering and the possibilities of their protection are presented in [34]. Methods of inspecting Cultural Heritage sites in Italy are presented in [1], in New Zealand in [3], and in Brazil in [13], in China [116] and in Romania [81]. An assessment of stone historic buildings is presented in [105]. Assessment and vulnerability are the subject of papers [10], [17], [28], [86], [108], and [111–112], and procedures for diagnosing the condition of [10]. Assessment and reinforcement were discussed in [2] and [41] in Switzerland [40], and cultural heritage resilience in [24]. The vulnerability of masonry historic buildings was discussed in [4], [6] and [91], and of monumental buildings in Switzerland in [28]. Information for owners is treated in [31]. Integrity was discussed in [71]. A significant contribution to the experimental research of architectural heritage was made by IZIIS from Skopje, especially on the vibro-platform (Shaking Table Testing) [60]. The design of seismically resistant buildings was discussed in [82] and [98], rehabilitation and strengthening in [99], and retrofitting in [87]. The seismic performance of historic and monumental buildings is discussed in [103].

Za zaštitu graditeljskog nasleđa od posebnog značaja su zidani objekti čija su analiza i ostali aspekti projektovanja šire tretirani u mnoštvu referenci, naročito u [19], [47], [90] i [110], a stari zidani objekti su šire tretirani u [52] i na Seminaru [2]. Odgovor starih zidova u ravni razmatran je u [121]. Prikaz i analiza geometrijskih karakteristika zidanih spomenika kulture u Santjagu–Čile predmet je rada [56], a prikaz kriterijuma seizmičke analize Crkve u Sv. Domingu, dat je u radu [57]. Priprema za ublažavanje posledica zemljotresa u Istočnoj Aziji i Pacifiku opisana je u [55], redukcija gubitaka u [15], a redukcija povredljivosti i pojačavanje istorijskih zgrada u [73]. Egipatske piramide, sa spuštanjem težišta što niže čime se povećava seizmička otpornost, razmatrane su u [37] i [53]. Pojačavanje kotraforima predmet je rada [80]. Šira razmatranja zaštite starih objekata arhitekture predmet su radova [9], [59] i [66], a spomenika u Jermeniji u [48]. Vremenom su razvijene i metode zaštite uvođenjem bazne izolacije [25], [44], [46], [88] i [105], a zaštita i restauracija dati su u [49]. Razvoj zaštite u Japanu opisan je u [85]. Prioritizacija za pojačavanje kulturnog nasleđa opisana je u [7]. Pouke iz dogođenih zemljotresa razmatrane su u [74]. Studije slučaja sa detaljnim analizama, za različite objekte: kulturno nasleđe grada Mendelej [87], minaret [79], Crkva Sv. Sofije [75], zamak [76], crkva u Meksiku [92], zamena kamena pri konzervaciji istorijskih zgrada. Konzervacija je razmatrana u [7], [20], [63] i [114], a njoj je posvećena Konferencija [107]. Problemi procene ponašanja zidanih zgrada i njihove restauracije prema Preporukama Međunarodnog saveta za spomenike i spomeničke celine (ICOMOS) su detaljno prikazani u [17]. Veza prirodnih nepogoda nasleđa u turističke svrha opisana je u [61].

U ovom radu sažeto je prikazan razvoj zemljotresnog inženjerstva, od najstarijih vremena do današnjih dana. Prikazani su neki objekti i mehanizmi koji obezbeđuju otpornost i/ili ublažavanje (mitigaciju) dejstva zemljotresa. Izlaganja su propraćena i osvrtom na naše i internacionalne tehničke propise koji su korišćeni ili se koriste za projektovanje seizmički otpornih konstrukcija. O tome je sačinjen širi popis literature kojom su obuhvaćeni očuvanje, konzervacija, stabilizacija, i mnogi aspekti u vezi s pregledom objekata posle zemljotresa, procenom oštećenja, povredljivosti i procenom ponašanja graditeljskog nasleđa pod seizmičkim dejstvima. Komentarisani su i neki reprezentativni objekti koji su opisani u citiranoj literaturi, uglavnom zidani objekti. Pomenuti su neki materijali i tehnike zaštite graditeljskog nasleđa. U radu nisu obuhvaćeni novi materijali, veće popravke, restauracije, rekonstrukcije, pojačavanja, adaptacije i niz drugih mera nakon zemljotresa, koje će biti predmet drugog rada.

Masonry buildings are especially important for the protection of the built heritage whose analysis and other aspects of design are more widely treated in many references, especially in [19], [47], [90] and [110], and old masonry buildings are more widely treated in [52], and at the Seminar [2]. The response of the old walls in the plane is discussed in [121]. The review and analysis of the geometric characteristics of the masonry cultural monuments in Santiago-Chile is the subject of the paper [56], and the review of the criteria for the seismic analysis of the Church in St. Domingo of [57]. Preparations for earthquake mitigation in East Asia and the Pacific are described in [55], loss reduction in [15], and vulnerability reduction and strengthening of historic buildings in [73]. The Egyptian pyramids, with the centre of gravity lowered as low as possible, which increases seismic resistance, were considered in [37] and [53]. Strengthening with buttresses is the subject of the paper [80]. A broader consideration of the protection of old architectural structures is the subject of papers [9], [59] and [66], and monuments in Armenia in [48]. Over time, protection methods have been developed by introducing the base insulation [25], [44], [46], [88], and [105], and protection and restoration in [49]. The development of protection in Japan is described in [85]. Prioritization of cultural heritage reinforcement is described in [7]. Lessons from the earthquakes were discussed in [74]. Case studies with detailed analyzes of different structures: the cultural heritage of the city of Mandalay [87], the minaret [79], for the Church of St. Sophia [75], Castle [76], Churches in Mexico [92], stone replacement in the conservation of historic buildings [106]. Conservation is discussed in [7], [20], [63], [114] and the Conference [107] was dedicated to it. Problems of assessing the behaviour of masonry buildings and their restoration according to the ICOMOS Recommendations are described in detail in [17]. The connection between natural disasters and heritage tourism is described in [61].

This paper summarizes the development of earthquake engineering since ancient times to the present day. Some structures and mechanisms that provide resistance and/or mitigation of earthquake effects are presented. The presentation has been accompanied by a review of our and international technical regulations that have been used or are being used for the design of seismic structures. A broader list of references has been prepared on this topic, which includes preservation, conservation, stabilization, and many aspects related to the inspection of buildings after the earthquake, assessment of damage, vulnerability and assessment of the behaviour of architectural heritage structures under seismic action. Some representative buildings described in the cited literature were also commented upon, mostly masonry buildings. New materials and techniques for the protection of architectural heritage are also included. The paper fails to include some materials, repairs, restorations, reconstructions, reinforcements, adaptations and other measures that will be the subject of another paper.

2 NAJSTARIJA ISKUSTVA U BORBI PROTIV ZEMLJOTRESA

Najstarije, praistorijske konstrukcije svakako nisu smišljane s namerom da budu zemljotresno otporne, pa ipak izbor teških, kamenih blokova koji su formirali praistorijske megalitske grobne komore, dolmene, uglavnom zadovoljava principe seizmički otpornih građevina. Ove džinovske strukture istovremeno ukazuju na način razmišljanja praistorijskih ljudi, uglavnom iz doba neolita, koji je, bez obzira na geografski položaj gde su ti ljudi živeli, bio skoro identičan. Svest da je potrebno upotrebiti što teže opterećenje da bi se stabilizovali vertikalni elementi uočljiva je kod svih očuvanih dolmena, a pojedine pokrivne ploče bile su teške preko 86 tona (slika 1a), (slika 1b). Slični su i dolmen u Portugaliji (slika 2a), i u Južnoj Koreji (slika 2b).

Slika 1. Dolmen Madlen, Francuska; Dolmen Pentru Ivan, Velika Britanija [122] i [123]
Figure 1. Dolmen de la Madeleine, France (a); Pentrefan Dolmen, Great Britain (b), after [122] and [123]

Slika 2. Dolmen Anta da Pedra da Orca, Portugalija; Dolmen Gočang, Južna Koreja, prema [124] i [125]
Figure 2. Dolmen Anta da Pedra da Orca, Portugal (a); Dolmen Gochang, South Korea (b), after [124] and [125]

Hronološki, prva upotreba zidova kruće obloge i mekog unutrašnjeg jezgra zabeležena je u Mesopotamiji i datira iz perioda stvaranja ove civilizacije, oko 3.700 p. n. e. Gradske zidine od kamena počele su da se formiraju i ranije, ali su njihove dimenzije bile tako velike, a kameni blokovi se oslanjali jedan na drugi, a pod silama pritiska i trenjem (formira se prirodni zglobov), slično praistorijskim zidinama (slika 3). Zidovi zgrada i utvrđenja su i u kasnijim periodima bili značajne debljine, u rasponu od 4 do 20 m. Spoljna obloga je bila od nepečene opeke, a jezgro od trpanca različitog sastava. Hramovi tipa zigurata bili su obloženi, takođe, nepečenom opekrom, retko kamenom, ali ispuna je bila od nasute zemlje ili nepečene opeke i svojom ogromnom težinom i oblikom bila je otporna na zemljotres.

Chronologically, the first use of walls with a rigid cladding and a soft inner core was recorded in Mesopotamia and it dates back to the period when this civilization was created, around 3,700 BC. The stone city walls began to form earlier, but their dimensions were so large, and the stone blocks leaned on each other, and under the forces of pressure and friction (a natural joint is formed), similar to prehistoric walls (Figure 3). The walls of buildings and fortifications were of considerable thickness in later periods, in the range of 4 - 20 m. The outer lining was made of unfired brick, and the core was made of riprap of different composition. Ziggurat-type temples were also lined with unfired brick, rarely with stone, but the filling was made of loose earth or unfired brick, and with its enormous weight and shape, it was resistant to earthquakes.

Iznuđene kao odbrana od velikih poplava bujičnih reka, osmišljene su visoke platforme na kojima su bile izgrađene palate i hramovi. Bile su izvedene od jednoobrazne i simetrično postavljene mase, a time su i značajno spuštale težište cele strukture i tako istovremeno predstavljale odbrambeni sistem od zemljotresa. Dimenzije površinskog zemljotresnog talasa bile su srazmerne dimenzijama platforme, tako da je zadatak velike, krute platforme bio da ublaži taj talas. Građevina na platformi bila je podvrgnuta samo prosečnom pomeranju tla usled zemljotresa, bez nepredvidljivih pikova (slika 4).

High platforms on which palaces and temples were built were a forced solution as a defence against large floods of torrential rivers. They were made of a uniform and symmetrically placed mass, and thus at the same time significantly lowered the centre of gravity of the entire structure and simultaneously represented the earthquake resistant system. The dimensions of the surface earthquake wave were proportional to the dimensions of the platform, so the task of the large, rigid platform was to mitigate that wave. The building on the platform was subjected to only average ground movement due to the earthquake, without unpredictable peaks (Figure 4).

Slika 3. Poprečni presek kroz zid Kapije boginje Ištar, Vavilon; Novosumerski zigurat u Uru, prema [126]
Figure 3. Cross section of the Ishtar Gate of Babylon; New-Sumerian ziggurat of Ur, after [126]

Slika 4. Rekonstrukcije Palate Sargona II u Korsabadu (Dur-Šarukin) i preseka kroz jugozapadni deo platforme sa oblogom i ispunom, prema [127]
Figure 4. Reconstruction of the Sargon II palace in Khorsabad (Dur-Sharrukin) and the cross section of the western part of the platform with the lining and fill, after [127]

Iskustvo egipatskih graditelja jedno je od najznačajnijih u istoriji građenja. Nekoliko hiljada godina pre naše ere egipatski graditelji su primenjivali neke postupke zaštite od zemljotresa, koji se i danas koriste. Iako ne postoje zapisi o planovima izgradnje ili tekstovi o načinima gradnje, arheološka istraživanja, ipak, daju određene podatke. Najveća pažnja je bila posvećivana pripremi terena ispod temelja, tako da se danas smatra da su Egipćani poznavali neke zakonitosti koje se u savremenoj praksi podvode pod mehaniku tla. Temelji koji su urađeni u kompleksu najstarije, Đoserove piramide, bili su kamene ploče koje su služile kao temelji, ali i kao trotoari. Mnoge druge strukture iz

The experience of Egyptian builders is one of the most significant in the history of construction. Several thousand years BC, the Egyptian builders implemented certain earthquake protection procedures, which are still used today. Although there are no records of construction plans or texts on construction methods, archaeological research still provides some information. The greatest attention was paid to the preparation of the ground below the foundations, so that it is nowadays considered that the Egyptians had knowledge of some laws that are in modern practice the subject of soil mechanics. The foundations that were made in the complex of the oldest, the Djoser pyramid, were stone

perioda starih dinastija, pre svega piramide, postavljane su na neku vrstu "temelja" koji su se sastojali od samo tri reda kamenih blokova. Keopsova piramida u Gizi izgrađena je na čvrstoj krečnjačkoj steni i zbog toga joj nisu bili potrebni posebni temelji. Od kasne četvrte dinastije (2613–2494 p. n. e.) i nadalje, temeljni blokovi bili su postavljeni u roveve urezane u zemlju i ispunjeni pustinjskim peskom.

Građevine postavljene na čvrstoj steni često nisu imale duboke temelje. U ranoj Dvanaestoj dinastiji (1991–1802. p. n. e.) prvi put se potvrđuje metoda izravnavanja tla. Mekana zemljišta su uklanjana i zamenjivana novim, peskovitim materijalom, što je i danas jedna od široko primenjivanih metoda. Jedan način bio je postavljanje velikog broja manjih blokova (koji se ponekad uzimaju iz starijih objekata) koji stvaraju neku vrstu podzemne platforme na kojoj je podignuta građevina. Drugi način je bio da se u pripremljene temeljne jame ili trake nasipa suvi pesak, koji je zbog svoje kompaktnosti izvanredno podnosio pritisak. Slično su Egipćani postupali i sa stenovitim podlogama, koje su nivelisali do horizontalnog položaja, a preko tako zaravnjene podloge nasipali su, takođe, sloj peska. Uloga pešćanog sloja bila je dvojaka. S jedne strane, opterećenje građevine ravnomerno se prenosilo na tlo, pa otuda nema koncentracije napona u temeljima. S druge strane, sloj peska je imao funkciju izolacionog sistema koji je upijao seizmičke talase i omogućavao građevini da klizi preko njega tokom pokreta tla (slika 5a i slika 5b).

slabs that served as foundations, but also as sidewalks. Many other structures from the period of the old dynasties, primarily the pyramids, were laid on a kind of "foundation" that consisted of only three rows of stone blocks. The Pyramid of Cheops in Giza was built on solid limestone and therefore did not need special foundations. Since the late Fourth Dynasty (2613-2494 BC) onwards, the foundation blocks were placed in trenches carved into the ground and filled with pure desert sand.

Buildings built on solid rock often were without deep foundations. In the early Twelfth Dynasty (1991-1802 BC), the method of levelling the ground was confirmed for the first time. Soft soils were removed and replaced with new, sandy material, which is still one of the widely used methods. One way was to set up a large number of smaller blocks (sometimes taken from older buildings) that created a kind of underground platform on which the building was erected. Another way was to pour dry sand into the prepared foundation pits or strips, which, due to its compactness, withstood the pressure extraordinarily well. The Egyptians acted similarly in the case of rock beds, which were levelled to a horizontal position, and also a layer of sand was poured over such a flat surface. The role of the sand layer was twofold. On one hand, the load of the building was evenly transferred to the ground, so there is no concentration of stress in the foundations. On the other hand, the sand layer had the function of an insulating system that absorbed seismic waves and allowed the building to slide over it during ground movement (Figure 5a and Figure 5b).

Slika 5. Platforma grobnog hrama u Deir-el-Bahariju; Kompleks grobnica graditelja piramida kod Gize, prema [101] i [129]

Figure 5. Platform of the sepulchral temple in Deir-el-Bahari (a); The complex of tombs of the Giza pyramid builders (b), after [101] and [129]

Mlađa, kritsko-mikenska (egejska) civilizacija (~3.000. do 1100. g. p. n. e) razvijala se na području Egejskog mora, poznatom po velikoj seizmičkoj aktivnosti. Česti zemljotresi su svakako, već u najstarije doba, zahtevali odgovarajuće iskustvo u građenju otpornih struktura. To se najbolje može saznati na osnovu istraživanja palate u Knososu, na Kritu (2100–1600. p. n. e). Konstrukcijski sistem palate uglavnom je rekonstruisan prilikom arheoloških otkopavanja, ali je dugo bilo otvoreno pitanje oblikovanja stubova, koji su bili širi pri vrhu, a uži pri dnu, što u graditeljskom smislu nije uobičajeno. Danas je predložena teorija da je

The younger, Cretan-Mycenaean (Aegean) civilization (~ 3,000 to 1100 BC) developed in the Aegean region, known for its high seismic activity. Frequent earthquakes certainly, from the earliest times, required appropriate experience in building resilient structures. This can best be learned from the research of the palace in Knossos, Crete (2100-1600 BC). The structural system of the palace was mostly reconstructed during the archeological excavations, but the issue of the pillars shape remained open for a long time, as they were wider at the top and narrower at the bottom which is uncommon in the architectural terms. Today, the

ovakav oblik stuba proistekao iz potrebe seizmičke otpornosti. Oblik kapitela stuba je pogodan da prihvati jedan deo gredne konstrukcije, dok je u bazi, sužavanjem stuba u odnosu na vrat, formiran zglob. Na taj način, stub može biti samo pritisnut, ali ne i izvijen. Pored ove osobenosti u oblikovanju stubova, osiguranje velikih trospratnih, pa i višespratnih zgrada bilo je izvedeno veoma dubokim fundiranjem velikog broja podužnih i poprečnih zidova, koji su međusobno bili povezani. Broj temeljnih zidova bio je znatno veći od broja zidova na spratovima zgrada (slika 6 a i b).

Slika 6. Deo palate sa stubovima u Knososu na Kritu; Ostaci palate u Malji na Kritu, prema [113 i [130]
Figure 6. Part of the palace with columns in Knossos on Crete (a); remains of the palace in Malia on Crete (b) after [113] and [130]

U Mikenskoj kulturi na prostoru ispod akropolja nalazile su se grobnice specifično oblikovane sa tzv. lažnim svodom nad kružnom osnovom. Analizom načina formiranja krivine u vertikalnom preseku, koja je bila dobijena postepenim ispuštanjem kamenih blokova, različite veličine oblika i težine, slaganih od baze ka temenu, kao i rasteretnih trougaonih šupljina nad otvorom i zemljanog nasipa koji je stvorio odgovarajući pritisak preko celokupne strukture može se zaključiti da su i tu bili zadovoljeni svi glavni principi aseizmičkog delovanja (slika 7).

In the Mycenaean culture, in the area below the acropolis, there were tombs specifically shaped with the so-called false vault over circular base. The tholos tomb was of a circular, underground, stone structure with an interior rising to a point. The stone construction was obtained with corbelled system where each higher row of stones overlaps or projects farther into space. The analyses of the way of forming the curve in the vertical section, as well as triangular hole over the entrance lintel and the weight of the earth above the construction that created the appropriate pressure over the entire structure indicate that all the main principles of seismic action were satisfied here as well (Figure 7).

Slika 7. Osnova, presek i ulaz "Atrejeve" riznice u Miken, prema [131]
Figure 7. Layout, section and entrance to the Treasury of Atreus in Mycenae, after [131]

Za razliku od kritsko-mikenske, arhitektura antičke Grčke i iz perioda helenizma nije tako uspešno odolevala zemljotresima, pošto je uočeno da je većina grčkih hramova bila oštećena u brojnim zemljotresima. Iako analize modela građevina koje su građene isto kao i grčki hramovi, bez bočnih potisaka, s ravnomerno opterećenim elementima od kamena i s potpunom simetrijom svih konstrukcijskih elemenata, pokazuju da do rušenja usled zemljotresa ne bi trebalo da dođe, grčki hramovi su urušeni, jer se na njima uočavaju dva nedostatka. Prvi se iskazuje u veoma visokom podignutom opterećenju delova same građevine, u obliku snažnih arhitravnih greda, frizeva, venaca i timpanona, a drugi se odnosi na neravnomernu krutost strukture.

Ogromna kamena masa koncentrisana na velikoj visini izaziva neizbežnu inerciju seizmičkih sila tokom potresa, koje ruše najveći deo građevine. Smatra se da su grčki graditelji pokušavali da se od zemljotresa brane konsolidacijom terena i pravilnim fundiranjem. Tako je Herin hram u Olimpiji, jedan od najstarijih primera dorskog stilskog reda (VI vek p. n. e.) bio podignut na posebnoj platformi sagrađenoj na gusto pobijenim šipovima, između kojih se nalazio nasip od lomljenog kamena i šljunka. S obzirom na to što su poluostrvo Peloponez na kojem se nalazi Olimpija, kao i cela Grčka, područje za koje je poznato da je često bilo pogađano zemljotresima, ovaj način temeljenja je, najverovatnije, bio smišljen kako bi se građevina oduprla seizmičkim udarima (slika 8 a i b).

Unlike Cretan-Mycenaean, the architecture of ancient Greece from the Hellenistic period failed to successfully withstand earthquakes since it was noticed that most Greek temples were damaged in numerous earthquakes. Although analyses of models of buildings built in the same way as Greek temples, without lateral thrusts, with evenly loaded stone elements and complete symmetry of all structural elements, show that the collapse due to earthquakes should not occur. Greek temples collapsed because they had two deficiencies. The first is the load of the parts of the building itself elevated to a great height, in the form of strong architrave beams, friezes, cornices and tympanums, and the second refers to the non-uniform rigidity of the structure.

A huge rock mass concentrated at a great height causes the inevitable inertia of seismic forces during earthquakes, which destroyed most of the building. It is believed that the Greek builders tried to protect from the earthquake by consolidating the terrain and by proper founding. Thus, the temple of Hera in Olympia, one of the oldest examples of the Doric style (6c. BC), was erected on a special platform built on densely driven piles, between which there was an embankment of crushed stone and gravel. Since the Peloponnese peninsula on which Olympia is located, as well as the whole of Greece, is a well-known area often affected by earthquakes, this method of foundation was designed to withstand seismic shocks (Figure 8 a and b).

Slika 8. Temeljne zone Herinog hrama u Olimpiji i Apolonovog hrama u Delfima, [72] i [62]
Figure 8. Foundation zones of the Temple of Hera in Olympia and Temple of Apollo in Delphi, after [72] and [62]

Današnje stanje grčkih hramova najbolje svedoči o navedenim nedostacima, pošto nijedan primer nije sačuvan u celosti, već im nedostaje upravo deo nadstublja, koji je bio najteži i koji se urušavao pri svakom zemljotresu. Najbolje sačuvanom grčkom hramu, Tezeonu (Hefestionu) na atinskoj agori, takođe nedostaje i krov, iako je veliki broj tavanjača ostao sačuvan (slika 9).

The present day condition of Greek temples is the best evidence of the mentioned shortcomings, because no structures have been preserved in their entirety, but they are missing exactly the part of the superstructure, which was the heaviest and which collapsed during every earthquake. The best-preserved Greek temple, Theseus (Hephaestion) on the Athenian Agora, also lacks a roof, although a large number of roof beams have been preserved (Figure 9a) and (Figure 9b).

Slika 9. Ostaci krovne konstrukcije hrama Tezeon (Hefestion) u Atini i urušena krovna konstrukcija hrama u Segesti, prema [prvi autor 62]

Figure 9. Remains of the roof structure of the temple of Theseus (Hephaestion) in Athens (a) and the collapsed roof structure of the temple in Segesta (b), after [authors] and [62]

Seizmički otporne konstrukcije nastale u doba Rimske imperije (do kraja V veka n. e.) i starijeg perioda stvaranja Vizantijskog carstva mogu se zajednički posmatrati, zbog graditeljskog iskustva koje se prenelo iz jednog stilskeg perioda u drugi. Rimska tehnika građenja seizmički otpornih građevina oslanja se na veštinu primene rimskog "betona" na zidanje svodnih konstrukcija, posebno kupola. Graditelji su se bavili i otpornošću lučnih konstrukcija i njihovih veza na seizmičke sile. Kao i u mnogim drugim slučajevima, i u ovom je za analizu najpogodnija konstrukcija velikog hrama posvećenog svim rimskim božanstvima, Panteona u Rimu, čije su osnovne karakteristike sa stanovišta seizmičke stabilnosti zadovoljavajuće. U analizi kupole Panteona, koja se sastoji iz dva skeletna sistema, koja su međusobno povezana, iznenađuje činjenica da se rebra ta dva sistema nigde ne poklapaju po vertikali, iako je očigledno da sistemi deluju jedinstveno (Slika 10).

Seismically resistant structures created during the Roman Empire (until the end of the 5th century AD) and in the early period of the Byzantine Empire creation can be observed as one, because of the construction experience that was transferred from one stylistic period to another. The Roman technique of building seismically resistant buildings relies on the skill of using to Roman "concrete" in the construction of vaulted structures, especially domes. The Roman builders also dealt with the resistance of arched structures and their joints to seismic forces. As in many other cases, the most convenient for an analysis is the structure of a large temple dedicated to all Roman deities, the Pantheon in Rome, whose basic characteristics are satisfactory from the aspect of seismic stability. In the analysis of the Pantheon dome, which consists of two skeletal systems, which are interconnected, it is surprising that the ribs of these two systems do not coincide vertically, although it is obvious that the systems act in unison (Figure 10).

Slika 10. Kupola hrama Panteon u Rimu: presek i izgled, prema [132]

Figure 10. Pantheon Temple dome, Rome: cross section diagram and appearance, after [132]

3 ISKUSTVA U BORBI PROTIV ZEMLJOTRESA TOKOM SREDNJEG I NOVOG VEKA

U graditeljskom smislu, nakon propasti Rimske imperije, stvaralaštvo se idejno postepeno razdvojilo u dva osnovna pravca. Istočni deo nekada ogromne države razvio se u Vizantijsko carstvo koje je snažno uticalo na svoje okruženje.

Proučavanje seizmičke stabilnosti vizantijskih građevina prevashodno se zasniva na konstrukcijskom umeću Antemija iz Trala i Isidora iz Mileta, primenjenom na Crkvi Svete Sofije u Carigradu u VI veku. Kako je ova crkva bila u velikoj meri predmet pažljivih i produbljenih istraživanja, pri čemu se stalno analiziraju i konstrukcijska rešenja i posledice nekoliko zemljotresa, koji i danas pogađaju ovo područje, ona ovde nije posebno prikazana. Ipak, treba istaći da njena otpornost na zemljotrese u gornjim zonama, gde se nalaze glavna kupola, podržavajuće polukalote i niže postavljene utežuće četvrtine sfera, nikada nije bila potpuno kvalitetna, ali da se povećavala kroz vreme, kako su graditelji empirijski sticali sve temeljnije iskustvo u građenju seizmički otpornih konstrukcija (slika 11) [4].

3 EXPERIENCES IN THE STRUGGLE AGAINST EARTHQUAKE DURING THE MIDDLE AND NEW AGES

In the architectural sense, after the decline of the Roman Empire, the creative art gradually bifurcated into two basic directions. The eastern part of the once huge state developed into the Byzantine Empire, which strongly influenced its surroundings.

The study of the seismic stability of Byzantine buildings is primarily based on the construction skills of Anthemius of Tralles and Isidore of Miletus, applied to the church of St. Sophia in Constantinople in the 6th century. As this church has been largely the subject of careful and in-depth research, and constant analyses of structural designs and the consequences of several earthquakes, which have hit this area to this day, it is not specifically presented here. However, it should be noted that its resistance to earthquakes in the upper zones, where the main dome, supporting semi-domes and lower bracing quarters of the spheres are located, was never of full quality, but increased over time as builders empirically gained more and more experience in construction of seismically resistant structures (Figure 11) [4].

Slika 11. Postepeno formiranje noseće konstrukcije velike kupole Crkve Svete Sofije u Carigradu, prema [67]
Figure 11. Gradual formation of the supporting structure of the large dome of the Church of St. Sophia in Constantinople, after [67]

Crkve kijevske Rusi, razvijane pod velikim uticajem vizantijskog iskustva, na prvom mestu Saborna crkva Svete Sofije u Kijevu, građene su tehnikom tzv. skrivenih ili uvučenih redova opeke, koji su spolja pokriveni malterom, koji deluju kao spojnice iste debljine kao i redovi opeke. Ispitivana su svojstva opeka i krečnog maltera s keramičkim aditivom (mehanička čvrstoća, mineraloške, hemijske i mikrostrukturne analize) i one su pokazale veliku sličnost s ranovizantijskim građevinama Carigrada, potvrđujući svojstva seizmički otpornih tehnika građenja i materijala koji su obezbeđivali kontinualne napone i dilatacije (slika 12).

U poznijim periodima srednjeg veka, religijske građevine u istočnim delovima Evrope nisu više bile tako velikih dimenzija, prilagođavajući nasleđenu primenu konstrukcijskih sistema i tehnika građenja.

The churches of Kievan Rus', developed under the considerable influence of the Byzantine experience, primarily the cathedral church of St. Sophia in Kiev, were built using the technique of so-called "hidden" or indented rows of bricks, which are covered with mortar on the outside, which appear as joints of the same thickness as the rows of bricks. The properties of bricks and lime mortar with ceramic additive (mechanical strength, mineralogical, chemical and micro structural analyzes) were examined and they showed great similarity with the early Byzantine buildings of Constantinople, confirming the properties of seismically resistant construction techniques and materials that are properties of continuous stress and expansion (Figure 12).

In the later periods of the Middle Ages, religious buildings in the eastern parts of Europe were no longer so large, adapting the inherited application of construction systems and construction techniques.

Slika 12. Prezentacija tehnike građenja i rekonstrukcija prvobitnog oblika Crkve Svete Sofije u Kijevu, prema [133]
Figure 12. Presentation of construction techniques and reconstruction of the original shape of the Church of St. Sophia in Kiev, after [133]

Izrazito trusno područje, a istovremeno veoma bogato srednjovekovnim građevinama, jesu Jermenija, Gruzija i zemlje bliskog Istoka i centralne Azije. Na ovom prostranom području iskustva su bila razna i ne uvek uspešna. Mnoge crkve, kao na primer ona u Bagaranu, ispunjavale su sve uslove postavljene s ciljem zaštite od zemljotresa. Druge, izuzetne arhitektonske prefinjenosti, kao crkva u Zvartnocu, rušile su se u zemljotresima, od kojih je naročito razoran bio u X veku. Uzrok rušenja bila je neravnomerna raspodela krutosti na nivou osnove prizemlja, kao i izvijanje do kojeg je došlo u osam svodova velikog raspona od kamena prilikom zemljotresa [5].

Prirodne katastrofe imale su velik uticaj na srednjovekovni svet. Postoji čitav niz svedočanstava o uništavanju gradova ili regiona i o desetinama hiljada mrtvih ili beskućnika. O ovim katastrofama: zemljotresima, poplavama, vulkanskim erupcijama pisali su hroničari tog vremena, koji su ostavili živopisne izveštaje o uništenju koje su prouzrokovali (slika 13). Među deset najtežih prirodnih katastrofa koje su se desile u srednjem veku u Evropi izdvaja se zemljotres na Siciliji iz 1169. godine. O njemu hroničar piše da je bogati grad Katanija bio tako pogođen da su sve kuće bile srušene.

The region of Armenia, Georgia and the countries of the Middle East and Central Asia are rich in the medieval buildings but also an area of high seismic activity. In this vast area, the experiences have been varied and not always successful. Many churches, such as the one of St. Theodor of Bagaran, satisfied all the conditions set for earthquake protection. Others, possessing exceptional architectural refinement, such as the Zvartnots Cathedral, collapsed in earthquakes, of which one in the 10th century was particularly devastating. The cause of the collapse was the uneven distribution of stiffness at the level of the ground floor, as well as the buckling that occurred in eight large span stone arches during the earthquake [5].

Natural disasters had a great impact on the medieval world. There is a number of testimonies about the destruction of cities or regions and about tens of thousands of people left dead or homeless. Chroniclers of the time wrote about these catastrophes: earthquakes, floods, volcanic eruptions, and left vivid reports of the destruction caused by disasters (Figure 13). Among the ten most severe natural disasters that occurred in the medieval times in Europe, the earthquake in Sicily of 1169 stands out. The chronicler wrote that the rich city of Catania was so affected that all the houses were destroyed.

Slika 13. Srednjovekovna predstava posledica zemljotresa i gravira srednjovekovnog zemljotresa iz XVI veka, prema [134] i [135]
Figure 13. Medieval representation of the effects of an earthquake and engraving of a medieval earthquake from the 16th century, after [134] and [135]

Većina srednjovekovnih zgrada fundirana je na plitkim temeljima. Obično su građene od bondruka, kamena ili opeke i raznih vrsta maltera kao veziva. Na zapadu Evrope, u pred-romaničko doba (do X veka), uobičajeni način postavljanja temelja na noseće tlo bilo je ubacivanje trpanca i raznih otpadaka u iskop, koji je bio jednak ili nešto širi od podzemnog dela građevine. Preko te ispuce sipan je vrlo loš (siromašan) malter kao vezivo. Veličina temelja po pravilu je zavisila od raspoloživog prostora, a ne od aktivnog opterećenja i nosivosti. Tipični romanički temelji (od XI do XIII veka) bili su pravljeni tako što se iskop oblagao velikim balvanima, a onda je u jamu bacan trpanac ili manje kamenje, a zatim je preko te mase sipan krečni malter (slika 14). Ponekad izbor terena nije bio dobro odmeren, pa su graditelji intervenisali, kao što je to bio slučaj prilikom izgradnje tornja-zvonika u Pizi na previše mekanom tlu.

Slika 14. Primeri romaničkog temeljenja, prema [96]
Figure 14. Examples of Romanesque foundations, after [96]

Temelji u periodu Gotike (XII–XVI vek) bili su, generalno, boljeg kvaliteta, s malterom dobrog kvaliteta i bolje isečenih kamenih blokova ili, kasnije, sa običnim opekama. Često su spoljašnje strane temelja bile obložene tesanicima. Veća pažnja je posvećivana izboru lokacija za građenje i to mesto je obično (ali ne uvek) bilo dobro izabrano, i kvalitet tla je prethodno proveravan. Temelji nisu uvek bili širi od zidova iznad njih, zidovi od opeke mogli su biti oslonjeni na slojeve kamenja, što je činilo da pritisak na tlo bude vrlo intenzivan. Postojali su i temelji u obliku kružnih jama punjenih zidarijom, pored kojih su građeni lukovi koji su se povezivali s temeljem na određenom nivou i tako služili kao podupirači. U naseljima pored reka, mora ili jezera gde se nije moglo kopati ispod nivoa vode ili zamenjivati mekano tlo peskom ili šljunkom, koristila se stara, još od Starog veka poznata, tehnika gustog pobijanja kratkih drvenih šipova (slika 15a). Time se opterećenje prenosilo na dublje slojeve sposobne da podnesu nosivost temelja. U poznijim periodima, od XVI stoleća počeli su da se koriste duži i deblji drveni šipovi u različitim kombinacijama s roštiljem preko njih (slika 15b). S obzirom na to što je većina srednjovekovnih

Most medieval buildings were founded on shallow foundations. They were usually built in post-and-rap system, stone or brick and various types of mortar as binders. In the west of Europe, in the pre-Romanesque period (until the 10th century), the usual way of laying the foundations on the soil was to place riprap and various debris into the excavation pit, which was equal to or somewhat wider than the underground part of the building. A very poor (lean) mortar was poured over that filling as a binder. As a rule, the size of the foundation depended on the available space, and not on the active load and bearing capacity. Typical Romanesque foundations (11th to 13th century) were made by lining the excavation pit with large logs, and then throwing riprap or smaller stones into the pit, and then pouring lime mortar over that mass (Fig. 14). Sometimes the choice of terrain was not the best, so the builders had to intervene, as it was the case with construction of the bell tower in Pisa on excessively soft ground.

Foundations in the Gothic period (12th to 15th/16th century) were, in general, of better quality, with good quality mortar and better cut stone blocks or, later, with ordinary bricks. The exterior sides of foundations were often lined with hewn stones. Greater attention was paid to the choice of construction sites and that location was usually (but not always) well chosen, and the quality of the soil was previously inspected. Foundations were not always wider than the walls above them, the brick walls could be supported by layers of stones, which made the pressure on the ground very intense. There were also foundations in the form of circular pits filled with masonry, with arches built next to them connected with the foundations at a certain level thus serving as supports. In settlements near rivers, seas or lakes where it was impossible to dig below the water level or replace the soft soil with sand or gravel, the old technique of densely driven short wooden piles, known since the ancient times, was used (Figure 15a). This transferred the load to deeper layers capable of providing the load-bearing capacity of the foundations. In later periods, starting with the 16th century, longer and thicker wooden piles began in various combinations to be used with a

građevina rađena u bondručnom sistemu, ili kao zidane zgrade od opeke, kamena ili u kombinaciji, sa ovakvim sistemima temeljenja nisu mogle da izdrže snažnije dejstvo zemljotresa. Usled toga je broj delimično ili potpuno porušenih naselja, kao i broj žrtava, kao posledica zemljotresa u srednjem veku bio velik. U pojedinim slučajevima, nakon ovakvih katastrofa, graditelji su sticali nova iskustva i dolazili do novih ideja zaslužnih za stvaranje novih stilskih i konstruktivnih dometa.

Slika 15. Primeri temeljenja na plitkim i dubokim šipovima u gotici, prema [96]
Figure 15. Examples of foundations on shallow (a) and deep (b) piles in the Gothic period, after to [96]

U graditeljskom smislu, odnos renesanse i srednjeg veka je veoma složen i zamršen. Humanisti su igrali odlučujuću ulogu u redefinisanoj funkcije arhitekta. Njihovo neograničeno divljenje za klasične modele u literaturi stimulisalo je proučavanje rimskih ostataka u svim oblastima stvaralaštva. Oni su očekivali da će taj novootkriveni rečnik formi biti upotrebljen i u savremenoj arhitekturi. Ostaci građevina iz rimskog doba bili su glavni uzori za novi stil, renesansu, koji se počeo razvijati dvadesetih godina XV stoleća u Italiji.

Renesansa je jedan od onih stilskih pravaca kod kojih je uobičajen dvojni arhitektonski jezik. Jedan način izražavanja je konstruktivno-strukturalan, a drugi je plastičan. To znači da tehnička struktura zgrade ne mora odgovarati arhitektonskoj artikulaciji. To je bila revolucionarna ideja u arhitekturi, jer je dekoracija, odnosno ukrašavanje zgrade, bila odvojena od konstrukcije i nije joj morala u potpunosti odgovarati. Zato nije bilo upadljivo novih konstrukcijskih inovacija kada je u pitanju temeljenje i formiranje korpusa građevine, ali su napredovali sistemi građenja svodnih i kupolnih konstrukcija.

Polazeći od konstrukcije kupole i cele strukture rimskog Panteona i njegove proverene seizmičke otpornosti, treba odmah, odstupajući od hronološke periodizacije, ukazati na zajedničku nit koja konceptijski povezuje i sve kasnije slične oblike kupola, kao što su renesansna kupola Crkve Santa Marija dei Fiori u Firenci (XV vek) i niz predloga za izgradnju kupole Svetog Petra u Rimu (XVI vek) [3]. Ideja o dva skeletna sistema, sastavljena od vertikalnih rebara i u horizontalnim redovima postavljenih lukova pokazala se do danas

grillage over them (Fig. 15b). Since most of the medieval buildings were made in the post-and-pan system, or as masonry buildings made of brick, stone or in their combination, with such foundation systems they could not withstand the more intensive effects of earthquakes. As a result, the number of partially or completely destroyed settlements, as well as the number of victims, due to earthquakes in the Middle Ages was large. In some cases, after such catastrophes, builders gained new experiences and came up with new ideas that were responsible for creating new stylistic and structural achievements.

In the architectural sense, the relationship between the Renaissance and the Middle Ages is very complex and intricate. Humanists played a decisive role in redefining the function of the architect. Their boundless admiration for classical models in literature stimulated the study of Roman remains in all areas of creative arts. They expected that this newly discovered vocabulary of form would be used in modern architecture as well. The remains of buildings from the Roman era were the main models for the new style, the Renaissance, which began to develop in Italy in the 15s.

The Renaissance is one of those styles in which a dual architectural language is common. One manner of expression is constructive-structural, and the other is plastic. This means that the technical structure of the building does not have to correspond to the architectural articulation. It was a revolutionary idea in architecture, because the decoration of buildings, was separate from the construction and did not have to correspond to it completely. That is why there were no noticeable new structural innovations when it comes to the foundations and formation of the building core, but rather there were improvements of building systems of vaulted and domed structures.

Starting from the construction of the dome and the whole structure of the Roman Pantheon and its proven seismic resistance, we should immediately, deviating from the chronological periodization, emphasize a common thread that conceptually connects all later similar forms of domes, such as the Renaissance dome of Santa Maria dei Fiori in Florence (15th century) (Figure 16a) and a number of proposals for the construction of

veoma otpornom, pa postoji niz primera izvedenih u različitim materijalima. S obzirom na to što o svim kupolama i, uopšte, konstrukcijama reprezentativnih zgrada novijeg doba postoje pisani tragovi od ideje do realizacije, a zatim, i o praćenju njihovog ponašanja, može se zaključiti da su sve one pokazale veliku otpornost na zemljotrese koji su, takođe, kroz istoriju od vremena nastanka tih građevina bili registrovani.

a)

b)

Slika 16. Aksonometrijski presek kroz kupolu Crkve Santa Maria dei Fiori u Firenci (a); Mikelandelov crtež preseka kupole Crkve Svetog Petra u Rimu (b), prema [136]

Figure 16. Axonometric cross section of the Santa Maria dei Fiori church dome in Florence (a); Michelangelo's drawing of the cross-section of the dome of St. Peter's Church in Rome (b), after [136]

U Japanu, izuzetno trusnom području tokom cele istorije, stari graditelji su unapređivali konstrukcije višespratnih hramova od drveta, pagoda, koje su prvobitno loše podnosile zemljotresne udare i rušile se. Kako bi anulirali nemogućnost prijema vibracija od zemljotresa, u vertikalnu osu građevine je ubačen stubac, postavljen u cilindričnu čašicu, koji je unosio pritisak i povećavao otpornost na savijanje konzolne konstrukcije. Pri vibriranju pagode usled zemljotresa, deo energije vibracija pretvarao se u vibracije stupca, koji je udarcima na strane čašice disipirao energiju (slika 17). U savremenim uslovima, isti rezultat postiže se opremom koja automatski reaguje na seizmička dejstva, što je predmet upravljanja konstrukcijama.

Ostali su tragovi da su mere zaštite posle nekog zemljotresa u Japanu, obavljene još 1362. Tada su na staroj učionici (Kodo) budističkog hrama u Kjotu bile postavljene horizontalne drvene grede kao ojačanje. Ista učionica bila je potpuno urušena u zemljotresu iz 1596. godine i ponovo podignuta upotrebom originalnih drvenih delova. Do danas su ostali tragovi tih upotrebljenih delova na vrhu i pri dnu unutrašnjih stubova. Japan se od davnina neprekidno bori s razarajućim posledicama zemljotresa i zato je njihov razvoj iskustva u načinima odbrane od ove prirodne nepogode veoma značajan [85].

In Japan, an area of exceptional seismic activity throughout history, ancient builders improved the construction of multi-storey timber temples, pagodas, which initially poorly withstood earthquakes and collapsed. In order to prevent the transfer of vibrations from the earthquake, a column was inserted into the vertical axis of the building, placed in a cylindrical socket, which introduced pressure and increased the resistance to bending of the cantilever structure. When the pagoda vibrated due to the earthquake, part of the vibration energy was converted into oscillations of the column, which dissipated energy by hitting the socket sides (Figure 17). In contemporary conditions, the same result is achieved with the equipment that automatically responds to seismic actions, which is the subject of structures management.

There are traces that protection measures were carried out after an earthquake in 1362. At that time, horizontal wooden beams were placed as reinforcement in the old teaching hall (Kodo) of the Buddhist temple in Kyoto. The same teaching hall was completely destroyed in the earthquake of 1596 and rebuilt using the original wooden parts. To this day, traces of these used parts remain at the top and bottom of the inner columns. Japan has long struggled with the devastating effects of earthquakes and that is why the development of their experience in defending against this natural disaster is very significant [85].

Slika 17. Shema višespratne pagode i Velika pagoda u Nari, prema [62]
Figure 17. Diagram of the multi-storey pagoda and the Great pagoda in Nara, after [62]

Do XIX stolecja konstrukcijski sistemi su stalno unapređivani, ali su revolucionarni pomaci vezani za nove materijale, tehnologije i tehnike građenja nastali krajem XIX i tokom XX veka i dalje su razvijani do danas.

Ipak, i u periodu baroka graditelji su, naročito u izrazito trusnim područjima, pokušavali da građenje prilagode odbrani kod katastrofalnih šteta, odnosno od potpunog rušenja objekata. Jedan od interesantnih načina odbrane nastao je u kolonijama, u kojima su katoličke misije, najčešće španske, izgradile mnogo crkvenih građevina.

Rezultati numeričkih analiza reprodukovali su uočena oštećenja i potvrdili da vanfazno propadanje fasada nije kritično kod ove vrste crkava u Meksiku. Veoma zanimljiv rezultat je da je poprečni pravac najfleksibilniji, s kulama/zvonicima ili bez njih. Vertikalna vibracija svodova je drugo globalno rešenje, a treće je podužna vibracija broda. To nastaje, uglavnom, zbog velike debljine bočnih zidova i debljine svoda. Bočne potpore pomažu u smanjenju vanjskih oštećenja bočnih zidova. Drugi zanimljiv rezultat je da prisustvo kula/zvonika povećava oštećenja fasada. Kule/zvonici građene su kao integralni deo s fasadom, a ne nezavisno. Kule/zvonici, zato, ograničavaju smanjeno kretanje van ravni bočnih zidova, ali povećavaju unutarnju ravan fasade (slika 18a) [92].

Na Filipinima je monaški red Augustinaca podigao nekoliko crkava u periodu 1790–1800. godine u izrazitoj "zemljotresnoj baroknoj" arhitekturi. Te crkve su bile zdepaste i nisu bile toliko visoke, i sledile su stil koji je usvojen u seizmičkim zonama Meksika i Južne Amerike; Stvorena je nova "mestizo" arhitektura i to se, najčešće, prevodi kao i "zemljotresni barok". Kada su 1863. i 1880. godine zemljotresi, ponovo, opustošili Manilu, skoro sve građevine su se urušile, izuzev, opet, Crkve Svetog Avgustina (slika 18b).

Until the 19th century, construction systems were constantly improved, but the revolutionary leaps related to new materials, technologies and construction techniques that emerged in the late 19th and during the 20th century have continued to develop to this day.

However, even in the Baroque period, builders, especially in extremely seismic areas, tried to adapt the construction to resist catastrophic damage, i.e. the complete collapse of buildings. One of the interesting ways of aseismic adaptations originated in the colonies, in which Catholic missions, mostly Spanish, built a large number of church buildings.

The results of numerical analyzes reproduced the observed damage and confirmed that out-of-phase deterioration of facades is not critical in this type of church in Mexico and South American countries. A very interesting result is that the transverse direction is the most flexible, with or without towers/bell towers. The vertical vibration of the vaults is the second global solution, and the third is the longitudinal vibration of the nave. This is mainly due to the great thickness of the side walls and the thickness of the vault. Side supports help reduce external damage to the side walls. Another interesting result is that the presence of towers/bell towers increases the damage to the facades. Towers/bell towers were built as an integral part with a facade, not independently. Towers/bell towers, therefore, restrict reduced movement outside the plane of the side walls, but increase the inner plane of the façade (Fig. 18a) [92]. The results of numerical analyzes reproduced the observed damages and confirmed that out-of-phase decay of facades is not critical in this type of churches.

In the Philippines, the Augustinian monastic order built several churches in the 1790-1800 period in a distinct "earthquake baroque" architecture. These churches were stocky and not too tall, and followed the style adopted in the seismic zones of Mexico and South America (Figure 18a). A new "mestizo" architecture was created and it is most often translated as "earthquake baroque". When the earthquakes of 1863 and 1880 again devastated Manila, almost all the buildings collapsed, except, again, the church of St. Augustine (Fig. 18b).

Slika 18. Tipična kolonijalna Crkva u J. Americi (a), Crkva Svetog Avgustina u Manili nakon zemljotresa 1880. godine, prema [92] i [62]

Figure 18. Typical western façade of Spanish colonial churches (a): Church of St. Augustine in Manila after the earthquake of 1880 (b), after [92] and [62]

Analize objekata građenih u različitim periodima potvrđuju da su se i stari graditelji načinom građenja suprotstavljali razornim zemljotresima. Pri tome su s posebnom pažnjom birali lokacije, a fundiranje prilagođavali njihovim specifičnostima. Dalje, sem korišćenja metoda fundiranja koje se oslanjaju na princip seizmičke izolacije, primenjivani su dodatni uređaji za ublažavanje vibracionog procesa koji se iz tla prenosi na objekat. Primenjivana su rešenja kojima se menjaju dinamička svojstva objekta da se izbegne rezonantno područje.

Analyzes of buildings erected in different periods confirm that builders of old, too, countered the destructive earthquakes by their building methods. In doing so, they chose locations with special care, and adapted the foundations to the specific conditions. In addition to the use of foundation methods that rely on the principle of seismic isolation, additional devices were used to mitigate the vibration process that is transmitted from the ground to the building. Designs changing the dynamic properties of the structure so as to avoid a resonant area have been applied.

4 O DELOVANJU ZEMLJOTRESA NA GRADITELJSKO NASLEĐE

Kulturno nasleđe se može smatrati trodimenzionalnim istorijskim dokumentom. Prošlost se, na osnovu graditeljskog nasleđa, može čitati kroz njegove oblike, primenjene materijale, tehnologiju građenja, upotrebu građevina kroz vreme i brojne druge vrednosti. Zato je potrebno znati što više o graditeljskom nasleđu, tkivu i konstrukciji građevina, kako bi se ta dragocena saznanja očuvala radi što duže kontinualne upotrebe, proučavanja i uživanja u nasleđu sadašnje generacije i budućih generacija.

Fizička briga za graditeljsko nasleđe obuhvata nekoliko faza rada. Moraju se uočiti i definisati faktori koji negativno utiču na opstanak građevine. Faktori su raznovrsni i mogu se podeliti u nekoliko uticajnih grupa:

1. Dejstva iz prirodnog okruženja;
2. Društvene pojave;
3. Uzroci propadanja koji se nalaze unutar samih građevina.

Od dejstava iz prirodnog okruženja, zemljotresno, vulkansko, i požarno dejstvo najčešće imaju katastrofalne posledice, a u svim slučajevima dolazi do narušavanja okruženja, rastresenosti konstrukcija i opšte degradacije nasleđa.

Brojne međunarodne konvencije i preporuke predviđaju niz mogućih i prihvatljivih intervencija koje obuhvataju očuvanje, stabilizaciju, popravke, restauraciju, rekonstrukciju, adaptaciju i niz drugih mera. Ti dokumenti, takođe, preporučuju procenu od

4 ON THE EARTHQUAKE EFFECTS ON THE BUILT HERITAGE

Cultural heritage can be considered as a three-dimensional historical document. The past, based on the architectural heritage, can be interpreted through its forms, employed materials, construction technology, use of buildings through time and numerous other values. Therefore, it is necessary to know as much as possible about the built heritage, fabric and structure of buildings, in order to preserve this valuable knowledge for as long continuous use as possible, for the study and enjoyment of the heritage of present and future generations.

The physical care for the built heritage includes several phases of work. Factors that negatively affect the survival of the building should be first identified and defined. The factors are diverse and can be classified into several influential groups:

1. Natural environment factors;
2. Social phenomena;
3. Intrinsic building dilapidation causes.

Among the natural environment factors, volcanic, earthquake and fire effects most often have catastrophic consequences, and in all cases, there is a disturbance of the environment, disintegration of structures and general degradation of heritage.

Numerous international conventions and recommendations provide for a range of possible and acceptable interventions that include conservation, stabilization, repair, restoration, reconstruction, adaptation and other measures. These documents also recommend

potencijalnog rizika od prirodnih procesa i ublažavanje tog rizika primerenim akcijama. Seizmičkoj zaštiti graditeljskog nasleđa u svetu se posvećuje velika pažnja, jer su iskustva pokazala da razaranja tokom jakih zemljotresa najčešće znače i nepovratan gubitak izvorne vrednosti nasleđa.

Srbija se nalazi u jednoj od aktivnih seizmičkih zona, pa je zato i graditeljsko nasleđe u značajnom riziku od iznenadnih seizmičkih udara ili onih s dugim trajanjem. Jedina sredstva kojima je moguće umanjiti efekte zemljotresa obuhvataju ojačanje tkiva i konstrukcije građevine. Bez obzira na to ko će preduzeti zaštitne korake i određene akcije, pojedinac ili institucija, vlasnik ili staratelj, smanjenje dugotrajnog uticaja od zemljotresa može se obaviti putem nekoliko obaveznih radnji, predviđenih u većini međunarodnih dokumenata. To su:

- dobro pripremljena dokumentacija;
- dobro održavanje i unapred pripremljen plan odbrane od tako neprijatnog događaja kao što je zemljotres.

4.1 Dokumentacija o graditeljskom nasleđu u funkciji posledica od zemljotresa

Potpuno ažurni podaci o spomenicima kulture treba da omoguće obnovu oštećenih ili nedostajućih delova građevina nakon zemljotresa. To su brojni grafički prilozi napravljeni na osnovu niza istraživanja, od vizuelnih opservacija do najsloženijih snimanja najsavremenijim instrumentima, kao i tekstualni prilozi koji obuhvataju razne vrste izvora, od arhivskih dokumenata, preko zapisa usmenih opisa pojedinaca do literarnih tekstova u kojima su na različite načine opisani građevina, njeni detalji ili čak samo emocije koje je kod autora izazivalo postojanje date građevine. Veći nivo detaljnosti dokumentacije pomaže da se obavi tačnija obnova.

Ovaj oblik dokumentacije treba da bude dopunjen drugim elementima u vezi sa istorijom zemljotresa koji su ugrožavali područje na kojem se danas nalazi vredno graditeljsko nasleđe. Sveobuhvatna analitički obrađena dokumentacija nesumnjivo je potrebna za spomenike kulture. Dok je, međutim, za obično dokumentovanje građevinskog fonda dovoljna analiza i interpretacija, koja će objasniti istoriju građevine onoliko koliko se to iz same građevine može sagledati, za spomenike kulture je potreban čitav niz dopunskih izvora i rasprava o značenju i značaju građevine u smislu njene uloge u istorijskom, društvenom, ekonomskom, religijskom, kulturnom i drugim razvojem određene civilizacije.

4.2 Dokumentacija o istorijskim zemljotresima

S obzirom na brzi porast populacije u mnogim zemljama, analiza seizmičkog hazarda postaje sve važnija, čak i u regionima s niskom seizmičnošću. To je od suštinskog značaja, naročito za procenu rizika na područjima s velikim strukturama kulturnih dobara ili prostornim kulturno-istorijskim celinama. Geofizičari i istoričari sarađuju kako bi odgovorili na pitanja, kao što su:

- Koliko su bili jaki zemljotresi tokom istorije u

assessing the potential risk of natural processes and mitigating that risk with appropriate actions. Great attention is paid to the seismic protection of the built heritage in the world, because experience has shown that destruction during strong earthquakes usually means an irreversible loss of the original value of the heritage.

Serbia is located in one of the active seismic zones, so the architectural heritage runs a significant risk of sudden seismic shocks or those with a long duration. The only means by which earthquake effects can be mitigated include reinforcement of the building fabric and structure. Regardless of who takes protective steps and certain actions, an individual or an institution, owner or guardian, the reduction of the long-term impact of the earthquake can be done through several mandatory actions, provided for in most international documents. They are:

- well-prepared documentation;
- proper maintenance and a pre-prepared plan of defence against such disastrous events as earthquakes.

4.1 Documents on the built heritage in terms of the earthquake effects

Completely updated data on cultural monuments should enable the restoration of damaged or missing parts of buildings after earthquakes. Numerous graphic contributions made on the basis of a series of researches, from visual observations to the most complex recordings using the most modern instruments, as well as textual contributions that include various types of sources, from archival documents, through records of oral descriptions of individuals to literary texts describing the building, its details or even just the emotions aroused in an author by the existence of a specific building. A higher level of documentation detail facilitates making a more accurate reconstruction.

This form of documentation should be supplemented with other elements related to the history of earthquakes that endangered the area where the valuable built heritage is located nowadays. Comprehensive analytically processed documentation is undoubtedly needed for cultural monuments. While, however, analysis and interpretation are sufficient for the usual documentation of the building stock, which will clarify the history of the building as much as can be seen from the building itself, cultural monuments require a number of additional sources and considerations on the meaning of the building in terms of its role in the historical, social, economic, religious, cultural and other developments of a particular civilization.

4.2 Documents on historical earthquakes

Considering the rapid population growth in many countries, seismic hazard analysis is becoming increasingly important, even in regions with low seismicity. This is essential, especially for risk assessment in places with large structures of cultural assets or spatial cultural-historical entities. Geophysicists and historians work together to answer questions such as:

- How strong have earthquakes been throughout

pojedinin krajevima i koji su bili regionalni specifični mehanizmi ispoljavanja?

- Koja je bila učestalost pojavljivanja zemljotresa na određenom području tokom vekova?
- Da li je položaj seizmički aktivne zone varirao na području kroz istoriju?
- Kakav seizmički hazard može da sledi na osnovu istorijskih istraživanja za neko određeno mesto?
- Koji se novi podaci mogu prikupiti o društvenim, ekonomskim, političkim, religijskim,
- kulturnim i drugim okolnostima u kojima se razvijalo graditeljstvo i eventualno bilo izloženo zemljotresima kroz istoriju?

Osnova našeg znanja o zemljotresima kroz istoriju nalazi se u savremenoj dokumentaciji i izvorima. Uglavnom se sastoje od tekstova, ali su veoma važne slike, gravire, fotografije i drugi likovni prilozi. U ređim slučajevima, veoma mnogo pomažu vizuelne opservacije o prirodi raznih specifičnosti, kao što su klizišta, oštećenja terena, devastacije i popravke građevina u različitim vremenskim periodima. Savremeni dokumenti mogu biti nedovoljno tačni, jer su podložni deformacijama nastalim tokom vremena, od strane autora koji su u različitim vremenima pisali o događaju. Rad počinje istraživanjem savremenog materijala, utvrđivanjem i upoređivanjem kasnijih tekstova sa izvorima. Jednom kada se tekst dešifruje, sledi interpretacija istorijskih geografskih naziva i prevođenje datuma iz starih kalendara kao i starih mera (razdaljina, dužine trajanja događaja, novčane jedinice računa kojima su plaćane popravke zemljotresom oštećenih građevina i drugo) u savremene merne sisteme.

Najteži deo posla je kritička analiza izvora. Brojni primeri tekstova prolaze kroz vreme različite obrade i promene. Vrednost izvora zavisi od toga s kog stanovišta se analiziraju – seizmološkog ili istorijskog. Sa stanovišta seizmologa, neophodno je da se izvor vrednuje na osnovu kriterijuma kao što su:

- pouzdanost [5];
- tačnost;
- potpunost.

Mapa područja na kojem se nekada u istoriji dogodio zemljotres služi kao izvor i kao primer klasifikacije. Ukoliko je neko iscrtao izoseizmičku kartu koristeći sve izvore, bez obzira na njihov kvalitet, oblici izolija veoma se razlikuju od onih koje će biti iscrtane korišćenjem samo pouzdanih izvora. Rezultati se moraju dopuniti "skalom ekvivalentnih vrednosti" kako bi mogli da budu uporedivi. Najnovije mape su date u SRPS EN 1998-1/NA (Nacionalni aneks) [95].

Značaj likovnog opisa, kao što su slike, crteži i fotografije, koji služi kao pomoć u interpretaciji efekata zemljotresa kroz istoriju, takođe je veoma značajan. Savremene likovne predstave neke građevine oštećene u zemljotresu mogu je prikazivati iz iste perspektive i zato je moguće neposredno upoređivanje. Smatraju se značajnim podatkom, iako mogu predstavljati upadljive razlike u oblicima. To se delimično može objasniti subjektivnim odnosom likovnog autora prema zemljotresu, ali i različitim potrebama naručioca likovnog dela, ukoliko postoji. Upoređenje likovnih i tekstualnih izvora može se, takođe, razlikovati. Na primer, opis u tekstu može sugerisati da su oštećenja znatno veća nego što je to likovno prikazano, ali i obrnuto, pa je

history in certain areas and what were the regional specific mechanisms of manifestation?

- What has been the frequency of earthquakes in a particular area over the centuries?
- Has the position of the seismically active zone varied in the area throughout history?
- What kind of seismic hazard can be established based on the historical research of a particular place?
- What new data can be collected on social, economic, political, religious,
- Cultural and other circumstances in which building activity developed and was possibly exposed to earthquakes throughout history?

The basis of our knowledge of earthquakes throughout history is found in modern documentation and sources. Documents mainly consist of texts, but paintings, engravings, photographs and other artistic contributions are very important. In rare cases, visual observations of various specifics in nature, such as landslides, terrain damage, devastation and repair of buildings in different periods of time, provide a valuable assistance. Contemporary documents may be insufficiently accurate, as they are subject to distortions created over time by authors who wrote about the event at different times. The work begins by researching contemporary material, identifying and comparing later texts with sources. Once the text is decoded, ensues the interpretation of historical geographical names and translation of dates from old calendars as well as old measures (distance, duration of events, monetary units of bills paid for earthquake-damaged buildings, etc.) into modern measuring

The most difficult part of the job is critical source analysis. Numerous examples of texts undergo various processing and changes. The value of the source depends on the point of view from which it is analyzed - seismological or historical. From the point of view of seismologists, it is necessary to evaluate the source on the basis of criteria such as:

- reliability [5];
- accuracy; and
- completeness.

A map of the area where an earthquake once occurred in history serves as a source and an example of classification. If someone drew an isoseismic map using all sources, regardless of their quality, the shapes of isolines are very different from those that will be drawn using only reliable sources. The results should be supplemented by a "scale of equivalent values" in order to be comparable. The latest maps are given in SRPS EN 1998-1/NA (National annex) [95].

Visual description, such as paintings, drawings and photographs, which aids in the interpretation of earthquake effects throughout history, is also very significant. Contemporary art representations of some buildings damaged in the earthquake can show it from the same perspective, and therefore a direct comparison is possible. They are considered significant piece of data, although they may exhibit striking differences in shapes. This can be partly explained by the subjective attitude of the artist towards the earthquake, but also by the different needs of the commissioner of the work of art, if any. The comparison of artistic and textual sources may also vary. For example, the description in the text may suggest that the damage is significantly greater

veoma teško utvrditi istinitost podatka.

Poznavanje zemljotresa tokom istorije može, tako, doprineti zbiru podataka o seizmičkim područjima i hazardu (definisan intenzitetom i povratnim periodom) [35] i [36]. Istraživanje zemljotresa kroz istoriju sastoji se od seizmološke i istorijske komponente. Prva ima cilj koji je jasno definisan, ali koji se teško može ostvariti. To je sticanje pouzdanog znanja o tome šta se stvarno dogodilo tokom zemljotresa i koji su numerički parametri zemljotresa i formiranja mapa hazarda zasnovanih na statističkim podacima. Najnovije mape seizmičkog hazarda naše zemlje date su uz Pravilnik o građevinskim konstrukcijama, tj. Aneksu [95]. Zemljotres ima i društvenu konotaciju. Istraživanje ovog aspekta obuhvaćeno je drugom komponentom istraživanja kroz istoriju. Očajanje i strah zbog iznenadnog i užasavajućeg događaja izaziva različite ljudske aktivnosti. Javna i privatna pomoć žrtvama zemljotresa, molitve, pisma, knjige, novinski članci daju uvid u religijski, filozofski, političku, ekonomsku i druge karakteristike perioda u kojem se zemljotres dogodio.

Ove dve metode istraživanja razlikuju se u više aspekata. U stvari, informacioni kapacitet, ono što nazivamo, vrednost pojedinih savremenih izvora o zemljotresima, zavisi od specijalnih saznanja. Tekst s podacima o zemljotresu, kada se pronađe, treba prvo da bude dešifrovan, odnosno preveden. Proučavanje istorijskih izvora zahteva i dobro profesionalno znanje odgovarajuće lingvističke grane. Tadašnji termini treba da budu prilagođeni seizmološkim terminima nastalim u XX veku. Delovi s terminima koji opisuju fenomen zemljotresa, kao što su razaranje ili zvučni efekti, danas, mogu da deluju strano. Istorijski metod utvrđuje i tačno datiranje, ukoliko je u tekstu korišćen neki drugačiji kalendar. Većina tih starih tekstova ne obuhvata analizu pojave kao ni dublju naučnu studiju zbivanja tokom i posle događaja. Sledeći korak je, zato, traženje informacija o podacima na koje se tekst poziva. U pojedinim slučajevima, to u studiji oduzima najviše vremena.

Za mnoge zemljotrese koji su se dogodili u srednjem veku ili ranije, savremeni izvori su izgubljeni ili se ne mogu naći. Ti događaji se mogu samo delimično rekonstruisati na osnovu pisanih svedočanstava. *Stemma*, odnosno genealoško stablo tekstova, pomaže da se shvati kako su mlađi tekstovi zavisili od starijih i kako su se činjenice o nekom zemljotresu transformisale različitim interpretacijama. Upoređivanjem grešaka dobija se predstava o tome kako se izvorni tekst deformisao kroz vekove i često izgubio smisao u delovima koji su najvažniji za sticanje podataka o zemljotresu. Ova analiza, koja se naziva kritika izvora, daje osnovu za procenu vrednosti prvobitnog opisa. U pojedinim slučajevima savremeni istorijski crteži mogu se koristiti kao značajni istorijski izvori.

Nakon zemljotresa u Lisabonu 1755. godine, osmišljena je i uspostavljena nova građevinska praksa. Ona je podrazumevala, po prvi put, da se pre izgradnje naprave i testiraju modeli zgrada kako bi se procenila njihova otpornost na udare zemljotresa. Simulacija vibracija izvedena je učešćem grupa portugalskih vojnih trupa koje su marširale oko modela. Do danas su mnoge zgrade nastale posle katastrofe u Lisabonu opstale kao svedoci prvih svetskih građevina planski izgrađenih u novom veku da budu otporne na zemljotres.

than it is artistically shown, but also vice versa, so it is very difficult to determine the veracity of the data.

Knowledge of earthquakes throughout history can thus contribute to the collection of data on seismic areas and hazards (defined by intensity and return period) [FEMA]. Earthquake research throughout history consists of a seismological and a historical component. The former aims at a goal that is clearly defined, but which is difficult to achieve. It is acquisition of a reliable knowledge about what really happened during the earthquake and what the numerical parameters of the earthquake are and about the formation of hazard maps based on statistical data. The latest maps of seismic hazard of our country are regulated by the Rulebook on building constructions, i.e. Annex [SRP EN 1998-1]. An earthquake also has a social connotation. Research on this aspect has been covered by the latter component of research throughout history. Despair and fear due to a sudden and horrifying event causes various human activities. Public and private assistance to earthquake victims, letters, books, newspaper articles provide insight into the religious, philosophical, political, economic and other characteristics of the period in which the earthquake occurred.

These two research methods differ in several aspects. In fact, the information capacity, what is called the "value" of some contemporary sources on earthquakes, depends on special knowledge. The text with the data on the earthquake, when it is found, should first be decoded, i.e., translated. The study of historical sources also requires good professional knowledge of the appropriate linguistic branch. The terms of that time should be adjusted to the seismological terms that originated in the 20th century. Sections with terminology that describe the earthquake phenomenon, such as destruction or sound effects, today, may seem foreign. The historical method also determines the exact dating, if a different calendar is used in the text. Most of these old texts leave out an analysis of the phenomenon as well as a deeper scientific study of what happened during and after the event. The next step is, therefore, to search for information about the data the text refers to. Sometimes, it takes the most time in the study.

For many earthquakes that occurred in the Middle Ages or earlier, contemporary sources have been lost or cannot be found. These events can only be partially reconstructed on the basis of written testimonies. The *stemma*, i.e. genealogical tree of texts, helps to understand how the younger texts depended on the older ones and how the facts about an earthquake were transformed by different interpretations. Comparing the errors gives an idea of how the original text has been deformed over the centuries and often lost its meaning in the parts that are most important for obtaining earthquake data. This analysis, called source criticism, provides a basis for assessing the value of the original description. In some cases, contemporary historical drawings can be used as significant historical sources.

After the earthquake in Lisbon in 1755, a new construction practice was designed and established. It meant, for the first time, that models of buildings were made and tested before construction in order to assess their resistance to earthquake shocks. The vibration simulation was performed with the participation of groups of Portuguese military troops marching around

the model. To this day, many buildings erected after the Lisbon disaster have survived as witnesses to the world's first buildings of the new age designed to be earthquake resistant.

Slika 19. Bakropis iz 1755. godine koji prikazuje Lisabon u plamenu i cunami koji je preplavio brodove u luci. (Original u: Museu da Cidade, Lisabon), prema [137]

Figure 19. Etching from 1755 showing Lisbon in flames and a tsunami that flooded ships in the harbour. (Original in: Museu da Cidade, Lisbon), after [137]

Razni katalozi zemljotresa koji su u svetu pravljani pokazuju kako su podaci vremenom postajali sve tačniji i potpuniji. Grafici o broju registrovanih zemljotresa u vremenu mogu se tumačiti kao vrsta "kulturne biografije", koja pokazuje kako se menjao koncept vremena i kako se izoštravala zainteresovanost za pitanja iz oblasti prirodnih nauka. Evropska zajednica zato podržava međunarodni projekt "Pregled zemljotresa kroz istoriju" [84], u okviru kojeg se istražuju zemljotresi koji su se dogodili u periodu od sto godina, tokom XVII i XVIII veka. Evropska Komisija za seizmologiju, u radnoj grupi "Podaci o istorijskim zemljotresima razmatraju pitanja istraživanja s ciljem revizija kataloga zemljotresa, sastavljanja i razvoja preporuke i formiranja monografije uporednih podataka o zemljotresima. U ovoj komisiji radi petnaest geofizičara i istoričara iz petnaest evropskih zemalja.

Očigledno je da se *proučavanju istorije zemljotresa pridaje poseban značaj kada je u pitanju graditeljsko nasleđe*. Razlog je što snažni zemljotresi mogu izazvati katastrofalne štete na spomenicima kulture, a jedno od prvih načela na osnovu kojih se oni proglašavaju jeste autentičnost oblika i materijala od kojih su nastali. Veoma je važno, zato, da se te vrednosti sačuvaju. Zemljotresi ne pripadaju onoj vrsti prirodnih fenomena koji se često i periodično događaju, kao što su poplave, jer se one efikasno sprečavaju preventivnim merama, kao što su odbrambeni nasipi. Zemljotresi se zbivaju iznenadno i ne u velikoj meri prema zakonima statistike. Tek kada se opservira dovoljan broj zemljotresnih događaja tokom odgovarajućeg vremenskog perioda, mogu se izvoditi zaključci o ukupnom zbiru podataka dobijenih statističkim metodama. Upravo zbog toga se vreme, lokacija i magnituda velikih zemljotresa ne može tačno predvideti danas poznatim metodama.

U Srbiji su poznati veliki zemljotresi, ali njihova statistička masa još uvek nije velika. Događa se, zato,

Various catalogues of earthquakes made in the world show how the data became more accurate and complete over time. Graphs on the number of registered earthquakes in time can be interpreted as a kind of "cultural biography", which shows how the concept of time has changed and how interest in issues in the field of natural sciences has sharpened. The European Community therefore supports the international project "Review of Earthquakes through History" [84], which investigates earthquakes that occurred over a period of one hundred years, during the 17th and 18th centuries. The European Commission for Seismology, in the working group "Data on historical earthquakes", considers research issues with the aim of revising the catalogue of earthquakes, compiling and developing recommendations and forming a monograph of comparative data on earthquakes. Fifteen geophysicists and historians from fifteen European countries work in this Commission.

It is obvious that *the study of the history of earthquakes is given special importance when it comes to the built heritage*. The reason is that strong earthquakes can cause catastrophic damage to cultural monuments, and one of the first principles on the basis of which they are proclaimed the cultural monuments is the authenticity of the shapes and materials from which they were created. It is very important, therefore, that these values are preserved. Earthquakes do not belong to the type of natural phenomena that occur frequently and periodically, such as floods, because they are effectively prevented by preventive measures, such as defensive embankments. Earthquakes occur suddenly and largely not according to the laws of statistics. Conclusions be drawn about the total sum of data obtained by statistical methods only when a sufficient number of earthquake events are observed during an adequate period of time. That is why the time, location

da projektovanje planiranih građevina zahteva podatke znatno veće preciznosti nego što se mogu dobiti na osnovu empirijskog seizmološkog znanja o određenoj lokaciji. Zato je rizik proizvod verovatnoće pojave hazarda i očekivanih gubitaka. Usled toga, čak i kada je verovatnoća da se dogodi zemljotres mala, povećana gustina gradnje u prostornim kulturno-istorijskim celinama predstavlja opasnost za okruženje. To, takođe, zahteva verniju procenu zemljotresnog hazarda, što se može ispuniti ukoliko se proširi posmatrano vreme seizmiciteta u prethodnim vekovima.

Ove okolnosti objašnjavaju zašto su zemljotresi kroz istoriju mogli povremeno predstavljati i predmet političkih rasprava i važnih odluka za pojedina društva. U savremenoj literaturi najčešće se spominju dva primera. Austrija je 1978. godine plebiscitom odbila rad nuklearne centrale u Zvetendorfu (Zwetendorf). Kao jedan od ključnih argumenata za to je da se 1590. godine dogodio veliki zemljotres, sa epicentrom trideset kilometara udaljenim od tog mesta. Isti razlog su 1989. godine naveli stručnjaci i građani koji su zaustavili izgradnju hidrocentrale u Nađmarošu na Dunavu, jer je 1763. godine u obližnjem gradu Komaromu zabeležen snažan zemljotres, i pored toga što je to ugrozilo ekonomiju Mađarske. To su primeri koliko je značajno što bolje poznavati istoriju zemljotresa na određenom području.

Registrowanje zemljotresa instrumentima počinje krajem XIX veka. Raniji izveštaji su se, uglavnom, zasnivali na pisanoj dokumentaciji o vidljivim, auditivnim i proživljenim efektima zemljotresa. Kroz istoriju su, takođe, beleženi interesantni fenomeni kao što su promene zemljinog reljefa, pojavljivanje i nestajanje izvora, stvaranje pukotina, te oštećenja građevina. To je vrednovanje na osnovu efekata zemljotresa na prirodu i objekte. Na osnovu toga razvijale su se skale seizmičkog identiteta. Od 1964. godine u Evropi seizmolozi koriste skalu intenziteta MSK (Medvedev, Sponheur i Karnik). Godine 1893. F. Omori i Dž. Miln započeli su posmatranje oštećenja nakon Mino-Ovari zemljotresa iz 1891. godine. Na osnovu toga izvedeni su eksperimenti koji su doveli do konstruisanja i usavršavanja potresne platforme između 1893. i 1910. godine; 1908. godine H. F. Rid opisao je teoriju povratne elastične sile u kojoj deformaciona energija geoloških raseda oslobađa vibracionu energiju iznenadnim klizanjem izazvanim smicanjem. K. Sujihiro konstruisao je vibracioni analizator 1926. godine, kojim je merio pomeranja klatna tokom zemljotresa, registrovao ih i utvrdio spektar odgovora za vrlo mala prigušenja. Dž. R. Frimen je 1932. godine najviše doprineo razvoju i instalaciji akceleroograma jakih pokreta tla. Dve godine kasnije, 1934. Dž. Blum je na osnovu svoje doktorske disertacije dalje razvio vezu između teorijskog modela građevina, uzimajući u obzir složenosti kao što su prigušenja i neelastičnost s posmatranjem na terenu i modele testirane na potresnoj platformi. Time je podignut nivo razumevanja odgovora građevina na zemljotres. Predviđanje seizmičkog intenziteta i crtanje tih izoseizmičkih mapa omogućili su i pretpostavljanje seizmičkih parametara, kao što je Rihterova skala magnituda ili akceleracija na lošem zemljištu, zahvaljujući poznatim empirijskim odnosima, objavljena 1935. godine. Dž. Osner je 1941. godine počeo da objavljuje proračune spektara odgovora sa akceleratora. Spektar odgovora izračunat sa akceleroograma

and magnitude of large earthquakes cannot be accurately predicted, by presently known methods.

Large earthquakes are known in Serbia, but their statistical mass is still small. It therefore happens that the design of planned buildings requires data of a much higher precision than it can be obtained on the basis of empirical seismological knowledge about a particular location. Therefore, the risk is a product of the probability of hazard occurrence and expected losses. As a result, even when the probability of an earthquake is small, the increased density of construction in spatial cultural and historical entities poses a danger to the environment. This also requires a more accurate assessment of the earthquake hazard, which can be satisfied if the observed time of seismicity in the previous centuries is extended.

These circumstances explain why earthquakes throughout history have occasionally been the subject of political debate and important decisions of individual societies. Two examples are most often mentioned in modern literature. In 1978, Austria rejected the operation of the nuclear power plant in Zvetendorf with a plebiscite. One of the key arguments was the fact that a great earthquake occurred in 1590, with the epicentre thirty kilometres away from that place. The same reason was given in 1989 by experts and citizens who stopped the construction of the hydroelectric power plant in Nagymaros on the Danube, because in 1763 a strong earthquake was recorded in the nearby town of Komarom, despite the fact that it was adverse to the Hungarian economy. These are the examples of how important it is to know the history of earthquakes in a certain area as well as possible.

Registration of earthquakes with instruments began at the end of the 19th century. Earlier reports were largely based on written documentation of the visible, auditory, and experienced effects of the earthquake. Throughout history, interesting phenomena have also been recorded, such as changes in the earth's relief, the appearance and disappearance of springs, the creation of cracks, and damage to buildings. It is an evaluation based on the effects of earthquakes on the nature and structures. Based on that, the scale of seismic identity was developed. Since 1964, seismologists in Europe have been using the MSK intensity scale (Medvedev, Sponheur and Karnik). In 1893, F. Omori and J. Milne began observing the damage after the 1891 Mino-Owari earthquake. Based on that, experiments were performed that led to the construction and improvement of the earthquake simulation platform between 1893 and 1910. 1908. H. F. Reed described the theory of elastic rebound theory in which the deformation energy of geological faults releases vibration energy by shear-induced sudden slip. K. Sujihiro constructed a vibration analyzer in 1926 with which he measured the displacements of the pendulum during an earthquake, registered them and determined the range of responses for very small damping. In 1932, J.R. Freeman contributed the most to the development and installation of accelerograms of intense ground movements. Two years later, in 1934, based on his doctoral dissertation, J. Blume further developed the relationship between the theoretical model of buildings, taking into account complexities such as damping and inelasticity, with field observations and models tested on an earthquake platform. This improved

informativni je način procene uticaja pokreta zemlje na vibrirajuće strukture. Od kada je E. I. Vilson počeo da stvara SAP (Opšti program strukturalne analize) program, 1970. godine, započeo je ubrzani razvoj modernih kompjuterskih programa koji imaju najveći značaj i primene u zemljotresnom inženjerstvu [51]. Dijagram toka 1 koristi se pri traganju za istorijskim i seizmološkim izvorima.

understanding of the building response to earthquakes. Prediction of seismic intensity and drawing isoseismic maps made it possible to assume seismic parameters, such as the Richter magnitude scale or acceleration on poor soil, thanks to well-known empirical relationships, published in 1935. In 1941, J. Osner began publishing accelerator response spectrum calculations. The response spectrum calculated from the accelerogram is an informative way of estimating the impact of ground motion on vibrating structures. Since E.I. Wilson began creating the SAP (General Structural Analysis Program) program in 1970, commenced the rapid development of modern computer software that have the greatest significance and applications in earthquake engineering [51]. Flowchart 1 is used in the search for historical and seismological sources.

*Dijagram toka 1. Metodološki proces istraživanja istorijskih zemljotresa, prema [63]
Flowchart 1 of the methodological process of researching historical earthquakes, after [63]*

5 METODOLOGIJA ISTRAŽIVANJA GRADITELJSKOG NASLEĐA POSLE ZEMLJOTRESA

Još značajniji oblik istraživanja odnosi se na utvrđivanje posledica zemljotresa, jer je u ovom slučaju potrebno brzo reagovati, kako bi se oštećenja uočila, pre nego što se stvori vremenski otklon u kojem može doći do dodatnog gubitka delova. To se dešava tokom raščišćavanja otpalih elemenata, odnošenjem materijala s lica mesta i drugim intervencijama.

U Italiji, koja se kroz celu istoriju graditeljstva suočavala s velikim gubicima usled delovanja zemljotresa, postepeno je razvijen metod pregleda seizmičkih oštećenja [11] i [18], koji se može i šire primenjivati, pa i u Srbiji. Utvrđivanje štete zasniva se na uočavanju šesnaest indikatora, od kojih svaki predstavlja mogući mehanizam kolapsa za makroelemente na koje se posmatrana građevina može podeliti. Podela na makro - elemente u vezi je sa identifikacijom arhitektonskih elemenata koje karakteriše svojstveno seizmičko ponašanje, skoro nezavisno od ostatka građevine. To mogu biti, na primer, spoljašnji zidovi, apside, kupole, kule-zvonici, ukoliko se radi o crkvenom graditeljstvu. Za svaki od tih makroelemenata, u zavisnosti od njihove tipologije i veze sa ostalim delovima crkve, moguće je identifikovati način oštećenja i mehanizam kolapsa. Tokom pregleda je potrebno definisati:

1. podelu na makroelemente;
2. nivo oštećenja (na skali od 0 do 3);
3. povredljivost građevine određenog mehanizma, a u odnosu na specifične detalje konstrukcije.

Ovi podaci omogućavaju da se napravi indeks oštećenja, u rasponu od 1 do 10, kao standardno sredstvo s vrednovanjem oštećenja putem indikatora. Svi, ovako prikupljeni, podaci, mogu biti korisno sredstvo za sticanje pouka za buduće formiranje projekata obnove oštećenih celina [45].

Problem seizmičke povredljivosti [18] u ovom istraživanju vezuje se tako za osnovnu tipologiju crkvenog graditeljstva i omogućuje formiranje baze podataka za buduće nepoželjne slučajeve, kada neki zemljotres ošteti strukturu istog ili sličnog tipa. Metodologija je formirana na osnovu sistematskog istraživanja oštećenja na nizu crkvenih objekata u italijanskim provincijama Umbrija i Marke, s podacima koji su počeli da se prikupljaju još 1944. godine, a zatim su, pri svakom novom zemljotresu, ti podaci proširivani novim saznanjima. Veliki broj od 3000 pregledanih i procenjenih crkava pružio je odličnu osnovu da se statističkom analizom podataka o oštećenjima i uzajamnom vezom s tipologijom građevina omogućući predviđanje posledica zemljotresa, od prve procene povredljivosti do brzih procesa opservacije oštećenja [67]. Tom metodologijom je utvrđeno da sledeći osnovni podaci treba da budu zastupljeni prilikom pregleda građevina nakon zemljotresa:

1. Tipološki podaci i dimenzije (ovi podaci se odnose na dekomponovane različite arhitektonske elemente, s posebnim beleženjem konstruktivnih elemenata u pogledu odgovora građevine na zemljotres – kontrafori, zatege i sl.);
2. Oštećenja elemenata umetničke vrednosti (beleže se oštećeni elementi u unutrašnjosti građevine i na njenoj spoljašnosti bez definisanja umanjenja

5 RESEARCH METHODOLOGY OF BUILT HERITAGE AFTER EARTHQUAKES

An even more important form of research refers to determining the consequences of an earthquake, because in this case it is necessary to react quickly, in order to register the damage, before there is a time lapse, in which additional loss of parts can occur. This happens during the clearing of elements that fell off, removal of materials from the site and other interventions.

In Italy, which throughout the history of building has faced great losses due to earthquakes, a method of examining seismic damage has been gradually developed, which can be applied more widely, and so in Serbia. The determination of damage is based on the observation of sixteen indicators, each of which represents a possible collapse mechanism for macro elements into which the observed structure can be divided. The division into macro elements is related to the identification of architectural elements, which are characterized by inherent seismic behaviour, almost independent of the rest of the building. They can be, for example, external walls, apses, domes, bell towers, if concerns church construction. For each of these macro elements, depending on their typology and connection with other parts of the church, it is possible to identify the manner of damage and the mechanism of collapse. During the review it is necessary to define:

1. division into macro elements,
2. damage level (on the 0-3 scale),
3. vulnerability of a building to a specific mechanism, in relation to the specific structural details.

These data facilitate making a damage index, in the range of 1-10, as a standard tool, with damage evaluation using indicators. All the data collected in this way can be a useful tool for acquiring lessons for the future formation of projects of damaged entities restoration.

The problem of seismic vulnerability [18] is thus related to the basic typology of church building and enables the formation of a database for future undesirable cases, when an earthquake damages a structure of the same or similar type. The methodology has been formed on the basis of systematic research of damage to a number of church buildings in the Italian provinces of Umbria and Marche, with data whose collection began in 1944, and then, with each new earthquake, these data were expanded with new knowledge. A large number of 3,000 inspected and assessed churches provided an excellent basis, throughout statistical analysis of damage data and the interrelationship with the typology of buildings, to enable the prediction of earthquake consequences, from the first vulnerability assessment to rapid damage observation processes [67]. This methodology determined that the following basic data should be represented during the inspection of buildings after the earthquake:

1. Typological data and dimensions (these data refer to decomposed different architectural elements, with special recording of structural elements in terms of the building's response to earthquakes - buttresses, braces, etc.);
2. Damage to the elements of artistic value

vrednosti);

3. Indeks oštećenja i indeks povredljivosti (identifikuje se šesnaest mogućih oštećenja i mehanizama kolapsa i karakteri različitih makroelemenata, tako što se za svaki mehanizam utvrđuje prisustvo mehanizma, veličina oštećenja, stvarna povredljivost građevine na taj mehanizam, kao deo indikatora povezanog sa specifičnim konstruktivnim slabostima);

4. Karakteristike zidanja (različita zidarija raznih makroelemenata opisuje se u formularu s pozivanjem na karakteristike obuhvaćenih elemenata i maltera, kompoziciju obrade lica zidova i poprečnih preseka);

5. Sigurnost (procena obrađivača o sigurnosti konstrukcije, sa izborom jedne od četiri mogućnosti: sigurno, sigurno delovanje prve pomoći, delimično sigurno i nesigurno);

6. Napomene-beleške obuhvataju sva dodatna zapažanja o građevini, u vezi sa opštom sigurnosti ili sa onim što nije registrovano pod 1. i 3;

7. Ilustracije podrazumevaju osnove, izgled, preseke i skice detalja, kako bi se što bolje razumeo specifičan mehanizam oštećenja.

Prikupljeni podaci putem jednostavnog uprosečavanja oštećenja makroelemenata i povredljivosti daju dva indeksa:

- Indeks oštećenja je broj od 0 do 1, kojim se iskazuje prosečni nivo oštećenja crkve definisan jednačinom:

$$i_d = \frac{1}{3N} \sum_{k=1}^{16} d_k \quad (1)$$

gde je d_k oštećenje u k mehanizmu (od 0 do 3), N broj mehanizama koji se mogu potencijalno aktivirati u crkvi ($N \leq 16$)

- Indeks povredljivosti, koji je vezan za podložnost crkve da bude oštećena u zemljotresu, dobija se iz jednačine:

$$i_d = \frac{1}{3N} \sum_{k=1}^{16} v_k \quad (2)$$

gde je V_k indikator povredljivosti, prisutan u k mehanizmu (od 0 do 2), N je broj mehanizama koji potencijalno mogu da se aktiviraju u crkvi, m je broj pitanja o povredljivosti na koja nije moguće odgovoriti (na primer, neke zone konstrukcije nije moguće pregledati, za neke elemente nije moguće doneti sud o povredljivosti, i tako dalje).

Na osnovu formirane dokumentacije o istoriji zemljotresa na određenom području i s predloženom metodologijom za procenu oštećenja, moguće je napraviti analizu seizmičkog rizika za sakralnu arhitekturu određenog područja. Ovako pripremljena baza podataka, koja omogućava preventivnu zaštitu, ali i brzo reagovanje nakon događaja, neophodan je strateški prioritet u oblasti zaštite graditeljskog nasleđa.

Za analizu uticaja zemljotresa na građevinske konstrukcije, potrebno je usvojiti odgovarajući dinamički model i definisati pobudu u zavisnosti od načina prikaza seizmičkog dejstva. Seizmička analiza sastoji se iz proračuna dinamičkih karakteristika konstrukcije, određivanja seizmičkih sila na osnovu mehaničkih

(damaged elements in the interior of the building and on its exterior are recorded without defining the value depreciation);

3. Damage index and vulnerability index (sixteen possible damages and collapse mechanisms and characters of different macro elements are identified, so that for each mechanism the presence of the mechanism, damage size, actual vulnerability of the building to that mechanism is determined as part of the indicator related to specific structural weaknesses);

4. Characteristics of masonry (different masonry of various macro elements is described in a form with the reference to the characteristics of the included elements and mortar, the composition of the wall faces and cross-sections treatment);

5. Safety (processor's assessment of the safety of the structure, with the choice of one of four alternatives: safe, safe action of first aid, partially safe and unsafe);

6. Notes include all additional observations on the building related to general safety or to what omitted under 1 and 3;

7. Illustrations include, layouts, views, sections and sketches of details, in order to better understand the specific mechanism of damage.

The data collected by simply averaging macro element damage and vulnerability yield two indices:

- Damage index is the number from 0 to 1, which expresses the average level of church damage, defined by the equation:

where d_k is the damage in the k mechanism (0-3), N is the number of mechanisms which can be potentially activated in the church ($N \leq 16$);

- Vulnerability index, which is related to the susceptibility of the church to the damage in an earthquake, is obtained from the equation:

where V_k is a vulnerability indicator, present in the k mechanism (0 to 2); N is the number of mechanisms that can potentially be activated in the church, m is the number of vulnerability questions that cannot be answered (for example, some structural zones cannot be inspected, for some elements it is impossible to make a judgment about vulnerability, etc.).

Based on the documentation formed on the history of earthquakes in a certain area and with the proposed methodology for damage assessment, it is possible to make a seismic risk analysis for the church architecture of a certain area. The database prepared in this way, which enables preventive protection, but also rapid reaction after the event, is a necessary strategic priority in the field of built heritage protection.

For the analysis of the impact of earthquakes on building structures, it is necessary to adopt an appropriate dynamic model and define the excitation depending on the way the seismic action is presented. Seismic analysis consists of the calculation of the dynamic characteristics of the structure, determination of

osobina konstrukcije objekta i zadatog pomeranja tla i iz proračuna uticaja u konstrukciji usled dejstva indukovanih seizmičkih sila. Kada se odrede uticaji u konstrukciji usled dejstva seizmičkih sila, sprovodi se dimenzionisanje svih kritičnih preseka za relevantnu kombinaciju seizmičkog dejstva i ostalih opterećenja. Nakon toga, uz primenu adekvatnih konstrukcijskih rešenja i razradu detalja specifičnih za aseizmičko projektovanje, obezbeđuje se potrebna nosivost i dovoljan kapacitet deformisanja razmatrane konstrukcije.

Potrebna nosivost prema aktuelnom konceptu seizmičke zaštite određuje se za uticaje u konstrukciji usled seizmičkih sila koje odgovaraju tzv. projektnom nivou (povratni period $T_r \approx 500$ god.) [39]. Ove sile određuju se primenom faktora redukcije koji se usvaja u zavisnosti od pretpostavljenog kapaciteta deformisanja konstrukcije. Konstrukcija koja je projektovana na ovakav način po pravilu može bez rušenja da izdrži zemljotresno dejstvo, pod uslovom da stvarne karakteristike dogođenog zemljotresa odgovaraju usvojenom seizmičkom hazardu. Nedostatak ovog koncepta ogleda se u tome što se na osnovu sprovedenog proračuna nema uvid u veličinu oštećenja noseće konstrukcije. Iskustva iz zemljotresa koji su se dogodili ukazuju da ovakvo projektovanje ne obezbeđuje uniformni rizik jer različite konstrukcije mogu imati različito ponašanje i veoma različit stepen oštećenja u toku istog zemljotresa.

Važan aspekt aseizmičkog projektovanja jeste sprečavanje naglog i nekontrolisanog rušenja konstrukcije. Sadašnja praksa projektovanja predstavlja tradicionalni pristup, zasnovan na silama i određivanju potrebne nosivosti. Poslednjih godina razvija se jedan novi pristup koji se, umesto na silama, zasniva na deformacijama i kontroli oštećenja. Njegova bitna prednost u odnosu na aktuelni koncept projektovanja jeste mogućnost procene seizmičkih performansi objekata, kao kombinacije ponašanja noseće konstrukcije i nenosećih elemenata, kojima se formira kompletan opis ukupnog stepena oštećenja objekta za više nivoa seizmičkog hazarda. Projektom konstrukcije i adekvatnim građenjem potrebno je sprečiti prevelika oštećenja noseće konstrukcije i povrede ljudi za dejstvo proračunskog zemljotresa. Istovremeno se mora obezbediti i adekvatan stepen zaštite za pojavu oštećenja i ograničenja u funkcionisanju objekta za zemljotrese koji se mogu dogoditi više puta u eksploatacionom veku zgrade, ali i dovoljna sigurnost od rušenja za zemljotrese s manjom verovatnoćom pojave od proračunate [34] i [38].

6 NEKI PROBLEMI ZAŠTITE GRADITELJSKOG NASLEĐA OŠTEĆENOG ZEMLJOTRESIMA

U svim oblastima rada, uključujući i radove na spomenicima kulture, postavlja se pitanje iz koje njihove prošlosti počinjemo da razmatramo problem. Da li je to ukupna prošlost ili je to prošlost spomenika kulture koji danas nalazimo i počinjemo se baviti njime. Razlog za ovo pitanje je evolucija koncepta restauracije koja je ostavila traga na zaostavštinu koju danas nalazimo u određenom fizičkom stanju. Ovde se možemo setiti nekih najuticajnijih koncepta. Počevši od E. Viole-

seismic forces based on the mechanical properties of the building structure and the given ground movement and from the calculation of the effects on the structure due to the action of induced seismic forces. When the influences in the structure due to the action of seismic forces are determined, the designing of all critical sections for the relevant combination of seismic action and other loads is performed. After that, with the application of adequate structural solutions and elaboration of details specific to seismic design, the required load-bearing capacity and sufficient deformation capacity of the considered structure are provided.

The required bearing capacity according to the current concept of seismic protection is determined for the impacts in the structure due to the seismic forces that correspond to the so-called design level (return period $T_r \approx 500$ years). These forces are determined by applying a reduction factor that is adopted depending on the assumed deformation capacity of the structure. A structure designed in this way can, as a rule, withstand an earthquake without collapse, provided that the actual characteristics of the earthquake correspond to the adopted seismic hazard. The disadvantage of this concept is that based on the conducted calculation, there is no insight into the extent of damage to the supporting structure. Experiences from earthquakes indicate that such design lack a uniform risk because different structures may have different behaviour and very different degrees of damage during the same earthquake.

An important aspect of seismic design is the prevention of sudden and uncontrolled collapse of the structure. Current design practice is a traditional approach, based on forces and determining the required load capacity. In recent years, a new approach has been developed which is based on deformations and damage control instead of forces. It is an important advantage over the current design concept is the ability to assess the seismic performance of buildings, as a combination of load-bearing structure and non-load-bearing elements behaviour, which enables forming a complete description of the total degree of damage to the structure for multiple levels of seismic hazard. Using a proper design of the structure and adequate construction, it is necessary to prevent excessive damage to the supporting structure and injuries to people during the action of a designed earthquake. At the same time, an adequate degree of protection against damage and limitations in the operation of buildings must be provided for the earthquakes that can occur several times in the service life of the building, but also a sufficient safety against collapse in the case of earthquakes with less probability of occurrence than the designed one [34] and [38].

6 SOME PROBLEMS OF PROTECTION OF BUILT HERITAGE DAMAGED IN EARTHQUAKES

In all areas of work, including works on cultural monuments, there is a question of what past moment should be the starting point for considering the problem. Is it the entire past or the past of the cultural monument that we find today and begin to deal with? The reason for this question is the evolution of the concepts of restoration that left their mark on the legacy that can be found today in a certain physical state. Some of the most influential concepts can be recalled here. Beginning with

Dika (Viollet-le-Duc, 1814–1879), učenje o strukturama i istraživanje starih tekstova i građevinskih dokumenata bilo je od velikog značaja. Tokom prve polovine XX veka pojavili su se različiti stavovi prema novim materijalima i njihovoj upotrebi. K. Boito (1836–1914) smatrao je da savremene materijale i savremene tehnike treba minimalno koristiti. G. Đovanoni (1873–1947) bio je mišljenja da moderne tehnike, naročito korišćenje armiranog betona, treba koristiti tamo gde tradicionalne metode i materijali nisu dovoljno pouzdani. A. Evans (1851–1941) koji je konzervirao palatu u Knossosu, koristio je beton u velikim količinama i na taj način značajno uticao na povećanu upotrebu ovog materijala od strane drugih konzervatora. N. Balanos (1860–1942) prihvatio je armirani beton, smatrajući ga korisnim, čvrstim i izdržljivim alatom za restauraciju najvažnijih grčkih antičkih građevina. Ovi pogledi bili su samo priprema za konačno prihvatanje i preporuku za upotrebu svih raspoloživih savremenih tehnika i materijala, posebno armiranog betona, što je zaključeno Atinskom poveljom 1931. godine. Prvi najvažniji dokument usvojen posle Drugog svetskog rata, Venecijanska povelja iz 1964. godine, preporučuje upotrebu tradicionalnih materijala za strukturalnu stabilizaciju i opštu obnovu. Nove materijale i tehnike treba koristiti samo u slučajevima kada se tradicionalni materijali ne mogu primeniti. U Italijanskoj povelji o restauraciji iz 1989. godine iskazano je nepoverenje u upotrebu novih materijala, uglavnom skrivenih unutar starih građevina, kao što su čelik, fugovanje cementnim malterom ili raznim smolama i beton. Ukazuje se na njihovu ograničenu trajnost, a najviše na nekompatibilnost sa originalnim materijalima, i stoga se naglašeno ističe posvećenost tradicionalnim materijalima koji su lakši za kontrolu i promenu. Danas se ne postavlja pitanje upotrebe novih materijala i tehnologija. Oni su postali neophodni, jer je njihov sastav i način primene takav da mogu ispuniti osnovne principe zaštite izgrađenog nasleđa, uključujući i osiguranje od prirodnih katastrofa, među kojima su zemljotresi, s obzirom na štete koje izazivaju, među najvažnijim [68].

6.1 Učenje iz prošlosti

Mnogi čine grešku misleći da su samo savremene generacije otkrile načine kako da se odupre pretnjama od zemljotresa u konstrukcijskom oblikovanju. Često se veruje da stariji oblici građevinske prakse moraju biti opasniji i štetniji samo zato što su nastali pre nego što su utvrđena savremena pravila građenja, seizmički kodovi i razvijena moderna inženjerska saznanja o zemljotresima [65] i [83]. Svakako, uvođenje čelika omogućava duktilnost tamo gde zidanje ne bi moglo. Ipak, otkriveno je da su otkazali varovi u preko 100 od 400 zgrada sa čeličnom konstrukcijom koje su preživele Nortridž zemljotres u Kaliforniji 1994. godine. To je ukazalo na opasnost koju zemljotres može da izazove i na najsavremenijim građevinama. Mnoge zidane zgrade, stradale u zemljotresima, nisu se uvek potpuno rušile. Kao što se može videti u Makedoniji, Crnoj Gori, Hrvatskoj, Srbiji, Jermeniji, Italiji, Turskoj, Iranu, urušavale su se i moderne armirano-betonske zgrade, dok su starije zidane zgrade u blizini ostale netaknute ili malo oštećene, pa su pružale utočište raseljenim

Viollet-le-Duc (1814-1879), learning about structures and researching old texts and construction documents was of great importance. During the first half of the 20th century, different attitudes towards new materials and their use emerged. C. Boito (1836-1914) considered that modern materials and modern techniques should be used minimally. G. Giovannoni (1873-1947) was of the opinion that modern techniques, especially the use of reinforced concrete, should be used where traditional methods and materials are insufficiently reliable. A. Evans (1851-1941), who conserved the palace at Knossos, used concrete in large quantities and thus significantly influenced the increased use of this material by other conservators. N. Balanos (1860-1942) accepted reinforced concrete, considering it a useful, solid and durable tool for the restoration of the most important ancient Greek buildings. These views were only a preparation for the final acceptance and recommendation for the use of all available modern techniques and materials, especially reinforced concrete, which was concluded by the Athens Charter of 1931. The first important document adopted after the Second World War, the Venice Charter of 1964, recommends the use of traditional materials for structural stabilization and general reconstruction. New materials and techniques should be used only in cases where traditional materials cannot be used. The Italian Charter of Restoration of 1989 expressed distrust in the use of new materials, mostly hidden inside old buildings, such as steel, grouting with cement mortar or various resins and concrete. The charter indicated their limited durability, but most of all the incompatibility with the original materials, and therefore the commitment to traditional materials that are easier to control and change is emphasized. Nowadays, the question of the use of new materials and technologies is not posed. They have become necessary because their composition and method of application are such that they can meet the basic principles of protection of the built heritage, including safeguarding against natural disasters, among which earthquakes, given the damage they cause, are among the most important ones [68].

6.1 Lessons of the past

Many make the mistake of thinking that only modern generations have discovered ways to resist earthquake threats in structural design. It is often believed that older forms of construction practice must be more dangerous and harmful only because they originated before modern building rules, seismic codes, and developed modern engineering knowledge of earthquakes were developed [65] and [83]. Certainly, the introduction of steel enables ductility where masonry could not. However, it was discovered that welds in over 100 of the 400 steel-built buildings that survived the 1994 Northridge earthquake in California failed. This indicated the danger earthquakes pose even to state-of-the-art buildings. Many masonry buildings, damaged in earthquakes, did not always completely collapse. As can be seen in Macedonia, Montenegro, Croatia, Serbia, Armenia, Italy, Turkey, Iran, modern reinforced concrete buildings collapsed, while older masonry buildings nearby remained intact or slightly damaged, providing shelter to the displaced residents of newer buildings. In various

stanovnicima novijih zgrada. Na različitim područjima, kao što su Turska, bivša Jugoslavija, Kašmir i Nikaragva, autohtoni oblici gradnje razvijeni su ili prilagođeni odgovorima na pretnju zemljotresa tamo gde su raspoloživi resursi zahtevali da se zidarija i dalje koristi. Istorijski izveštaji potvrđuju da su ove zgrade bolje podnele zemljotres nego obližnje zgrade naših dana.

Danas se mnogi zalažu da se ovim vernakularnim građevinama obavi zamena postojećih sa armirano-betonskim konstrukcijama, koje se zbog loših lokalnih građevinskih praksi mogu pokazati kao manje otporne od svojih niskotehnoloških, neinženjerskih istorijskih prethodnika (zasnovano na empiriji). Čak i stručnjaci za zaštitu i obnovu ponekad ne uspevaju da razumeju suštinu seizmičke otpornosti u starijim strukturama. Verujući da su građevini neophodno potrebne nosivost i krutost, oni uništavaju originalne konstrukcijske sisteme da bi se intervencijama stekla snaga na štetu ranijih rešenja koja i dalje mogu biti korisna. Primer bi mogao da se nađe u Dubrovniku, gde su restauratori jedne istorijske palate otkrili unutrašnji zid za koji su mislili da je čvrsto zidan, a, u stvari, u unutrašnjosti je imao segmente nalik pletenoj korpi od malih drvnih škrljaca, sa ispunom od opeke ili kamena, lagano uklopljenom među čepove. Na konferenciji je data izjava da je loše izgrađeni zid odmah uklonjen i zamenjen tokom restauracije zgrade. Umesto što je zaključeno da je "loše izgrađen", moglo se razmisлити o tome da je ovaj zid, možda, namerno bio izgrađen na ovaj način kako bi se odupro zemljotresima. Srušeni zid najverovatnije predstavlja rezultat pouka iz prošlosti, jer je Dubrovnik gotovo u potpunosti bio uništen tokom zemljotresa 1667. godine. Struktura zida je, možda, ukazivala na daleko veće razumevanje seizmičkog inženjerstva nego što se danas može pretpostaviti. Građevine od bondruka ili nepečene opeke često su manje stradale od betonskih tokom zemljotresa u Skoplju 1963. godine (slika 20 a i b).

places, such as Turkey, the former Yugoslavia, Kashmir and Nicaragua, autochthonous forms of construction have been developed or adapted to respond to the earthquake threat where available resources have necessitated the continued use of masonry. Historical reports confirm that these buildings withstood the earthquakes better than the nearby contemporary buildings.

Today, many advocate replacing these vernacular structures with reinforced concrete structures, which due to poor local construction practices may prove less resistant than their "low-tech", non-engineered historical predecessors (based on empiricism). Even conservation and restoration experts sometimes fail to understand the essence of seismic resistance in older structures. Believing that buildings need load-bearing capacity and rigidity, they destroy the original structural systems in order to improve strength through interventions to the detriment of earlier solutions that can still be useful. An example could be found in Dubrovnik, where the restorers of a historic palace discovered an interior wall that they thought was solidly built and, in fact, inside it had segments resembling a wicker basket of small wooden slates, with a brick filling or stone, lightly fitted between the plugs. A statement was made at the conference that "the poorly built wall was immediately removed and replaced during the restoration of the building." Instead of concluding that it was "poorly built", this wall may have been intentionally built in this way to withstand earthquakes. The demolished wall was probably the result of lessons from the past, because Dubrovnik was almost completely destroyed during the earthquake in 1667. The structure of the wall may have indicated a far greater understanding of seismic engineering than can be assumed today. Buildings made on post-and-pan system or unfired bricks, or adobe were often less damaged than concrete ones during the earthquake in Skopje in 1963 (Figure 20 a and b).

Slika 20. Kuća bondručne konstrukcije i Železnička stanica, efekti skopskog zemljotresa iz 1963. godine, prema [67]
Figure 20. House of post-and-pan structure and Railway Station, effects of the Skopje earthquake from 1963, after [67]

6.2 Tehnički propisi i neke tehničke mere

Evropska zajednica neprekidno teži da usaglasi pravila koja važe u različitim zemljama i da ih objedini u jedinstvena pravila. Taj problem, kada je u pitanju graditeljsko nasleđe u različitim zemljama, pokušava se rešiti jedinstvenim univerzalnim merama i preporukama. Kada su u pitanju pravilnici za projektovanje konstrukcija, naglašava se potreba da se za istorijske zgrade izdvoji posebna šifra. Ovaj kodeks treba da se zasniva na ciljnim performansama, a ne na standardnim procedurama. Međunarodni standardi koji se podjednako odnose i na nove i stare zgrade, ne obuhvataju specifičnosti istorijskih tipova zgrada, koje se razlikuju od regiona do regiona. Ono što se smatra dobrom praksom na jednom području, može delovati destruktivno na nekim područjima s drugim kulturološkim vrednostima. Posebne odredbe za istorijske zgrade sa arhaičnim sistemima gradnje i starijim programima prostorne organizacije treba da se uključe u pravilnike ili će mnoge stare zgrade delimično ili potpuno izgubiti svoju vrednost. Republika Srbija je promovisala Zakon o vanrednim situacijama u 2010. godini (Službeni glasnik, 2010). Nacionalna strategija za zaštitu i spašavanje u vanrednim situacijama, usvojena u novembru 2011. godine, nije toliko izraz planiranja za budućnost, već je više neposredna reakcija na elementarne katastrofe, najčešće poplave, s kojima se u poslednje vreme suočava država. Diskusija o odgovarajućim kodeksima, profesionalnoj odgovornosti, pa čak i temama u oblasti naučnog istraživanja, svakako mora da obuhvati i raspravu o definisanju neophodnog nivoa seizmičke zaštite.

Tehnički propisi i pravilnici koriste se za uspostavljanje donje granice performansi koje se primenjuju na građevinu zavisno od njene vrednosti i očuvanosti [103]. Ovo je noviji pristup koji se koristi u projektovanju intervencija na konstrukciji objekta. Prvenstveno se moraju obezbediti performanse: zaštita života, i/ili ograničenje oštećenja zavisno od značaja građevine. Da bi se postigle ciljne performanse, nužna je tehnno-ekonomska analiza. Zbog toga se očekuje da se utvrdi i obezbedi finansiranje. Seizmička zaštita, naročito za velike javne projekte, uključuje učešće državnih fondova. Smatra se da određivanje ukupne sume novca, koju za te radove treba planirati dovodi do nesuglasica i da usled toga nema konsenzusa. U mnogim građevinskim propisima odredbe i preporuke odnose se na nove ili postojeće zgrade, znatno manje se odnosi na "stare", tj. istorijske zgrade koje predstavljaju kulturna dobra. Mnogi inženjeri i arhitekti, međutim, nisu uvek spremni da definišu obim prihvatljive štete za istorijske zgrade. U pojedinim slučajevima, naročito kod bondručnih zgrada sa ispunom od opeke, ponekad se uslovljava da se obezbede mere za sprečavanje urušavanja, iako se radi o tipu zgrada koji u prošlosti nije previše stradao u zemljotresima. Teškoće i nesigurnosti s kojima se u ovim slučajevima primene tehnologije suočavaju konzervatori i drugi, uključeni u očuvanje građevinske baštine, ogledaju se u članu 10 Krakovske povelje [107].

Razumevanje delovanja zemljotresa intenzivno se poboljšava u poslednjih sto godina. Predloženo je na desetine parametara za kvantifikaciju zemljotresnog dejstva širom sveta. Njima se definiše složenost

6.2 Technical regulations and some technical measures

The European Union is constantly striving to harmonize the rules that apply in different countries and to unite them into uniform rules. When it comes to the built heritage in different countries, this problem, is being solved with single and universal measures and recommendations. When it comes to regulations for the design of structures, the need to allocate a special code for historic buildings is emphasized. This code should be based on a targeted performance, not standard procedures. International standards, which apply equally to new and old buildings, fails to cover the specifics of historical building types, which differ from region to region. What is considered good practice in one area can be destructive in some areas with other cultural values. Special provisions for historic buildings with archaic building systems and older spatial organization programs should be included in the codes or many old buildings will partially or completely lose their value. The Republic of Serbia promoted the Law on Emergency Situations in 2010 (Official Gazette, 2010). The National Strategy for Protection and Rescue in Emergency Situations, adopted in November 2011, is not so much an expression of planning for the future, but more of a direct reaction to natural disasters, most often floods, which the country has been facing lately. The discussion of appropriate codes, professional responsibility, and even topics in the field of scientific research should certainly include a discussion on defining the necessary level of seismic protection.

Technical regulations and codes are used to establish the lower performance limit applicable to a building depending on its value and preservation condition [103]. This is a newer approach used in the design of interventions on building structures. Primarily protection of life, and / or limitation of damage depending on the importance of the building. In order to achieve the target performance, a techno-economic analysis is necessary. It is therefore expected to identify and secure funding. Seismic protection, especially of large public projects, involves the participation of state funds. It is believed that designation of the total amount of money to be planned for these works leads to disagreements and consequently no consensus. In many building regulations, the provisions and recommendations refer to new or existing buildings, much less to the "old", i.e. historic buildings that represent cultural property. Many engineers and architects, however, are not always ready to define the extent of acceptable damage to historic buildings. In some cases, especially in post-and-pan buildings with brick infill, it is sometimes necessary to provide measures to prevent collapse, although this is a type of building that has not suffered excessively in the past earthquakes. The difficulties and uncertainties faced by conservators and others involved in the preservation of built heritage in these technology application cases are reflected in Article 10 of the Krakow Charter [107].

Understanding the effects of earthquakes has been improving rapidly over the last hundred years. Dozens of parameters for quantification of earthquake action around the world have been proposed. They define the complexity of the problem and contribute to a better

problema i doprinosi boljem razumevanju inženjerskog pristupa rešavanju [54]. Ovde je prikazan samo jedan, dijagram toka 2, u nizu procesa kojima se definiše redosled radnji kojima se utvrđuje odluka kako je zemljotres uticao na građevinu i shodno tome kakva će biti njena sudbina, odnosno da li će se popravljati, uklanjati ili delimično uklanjati [115].

understanding of the engineering approach to solving it. Here is just one flow chart in a series of processes that define the sequence of actions that determine the decision on how an earthquake affected the building and, accordingly, what its fate will be, i.e. whether it will be repaired, removed or partially removed [115].

Slika 21. Evolucija zemljotresne katastrofe, prema [115]
Figure 21. Evolution of earthquake disaster [115]

U popisu literature su navedene norme i pravilnici koji se primenjuju u Evropi iz seta (EN 1998) [32-33] koji se odnose na zemljotresno inženjerstvo, a nedavno su usvojeni i kao Standardi koji se moraju primenjivati i kod nas [94]. Pored toga, u popisu su navedeni i dokumenti FEMA [35] koji se primenjuju u SAD i u mnogim zemljama u kojima je s manjim modifikacijama preporučeni kao meritorni dokumenti. Ovi dokumenti su, u najvećem delu, posvećeni određivanju seizmičkih dejstava za primenu u analizi konstrukcija, a zbirka propisa svih zemalja u, seizmički aktivnim područjima, data je u [30], dok je kolekcija istorijskih zemljotresa data u [104]. Seizmičnost Mediterana analizirana je u [23], u Italiji u [46], a takođe i u projektovanju konstrukcija i veza nenosećih elemenata s konstrukcijom [36]. Važno mesto zauzimaju i aspekti klasifikacije oštećenja i upotreb-

The bibliography lists the norms and Regulations that are applied in Europe from the set (EN 1998) [32-33] which refer to earthquake engineering, and were recently adopted as Standards that must be applied in our country as well [94]. In addition, the list also includes FEMA documents [35] that are applied in the USA and in many countries where it is recommended as a referential document with minor modifications. These documents are, for the most part, devoted to determining seismic effects for application in structural analysis, and a collection of regulations of all countries in seismically active areas is provided in [30], and a collection of historical earthquakes [104]. The seismicity of the Mediterranean was analyzed in [23], in Italy in [46], and also in the design of structures and connections of non-bearing elements with the structure [36]. An important

ljivosti objekata, što se, imajući u vidu obim rada, ne obrađuje šire ovde. Takođe, uporedna analiza EN i naših pravilnika razmatrana je u [38] i [39], a i aktuelne metode koje se pri tome primenjuju.

6.3 Neki materijali i tehničke mere

Moderna inženjerska nauka, novi materijali i aktuelni kodovi prešli su dug put s ciljem smanjenja straha od smrti u zemljotresu. Ipak, uprkos tome, potresi su izazivali ozbiljne posledice. Pristupi su se, naročito posle razornih zemljotresa, menjali uz stalnu transformaciju pa i u moderno doba, zahvaljujući napretku računara. Proučavanjem razvoja tehničkih propisa uočava se da su oni unapređivani posle jakih zemljotresa, naročito u Japanu, i SAD (Kalifornija) [38]. Projektovanje seizmički otpornih zgrada je evoluirajući menjano, uglavnom zato što su snažni zemljotresi relativno retki, ali kada se dogode, očekuju se i značajna konstruktivna oštećenja. Linija između prihvatljivog i neprihvatljivog rizika i performansi nedovoljno je jasno određena. Tradicionalno, veće zgrade bile su zidane konstrukcije, a zidovi su oslanjani direktno na zemlju. S trenutnom dominacijom čelika i armiranog betona (AB) kao materijala za građenje, noseća konstrukcija je najčešće ramovska, na koju se pričvršćuje obloga. Početkom XXI veka kontrast između starog i novog sistema postao je posebno uočljiv. Budući da se "postmoderna" orijentacija vraća ka istorijskim formama i detaljima, ovaj pomak stila vratio je želju za projektovanjem zgrada koje imaju noseće masivne zidove kao što su rađene u prošlosti. Često, međutim, na njima nisu uspešno prikazivani tekstura i značenje kao u starijim zgradama.

Zahvaljujući razvoju računarstva i mogućnostima obrade složenih matematičkih problema, inženjeri rade na modeliranju zidanih zgrada. Pri tome ne koriste samo približne metode već sve češće modeliraju nelinearno ponašanje konstrukcije istorijskih zidanih zgrada. To je za zidariju veoma kompleksno pa se primenjuju i druge metode, tj. modeli. Modeli za njihovu analizu su: ekvivalentni model ramova, kruti makroblok model, i metoda konačnih elemenata (MKE- FEM). Ova transformacija u građevinskoj tehnologiji paralelna je sa sličnom promenom inženjerske prakse koja se oslanja i na brze uprošćene analize za projektovanje konstrukcija. Ipak, mnoštvo je objekata graditeljskog nasleđa sa zidanim konstrukcijama. Stabilnost masivnih zidova obično prkosi analizi kompleksnim metodama. Te strukture izdržale su velike zemljotrese u prošlosti, a evidencija štete je poznata [59]. Na primer, brojnim istorijskim zgradama u Srbiji koje su preživele zemljotres u Mionici 1998. i Kraljevu 2010. godine, više prete članovi Zakona o ublažavanju opasnosti [119] nego budući zemljotresi – slika 21 a i b [42].

place is occupied by aspects of the classification of damage and serviceability of buildings, which, given the scope of work, is not covered here. Also, a comparative analysis of EN and our Regulations is discussed in [38] and [39], as well as the current methods used.

6.3 Some materials and technical measures

Contemporary engineering science, new materials and current codes have come a long way with the goal of reducing the fear of death in an earthquake. Nevertheless, the earthquakes have serious consequences. Approaches, especially after the devastating earthquakes, transformed constantly, even in the modern times, thanks to the progress of computers. A study of the development of technical regulations shows that they were improved after strong earthquakes, especially in Japan and the United States (California) [38]. The designing seismically resistant buildings has evolved, mainly because strong earthquakes are relatively rare, but when they occur, significant structural damage is also expected. The line between acceptable and unacceptable risk and performance is unclearly defined. Traditionally, larger buildings were masonry structures, and the walls were supported directly on the ground. With the current dominance of steel and reinforced concrete (RC) as the building material, the load-bearing structure is usually a frame to which the cladding is attached. At the beginning of the 21st century, the contrast between the old and the new system became particularly prominent. As the "post-modern" orientation returns to historical forms and details, this shift in style has restored the desire to design buildings that have massive load-bearing walls as they used to in the past. Often, however, they unsuccessfully display the texture and meaning as in older buildings.

Owing to the development of computing and the ability to process complex mathematical problems, engineers use work on modelling masonry buildings. In doing so, they not only use approximate methods, but increasingly model the nonlinear behaviour of the of historic masonry buildings structure. This is very complex for masonry, so other methods are used, i.e. models. Models for their analysis are: equivalent frame model, rigid macro-block model, and finite element method (FEM) [18]. This transformation in construction technology is parallel to a similar change in the engineering practice that relies on rapid simplified analyses for structural design. However, there are many buildings of built heritage having masonry structures. The stability of massive walls usually defies analysis by complex methods. These structures have withstood major earthquakes in the past, and damage records are known [59]. For example, numerous historical buildings in Serbia that survived the earthquake in Mionica in 1998 and Kraljevo in 2010 are more threatened by the articles of the Law on Mitigation of Danger [118] than by future earthquakes (Figure 21 a and b) [42].

Slika 21. Oštećene zgrade u Mionici i Kraljevu, prema [Foto Ž. Krsmanović]
Figure 21. Damaged buildings in Mionica (a) and Kraljevo (b), [Photo Ž. Krsmanović]

Istorijske zgrade nemaju svoj kulturni značaj samo kao relikvije iz prošlosti. Kulturno značenje mnogih zaštićenih istorijskih građevina odnosi se na njihovu ukupnost. Istorijska konstrukcija je, zato, važna, jer je svedočanstvo nivoa graditeljske veštine i smelosti graditelja neke epohe. Seizmička zaštita i pojačavanje graditeljskog nasleđa prisiljavaju nas, međutim, da se suočimo s jednom od glavnih dilema očuvanja istorijskog tkiva i konstrukcije. Činjenica je da proces očuvanja mora da obuhvati promene i obnovu pojedinih, nekada i većine, delova građevine. Za razliku od održavanja i sanacije stare građevine koja kroz vreme propada, seizmički projekat zaštite dekomponuje istorijsko tkivo zgrade koja može biti i u dobrom stanju i čini je gotovo potpuno novom iz aspekta konstrukcije i materijala. Ponekad se seizmički projekti zaštite promovišu i kao mogućnosti za "vraćanje" prvobitnog izgleda zgrade, uz uklanjanje svih kasnije nastalih izmena (potpuna rekonstrukcija) [69]. Na primer, posle crnogorskog zemljotresa 1979. godine, mnoge građevine u istorijskim gradovima Dubrovniku, Kotoru i Budvi, koji predstavljaju svetsko kulturno nasleđe, rekonstruisane su sa armirano-betonskim (AB) međuspratnim konstrukcijama, koje su zamenile originalnu drvenu građu. Nekim od zgrada su u zidove ubačeni AB stubovi, koji formiraju potpuno nove "AB konstrukcije". Torkretiranje je korišćeno za tambure, kupole i zidove građevina tako da su oni sada deblji nego što su bili u izvornom stanju. Pored toga, nepovratnim čvrstim povezivanjem starih zidova sa dodatim AB elementima, uništen je integritet tih zidova kao pravih, izvornih zidova. Jedna od glavnih prednosti zidanja u kamenu ili opeci je ta što se zidna masa može popraviti uklanjanjem samo oštećenih delova i preslaganjem. U ovom slučaju je, međutim, originalni zid spojen u jednu čvrstu, sraslu masu s betonom. Godinama kasnije, neće biti moguće popraviti takve zidove bez još većeg oštećenja dragocenog originalnog materijala. U crnogorskom zemljotresu 1979. godine svodna konstrukcija Tvrdave Svetog Ivana u Dubrovniku bila je oštećena, napukla i zidovi su se međusobno razdvojili. Najveće konstruktivne intervencije u obnovi tvrđave bile su izvedene 1982. godine. Postavljeni su horizontalni serklaži, ploče od armiranog betona su postavljene između podrmskih svodova, a bilo je uvedeno i vertikalno proširenje ka gradskim zidinama. To je dobar primer u kojem je originalno tkivo

Historic buildings do not have their cultural significance only as relics from the past. The cultural significance of many protected historical buildings refers to their totality. Historical structure is, therefore, important, because it is a testimony to the level of construction skills and boldness of the builders of an era. Seismic protection and the reinforcement of the built heritage compel us, however, to face one of the main dilemmas of preserving the historical fabric and structures. It is the fact that the preservation process should include changes and renovations of certain, sometimes of most parts of the building. Unlike the maintenance and rehabilitation of an old building that is deteriorating over time, the seismic protection project recomposes the historic fabric of the building, which can be in good condition and makes it almost completely new in terms of structure and materials. Sometimes seismic protection projects are also promoted as opportunities to "restore" the original appearance of the building, with the removal of all subsequent changes (complete reconstruction)[69]. For example, after the Earthquake in Montenegro of 1979, many buildings in the historic cities of Dubrovnik, Kotor and Budva, which represent world cultural heritage, were reconstructed with reinforced concrete (RC) floor structures, which replaced the original timber. In some of the buildings, RC columns are inserted in the walls, forming in this way completely new "RC structures". Shotcrete was used for the drums, domes and walls of the buildings so that they are now thicker than they were in their original condition. In addition, by irreversibly firmly connecting the old walls with the addition of RC elements, the integrity of those walls as original walls was destroyed. One of the main advantages of building in stone or brick is that the wall mass can be repaired by removing only the damaged parts and rearranging them. In this case, however, the original wall is joined into a single solid, fused mass with concrete. Years later, it will be impossible to repair such walls without even greater damage to the precious original material. In the Montenegro earthquake in 1979, the vaulted structure of the fortress of St. John in Dubrovnik was damaged, cracked and the walls separated from each other. The largest structural interventions in the reconstruction of the fortress were carried out in 1982. Horizontal tie beams were installed, reinforced concrete slabs were placed between the

tvrdave čvrsto povezano sa armiranim betonom i više se ne može dezintegrirati i povratiti u prvobitno stanje. Mogućnost povratka u prvobitno stanje je jedno od osnovnih načela svih radova na kulturnom nasleđu – slika 22 (Zavod za obnovu Dubrovnika, 1982–85).

ground vaults, and a vertical extension to the city walls was introduced. This is a good example showing how the original fabric of the fortress is firmly connected to the reinforced concrete and can no longer be disintegrated and restored to its original state. The possibility of reversibility is one of the basic principles of all cultural heritage works (Figure 22) (Institute for the Reconstruction of Dubrovnik, 1982-85).

Slika 22. Tvrđava Svetog Ivana u Dubrovniku, posle obnove, prema [66]
Figure 22. The Fortress of Saint John, Dubrovnik, after renewal, after [66]

Postoje i primeri kod kojih je doneta odluka da se uklone neki elementi na građevini bez dubljeg razumevanja njihove uloge u njoj. Kroz obimne zidove crkve manastira Petkovica na Fruškoj gori bile su pre više od 100 godina provučene zatege kao odbrana od zemljotresa. Sa spoljne strane zidova bile su vidljive pločice od livenog gvožđa kojima je zatega bila oslonjena na obimne zidove. Tokom konzervacije, ove zatege su uklonjene. Ta zatega je, međutim, bila svedočanstvo da je crkva utezana da bi se sprečilo razmicanje zidova i njihovo postepeno urušavanje [39].

R. Žarnić sažeo je savremeno iskustvo očuvanja u svom izveštaju o tehnologijama za zaštitu spomenika baštine u Sloveniji [120]. Koncept sanacije zida uključuje skup mera koje uspostavljaju krut odgovor kao reakciju zgrade na zemljotresnu pobudu. Predlaže sledeće tehničke mere koje su neophodne za uspostavljanje stabilnosti i zemljotresne otpornosti zidane baštine:

- konsolidacija temelja;
- spajanje zidova i podne konstrukcije;
- pojačavanje zidova fugovanjem i / ili injektiranjem pukotina;
- pojačavanje zidnih svodova;
- sistematsko obnavljanje postojećih podnih konstrukcija ili njihova zamena novim;
- obnova drvene krovne konstrukcije, popravka i pojačavanje nekonstruktivnih elemenata.

U praksi postoje razne vrste metoda zaštite, od onih u kojima se zahteva strogo pridržavanje tradicionalnih zanata i tehnika do onih u kojima se uvode u potpunosti novi materijali i konstruktivni sistemi [8], [12] i [25]. Poslednjih decenija i u celom regionu bivše Jugoslavije razvijane su, ili modifikovane i poboljšane različite tehnologije korišćenjem rezultata laboratorijskih

There are also examples where the decision was made to remove some elements on the building without a deeper understanding of their role in it. More than 100 years ago, a brace was installed through the extensive walls of the church of the Petkovica monastery on Fruška Gora as a defence against earthquakes. On the outside of the walls, cast iron tiles were visible, with which marked the contact of points of the brace and the large walls. During conservation, these braces were removed. That brace, however, was a testimony that the church was braced in order to prevent the walls from spreading apart and gradually collapsing [39].

R. Žarnić summarized the contemporary experience of preservation in his report on heritage monument protection technologies in Slovenia [120]. The concept of remediation of the wall includes a set of measures that establish a rigid response as a reaction of the building to the earthquake excitation. He proposed the following technical measures necessary to establish the stability and earthquake resistance of the heritage masonry buildings:

- consolidation of foundations,
- joining walls and floor structures,
- strengthening of walls by pointing joints and/or grouting cracks,
- strengthening of wall vaults,
- systematic renovation of existing floor structures or their replacement with new ones,
- renovation of timber roof structure, repair and reinforcement of non-structural elements.

In practice, there are various types of protection methods, from those that require strict adherence to traditional crafts and techniques to those that introduce completely new materials and structural systems [8], [12]

eksperimentalnih istraživanja podržanih analitičkim istraživanjima [50]. Posebno velika pažnja se posvećuje izvođenju što bezbolnijih i kvalitetnijih povezivanja starih i novih materijala, jer te veze utiču na očuvanje stilske celine cele građevine i dugotrajnost spregnute (staro-novo) konstrukcije. Kao jedan od materijala, još uvek aktuelan za povezivanje, jesu mešani materijali na bazi epoksida. Prethodno je neophodno proceniti kompatibilnost fizičkih / mehaničkih svojstava (gustina, linearna toplotna ekspanzija) materijala za povezivanje i materijala koji se povezuju, zapreminu materijala kojim se spaja, veličinu spoja koji se puni i temperaturu oko spoja da bi se sprečilo naprezanje između smole i okolne konstrukcije [104]. Značajna novina na polju očuvanja graditeljskog nasleđa bila je pojava i upotreba polimera ojačanih vlaknima (FRP). Njihov razvoj je tekao veoma brzo, od upredenih vlakana do tkanina praktično neograničenih dimenzija. U obnovi kulturnih dobara od posledica zemljotresa upotreba FRP vlakana je danas skoro nezamenljiva [26]. Ipak, rasprava o tome koja vlakna su najprikladnija za vezivanje sa starim građevinskim materijalima, vlakna od ugljenika, aramidna ili stakla i dalje je veoma živa [21].

Jedan od obećavajućih pravaca u obnovi graditeljskog nasleđa posle zemljotresa je upotreba starih, tradicionalnih materijala značajno unapređenih novim tehnologijama. Njihova primena u obnovi graditeljskog nasleđa omogućava poštovanje jednog od osnovnih principa konzervacije, reverzibilnost. Slično unapređenim starim materijalima, potpuno novi nano materijali omogućavaju delikatne intervencije kojima se maksimalno čuva originalno tkivo građevina koje je ostalo neoštećeno ili malo oštećeno u zemljotresima. O novim materijalima i tehnikama obnove graditeljskog nasleđa, s obzirom na složenost i obim pregleda, biće raspravljano u drugom tekstu

U svetu, a naročito u zemljama koje često pogađaju zemljotresi, mnoštvo je preporuka kako pristupiti ublažavanju dejstva zemljotresa. Veoma teško je pratiti i prikazati sve, u nekim zemljama se te preporuke unapređuju i dopunjuju. Ipak, među preporukama ima dosta sličnosti, jer je problem uvek isti. Novi Zeland je zemlja koju zemljotresi često pogađaju i vrlo je aktivna u objavljivanju preporuka, naročito u predstavljanju koraka u postupcima procene i tehnikama analize [3]. Autori s Novog Zelanda predložili su uprošćenu analizu bočnih mehanizama, SlaMA (Simple Lateral mehanizam Analysis). To su ključni koraci koji su vrlo korisni za ublažavanje mogućih efekata zemljotresa [109]:

- Korak 1: Procena konfiguracije i puteva sila radi identifikacije ključnih konstruktivnih elemenata, potencijalnih slabosti i ozbiljnih konstruktivnih slabosti;

- Korak 2: Sračunavanje relevantne verovatne nosivosti i kapaciteta deformisanja pojedinih elemenata.

- Korak 3: Određivanje verovatnog neelastičnog ponašanja elemenata upoređenjem verovatnog kapaciteta i vrednovanje hijerarhije nosivosti.

- Korak 4: Procena podsistema neelastičnog mehanizma proširenjem lokalnog u globalno ponašanje.

- Korak 5: Formiranje izgleda potencijalnog upravljačkog mehanizma za celokupnu građevinu kombinovanjem različitih pojedinačnih mehanizama i proračun verovatne smičuće sile u osnovi i merenje ukupnog kapaciteta pomeranja vrha primarne konstrukcije za bočne sile. Ukupni kapacitet pomeranja

and [25]. In recent decades, various technologies have been developed or modified and improved in the entire region of the former Yugoslavia, using the results of laboratory experimental research supported by analytical research [50]. Particular attention has been paid to the least intrusive and best quality connections between old and new materials, because these connections affect the preservation of the stylistic unity of the entire building and the longevity of the combined (old-new) structure. Epoxy-based mixed materials are still relevant for bonding as one of such materials. It is previously necessary to assess the compatibility of physical/mechanical properties (density, linear thermal expansion) of the bonding material and the bonded materials, the volume of the bonding material, the size of the bonding joint and the temperature around the joint to prevent stress between the resin and the surrounding structure [104]. A significant novelty in the field of preservation of architectural heritage was the emergence and use of fibre-reinforced polymers (FRP). Their development was very fast, from twisted fibres to fabrics of practically unlimited dimensions. In the restoration of cultural property from the effects of earthquakes, the use of FRP is almost irreplaceable today. Nevertheless, the debate over which fibres are most suitable for bonding with old building materials, carbon fibre, aramid, or glass is still very lively [21].

One of the promising directions in the restoration of the architectural heritage after the earthquake is the use of old, traditional materials considerably improved by new technologies. Their application in the restoration of the built heritage ensures the observation of one of the basic principles of conservation, reversibility. Similar to the improved old materials, the completely new nano-materials enable delicate interventions that maximally preserve the original fabric of buildings that remained intact or slightly damaged in earthquakes. New materials and techniques for the restoration of built heritage, given the complexity and scope of the review, will be discussed in another text.

In the world, and especially in countries that are often affected by earthquakes, there are many recommendations on how to approach the mitigation of earthquakes. It is very difficult to follow and show everything, in some countries these recommendations are being improved and supplemented. Yet, there are a lot of similarities between the recommendations, because the problem is always the same. New Zealand is a country that is often affected by earthquakes and is very active in publishing recommendations, especially in presenting steps in assessment procedures and analysis techniques [3]. Authors from New Zealand proposed a simplified analysis of lateral mechanisms, SlaMA (Simple Lateral Mechanism Analysis). These are the key steps that are very useful for mitigating the possible effects of an earthquake [109]:

- Step 1: Assess the structural configuration and load paths to identify key structural elements., potential structural weaknesses (SSWs) and severe structural weaknesses (SSWs).

- Step 2: Calculate the relevant probable strength and deformation capacities for the individual members.

- Step 3: Determine probable inelastic behaviour of elements by comparing probable member capacities and evaluating the hierarchy of strength.

se ograničava, za sistem s najnižim kapacitetom pomeranja.

- Korakom 6 određuje se ekvivalentni SDOF (Single Degree of Freedom) sistem, i definišu seizmički zahtevi.

Za zidane konstrukcije, kako je već naglašeno, sve analize su znatno kompleksnije nego za konstrukcije od AB ili čelika. Za procenu ponašanja istorijskih zidanih konstrukcija, pod seizmičkim dejstvima, u [4] opisana je metodologija koja uključuje i restauraciju sa sledećih osam koraka: 1) istorijska i eksperimentalna dokumentacija; 2) karakteristike materijala; 3) model konstrukcije; 4) dejstva; 5) analize; 6) kriterijumi loma i procena nosivosti; 7) odluka za intervencije usmerene na sanacije i/ili pojačavanja i ponovna analiza; 8) izveštaj sa objašnjenjem. Ova metodologija je zasnovana i usaglašena s Preporukama ICOMOS-a. Od značaja je pomenuti da se u koraku 1 sumiraju podaci dobijeni pregledom objekata posle zemljotresa, ali i rezultati eksperimentalnih istraživanja, korišćenjem ambijent-vibracija, do najsloženijih ispitivanja na vibro-platformama na čemu se zasnivaju mnogi numerički modeli [60].

7 ZAVRŠNE NAPOMENE I ZAKLJUČCI

Veoma značajno je proučavanje empirijskog iskustava graditelja iz prošlosti koji su se, kao i danas, suočavali s potrebom zaštite građevina od zemljotresa. Evolucijom tog iskustva došlo se do savremene prakse koja se zasniva na nataloženom teorijskom iskustvu i sada dostupnim moćnim računarima. To potvrđuje potrebu da se graditeljsko nasleđe, njegovo tkivo, tj. konstrukcija pažljivo prouči pre projektovanja i izvođenja intervencija na njemu.

Od značaja je upotreba adekvatnih materijala i tehnologija izvođenja radova, tj. intervencija na konstrukciji i ostalim komponentama građevina. Mogu se primeniti i inovativni materijali kojima se ne narušava autentičnost građevine [77]. Potrebno je da njihov sastav i način primene bude takav da mogu ispuniti osnovne principe zaštite izgrađenog nasleđa. To obuhvata i zahtev ostvarivanja visokog stepena otpornosti od prirodnih nepogoda i katastrofa, među kojima su zemljotresi među najvažnijim.

Svaka intervencija treba da bude odmerena tako da bude samo minimalno neophodna za opstanak, prihvatljiva samo uz minimalan gubitak postojećeg tkiva. Planirani novi radovi treba da budu jasno razdvojeni od originalnog tkiva i za to postoje raznovrsne tehnike i materijali koji se pažljivo biraju. Svi novi, primenjeni materijali i tehnike treba, u najvećoj meri, da poštuju tradicionalnu praksu. Upotreba savremenih materijala, kao zamena za originalne materijale, pogodna je samo ukoliko ispunjava nekoliko preduslova:

- Step 4: Assess the sub-system inelastic mechanisms by extending local to global behaviour.

- Step 5: Form a view of the potential governing mechanism for the global building by combining the various individual mechanisms and calculate the probable base shear and global displacement capacity measured at the top of the *primary* lateral structure. The global displacement capacity will typically be limited to that for the system with the lowest displacement capacity.

- Step 6: determines the equivalent SDOF (Single Degree of Freedom) system, seismic demand and % NBS.

For masonry structures, as already pointed out, all analyses are significantly more complex than for RC or steel structures. To assess the behaviour of historic masonry structures, under seismic action, a methodology is described in [4] that includes restoration with the following eight steps: 1) historical and experimental documentation; 2) material characteristics; 3) structural model; 4) actions; 5) analyses; 6) failure criteria and bearing capacity assessment; 7) decision for interventions aimed at repairs/strengthening and reanalysis; 8) report with an elucidation. This methodology is based on and harmonized with the ICOMOS Recommendations. It is important to mention that in step 1, the data obtained by examining structures after the earthquake are summarized, but also the results of experimental research using ambience vibrations, up to the most complex tests on vibro-platforms on which many numerical models are based [60].

7 CLOSING REMARKS AND CONCLUSIONS

It is very important to study the empirical experience of builders from the past who, same as today, needed to protect buildings from earthquakes. The evolution of that experience led to the modern practice based on accumulated theoretical experience and on the powerful computers now available. This confirms the need to carefully study the built heritage, its fabric, i.e. its structure prior to designing and performing interventions on it.

The use of adequate materials and technologies for the execution of works is important, i.e. intervention on the structure and other components of buildings. Innovative materials that do not compromise the authenticity of the building can also be used [77]. It is necessary that their composition and manner of application be such that they can meet the basic principles of protection of the built heritage. This includes the requirement to achieve a high degree of resilience to natural disasters and catastrophes, the earthquakes being among the most important of them.

Each intervention should be designed so that it provides only the minimum necessary for survival, acceptable only with a minimal loss of the existing building fabric. The planned new works should be clearly separate from the original fabric and for that there are various techniques and materials that are carefully selected. All new, used materials and techniques should observe the traditional practice to the greatest extent. The use of modern materials as a replacement for the original ones is suitable only if it meets several prerequisites:

- pruža značajnu prednost koja se može prepoznati;
- njihova upotreba ima čvrstu naučnu osnovu;
- njihova upotreba je podržana iskustvom.

Ukoliko se koriste novi materijali, nužno je birati takve koji su kompatibilni sa izrazom, izgledom, teksturom i oblikom originalnih. Novi materijali treba, takođe, da ispunjavaju zahteve i fizičkih i geografskih karakteristika podneblja, kao i lokalnih načina života stanovništva.

Kada je u pitanju zaštita graditeljskog nasleđa od zemljotresa, idealno bi bilo da se ona preventivno realizuje, naročito u zemljama sa izraženom seizmičkom aktivnošću. To je, međutim, najčešće teško izvodljivo, pre svega iz finansijskih razloga i složenih imovinskih problema. U okviru UNESCO-a, u oblasti kulture neprekidno se razmatraju mogućnosti donošenja međunarodnog normativnog instrumenta u ovoj oblasti, koji bi sadržao tehničke i pravne mere zaštite graditeljskog nasleđa u trusnim područjima. Međunarodni komitet za spomenike spomeničke celine ICOMOS, takođe, daje smernice za preventivnu zaštitu i obnovu kulturnih dobara ugroženih zemljotresom, a koje slede osnovne principe i preporuke zaštite graditeljskog nasleđa. To je trajan proces u kojem se postepeno menjaju pojedini zaključci, uz praćenje savremenog razvoja novih saznanja u oblastima seizmologije, seizmičkog inženjerstva, materijala, tehnologija i tehnika.

- it provides a significant recognizable advantage;
- their use has a solid scientific basis;
- their use is supported by experience.

If new materials are used, it is necessary to choose those that are compatible with the expression, appearance, texture and shape of the original. The new materials should also meet the requirements of both the physical and geographical characteristics of the climate as well as of the local lifestyles of the population.

Considering the protection of the built heritage from earthquakes, it would be ideal if it were preventive, especially in countries with a pronounced seismic activity. The need to prevent damage and destruction of the built heritage is emphasized in many recommendations such as [24]. However, this is usually difficult to accomplish, primarily due to financial reasons and complex property problems. Within the framework of UNESCO, in the field of culture, the possibilities of adopting an international normative instrument in this field, which would contain technical and legal measures for the protection of the built heritage in seismic areas, are constantly being considered. The International Council Monuments and Sites (ICOMOS) also provides guidelines for the preventive protection and restoration of cultural property endangered by earthquakes, which follow the basic principles and recommendations for the protection of the built heritage. It is an ongoing process in which individual conclusions are gradually changing, following the modern development of new knowledge in the fields of seismology, seismic engineering, materials, technologies and techniques.

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REZIME

PROŠLOST I NEKI AKTUELNI PROBLEMI ZAŠTITE GRADITELJSKOG NASLEĐA OD ZEMLJOTRESA

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Graditeljsko nasleđe neprestano je izloženo prirodnim nepogodama među kojima su i brojni zemljotresi. Zbog toga je važno preduzeti mere za redukciju povredljivosti i povećanje zaštite objekata u zavisnosti od izloženosti seizmičkom hazardu i značaju zgrade. Proučavanjem istorije građenja, nalaze se primeri građenja zgrada s ciljem da se zaštite od zemljotresa. Zbog toga su i ovde prezentirani takvi primeri, počev od objekta iz daleke prošlosti sve do sada. Komentarisani su dokumentacija, u vezi s delovanjem zemljotresa kroz istoriju, i postupci pri planiranju mera za zaštitu objekata da bi se nasleđe sačuvalo od propadanja. Prikazani su primeri nepravilne primene materijala i tehnologija građenja kojima se oštećuje originalno tkivo, a time i vrednost koje određeno kulturno dobro ima.

Ključne reči: seizmička dejstva, graditeljsko nasleđe, dokumentacija, ublažavanje povredljivosti, značaj objekata, planiranje intervencija.

ABSTRACT

PAST AND SOME TOPICAL PROBLEMS OF BUILT HERITAGE PROTECTION FROM EARTHQUAKES

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Built heritage is incessantly exposed to natural disasters including numerous earthquakes. Therefore, it is important to take measures to reduce vulnerability and increase the protection of buildings depending on the exposure to seismic hazard and the importance of the building. Studying the history of construction reveals examples of building constructions aimed at protecting against earthquakes. For this reason, such examples are presented here, starting with the buildings from the distant past until now. The documentation related to the action of earthquakes throughout history and the procedures in planning the building protection measures in order to preserve the heritage from dilapidation were commented. The paper, also, presents some examples of incorrect use of materials and construction technologies that damage the original structural fabric, and thus, the value of a certain cultural property.

Key words: Seismic action, built heritage, documentation, vulnerability mitigation, structure importance, intervention planning