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PROCENA ČVRSTOĆE BETONA PRI PRITISKU, KORIŠĆENJEM VEŠTAČKIH NEURONSKIH MREŽA

ESTIMATION OF CONCRETE COMPRESSIVE STRENGTH USING ARTIFICIAL NEURAL NETWORK

Srđan KOSTIĆ
Dejan VASOVIĆ

ORIGINALNI NAUČNI RAD
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1 UVOD

Analiza čvrstoće betona pri pritisku predstavlja jedan od primarnih zadataka laboratorijskih ispitivanja za različite potrebe inženjerske prakse, pre svega u zgradarstvu, tunelogradnji, putarstvu, pri izgradnji brana i mostova, kao i pri izvođenju različitih podzemnih i površinskih konstrukcija u rudarstvu. Zavisno od zahteva projekta, ispitivanje čvrstoće betona izvodi se za uzorke različite starosti s promenljivim vodocementnim faktorom, raznim tipovima i količinom aditiva (leteći pepeo, silikatna prašina, metakaolin i mlevena granulisana zgura iz visokih peći kao mineralni aditivi, odnosno plastifikatori, različiti akceleratori i retarderi, kao hemijski aditivi), te u različitim spoljašnjim uslovima ugradnje betona (s naglaskom na otpornost betona pri izlaganju mrazu). Pri tome, pouzdanost dobijenih rezultata najčešće predstavlja direktnu funkciju broja ispitanih uzoraka, tj. veći broj ispitanih uzoraka betona doprinosi pouzdanijem određivanju njegovih svojstava. Međutim, sredstva predviđena programom istraživanja, u najvećem broju slučajeva, nisu dovoljna za analizu brojnih uzoraka, već se najčešće pristupa interpolaciji malog, vrlo često i nedovoljnog broja podataka ispitivanja. U tom smislu, modeli za procenu čvrstoće betona predstavljaju posebno važnu tehniku koja omogućava utvrđivanje relacije između zrelosti betona i njegove čvrstoće,

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1 INTRODUCTION

Analysis of concrete compressive strength represents one of the primary tasks in laboratory studies for different needs of engineering praxis, including architectural engineering, tunnelling, road engineering, construction of dams and bridges, and for the purpose of surface and underground mining activities. Depending on the Project demand, concrete compressive strength is examined for the specimens of different age and with distinct w/c ratio, for different types and amounts of additives (flying ash, silica fume, metakaolin and ground granulated blast furnace slag, as mineral additives, and plasticizers, different accelerators and retarders, as chemical additives). In this case, reliability of the obtained results regularly represents a direct function of the number of examined concrete samples. In other words, the larger the number of analyzed specimens, the more precise their properties are determined. However, only a small part of the project funding is used for laboratory analyzes, which is often scarce for conducting the analysis of larger number of samples. Instead, the analysis is often based on the approximation of small and insufficient data. Therefore, existing models for estimation of concrete compressive strength have valuable importance, enabling us to determine the relation between the maturity of concrete and its compressive

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odnosno ocenu razvoja čvrstoće betona s vremenom na bazi relativno malog broja ispitanih uzoraka. Jedan od prvih uspešnih postupaka procene čvrstoće betona pri pritisku dao je Plouman [1], koji je vezu između čvrstoće i zrelosti po Solu izrazio u obliku logaritamske funkcije. S druge strane, Bernhart [2] je pokazao da je brzina razvoja relativne čvrstoće betona proporcionalna veličini nehidratisanog dela betona, koju je uveo preko konstante proporcije *k*. Karino [3] je takođe predložio ocenu čvrstoće pri pritisku uzoraka betona, pod pretpostavkom da očvršćavanje betona počinje tek nakon određenog vremena od ugradnje betona. Yi i dr. [4] u svoju jednačinu za procenu čvrstoće betona pri pritisku uveli su efekat difuzione ljuske, konstantu brzine, graničnu čvrstoću i reakcioni koeficijent.

Uprkos činjenici da ovi konvencionalni modeli daju ocenu pritisne čvrstoće betona sa zadovoljavajućom tačnošću za potrebe inženjerske prakse, razvoj novih smeša betona, s različitim tipovima i količinom aditiva, povećava broj sastavnih elemenata betona, što otežava uspostavljanje jasnih veza između različitih komponenata. Iz tog razloga, tokom poslednjih godina, sve češća je primena veštačkih neuronskih mreža za potrebe modelovanja različitih svojstava betona, poput skupljanja pri isušivanju [5], trajnosti betona [6], čvrstoće normalnog betona i betona visoke čvrstoće pri pritisku [7–12], konsistencije betona s metakaolinom i letećim pepelom [13–14], mehaničkog ponašanja betona na visokim temperaturama [15], kao i dugotrajnog efekta letećeg pepela i silikatne prašine na čvrstoću betona pri pritisku [16]. Glavna prednost primene veštačkih neuronskih mreža u odnosu na standardne konvencionalne prediktore [1–4], leži u mogućnosti analize čvrstoće velikog broja uzoraka betona s različitim vodocementnim faktorom, uključujući i efekat izlaganja dejstvu mraza. Za razliku od veštačkih neuronskih mreža, konvencionalnim prediktorima procenjuje se razvoj čvrstoće pri pritisku uzoraka betona istog sastava (jednak vodocementni faktor), koji su negovani u izotermalnim uslovima.

Pored navednih konvencionalnih modela i veštačkih neuronskih mreža, neretko se koriste i drugi modeli procene čvrstoće betona pri pritisku, koji se zasnivaju na razmatranju efekta različitih proporcija vode, cementa i agregata [17–18], odnosno koji koriste sisteme na bazi adaptivne mreže [19–21] ili fazi logike [22–24].

U ovom radu razvijen je model procene čvrstoće betona pri pritisku na bazi veštačkih neuronskih mreža, korišćenjem rezultata eksperimentalnih ispitivanja, u zavisnosti od četiri kontrolna faktora: vodocementni faktor, starost betona, broj ciklusa zamrzavanja/otkravljivanja i količina superplastifikatora.

2 SVOJSTVA BETONA

2.1 Cement

Za pripremu uzoraka betona za ispitivanje korišćen je CEM I normalni Portland cement (PC 42,5 N/mm^2) sa

strength, providing, in that way, an evaluation of compressive strength development with time on the basis of relatively small number of examined samples. One of the first successful prediction models was provided by Plowman [1], who expressed the relationship between strength and maturity by Saul as a natural logarithmic function. Soon afterwards, Bernhardt [2] showed that relative strength development ratio of concrete is proportional to the size of unhydrated portion of the concrete and introduced rate constant *k*. Carino [3] also suggested the equation of prediction of concrete compressive strength under the assumption that the hardening of concrete starts at a certain time after the concrete placement time. Yi et al. [4] incorporate the effect of diffusion shell, rate constant, limiting strength and reaction coefficient, as functions of curing temperature, in the equation of concrete strength prediction.

Despite the fact that previous conventional models give reasonable prediction accuracy for engineering purposes in reference to concrete compressive strength, development of new concrete mixtures, with different types and percentage of additives, increase the number of concrete constituents, thus, making harder to obtain reliable results among various concrete components. Therefore, in recent years, artificial neural networks (ANN) have been used for the purpose of modelling different properties of concrete, such as drying shrinkage [5], concrete durability [6], compressive strength of normal concrete and high performance concrete [7-12], workability of concrete with metakaolin and fly ash [13-14], mechanical behaviour of concrete at high temperatures [15] and long term effect of fly ash and silica fume on compressive strength [16]. The main advantage of ANN approach over the standard conventional predictors [1-4] lies in the possibility to examine the compressive strength of large number of concrete specimens with different *w/c* ratio, including the effect of exposure to various freeze/thaw cycles. Opposite to the ANN approach, conventional predictors estimate the development of compressive strength of concrete specimens of the same properties (equal w/c ratio) cured at isothermal conditions.

Besides conventional models and the ANN approach, there are other types of models which are frequently used for prediction of compressive strength. The first of them is based on the combination of input variables, water, cement and aggregates [17-18], while the second approach is using adaptive network-based fuzzy inference system [19-21] and fuzzy logic techniques [22-24].

In present paper, the ANN model is developed for estimation of concrete compressive strength based on the results of a series of experiments. The present research is focused on compressive strength of concrete samples, depending on four main factors: *w/c* ratio, age, number of freeze/thaw cycles and amount of superplasticizer.

2 PROPERTIES OF MATERIALS

2.1 Cement

The examined concrete specimens were made of CEM I normal Portland cement (PC 42.5 N/mm^2) with specifičnom težinom ρ=3,10 g/cm^3. Početno i finalno vreme vezivanja cementa bilo je 2^h 30min i 3^h 30min, redom, dok je specifična površina po Blejnu iznosila 3450 cm^2/g. Fizičko-mehanička svojstva cementa prikazana su u Tabeli 1, dok je njegov hemijski sastav dat u Tabeli 2.

specific gravity ρ=3.10 g/cm^3. Initial and final setting times of the cement were 2^h 30min and 3^h 30min, respectively. Its Blaine specific surface area was 3450 cm^2/g. Physical and mechanical properties of cement are summarized in Table 1, while its chemical composition is given in Table 2.

Tabela 1. Fizičko-mehanička svojstva Portland cementa
Table 1. Physical and mechanical properties of Portland cement

Svojstvo / Property	Vrednost / Value	
Specifična težina Specific gravity (g/cm^3)	3,10	
Specifična površina Specific surface (cm^2/g)	3450	
Početno vreme vezivanja Setting time initial (min)	150	
Finalno vreme vezivanja Setting time final (min)	210	
Povećanje zapremine Volume expansion (mm^3)	0,50	
Čvrstoća na pritisak Compressive strength (MPa)	2 dana / days	28 dana / days
	15,1	49,5
Čvrstoća na savijanje Flexural strength (MPa)	2 dana / days	28 dana / days
	3,5	8,7

Tabela 2. Hemijski sastav Portland cementa
Table 2. Chemical composition of Portland cement

Oksid Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CaO	Na_2O	K_2O
Cement Cement	20.58	6.04	2.54	58.79	2.66	3.08	2.16	0.29	0.76

2.2 Agregat

Kao agregat za betonske smeše korišćen je rečni šljunak, s maksimalnom nominalnom veličinom do 16mm, i s maksimalno 5% učešća veće frakcije. Upijanje vode iznosi 1,5%, dok je relativna gustina agregata zasićenog vlagom i sa suvom vidnom površinom - 2.72 g/cm^3. Granulometrijski sastav agregata prikazan je u Tabeli 3.

2.2 Aggregate

Natural river aggregate was used in concrete mixture. The gravel was 16 mm maximum nominal size with 5% of the oversize particles. The water absorption was 1.5 % and its relative density at saturated surface dry (SSD) condition was 2.72 g/cm^3. Grading of the mixed aggregate is shown in Table 3.

Tabela 3. Granulometrijski sastav agregata
Table 3. Grading of the mixed aggregate

Veličina sita Sieve size (mm)	0,09	0,13	0,25	0,5	1	2	4	8	11,2	16	22,4
0/4 (% prošlih) 0/4 (% passed)	1	4	21	67	76	84	94	100	100	100	100
4/8 (% prošlih) 4/8 (% passed)	0	0	0	0	0	1	12	97	100	100	100
8/16 (% prošlih) 8/16 (% passed)	0	0	0	0	0	0	0	19	67	95	100

2.3 Plastifikator

Superplastifikator (SP) tipa melamin korišćen je radi održavanja konsistencije i sleganja sveže betonske smeše. Količina dodatog superplastifikatora za različte betonske smeše data je u Tabeli 4. Dodavanjem plastifikatora proporcionalno je smanjivana količina vode.

2.3 Plasticizer

A mellamine-type superplasticizing admixture (SP) was used at various amounts to maintain slump and workability of fresh concrete mixture. The amount of SP used in the different concrete mixtures is given in Table 4. The amount of water was decreased for the amount of SP added.

Tabela 4. Proporcije smeša betona i njihova konsistencija
Table 4. Concrete mixture proportions and consistency

Uzorak br. Sample No.	C (kg)	A (kg)	VC	SP (%)	Sleganje Slump (cm)	Vebe (s)	Tečenje Flow (cm)
D1	350	1930	0,45	2,0	8	4	36
D2	350	1930	0,40	2,0	5	5,5	32
D3	350	1930	0,50	1,4	17	1,5	57
D4	350	1930	0,55	1,4	25,5	0	67
D5	350	1930	0,35	4,0	2	10	25

2.4 Priprema uzoraka

Smeše betona pravljene su u laboratorijskom mikseru tipa ,,Eirich”, s periodom mešanja od tri minuta za sve smeše. Za testiranje su pripremljeni kockasti uzorci betona (100x100mm). Livenje betona izvedeno je na vibracionom stolu sve do potpune konsolidacije. Konsistencija svežeg betona određivana je pomoću testa sleganja [25], testa po Vebeu [26] i testa tečenja [27].

2.4 Preparation of specimens

Concrete was made in a laboratory counter-current concrete mixer (type “Eirich”). Mixing period was 3 minutes for all mixtures. Cubic samples (100x100mm) were made for testing. Casting was performed at vibrating table until a complete consolidation was achieved. Consistency of fresh concrete was measured by applying the slump test [25], Vebe test [26] and flow test [27].

3 POSTUPAK TESTIRANJA

Nakon što je beton izliven u metalne kalupe, uzorci su ostavljeni na sobnoj temperaturi (+20°±2^{0}C) sa 90 – 95% RH. Nakon 24,^{h} uzorci su izvađeni iz kalupa i potopljeni u vodu na istoj temperaturi (+20°C) sledećih šest dana. Sedmog dana, četiri serije od osam serija uzoraka betona izlagane su mrazu. Čvrstoća pri pritisku određivana je nakon 50 i 100 ciklusa zamrzavanja/otkravljivanja (jedan ciklus podrazumeva izlaganje uzorka mrazu u trajanju od 4^h u komori na temperaturi –20°±2^{0}C, a potom se uzorak izlaže sobnoj temperaturi od 20°±2^{0}C u vodi u trajanju od 4^h). Nakon toga, izmerena vrednost čvrstoće poređena je sa čvrstoćom kontrolne grupe uzoraka (koji su neprekidno negovani u vodi na temperaturi 20°±2^{0}C) za ekvivalentnu starost [28–29]. Čvrstoća na pritisak i nasipna gustina određeni su prema važećim standardima [30–31]. Čvrstoća pri pritisku uzoraka betona određivana je pomoću ,,Amsler” hidrauličke prese kapaciteta 2000 kN, pri brzini pritiska od 0,4 MPa/s.

3 TEST PROCEDURE

After the concrete was casted in metal moulds, samples were left at ambient room temperature (20°±2^{0}C) with 90 – 95% RH. After 24 h the concrete samples were demoulded and soaked in the water at the same temperature (20°C) for the next six days. After seven days, four out of eight series of the concrete samples were exposed to freezing and thawing. Compressive strength was determined after 50 and 100 cycles (one cycle lasted for 4^h in environmental chamber at –20°±2^{0}C and 4^h soaked in water at 20°±2^{0}C). Afterwards, measured strength was compared with the strength of control group of specimens (continually cured in water at 20°±2^{0}C) at the equivalent age [28-29]. The compressive strength and bulk density of hardened concrete were tested according to the existing standards [30-31]. Compressive strength measurements were carried out using “Amsler” hydraulic press with a capacity of 2000 kN and 0.4 MPa/s loading rate.

4 EKSPERIMENTALNI REZULTATI

Eksperimentalno dobijeni rezultati jasno ukazuju na uticaj vodocementnog faktora na čvrstoću betona pri pritisku (Tabela 5). Uzorci betona s nižim vodocementnim faktorom pokazuju mnogo veću čvrstoću pri pritisku, koja je određena granulometrijskim sastavom agregata i

4 EXPERIMENTAL RESULTS

The obtained results clearly indicate the impact of *w/c* ratio on compressive strength of concrete (Table 5). Samples of concrete with lower *w/c* ratio have higher compressive strength which is determined by the aggregate grading and amount of cement in the mixture.

količinom cementa u betonskoj smeši. Dalje smanjivanje vodocementnog faktora dovodi do smanjenja čvrstoće pri pritisku, s obzirom na to što beton gubi konsistenciju. S druge strane, izloženost mrazu smanjuje čvrstoću betona pri pritisku, naročito pri visokim vrednostima vodocementnog faktora. Kada je reč o aditivu, dodatak superplastifikatora ne utiče negativno na pritisnu čvrstoću betona izloženog dejstvu mraza. Štaviše, uzorci betona sa supreplastifikatorom izloženi dejstvu mraza pokazuju povećanje pritisne čvrstoće već nakon 50 ciklusa, a sasvim jasno nakon 100 ciklusa zamrzavanja/otkravljivanja.

Further decrease of *w/c* ratio also decreases compressive strength due to the loss of workability. Moreover, exposure to freeze/thawing cycles decreases the concrete strength, especially at higher *w/c* ratios. When it comes to effect of additives, addition of SP does not influence compressive strength of the concrete exposed to freezing. On the contrary, concrete samples with SP exposed to freezing show increase in strength even after 50, and more clearly after 100 cycles.

*Tabela 5. Čvrstoća betona na pritisak – eksperimentalni rezultati**
*Table 5. Compressive strength of concrete – experimental results**

Uzorak Sample	VC W/C	SP (%)	starost (dani) t (days)	Z/O F/T	σ_p (MPa)	Uzorak Sample	VC W/C	SP (%)	starost (dani) t (days)	Z/O F/T	σ_p (MPa)
D1-1	0,45	2,0	32	100	50,30	D3-9	0,50	1,4	32	0	43,40
D1-2	0,45	2,0	32	100	51,00	D4-7	0,55	1,4	32	0	36,40
D1-3	0,45	2,0	32	100	49,00	D4-8	0,55	1,4	32	0	37,20
D2-1	0,40	2,0	32	100	51,00	D4-9	0,55	1,4	32	0	39,40
D2-2	0,40	2,0	32	100	55,00	D5-7	0,35	4,0	32	0	55,00
D2-3	0,40	2,0	32	100	50,20	D5-8	0,35	4,0	32	0	56,50
D3-1	0,50	1,4	32	100	43,90	D5-9	0,35	4,0	32	0	51,00
D3-2	0,50	1,4	32	100	44,00	D1-10	0,45	2,0	20	0	42,70
D3-3	0,50	1,4	32	100	39,80	D1-11	0,45	2,0	20	0	48,90
D4-1	0,55	1,4	32	100	40,00	D1-12	0,45	2,0	20	0	48,50
D4-2	0,55	1,4	32	100	43,00	D2-10	0,40	2,0	20	0	51,00
D4-3	0,55	1,4	32	100	37,20	D2-11	0,40	2,0	20	0	49,30
D5-1	0,35	4,0	32	100	59,00	D2-12	0,40	2,0	20	0	47,70
D5-2	0,35	4,0	32	100	59,00	D3-10	0,50	1,4	20	0	40,40
D5-3	0,35	4,0	32	100	59,00	D3-11	0,50	1,4	20	0	40,10
D1-4	0,45	2,0	20	50	49,00	D3-12	0,50	1,4	20	0	39,50
D1-5	0,45	2,0	20	50	48,20	D4-10	0,55	1,4	20	0	30,20
D1-6	0,45	2,0	20	50	47,60	D4-11	0,55	1,4	20	0	31,80
D2-4	0,40	2,0	20	50	50,00	D4-12	0,55	1,4	20	0	31,00
D2-5	0,40	2,0	20	50	47,20	D5-10	0,35	4,0	20	0	51,00
D2-6	0,40	2,0	20	50	50,70	D5-11	0,35	4,0	20	0	49,80
D3-4	0,50	1,4	20	50	30,90	D5-12	0,35	4,0	20	0	49,80
D3-5	0,50	1,4	20	50	35,20	D1-13	0,45	2,0	7	0	39,80
D3-6	0,50	1,4	20	50	38,80	D1-14	0,45	2,0	7	0	20,80
D4-4	0,55	1,4	20	50	32,00	D1-15	0,45	2,0	7	0	38,70
D4-5	0,55	1,4	20	50	32,60	D2-13	0,40	2,0	7	0	36,80
D4-6	0,55	1,4	20	50	31,50	D2-14	0,40	2,0	7	0	43,40
D5-4	0,35	4,0	20	50	51,20	D2-15	0,40	2,0	7	0	43,40
D5-5	0,35	4,0	20	50	53,60	D3-13	0,50	1,4	7	0	25,90
D5-6	0,35	4,0	20	50	49,90	D3-14	0,50	1,4	7	0	26,00
D1-7	0,45	2,0	32	0	51,20	D3-15	0,50	1,4	7	0	26,60
D1-8	0,45	2,0	32	0	44,50	D4-13	0,55	1,4	7	0	24,40
D1-9	0,45	2,0	32	0	48,80	D4-14	0,55	1,4	7	0	24,60
D2-7	0,40	2,0	32	0	50,20	D4-15	0,55	1,4	7	0	23,80
D2-8	0,40	2,0	32	0	50,20	D5-13	0,35	4,0	7	0	46,00
D2-9	0,40	2,0	32	0	36,20	D5-14	0,35	4,0	7	0	44,80
D3-7	0,50	1,4	32	0	44,00	D5-15	0,35	4,0	7	0	35,80
D3-8	0,50	1,4	32	0	43,80						

*V/C – vodocementni faktor, Z/O – broj ciklusa zamrzavanja/otkravljivanja, σ_p – čvrstoća pri pritisku betona.
**t* denotes the age of concrete, *F/T* – number of freeze/thaw cycles, σ_p – compressive strength of concrete.

5 PROCENA ČVRSTOĆE PRI PRITISKU BETONA

U drugoj fazi istraživanja, nakon eksperimentalnog dela, pristupilo se razvoju modela na bazi veštačkih neuronskih mreža, s četiri ulazna podatka i samo jednim izlaznim podatkom (Tabela 6). Sličan pristup je već korišćen u prethodnim istraživanjima [18, 21, 32–33].

5 ESTIMATION OF CONCRETE COMPRESSIVE STRENGTH

In the second phase of the research, after performing experimental tests, we turn to development of a neural network model, with four input parameters and a single output unit (Table 6). Similar approach was already used in [18, 21, 32-33].

Tabela 6. Raspon vrednosti ulaznih i izlaznih podataka za obučavanje neuronske mreže
Table 6. Input-output parameters for the ANN training and their range

Podaci Type of data	Parametar Parameter	Raspon vrednosti Range
Ulazni Inputs	vodocementni faktor (%) *w/c* ratio (%)	0.35–0.55
	starost (dani) age (days)	7–32
	količina superplastifikatora (%) amount of superplasticizer (%)	1.4–4
	broj ciklusa zamrzavanja/otkravljivanja number of freeze/thaw cycles	0–100
Izlazni Output	čvrstoća na pritisak (MPa) compressive strength (MPa)	21.4–55

Na osnovu predloga Rumelharta i dr. [34], Lipmana [35] i Sonmeza i dr. [36], analizirana je veštačka neuronska mreža sa samo jednim skrivenim slojem, dok je broj jedinica u skrivenom sloju određen korišćenjem heurističkih obrazaca [36]. Kao što se u Tabeli 7 može videti, na osnovu broja ulaznih i izlaznih podataka, broj jedinica u skrivenom sloju je u rasponu od 1 do 12. U ovom slučaju, pristupilo se ispitivanju veštačkih neuronskih mreža s jednom jedinicom, tri jedinice, te osam i dvanaest jedinica u skrivenom sloju, radi određivanja modela s najpreciznijom procenom čvrstoće pri pritisku betona.

Following the suggestion of Rumelhart et al. [34], Lippmann [35] and Sonmez et al. [36] one hidden layer was chosen in present study, while the number of hidden neurons was determined using heuristics [36]. As it is clear from Table 7, the number of neurons that may be used in the hidden layer varies between 1 and 12. In present study, the number of hidden neurons was selected as 1, 3, 8 and 12 separately to establish the most effective ANN architecture.

Tabela 7. Heuristički obrasci za određivanje broja jedinica u skrivenom sloju
*(**N_i**: broj ulaznih jedinica, **N_0**: broj izlaznih jedinica)*
Table 7. The heuristics used for the number of neurons in hidden layer
*(**N_i**: number of input neurons, **N_0**: number of output neurons)*

Heuristički obrazac Heuristic	Calculated number of neurons for this study
$\leq 2 \times N_i + 1$	≤9
$3 \times N_i$	12
$(N_i + N_0)/2$	2,5 (3)
$\frac{2 + N_0 \times N_i + 0.5 N_0 \times (N_0^2 + N_i) - 3}{N_i + N_0}$	1,1 (1)
$2N_i/3$	2,7 (3)
$\sqrt{(N_i + N_0)}$	2,2 (2)
$2N_i$	8

U svim ispitvanim slučajevima, razmatrani skup podataka podeljen je na sledeći način: 60% za treniranje (45 podataka), 15% za validaciju (11 podataka) i 25% za testiranje (19 podataka), što odgovara predlogu Lunija [37] od 25% podataka za testiranje, kao i preporukama Nelsona i Ilingvorta [38] od 20–30% podataka za testiranje.

Treniranje neuronskih mreža izvedeno je za različiti broj jedinica u skrivenom sloju, kako je već i prethodno definisano u Tabeli 7. Imajući u vidu da se kao aktivaciona funkcija koristi sigmoidna funkcija, koja daje izlazne vrednosti u intervalu od 0 do 1, a s obzirom na to što ulazni i izlazni podaci imaju različite merne jedinice prema SI sistemu, neophodno je najpre izvršiti skaliranje podataka koristeći sledeću relaciju:

In all the examined cases, the total data set has been divided as following: 60% for training (45 recordings), 15% for validation (11 recordings) and 25% for testing (19 recordings), which corresponds well with the suggestion of Looney [37], who proposed 25% for testing, and with recommendation made by Nelson and Illingworth [38] who supported the idea of 20-30% of data for testing.

The possible ANN architectures were trained by using combinations of the number of hidden neurons defined above. Concerning the fact that we use sigmoid function as an activation function, which gives the output values in the range [0,1], and since the input and output data have different units according to IS system, scaling the input and output parameters was necessary, and it was performed in the following way:

$$\text{skalirana vrednost} = \frac{\text{maksimalna vrednost - neskalirana vrednost}}{\text{maksimalna vrednost - minimalna vrednost}}$$

$$\text{scaled value} = \frac{\text{max.value} - \text{unscaled value}}{\text{max.value} - \text{min.value}} \qquad (1)$$

Na ovaj način, sve posmatrane vrednosti normalizovane su u intervalu [0,1].

Da bismo odredili neuronsku mrežu s najpouzdanijom procenom čvrstoće pri pritisku betona na osnovu izmerenih vrednosti, koristili smo neuronsku mrežu s prostiranjem signala unapred i s propagacijom greške unazad. Obučavanje neuronskih mreža izvedeno je korišćenjem Levenberg-Markart algoritma obučavanja, kao najbrže metode za treniranje neuronskih mreža srednje veličine [39], što predstavlja prvi izbor kada je u pitanju nadgledano učenje, kao u ovoj analizi. Prethodno je već pomenuto da se kao aktivaciona funkcija koristi sigmoidna funkcija, što je vrlo čest izbor u prethodnim istraživanjima [36].

Razvijena su četiri različita modela neuronskih mreža, s jednom jedinicom, tri jedinice, te osam i dvanaest jedinica u skrivenom sloju, radi određivanja neuronske mreže s najpouzdanijom procenom čvrstoće, i s najboljim poklapanjem u odnosu na eksperimentalno dobijene rezultate. Da bi neuronska mreža dala pouzdane rezultate, najpre je potrebno isključiti mogućnost ,,pretreniranja", odnosno prividnog povećanja tačnosti procene neuronskih mreža, kada se greška pri treniranju mreže smanjuje, a istovremeno povećava pri validaciji i testiranju. U ovom slučaju, kao što se može videti sa slike 1, srednja kvadratna greška (MSE) teži konstantnoj vrednosti s povećanjem broja iteracija za cikluse treniranja, validacije i testiranja za sve ispitivane modele neuronskih mreža, čime se isključuje mogućnost ,,pretreniranja".

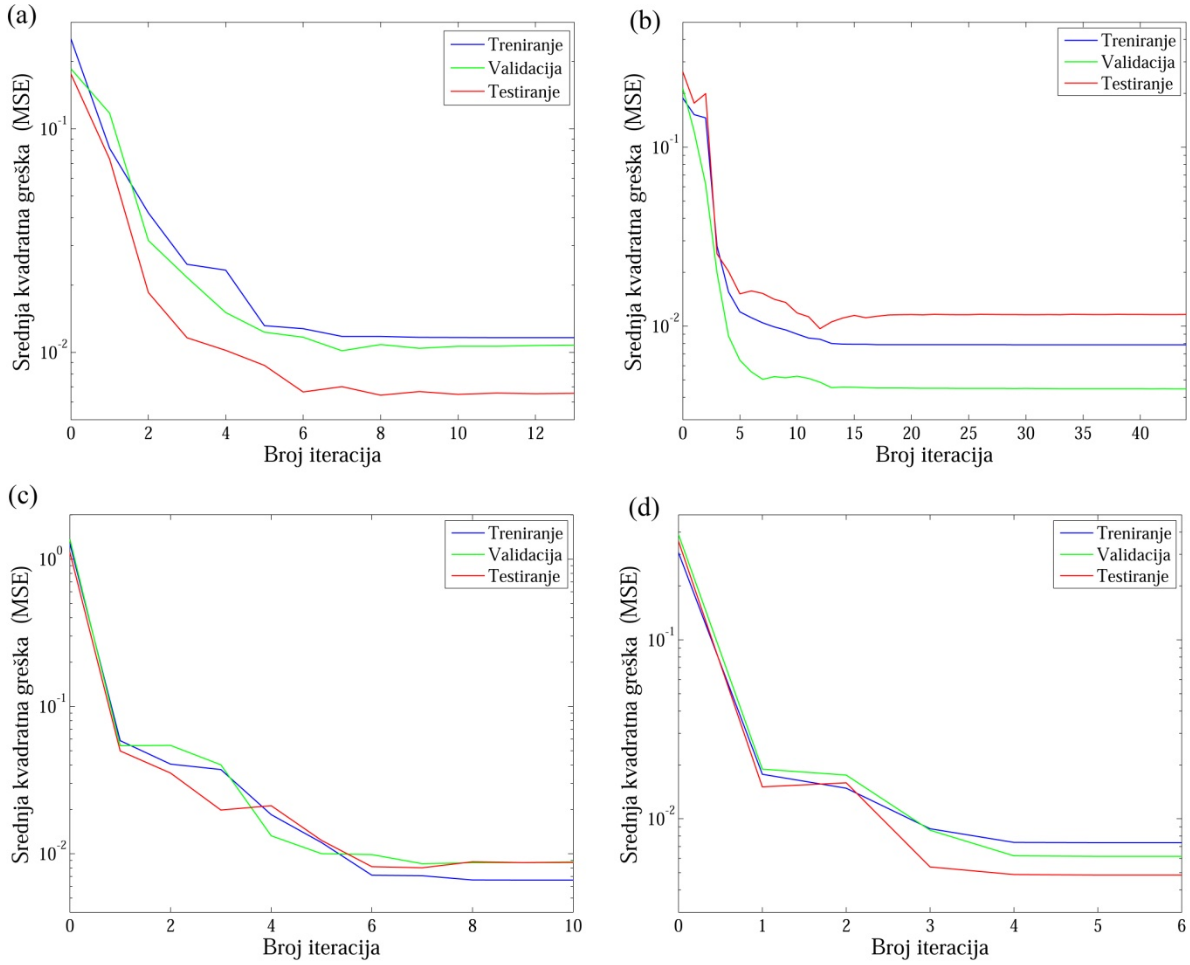
Vrednovanje preciznosti procene pritisne čvrstoće pomoću neuronskih mreža s različitim brojem jedinica u skrivenom sloju, dato je na slici 2. Na osnovu vrednosti koeficijenta korelacije (R≈0,97) i srednje kvadratne greške (0,005–0,007), očevidno je da veštačka neuronska mreža sa 12 jedinica u skrivenom sloju daje najpreciznije rezultate u poređenju sa eksperimentalno dobijenim vrednostima čvrstoće pri pritisku betona.

In that way, numerical values of the analyzed parameter were normalized in the range of [0,1].

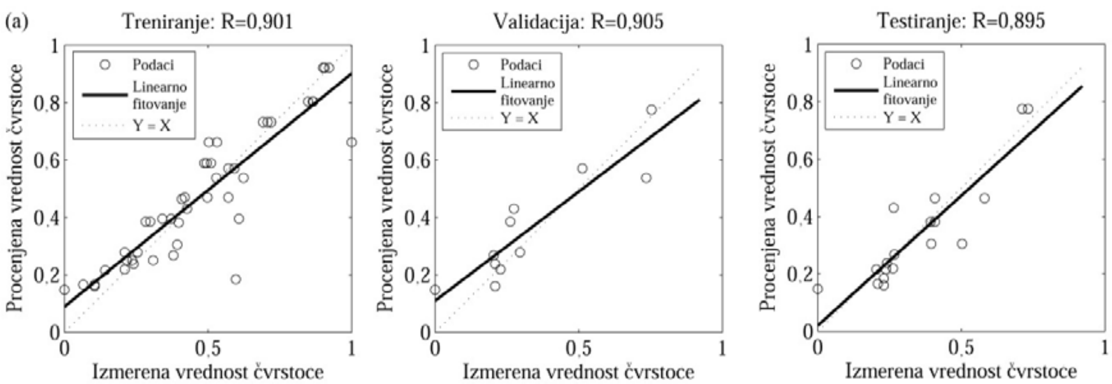
In this paper, in order to create an adequate ANN model for estimation of concrete compressive strength, based on the recorded data, a three-layer back propagation artificial neural network is chosen using Levenberg-Marquardt learning algorithms. This training algorithm is commonly considered as the fastest method for training moderate-sized feed-forward neural networks [39], and it is the first choice for solving the problems of supervised learning, which is the case in present analysis. A sigmoid function was chosen for the activation function, as the most common transfer function implemented in the literature [36].

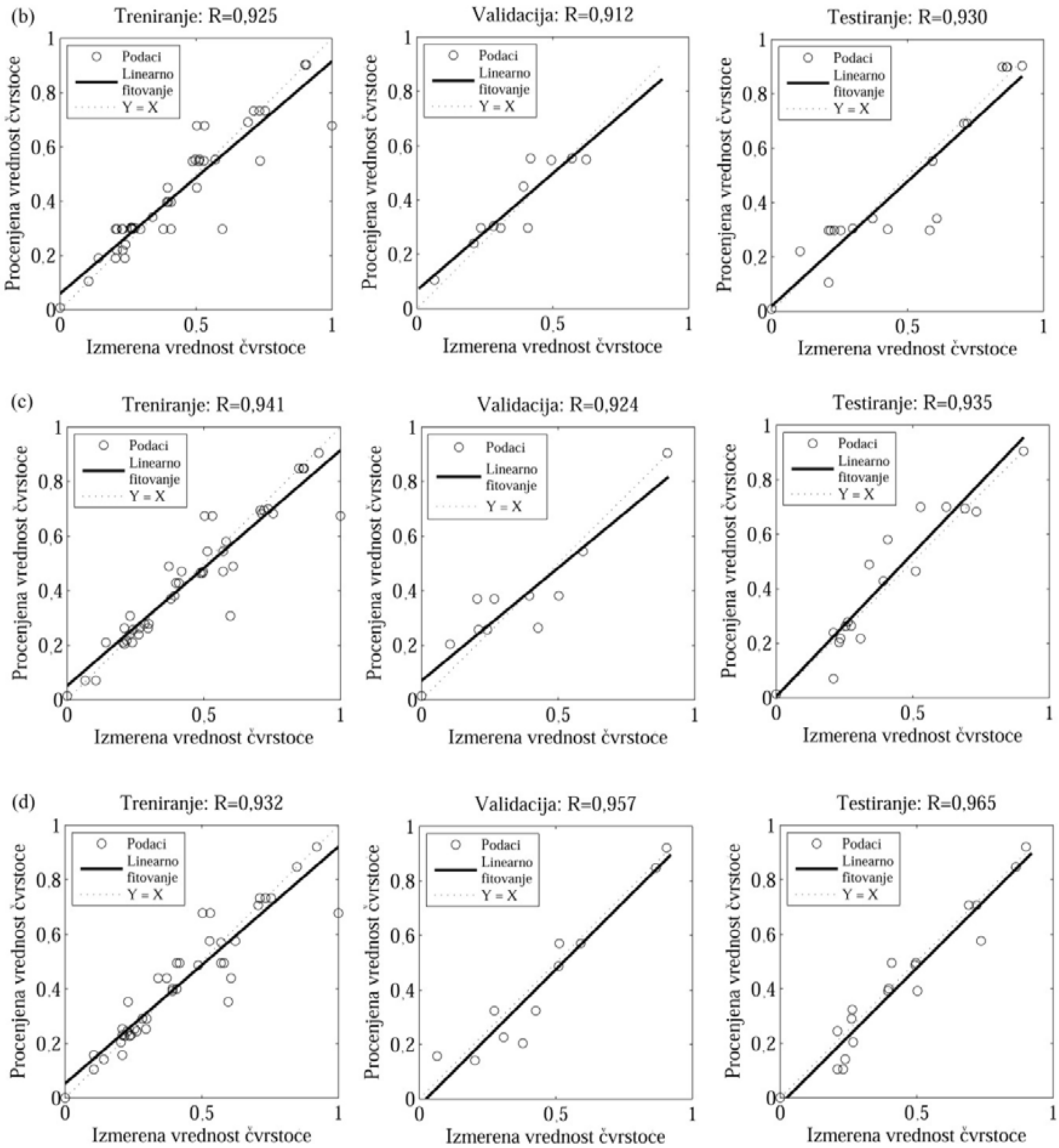
Four different ANN models with 1, 3, 8 and 12 hidden neurons in a hidden layer were developed, in order to create a model with most accurate response, i.e. a response which is most comparable with experimental results. In order to obtain reliable results, we firstly need to exclude the possibility of overfitting, when the ANN model only seemingly learn the data, which is implied by the decrease of training error and the increase of validation and testing error. In present study, as it can be seen from Figure 1, mean squared error (MSE) saturates with the increase of number of epochs for training and validation data, for all four examined cases with different number of hidden neurons, excluding in that way the possibility of overfitting.

Estimation of the resulting neural network models with scaled values for training, validation and testing set are shown in Figure 2 for different number of hidden nodes. It is clear that the ANN model with twelve hidden nodes has the highest coefficient of correlation (R≈0.97) for testing set, approximately the same value of R for training and validation set and with statistically small value of MSE (0.005-0.007), indicating good performance of the proposed network.



Slika 1. Srednja kvadratna greška u funkciji broja iteracija za treniranje, validaciju i testiranje, za različiti broj jedinica u skrivenom sloju: (a) 1, (b) 3, (c) 8 i (d) 12
Figure 1. MSE versus the number of epochs for training, validation and testing data, with different number of hidden neurons: (a) 1, (b) 3, (c) 8 and (d) 12.





Slika 2. Poređenje skaliranih procenjenih i izmerenih vrednosti čvrstoće pri pritisku betona za podatke iz ciklusa treniranja, validacije i testiranja, korišćenjem neuronske mreže s različitim brojem jedinica u skrivenom sloju: (a) 1, (b) 3, (c) 8 i (d) 12

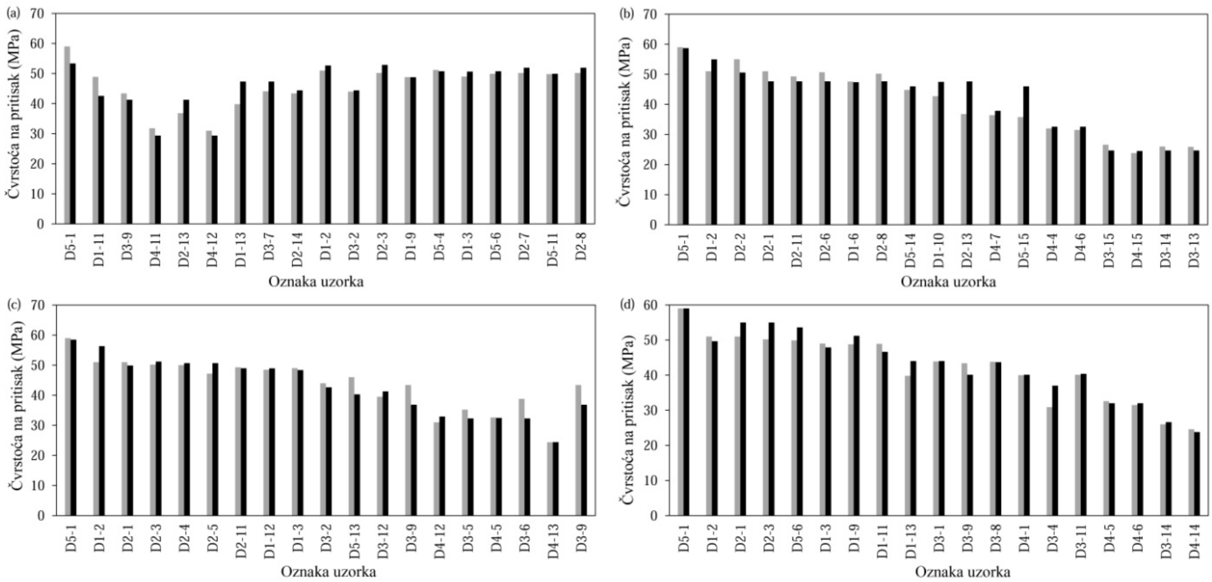
Figure 2. Comparison of the scaled estimated and measured values of concrete compressive strength showing training, validation and testing set, for the following number of hidden nodes: (a) one, (b) three, (c) eight and (d) twelve

6 OCENA USPEŠNOSTI MODELA

Ocena preciznosti predloženih modela veštačkih neuronskih mreža s različitim brojem jedinica u skrivenom sloju može dalje biti izvedena na osnovu poređenja njihovih neskaliranih vrednosti (iz ciklusa testiranja) sa eksperimentalnim rezultatima (slika 3). Jasno je da se u svim ispitivanim slučajevima veštačkim neuronskim mrežama daje pouzdana procena čvrstoće pri pritisku betona. Neophodno je naglasiti da se na slici 3 različiti uzorci koriste za testiranje u svakom od ispitivanih slučajeva s različitim brojem skrivenih jedinica, zbog nasumično odabranih početnih uslova.

6 EVALUATION OF MODEL PERFORMANCE

On the basis of the proposed ANN model with different number of hidden nodes, their precision of estimation could be further evaluated by comparing the unscaled predicted values (testing data) with experimental results (Figure 3). It is clear that in most of the examined cases, ANN gives reasonable value of concrete compressive strength. One should note that different samples are used for testing in each of the examined cases with different number of hidden nodes, due to random initial conditions.



Slika 3. Poređenje neskaliranih procenjenih i izmerenih vrednosti čvrstoće na pritisak uzoraka betona, korišćenjem neuronske mreže s različitim brojem jedinica u skrivenom sloju: (a) 1; (b) 3; (c) 8 i (d) 12. Sivim su označene izmerene vrednosti, a crnim procenjene vrednosti čvrstoće na pritisak betona. Različiti uzorci koriste se za testiranje u svakom od ispitivanih slučajeva s različitim brojem skrivenih jedinica, zbog nasumično odabranih početnih uslova

Figure 3. Comparison of measured and estimated compressive strength of concrete specimens by using ANN models with different number of hidden neurons: (a) 1; (b) 3; (c) 8 and (d) 12. Grey bars stand for the measured values; black bars denote estimated values of compressive strength. Different samples are used for testing in each of the examined cases with different number of hidden nodes, due to random initial conditions

Preciznost razvijenih modela s različitim brojem skrivenih jedinica može se dalje oceniti izračunavanjem vrednosti različitih standardnih statističkih grešaka, datih u Tabeli 8 [40].

Performances of the developed models with different number of hidden nodes could be further evaluated using different standard statistical error criteria given in Table 8 [40].

*Tabela 8. Pregled statističkih grešaka korišćenih za ocenu uspešnosti predloženog modela**
*Table 8. Preview of statistical error parameters used for models' evaluation**

Statistička greška Statistical parameter	Jednačina Equation
Srednja apsolutna greška (MAPE) Mean Absolute Percentage Error (MAPE)	$MAPE = \frac{1}{n} \times \left[\sum_{i=1}^{n} \left\| \frac{t_i - x_i}{t_i} \right\| \right] \times 100$
Varijansa relativne vrednosti apsolutne greške (VARE) Variance Accounted For (VAF)	$VARE = \frac{1}{n} \times \left[\sum_{i=1}^{n} \left(\left\| \frac{t_i - x_i}{t_i} \right\| - mean \left\| \frac{t_i - x_i}{t_i} \right\|^2 \right) \right] \times 100$
Medijana (MEDAE) MEDian Absolute Error (MEDAE)	$MEDAE = median\left(t_i - x_i\right)$
Sračunata varijansa (VAF) Variance Absolute Relative Error (VARE)	$VAF = \left[1 - \frac{\mathrm{var}\left(t_i - x_i\right)}{\mathrm{var}(t_i)} \right] \times 100$

*t_i predstavlja izmerenu vrednost čvrstoće pri pritisku, a x_i predstavlja procenjenu vrednost čvrstoće pri pritisku.
*t_i represents measured value of compressive strength, while x_i denotes predicted value of compressive strength.

Izračunate statističke greške za veštačke neuronske mreže s različitim brojem jedinica u skrivenom sloju date su u Tabeli 9. Jasno je da veštačka neuronska mreža sa dvanaest jedinica u skrivenom sloju daje najmanje vrednosti srednje apsolutne greške (MAPE), varijanse relativne vrednosti apsolutne greške (VARE) i medijane (MEDAE), a najveću vrednost sračunate varijanse (VAF) u odnosu na neuronske mreže s jednom jedinicom, tri jedinice i osam jednica u skrivenom sloju.

Calculated values of statistical errors for neural networks with different number of hidden nodes are given in Table 9. It is clear that ANN model with twelve hidden nodes has the lowest values of MAPE (Mean Absolute Percentage Error), VARE (Variance Absolute Relative Error) and MEDAE (MEDian Absolute Error), and the highest value of VAF (Variance Accounted For), in comparison to the ANN models with one, three or eight hidden nodes.

Tabela 9. Statističke greške u proceni čvrstoće pri pritisku uzoraka betona korišćenjem neuronske mreže s različitim brojem jedinica u skrivenom sloju
Table 9. Statistical errors of the ANN models with different number of hidden nodes for estimation of concrete compressive strength

Veštačka neuronska mreža ANN model	Statističke greške Statistical errors			
Broj jedinica u skrivenom sloju No. of hidden nodes	MAPE	VARE	MEDAE	VAF
1	5,47	5,44	1,74	90,77
3	7,31	7,25	1,65	81,81
8	5,74	5,71	1,35	88,21
12	4,61	4,59	1,10	92,80

7 ZAKLJUČAK

U radu je predloženo nekoliko modela veštačkih neuronskih mreža za procenu čvrstoće pri pritisku betona, korišćenjem rezultata opita na 75 uzoraka s različitim vodocementnim faktorom i količinom super-plastifikatora. Uzorci betona izlagani su različitom broju ciklusa zamrzavanja i otkravljivanja, a njihova čvrstoća na pritisak određivana je nakon 7, 20 i 32 dana. Eksperimentalni rezultati ukazuju na to da sa smanje-njem vodocementnog faktora, čvrstoća pri pritisku betona raste do vrednosti koja je određena granulo-metrijskim sastavom agregata i količinom cementa u betonskoj smeši. Dalje smanjenje vodocementnog faktora dovodi do smanjenja pritisne čvrstoće, s obzirom na to što betonska smeša gubi konsistenciju. S druge strane, smenjivanje ciklusa zamrzavanja i otkravljivanja takođe smanjuje čvrstoću pri pritisku, naročito pri visokim vrednostima vodocementnog faktora. Uzorci betona sa superplastifikatorom izloženi zamrzavanju pokazuju povećanje čvrstoće pri pritisku čak nakon 50 i 100 ciklusa zamrzavanja/otkravljivanja.

Na bazi ovako dobijenih eksperimentalnih rezultata, predloženo je nekoliko modela veštačkih neuronskih mreža, s različitim brojem jedinica u skrivenom sloju, određenih na osnovu broja ulaznih i izlaznih jedinica. U svim modelima primenjena je veštačka neuronska mreža s prostiranjem signala unapred i s propagacijom greške unazad, korišćenjem Levenberg-Markart algoritma obu-čavanja. Rezultati izvedenog istraživanja pokazali su da neuronska mreža sa 12 jedinica u skrivenom sloju daje najprecizniju procenu pritisne čvrstoće betona, s najma-njom vrednošću statističkih grešaka MAPE, VARE i MEDAE, i najvećom vrednošću sračunate varijanse (VAF).

7 CONCLUSIONS

In present paper, the ANN model for estimation of concrete compressive strength is proposed using the experimental results on 75 specimens with different *w/c* ratio and different amount of superplasticizer. The concrete samples were exposed to different number of freeze/thaw cycles, while their compressive strength was determined at different age (7, 20 and 32 days). Experimental results indicate that by decreasing the *w/c* ratio, the compressive strength increases up to some level, which is determined by the aggregate grading and amount of cement in the mixture. Further decrease of *w/c* ratio also decreases compressive strength because the concrete mixture is losing workability. On the other hand, freezing and thawing cycles also decreases the concrete strength, especially at higher *w/c* ratios. Concrete samples with SP exposed to freezing show increase in strength even after 50, and more clearly after 100 cycles.

On the basis of the obtained experimental results, several ANN models were developed, using different number of hidden nodes, which were determined according to the number of input and output nodes. In all the examined cases, a three layer feed-forward back-propagation network with Levenberg-Marquardt learning algorithm was used. The performed research showed that the ANN model with twelve hidden nodes provides the most accurate estimation of concrete compressive strength, comparable to the experimental results. Further analysis indicated that neural network with 12 hidden nodes has the lowest values of MAPE, VARE and MEDAE, and the highest value of VAF, confirming this model as the most precise one for estimation of concrete compressive strength.

Međutim, uprkos visokoj preciznosti predložene veštačke neuronske mreže, jedno od glavnih ograničenja ove analize predstavlja relativno jednostavan sastav ispitivanih betonskih smeša. Svakako bi važno bilo da se, u okviru budućih analiza, u obzir uzmu i uzorci betona s različitim savremenim aditivima (leteći pepeo,zeolit, topioničarska zgura i dr.), što bi dovelo do poboljšanja predloženog modela neuronske mreže i njegove veće primenljivosti u svakodnevnoj praksi. Sa stanovišta konstrukcije veštačke neuronske mreže, detaljnija analiza pouzdanosti modela s različitim algoritmima učenja i propagacije greške sigurno bi doprinela boljem razumevanju mogućnosti primene ovih metoda za procenu čvrstoće betona pri pritisku.

However, despite the high predictive power of the proposed ANN models, one of the main limitations of the analysis is certainly simple composition of the concrete specimens. What could be interesting in future analyzes are certainly concrete samples with different additives (plasticizer, fly ash, furnace slag, etc.), which would further improve the proposed ANN model and make it more usable in daily practice. Moreover, it would be interesting to examine the estimation accuracy of the ANN models with different learning algorithms, which may further upgrade the presented approach, with better understanding of the possible use of these methods for estimation of concrete compressive strength.

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REZIME

PROCENA ČVRSTOĆE BETONA PRI PRITISKU, KORIŠĆENJEM VEŠTAČKIH NEURONSKIH MREŽA

Srđan KOSTIĆ
Dejan VASOVIĆ

U radu se daje procena čvrstoće betona pri pritisku, primenom veštačkih neuronskih mreža s prostiranjem signala unapred i propagacijom greške unazad. Obučavanje mreže sprovodi se korišćenjem Levenberg-Markart algoritma obučavanja za četiri različite arhitekture neuronskih mreža, s jednom jedinicom, tri jedinice, te osam i dvanaest jedinica u skrivenom sloju, radi odbacivanja efekta ,,pretreniranja". Treniranje, validacija i testiranje neuronskih mreža izvodi se na osnovu rezultata eksperimentalnog ispitivanja čvrstoće pri pritisku na 75 uzoraka betona, s različitim vodocementnim faktorom i količinom superplastifikatora tipa melamina. Ispitivani uzorci betona izlagani su različitim ciklusima zamrzavanja/otkravljivanja, a njihova čvrstoća pri pritisku određivana je nakon 7, 20 i 32 dana. Dobijeni rezultati ukazuju na to da neuronska mreža s dvanaest jedinica u skrivenom sloju daje ocenu čvrstoće zadovoljavajuće tačnosti u poređenju sa eksperimentalno dobijenim podacima (R≈0,97, MSE=0,005). Rezultati izvedene analize dodatno su potvrđeni sračunavanjem vrednosti standardnih statističkih grešaka: najmanjom vrednošću srednje apsolutne greške (MAPE), varijanse relativne vrednosti apsolutne greške (VARE) i medijane (MEDAE), kao i najvećom vrednošću sračunate varijanse (VAF) za izabranu arhitekturu neuronske mreže.

Ključne reči: čvrstoća betona, vodocementni faktor, superplastifikator, zamrzavanje/otkravljivanje, starost, veštačka neuronska mreža

SUMMARY

ESTIMATION OF CONCRETE COMPRESSIVE STRENGTH USING ARTIFICIAL NEURAL NETWORK

Srđan KOSTIC
Dejan VASOVIC

In present paper, concrete compressive strength is evaluated using back propagation feed-forward artificial neural network. Training of neural network is performed using Levenberg-Marquardt learning algorithm for four architectures of artificial neural networks, one, three, eight and twelve nodes in a hidden layer in order to avoid the occurrence of overfitting. Training, validation and testing of neural network is conducted for 75 concrete samples with distinct *w/c* ratio and amount of superplasticizer of melamine type. These specimens were exposed to different number of freeze/thaw cycles and their compressive strength was determined after 7, 20 and 32 days. The obtained results indicate that neural network with one hidden layer and twelve hidden nodes gives reasonable prediction accuracy in comparison to experimental results (R=0.965, MSE=0.005). These results of the performed analysis are further confirmed by calculating the standard statistical errors: the chosen architecture of neural network shows the smallest value of mean absolute percentage error (MAPE=, variance absolute relative error (VARE) and median absolute error (MEDAE), and the highest value of variance accounted for (VAF).

Keywords: concrete strength, *w/c* ratio, superplasticizer, freezing/thawing, age, artificial neural network

EVALUATION OF STRUCTURAL RELIABILITY USING SIMULATION METHODS

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1 INTRODUCTION

Reliability is defined in EN 1990 (Eurocode 0 – Basis of structural design, [1]) as "the ability of a structure or a structural member to fulfill the specified requirements, including the design working life, for which it has been designed". Reliability is usually expressed in probabilistic terms and it covers safety, serviceability and durability of a structure (see [1]). The following relation between the "probability of failure" P_f and the index of reliability β is given in EN 1990, Annex C:

$$P_f = \Phi(-\beta) \quad (1)$$

where Φ is the cumulative distribution function of the standardized Normal distribution. The probability of failure can be expressed through a performance function *g* (also referred to as "limit state function", see [5], [6]) such that a structure is considered to survive if $g>0$ and to fail if $g\leq 0$. According to EN 1990, P_f and β are only notional values that do not necessarily represent the actual failure rates. They are used as operational values for code calibration purposes and comparison of reliability levels of structures. For structural elements of Reliability Class RC2 (as defined in EN 1990, Annex B), for the ultimate limit state, the recommended value of β is 3.8.

In general, a limit state function "*g*" as defined above can be formulated for a given structure or structural member, but the probability of this function being smaller than zero or equal to zero, i.e. the probability of failure, is not always easy to be assessed. This is mainly due to the fact that the limit state function in general contains a large number of variables, with different probability distribution functions. Exact analytical integration, numerical integration, approximate analytical methods and simulation methods are among the most used methods of solving the probability of structural failure. Analytical integration and approximate analytical methods such as First Order Reliability Method (FORM) are limited to simple models. Numerical integration can handle more complex models, but however, the application is limited. Simulation methods have been developed lately along with the development of computers and practically, they can lead to solution for very complex models.

Simulation methods are used in this paper for the reliability analysis of a reinforced concrete bridge pier. Using computer simulations has an important advantage among the other methods; it allows a large number of variables into analysis. The limit state function "*g*" can contain several geometric variables (such as length of elements, dimensions of cross sections, rebar diameters etc.), resistance variables (concrete strength, steel yield strength etc.) and action variables (self-weight of materials, environmental actions and imposed loads). Assessing the probability of a function "*g*" with many independent variables being equal to or smaller than zero would be almost impossible without simulations.

A Monte Carlo simulation is a mathematical technique that involves a (usually) large number of iterations with different random values of inputs, each of which produces a different outcome. Monte Carlo simulations make it possible to study very complex problems and they suit the needs of reliability analysis of structures. Reliability design concepts and techniques are explained further in [5], [6] and [7].

2 RELIABILITY ANALYSIS

2.1 Description of the bridge pier

The transversal section of the bridge is shown in Figure 1. The bridge has several piers in a distance of 20m (span length). For the analysis of the pier, the

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simplified cantilever model shown in Figure 1 was used, with H=8m and concentrated mass "m".

The study is focused on the seismic design situation. The loads acting on the bridge pier are the axial forces from self-weight and traffic (N), bending moment (M) from eccentricity of traffic loads and the seismic forces. The pier is considered to be adequately fixed at basement. Geotechnical aspects are not considered further in this paper for the reliability analysis of the pier.

The cross section of the bridge pier shown in Figure 1 has nominal dimensions h=3.4m, b=2.2m and R=1.1m. The ground type according to Eurocode 8 (see [3]) is considered of Type A.

2.2 Definition of variables

When a structure is designed or when an existing structure is assessed, it is impossible to have perfect knowledge for all the factors that influence the results of calculations. Even for the simplest structures, several uncertainties exist. As it is shown in Figure 2, for the bridge pier, it cannot be sure if the cross section has the required dimensions, if reinforcement bars are placed perfectly correct, if their diameter is equal to the specified diameter or if the shape of the bars matches perfectly with the design. Also, it cannot be sure if concrete strength and yield strength of steel will be higher or lower than those specified. The same uncertainties apply to permanent actions, seismic and traffic loads and even the design model of the reinforced concrete section (e.g. the stress block dimensions).

The pier can be either a new one or an existing one. In the case of a new pier, the Probability Distribution Functions (PDFs) of the variables would represent the probable values. In case of existing bridges, if sufficient tests are available these PDFs will represent the actual distributions.

Recommendations from literature have been used in this paper for the distribution functions of the variables summarized in Table 1. For resistance and loads, the distributions have been chosen with mean value and coefficient of variation such that the characteristic fractile corresponds to a predefined value (see the comments column in Table 1). Model uncertainties have been introduced as multiplicative stochastic variables in the design equations (e.g. multiplying the other variables), with mean value equal to 1. In Table 1 (F) denotes actions, (R) resistances and (a) geometry variables.

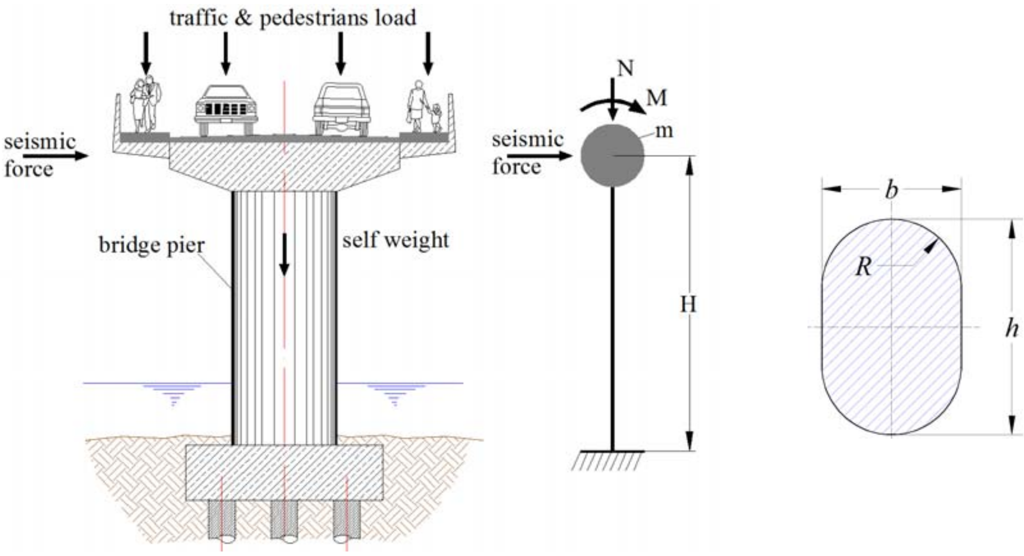

Figure 1. Section of the bridge showing the pier under analysis (left), structural model (middle) and cross section of pier (right)

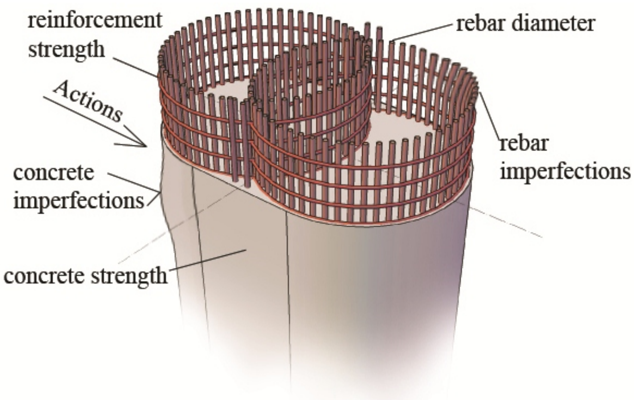

Figure 2. Some of the possible imperfections and uncertainties in the reinforced concrete pier

Table 1. Definition of variables considered

Nr.	Variable	Distribution	Mean	Coef. of variation	Unit	Comment
1	Weight of reinforced concrete (*F*)	Normal	25	10%	kN/m^3	Based on [9]
2	Traffic loads (*F*)					LM1 with 5% probability of exceedance in 50 years, see [2], [4]
3	Seismic action (*F*)					a_g=0.25g with 10% probability of exceedance in 50 years, [3]
4	Concrete compression strength (*R*)	LogNormal	38	15%	MPa	Characteristic value 30MPa (5% fractile), [1], [5], based on [9]
5	Reinforcement yield strength (*R*)	LogNormal	430	5%	MPa	Characteristic value 400MPa (5% fractile), [1], [5], based on [9]
6	Model uncertainty	LogNormal	1	5%	-	Multiplicative variable, based on [9]
7	Concrete modulus of elasticity (*R*)	Normal	3.4×10^7	1%	kN/m^2	Assumption
8	Reinforcement modulus of elasticity (*R*)	Normal	2.0×10^8	0.6%	kN/m^2	Assumption
9	Height of the pier (*a*)	Normal	8.0	0.06%	m	Assumption
10	Span length (*a*)	Normal	17.0	0.06%	m	Assumption
11	Deck section area (*a*)	Normal	10.22	0.1%	m^2	Assumption
12	Height of pier section (*a*)	Normal	3.4	0.06%	m	Assumption
13	Pier rebar diameter (*a*)	Normal	30	0.3%	mm	Assumption
14	Weight of road layers (*F*)	Normal	28	10%	kN/m^3	Assumption, based on [9]

The seismic hazard for the bridge pier is represented by a reference ground acceleration a_{gR}=0.25g with a probability of exceedance equal to 10% in 50 years. Assuming that the maximum ground acceleration is inaccurately known, a random ground acceleration (larger than 0.25g) multiplied by a Bernoulli variable with mean value 0.1 (as shown in Figure 3) is assumed to represent the "strong" seismic event. For earthquakes with ground acceleration smaller than 0.25g, the bridge pier was analyzed separately.

Considering the seismic design situation, the probability of simultaneous occurrence of maximum values of seismic actions and traffic actions was assumed to be 1%. Further studies are required for a more accurate assessment of the probability of simultaneous occurrence of these two actions.

The stress strain curves for concrete and steel were also considered stochastic, based on the distribution functions of concrete strength and steel yield strength. For a random value of concrete strength and yield strength of reinforcement, the stress strain curves are shown in Figure 4.

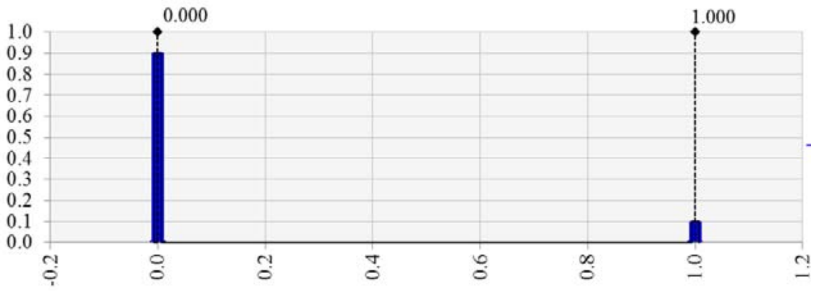

Figure 3. PDF of the multiplicative Bernoulli variable representing the "strong" seismic event

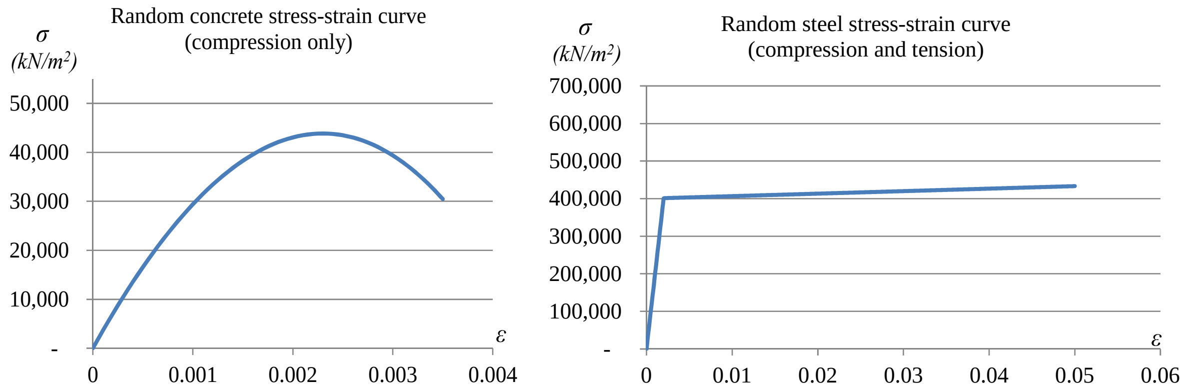

Figure 4. Stress strain curves of concrete and reinforcement for a random sample

In total 14 independent variables were considered for analysis. In general, more detailed and accurate distribution functions can enter the analysis if sufficient information is available (for example, from tests).

2.3 Description of the procedure

A worksheet in Microsoft Excel was built for the analysis of the pier. The basic idea is to run the procedure contained in the worksheet a large number of times while giving random values to the input variables and to collect and analyze the results. In other words, the random process of structural failure or survival has been modelled through a Monte Carlo simulation. In order to perform this simulation, specialized software Palisade @Risk was used. Figure 5 describes the whole procedure using a schematic algorithm.

After the definition of the input variables, the next step is “sampling”. For each of the input variables defined in Table 1, samples are taken using the Monte Carlo method, then the internal forces and displacements are calculated through the worksheet and the results are stored in Microsoft Excel to be further processed. The procedure is repeated until a predefined number of iterations are performed.

The number of iterations performed in a simulation is important. The expected probability of failure is in the range of 1×10^{-4} or less, because for an index of reliability β=3.8, the probability of failure will be:

$$P_f = \Phi(-\beta) = \Phi(-3.8) = 0.00007235 \qquad (2)$$

In other words, if only 10,000 iterations were performed in a simulation, 0 or 1 failure event could have been observed, which means that the possible error is high. In order to reduce the uncertainty of the estimate of probability, several simulations were performed, with number of iterations per simulation ranging from 100,000 to 2,000,000 until a satisfactory convergence was achieved. The estimated probability of failure at the end of the simulation is calculated as:

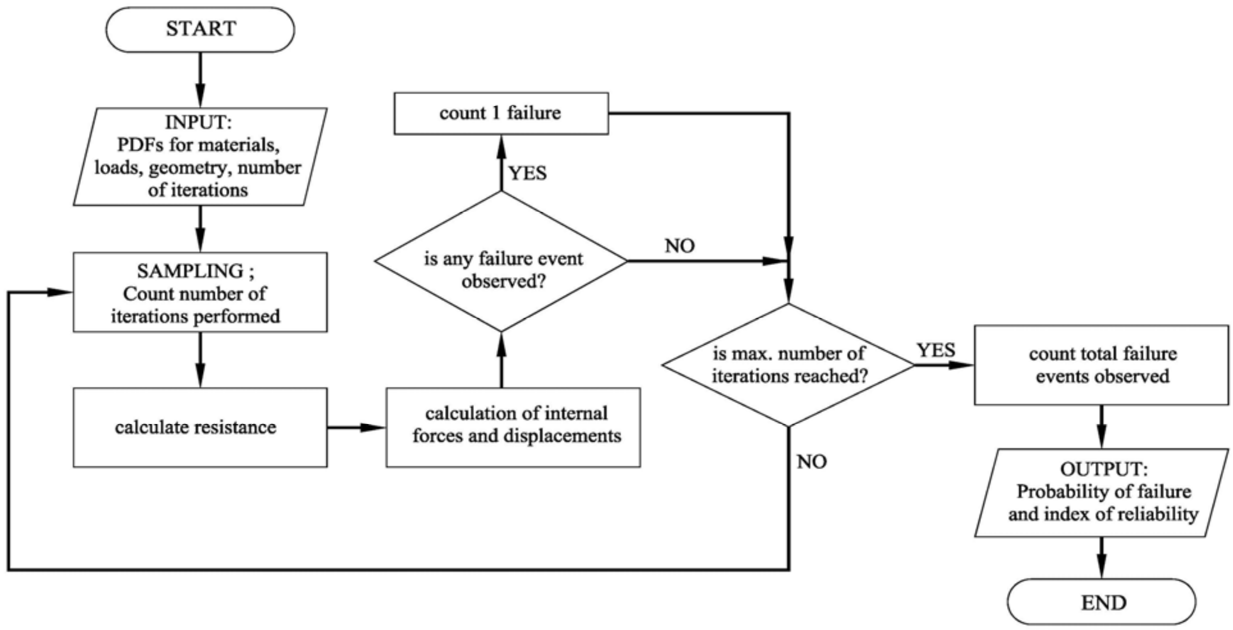

Figure 5. General algorithm for the estimation of index of reliability through Monte Carlo simulation

$$P_f = \frac{number\,of\;\,failures\,observed}{number\,of\;iterations\;performed} \tag{3}$$

2.4 Limit state function

Rather than formulating a limit state function "*g*" as the difference between the resistance and the action effects, a logical function that takes only values "1" and "0" was built (see the algorithm of Figure 5). If failure is observed, the function "*g*" takes value "1", otherwise its value is "0". So, the distribution function of "*g*" is a Bernoulli function with its mean value equal to the probability of encountering value "1", i.e. equal to the probability of failure.

In order to calculate the resisting bending moment and axial force, the cross section was divided into layers as described in Penelis and Kappos [8]. For each iteration, the resisting axial force and the corresponding moment were calculated from the equilibrium of forces resulting from strain profile in Figure 6, with the assumption that plane sections remain plane after deformation.

In Figure 6, x is the depth of neutral axis and ε denotes the strain of concrete (where index "*c*" is used) or steel (with index "*s*") at any layer i. The following equilibrium equations shall apply when 20 layers are considered:

$$\begin{cases} N = \sum_{i=1}^{20} \sigma_{ci} A_{ci} + \sum_{i=1}^{20} \sigma_{si} A_{si} \\ M = \sum_{i=1}^{20} \sigma_{ci} A_{ci} y_{ci} + \sum_{i=1}^{20} \sigma_{si} A_{si} y_{si} \end{cases} \tag{4}$$

The stresses σ are calculated from the stress-strain diagrams presented in paragraph 2.2 for a given strain ε. Because of the shape of the pier and the reinforcement layout, the same number of layers was used for both concrete and steel. The equilibrium in (2.3) is fulfilled for a neutral axis depth x which is calculated through iterations (see [8]).

Shear resistance of the pier was excluded in reliability analysis. Further studies can consider shear resistance and all the relevant failure modes, including geotechnical aspects.

Action effects are calculated based on Figure 7.

The seismic force is calculated through the elastic response spectrum for ground Type A as the product of mass "*m*" with the spectral acceleration calculated using Eurocode 8. The mass is calculated for each iteration of the simulation, and it takes into consideration the self-weight of the bridge superstructure and pier and the traffic loads (if present).

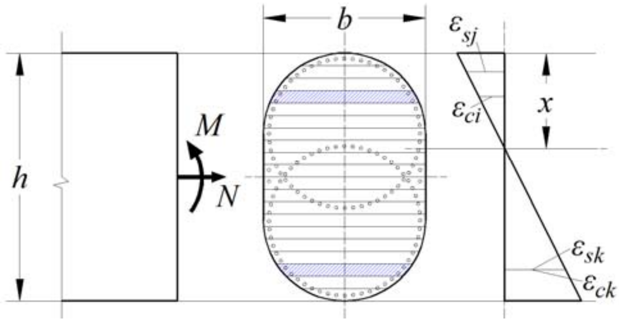

Figure 6. Cross section of the pier and the strain profile

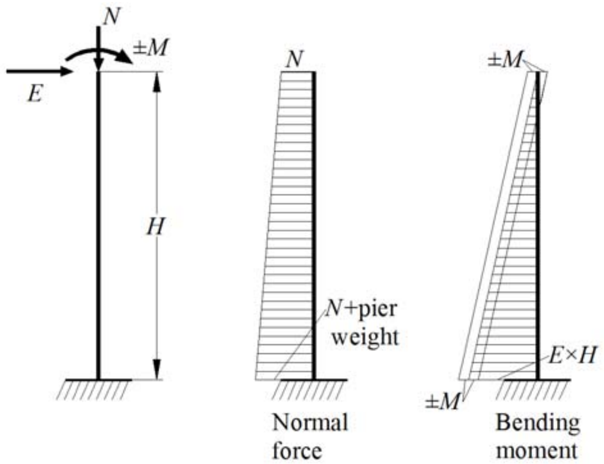

Figure 7. Normal force and bending moment in the bridge pier

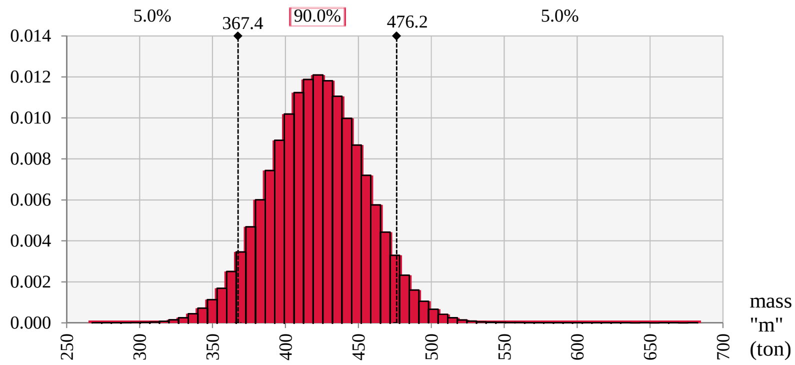

Figure 8. PDF of mass of the deck and pier in tons

Table 2. Estimated probability of failure for different number of iterations performed

	Number of iterations in a simulation			
Description	100,000	500,000	1,000,000	2,000,000
Probability of failure of the pier	0.0000100	0.0000110	0.0000200	0.0000205
Index of reliability β	4.26	4.24	4.11	4.10

No partial factor or combination factor was included in the calculations presented above. The direct comparison of resistances with action effects described above leads to the result of g=1 or g=0 in an iteration. The procedure then follows the algorithm of Figure 5.

3 RELIABILITY ANALYSIS RESULTS

As described in paragraph 2.2, the ground acceleration during simulation exceeds 0.25g in roughly 10% of iterations. Figure 8 shows the PDF of the concentrated mass "m" (see Figure 1). The variation of mass is due to geometrical variables, self-weight variables and the traffic variables. It is very important because it has direct influence on the fundamental period of the structure and the seismic force.

The analysis results are given in Table 2, for 100000, 500 000, 1000 000 and 2000 000 iterations per simulation. The probability of failure and the accompanying index of reliability are calculated in the spreadsheet for each case and reported in the last row of the table.

Trial simulations with more than 2 million iterations showed that the probabilities estimated have insignificant differences. As a conclusion, based on Table 2, the bridge pier has a reliability level higher than the target value of "3.8".

4 COMPARISON WITH PARTIAL FACTOR METHOD OF EUROCODES

The already created spreadsheet was used for the design of the reinforced concrete pier according to Partial Factor Method of Eurocodes, considering the seismic design situation. This time, the design values of the variables were used in the design equations, taken from the characteristic value, as defined in the Eurocodes, multiplied or divided by the relevant partial factors. The traffic loads LM1 were multiplied by the factor $\psi_{2,1}$=0.2 (see [1] to [5]).

In order to make the comparison possible, the design of the reinforced concrete pier according to Eurocodes using partial factors was done prior to the reliability analysis presented in the previous paragraphs. So, the area of reinforcement that resulted from the design according to Eurocodes is the same as the area of steel used for the reliability analysis. A design according to Eurocodes should lead to a reliability index larger than 3.8 (see [1]). The exact value of the index is "invisible" while designing using the partial factors.

On the other hand, the reliability analysis described in this paper leads to an estimation of the index of reliability. In our case, β=4.1.

5 CONCLUSION

Nowadays, computers offer a great tool for the structural engineer to solve complicated tasks. This paper presented in brief the procedure followed for the assessment of structural reliability of a reinforced concrete bridge pier. It was shown that simulation models can be implemented in calculation spreadsheet in order to solve complicated probability problems related to structural engineering. Given sufficient data is available, it is possible to actually design a structure or to assess its resistance and capacity based on the target reliability level. For the studied pier, the Eurocode Index of Reliability estimated through simulations resulted greater than the target index equal to 3.8. This means that, with the given input data, a more economical design could be possible. Especially for important structures such as bridges, simulation methods can lead to a realistic assessment of structural risk. The index of reliability gives a more clear idea regarding the safety of a structure. Especially for structures being designed with a target index of reliability different from 3.8 (smaller or larger), for which there are no explicitly recommended partial factors in Eurocode, reliability analysis through simulations can be useful to compare the level of reliability with the target level.

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SUMMARY

EVALUATION OF STRUCTURAL RELIABILITY USING SIMULATION METHODS

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Eurocode describes the "index of reliability" as a measure of structural reliability, related to the "probability of failure". This paper is focused on the assessment of this index for a reinforced concrete bridge pier. It is rare to explicitly use reliability concepts for design of structures, but the problems of structural engineering are better known through them. Some of the main methods for the estimation of the probability of failure are the exact analytical integration, numerical integration, approximate analytical methods and simulation methods. Monte Carlo Simulation is used in this paper, because it offers a very good tool for the estimation of probability in multivariate functions. Complicated probability and statistics problems are solved through computer aided simulations of a large number of tests. The procedures of structural reliability assessment for the bridge pier and the comparison with the partial factor method of the Eurocodes have been demonstrated in this paper.

Key words: structural reliability, index of reliability, probability of failure, Monte Carlo simulation, bridge pier

REZIME

VREDNOVANJE KONSTRUKIJCKE POUZDANOSTI KORIŠĆENJEM METODA SIMULACIJE

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U Evrokodu 0 opisan je „indeks pouzdanosti“ kao mera konstrukcijske pouzdanosti, koja se odnosi na „verovatnoću otkaza“. U članku naglasak je na procenu pomenutog indeksa za armiranobetonski stub mosta. Nije uobičajeno eksplicitno korišćenje koncepta pouzdanosti u projektovanju konstrukcija, ali se problem konstrukcijskog inženjerstva bolje se razume preko nje. Neke od najvažnijih metoda za procenu verovatnoće otkaza su egzaktna analitička integracija, numerička integracija, aproksimativne analitičke metode i metode simulacije. U ovom radu je korišćena metoda Monte Karlo simulacije, jer nudi veoma dobar alat za procenu verovatnoće u multivarijante funkcija. Komlikovana verovatnoća i statistički problemi su rešeni pomoću kompjutera koristeći simulacije velikog broja ispitivanja. Procedure procene konstrukcijske pouzdanosti supca most i upoređenje sa metodom parcijalnih faktora Evrokodova su ilustrovane u ovom radu.

Ključne reči: konstrukcijska pouzdanost, indeks pouzdanosti, verovatnoće otkaza, Monte Karlo simulacija, stubac mosta

METODE ODREĐIVANJA POTENCIJALA ZA REVITALIZACIJU GRADITELJSKOG NASLEĐA – Pouke grada Berna

METHODS FOR DETERMINATION OF REVITALIZATION POTENTIAL OF BUILT HERITAGE - Lessons learned on the city of Bern

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1 UVOD

U novoj situaciji, nastaloj poslednjih decenija u Centralnoj i Jugoistočnoj Evropi, kada je reč o graditeljskom nasleđu i njegovoj ulozi u budućnosti grada, korisno je obaviti uporedno proučavanje raznih alternativnih pristupa rešavanju problema. Osnovno pitanje koje se može postaviti jeste kakve su mogućnosti prenosa iskustva iz sredina s tržišnom ekonomijom i na koji način se mogu primeniti u društvu koje je u dugoročnoj, iscrpljujućoj tranziciji, kao što je srpsko društvo.

Evropski stavovi o politici upotrebe nasleđa uglavnom su usmereni ka politici revitalizacije istorijskih centara zbog sledećih razloga:

- U istorijskim gradovima revitalizacija centra je bitna komponenta urbanog menadžmenta. To je „alatka” za formulisanje politike i implementaciju, te deluje kao ključni faktor za uspeh revitalizacije gradskog centra.
- Mnogi gradovi u Centralnoj i Jugoistočnoj Evropi nemaju jasnu politiku revitalizacije, odnosno regeneracije istorijskih centara. Dramatične promene u ovim delovima Evrope, koje su samo površinski stišane, zahtevaju novi pristup odnosu prema nasleđu i nove instrumente za upravljanje ovim tipom urbanih promena.
- Postepeno propadanje grada i proces njegove regeneracije treba interpretirati u širem kontekstu urbane dinamike. Ovi procesi su veoma nejasni i rasplinuti. Uporedna analiza može pomoći da se brže dođe do objašnjenja, koristeći iskustva onih zemalja u kojima su pojedini problemi uspešno savladani.

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1 INTRODUCTION

In the new circumstances created in the Central and Southeast Europe in the recent decades, when the built heritage and its role in the future of the cities are concerned, it is useful to undertake a comparative study of various alternative approaches to the problem solution. The fundamental question which can be posed is what is the potential for transferring the experiences from the environments with market economies, and in what way they can be implemented in a society in a long-running, exhausting transition, such as the Serbian one.

The European position on the policy of heritage treatment is mostly directed towards the policy of revitalization of historical centres because:

- In the historical cities, revitalization of the centre is an important component of urban management. It is a “tool” for policy formulation and acts implementation as a key factor for success of city centre revitalization.
- Many cities in Central and Southeast Europe have unclear revitalization policy, i.e. regeneration policy of historical centres. Dramatic changes in these parts of Europe, which only superficially abated, demand a new approach in the attitude towards the heritage and new instruments for management of this type of urban changes.
- Gradual deterioration of the city and the process of its regeneration should be interpreted in a wider context of urban dynamics. These processes are very vague and divergent. A comparative analysis can help to

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− Pojedina rešenja u domenu primene instrumenata određene politike prema nasleđu mogu se prihvatiti iz primera zapadne demokratije, ali uz izuzetno pažljivo prilagođavanje lokalnom kontekstu. U suprotnom, rezultati mogu biti pogubni.

Upravo zbog opasnosti koja postoji kada je reč o prihvatanju iskustva, postavlja se pitanje konteksta. Instrumenti politike moraju biti kompatibilni s lokalnim kontekstom koji je određen stavom okruženja i kulture, te političkim i ekonomskim promenama. Procenjuje se da će prilagođavanje politika promenjivom kontekstu biti, ipak, dug i složen proces, uz niz pokušaja i grešaka. Razumevanje razlika i sličnosti u transformaciji gradova koji su postigli određene pozitivne rezultate može pomoći da se definišu specifične karakteristike određenih lokalnih sredina i da se, shodno tome, modifikuju instrumentacijska rešenja.

Iz niza sredstva kojima se zapadna demokratija koristi u svojoj politici uređenja gradskih jezgara, mogu se izdvojiti ona koja mogu iskustveno poslužiti u našoj sredini. Ključni faktori za politiku revitalizacije jesu:

− postavljanje održivih i realno ostvarivih ciljeva;

− kombinovanje različitih klasičnih i inovativnih instrumenata za formulisanje i implementaciju;

− stvaranje snažne vizije (putem projekta) i utvrđivanje jasnih pravila javno-privatne kooperacije.

Na osnovu stranih iskustava, odmah se može zaključiti da je to umetnost postizanja kompromisa u okviru kulturno održive ekonomske revitalizacije gradskog jezgra. Upravljanje konfliktnim ciljevima i pristupima jeste suština prostorne politike. Ovo opšte zapažanje dobija posebno značenje kada je reč o planiranju u istorijskim gradovima, gde su osnovni urbani sukobi između ekonomskog razvoja i kulturnih vrednosti nesumnjivo najdramatičniji.

reach the explanation sooner, using experience of those countries where certain issues have been overcome.

− Certain solutions in the domain of implementation of instruments of a certain policy towards the heritage can be accepted from the examples of western democracy, but with extremely careful adaptations to local contexts. Otherwise, the results can be devastating.

Exactly because of a certain risk inherent in accepting the experiences, the issue of context is emphasized. The policy instruments should be compatible with the local context which is determined by the attitude of the environment and the culture, and political and economic changes. It is estimated that the adaptation of policies to the variable contexts will be a long and complex process, with a series of trials and errors. Understanding differences and similarities in transformation of the cities which achieved certain positive goals can help in defining specific characteristics of local environments and accordingly modify instrumentation solutions.

Out of the number of instruments used by the western democracies in their policy of arrangement of city cores, those which can be empirically used in our practice are singled out. The key factors for revitalization policy are:

− Setting of sustainable and realistically attainable goals

− Combining various classical and innovative instruments for formulation, and

− Creating a powerful vision (through a design) and establishment of clear rules of public-private cooperation.

From the foreign experience it can be concluded that it is an art of compromise and negotiations within culturally sustainable economic revitalization of the city is the

Tabela 1. Lista ciljeva politike regeneracije gradskog istorijskog centra sastavljena na osnovu suprotstavljenih pristupa [2]

Pristup razmene vrednost / tržišna vrednost	Pristup upotrebne vrednosti
- promovisanje promene	- održavanje stabilnosti, zaštita postojećih vrednosti
- stimulisanje ekonomskog razvoja	- zaštita postojećih aktivnosti, fizičke i društvene strukture
- podsticanje novih, ekonomski isplativih aktivnosti i - shodno tome - promene zemljišne politike - intenziviranje i koncentrisanje aktivnosti i novi razvoj radi pokrivanja troškova maksimalizacije zemljišne rente i povećanja poreske osnovice	- ograničenje intenziteta korišćenja i gustine razvoja; decentralizacija pojedinih servisnih funkcija iz istorijskih područja, kako bi se izbeglo pretrpavanje kapaciteta područja; povećanje finansijske pomoći i drugih oblika društvene potrošnje koji ohrabruju vlasnike da čuvaju istorijske strukture

Table 1. List of goals of the policy of regeneration of historical city centre composed based on the conflicting approaches [2]

Exchange approach value/market value	Approach usable value
Change promotion	Maintaining stability, protection of existing values
Stimulation of economic development	Protection of existing activities, physical and social structure
Stimulation of new, economically more profitable activities, and accordingly, changes of land policy Intensification and concentration of activities and new development for the purpose of covering the costs of maximization of land fee and increase of taxable value	Limitation of intensity of usage and density of development; decentralization of certain service functions from the historical areas in order to avoid overloading of the area capacity; increase of financial aid and other forms of social spending which encourage the owners to preserve historical structures.

- povećanje konkurentnosti istorijskog jezgra kao investicione lokacije; privlačenje novih „unutrašnjih” ulaganja putem pojačanog marketinga istorijskog jezgra i upotrebom raznih logističkih podršaka	- podrška odnosno pomoć postojećem lokalnom biznisu i zaštita stanovnika s malim primanjima; izbegavanje izmeštanja stanovnika; promovisanje svesti o zajedništvu i identitetu, kao i osnivanje pokreta „samopomoći”
- modernizacija urbane strukture i promovisanje marketinških smernica za nove arhitektonske forme koje su značajno slobodnije, fleksibilnije i odgovarajuće tržištu	- zaštita i očuvanje starih struktura i stilova kroz strogu kontrolu prostornih promena i estetskih standarda
- stvaranje novih i snažnih vizija o istorijskom jezgru grada, kao simbolu ekonomske i političke moći korišćenjem novog jezika urbanih formi i stvaranjem nove skale vrednosti	- čuvanje prostorne slike istorijskog jezgra kao simbola duhovnih i kulturnih vrednosti; čuvanje postojećih urbanih odnosa i semiotike gradske slike

Increase of competitiveness of historical core as an investment location; attraction of new “internal” investment using intensified marketing of the historical core and using diverse logistical support.	Support, i.e. aid to the existing local business and protection of population with low income; avoiding population displacement; promotion of community awareness and identity and founding of the “self-support” movement
Modernization of the urbane structure and promotion of marketing guidelines for new architectonic forms which are considerably freer, more flexible and more appropriate for the market.	Protection and preservation of old structures and styles through the strict control of spatial changes and aesthetic standards.
Creation of new and powerful visions on the historical core of the city, as a symbol of economic and political power, using new language of urban forms, and creating a new scale of values	Preservation of the spatial image of a historical core as a symbol of spiritual and cultural values; preservation of existing urban relationships and semiotics of urban image

Nakon uočavanja razlika, može se postaviti pitanje da li se ekonomski razvoj i kulturne vrednosti uzajamno isključuju. Niz veoma uspešno rešenih primera revitalizacije istorijskih gradskih jezgara u Evropi, pa i u Americi, pokazuje da se ovi konflikti mogu ublažiti, pa čak i potrti. Urbana politika je umetnost kompromisa. Zato se regeneracija gradskog jezgra definiše kao niz programa i planiranih akcija, osmišljenih tako da učine održivim i unaprede postojeće urbano tkivo, ali i da uvedu nove aktivnosti koje mogu da unaprede ekonomsku bazu grada.

U međunarodnom iskustvu ovaj pristup naziva se *kulturno održiva ekonomska revitalizacija istorijskog gradskog jezgra* [14]. U izvesnom smislu, ovaj termin nastao je pod uticajem ideje o održivom razvoju, ali pored toga, sadrži u sebi i prihvata još neke pristupe kao što su: istorijska zaštita, integrativna konzervacija; „meka ili oprezna obnova”; koncept „zdravog grada”; stavovi pokreta „stvaranje životnog grada”, i druge. Osnovna ideja jeste da se pozitivno posreduje u konfliktu između ekonomskih interesa, zaštite nasleđa i unapređivanja okruženja. Kao primer veoma povoljno primenjene *kulturno održive ekonomske revitalizacije istorijskog gradskog jezgra*, izdvaja se primer grada Berna u Švajcarskoj, koji će u ovom radu biti analitički obrađen, s namerom da se izvuku određene pouke pogodne za rešavanje brojnih problema u gradovima Srbije.

essence of spatial policy. This general observation gains a special meaning when planning in historical cities is concerned, where the fundamental urban conflicts between the economic development and cultural values are undoubtedly most dramatic.

After observing differences, one may pose a question whether economic development and cultural values are mutually exclusive? A number of successfully solved examples of revitalization historical city cores in Europe and America indicate that these conflicts can be attenuated, and even annulled. Urban policy is the art of compromise. For that reason regeneration of city core is defined as number of programmes and planned actions conceived so as to make the existing city fabric sustainable and improve it, but also to introduce new activities which can improve the economic basis of the city.

In the international practice, this approach is called “culturally sustainable economic revitalization of the city core "[14]. In a sense, this term was created under the influence of the idea of sustainable development, but contains and endorses some other approaches such as: historical protection, integrative conservation; “soft or careful renovation”; "healthy city" concept; positions of the movement "creation of a vital city", and others. The basic idea is to be positive intermediary in the conflict between the economic interests, protection of heritage and improvement of the environment. The example of the city of Bern, Switzerland, stands out as an example of a very favourably implemented “culturally sustainable economic revitalization of the city core", and it will be analytically treated in this paper, with the intention to draw certain lessons suitable for solving problems which piled up in the cities of Serbia.

2 PRISTUP PROCESU REVITALIZACIJE

Zaštićene zgrade su osnovni oblik našeg kulturnog pejzaža. Oni su vodilja u razvoju jednog mesta u kome se nalaze u smislu „korporativne arhitekture”, odnosno kako pojedinačnog, tako i zajedničkog interesa. Korist od „korporativne arhitekture” samih objekata ima, pre svega, kompanija koja je taj objekat obnovila, odnosno koja ga je obnovljenog stavila u funkciju. Budući korisnici, međutim, trebalo bi da budu svesni vrednosti istorijskog i ekonomskog karaktera takvih zaštićenih objekata.

U isto vreme, postoje mnogi istorijski zaštićeni objekti kojima preti propadanje i rušenje usled nekorišćenja. Oživljavanjem takvih objekata može biti spasen ne samo izuzetan objekat, već se može oživeti i cela gradska sredina u kojoj se taj objekat, odnosno ti objekti nalaze. No, to zahteva primenu novih ideja i metoda za procenu upotrebljivosti objekata kada je reč o potencijalnim korisnicima.

Karakteristika strukturâ praznih spomenika kulture jeste da su smešteni u postojećim „luksuzima praznine”. Pravi primeri za buduće korišćenje ovih zaštićenih objekata jesu oni objekti koji su revitalizovani i na kojima su sve potrebne mere kompenzacije izvedene. Mere kompenzacije su procenjene prema podobnosti zaštićenog spomenika kulture koji se revitalizuje.

Ovaj rad zasnovan je na polazištu da su u zaštićenim spomenicima kulture utemeljene i imanentne poruke jedne epohe. Istovremeno, analizirajući istorijske objekte i zgrade u vezi sa ovim procesom, mogu se identifikovati potencijali njihovih potreba i njihovog očuvanja.

Nakon analize ovog procesa, koji se odnosi na potrebu očuvanja istorijskih objekata i zgrada, sledeći postupak jeste usmereni pristup zaštićenim objektima.

Istraživački proces koristi odgovarajuće analize i kreativne metode za postizanje održivog razvoja, odnosno održive koristi, što ima za posledicu regeneraciju zaštićenih objekata.

Zato je osnovni cilj ove metode da se otkriju potencijali revitalizacije da bi se povećala konkurentnost objekta u urbanom tkivu.

Pristup revitalizaciji zaštićenih spomenika kulture, u svrhu budućeg korišćenja, može se podeliti u četiri modula.

Modul 1 Uključenje zgrade u savremeni život na osnovu korišćenja istorijskih procesa i njenih samih karakterističnih parametara. Nove ideje se generišu i koriste u sledećem modulu.

Modul 2 Utvrđivanje koristi od istraživačkih kreativnih radionica, koje ocenjuju budući korisnici.

Modul 3 Upoređivanje zahteva za budući život, u pogledu upotrebe i funkcije postojeće zgrade. Kao rezultat toga, proizlaze mere kompenzacije kojima se raspolaže.

Modul 4 Ispitivanje podobnosti očuvanja objekta iz perspektive korisnika. Uspešnost opisane metodologije proverena je na primerima analiziranim u gradu Bernu. Na osnovu analiziranog procesa primene metode, zaključeno je da se ona može, uz prilagođavanje našem zakonodavstvu, primenjivati u našoj sredini.

2 APPROACH TO REVITALIZATION PROCESS

Listed buildings are the basic form of our cultural landscape. They are guiding principles in development of a place where they are situated in a capacity of “corporative architecture”, i.e. as both individual and common interest. The “corporative architecture” of the buildings themselves is useful primarily for companies which renovated the building or put it working order after renovation. The future users should, however be aware of the historic and economic value of such protected buildings.

Simultaneously, there are a large number of historically protected buildings which are in danger of dilapidation and collapse due to the disuse. Revitalization of such structures, may not only salvage a remarkable building, but can revitalize the entire city neighbourhood where such building or buildings are situated. This calls for application of new ideas and methods for evaluation of usability of structures for the potential users.

The characteristic of the structures of abandoned (empty) cultural monuments is that they are situated in the existing “luxury voids”. True examples for the future usage of protected buildings are those buildings which were revitalized on which all the compensation methods were performed. The compensation methods are assessed according to the suitability of the protected cultural monument being revitalized.

This paper is based on the viewpoint that the listed cultural monuments embody immanent messages of an epoch. By analysing historical buildings related to this process, the potential of their needs and their preservation can be identified.

After analysing this process, which refers to the need for preservation of historical buildings and structures, the following procedure is the process of directed approach to the protected structures.

The research process utilises adequate analyses and creative methods for achieving sustainable development, i.e., sustainable usefulness, which results in regeneration of the protected buildings.

For that reason the basic goal of this method is to discover the potential for revitalization in order to increase competitiveness of the structures in the urban fabric.

The approach to the revitalization process of protected cultural monuments for the purpose of the future use can be divide into four modules.

Module 1 Inclusion of the building into contemporary life, based on the utilisation of historical processes and characteristic parameters. New ideas are generated and used in the next module.

Module 2 Determination of usefulness of research creative workshops, as assessed by the future users.

Module 3 Comparison of the demands for the future life, which are related to the use and function of the existing building. The result is the compensation measures available.

Module 4 Testing the structure of preservation suitability from the users’ perspective.

The capability of the described methodology was verified on the examples analysed in the city of Bern. Based on the analysed process of method application, it is concluded that it can be implemented in our practice after being adapted to our legislation.

2.1 Teoretski okvir definisanja metode revitalizacije

Teoretski okvir predstavlja istraživanje nastanka i razvoja predložene metodologije i proveravanje potencijala unapređenih načina korištenja nekretnina. Analiza korištenja istorijskih objekata formulisana je kao odnos „istorijskog korišćenja" i izgrađene strukture. *Osamdesetih godina prošlog veka došlo je do „ponovnog otkrića" starih kuća u starim delovima gradova, kao izvor materijanih kulturnih resursa, koje je bilo prekinuto. Sada se u strategijama postavljaju principi kao što su „očuvanje materijalnog" i „opreznost u zaštiti" koji su u osnovi bitni za dalju analizu. Daljom analizom ova dva principa pomenutim strategijama najverovatnije daju svoju sledeću dimenziju – „dimenziju trajnosti".*[2]

Mogu se postaviti pitanja na koje građevine bi se ovaj princip mogao odnositi, te koji su to prostori koji su napušteni i prazni i kako bi se mogao organizovati i aktivirati život u njima. Na ta pitanja odgovori se mogu dobiti poznavanjem fizičke strukture, odnosno primenjenih materijala, kao i angažovanjem eksperata koji imaju transdisciplinarno znanje u oblasti revitalizacije. Pored stručnog, tehničkog znanja, to obuhvata i saznanje o jasnoj predstavi celokupnog socijalnog životnog ciklusa građevine. Očigledno je da postoji potreba da se osmisle nove ideje kojima bi se istorijski proces korišćenja zgrade nastavio primenom elemenata realne zaštite koja može da regeneriše strukturu zgrade. Da bi se to ostvarilo, potrebno je prvo preispitati dosadašnji pristup problemu revitalizacije objekata u kojima više nema aktivne funkcije. Inventarisanjem objekata i prilagođavanjem metoda rada može se generisati nova upotreba, a taj proces je bolje prilagođen fizičkoj strukturi objekata nego u konvencionalnim metodama odlučivanja prilikom izbora buduće namene objekta. Potencijalnim korisnicima, koji se uvode u proces, nudi se da sami procene da li karakteristike građevine zadovoljavau njihove individualne funkcionalne zahteve, za šta je potrebna dodatna akcija. Ta akcija zasniva se na razvijanju metode kojom se analizira i vrednuje ekonomska isplativost istovremene zaštite i korisnosti objekta.

Postojeći objekti građeni su u uslovima i na osnovu principa koji su postojali u vreme njihove gradnje. Pošto se zahtevi korisnika stalno menjaju, onda se i namena zgrada veoma često prilagođavala tim zahtevima, o čemu svedoče brojni primeri kroz istoriju. Zato je veoma važno da se koncept i svojstva postojeće građevine mogu optimalno prilagoditi zahtevima budućeg korisnika, bez bitnijih izmena fizičke strukture. Uvođenjem strategije upravljanja objektom u veoma ranoj fazi rada na revitalizaciji, moguće je objekat prilagoditi uslovima budućih korisnika, poštujući ograničenja koja se postavljaju kada je reč o zaštićenim građevinama. Izrazito ograničavajući faktor jeste zaštita vlasništva nad istorijskim objektima, koju treba poštovati, istovremeno prilagođavajući građevinu novim potrebama. U Švajcarskoj se primenjuje tradicionalni stav da je „važno očuvanje slikovitog izgleda", kao i to da „u procesu planiranja buduće upotrebe objekta i njegove prenamene treba i dalje nastaviti sa vidljivim originalnim osobenostima objekta". [3]

Predložena metodologija proverena je na području Starog dela grada Berna, glavnog grada Švajcarske, koji je 1983. godine zaštitio UNESCO, te se nalazi na Listi

2.1 Theoretical framework for defining the revitalization method

The theoretical framework is the research of the emergence and development of the proposed methodology and checking of potential of the improved ways of usage of real property. The analysis of the process of usage of historical buildings is defined as a relationship of "historical use" and constructed structure. „In the eighties of the previous century there was a "rediscovery" of old houses in the old parts of cities, as a source of material cultural resources, which was already forgotten. Now the strategies have the principles such as "preservation of the fabric" and "cautious protection" set, which are fundamentally important for the further analysis. Further analysis of these two principles provides a new dimension, i.e. the dimension of sustainability.*"*[2]

A question might be posed, to which buildings this principle could apply, and what spaces which are deserted and empty could be organized and life in them activated. This question can be answered by knowing physical structure, that is, applied materials, and by engaging experts who have trans-disciplinary knowledge in the area of revitalization. Apart from the technical expertise, this includes a clear concept of the entire social life cycle of buildings. It is obvious that there is a need to invent new ideas which would ensure continuation of the historical process of building usage by means of implementation of the real protection elements which can regenerate the building structure. In order to realize that it is first necessary to question the current approach to the issue of revitalization of structures which function inactively. New use can be generated through entering the structures into an inventory and adaptation of the operating method. This process is better suited to the physical structure of the buildings, than in the conventional decision-making methods in selection of the future use of the buildings. The potential users which are introduced into the process are offered to assess whether the characteristics of the building meet their individual functional requirements, and that it requires additional action. This action is based on the development of the method analyzing and evaluating economic profitability of simultaneous protection and usefulness of the building.

The existing buildings are constructed in the conditions and on the basis of the principles which existed in time when they were built. Since the requirements of the users constantly change, the use of the buildings was often adapted to those requirements, which is attested by numerous historical examples. That is why it is very important that the concept and properties of the existing building can be optimally adapted to the conditions of future users, without considerable changes of its physical structure. By introducing the strategy of building management in the early phase of revitalization work, it is possible to adapt the building to the conditions of future users, observing the limitations set when the protected buildings are concerned. An extremely limiting factor is protection of ownership over the historical buildings, which should be observed, simultaneously adapting the building to the new requirements. In Switzerland, a traditional attitude is svetske baštine.[20] S obzirom na to što su pojedinačna rešenja dala veoma pozitivne rezultate, smatra se korisnim da se naša sredina upozna sa specifičnom metodologijom revitalizacije koja je omogućila te rezultate. Da bi se što bolje definisala metodologija rada tokom revitalizacije građevina, prvo su postavljena pitanja koja se mogu formulisati na sledeći način:

1. Da li se nove ideje generišu kontinualno, počevši od istraživanja istorijskog procesa nastanka i razvoja objekata, pa do korišćenja postojećih objekata?
2. Kako bi investitor mogao da pronađe buduću funkciju objekata zaštićenih kao spomenici kulture, a koja bi bila pogodna za buduće korisnike i vlasnike?
3. Koje su osnovne karakteristike (svojstva) zaštićenog spomenika kulture i koja ograničenja iz toga proizlaze za njegovo buduće korištenje?
4. Kako bi donošenje odluka o održivoj zaštiti moglo postati pristupačnije za revitalizaciju i korištenje zaštićenih objekata?
5. Kojim se fizičkim merama mogu nadoknaditi ili popraviti razni nedostaci?
6. Koje zahteve moraju da uvaže nadležne službe koje se bave zaštitom u gradu Bernu da bi se investitorima nadoknadila određena ograničenja koja treba da poštuju?

implemented: “It is important to preserve the picturesque appearance”, as well as that “in the process of planning of the future use of the building and its conversion, the visible original properties of the structure should be perpetuated“. [3]

Verification of the proposed methodology was performed in the area of the Old city of Bern, the capital of Switzerland, which is inscribed in the World Heritage List since 1983. Since the individual solutions yielded very positive results, it is considered useful to introduce our public to the specific methodology of revitalization process which produced those results. In order to define the methodology of work during building revitalization, questions were asked which can be formulated in the following way:

1. Are new ideas generated continually, starting from the research of the historical process of emergence and development of buildings, to the utilization of the existing buildings?
2. How could an investor find a future function of the buildings listed as the cultural monuments, and which would be suitable for the future users and owners?
3. What are the basic characteristics (properties) of the listed cultural monuments and what are the resulting limitations to its future utilization?
4. How could the decision making process on the sustainable protection become more accessible to revitalization and utilization of listed buildings?
5. What physical measures can compensate for or mend various deficiencies?
6. What demands should be recognized by the competent protection services in the city of Bern in order to recompense certain limitations that the investors are obliged to observe?

2.2 Metode proučavanja postojećeg stanja nasleđa

Istraživanjem metodom terenskog snimanja postojećeg stanja beleže se sačuvani objekti, koji su uvršteni u vredne primere arhitektonskog stvaralaštva, u ovom slučaju u gradu Bernu. Prilikom snimanja stanja, po pravilu, konstatuje se da su mnogi objekti promenili svoj izvorni izgled i da je potrebno istraživanje originalnih dokumenata da bi se utvrdili autentična struktura i autentični oblik.

Istorijskom metodom se pronalazi i proučava dostupna arhivska građa, autentične fotografije i drugi pisani materijal. U istorijskoj metodi, koriste se primarni izvori, odnosno originalna istorijska dokumenta, kao i sekundarni, nastali posredno.

Metodom teorijske analize proučavaju se pisani izvori koji se odnose na nastanak i razvoj svih arhitektonskih oblika u bližem okruženju. Ova metoda služi da se stekne šire znanje o građevini i njenom statusu u širem kontekstu gradskog tkiva Berna.

Intervju sa delom relevantnih subjekata kao metod istraživanja ima ograničenu verodostojnost, ali se ipak radi, jer se smatra da je dobro uporediti dobijene podatke s nekim od pisanih izvora.

Druga faza istraživanja je ona u kojoj se, na osnovu navedenih ulaznih podataka, definiše rešenje za revitalizaciju pojedinačnih građevina, odnosno utvrdili procesni modeli, u zavisnosti od formulisanih kriterijuma i parametara.

2.2 Methods of the study of the existing heritage status

The research employing field appraisal of the current status enables recording of the preserved buildings which are listed as valuable examples of architecture practice, in this case in the city of Bern. On the occasion of the status appraisal, as a rule, it is found that many structures changed their original appearance, and that it is necessary to investigate the original documents to determine their authentic structure and form.

The historical method finds and studies available archive documents, authentic photographs and other written material. When using historical method, the primary sources are used, i.e. original historical documents, as well as the secondary ones, created indirectly.

The theoretical analysis method studies the written records, related to the emergence and development of all architecture forms in the immediate environment. This method is used to acquire broader knowledge of a building and its status in the wider context of the city fabric of the city of Bern.

Interviews with the part of relevant subjects as a research method has a limited reliability, but is still performed, since it is considered that it is desirable to compare the obtained data with some written sources.

In the second stage, based on the input data, a solution for revitalization of individual buildings is defined, i.e. process models are determined, depending on the

Komparativna analiza i sinteza služe za izvođenje konačnih rezultata. Kriterijumi izbora svode broj objekata na najvrednije i najreprezentativnije predstavnike Fonda kulturne baštine, za koje se definišu rešenja i izvode preporuke za primenjivost i standardizaciju tih rešenja u Srbiji. Sama metodologija predstavlja praktično sredstvo za „analizu korišćenja” u slučaju upotrebe praznih istorijskih zgrada u kreativnom smislu.

Način sprovođenja analize potencijala postojećih objekata jeste takav da se dobijaju rezultati koji su optimalni za primenu neophodnih kompenzacionih mera. Ove mere treba da budu kontrolisane tako što se utvrđuje korist koju one donose budućim korisnicima, te se na osnovu njih daju predlozi za preventivnu zaštitu. Primenom ove analize korišćenja, budući korisnici i investitori dobijaju mogućnost da provere rezultate podobnosti i dobijaju instrument pogodan za dovođenje navedenih nekretnina na željeni, upotrebni nivo.

formulated criteria and parameters.

Comparative analysis and synthesis are used for production of the final results. The Selection criteria bring down the number of buildings to the most valuable and most representative examples of the Cultural Heritage Fund, for which the solutions are defined and recommendations are made for feasibility and standardization of such solutions in Serbia. The methodology itself represents a practical instrument for “utilization analysis” in case when abandoned historical buildings are used in a creative manner.

The method of conducting the analysis of potential of existing structures is such that the results optimal for implementation of necessary compensation measures are obtained. These measures should be controlled by determining the benefit for their future users and on whose basis the proposals for preventive protection are given. By implementing this utilization analysis, the future users and investors obtain the possibility to check the suitability results and obtain an instrument convenient for bringing the mentioned real property to a desirable, usability level.

2.3 Definisanje primenjenih principa, terminologije i metoda rada

Na temu revitalizacije, kada su u pitanju prazni istorijski objekti, u literaturi se mogu pronaći uglavnom osnovne informacije. Praktično dejstvo revitalizacije iskazuje se u delu izrade projekta. Koncept je prvenstveno namenjen za revitalizaciju unutrašnjih delova onih delova zgrade koji su prazni odnosno napušteni. Zadovoljavanje uslova korisnika i investitora zaštićenih spomenika kulture samo je početna tačka u postavljanju ciljeva. Korišćenje i održivost objekata je pitanje o kojem se u oblasti zaštite i očuvanja graditeljskog nasleđa nije puno diskutovalo.[9]

Većina savremenih zakona o zaštiti nasleđa sadrži zahteve za „održivu zaštitu” i upotrebu, ali sam postupak nije precizno definisan. Moderna interpretacija zaštite istorijskih objekata, za koju se u ovom radu zalaže, zasnovana je na otvorenosti upotrebe spomenika kulture. Proces orijentisanog pristupa, koji se temelji na polazištima ovog rada, nalazi svoje osnove u ponovnom upravljanju objektom (*Facility Management)*. Kreativne metode su na veoma jasan način opisane u brojnoj literaturi. Postoji, međutim, neslaganje u određivanju i postizanju ciljeva svake metode pojedinačno.

Sistematizacija zahteva, odnosno tipa novih potreba, koje se razlikuju od izvornih, ne postoji. Bilo bi veoma efikasno kada bi se na osnovu želja potencijalnih korisnika mogli odmah praviti i odgovarajući projekti. Jedinstvenu klasifikaciju, međutim, komplikuju specifični zahtevi budućih korisnika, kao i njihova neodlučnost i potreba da se stalno unose promene u zahteve. Izuzetak su jedino slučajevi kada su u pitanju Švajcarske državne norme (SIA).[17]

Test i metode za ispitivanje korišćenja dobrih i sigurnih spomenika kulture mogu se primeniti na taj način. Za opis kompenzacionih mera nudi se struktura izražena prema Normi SIA 480, „troškovi u građevinarstvu”. [18]

Predmet istraživanja su zaštićene slobodne, odnosno nenaseljene zgrade koje su spomenici kulture. Fokusiranje na zaštićene objekte učinjeno je iz dva

2.3 Definition of applied principles, terminology and working method

Regarding revitalization, when it comes to the abandoned historical buildings only basic information can be found in references. Practical effects of revitalization are manifest in the design production phase. The concept is primarily intended for revitalization of internal parts of those parts of the building which are empty, i.e. abandoned. Meeting the conditions of users and investors of the listed cultural monuments is only an initial point in goal setting. Utilization and sustainability of structures is an issue which has never been extensively discussed in the field of protection and preservation of built heritage. [9]

Majority of contemporary regulations on the heritage protection contains the demands for “sustainable protection” and usage, but the procedure itself is not precisely defined. Contemporary interpretation of historical building protection, which is advocated in this paper, is based on the openness of the cultural monument to usage. The process of oriented approach of this paper is based on the reintroduced *Facility Management*. The creative methods are in a very clear way described in the literature. There is, however, disagreement in setting and achievement of the goals of each individual method.

Systematization of requirements, i.e. type of new demands which differ from the original ones, does not exist. It would be very efficient if adequate designs were immediately created based on the wishes of potential users. A uniform classification, however, is complicated by the specific requirements of the future users, as well as their indecisiveness and need to continually alter the requirements. The exceptions are only those cases when *Swiss state standards* are concerned, (S*IA)*. [17]

The test and testing methods for good and safe cultural monuments can be implemented in this way. For description of compensation measures, the structure expressed according to Norm SIA 480 is offered, „Costs in civil engineering”. [18]

The subject of the research are listed vacant, that is, razloga:

1. Prvi razlog je to što postoje značajna ograničenja kada je u pitanju adaptacija zgrada, određena modernim zahtevima korisnika. Svaka mera koja se preduzima mora biti koordinirana sa stavovima državne službe zaštite. Za nenaseljene zgrade koje nisu spomenici kulture, znatno brže se donose odluke da se sruše, iako se i one mogu prilagoditi savremenim zahtevima.

2. Drugi razlog jeste to što spomenici kulture poseduju određena svojstva koja ograničavaju potpunu slobodu odabira nove upotrebe objekta. Izvorna upotreba objekata i prenamena kroz istoriju mogu se pronaći u arhivama pod nazivom „Inventar" Agencije za zaštitu spomenika Švajcarske i veoma su dobro dokumentovani.

Falk definiše termin „revitalizirati" na sledeći način: „Pod revitalizacijom i rekonstrukcijom se podrazumeva prilagođavanje opreme i kvaliteta vlasništva promenjivim tržišnim uslovima, dok u isto vreme zadržavaju postojeću upotrebu."[7] Razgraničenje koncepta adaptacije, uz zadržavanje postojeće upotrebe objekta, takođe je definisano i obrađeno u ovom radu.

„Revitalizacija", direktno prevedena, znači da nešto treba da „oživi", bez obzira na to što će objekat možda dobiti novu namenu. U tom smislu, konverzija je subjekt revitalizacije. [13]

Istraživanje i formiranje rešenja obavljaju se u nekoliko koraka:

1) Analitičko-opisni deo

U analizi se polazi od činjenice da istorijske zgrade imaju specifične karakteristike, prema kojima se prvobitna upotreba i druge prethodne upotrebe objekta mogu jasno definisati. Sigurnost identifikacije originalne namene veća je kada je reč o velikim objektima. Drugo ispitivanje se odnosi na utvrđivanje toga da li je i koliko je moguće odrediti obuhvat održive zaštite za ove slučajeve. Problem mnogih slobodnih, praznih, istorijskih spomenika jeste pronalaženje odgovarajuće namene, zbog ograničenja koja su nametnuta pravnom zaštitom, odnosno strožim uslovima promena fizičke strukture. Zbog toga je razvijen metod, na osnovama istorijske upotrebe objekata, i generišu se potencijalne mogućnosti savremene upotrebe.

Drugom analizom treba utvrditi odgovarajući metod kojim se određuje kvalitet vlasništva u odnosu na korištenje, odnosno stanje i sigurnost tog kvaliteta. Ovom analizom ispituje se i tenzija koja postoji između istorijskog razvoja same nekretnine, uprave nadležne za objekat i konzervacije.

Na osnovu nalaza ovih analiza, formira se rešenje, takođe podeljeno na dve faze:

- Faza 1: Formiranje metoda za identifikaciju korisnika;
- Faza 2: Formiranje metodologije za procenu uticanja zahteva korisnika na svojstva postojećih objekata.

Za formiranje metoda za identifikaciju budućeg korisnika (Faza 1) ispituju se odgovarajuće mere. Bitno je da se cilj može prilagoditi mogućnostima pronalaženja budućeg korisnika zgrade. Tokom formiranja metode,

uninhabited buildings which are cultural monuments. There were two reasons for focusing on the listed buildings:

1. The first reason is that there are considerable limitations related to building adaptation, determined by the contemporary demands of the users. Each measure taken must be coordinated with the principles of national protection service. In the case of the abandoned buildings which are not cultural monuments, the decisions to demolish them are more quickly made, even though they can be adapted to contemporary demands as well.

2. The second reason is that the cultural monuments possess certain properties which limit the freedom in selection of a new use of the building. The original function of the buildings and conversion through history can be found in the archives under „Inventory" of the Agency for monument protection of Switzerland, and they are very well documented.

Falk defines the term „revitalize" in the following manner: „Under revitalization and reconstruction is comprised: adaptation of equipment and quality of ownership to the changeable market conditions, while simultaneously retaining the existing use."[7] The disambiguation of the adaptation concept, while retaining the existing use of the building, is also defined and treated in this paper.

„Revitalization", in direct translation means that something should "come to existence" regardless of the fact that the structure might obtain a new use. In that sense, conversion is the subject of revitalization. [13]

Research and solution generation is performed in several steps:

1) Analytical-descriptive part

The analysis starts from the fact that historical buildings have specific characteristics, which allow to clearly define the original and other preceding uses of the building. Positive identification of the original use is higher when the large structures are in question. The second research refers to determination whether and to what extent it is possible to determine the scope of sustainable protection of these cases. The problem of many free, abandoned historical monuments is finding the adequate use, because of the limitations imposed by the legal protection, that is, because of more strict conditions for change of the physical form. Therefore, on the basis of the buildings historical use a method is developed, and a potential for contemporary use is generated.

The second analysis should determine the adequate method for specifying the quality of ownership in respect to the use, that is, condition and safety of the quality. This analysis investigates the tension between the historical development of the real property, authority competent for the structure and conservation.

Based on the findings of these analyses, a solution is formed, which is also divided into two phases:

- Phase 1: Formation of the method for users identification;
- Phase 2: Formation of the methodology for users influence assessment on the characteristics of the existing buildings.

Appropriate measures are tested due to establish the method for future users identification (Phase 1). It is important to adapt the goal to the potential of finding the mogu se uočiti dve alternative, definisane na sledeći način:

• Alternativa 1: Poređenje svojstva zgrade sa zahtevima raznih budućih korisnika da bi se izbegle neprikladne namene korišćenjem regulativnih kriterijuma, a istovremeno identifikovao i ograničio broj pogodnih (odgovarajućih) namena.

Prednost ove alternative je to što proces može biti razvijan kao instrument za ocenjivanje, zasnovan na naučnoj osnovi; mana je to što su moguće namene već zadate. U tom slučaju, izostaje kreativni momenat, a i osobenosti pojedinačnih objekata su smanjene i ne mogu se uzimati u obzir.

• Alternativa 2: U okviru neke ustanove, biroa ili studija ostvaruje se uspešan odabir potencijalnog korisnika, putem specifičnog, kreativnog procesa, problemski postavljenog.

Prednost ove alternative jeste činjenica da je moguće pronaći nova i netradicionalna rešenja koja su uspešna. Potencijal objekta sagledava se putem procesa koji se kasnije može iskoristiti za marketing. Mana ovog metoda je to što nije naučno zasnovan. Rezultati zavise od dobre pripreme i kvalitetno urađenog posla arhitekata i drugih zaposlenih.

Upoređivanjem prednosti i mana navedenih alternativa, može se zaključiti da Alternativa 2 pruža više mogućnosti za uspešan praktični rad. Kreativne ideje se dalje preispituju i proveravaju.

2) Predlog za akciju i opis metodologije

Objekat je ispitan imajući u vidu mogućnost objektivnog adekvatnog korišćenja, bez saznanja da li je implementacija korištenja nekog konkretnog korisnika moguća. Ovakvo ispitivanje omogućava neku vrstu standardne ponude za različite namene, bez obzira na korisnika.

Pošto ne postoji popis zahteva za različite upotrebe, stvara se opšta lista – s jedne strane, parametara zgrade; s druge strane, zahteva korisnika za procenu uspešnog korištenja uz održivost zaštite. Obim procene ispitan je radi ocenjivanja praktičnosti i tačnosti dobijenih rezultata. Konačni rezultat dobijen je u vidu jedne vrste agende s listom mogućih namena, koja stoji na raspolaganju svima zaineresovanima.

Na primeru praznih, nenaseljenih, a zaštićenih zgrada, koje su bile u vlasništvu Kantona Bern, Menadžment i Direkcija za zaštitu objekata grada Berna ispitali su ovu razvojnu metodu i primenili je u praksi na način prikazan u Tabeli 2.

Učešće švajcarske države u ukupnom finansiranju UNESCO-a izraženo je u procentima ekonomske moći, a iznosi 1,22% ili, pretvoreno u brojke – oko 5,2 miliona švajcarskih franaka. Švajcarska je na četrnaestom mestu po finansiranju UNESCO-a. Imajući u vidu veličinu države i broj stanovnika, iznos koji je Švajcarska izdvojila veoma je velik. Ovoliko izdvajanje, kao ni znatno manje, Republika Srbija ne može da realizuje, što može otežati primenu modela zaštite i revitalizacije spomenika kulture na listi Svetske baštine u Srbiji.

future user of the building. In the course of method formation, two alternatives can be noticed, and they are defined in the following way:

• Alternative 1: Comparison of the building properties with the requirements of various future users in order to avoid the improper uses applying regulatory criteria, and to simultaneously avoid and identify the number of suitable (appropriate) uses.

The advantage of this alternative is that the process can be developed as an instrument for assessment, based on the scientific grounds. The drawback is that the potential use is already set. In this case, there is no creativity, and the characteristics of individual buildings are reduced, and cannot be taken into consideration.

• Alternative 2: In an institution or bureau the successful selection of a potential user is performed, through a specific problem oriented creative process.

The advantage of this alternative is the fact that it is possible to find new and non-traditional solutions which are successful. The potential of the building is viewed through the process which later can be used in marketing process. The disadvantage of this method is that it is not scientifically based. The results depend on the good implementation and the quality performance of the architects and other participants...

By comparing the advantages and disadvantages of these two mentioned alternatives, it can be concluded that the Alternative 2 provides more potential for successful practical work. The creative ideas are further questioned and verified.

2) Action proposal and methodology description

The building is tested for the potential of objectively adequate use, with no knowledge whether the implementation of the use of some concrete user is possible. Such testing enables some kind of a standard offer for different uses, irrespective of the uses.

Since there is no list of requirements for different uses, a general list is generated: on one hand the building parameters are listed, and on the other, the requirements of the users for the assessment of successful use with sustainable protection. The scope of the assessment was tested for the purpose of appraising the practicality and accuracy of the obtained results. The end result obtained was in the form of an agenda with the list of possible uses, which is at disposal of all the interested parties.

The Management and authorities for protection of the buildings in the city of Bern tested this development method and put it in practice in the way displayed in the Table 2, on the example of abandoned, uninhabited, and listed buildings which were owned by the Bern canton.

The share of the Swiss state in the total financing of UNESCO is expressed in the percentage of economic power, and it amounts to 1, 22% or, converted to numbers, around 5, 2 million of Swiss Francs. Switzerland is ranked 14^{th} in terms of financing. The Swiss contribution of 5.2 million Swiss francs is very high for a state of its size and number of inhabitants. The Republic of Serbia cannot realize such a high (nor even considerably lower) contribution, which may complicate implementation of the protection and revitalization model of the World Heritage monuments in Serbia.

Tabela 2. Prikaz razvojne metode za nenaseljene zaštićene zgrade
Table 2. Development method for inhabited protected houses

	SADRŽAJ / CONTENTS	METODA / METHOD
Analitičko-deskriptivni deo Analytical descriptive part	Pregled između istraživačkih projekata i menadžmenta zaštite Overview of research projects and protection management	Izazovi rada i problematika Working challenges and problems
	⇩	
	Fokusiranje na prazne zaštićene objekte (imobilije) Focusing on abandoned listed buildings	Specificiranje tema Specification of topics
	⇩	
Predlog rada i dogovora/Opis metodologije Work and agreement proposal/description of methodology	Izvodljivost i metodologija iskorišćenosti Feasibility and degree use methodology	Istraživanje i pregled različitih kreativnih metoda Research and overview of various creative methods
	⇩	
	Izvodljivost metodologije za ispitivanje održivog korištenja Feasibility of methodology for testing of sustainable use	Pregled i kategorizacija zahteva za potražnju i iskorištenost Overview and categorization of requirements for demand and degree of use
	⇩	
	Izvodljivost i neophodne kompezacione mere Feasibility and necessary compensation measures	Pregled i kategroizacija neophodnih kompenzacionih mera Overview and categorization of necessary compensation measures.
	Ispitivanje zaštitnih mera Testing protective measures	Pregled različitih metoda za testiranje Overview of various testing methods
Primer Example	Ispitivanje, provera metoda i provođenje u praksi Testing and verification of methods and practical implementation	Pregled primera u praksi Overview of examples in practice
Rezultat Result	Rezultati i zaključci Results and conclusions	Kvalitetni pregled rezultata i pogled na dalja istraživanja Quality overview of results and perspective of future research

2.4 O staroj gradnji i njenoj zaštiti u Bernu

Objekti koji su zaštićeni kao spomenici kulture dokazi su društvenog života prošlih vremena. Oni su deo kulture jednog društva i svedoče o načinu života stanovništva na jednom području.

Razumevanje objekta zavisi od što tačnijeg poznavanja vremena kada je izgrađen i svih promena koje su na njemu nastale tokom upotrebe. Prikupljene informacije o istorijskom životu zgrade i njene okoline omogućavaju uspešnu sveobuhvatnu obnovu, rekonstrukciju i buduće korištenje koje će produžiti život zgrade kao spomenika kulture.

Svi prikupljeni podaci, zajedno s tehničkom dokumentacijom i fotodokumentacijom, služe kao podloga za formiranje smernica u pogledu toga kako sa zgradom postupati u budućnosti, koje su intervencije moguće, a koje nisu, te kakve su mogućnosti za promenu namene, ukoliko je to rešenje da se građevina sačuva i uključi u savremeni život grada. Na taj način, stvara se baza podataka, odnosno inventar kulturnih dobara koji služba zaštite spomenika kultre i kancelarija kantona koriste za razne svrhe. S obzirom na broj i preciznost prikupljenih podataka, na osnovu tog inventara moguće je definisati celovit plan delovanja, kao i finansijsku strukturu troškova za svaku potencijalnu, pojedinačnu intervenciju, kao što su konzervacija, sanacija, prenamena funkcije i revitalizacija kao oblik zaštite građevine u njegovoj fizičkoj i duhovnoj celovitosti.

Kada je u pitanju revitalizacija, postoji veoma čvrsto utemeljen uslov da – bez obzira na druge intervencije – spoljni izgled objekta mora da zadrži postojeći izgled. Nikakve intervencije na fasadama u drugim materijalima nisu dozvoljene, osim s kamenom, i to boje koja je karakteristična za Stari grad Bern. Što se tiče izmena u unutrašnjosti objekata, to je regulisano Pravilnikom o zaštiti, tj. nova namena nekog objekta može se ostvariti samo ukoliko se sprovedu sve mere savremene zaštite, uz poštovanje koncepta budućeg korisnika. Zato je u interesu gradske vlasti da, ukoliko je potrebno izvesti prenamenu prostorija ili celog zaštićenog objekta s ciljem njegovog opstanka, u što kraćem periodu pronađe novog korisnika i u saradnji s njim odredi buduću namenu. Ovaj postupak podrazumeva to da se nova namena, koja će se uvesti u objekat, nalazi u registru delatnosti za koje je prethodno utvrđeno da su adekvatne prostoru i mestu u istorijskom, zaštićenom starom gradu. U zavisnosti od vrste nove funkcije, moguće je da su potrebne samo preventivne, jednostavne popravke manjeg obima i one se veoma uspešno obavljaju. Kada nova namena zahteva značajnije promene u unutrašnjem tkivu građevine, onda su često potrebna i nova, savremena rešenja koja će omogućiti revitalizaciju enterijera. Primenjeni materijali za buduće intervencije na objektima ne smeju biti štetni i zagađujući za ljude i okolinu. Obavezan zahtev je da se ovakve intervencije i eventualno dodatno građenje mora obaviti primenom konvencionalnog načina gradnje i ekološki orijentisane konstrukcije.

U tom slučaju, zahtevi novih korisnika već su na neki način unapred sagledani u inventaru mogućih namena, te nailaze na spremnu i ekspeditivnu gradsku službu po svim pitanjima zaštite i revitalizacije.

2.4 On the old building stock and its protection in Bern

The structures which are listed as cultural monuments are evidence of social life of past times. They are a part of the culture of one society and testify the lifestyle of population in certain area.

Building comprehension depends on the accurate knowledge about the time when it was built and the changes it experienced during the long service. The collected information about the historical life of a building and its environment allow a successful comprehensive renovation, reconstruction and future usage which will extend the life of the building as a cultural monument.

All the collected data, along with the technical and photo documents serve as a basis for formation of guidelines of how to treat the building in the future, for finding which interventions are possible, and which are not, and what the potential for function conversion is, if the solution comprises preservation of the building and inclusion in contemporary life of the city. Data basis is created in this way, i.e. inventory of cultural assets which are used by the Cultural monuments protection service and the canton Chancellery office for various purposes. Regarding the number and accuracy of collected data, on the basis of the Inventory, it is possible to define an integral action plan and a financial structure of the costs for each potential, individual intervention such as conservation, rehabilitation, function conversion and revitalization as a form of protection of a building in its physical and spiritual entirety.

When the revitalization is concerned there is a firmly founded condition that, regardless of other interventions, the external appearance of the building should retain the existing appearance. No interventions using different materials on the facades are allowed except with stone, in the colour characteristic of the Old city of Bern. As for the changes inside the buildings, it is regulated by the *Code on protection,* i.e. new function of a structure can be realized only if all the measures of the contemporary protection are conducted with observation of the concept of the future users. Therefore, it is in the interest of the city authorities to convert the rooms or entire listed building if necessary, so it may survive, and to find a new user as soon as possible as well as to determine the future use in cooperation with him. This procedure comprises the new use which will the building in the register be introduced in of the activities which were previously approved to be adequate for the space and location in the historical, protected old town. Depending on the type of the new function, it is possible that only preventive, simple non-extensive repairs are required, and they are very successfully performed. When a new use calls for considerable repairs in the interior fabric of the building, then frequently, new contemporary solutions are required which will enable revitalization of the interior. The implemented materials in future intervention on the structures should be harmless and unpolluted. The basic requirement is that such interventions and potential building extensions should be performed applying conventional method of construction and environmentally oriented structures.

In this case, requirements of new users are, in a way, anticipated through the Inventory of potential uses, and the city service is ready and efficient for all the issues of protection and revitalization.

2.5 Održavanje graditeljskog nasleđa grada Berna

„Održavajte svoje spomenike i nećete imati nikakve probleme i razmišljanja u vezi s tim, ako treba da ih popravite, vi ih popravite. Popravke na krovu izvršite, granje i jesenje lišće na vreme pokupite i očistite, zaštitite krov, kao i fasade od oštećenja. Održavajte staru zgradu s velikom pažnjom. Brojite svoje kamenje kao da su dragulji ili drago kamenje, postavite straže za održavanje kao u palatama ili na kapijama velikih gradova. Poduprite zidove sa železnim stubovima gde počinju pucati, poduprite stubovima gde počinju da se naginju. Bolje je nešto imati u ruci, pa makar i štake, nego izgubljenu zemlju za gradnju; poslednji dan objektu će sigurno doći, ali ga odugovlačite i onda ga sami odredite." Ovu misao je izrekao Džon Raskin*,* veliki engleski mislilac, koji je još sredinom devetnaestog veka bio svestan značaja kontinuiranog održavanja građevina, naročito spomenika kulture. [16]

Raskin je imao pravo. S malim naporima, može se postojeće stanje zgrade zaštititi, a rekonstrukcija i obnova mogu doneti uštedu, ukoliko se sve redovno održava. Apsurdno je da se jedan spomenik kulture potpuno zanemari, a da se onda preduzimaju mere zaštite. Obim i vrste mera zaštite za tako drastično zapuštene slučajeve mnogo koštaju. Nemaran odnos prema vrednim spomenicima kulture češći je među vlasnicima privatnih poseda, pa se u praksi događa da se jedan isti objekat mora potpuno obnavljati u vremenskom razmaku od dve generacije. Radovi na zaštiti i obnovi spomenika kulture u privatnom vlasništvu obavljaju se nakon dogovora između vlasnika objekta i Komisije za zaštitu spomenika kulture, što može potrajati dok se obezbede finansije, a objekat u međuvremenu i dalje propada. Komisija za zaštitu spomenika kulture zna da takav pristup održavanja objekata nije dobar, jer uzrokuje propadanje objekata, kao i velike, neplanirane troškove budućeg renoviranja, ali nije uvek u stanju da to spreči.

Institucije i pojedinci, odnosno oni koji su odgovorni za zaštitu i revitalizaciju objekata, ranije su preduzimali tzv. jednostavne mere preventivne zaštite, koje daju rezultate na duži period. U međuvremenu, primenjuju se još mnoge mere preventivne zaštite, kojima je sačuvan veći broj spomenika kulture, što je i omogućilo da zaštićeni grad Bern dospe na listu Svetske baštine UNESCO-a. Mehanička vrsta zaštite pokazala se veoma efikasnom. To je, u suštini, veoma praktična mera kojom se spomenik može popravitii ili prepraviti, poštujući princip reverzibilnosti. Ova vrsta zaštite dolazi do izražaja kada je primenjuju vlasnici privatnih objekata koji su pod zaštitom, jer se s malim troškovima postiže veći učinak zaštite. Na primer, jedna od tehnika koja se koristi u svrhu preventivne zaštite jeste očvršćavanje kamena peščara, od koga je grad Bern sazidan, jednom vrstom cementa pomešanog s krupnijim frakcijama mlevenog kamena. Taj materijal koristi se s jednom vrstom lepka, čija je receptura specijalno napravljena za potrebe konzerviranja starog grada. Materijal je kompozitan i nov, sastavljen na preporuku Zavoda za zaštitu spomenika, da bi se sprečio i rešio viševekovni problem s vodom. Vlaga i kapilarno penjanje vode kroz materijale od kojih je napravljen Stari grad (sivi kamen peščar) predstavljali su ogroman problem u zaštiti grada. Da bi se izbegle kompletna rekonstrukcija i obnova,

2.5 Care and maintenance of the built heritage of the city of Bern

„Take proper care of your monuments and you will not need to restore them. A few sheets of lead put in time upon the roof, a few dead leaves and sticks swept in time out of a water-course, will save both roof and walls from ruin. Watch an old building with an anxious care. Count its stones as you would jewels of a crown; set watches about it as if at the gates of a besieged city; bind it together with iron where it loosens; stay it with timber where it declines. Better a crutch than a lost limb. Its evil day must come at last; but let it come declaredly and openly. " This is a thought of John Ruskin*,* great English thinker, who was as early as by the mid of nineteen century aware of the importance of continuing maintenance of buildings, especially of cultural monuments. [16]

Ruskin was right. With small efforts, one can preserve the condition of a building and postpone reconstruction and renovation, and save considerable finances if everything is regularly maintained. It is absurd to completely neglect a cultural monument, and only then undertake a protective measure. The scope and type of protective measures for so drastically neglected cases require considerable financial resources. Neglect for the valuable cultural monuments is more frequently present among private property owners, thus, in practice, one and the same building should be fully renovated in a short time span of two generations. The protection and renovation works of the privately owned cultural monuments are performed after agreement between the property owner and the Historical Protection Commission, which may be a prolonged process until finances are provided, while the structure is exposed to further dilapidation in this period. The Historical Protection Commission is aware that such approach to building maintenance is inadequate, since it causes dilapidation of buildings and high unscheduled cost of future renovation, but is unable to prevent it in all the cases.

Institutions and individuals, i.e. those who are responsible for protection and revitalization of buildings undertook in the past the so called "simple" preventive protection measures and those measures have long term effects. In the interim period, a large number of additional preventive protection measures were implemented and thus, preserved lots of cultural monuments that enabled the protected city of Bern to be added to the List of UNESCO World heritage. The mechanical protection proved to be very efficient. It is, in essence, a very practical measure, which can repair or change the monument; the principle of reversibility is observed in the process. This protection measure is significant in the cases when the private owners possess the listed buildings, because little expenditure provides high protection effects. For instance, one of the techniques used for preventive protection is hardening of sandstone, which was used for building the city of Bern, using a sort of cement mixed with coarse fractions of ground stone. This material is used along with an adhesive whose mix was specially designed for the purposes of conservation of the old town. It is a new composited material, designed following the recommendation of the Monument protection Institute, in order to solve a several centuries lasting problem with mora se primeniti preventivna zaštita koja ima isti značaj kao i redovna zaštita koja se uobičajeno primenjuje na spomenike kulture. Preventivna zaštita, u ovom slučaju znači „sprovoditi redovnu obnovu i kontrolu”.

U Bernu, Komisija za održavanje spomenika, nakon izrade završnog računa i urađene evidencije obavljenih preventivnih mera, oba izveštaja šalje vlasnicima zaštićenih objekata da budu u toku s delatnošću u toku jedne godine. U istom izveštaju nalaze se i predlozi za periodične kontrole spomenika kulture. Vlasnicima se nudi da se, na primer, svake dve godine obave kontrole krovova i da se konstatuje njihovo stanje, o čemu bi vlasnici bili obavešteni. Dalje, u popisu predloga nalaze se i izveštaji o podovima u unutrašnjim prostorijama, kao i saveti o tome kako se najbolje održavaju. Ove stavke, koje govore o tome kako bi nešto trebalo da izgleda u prostoru, mogu se navesti i u glavnom ugovoru koji se sklapa između Komisije za istorijsku zaštitu (odgovara Zavodu za zaštitu spomenika kulture u Srbiji) i vlasnika zaštićenog objekata.

Mnogi objekti u gradu Bernu su javnog sadržaja i u privatnom su vlasništvu, tako da je i na njih primenjen Zakon o zaštiti. Za otvorene (objekti javnih i poslovnih sadržaja) javne objekte dogovoreno je da se, u odgovarajućim periodima od nekoliko godina, sazivaju sastanci predstavnika Komisije i organizacija ili firmi koje su u objektima privatnog vlasništva, na kojima će se dogovarati o daljim aktivnostima. Ti sastanci su nesumnjivo veoma značajni, jer se na njima dogovori postižu veoma brzo, posebno ukoliko se konstatuje da nisu potrebna velika ulaganja.

Na primer, ukoliko se uoče manja oštećenja na fasadnom platnu, jer su fuge na fasadi popustile, ili ako su oštećene stepenice, ako se ogulila boja na ulaznim vratima ili su vidljiva i neka druga osetljiva, ali minimalna oštećenja na zgradi, Komisija može reagovati veoma brzo. Ona predlaže zaključenje jednog kontrolnog ugovora s firmom koju će izabrati na pozivnom konkursu. Firme iz te oblasti poznate su Komisiji i od njih nekoliko, obično su tri do četiri renomirane za potrebnu vrstu posla.

Po pozivu, firme daju svoje ponude, a komisija je ta koja određuje ko će da dobije posao održavanja određenog objekta. Ugovor se prosleđuje vlasniku javnog objekta koji daje ili ne daje pristanak na to. Ako vlasnik pristane, potpisan ugovor vraća se u Zavod, koji poziva izabranu firmu da započne obavljanje zaštite. Preliminarni ugovor koji je potpisan s firmom za održavanje ima dejstvo dve godine, s mogućnošću raskida posle godinu dana. Firma koja održava objekat podnosi izveštaj u kome mora biti navedeno: šta je kontrolisano i u kakvom je stanju, da li su potrebne neke mere zaštite, obnove ili rekonstrukcije. Time je obezbeđeno da mala oštećenja budu na vreme otkrivena i ako je potrebno, sanirana.

Navedenim merama sprečava se pojava velikih oštećenja, jer se, s obzirom na kontrolu, ne mogu razviti. Svi izveštaji o urađenim kontrolama moraju se blagovremeno dostaviti i ništa se ne sme zanemariti. Službe koje su nadležne za tu vrstu posla moraju biti do detalja informisane o tome kako će se sve popravke obaviti ili kako će se objekat zaštititi, koliko vremena treba da se to uradi i koliko će košati. Svi detalji moraju objektivno biti predstavljeni i trajno dokumentovani.

U Bernu je bilo velikih propusta u zaštiti istorijskog

water. Moisture and capillary rise of water through the materials used for building of the Old town (which is build of the grey sandstone), were a huge issue in protection of the city.

In order to avoid the process of a total repair and protection (reconstruction and renovation) preventive protection should be implemented and it is equally important as the regular protection which is usually used for cultural monuments. Preventive protection, in this case means “performing regular renovation and control”. After the final balance has been done and after registering all the performed preventive measures, the Historical Preservation Commission of Bern sends both reports to the owners of the listed buildings so they can keep the record of the activities within a year. In the same report, there are proposals for periodical controls of cultural monuments. The owners are offered that, for example, every two years roof controls are performed and their condition established. The owners are informed of the findings. Further, in the list of proposals, there are reports about floors in interior rooms, and the advice about how to maintain them in the best manner. These items, describing how something should look like in space, can also be included in the main contract signed by the Historical Preservation Commission and the owner of the listed building.

Many buildings in the city of Bern have public use but are privately owned, so the Law on protection applies to them as well. It is agreed that the open public buildings (buildings with public and business uses), will be a subject matter of the meetings between the representatives of the Commission and the organization and companies, in the appropriate several years intervals, where the further activities will be discussed. Those meetings are, undoubtedly, of great significance and they proved to be important, because agreements can be reached very quickly if it is established that no major investment is required.

For instance, the Commission can react very quickly if small damage are observed on the façade walls because the pointing joints cracked, or stairways are damaged, or the paint on the entrance doors peeled off or some other sensitive but minimum damage is visible on the building. They propose making a control contract with a company to be selected at an invitation to bid. The companies dealing in this field are known to the Commission, and out of several of them, usually 3-4 are specialized for this type of works.

After the invitation, the companies give their offers, and the Commission decides on whom to entrust the maintenance of a certain building. The contract is forwarded to the owner of the public building, which he may or may not give consent for. If the consent is given, the signed contract is returned to the Commission, which invites the selected company to start with the protection works execution. The preliminary contract which is signed with the maintenance company has a validity of two years, with the provision for termination after a year. The company maintaining the building submits a report which should include: what was controlled and in what condition it is, and if some protective, renovation or reconstruction measures are required. This provides early discovery and potential repair of small damage.

These measures prevent the onset of a major damage, which cannot develop due to the control. All the nasleđa pre Drugog svetskog rata, ali navedene mere, uvedene pre sedam do osam decenija, tu situaciju su značajno promenile. Ta promena se manifestuje, pre svega, u postupnom, ali stalnom posmatranju spomenika, te blagovremenim popravkama, kako se ti propusti ne bi ponovili.

2.6 Inventarisanje spomenika kulture kao preventivna zaštita

Veoma dugo su u Bernu samo neke javne i sakralne građevine bile označene kao spomenici kulture. Na primer, Gradska palata, jedna od najstarijih palata istorijskog dela Berna, od vlasnika i u političkim krugovima označena kao bitan objekat u memoriji grada Berna, kao i Katedrala (Münster), započeta 1421. godine, najviša u Švajcarskoj. Broj spomenika kulture se pažljivo i postepeno proširivao.

S velikom pažnjom i brigom, Komisija za održavanje spomenika kulture priprema i sastavlja izveštaje tako da budu razumljivi i ljudima koji nisu stručnjaci, da bi svi bili upoznati s radovima koji će se izvoditi na spomenicima kulture. Ipak, ti spiskovi nisu uvek ispunjavali sve uslove i zato se poslednjih dvadesetak godina intenzivno radi na vrednovanju graditeljskog nasleđa da bi ono moglo da se što kvalitetnije inventariše. Istovremeno, ovaj inventar se digitalizuje u centralnoj bazi podataka, u kojoj se, prilikom popisa, ispunjavaju svi državni, kantonalni i gradski zakoni zaštite objekata. Od početka rada, Komisija se veoma trudila da ono što radi naiđe na razmevanje i prihvatanje građana Berna, jer upravo građani putem raznih poreskih oblika plaćaju rad Komisije. Pre nekoliko godina, ustanove građanske inicijative uspele su da se izbore za pravo odlučivanja i uticaja na odlučivanje prilikom upisa zaštićenih zgrada u spisak Inventara.

Oblici građanske inicijative dobili su „zeleno svetlo" u ministarstvima Kantona Bern i pravo odlučivanja stanovnika grada podignuta su na viši nivo. Sistem u praksi funkcioniše tako što Komisija popisuje objekte, klasifikuje ih, određuje kategoriju zaštite, ali ukoliko, na osnovu stručnih istraživanja, Komisija odluči da se spomenik kulture mora srušiti ili značajno renovirati, bez obzira na to što će to skupo koštati poreske obveznike, tada građani istupaju sa svojom inicijativom. Građanska inicijativa je mehanizam koji se u Švajcarskoj, pa tako i u Bernu, maksimalno koristi. Čim građani konstatuju da treba da reaguju, oni prikupljaju potpise i raspisuje se referendum o tom problemu, o tome da li treba da se prihvati odluka Komisije ili ne.

Rezultati referenduma obavezujući su za sve učesnike tog procesa. S tim mehanizmom odlučivanja, procesi se odvijaju na obostranu korist. Na taj način, procenjuje se, odnosno prihvata ili kritikuje rad Komisije. Komisija za zaštitu objekata uvek je pod lupom javnosti, njen rad je potpuno transparentan. Javnost i transparentnost glavna su obeležja u radu ove institucije. Osnovni pristup u radu jeste da se problemi rešavaju na

reports of performed controls should be timely submitted and nothing neglected. The services competent for that sort of the work should be informed in detail about how the repairs or protection will be performed, what time is needed and how much it will cost. All the details should be objectively presented and permanently documented.

In Bern, there were large failures in protection of the historical heritage before the WWII, but the mentioned measures, introduced seven to eight decades ago, considerably changed this situation. This change is manifested primarily in gradual but continuous monitoring of the monuments, timely repairs so that the failures are unlikely to happen again.

2.6. Making an inventory of the cultural monuments as a preventive protection measure

For very long time, only some public and sacral buildings were listed and marked as cultural monuments in Bern. The examples are the Town Palace, which is one of the oldest palaces of the historical part of Bern, which was by the owner and in certain political circles marked as an important structure in the memory of the city of Bern, as well as the Cathedral (*Münster*) whose construction began in 1421 as the tallest cathedral in Switzerland. The number of cultural monuments carefully and gradually expanded.

The Historical Protection Commission with great care and attention prepares and composes the reports, so that they are readily understandable to the people who are not experts, so that they will be acquainted with the works to be executed on the cultural monuments. Yet, these lists sometimes fail to meet all the requirements and therefore, there has been an intensive effort in the past twenty years to evaluate the building heritage, so that it could be entered in an inventory. Simultaneously, this inventory is digitalized in the central data bank, according to all federal, cantonal and city laws. Since the beginning of work, the Commission endeavoured to have its activities accepted and understood by the citizens of Bern, since the citizens pay for the operation of the Commission, through various forms of taxes. Several years ago, the citizens' initiatives establishments succeeded in gaining right to decide and affect decision making on the occasion of including listed buildings in the Inventory list.

The forms of citizens' initiatives got the green light in the ministries of the Bern Canton and the citizens decision making rights were brought to a higher level. In practice, the system work comprises the Committee making a list of the buildings, classifying them, determining the protection category; but if the Committee, based on the professional expertise, decides to demolish the cultural monument, or to extensively renovate it, regardless of the high cost for the tax payers, then the citizens come forth with their initiative. The citizens' initiative is mechanism that is used to the maximum in Switzerland and thus in Bern. As soon as the citizens conclude that they should react they gather signatures and put the issue on a referendum whether to accept the Committee decision or not.

The referendum results are binding for all the participants of the process. With this decision-making mechanism, the processes are beneficial for both sites. In this way the work of the Committee is assessed, i.e.

samom početku, i to dijalogom i dogovaranjem, da posle ne bi došlo do konfliktnih situacija, jer tada svi građani snose posledice. Zato se sve opcije rada na spomenicima kulture predstavljaju odmah na početku, iznose se na javnu raspravu, organizuje se skupština građana i donose se zaključci.

2.7 Preventivna zaštita koju nalažu zakonski propisi

Ukoliko se pojavi problem, odnosno ako treba da se donese odluka o tome da li će se neki objekat rušiti ili obnavljati, treba obaviti određena istraživanja po fazama. Iskustvo je pokazalo da prvo treba odrediti vrstu namene parcele, zatim namenu objekta na toj parceli, a potom napraviti predlog na koji način se može spasti objekat, odnosno mora li se srušiti.

Obim radova unapred je određen, pa je zato veoma važno da Komisija za održavanje objekata unapred dobije kompletna uputstva u vezi s postojećim objektom. Zakon grada Berna sadrži sve što je potrebno u vezi s gradnjom i zaštitom osetljivih objekata, kako u samom gradu, tako i u Kantonu Bern. Zakoni su potpuno određeni, naročito deo zakonskih odredaba koje se odnose na zaštićeni istorijski deo, poznat kao Stari Bern. Ova stavka nije baš povoljna za buduće investitore koji bi želeli da ulažu u okviru Starog grada, bilo da je reč o stambenim ili javnim objektima. Zakonske odredbe su jasne i ne mogu se drugačije tumačiti osim onako kako su u zakonu propisane i svi učesnici, uključujući i sve stanovnike Berna, saglašavaju se s tim. U Gradskom građevinskom zakonu grada Berna iz 1979. godine u članu 75, paragraf 3, piše: „Zgrada, grupa zgrada, blokovi i delovi istorijske arhitekture imaju ulogu u specijalnoj zaštiti, i podrazumeva se da se neprihvatljivi poslovi na zgradama ne obavljaju, jer bi to moglo da izazove sukob s javnim mnjenjem. Opisane su granice, razdaljine među zgradama, Mehrlangenzuschlage, rastojanja od građevinske linije i visine zgrada koje se moraju održavati. U slučaju katastrofe, stari zaštićeni objekti treba da se izgrade na originalnim mestima, sa identičnim fasadama, atrijima i karakterom koji treba da se sačuva. Celokupni karakter se ne može promeniti renoviranjem i dogradnjama na zgradama." Dodatak br. 4 glasi: „Nove građevine kao ni dogradnje u Starom gradu ne smeju da promene gradsku perspektivu. Izuzeci za gradnju višespratnih dodataka neće biti prihvaćeni."[20]

Ovaj zakon, s jasno definisanim odrednicama o zaštiti, važi samo za Stari grad Bern [25] koji je zadržao originalan izgled [23]; izvan granica tog područja, zakon nema tako striktno dejstvo. Na teritoriji Starog grada zadaci Komisije za održavanje spomenika kulture zasnivaju se na Kantonalnim zakonima. Na delovima gradske teritorije koja nije pod zaštitom države veoma je važno kako će se planirati zaštita i revitalizacija. Tokom rada u toj oblasti, Komisija je istovremeno izložena kontroli javnosti i stanovnika grada Berna kao neposred-

accepted or criticized. The Cultural monument protection Committee is always in view of the vigilant public; its work is fully transparent. Public character and transparency are the main traits of the operation of this institution. The basic approach to the work is to solve the problems at the very outset, through a dialogue and agreement in order to avoid the conflicting situations, because all the citizens have to bear the consequences resulting from the problematic situation. Therefore, all the options of the work on the cultural monuments are presented at the beginning, taken to public discussion, an assembly of the citizens is organized and conclusions are drawn.

2.7 Preventive protection prescribed by the legal regulations

Certain research is performed in phases if a problem occurs; that means a decision is made on whether a building will be demolished or restored. The experience has shown that the use of the building lot should be determined first, then the use of the building on the lot and then to make a proposal in what way the building can be salvaged or it should be pulled down.

The scope and amount of work is determined in advance, so, therefore, it is very important that the Commission for building maintenance receives the complete instructions related to the existing building in advance. The law of the city of Bern comprises all necessary details concerning construction and protection of sensitive buildings, both in the city itself and in the Bern Canton. The regulations are entirely determined, especially the part relating to the listed historical part known as the Old Bern. This fact is beneficial for the future investors who would like to invest, within the Old city, regardless of whether those are housing or public buildings. The legal regulations are clear and inaccessible to a different interpretation except as laid down by law, and all the participants, including all the citizens of Bern, agree with that. In the City building regulations, Bern 1979, Article 75, paragraph 3 is quoted: "A building, group of buildings, blocks and parts of historical architecture have the role in special protection, and it is comprised that the unacceptable interventions on the buildings are not carried out, which could create conflict with the public opinion. The city inventory explains the parts of the cantonal law (article 8/19 Bau, article 12 Bau V). Bordering lines, distances between buildings, distances from the frontage line and heights of the buildings which should be maintained are described. In the case of a catastrophe, the old listed buildings should be constructed in their original places with identical facades, atria, and character which must be preserved. The overall character must not be changed with renovations or extensions on buildings." Addition no. 4 defines that: "new buildings nor extensions in the Old city must not change the cityscape". The exceptions for construction of multi-storey extensions will not be accepted."[20]

This law, with clearly defined protection provisions, is valid only for the Old city of Bern [25], which retained its original appearance, [23] while outside this area the law is leniently enforced. In the territory of the Old city, the tasks of the Historical Protection Commission are based on the Canton regulations. It is very important to plan nih korisnika graditeljskog nasleđa.

Jedno od važnih pravila za gradnju u Bernu jeste da su izgradnja i namena objekta na svakoj parceli jasno precizirani: dužina građenja (okvirno), dubina iskopa, visina spratnosti, koeficijenti izgrađenosti, minimalan broj parking mesta, izgradnja skloništa i drugo. Detaljno određenje pomenutih parametara propisuje Gradska kancelarija za planiranje po planu o izgradnji grada iz 1987. godine, i ona se, takođe, brine o tome da tradicionalni stambeni blokovi pružaju visok stambeni komfor, kao i da se održe dizajn, jedinstvo i čistoća tih delova grada. Planirani koeficijent novih zgrada je određen u skladu s postojećim očuvanim objektima. Dozvoljena je gradnja na mestima gde je moguće razviti urbani prostor ili gde se očekuje intenzivniji razvoj ekonomskih aktivnosti. Plan o izgradnji grada nije izričito povezan s planom zaštićenih spomenika kulture. Plan ne objašnjava to da li se prostor koji je potreban za život stanovnika mora obezbediti s postojećim zgradama ili je potrebno graditi nove zgrade. Ipak, ovako definisan, plan je u većini slučajeva eliminisao pretnju da će mnogi postojeći objekti biti srušeni usled zahteva javnosti za novim prostorima. U većini slučajeva nema finansijskog opravdanja da se zgrada sruši i da se gradi nova. U tom smislu, *Bauklassenplan* grada Berna imao je značajnu ulogu. To je posebno uočljivo kada je reč o građevinskoj klasi E (ocena postojeće konstrukcije), jer se u okruženju može graditi samo u skladu sa zaštićenom zgradom. [2]
U planu za izgradnju u građevinskoj klasi E ne navodi se konkretno da li se specifična zgrada treba održavati ili ne. Međutim, ukoliko se novi objekat gradi na mestu starog, koji je označen kao klasa E, onda novi objekat mora da zadrži plan volumena i visinu stare zgrade. Dogradnja je jedna od mogućnosti da se poboljšaju uslovi stanovanja, ali samo ukoliko taj dodatak zadrži istorijske odlike postojeće građevine. Tim merama plan sprečava nepotrebna rušenja postojećih zgrada, kao i spomenika kulture, što se pre donošenja plana često događalo.

3 PROSTORNI I URBANISTIČKI PLANOVI KAO VID ZAŠTITNE MERE

Ukoliko se u nekim delovima grada stvore nezadovoljavajući uslovi, onda se rade specijalni planovi za budući razvoj tog područja.[2] U Bernu, kao i u celoj Evropi, planiranje dalje budućnosti neke gradske strukture može uzrokovati zabrinutost javnosti ukoliko se predlažu neprimerena rešenja. Ovo uključuje i problem vlasništva istorijskih zgrada koje imaju specijane planove u pogledu revitalizacije. Tradicionalno, one su poznate *kao zaštićeno privatno vlasništvo, zaštićena* ili *privatna svojina.* Planiranjem se privatni i javni problemi uglavnom podjednako razmatraju. Zabrinutost za značaj-

protection and revitalization of those areas of city territory which is not under the federal protection. During the work in this area, the Commission is simultaneously subject to control of the mentioned public and citizens of the city Bern, as direct beneficiaries of the building heritage.

One of the important construction rules in the city of Bern is that construction and use of buildings on each lot are clearly defined: the construction duration (approximately), depth of excavation, number of floors, floor area ratio, minimum number of parking space, construction of shelters etc. A detailed determination of the mentioned parameters is prescribed by the City planning office according to the city building plan of 1987, and it also takes care that the traditional housing blocks offer high living comfort as well as to maintain design, unity and cleanliness of these parts of the city. The planned coefficient of the new buildings is determined in agreement with the already existing preserved buildings. The construction is permitted at the locations where it is possible to develop the urban space or where an intensive development of economic activities is expected.

The city building plan is indirectly connected with the plan of listed cultural monuments. The plan fails to explain whether the space required for the life of the citizens should be provided with the existing buildings, or if it is necessary to build the new ones. Yet, the plan thus defined in most cases eliminated the threat that many existing buildings will be demolished due to the public demand for new areas. In majority of the cases, there is no financial justification to demolish a building and to build a new one. In this sense, *Bauklassenplan* of the city of Bern played an important role. It is especially noticeable when it comes to the building class E (evaluation of the existing structures), since in the given environment, it is permitted to build only in harmony with the listed buildings. [2]

In the construction plan for the building class E there are no concrete guidelines whether the specific building needs maintenance or not. However, if the new building is constructed in place of the old one, which was designated as class E, than the new building should retain the layout and height of the old building. Extension is one of the possibilities to improve the living conditions, but only if this extension retains the historical characteristics of the existing building. These measures of plan prevent the unnecessary demolition of the existing buildings, as well as the cultural monuments, which was often the case prior to enactment of the plan.

3 SPATIAL AND URBAN PLANS AS A PROTECTIVE MEASURE

If unsatisfactory conditions are created in some parts of the city, then the special plans are produced for the future development of that area.[2] In Bern, as well as in all of Europe, planning of distant future of a city structure may lead to the raised concern of the public, if the unsuitable solution are proposed. This entails the problem of ownership of historical buildings which have special plans related to revitalization. Traditionally, they are known as “protected private property” or „private property“. By planning, both private and public problems are mostly equally considered. Concern for the cultural ne spomenike kulture samo je jedan od mnogih faktora. Može se dogoditi da interesi političkih vlasti i glasača mogu vredeti manje od ekonomskih interesa i da se zaštita spomenika kulture može odbiti.

Svaki potencijalni sukob u planskom procesu treba da se izbegne ili da se odloži za neko vreme, da bi se o tome raspravljalo na nekim kasnijim sastancima. Iz perspektive zaštite, veoma je važno da se sačini spisak zgrada koje nisu od izuzetne istorijske vrednosti. Ipak, prilikom budućeg korišćenja tih objekata vodi se briga ne samo o finansijskoj isplativosti, nego i o kvalitetu zaštite njihovih istorijskih osobina. Primer za to jeste provizija koja se dobija po završetku zadatka. Kad je reč o najvrednijim spomenicima i njihovim vrednostima, konsenzus o dugoročnoj zaštiti treba da bude obezbeđen. Efektivni načini preventivne konzervacije su u Bernu, nažalost, ograničeni.

Kao deo Naredbe o izgradnji, vlasnici finansija će uživati korist kada se određena zgrada ne koristi, pa se restaurira i dobije novu namenu. U Uredbi Zavoda za izgradnju grada za korištenje javnog zemljišta na kojem se nalaze spomenici kulture stoji da polovinu troškova plaćaju poreski obveznici, a ta sredstva se koriste za restauraciju zgrada, te se tako izbegava dodatno finansiranje iz budžeta građana.

Preventivna konzervacija predstavlja reakciju koja je proizašla iz specifičnih okolnosti. Istorijska konzervacija ima mnogo nivoa i mnogo alata za preventivne mere zaštite. Tokom poslednjih dvadeset godina, pokušavajući da se zaštiti, grad Bern je usvojio mnoge od tih metoda i sproveo ih u praksu. Deo procesa je završen, ali konačan cilj još nije dostignut.

3.1 Idilična zaštita okoline u gradu Bernu

Grad Bern je 1979. godine formirao posebnu gradsku Agenciju za istorijsku zaštitu. To je bio odgovor na zabrinutost države i Bernskog kantonalnog konzervatora, pogotovo zbog ubeđenja gradske vlasti i građana u to da je stari grad Bern, kao celina, baština međunarodne vrednosti i da je intenzivna zaštita preko potrebna. Međutim, već od početka, rad agencije nije bio ograničen samo na Stari grad, uključene su takođe i važne istorijske zgrade u predgrađu, a kasnije i vredne građevine modernog doba. Podela odgovornosti i rada određena je geografskom podelom, a za sve poslove konačno je nadležna Gradska stručna komisija, bez obzira na kategorizaciju objekata.

Bliska saradnja s kantonalnom službom za preventivnu zaštitu umnogome je doprinela boljoj brizi za nasleđe. S ciljem da bude što manje nepravilnosti, doneta je odluka da Gradska konzervatorska komisija bude jedina odgovorna za sve finansijske kredite budućih projekata u oblasti zaštite. Na taj način, jednom peticijom, odnosno prigovorom, moguće je prijaviti nepravilnosti u radu i kontroli transparentnosti rada ove komisije. Jasno definisanom metodom obračuna servisnih usluga od strane Udruženja švajcarskih zaštitara, omogućeno je da se izračuna čist, transparentno vidljiv doprinos koji mora da se obezbedi.[20] Pod vođstvom različitih kreditnih agencija, doprinosi su počeli da se uplaćuju. Doprinosi su jedan od elemenata na kojima se bazira rad Agencije za zaštitu grada Berna, iako je ona,

monuments of outstanding value is only one of many factors. It may occur that the interest of political authorities and voters may be outweighed by the economic interest, and that protection of cultural monuments is rejected.

Every potential conflict in the planning process should be avoided or postponed for a certain time, so that it could be discussed in some later meetings. From the perspective of protection, it is very important to make a list of buildings which are not of special historical value. Yet, in the future use of these buildings, care is taken not only about the financial profitability but also about the quality of protection of their historical characteristics. An example for that is the fee obtained upon completion of the task. When the most valuable monuments are concerned, the consensus on the long-term protection should be provided. The efficient methods of preventive conservation in Bern are, unfortunately, limited.

As a part of the Building order, the financers can make profit in cases when a certain building is disused and is then restored and put to a new use. The decree of the City building Agency prescribes that half of the costs of the land occupied by the cultural monuments is borne by the tax payers, and those resources are used for buildings restoration, and thus the additional financing from the citizens' budget is avoided. Preventive conservation represents a reaction resulting from the specific circumstances. Historical conservation has multiple levels and tools for preventive protection measures. During the last twenty years, in an attempt to protect itself, the city of Bern adopted many methods and put them in practice. A part of the process is completed, but the final goal has not yet been achieved.

3.1 Idyllically protection of the environment in the city of Bern

The city of Bern established a special city protection agency in 1979. It was a response caused by the concern of the state and the cantonal conservationist of Bern, but also by the deep conviction of the city authorities and citizens that the old town of Bern as a whole was a heritage of an international importance and that the intensive protection was required. However, from the outset, the work of the agency was unlimited to the old town, included were many important historical buildings in the suburbs, and in the later period some valuable modern age building. The division of competences and work is determined by the geographic division, and the Professional city Committee is ultimately competent for all the works irrespective of the building categorization.

Close cooperation with the cantonal service for preventive protection largely contributed to a better level of care about of the built heritage. A decision was made to make the city`s Historical Protection Commission be solely responsible for all the financial credits of the future protection projects. Thus, by only one petition, i.e. objection, it is possible to report the irregularities in the work and control of the work of this Commission. Due to the clearly defined method of billing of services by the Swiss Agency for the Protection of Cultural Property it is possible to calculate a clear and transparent contribution which should be provided. [20] Under guidance of uglavnom, nadzorno i savetodavno telo.

Agencija, takođe, nadgleda projekte za glavne poslove, kao što je formiranje inventara spomenika kulture. Predsedavajući u ovoj agenciji je konzervator iz Komisije za istorijsku zaštitu. Ova komisija svake dve godine dodeljuje nagradu *dr Jost-Hartmann*, za „najbolje revitalizovanu i zaštićenu kuću u Starom Bernu".[22]

Nagrađuju se osobe koje su, preduzimajući restauraciju, sledile principe zaštite i očuvale integritet vredne građevinske strukture. Nagrade se dodeljuju arhitektima i građevinskim koncernima, inženjerima i restauratorima, zanatlijama, ali i zaslužnim političarima. Članovi Agencije godinama se ne menjaju, da bi se očuvali ustanovljeni kriterijumi. Imajući u vidu broj spomenika kulture koji su pod njihovom brigom, njihovi uslovi za delovanje su skromni. Poslednje četiri godine izvori finansija su se smanjili, uglavnom za prateću administraciju.[22]

3.2 Četiri izveštaja o preventivnoj zaštiti grada Berna

U petom setu četvorogodišnjih izveštaja o preventivnoj zaštiti, koji pokriva period od 1997. do 2000. godine, uočavaju se mogućnosti da se rad Agencije predstavi široj javnosti, da bi se opisali glavni doprinosi, uslovi, kao i razne poteškoće s kojima se članovi u radu susreću.[24] Dugoročni planovi i trendovi takođe su uključeni u izveštaje. Ovaj četvorogodišnji izveštaj objavljuje se u „Bernskom magazinu istorije i lokalne istorije". Prikazani primeri, odnosno zaštićene zgrade predstavnici su svih funkcionalnih oblika i služe kao uzori za mnogobrojne potonje restauracije, u kojima se javljaju slični problemi.

Pomoću tih primera uspešnih restauracija i konzervacija, uspostavljaju se opšteprihvaćene smernice za istorijsku konzervaciju. Pojedinačni autori, vlasnici zgrada i arhitekte, obrazlažu svoje lične primere angažovanja. Većina tekstova odnosi se na određivanje vrednosti spomenika kulture. Uočava se i učešće onih koji nisu neposredno vezani ličnim interesom za neki spomenik kulture, ali osećaju moralnu ili profesionalnu obavezu da skrenu pažnju na vrednosti koje zapažaju. [5] U arhivima se čuva i obiman materijal, ne samo o spomenicima kulture, već i dokumentacija o restauratorskim radovima koji su na njima do sada obavljeni. Ova dokumentacija je svima dostupna, a njen dodatak predstavlja i zvanični detaljni interni izveštaj. U tom izveštaju navedeni su nerešeni problemi u pogledu istorijata zgrada, njenog nastanka i promena tokom životnog veka, kao i posebni problemi koji su uočeni tokom restauracije. U godišnjim izveštajima grada Berna nalaze se, takođe, lista objekata na kojima su izvršeni restauratorski radovi, ali i lista projekata koji su odbačeni. Najdramatičniji događaj iz perioda koji pokrivaju ovi izveštaji jeste nesreća u ulici *Randbjunkerngasse*, početkom 1997. godine, kada se nekoliko kuća srušilo. Velike štete utvrđene su na pet

various credit agencies, the contributions began to pay off. The contributions are one of the elements on which the operation of the Agency for Protection of the City of Bern is based, even though it is mostly concerned with supervision and consulting.

The Agency also supervises the projects of the major tasks, such as establishing the cultural monuments inventory. The chairman of the Agency is a conservationist belonging to the Historical Protection Commission, and the other members are respectable professionals in fields relevant for the cultural property protection. The Commission biannually awards the *dr Jost-Hartmann* prize, for the best revitalized and protected house in Old Bern". [22]

The prizes are awarded to the individuals who, undertaking restoration, followed the protection principles and preserved the integrity of a valuable building structure. The buildings are awarded to architects and contracting concerns, engineers and restorers, craftsmen and politicians. The members of the Commission remain the same for years, in order to retain the established criteria. In comparison to the number of cultural monuments in their care, their working conditions are modest. In the last four years, the financial resources were reduced, mostly for the accompanying administration. [22]

3.2 Four reports on the preventive protection of the city of Bern

In the fifth set of four-year reports on preventive protection, covering the period 1997-2000, there is potential to present the work of the Agency to the wide public, in order to describe the main contributions, conditions and various difficulties the members encounter in their work.[24] The long-term plans and trends are also included in the reports. This four year report is published in the "Bern journal of history and local history". The presented examples, i.e. the protected buildings are representatives of all the functional forms and they serve as models for numerous subsequent restorations that feature similar problems.

With the aid of these examples of successful restorations and conservations, generally accepted guidelines for historical conservation are established. Individual authors, such as the building owners and architects explain their personal actions. The most of the texts refer to the determination of the values of the cultural monuments. Also notable is the participation of those who are not personally involved with a cultural monument, but who feel the moral or professional obligation to draw the public attention to the values they perceive.[5] Extensive material is being kept in the archives, concerning not only cultural monuments, but documents on the restoration works performed on them up to now. These documents are widely available. An official detailed internal report is an addition to these documents. The report lists the unsolved problems concerning the historical background of the buildings, their construction and changes they underwent during their life time, as well as special problems detected during the restoration. The yearly reports of the city of Bern also comprise the list of buildings which underwent the restoration works, but also the list of rejected designs. The most dramatic event from the period vrednih istorijskih zgrada. Požar, koji je ovu štetu izazvao, naveo je građane Berna da u narednim mesecima reaguju u smislu donošenja važnih odluka o zaštiti nasleđa.

Iskazana je velika zabrinutost za Stari grad. Projekti restauracija, preduzeti nakon ove nesreće, obuhvatili su i dodatne mere zaštite i predstavljali su nov izazov za stručnjake. [24]

3.3 Spomenik kulture kao vlasništvo

Zaštićeni spomenici kulture dugo nisu bili atraktivni za poslovanje nekretninama. Uzrok za to bio je ograničenje u izboru namene, kao i dizajna koji se može primeniti na neku zaštićenu istorijsku građevinu. Poslednjih decenija došlo je do značajnih promena u pristupu ovim problemima i njihovom rešavanju. Zaštićene građevine danas imaju tržišnu vrednost i visoko se kotiraju kada je u pitanju prodaja, ali i iznajmljivanje, zbog njihove upotrebne vrednosti.

Zaštićene građevine imaju period dugog korišćenja i najčešće se nazivaju građenim slojem prve klase. Za mnoge takve građevine pojavljuje se problem daljeg opstanka. Razlozi za to su razni: makroekonomske promene, migracija stanovništva, kao i promene u okruženju, a sve to uzrokuje neželjene efekate devastacije građevinskog tkiva. Najčešći uzrok propadanja jeste prevaziđena originalna, izvorna, funkcija tih građevina, što je ljude koji su u njima stanovali ili radili navodilo da ih napuste. Logičan zaključak jeste da u tom slučaju treba promeniti namenu građevine. To je, međutim, veoma teško kada su u pitanju zaštićeni spomenici kulture, jer promene fizičke strukture koje, po pravilu, treba obaviti tako da se očuvaju spomenička svojstva zbog kojih je zgrada zaštićena, iziskuju veliku pažnju i senzibilitet arhitekata, a i mnogo koštaju. Buduća dobit od investicije u prenamenu istorijske građevine zavisi od nekoliko faktora: faktora ograničenja u budućoj nameni, faktora pratećih troškova u fazi daljeg životnog veka građevine i faktora povećanja investicija zbog zahteva maksimalnog očuvanja originalnih svojstava objekta.

Metode zaštite i promena namene građevine treba da budu potpuno usaglašene. Određeni stepen tolerancije pri izgradnji novih zgrada ne postoji kada se obavljaju radovi na zaštićenim istorijskim spomenicima. Zato budući korisnik postavlja pitanja da li će uspešno moći da se ispune svi postavljeni zahtevi, a da se prilikom investiranja u zgradu smanji uloženi kapital radi što većeg profita.

Ovaj proces, putem kog se moraju rešavati problemi funkcije i potencijala u savremenim uslovima zaštićenih spomenika kulture, u punom smislu reči jeste *revitalizacija* - „ponovno vraćanje u život".

3.4 Definicija graditeljskog nasleđa po švajcarskim zakonima

Graditeljsko nasleđe predstavlja nasleđe koje nije važno samo za jedan deo švajcarske teritorije, odnosno

covered by these reports is the disaster in *Randbjunkerngasse* Street, at the beginning of 1997, when several houses collapsed, and when extensive damage was caused on five historical buildings. The fire which broke out and caused this damage, led the citizens of Bern to react in the ensuing months, in terms of making some decisions related to the heritage protection.

A high concern was expressed for the Old town. The restoration designs following the disaster included the additional protection measures and represented a new challenge for all the experts. [24]

3.3 Cultural monuments as property

Listed cultural monuments were not attractive to real estate business for a long time. The main reason was the limitation concerning the use and design which can be adopted for a listed historical building. In the recent decades, there have been considerable changes in the approach to solving these issues. The listed buildings nowadays have market value, and they rank high both in terms of sales and in renting, due to their practical value.

The listed buildings have been used for a long time, and they are most often called the built layer of the first class. The further existence of many of them was threatened. There were diverse reasons for this: macroeconomic changes, population migration, environment changes, all leading to the undesirable effects of urban fabric devastation. The most common cause of dilapidation was the outdated function of the building which led people who were residing or working in it to abandon it. The logical conclusion is that the use of the building ought to be changed in such situations. However, this is very difficult when it comes to the listed cultural monuments, since the changes of the physical structure, which, as a rule, must be performed so as to preserve the monumental properties for which the building was listed in the first place, require considerable attention and sensibility from the architects, as well as considerable financial resources. The future profit resulting from the investment in the conversion of a historical building depends on several factors: the limiting factors of the future use, factor of running costs in the future phase of the building service life, and the factor of increase of investment due to the requirement of preservation of the original building properties.

Protection methods and conversion of the building must be in full agreement. A certain degree of tolerance which is normal in construction of new buildings cannot be implemented when it comes to the works on the listed historical monuments. For this reason, the future user wants to know whether all the requirements will be successfully met, while keeping the investment in the process at the lowest possible level in order to maximize the profit margin.

This process, through which the issues of function and potential of contemporary listed cultural monuments must be solved, is a fully fledged *revitalization*, "bringing back to life".

3.4 Definition of the built heritage according to the Swiss legislation

The built heritage is the heritage which is not only important for a part of Swiss territory, or belongs to koje je vlasništvo pojedinca, već je bitno za opšte i javno dobro celokupnog društva u celini. Ono se identifikuje, proučava i prenosi na buduće generacije tako što se beleži, evidentira, štiti i ostavlja za dobrobit celokupnom švajcarskom društvu i celom svetu.

Graditeljsko nasleđe odražava regionalnost, različite tipove građevina i tradicije uopšte. Ono može da obuhvata: od farme do velikog grada, nadogradnju, komercijalne industrijske komplekse, radnička naselja, zamkove, kao i arheološka nalazišta. Spomenici kulture nisu samo arhitektonski objekti iznad prosečnog kvaliteta, već to mogu biti i jednostavni, ali za društvo važni istorijski subjekti koji doprinose uravnoteženju današnje slike gradova. Graditeljsko nasleđe podrazumeva sve što je u prošlosti sagrađeno, a ima spomeničke vrednosti. Sve što je proglašeno graditeljskim nasleđem mora biti zaštićeno, a ako je zaštićeno, onda ***mora*** biti ***sačuvano***.[21]

individuals, but is important public and general resource of the entire society. It is identified, studied and passed on to the future generations, by being recorded, listed and left to the benefit of the entire Swiss society and the world.

The built heritage reflects regional traits, various types of buildings and tradition in general. It can include: farms and big cities, extended buildings, commercial industrial complexes, working people districts, castles and archeological sites. The cultural monuments are not only exceptional quality architecture, but those can be simple, but socially important historical subjects which characterize and contribute to the balancing of the contemporary image of the cities. The built heritage comprises everything built in the past, possessing the monumental value. Every item declared building heritage must be listed, and if listed, it ***must*** be ***preserved***. [21]

4 FAKTORI KOJI UTIČU NA PROCES REVITALIZACIJE

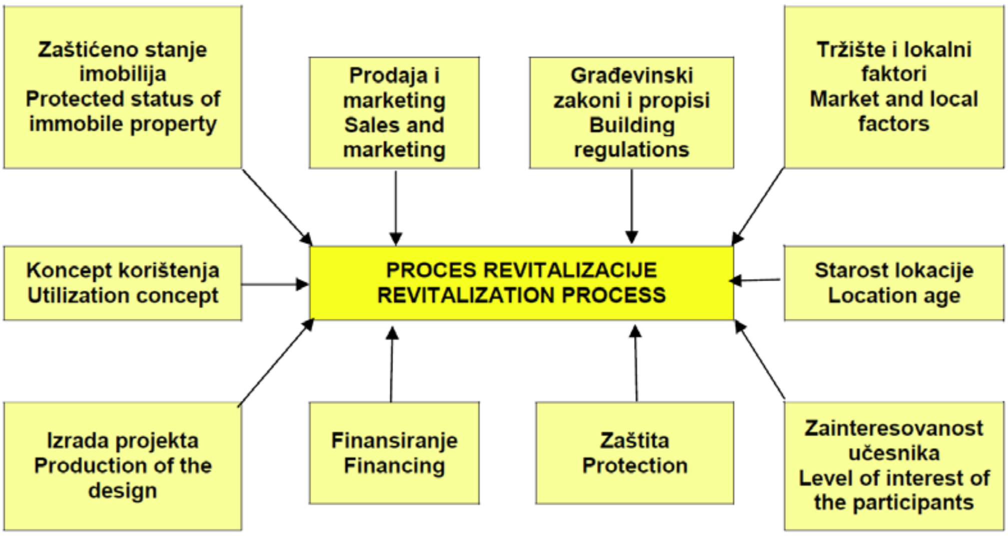
Revitalizacija nekorišćenih istorijskih spomenika jeste proces u koji je uključeno nekoliko odlučujućih faktora. Ti faktori su konstante i utiču na pojedine faze revitalizacije. Sama revitalizacija nije jednoznačno određena, pošto se spomenici kulture razlikuju po svojim karakteristikama i lokacijama. Ipak, mogu se postaviti određene smernice – kao svojevrsni akcioni vodič koji se, potom, prilagođava pojedinačnim slučajevima.

Faktori koji utiču na proces revitalizacije nekorišćenih, odnosno napuštenih, spomenika kulture i njihove međusobne veze prikazani su na Shemi 1.

4 FACTORS INFLUENCING THE PROCESS OF REVITALIZATION

Revitalization of disused historical monuments is a process which includes several decisive factors. Those factors are constantly present and they affect individual phases of revitalization. The process itself is not universal, since the cultural monuments differ in terms of their characteristics and locations. Yet, certain guidelines can be provided as certain action guide, which is, subsequently adapted to the individual cases.

The factors affecting the revitalization process of unused, i.e. abandoned cultural monuments and their mutual relations are displayed in Scheme 1.

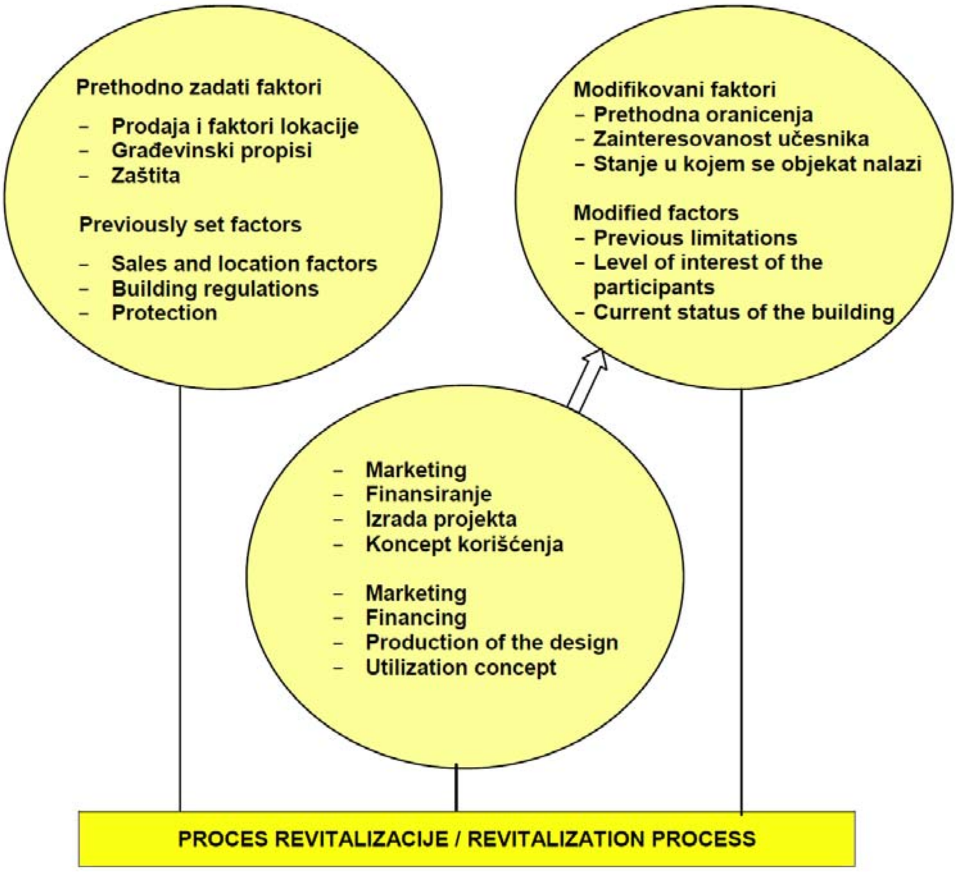


Shema 1. Faktori koji utiču na proces revitalizacije
Scheme 1. Factors influencing the revitalization process

Faktori, osim što su stalno prisutni, pomažu i u pojedinačnim fazama rada. Zbog toga se veze između faktora na grafikonu mogu koristiti kao preporuka prilikom praktičnog rada. Neke faktore, do određenog stepena, mogu kontrolisati razni učesnici. Pojedini, međutim, moraju se usvojiti takvi kakvi jesu. To su,

The factors, apart from being ever present, help in the individual work phases. For that reason, the relations between the factors in the chart can be used as a recommendation in the practical work. Some factors can be controlled to a certain degree by the various participants. Some of them, however, should be adopted uglavnom, faktori tržišta i lokacije. Na druge faktore, kao, na primer, postojeće stanje nekretnina, može se uticati. Pri revitalizaciji, mora se voditi računa o vodećim tačkama u procesu i ograničenjima koje treba poštovati. Shema 2. prikazuje preporuke, u obliku akcionog plana, koje značajno unapređuju kvalitet revitalizacije.

as they are. Those are, prevalently, the market and location factors. The other factors, such as, for instance, the current status of the real estates, can be affected. While performing revitalization, one should take care about the major points of the process and of the limitations to be observed. The following scheme displays the recommendations, in the form of an action plan, which considerably improves the revitalization process quality.



Shema 2. Preporuke za uspešan proces revitalizacije [21]
Scheme 2. Recommendations of successful revitalization process [21]

Akcioni plan prvenstveno uključuje aktivne dizajnerske faktore. Za održivost projekta bitna je ujednačenost svih faktora koji najviše utiču na revitalizaciju. Zbog toga je veoma važno prepoznavanje i pronalaženje novih ideja prilikom dodeljivanja nove namene objekata.

4.1 Interesi u procesu revitalizacije i akcionari

Analiza moguće namene praznih, napuštenih istorijskih građevina jedna je od najvažnijih faza revitalizacije.

Početak izrade projektnog plana zasniva se na pretpostavkama da se u procesu revitalizacije originalna, izvorna namena i struktura zgrade mogu donekle izmeniti, u zavisnosti od njene procenjene istorijske, estetske, arhitektonske i konstruktivne, te društvene vrednosti. Kada se utvrdi taj obim mogućih izmena, nadalje o tim ograničenjima nadležnost preuzima menadžer objekta. U zavisnosti od veličine građevine i razloga za njenu

The action plan primarily involves the active designing factors. The project sustainability requires balance and uniformity of all the factures which mostly affect the process. For that reason, recognition and finding new ideas when converting the buildings is very important.

4.1 Diverse interests in the revitalization process and shareholders

An analysis of the potential use of the empty, abandoned historical buildings is one of the most important phases of revitalization.

The onset of production of the project plan is based on the assumptions that in the revitalization process, the original function and structure of the building can be changed to a certain degree, depending on its assessed historical, esthetic, architectonic and structural, as well as social value. When the scope of potential changes revitalizaciju, cilj revitalizacije može se ostvariti uz pomoć specijalizovanog graditelja ili arhitekte, ukoliko je reč o manjim objektima. Preporuke i sugestije za formiranje veza u različitim razvojnim fazama revitalizacije prikazane su na Shemi 3.

Revitalizacija se u ovoj shemi definiše kao deo koncepta, ali deo koji se odnosi na neiskorišćenost same građevine može biti dodatno od pomoći.

Uglavnom, cilj je da se izradi analiza namene i da se koordiniraju akcionari, odnosno deoničari koji učestvuju u revitalizaciji. Namera zainteresovanih strana jeste da se projekat izloži njihovim pretpostavljenima, menadžerima projekta ili planerima. Primena ove analize omogućava pokretanja projekta.

Interes vlasnika napuštenog, praznog objekta, jeste da ga što bolje proda, odnosno, ukoliko ga zadrži u svom vlasništvu, da ga iznajmi na što duži period.

Interes izvođača radova i investitora jeste sticanje profita, što projektom revitalizacije, odnosno uvođenjem nove, odgovarajuće namene, može da se ostvari. U izboru odgovarajuće, najprimerenije namene mogu da učestvuju sve zainteresovane strane. Prilikom izbora, mora se voditi računa o tome da se ostvari harmonija između postojećih karakteristika objekta koje čine njegovu vrednost, i zahteva koje postavlja buduća namena objekta.

Dobro poznavanje prednosti revitalizacije leži u prethodnom poznavanju dve vrste parametara - onih kojima se određuju dodatni poslovi i onih u pogledu ograničenja usled zaštićenih vrednosti građevine, koji mogu biti preovlađujući faktor pri odluci da se investira u projekat revitalizacije.

Za korisnike objekta važno je da znaju koja su ograničenja objekta prilikom odabira buduće namene. Ograničenja koja utiču na novu namenu korisnicima saopštava menadžer objekta. Prethodno, on može da koristi analize o nameni i strategijskom planiranju, te da to uključi u planiranje, koje obuhvata i strategijsko upravljanje objektom. Za arhitektu-konzervatora, koji je predstavnik javnog interesa, glavna prednost koju ima od analiza jeste to što, pomoću njih, minimalizuje gubitke, zbog različitih svojstava istorijske zgrade, tokom prilagođavanja objekta budućoj nameni.

has been determined, in the further process the manager of the building is competent for these limitations. Depending on the size of the building, and reasons for its revitalization, the goal of the revitalization can be achieved with the aid of the specialized builder or architect, if small size buildings are concerned. The recommendations and suggestions for formation of relations in various phases of revitalization development are displayed in scheme 3.

Revitalization is in this scheme defined as a part of the concept, but the part referring to the unused capacity of the building itself can be of additional help.

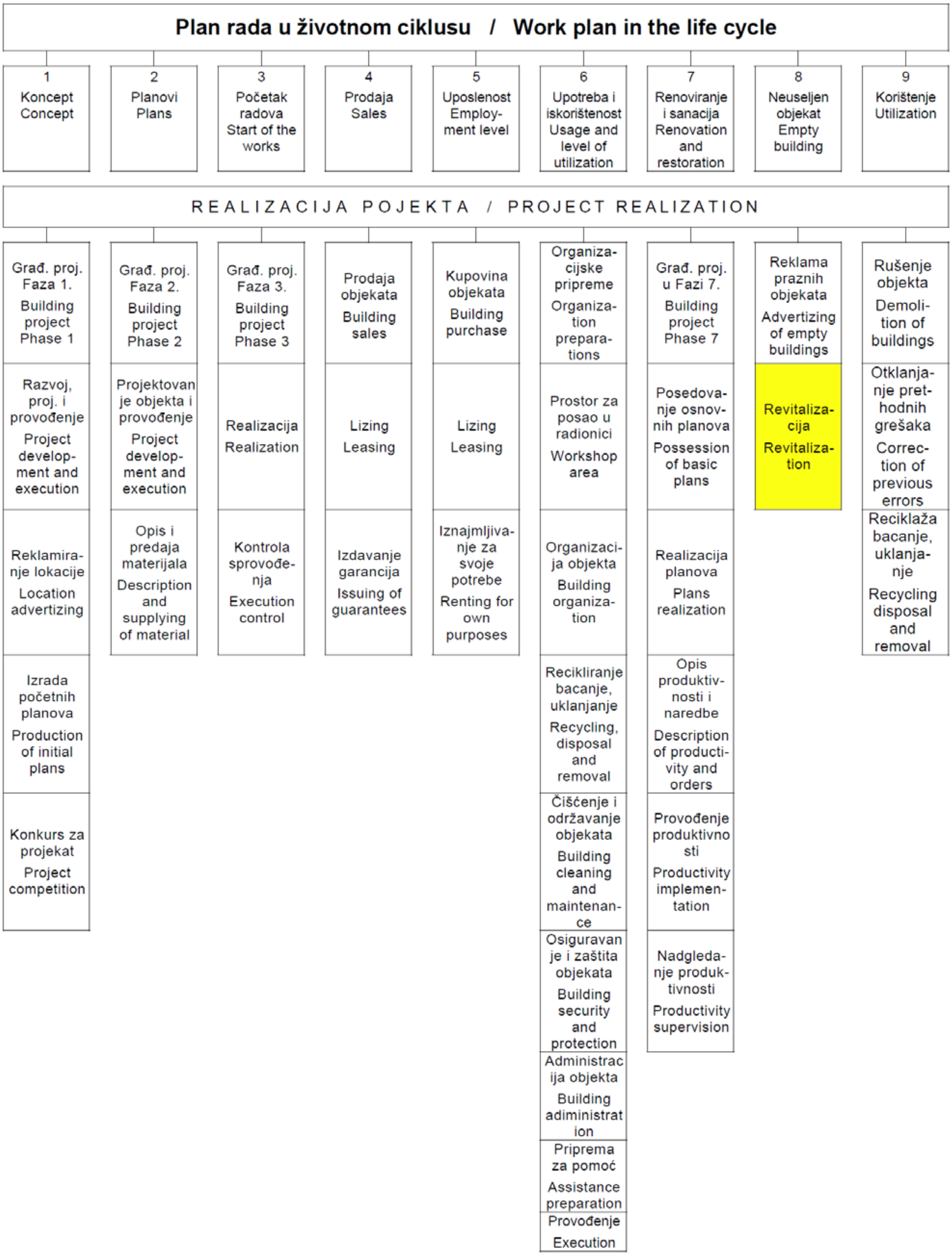
The goal is, prevalently, to make an analysis of the use, and coordinate the shareholders taking part in the revitalization. The intention of the stakeholders is to display the project to their superiors, project managers or planners. The application of this analysis makes it possible to start the project.

The interest of the owner of an abandoned, i.e. empty building is to sell it with the best profit, or, if the ownership over the building is retained, to attempt to rent it for as long period as possible.

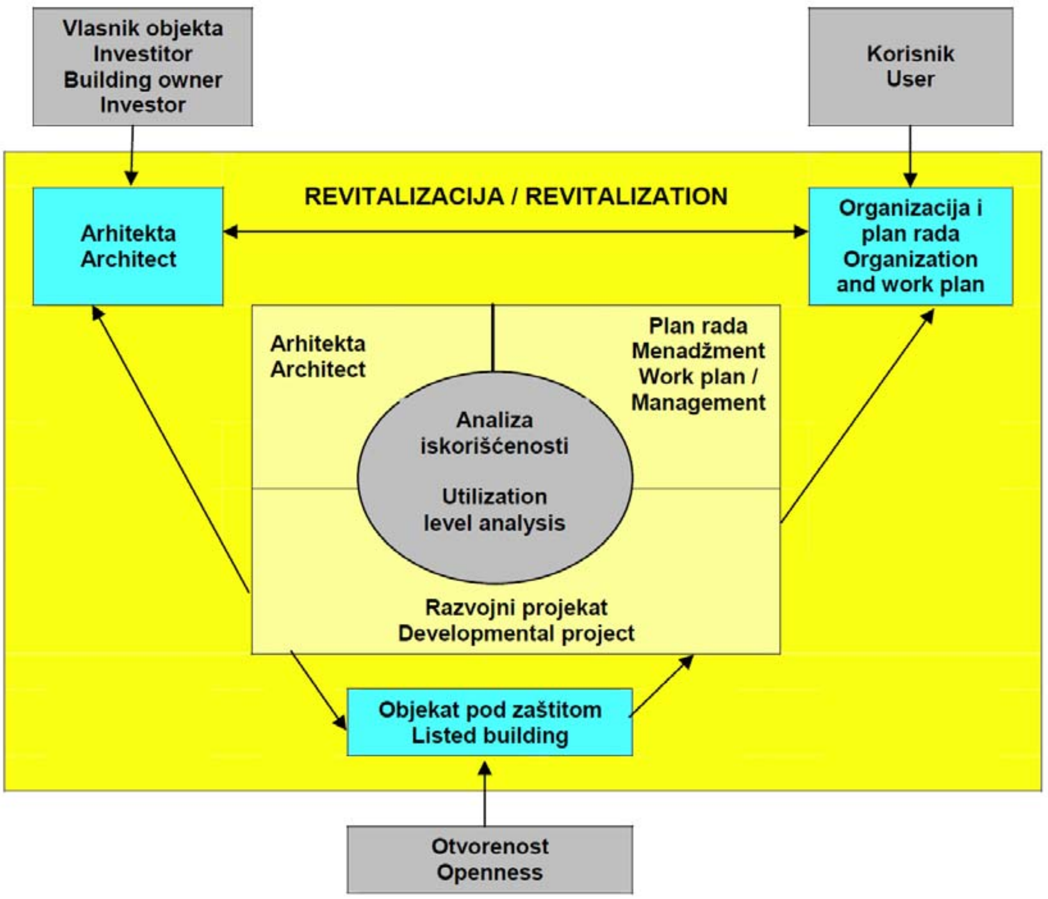
The interest of the contractor and investor is to make profit, which can be achieved through the revitalization project, i.e. through introduction of a new, appropriate use. All the stakeholders can participate in the choice of the most appropriate use. When making a choice one should take care to create harmony between the current characteristics of the building, which constitute its value, on one hand, and the requirements posed by the future use of the building, on the other hand.

Good knowledge of the advantages of revitalization comprises previous knowledge of two types of parameters, one type determining the additional works, and the other related to the limitations due to the protected values of the building, which can be a prevailing factor when making a decision to invest in the revitalization project.

When choosing the future use, it is important for the users of the building to know what the limitations of the building are. The users are informed about the limitations affecting the new use from the building manager. He can previously utilize the analyses of the use and strategic planning, and include it in the planning process, which comprises the strategic management of the building. For and architect-conservationist, who represents the public interest, the main advantage of the analyses is that, using them, he can minimize the losses related to the various properties of the historical buildings, in the process of adapting the building to the future use.



Shema 3. Linearna shema plana rada u ciklusima revitalizacije, sa životnim fazama (FM-Facility Manangement sa glavnim procesima) [21]
Sheme 3. Linear diagram of the working plan in the revitalization cycles, with life stages (FM-Facility Management with the main processes) [21]



Shema 4. Učesnici u procesu revitalizacije i njihove veze [21]
Sheme 4. Participants in the revitalization process and their relations [21]

4.2 Promene na tržištu – ponovno otkrivanje istorijskih vrednosti objekata – odnos korisnika i investitora

Na tržištu nekretnina, rokovi za izradu projekata veoma su kratki i nikada nema dovoljno vremena da se o njima ozbiljno promisli. Umesto „proizvoda – (rezultata) razmišljanja" [4] na početku revitalizacije na gradilištima nisu postojali nikakvi istaknuti podaci kojima se, atraktivnim reklamama, privlače potencijalni korisnici, odnosno investitori.

Tradicionalno *teški* faktori, koji se, po pravilu, povezuju s lokacijom, odnosno s dobiti uslovljenom infrastrukturom, bili bi pod znakom pitanja, a formulisanje novih *mekih* kriterijuma lokacije, na prvi pogled, manje atraktivnih, bili bi u drugim slučajevima zanemareni."[4]

<u>Osnovni principi kojima se rukovode</u> moderni građevinski projekt jesu veća orijentacija prema korisnicima (tržišna orijentacija), te veća osetljivost u pogledu situacije (orijentacija prema okruženju). [4] Kada su zaštićene zgrade u pitanju, one imaju koristi od ovih principa, jer se, u njihovom slučaju, primenjuju *mekani* faktori.

U „Spomeničkoj studiji Berna" izneti su podaci ankete u kojoj su korisnici i investitori ispitani o njihovom

4.2 Changes in the market – rediscovery of the historical values of the buildings – relations of the users and investors

In the real estate market, the deadlines for production of projects are very short, and there is never sufficient time to dwell upon them. Instead of "the product – (result) of deep thinking" at the beginning of revitalization, there were no displayed data on the construction sites, which could, as an attractive advertisement, attract potential users, i.e. investors.

„The traditional *heavy* factors, which are, as a rule, related to the location, that is, to the profits related to the infrastructure, would be questioned, and formulation of new *soft* criteria of the location, which are, at first sight, less attractive, would be neglected."[4]

The basic principles of contemporary construction projects are increased orientation towards the users (market oriented projects), and an increased sensitivity in respect to the situation (environment oriented projects). [4] When the listed buildings are concerned, they can benefit from these principles, since in their case, the *soft* factors are implemented.

In "The Monumental study of Bern" the data from the survey in which the users and the investors were questioned about their experience in revitalization and the iskustvu s revitalizacijom i izborom novih namena zaštićenih objekata obuhvaćenih ovom studijom.[9]

Prednosti i koristi istorijskih zgrada, koje su bile navedene u tom istraživanju, jesu sledeće:

- prednost lokacije: istorijske zgrade obično su smeštene u samom centru grada;
- istorijske zgrade se stalno održavaju;
- kvalitet opremljenosti objekata infrastrukturom;
- dobra ocena servisnih usluga, kuhinja i sanitarnih prostorija;
- prirodna ventilacija;
- atraktivnost okruženja.

Nedostaci, zabeleženi u ovom istraživanju, jesu:

- nedovoljna fleksibilnost namene: previše zaštitnih ograničenja u prostornoj organizaciji i procesu korišćenja;
- upotreba samo određenih, odabranih materijala, koji su pogodni za okruženje;
- nedovoljno prirodno osvetljenje.

Podatak koji je iznenađujuć jeste težnja da se ostvari više kancelarijskog prostora po zaposlenom radniku. „Na kraju ankete, preko 21% ispitanika ocenilo je da je prostor u istorijskim zgradama previše skučen, kada se poredi s prosečnim standardom, u odnosu na savremeni prostor od 17.2 m^2 po zaposlenom (napomena autora). Ipak, uopšteno posmatrano, u rezultatima ankete naslućuje se da kompanije sa uvažavanjem procenjuju situaciju i ostavljaju više prostora pojedinačnim radnicima."[9] Ove promene počele su da utiču na upravljanje prostorom kada je reč o zaštićenim zgradama. Konstatovano je da vrednost spoljašnjeg i unutrašnjeg izgleda zgrade, kao i zadovoljstvo zaposlenih njihovim radnim prostorom, utiču više nego čistoekonomska efikasnost.

Uz pozitivnu procenu zadovoljstva zaposlenih, ide i podatak da ljudi provode u ovim objektima više od šest godina na radnom mestu. U nastavku ove analize, kao ostali *mekani* faktori koji su bili pozitivno ocenjeni, jesu:

- izgled građevine;
- istorijska arhitektura;
- prepoznatljivost zgrade u okruženju;
- poboljšanje radne atmosfere;
- moderan ukus;
- poznata, prepoznatljiva adresa;
- korporativna arhitektura: identitet vlasnika (kompanije, na primer) povezuje se s prepoznatljivim spoljašnjim izgledom zgrade.

Za stanove, na primer, koji se nalaze u prepoznatljivim, istorijskim objektima može se odrediti i dobiti viša stanarina, jer su takvi objekti atraktivniji kao investicija. Ipak, zakonski, istorijske građevine mogu biti teret za klijenta, odnosno vlasnika, jer i pored navedenih pozitivnih ocena, mogu i dalje postojati zahtevi da se takve zgrade održavaju na specifičan način, kao i to što su propisane obavezne redovne popravke.[7] Uslovi preventivne zaštite mogu, takođe, biti povezani sa značajnim ograničenjima kojih se korisnik mora pridržavati.

Preventivna zaštita obuhvata:

1. *Fleksibilnost*: Istorijski objekat ima ograničenja u prostornoj organizaciji. To, međutim, uglavnom ne utiče na većinu korisnika. Može se zapaziti da postoji sukob između ukupnog zahteva za fleksibilnošću i pojedinačne procene fleksibilnosti prostora u zaštićenim objektima.

choice of new uses of the listed buildings which were included in the study were published. [9]

Advantages and uses of the historical building which were listed in that research are as follows:

- Advantage of the location: historical buildings are usually located in the centers of the cities;
- Historical buildings are continuously maintained;
- The buildings are well-equipped in terms of infrastructure;
- Good assessment of services, kitchens and sanitary facilities;
- Natural ventilation;
- Attractive environment.

The deficiencies, recorded in this research, are:

- Insufficient flexibility of use: too many protective limitations in the spatial organization and process of usage;
- The use of certain, selected materials which are fitting for the environment;
- Insufficient natural lighting.

A surprising piece of data is the tendency to provide additional office area per an employee. „Eventually, the survey showed that over 21% of the questioned people evaluated that the space in the historical buildings is excessively cramped, in comparison to the average contemporary standard of 17.2 m^2 per an employee, (author's note). Yet, in general terms, the survey results suggest that the companies appreciate the situation and leave additional space for individual employees."[9] These changes started to affect the space management when it comes to the listed buildings. It is concluded that the value of the external and internal appearance of the building, as well as the satisfaction of the employees with their working space, have more impact that the purely material efficiency.

The positive assessment of the employees' satisfaction is accompanied by the data that people spend more than six years working in these buildings. Further in the analysis, the other positively assessed *soft* factors were:

- Appearance;
- Historical architecture;
- Recognizability of the building in its environment;
- Improvement of the working atmosphere;
- Modern taste;
- Known, recognizable address;
- Corporate architecture: owner's identity (company, for instance) is related to the recognizable external appearance of the building.

For instance, the flats located in the recognizable, historical buildings, can be rented at a higher cost since such buildings are more attractive as an investment. Yet, in legal terms, the historical buildings may be a burden for the client, i.e. owner, because apart from the mentioned positive assessments, there can still exist requirements to maintain the buildings in a specific way, and to repair the building in regular and prescribed intervals. [7] The preventive protection conditions can also be related to considerable limitations which should be adhered to by the user.

Preventive protection comprises:

1. *Flexibility*: A historical building has limitations in spatial organization. This, however, does not affect the

Ispitivanje istorijskih zgrada u Bernu pokazuje da, bez obzira na to ograničenje, postoji specifično interesovanje korisnika za spomeničke nekretnine.[9]

2. *Upravljanje energijom*: Popravka i osavremenjavanje izolacije u spoljašnjim zidovima istorijskih zgrada nisu tako jednostavni kao kod ostalih zgrada, zato što se tim intervencijama često ne može izbeći promena izgleda zgrade.

4.3 Vrednosti spomenika kulture – različiti stavovi u javnosti

Cilj preventivne zaštite jeste da se zaštite istorijski važne zgrade u interesu javnosti: „Preventivna zaštita i konzervacija imaju zadatak da zaštite kulturne spomenike, da ih održavaju i nadgledaju njihovo stanje, a naročito da sprečavaju nedozvoljene radnje, promovišu otkrivanje kulturnih spomenika, te da ih registruju i stručno ispituju."[11]

Kulturni spomenici smatraju se „vrednim poklonom" zbog njihovog dugoročnog postojanja, a njihovo vrednovanje izražava se kulturnim poštovanjem.[15] Javni interes za konzervaciju graditeljskog nasleđa, u formi zaštitnih zakona, ima prednost ispred interesa nad vlasništvom. Zbog toga su spomenici kulture uvek u centru sukoba interesa javnosti i investitora koji žele profit. Da bi se ta dva interesa harmonizovala, treba da se uoči razlika između – „praktične koristi koju spomenik kulture ima sam po sebi i prisutne vrednosti spomenika", kao i „duhovne vrednosti koja je vezana za prošlost zgrade".[6]

Praktična korist i duhovna vrednost odražavaju se na ukupnu vrednost koja se može pripisati spomeniku:[8]

- Korisnost zavisi od željenih ciljeva. Tržišna vrednost odnosi se na trenutnu korisnost koja se može samo delimično uočiti kod istorijskih objekata. Razvojne vrednosti predstavljaju polazište, a ugrađene su u trenutne i buduće zahteve. Iz ekonomskig aspekta, korisnost je subjektivna vrednost, odnosno, za zgrade je korisno da nastave da postoje kao fizička struktura. Ovo se razlikuje od tržišne vrednosti, a rezultira od prodaje vlasništva u zavisnosti od „vrednosti koja je obavezujuća za sve".[12]
- Istorijska vrednost strukture zgrade smatra se objektivnim istorijskim dokumentom i povezana je s materijalnim postojanjem strukture.
- Vrednost sećanja ukazuje na interes javnosti za prošlost, što je povezano sa istorijskim objektom. Ukoliko je reč samo o sentimentalnoj vrednosti, to često može usmeriti radove ka rekonstrukciji, čime se samo delimični delovi istorije „vraćaju nazad u život".
- Vrednost predstavlja i različitost istorijskih struktura u poređenju sa sadašnjim formama. Iskustvom koje se povezuje sa istorijskim zgradama, istorija postaje bliža ljudima. Zbog toga je javni interes veoma izražen.

Svaka građevina ima određenu strukturu, koja se manifestuje putem: funkcije, forme, materijala i konstrukcije.

most of the users. It can be seen that there is a conflict between the overall requirement for flexibility and individual assessments of the flexibility of space in the listed buildings. The examination of the historical buildings in Bern indicates that, regardless of the limitations, there is a specific interest of the users for the monumental property.[9]

2. *Energy management*: Repair and updating of insulation in the external walls of the historical buildings is not as simple as in the case of other buildings, because this intervention often changes the external appearance of the buildings.

4.3 The value of historical monuments – various attitudes of the public

The goal of preventive protection is to list the historically important buildings, in the best interest of the public: „Preventive protection and conservation have a task to protect the cultural monuments, to maintain them and monitor their status, and in particular to prevent the unsanctioned alterations, to promote the discovery of cultural monuments, to register them and examine them in a professional way."[11]

Cultural monuments are considered a "valuable gift" because of their longevity, and they are valued through the cultural respect for them. [15] The public interest for conservation of the built heritage, in the form of protective legislation takes precedence over the ownership interest. For that reason the cultural monuments are always in the focus of the public interest and the profit seeking investors. In order to harmonize these two interests, one must differ between – "the practical use the monument itself possesses, and the inherent value of the monument" as well as "the spiritual value related to the building's past". [6]

The practical utility and spiritual value are reflected in the total value which can be ascribed to the monument. [8]

- Utility depends on the desired goals. The market value refers to the current utility which can be only partially recognized in historical buildings. The developmental values represent a starting point, and they are a part of the current and future requirements. In economical perspective, utility is a subjective parameter, that is, it is useful for the building to continue to exist as a physical structure. This differs from the market value and it is a result of the sale of the property depending on the "obligatory value".[12]
- The historical value of the building is considered an objective historical document and it is related to the material existence of the structure.
- The value of the memory indicates the public interest for the past, which is related to the historical building. If it is only a sentimental value, this can often direct the reconstruction works, which bring back to life only certain parts of history.
- The value is also constituted in the diversity of historical structures in comparison with the contemporary forms. People become more intimate with the history through the experience of the historical buildings. For this reason the public interest is very pronounced.

Materijali i konstrukcija ukazuju na to kako je zgrada građena i na vreme u kojem je građena. Ovo se odnosi kako na celokupni objekat, tako i na njegove pojedinačne komponente. Funkcija određuje praktičnu vrednost objekta, odnosno njegovu moguću savremenu upotrebljivost. Ovakav pristup dovodi nas do teze da procesi na građevini, ukoliko se promišljeno sprovode, odnosno ukoliko se pravilno sagleda i vrednuje prilagodljivost oblika, konstrukcije, materijala i prostorne organizacije, do mere koja ne ugrožava spomeničku vrednost, mogu da generišu novu namenu i nastavak života devastirane građevine.

4.4 Korisne namene zaštićenih objekata

Odnos između investitora i konzervatora uvek je bio zategnut, kada se imaju u vidu i vrednosti nekretnina i spomenička vrednost kulturnog nasleđa. S jedne strane, subjektivni stavovi investitora koji žele da imaju visok povraćaj profita, a s druge strane održavanje istorijske vrednosti spomenika kulture – stalno su u sukobu. Najčešći sukobi oko očuvanja spomenika kulture jesu, na primer:[10]

- Kratkoročni ekonomski modeli, koji nisu zasnovani na principima spomeničke korisnosti, nisu pogodni za očuvanje istorijskih zgrada (brz profit na uložene investicije korišćenjem vlasništva);
- Zakoni i standardi zasnovani su na principima izgradnje i eksploatacije novih, savremenih zgrada. Kada su spomenici kulture u pitanju, mnogi od zakona i standarda ne mogu da se slede da se ne bi prouzrokovala šteta u procesu rehabilitacije spomenika;
- Preobimno korišćenje zgrade, kada se, na primer, preterano preoblikuje potkrovlje, često značajno narušava originalnost objekta.

Jedino interesi korisnika istorijskih objekata mogu da dovedu do promene u tržištu nekretnina. Švajcarske publikacije kao što su „Spomenik kao vlasništvo” [9] ili „Spomenik kao investicija”[1] ukazuju na sporo usklađivanje i povezivanje upotrebe spomenika kulture kao nekretnine i njegovog istorijskog očuvanja. Da bi se naglasio značaj istorijskog spomenika, koji ne treba posmatrati kao praznu školjku, sada je uveden izraz „upravljanje istorijskim spomenicima”. Pored toga, treba imati stalno na umu da vrednost spomenika kulture nije samo u njegovom spoljašnjem izgledu, što ponekad zanemaruju i stručnjaci koji se neposredno bave zaštitom kulturne baštine.[10]

4.5 Mogućnosti i rizici revitalizacije istorijskih zgrada

Na osnovu iznetog, može se zaključiti da korisnici i investitori, ipak, pozitivno prihvataju korišćenje istorijskih, zaštićenih, građevina. U daljem razvoju projekta revitalizacije, međutim, postoje određeni rizici. Na primer:[3]

- Lokacije istorijskih objekata dobro su dokumentovane i određene, ali skupa infrastruktura, koja

Every building has a certain structure, manifested through: function, form, material and structure.

Materials and structure reflect the building process of the time in which it was built. This refers both to the entire buildings and its individual components. Function determines the practical value of the building, that is, its potential contemporary serviceability. Such approach promotes a thesis that the processes on the building can generate a new use and continuation of life of a dilapidated building, if it is conducted in a well-conceived manner, i.e. if the adaptability of forms, structure, materials and spatial organization is appropriately considered and valued, so as not to endanger the monumental value.

4.4 Practical uses of listed buildings

There has always been a tense relationship between the investors and conservationists when the ratio of the property value and monumental value of the cultural heritage is considered. Subjective attitudes of the investors who want to have a high profit return on one hand, and conservation of the historical value of the cultural monument, on the other, are in permanent conflict. The most common conflicts regarding the preservation of cultural monuments are, for instance: [10]

- Short term economical models which are not based on the principles of monumental utility, are not suitable for preservation of historical buildings (fast profit from the invested finances, through utilization of ownership);
- The laws and standards are based on the principles of construction and usage of new, contemporary buildings. When this concerns the cultural monuments, many of the laws and standards cannot be observed since they will cause damage in the process of monument rehabilitation;
- Excessive usage of the building, for example, when the attic is excessively altered often causes considerable loss of building originality.

Only the interests of the users of historical buildings can bring about change in the real estate market. The Swiss publications, such a “Monuments as a property” [9] or „Monument as an investment” [1] indicate a slow harmonization and linking of the cultural monument use, as an immobile property, with its historical preservation. In order to emphasize the importance of the historical movement, which should not be viewed as an empty shell, the term “historical monument management” has been introduced. After that, one should constantly bear in mind that the value of the cultural monuments is not in their external appearance, which is at times overseen even by the professional engaging directly in the cultural heritage protection. [10]

4.5 Potential and risks of historical building revitalization

On the basis of the discussion, one can conclude that, usage of historical, listed buildings has been positively accepted by the users and investors. In the further development of revitalization project, however, there are certain risks, such as, for instance: [3]

- Locations of historical buildings are well documented and determined, but the expensive nedostaje, može značajno da utiče na ove projekte;

- Spomenici kulture već imaju stvorenu pozitivnu sliku, što je polazište u službi tržišta, ali preterano ambiciozna promena namene može da izazove određenu odbojnost;
- Spomenici kulture, po pravilu, smešteni su na istaknutim gradskim lokacijama i to doprinosi ogromnom potencijalu vrednosti, koja se neadekvatnom namenom može degradirati;
- Zbog istaknute lokacije, a na osnovu istraživanja koja se prave pri planiranju gradskih prostora, unapred je poznat broj korisnika i prolaznika koji će registrovati objekat, a neatraktivna namena tu privlačnost može da negira;
- Tržište, konkurenti i njihovi odnosi mogu da se prognoziraju, ali su delikatni i uvek postoje faktori iznenađenja.

Postojanje strategije i planova zaštite za istorijska područja, kao i pojedinačne zgrade, omogućava razmatranje ponuđenih namena za određene prostore istorijskog objekta, koje mogu da pokrenu revitalizaciju i više slobodnih, napuštenih ili loše korišćenih objekata, koji nisu do sada razmatrani zbog uvreženih osećanja nepromenjivosti zaštićenih objekata kao i raznih pravila u vezi sa istorijskim zgradama. Iako su zahtevi prilikom revitalizacije zaštićenih objekata veoma visoki, za razliku od projektovanja nove gradnje, ovaj proces je moguće sprovesti i na taj način sačuvati istorijsku građevinu i omogućiti joj dalji život prilagođen savremenim uslovima. Tokom revitalizacije, međutim, pojavljuje se nekoliko vrsta rizika koji su ovde definisani:[3]

- *Rizik namene*: Korišćenje istorijskih zgrada ograničeno je izborom namene koja zavisi od karakteristika i svojstava samog objekta. Fleksibilnost namene omogućava se namenskim finansiranjem od strane banaka i odgovarajućim zahtevima koje prilikom revitalizacije treba ispuniti. Ovaj rizik bi trebalo da bude sveden na minimum ranim upravljanjem rizicima u procesu revitalizacije.
- *Rizik zgrade:* Rehabilitacija postojećih istorijskih objekata može uvek da neugodno iznenadi i da bude skupa, ukoliko se do detalja ne prouči stanje u kojem se zgrada nalazi. Finansiranje može da bude opterećeno i zagađenim zemljištem, površinskim zagađenjem lokacije i drugim zagađivačima, kao negativnim faktorima koji nisu blagovremeno sagledani. Ukoliko se ovi rizici registruju u početnoj fazi zatečenog stanja, mogu se značajno umanjiti.
- *Tehnički rizik:* Ekonomski život postojećeg istorijskog objekta mora da bude usaglašen sa zahtevima njegove zaštite. Naknadna ograničenja i društveni rizik, kao što je neodgovarajuće isticanje već utvrđenih vrednosti, loš i/ili neodgovarajući izgled nastao tokom novih intervencija, mogu da budu izbegnuti sprovođenjem detaljnih analiza i scenarija u toku projekta.

Postoje, takođe, i drugi opšti rizici koji su povezani s projektom revitalizacije, ali koji postoje i pri projektima savremenih građevina:[19]

- rizik odobravanja projektnog procesa i konačnog rešenja;
- rizik geomehaničkih karakteristika tla;
- finansijski rizik ulaganja u revitalizaciju;
- rizik koštanja projekta i izvođenja radova, usled nepredvidivih aktivnosti;

infrastructure, which is missing, may have a significant impact on these projects;

- The cultural monuments have an already created positive image, which is a starting point serving for the market purposes, but an excessively ambitious conversion can cause a certain repulsion;
- The cultural monuments, are, as a rule, situated on the prominent urban locations, and this contributes to the immense potential of value, which can be degraded through an inadequate use;
- The number of users and passers-by who will notice the buildings due to their prominent locations, and on the basis of the researches created during the planning of urban area is known in advance; an unattractive use can negate this attractiveness;
- The market, competitors and their relations can be predicted, but they are delicate, and there are always possible surprise elements.

The existence of strategy and plans of protection of historical areas, as well of individual buildings, facilitates consideration of the offered uses for certain areas of a historical building, which can trigger revitalization of free, abandoned or poorly used buildings, which have not been taken into consideration because of the deep-seated feelings of unchangeable character of the listed buildings, and because of various regulations related to the historical buildings. Even though the requirements during revitalizations of the listed buildings are very high, as opposed to the design of the new buildings, this process can be accomplished, and in this way a historical building can be preserved and a new life adapted to the contemporary conditions can be provided. During revitalization, there are several types of risk which are defined here: [3]

- *Use risk*: Utilization of historical buildings is limited by the choice of the use which depends on the characteristics and attributes of the building itself. The flexibility of use is facilitated by the targeted financing by the banks and by observing the appropriate requirements which must be met in the course of revitalization. This risk should be reduced to the minimum by the early risks management in the revitalization process.
- *Building risk:* Rehabilitation of the existing historical buildings can always be an unpleasant and expensive surprise, unless the condition of the building is not examined in detail. Financing can be encumbered by the polluted soil, superficial location pollution or other polluters, as well as by other factors which were not observed in good time. If these risks are registered in the initial phase of the analysis of “as is” building condition, they can be considerably reduced.
- *Technical risk:* The economical life of an existing historical building must be harmonized with the requirements for its protection. Subsequent limitations, and social risk, such as the poor and/or inadequate appearance formed in the course of new interventions, can be avoided by implementation of detailed analyses and scenarios during the project.

There are also other general risks related to the revitalization project but which are present in the contemporary buildings projects: [19]

- Risk of approval of the project process and of final design;
- Risk of geomechanical soil characteristics;

• rizik vremena, odnosno prognoziranje trajanja revitalizacije;

• rizik razvoja.

5 ZAKLJUČNA RAZMATRANJA I PREPORUKE

Najvažniji rezultati uspešne revitalizacije, prema ovom švajcarskom istraživanju i iskustvu, jesu sledeći:

− Proces revitalizacije treba proučavati u kontekstu ciklusa životnog veka zaštićenog spomenika kulture. Postojeći koncept revitalizacije proširen je na intenzivno uvođenje novih namena u napuštene istorijske objekte, sa idejom da se ponovno koriste, a ne da se uklanjaju.

− Faktori uticaja određeni su kao privremeni, ali su uključeni u analize koje su dalje razvijane i na osnovu kojih su preporučeni pravci implementacije revitalizacije na zaštićenim spomenicima kulture.

− Rezultati revitalizacije zavise od uvođenja nekoliko analiza, koje nisu uobičajene prilikom ustaljenog procesa obnove istorijskih spomenika kulture. Jedna od takvih analiza jeste <u>analiza korišćenja</u> koja se uključuje u koncept analize celokupne revitalizacije zaštićenih spomenika kulture, a zavisi od istorijske metode vrednovanja spomenika u samom procesu.

Ova analiza osmišljena je da se primeni prvenstveno za nekretnine – spomenike kulture, koji zbog istorijske upotrebe i bez specijalnih prilagođavanja, veoma teško mogu da budu predmet interesovanja potencijalnih korisnika, bilo da je reč o iznajmljivanju ili kupovini, te usled toga sve više propadaju.

− Za istorijske objekte koji zadržavaju svoju *namenu*, na sadašnjem tržištu nekretnina veoma je teško da nađu potencijalnog novog korisnika. *Analiza namene,* naročito za stambene objekte, dosta je skupa. Kao primer može poslužiti bivša Ženska bolnica u Bernu, za čiju zgradu je analizom namene otkriven veliki upotrebni potencijal, pa je prostorna organizacija prilagođena potrebama Univerziteta u Bernu, koji je tako dobio značajno proširenje u neposrednoj blizini već postojećih kapaciteta.

Analiza namene za ovaj primer veoma uspešno je sprovedena u dve faze, sukcesivno izvedene:

Faza 1 obuhvatila je trenutnu mogućnost vlasnika da identifikacijom potencijalne namene objekta cilja na specifičnu grupu mogućih korisnika. Zbog toga je primena marketinga u ovoj fazi izuzetno značajna. Identifikacija buduće namene napuštenih istorijskih građevina jeste sistematski proces, zasnovan na metodi otvorenog pristupa, odnosno kreativnoj metodi *brainstorm*, tokom koje svi zainteresovani sarađuju i razmenjuju ideje. U svojevrsnoj kreativnoj radionici poštuju se neki parametri koji imaju u vidu istorijsku vrednost građevine i delovanje različitih uticaja na objekat. Delovanje ovih parametara mora da bude fleksibilno, to jest da u okviru određenih granica mogu da se prilagođavaju. Moderator mora da omogući učesnicima da stvore realnu sliku o istorijskim karakteristikama objekta (npr. arhitektonskim, konstruktičnim, stilskim). Ovi parametri služe da se zgrada dobro proceni u svojoj ukupnosti i obradi u skladu sa analizama predviđenim u procesu revitalizacije.

• Financial risk of investment in revitalization;

• Project cost and works execution risk, due to the unpredictable activities;

• Risk of time, that is predictions of revitalization duration;

• Development risk

5 CONCLUSION REMARKS AND RECOMMENDATIONS

The most important results of a successful revitalization according to this Swiss research and experience are as follows:

− revitalization process should be studied in the context of the life cycle of a listed cultural monument. The existing concept of revitalization is extended to the intensive introduction of new uses into the abandoned historical buildings, following the idea to use them again, and not to remove them.

− the influence factors are defined as temporary, but involved in the analyses which are further developed and which served as a basis for making the recommendations about directions of implementation of revitalization of the listed cultural monuments.

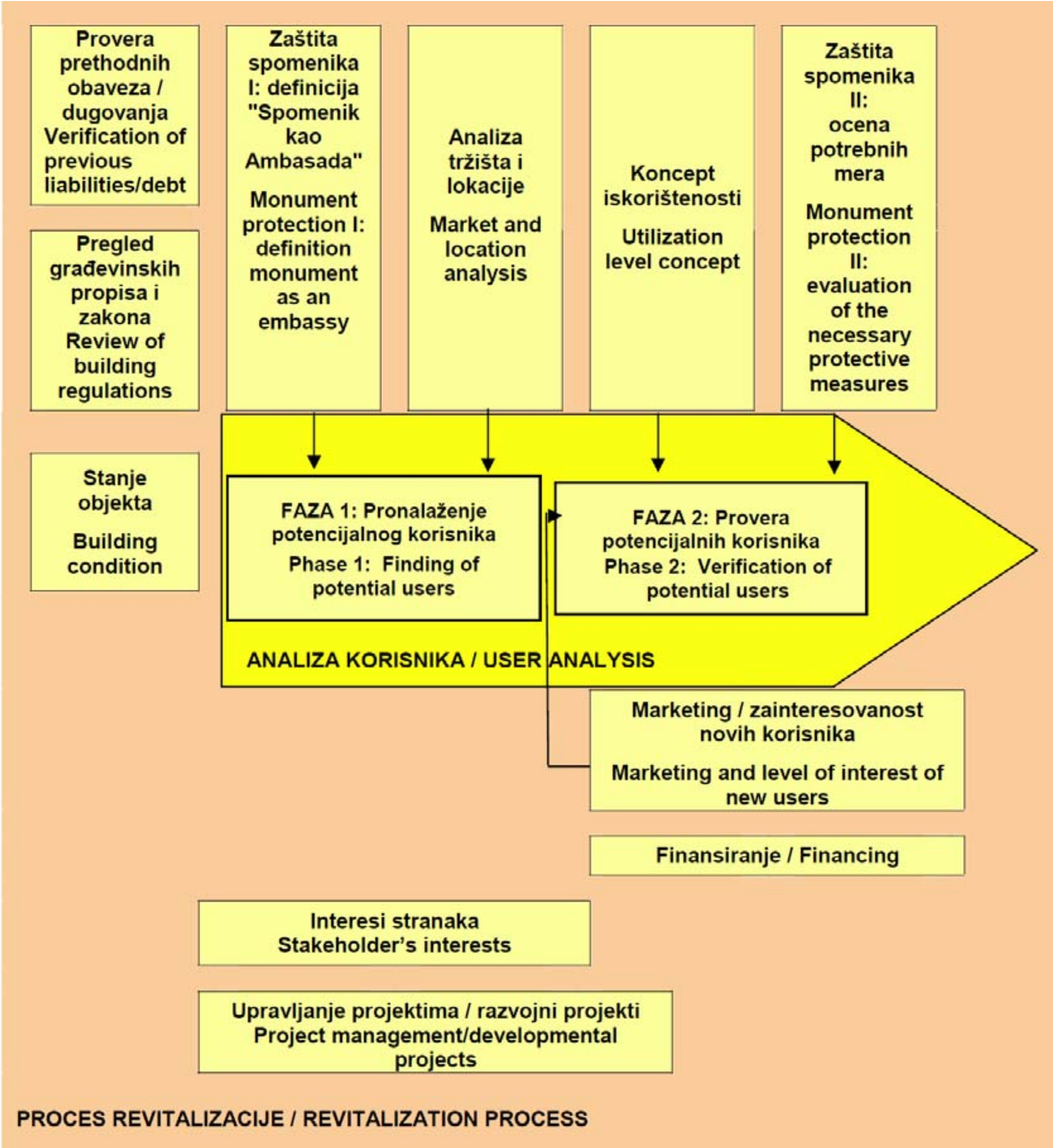
− the revitalization results depend on the introduction of several analyses which are not common in the regular process of revitalization of historical cultural monuments. One of such analyses is the <u>analysis of utilization</u>, which becomes a part of the concept of analysis of entire revitalization of the protected cultural monuments, and which depends on the historical method of assessment of monuments in the process itself.

This analysis is conceived so as to be implemented for the immovable property, historical monuments, which through historical use and without special adaptations can hardly be interesting for potential users, either in terms of renting or purchasing, and which consequently continue to deteriorate further.

− It is very difficult to find a potential new user for the historical buildings which retain their ***use.*** <u>The analysis of use,</u> especially for the housing buildings, is fairly expensive. Such an example is former Women's Hospital of Bern, a building for which the use analysis yielded high potential for utilization, so the spatial organization is adapted according to the needs of the University of Bern, which thus obtained a significant extension in the vicinity of already existing premises.

The analysis of use for this example is very successfully conducted through two phases, which are separately realized:

Phase 1 included the current option of the owner to target the specific group of potential users through identification of potential use of the building. Therefore, the application of marketing in this phase is extremely important. Identification of the future use of derelict historical buildings is a systematic process, based on the open approach method, that is, the *brainstorm* creative method, where all the interested parties cooperate and exchange ideas. Within a creative workshop of kind, some parameters relating to the historical value of the building and action of various impacts on the building are observed. The impact of these parameters must be flexible, that is, they can be adapted within certain limits. A moderator must facilitate creation of a realistic picture



Shema 5. Predloženi pravci delovanja u procesu revitalizacije
Scheme 5. Proposed courses for action in the revitalization process

Faza 2 nadovezuje se na *fazu 1*, ispitivanjem upotrebe objekta prvobitnog i zatečenog stanja i neophodnih mera prilagođavanja. Uspostavlja se veza između postojećih karakteristika zgrade i budućih zahteva korisnika.

Analiza namene ne može da zameni analizu tržišta i gradilišta. Sve tri analize moraju biti sprovedene i veoma su važne pri određivanju nove funcije. Analiza namene je koristan dodatak analizama tržišta i lokacije za tzv. kuće - spomenike kulture. Prenosnom definicijom S*pomenik kao ambasada* (tumači se kao zastupnik vrednosti jednog vremena), mnogi sukobi između službe zaštite, investitora i budućeg korisnika, u pogledu tretmana zaštite spomenika kulture, mogu da se izbegnu. Problem nastaje kada administrativne vlasti koje se bave zaštitom ne žele da ulože dodatni trud da bi opravdale i potvrdile sopstvenu procenu da je objekat vredan spomenik kulture. To je neophodno obaviti da bi se mere kompenzacije mogle utvrditi od strane gradske vlasti, i to

of the historical characteristics (architectonic, structural, style) of the buildings for the participants. These parameters serve to well assess the buildings in their entirety, according to the analyses proscribed in the revitalization process.

Phase 2 is a continuation of *Phase 1* through the investigation of the original and current building uses and the necessary adaptation measures. A connection between the existing building characteristics and future user requirements is established.

The use analysis cannot replace the analysis of the market and construction sites. All three must be conducted, and they are very important in determination of the new function. The use analysis is a valuable addition to the market and location analyses for the so-called "houses as cultural monuments". Using the definition "Monument as an embassy", (shall be construed as representative values of a time) many conflicts between the protection office, investors and future users in terms onog njenog segmenta kojem je primarni cilj zaštita istorijskog jezgra grada. Kompenzacija, na primer, nedovoljnog prostora za novu namenu, može da obuhvati nadogradnju, adaptaciju unutrašnjosti bez većih rušenja pregradnih zidova, korišćenje podrumskog prostora, povećanje iskorišćenosti unutrašnjeg prostora objedinjavanjem u veće prostorne jedinice, izgradnju novog segmenta građevine koji se integriše u postojeći objekat i slično. Povećanje mera kompenzacije praćeno je utvrđivanjem neophodnih troškova koji povećavaju cenu revitalizacije, ali zato čine istorijski objekat atraktivnijim za tržište.

U celokupnom procesu revitalizacije napuštenih, neiskorišćenih, zaštićenih građevina u istorijskom jezgru Berna uočavaju se dva problema koja još nisu dovoljno razrešena. Prvi je nedovoljno jako uporište u naučnom pristupu zaštiti graditeljskog nasleđa, jer je uočljiva subjektivnost individualnih ocena i procena. Pošto su zahtevi korisnika uvek subjektivne prirode, doza arbitrarnosti svakako postoji.

Analiza tržišta na kojem se nalaze i istorijski objekti nije stabilna. Razlog jeste to što je švajcarsko tržište veoma liberalizovano i izuzetno atraktivno zbog velike kupovne moći stanovništva. Bez obzira na to da li je reč o kupovini istorijskog objekta ili samo o njegovom zakupu, mogućnost revitalizacije ili čak i rekonstrukcije, dostupna je kako pojedincima, tako i raznim pravnim licima, na primer, velikim robnim lancima, što najčešće podrazumeva obuhvat nekoliko povezanih istorijskih zgrada i predstavlja složen i zahtevan poduhvat.

Preispitivanje finansijskog opterećenja svih etapa revitalizacije nije bilo predmet ovog rada, s obzirom na to što zavisi od niza faktora, pre svega od veličine samog istorijskog objekata, a zatim i od obima intervencija u procesu revitalizacije.

Ovaj uspešni metod određivanja potencijala za revitalizaciju graditeljskog nasleđa, kao švajcarsko iskustvo, može naći svoju primenu u Srbiji, budući da ekonomska, odnosno tržišna vrednost graditeljskog nasleđa ovde još uvek nije prihvaćena kao osnova velikog potencijala koje nasleđe može da ugradi u razvoj privrede i kulture društva. Da bi se to ostvarilo, pored razvijanja društvene svesti o koristi takvog pristupa, neophodna je i izmena ili dopuna čitavog niza zakona, koji u ovom obliku nisu kompatibilni i ne mogu da podrže navedene aktivnosti. Prvi korak bi trebalo da bude usklađivanje odavno prevaziđenih, zastarelih zakona u pogledu zaštite kulturnih dobara, sa zakonodavstvom Evropske zajednice. Švajcarska država je svoje zakonodavstvo prvo uskladila s međunarodnim zakonodavstvom, pa je tek onda počela da razvija navedenu strategiju revitalizacije.

Najveći izazov s kojim se susreću svi akteri prilikom revitalizacije jeste to da svojim umećem doprinesu da kvalitetno odabrana nova namena, putem kreativno osmišljene ideje revitalizacije, doprinese produženju životnog veka istorijske građevine i da unapredi njene već utvrđene vrednosti.

of treatment of the protection status of the cultural monument can be avoided. The problem occurs when administrative authorities engaged in protection do not wish to put more effort in justifying and confirming their own assessment that a building is a valuable cultural monument. This is necessary to accomplish in order to determine the compensation measures by the city authorities, particularly the segment dealing with the primary goal of protection of historical core of the town. The compensation, for instance, of the insufficient space for the new use can include extension, interior adaptation without demolishing of partition walls, usage of basement space, and increase of utilization of interior space by unifying it into large spatial units, construction a new segment of the building, which is integrated in the existing building etc. The increase of the compensation measures is followed by determination of the necessary costs increasing the revitalization costs, but which render the historical building more attractive for the market.

The entire process of revitalization of abandoned, disused, listed buildings in the historical core of Bern features two problems which have not been properly resolved. The first problem is insufficiently strong scientific foundations of the approach to protection of the building heritage, because there are a lot of individual assessments and evaluations. Since the demands of the users are always subjective in nature, some arbitrariness is surely present.

The analysis of the market which includes historical buildings is unstable. The reason for that is that the Swiss market is much liberalized and extremely attractive because of the high economic power of the population. Regardless of whether a historical building is purchased or rented, the potential for revitalization or even reconstruction is available both to the individuals and various legal entities, for instance large department store chains, which most frequently comprises inclusion of several adjacent historical buildings, and represents a complex and demanding undertaking.

Analysis of the financial load of all the stages of revitalization was not the subject of this paper, considering that it depends on a number of factors, primarily on the size of the historical building itself, and on the scope of interventions in the revitalization process.

Yet, the method of determination of potential for revitalization of historical heritage, as a Swiss experience, can be implemented in Serbia, regarding that the economy, that is, market value of the built heritage has not been accepted locally as basis of a high potential for development of the economy and culture of the society. In order to accomplish that, in addition to the development of the social awareness of the benefits of such approach, it is necessary to change or amend a number of regulations which are not compatible with these goals and cannot support the mentioned activities. The first step should be the harmonization of the Serbian (outdated) legal regulations referring to the protection of the cultural assets with the EU regulations. The Swiss state firstly harmonized their regulations with the international ones, and only then started to develop the mentioned revitalization strategy.

The biggest challenge encountered by all the participants in the revitalization process is how to implement their skill to contribute so that the well-chosen new use can extend the service life of a historical building and improve its existing values through a creatively conceived revitalization.

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REZIME

METODE ODREĐIVANJA POTENCIJALA ZA REVITALIZACIJU GRADITELJSKOG NASLEĐA – POUKE GRADA BERNA

Goran STANIŠIĆ
Nađa KURTOVIĆ FOLIĆ

Srpski konzervatori mogu naučiti mnogo iz primera revitalizacije Starog grada Berna. Analize pokazuju da ovaj primer načina revitalizacije i zaštite napuštenih, nenaseljenih spomenika kulture zavisi od njihovog budućeg korišćenja. Analiza buduće namene nasleđa nije dovoljna da se koristiti kao postupak za njegovu revitalizaciju. Primena novih ideja na osnovu istorijskog značaja zaštićenog objekta generiše njegovu strukturu. Različitim analizama testiran je pristup revitalizaciji putem strukturiranja spomenika kulture i njihovog prilagođavanja za novu namenu. Utvrđeno je da se buduća namena spomenika kulture ne može utvrditi samo definisanjem metoda revitalizacije koji je odredio neki javni organ, već da budući vlasnik zgrade mora aktivno učestvovati u svemu tome. Date su i preporuke za prenos ove metodologije pri rešavanju problema srpskog graditeljskog nasleđa.

Ključne reči: metode revitalizacija, graditeljsko nasledje, ekonomski potencijal, funkcionalna iskorišćenost, grad Bern.

SUMMARY

METHODS FOR DETERMINATION OF REVITALIZATION POTENTIAL OF BUILT HERITAGE – LESSONS LEARNED ON THE CITY OF BERN

Goran STANISIC
Nadja KURTOVIC FOLIC

Serbian conservationists could learn a lot from the revitalization example of the Old city of Bern. Analyses of this example show that the method of revitalization and protection of listed, but abandoned and inhabited, buildings depends on its future use. Alone analyses of future purpose of built heritage cannot be used as a method for its revitalization. The use of new ideas based on historical importance of the protected building generates the building`s structures. The approach of revitalization through the process of building structuring and adaptation to new purpose has been tested through different analyses. It was found that the future purpose of building cannot be determined only by defining the revitalization method, set by public body, but in this process the future owner of building should actively participate. The recommendations for transferring this methodology in solving Serbian built heritage problems are given.

Key words: methods of revitalization, architectural heritage, economic potential, functional utilization, city of Bern.

PRIMENA SLOJEVITIH KONAČNIH ELEMENATA U NUMERIČKOJ ANALIZI LAMINATNIH KOMPOZITNIH I SENDVIČ-PLOČA I LJUSKI S DELAMINACIJAMA

APPLICATION OF LAYERED FINITE ELEMENTS IN THE NUMERICAL ANALYSIS OF LAMINATED COMPOSITE AND SANDWICH STRUCTURES WITH DELAMINATIONS

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1 UVOD

Laminatni kompoziti su moderni materijali koji se široko primenjuju u različitim granama industrije, a najviše u mašinstvu i građevinarstvu. Ovi materijali, kao što su ugljenična vlakna, staklena vlakna ili polimeri ojačani vlaknima, imaju izuzetno visoku čvrstoću i krutost, uz relativnu malu sopstvenu težinu. Na primer, konstrukcije koje se primenjuju u avio i svemirskoj industriji izgrađene su od tankozidnih kompozitnih cilindričnih ili sferičnih delova [1], koji imaju odličnu otpornost na zamor ili koroziju. Zbog velikog potencijala za različite primene, laminatni kompoziti neprekidno privlače pažnju mnogih istraživača [2–4]. Drugi tip materijala koji se mogu analizirati primenom predloženog numeričkog modela jesu sendvič-paneli s mekim jezgrom, koji se zbog male težine primenjuju u građevinarstvu u vidu lakih krovnih i fasadnih termoizolacionih panela.

Osnovni faktor koji skraćuje životni vek laminatnih kompozitnih konstrukcija jeste prisustvo delaminacije koja nastaje kao posledica grešaka pri spajanju lamina u fabričkoj proizvodnji. U slučaju sendvič-panela veoma je bitno da idealna veza između obloge panela i mekog jezgra ne bude narušena, kako bi se panel ponašao u skladu s projektovanim zahtevima. Autori su ranije pokazali da prisustvo delaminacije ozbiljno utiče na mehaničke karakteristike laminatnih kompozitnih i sendvič-ploča [5–6].

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1 INTRODUCTION

Laminar composites are modern engineering materials applied widely in different industries, mostly in the mechanical and civil engineering. These materials, such as carbon-fiber, glass-fiber or fiber-reinforced polymers allow for high strength and stiffness at a relatively low weight. For example, the aerospace structures are generally made of thin-walled composite cylindrical or spherical shell components [1], which have an excellent fatigue and corrosion resistance properties. Because of a great potential for the structural applications, laminar composites continuously attract the attention of many researchers [2, 3, 4]. Another type of plate structures relevant for the considered numerical model is a soft-core sandwich panel, which low weight property makes them applicable in civil engineering as light roof and wall panels to provide the thermal isolation of buildings.

A major limiting factor for the lifetime of laminated composite structures is the presence of embedded delamination, resulting from the different fabrication-induced faults in the joining of laminas. In the case of sandwich panels it is important that the perfect bond between the face sheets and the soft-core remain intact for the panel to perform on the designed level. Authors have already shown that the presence of embedded delamination seriously influences the mechanical properties of laminated composite and sandwich plates [5, 6].

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Odgovor tankih laminatnih konstrukcija može se precizno sračunati primenom dvodimenzionalnih teorija ploča i ljuski. Globalni odgovor može se odrediti primenom relativno jednostavnih Equivalent Single Layer (ESL) teorija, koje ipak nisu potpuno adekvatne iz dva razloga: (1) smičuće deformacije su izraženije kod laminatnih kompozita u poređenju sa izotropnim pločama i (2) ESL teorije daju previše krut odgovor zbog uprošćenja koja se odnose na klasičnu kinematiku ploča i ljuski [7–9]. Klasična teorija ljuski bazirana na Kirchhoff-Love-ovim pretpostavkama potcenjuje vrednosti ugiba i precenjuje veličine sopstvenih frekvencija [10]. U smičućoj teoriji ploča prvog reda (FSDT) efekti smičuće deformacije uzimaju se u obzir primenom smičućih korekcionih faktora. Reddy je primenjivao konačni element baziran na FSDT za analizu savijanja laminatnh kompozitnih ljuski [11] kao i za geometrijski nelinearnu analizu neoštećenih laminatnih kompozita [12]. U radu [13] konačni element baziran na FSDT podeljen je na oštećene i neoštećene delove pri proračunu sopstvenih frekvencija i tonova oscilovanja laminatnih kompozitnih ploča s delaminacijom. Kako bi se preciznije uzelo u obzir krivljenje poprečnog preseka, Reddy [14] je razvio smičuću teoriju ploča višeg reda (HSDT), gde je polje pomeranja po visini poprečnog preseka aproksimirano kubnom funkcijom koordinate u pravcu debljine ploče. U prethodnim radovima [15], Vuksanović je koristio konačne elemente bazirane na jednoslojnom modelu ploča višeg reda za proračun statičkog i dinamičkog odgovora neoštećenih kompozitnih ploča. Pored primene u analizi laminatnih kompozitnih ploča, konačni elementi bazirani na HSDT primenjeni su i u analizi kompozitnih sendvič-panela, u radovima [16–17]. Metod diferencijalne kvadrature (DQ) kao i opšti metod diferencijalne kvadrature (GDQ) takođe su primenjeni za proračun sopstvenih frekvencija laminatnih kompozita [18–22], uz neka analitička rešenja [23–27].

Ograničenja u ESL teorijama motivisala su istraživače da razviju složene (slojevite) teorije ploča i ljuski, koje svaki materijalni sloj razmatraju posebno, pretpostavljajući jedinstveno polje pomeranja po debljini svakog sloja. Reddy-eva opšta laminatna teorija ploča (GLPT) [28], koju su kasnije unapredili Barbero i Reddy [29], postala je osnova za razvoj familije slojevitih konačnih elemenata koji imaju mogućnost da opišu nezavisno kretanje svakog sloja posebno. Ćetković i Vuksanović su razvili analitičko i numeričko slojevito rešenje opšte laminatne teorije ploča za analizu laminatnih kompozitnih i sendvič-ploča bez oštećenja [30] i verifikovali su model primenom postojećih eksperimentalnih i numeričkih rezultata [31–34]. Alnefaie [35] je koristio potpuni slojeviti numerički model baziran na MKE za proračun dinamičkih karakteristika laminatnih ploča uz uzimanje u obzir oštećenja između slojeva. Kontakt između slojeva tokom fenomena „disanja" delaminacije kod „pametnih" kompozitnih ploča uveden je u radovima [36–37]. Korišćen je slojeviti model ploče za ispitivanje linearnih i nelinearnih odgovora „pametnih" kompozitnih ploča s delaminacijom.

Istraživači se uglavnom fokusiraju na analizu laminatnih kompozitnih ploča primenom slojevitih konačnih elemenata, dok još uvek postoji mali broj istraživanja mogućnosti primene slojevitih konačnih elemenata u analizi laminatnih kompozitnih ljuski s delaminacijama. Başar sa saradnicima [38–39] razvio je

The structural response of thin laminated structures can be accurately determined by the use of the two-dimensional plate and shell theories. The global structural response can be determined by the use of relatively simple Equivalent Single Layer (ESL) laminate theories, which are partially inadequate for two reasons: (1) the transverse shear deformations for composite laminates are more pronounced compared to those of isotropic structures and (2) ESL theories give too stiff response because of the simplifications associated with the classical plate and shell kinematics [7-9]. The classical shell theory based on Kirchhoff-Love's assumptions underpredicts the deflections and overpredicts the natural frequencies [10]. In the First-Order Shear Deformation Theory (FSDT) transverse shear effects are taken into account by means of the shear correction factors. Reddy used the shear deformable finite element based on the FSDT for the bending analysis of laminated composite shells [11] and also for the geometrically nonlinear analysis of intact laminated composites [12]. Ju et al. [13] divided the FSDT finite element into delaminated and intact segments and calculated the natural frequencies and mode shapes of delaminated composite plates. In order to account for more accurate cross-sectional warping Reddy [14] developed a Higher-Order Shear Deformation laminate theory (HSDT) where displacement expansion through the plate thickness was approximated using the cubic series expansion of thickness coordinates. In previous works [15], Vuksanović has used finite elements based on the single layer models of higher order for the calculation of the static and dynamic response of intact composite plates. Beside the application to the analysis of laminated composite plates, finite elements based on the Higher-Order Shear Deformation Theory were applied in the analysis of composite sandwich plates, in works of Nayak et al. [16-17]. The method of differential quadrature as well as Generalized Differential Quadrature Method (GDQ) was also used for the calculation of natural frequencies of laminated composite structures [18-22], along with some analytical solutions [23-27].

The limitations of the ESL theories motivated the researchers to derive refined (layerwise) plate and shell theories, which consider each material layer separately by assuming the unique displacement field through the thickness of each layer. The Generalized Layerwise Plate Theory (GLPT) proposed by Reddy [28] and further improved by Barbero and Reddy [29] became the basis for the development of family of layered finite elements capable to describe the independent motion of each layer separately. Ćetković and Vuksanović have derived both the analytical and numerical layerwise solution of the GLPT for the analysis of intact laminated composite and sandwich plates [30] and verified the model using the existing experimental and numerical results [31-34]. Alnefaie [35] used a full layerwise finite element model, for calculation of the fundamental dynamic characteristics of laminated plates considering interlaminar damage. Ghoshal et al. [36-37] incorporated interlaminar contact during the "breathing" phenomena in the delaminated zone of smart composite plates. They have used a layered plate model to investigate linear and nonlinear responses of smart composite structures with delamination.

While researchers mostly focused their attention on familiju slojevitih elemenata ljuske za proračun slobodnih vibracija laminatnih kompozitnih cilindričnih i hiperboličnih ljuski, bez razmatranja delaminacija. Botello je sa saradnicima [40] razvio trougaoni slojeviti konačni element baziran na Reddy-evoj GLP Teoriji, za analizu neoštećenih kompozitnih ploča i ljuski. Oni su takođe uveli i tehniku podstruktura tokom procesa formiranja karakterističnih globalnih matrica, kako bi eliminisali stepene slobode u ravni ploče.

U ovom radu prikazani su određeni moderni pristupi u numeričkoj analizi oštećenih kompozitnih i sendvič-ploča primenom slojevitih konačnih elemenata. Na početku je dato poređenje između dinamičkih karakteristika laminatnih kompozitnih i sendvič-ploča različitih oblika, s prisustvom ili bez prisustva delaminacije. Slojeviti konačni element prikazan u ovom radu primenjen je u uporednim numeričkim proračunima slobodnih vibracija laminatnih kompozitnih ploča s delaminacijama. Nakon toga predloženi model je primenjen u dinamičkoj analizi oštećenih kompozitnih i sendvič-panela. Zatim je model ploče proširen na numeričku analizu laminatnih kompozitnih ljuski s delaminacijama. Primenjena je Reddy-eva GLP Teorija, u kojoj je pretpostavljena nezavisna interpolacija komponenata pomeranja u ravni ploče i upravno na ravan, kao i mogućnost pojave diskontinuiteta na granicama susednih slojeva. U obzir je uzeta linearna promena pomeranja u ravni od sloja do sloja, kao i konstantan ugib po visini ploče. Laminatne kompozitne ljuske modelirane su kao skup malih trougaonih pločastih konačnih elemenata [41]. Krivljenje poprečnog preseka uzeto je u obzir slojevitim razvojem pomeranja po visini laminata. Konzistentna matrica masa uvedena je integracijom odgovarajućih inercionih članova po visini laminata. Konačni elementi implementirani su u originalni računarski program napisan u MATLAB®-u. Za generisanje modela i očitavanje rezultata korišćen je GiD® Pre/Post Processing program [42] razvijen u CIMNE-u, Barselona.

the analysis of laminated composite plate structures using the layered finite elements there is still a lack of investigations regarding the applicability of layered finite elements for the analysis of laminated composite shells with delaminations. Başar et al. [38-39] developed a family of layered shell elements to calculate the free vibration response of laminated composite cylindrical and hyperboloid shells, without considering delamination. Botello et al. [40] derived the triangular layered finite element based on the Reddy's GLPT for the analysis of intact composite plate and shell structures, and also presented the substructuring technique to eliminate the in-plane degrees of freedom during the assembly process.

In this paper some recent advances in the numerical analysis of delaminated composite and sandwich plates using layered finite elements are presented. At first, the comparison between fundamental dynamic characteristics of laminated composite and sandwich plates of different shapes, with or without the presence of embedded delamination, is investigated numerically. The layered finite element developed in this paper is used to perform the comparative numerical calculation of free vibrations of laminated composite plates with embedded delaminations. After that the proposed model is used to perform the transient analysis of delaminated composite and sandwich plates. The plate model is then extended for the numerical analysis of laminated composite shells with embedded delaminations. Reddy's GLP Theory is used, which assumes independent interpolation of in-plane and out-of-plane displacement components, as well as possible discontinuities along the interfaces between adjacent layers. Piece-wise linear variation of in-plane displacement components and constant transverse displacement through the thickness are imposed. The laminated composite shells are modelled as the assembly of small triangular flat elements [41]. Cross-sectional warping is taken into account using the layerwise expansion of the displacements. A consistent mass matrix is employed by the integration of inertia terms through the thickness of the laminate. The finite elements have been implemented into the original program coded in MATLAB. The GiD® Pre/Post Processing software [42] developed in CIMNE, Barcelona is employed for generation of models and results of numerical examples.

2 FORMULACIJA TEORIJE

2.1 Osnovne pretpostavke

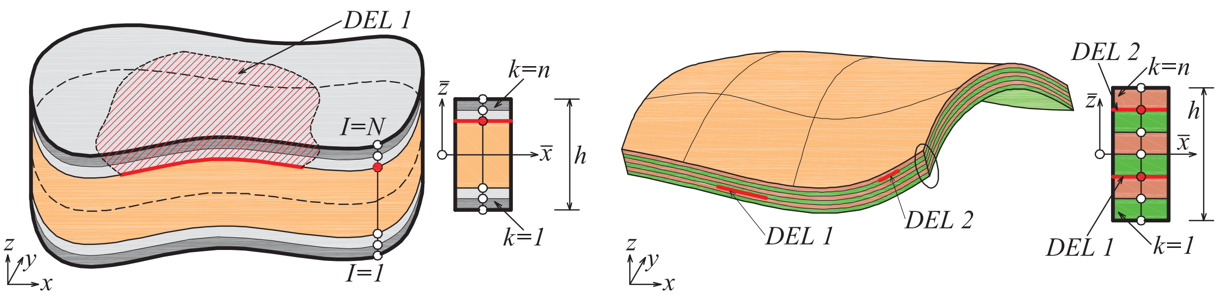
U ovom radu razmatraćemo laminatne kompozitne i sendvič-ploče i ljuske konstantne debljine, sačinjene od *n* ortotropnih slojeva (Slika 1). Globalni koordinatni sistem je Dekartov koordinatni sistem, označen sa *xyz*, kao na Slici 1. Orijentacija vlakana svakog sloja definiše lokalnu *x*-osu materijalnih koordinata. Ugao između globalne *x*-ose i lokalne materijalne *x*-ose definiše orijentaciju vlakana svakog sloja koja će biti od značaja pri određivanju matrica transformacije. *N* predstavlja broj dodirnih površina između materijalnih slojeva (uključujući i spoljne) u kojima se nalaze čvorovi po debljini laminata (obično se usvaja $N=n+1$), dok *ND* predstavlja broj spojeva u kojima postoji delaminacija. Ukupna debljina laminata označava se sa *h*, dok se debljina *k*-tog sloja

2 FORMULATION OF THE THEORY

2.1 Basic assumptions

In this work we will consider laminated composite and sandwich plates and shells of constant height, composed of *n* orthotropic laminas (Figure 1). The global coordinate system is Cartesian coordinate system, denoted as *xyz*, as shown in Figure 1. The fiber direction of each lamina coincides with the local *x*-axis of material coordinates. The angle between the global *x*-axis and the local material *x*-axis defines the fiber direction of each lamina, which will serve for the calculation of the transformation matrices. *N* is the number of interfaces between the material layers (including the outer surfaces) in which nodes through the thickness are located (usually adopted as $N=n+1$), while *ND* represents the number of delaminated numerical layers. The overall označava sa h_k.

laminate thickness is denoted as h, while the thickness of the k^{th} lamina is denoted as h_k.



Slika 1. Kompozitna sendvič-ploča (levo) i laminatna kompozitna ljuska (desno) s delaminacijama, u globalnom koordinatnom sistemu xyz

Figure 1. Composite sandwich plate (left) and laminated composite shell (right) with embedded delaminations, in the global coordinate system xyz

Prošireni oblik opšte laminatne teorije ploča [28] zasnovan je na sledećim pretpostavkama:

1. Svi slojevi su međusobno idealno spojeni, osim u prethodno definisanoj zoni delaminacije, gde se mogu javiti skokovi u polju pomeranja u tri ortogonalna pravca.
2. Materijal je linearno elastičan i poseduje tri ravni simetrije. Svi slojevi su homogeni, bez mogućnosti pojave poprečnih prslina.
3. Prethodno definisana zona delaminacije je konstantna tokom mehaničkih procesa. Sprečeno je međusobno prodiranje sloja u sloj (overlapping).
4. Primenjene su nelinearne Von Kármán-ove kinematičke relacije kako bi se u obzir uzele umerene rotacije i male dilatacije.
5. Uzeta je u obzir neistegljivost linijskog elementa upravnog na srednju ravan ploče pre deformacije.

The GLP Theory [28] in its extended version is based on the following assumptions:

1. All layers are perfectly bonded together, except in the previously imposed delaminated area, where the jump discontinuities in three orthogonal directions may occur.
2. The material is linearly elastic and has three planes of material symmetry. All layers are considered as homogeneous materials, without the possibility of transverse cracking.
3. The previously imposed delaminated zone is kept constant during the mechanical process. The overlapping of layers is prevented.
4. Nonlinear kinematics according to von Kármán is incorporated to account for moderately large rotations and small strains.
5. Inextensibility of the transverse normal is imposed.

2.2 Polje pomeranja

Komponente pomeranja (u_1,u_2,u_3) u proizvoljnoj tački laminata (x,y,z) i proizvoljnom trenutku vremena t mogu se napisati kao:

2.2 Displacement field

The displacement components (u_1,u_2,u_3) at an arbitrary point (x,y,z) of the laminate and arbitrary time instant t can be written as:

$$
\begin{aligned}
u_1(x,y,z,t) &= u(x,y,t)+\sum_{I=1}^{N} u^I(x,y,t)\Phi^I(z)+\sum_{I=1}^{ND} U^I(x,y,t)H^I(z)\\
u_2(x,y,z,t) &= v(x,y,t)+\sum_{I=1}^{N} v^I(x,y,t)\Phi^I(z)+\sum_{I=1}^{ND} V^I(x,y,t)H^I(z)\\
u_3(x,y,z,t) &= w(x,y,t)+\sum_{I=1}^{ND} W^I(x,y,t)H^I(z)
\end{aligned}
\tag{1}
$$

U jednačini (1), (u,v,w) su apsolutne komponente pomeranja u srednjoj ravni laminata, (u^I,v^I) su relativne vrednosti pomeranja u I-tom numeričkom sloju u odnosu na pomeranja srednje ravni, (U^I,V^I,W^I) su skokovi u polju pomeranja u I-tom sloju gde postoji delaminacija. Promenljiva W^I predstavlja otvaranje delaminacije (mod I) u I-tom sloju gde postoji delaminacija. Kako bi se sprečilo prodiranje sloja u sloj u dinamičkoj analizi usvojen je uslov $W^I \geq 0$. Front delaminacije uvodi se zadavanjem graničnih uslova po pomeranjima U^I=V^I=W^I=0 na granici I-te delaminacije. $\Phi^I(z)$ su

In Eq. (1), (u,v,w) are the absolute displacement components in the middle plane of the laminate, (u^I,v^I) are the relative displacements in the I^{th} numerical layer in relation to the mid-plane displacements, (U^I,V^I,W^I) are jump discontinuities in the displacement field in the I^{th} delaminated layer. The variable W^I represents delamination opening (mode I) in the I^{th} delaminated interface. The condition $W^I \geq 0$ is adopted in the transient analysis to provide the non-penetration condition for delaminated surfaces within the I^{th} interface. The delamination front is represented by setting the essential linearne funkcije z-koordinate, kontinualne od sloja do sloja, kojima se interpoliraju komponente pomeranja u ravni. $H^I(z)$ su Heaviside-ove funkcije koje opisuju kinematiku delaminacije u *I*-tom sloju gde postoji oštećenje [5, 6, 8, 29]. Predloženim modelom ploče moguće je razmatrati proizvoljan broj delaminacija primenom odgovarajućeg broja dodatnih funkcija $H^I(z)$ u polju pomeranja.

2.3 Kinematičke relacije

Kinematičke relacije kojima se pretpostavljaju male dilatacije i umereno male rotacije u skladu sa Von Kármán-ovim pretpostavkama definišu polje deformacija, koje se može podeliti na linearan (*L*) i geometrijski nelinearan (*NL*) deo:

boundary conditions $U^I=V^I=W^I=0$ on the I^{th} crack boundary. $\Phi^I(z)$ are linear layerwise continuous functions of the z-coordinate for interpolation of in-plane displacement components. H^I are Heaviside step functions to describe the delamination kinematics in I^{th} delaminated layer [5, 6, 8, 29]. The proposed plate model allows for the consideration of an arbitrary number of delaminations by using an arbitrary number of additional delamination expansions in the displacement field. In-plane displacements are piece-wise continuous through the thickness of the laminate in the intact region with discontinuities at the delaminated interfaces.

2.3 Kinematic relations

Kinematic relations assuming the small strains and moderately large rotations according to von Kármán's assumptions define the strain field which can be divided into a linear (*L*) and geometrically nonlinear (*NL*) part:

$$\begin{aligned}
\varepsilon_x^L &= \frac{\partial u}{\partial x} + \sum_{I=1}^{N} \frac{\partial u^I}{\partial x}\Phi^I + \sum_{I=1}^{ND} \frac{\partial U^I}{\partial x} H^I \\
\varepsilon_y^L &= \frac{\partial v}{\partial y} + \sum_{I=1}^{N} \frac{\partial v^I}{\partial y}\Phi^I + \sum_{I=1}^{ND} \frac{\partial V^I}{\partial y} H^I \\
\gamma_{xy}^L &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + \sum_{I=1}^{N}\left(\frac{\partial u^I}{\partial y} + \frac{\partial v^I}{\partial x}\right)\Phi^I + \sum_{I=1}^{ND}\left(\frac{\partial U^I}{\partial y} + \frac{\partial V^I}{\partial x}\right) H^I \\
\gamma_{xz}^L &= \frac{\partial w}{\partial x} + \sum_{I=1}^{N} u^I \frac{d\Phi^I}{dz} + \sum_{I=1}^{ND} \frac{\partial W^I}{\partial x} H^I \\
\gamma_{yz}^L &= \frac{\partial w}{\partial y} + \sum_{I=1}^{N} v^I \frac{d\Phi^I}{dz} + \sum_{I=1}^{ND} \frac{\partial W^I}{\partial y} H^I
\end{aligned} \tag{2}$$

$$\begin{aligned}
\varepsilon_x^{NL} &= \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 + \frac{\partial w}{\partial x}\sum_{I=1}^{ND}\frac{\partial W^I}{\partial x}H^I + \frac{1}{2}\sum_{I=1}^{ND}\sum_{J=1}^{ND}\frac{\partial W^I}{\partial x}\frac{\partial W^J}{\partial x}H^I H^J \\
\varepsilon_y^{NL} &= \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 + \frac{\partial w}{\partial y}\sum_{I=1}^{ND}\frac{\partial W^I}{\partial y}H^I + \frac{1}{2}\sum_{I=1}^{ND}\sum_{J=1}^{ND}\frac{\partial W^I}{\partial y}\frac{\partial W^J}{\partial y}H^I H^J \\
\gamma_{xy}^{NL} &= \frac{\partial w}{\partial x}\frac{\partial w}{\partial y} + \sum_{I=1}^{ND}\sum_{J=1}^{ND}\frac{\partial W^I}{\partial x}\frac{\partial W^J}{\partial y}H^I H^J + \frac{\partial w}{\partial x}\sum_{I=1}^{ND}\frac{\partial W^I}{\partial y}H^I + \frac{\partial w}{\partial y}\sum_{I=1}^{ND}\frac{\partial W^I}{\partial x}H^I \\
\gamma_{xz}^{NL} &= \gamma_{yz}^{NL} = 0
\end{aligned} \tag{3}$$

2.4 Konstitutivne relacije pojedinačnog sloja

U ovom radu je usvojen konstitutivni model koji pretpostavlja ravno stanje napona u ploči, jer je u slučaju tankih ploča 3D konstitutivni model numerički nestabilan [5, 6]. Uz pretpostavku Hooke-ovog zakona linearne elastičnosti, konstitutivne relacije k-tog sloja za ravno stanje napona, u globalnom koordinatnom sistemu, mogu se prikazati kao:

2.4 Constitutive relations of the individual layer

A plane stress constitutive model is adopted because thin plates 3D constitutive model suffer the numerical instabilities [5, 6]. The constitutive equations of the k^{th} orthotropic lamina for the plane stress state that follows linear elastic Hooke's law, in the global coordinate system, can be written as:

$$\{\sigma\}^{(k)} = \left[\bar{\boldsymbol{Q}}\right]^{(k)} \{\varepsilon\}^{(k)} \tag{4}$$

U jednačini (4), $\left[\bar{\boldsymbol{Q}}\right]^{(k)}$ je redukovana matrica krutosti k-tog sloja u globalnom koordinatnom sistemu, dobijena iz matrične jednačine ($[\boldsymbol{T}]^{(k)}$-matrica transformacije):

In Eq. (4), $\left[\bar{\boldsymbol{Q}}\right]^{(k)}$ is the matrix of reduced stiffness components of the k^{th} lamina in the global coordinate system, derived using the matrix relation ($[\boldsymbol{T}]^{(k)}$– transformation matrix):

$$\left[\bar{\boldsymbol{Q}}\right]^{(k)} = \left[T\right]^{(k)-1} \left[\boldsymbol{Q}\right]^{(k)} \left[T\right]^{(k)} \tag{5}$$

2.5 Princip virtualnog rada

Princip virtualnog rada za dinamički opterećene konstrukcije u vremenskom intervalu [0, T] izveden je primenom Hamilton-ovog principa:

2.5 Virtual work statement

The virtual work statement for dynamically loaded structures within the time interval [0, T] is derived using Hamilton's principle:

$$\int_0^T \left\{ \int_V \left[\sigma_{ij}\delta\varepsilon_j - q(x,y,t) - \rho\left(\ddot{u}_1\delta u_1 + \ddot{u}_2\delta u_2 + \ddot{u}_3\delta u_3\right) \right] dV \right\} dt = 0 \tag{6}$$

U jednačini (6) q predstavlja poprečno raspodeljeno opterećenje u srednjoj ravni ploče, $\ddot{u}$ je vektor ubrzanja, ρ je gustina i V je zapremina razmatranog domena. Ukoliko uvedemo presečne sile kao integrale komponentalnih napona po visini ploče dobijamo princip virtualnog rada u sledećem obliku:

In Eq. (6) q denotes the transverse mid-plane loading, $\ddot{u}$ denotes the acceleration vector, ρ is the mass density and V is the volume of the considered domain. If we introduce the stress resultants as the integrals of the componential stresses through the plate thickness we obtain the following form of the virtual work principle:

$$\int_0^T \left(\delta U^L + \delta U^{NL} + \delta V - \delta K \right) dt = 0 \tag{7a}$$

$$\delta U^L = \int_\Omega \left\{ \begin{aligned} & N_x \frac{\partial \delta u}{\partial x} + N_y \frac{\partial \delta v}{\partial y} + N_{xy}\left(\frac{\partial \delta u}{\partial y} + \frac{\partial \delta v}{\partial x}\right) + Q_x \frac{\partial \delta w}{\partial x} + Q_y \frac{\partial \delta w}{\partial y} + \\ & + \sum_{I=1}^{N} \left(N_x^I \frac{\partial \delta u^I}{\partial x} + N_y^I \frac{\partial \delta v^I}{\partial y} + N_{xy}^I \left(\frac{\partial \delta u^I}{\partial y} + \frac{\partial \delta v^I}{\partial x} \right) + Q_x^I \delta u^I + Q_y^I \delta v^I \right) + \\ & + \sum_{I=1}^{ND} \left(\bar{N}_x^I \frac{\partial \delta U^I}{\partial x} + \bar{N}_y^I \frac{\partial \delta V^I}{\partial y} + \bar{N}_{xy}^I \left(\frac{\partial \delta U^I}{\partial y} + \frac{\partial \delta V^I}{\partial x} \right) + \bar{Q}_x^I \frac{\partial \delta W^I}{\partial x} + \bar{Q}_y^I \frac{\partial \delta W^I}{\partial y} \right) \end{aligned} \right\} d\Omega \tag{7b}$$

$$\delta U^{NL} = \int_\Omega \left\{ \begin{aligned} & N_x \frac{\partial w}{\partial x}\frac{\partial \delta w}{\partial x} + N_y \frac{\partial w}{\partial y}\frac{\partial \delta w}{\partial y} + N_{xy}\left(\frac{\partial w}{\partial y}\frac{\partial \delta w}{\partial x} + \frac{\partial w}{\partial x}\frac{\partial \delta w}{\partial y} \right) + \\ & + \bar{N}_x^I \left(\frac{\partial \delta w}{\partial x} \sum_{I=1}^{ND} \frac{\partial W^I}{\partial x} + \frac{\partial w}{\partial x} \sum_{I=1}^{ND} \frac{\partial \delta W^I}{\partial x} \right) + \bar{N}_y^I \left(\frac{\partial \delta w}{\partial y} \sum_{I=1}^{ND} \frac{\partial W^I}{\partial y} + \frac{\partial w}{\partial y} \sum_{I=1}^{ND} \frac{\partial \delta W^I}{\partial y} \right) + \\ & + \bar{N}_{xy}^I \left(\frac{\partial \delta w}{\partial x} \sum_{I=1}^{ND} \frac{\partial W^I}{\partial y} + \frac{\partial w}{\partial x} \sum_{I=1}^{ND} \frac{\partial \delta W^I}{\partial y} + \frac{\partial \delta w}{\partial y} \sum_{I=1}^{ND} \frac{\partial W^I}{\partial x} + \frac{\partial w}{\partial y} \sum_{I=1}^{ND} \frac{\partial \delta W^I}{\partial x} \right) + \\ & + \bar{N}_x^{IJ} \sum_{I,J=1}^{ND} \frac{1}{2} \left(\frac{\partial W^J}{\partial x}\frac{\partial \delta W^I}{\partial x} + \frac{\partial W^I}{\partial x}\frac{\partial \delta W^J}{\partial x} \right) + \bar{N}_y^{IJ} \sum_{I,J=1}^{ND} \frac{1}{2} \left(\frac{\partial W^J}{\partial y}\frac{\partial \delta W^I}{\partial y} + \frac{\partial W^I}{\partial y}\frac{\partial \delta W^J}{\partial y} \right) + \\ & + \bar{N}_{xy}^{IJ} \sum_{I,J=1}^{ND} \left(\frac{\partial W^J}{\partial y}\frac{\partial \delta W^I}{\partial x} + \frac{\partial W^I}{\partial x}\frac{\partial \delta W^J}{\partial y} \right) \end{aligned} \right\} d\Omega \tag{7c}$$

$$\delta V = -\int_{\Omega} \left(q \delta w \right) d\Omega \quad (7d)$$

$$\delta K = -\int_{\Omega} \left\{ \begin{array}{l} I_0 \left(\ddot{u}\delta u + \ddot{v}\delta v + \ddot{w}\delta w \right) + \sum_{I=1}^{N} I^I \left(\ddot{u}^I \delta u + \ddot{v}^I \delta v + \ddot{u}\delta u^I + \ddot{v}\delta v^I \right) + \sum_{I=1}^{N}\sum_{J=1}^{N} I^{IJ} \left(\ddot{u}^I \delta u^J + \ddot{v}^I \delta v^J \right) + \\ + \sum_{I=1}^{ND} \overline{I}^I \left(\ddot{U}^I \delta u + \ddot{V}^I \delta v + \ddot{W}^I \delta w + \ddot{u}\delta U^I + \ddot{v}\delta V^I + \ddot{w}\delta W^I \right) + \\ + \sum_{I=1}^{N}\sum_{J=1}^{ND} \left(\overline{I}^{IJ} \left(\ddot{u}^I \delta U^J + \ddot{v}^I \delta V^J \right) + \overline{I}^{JI} \left(\ddot{U}^I \delta u^J + \ddot{V}^I \delta v^J \right) \right) + \sum_{I=1}^{ND}\sum_{J=1}^{ND} \tilde{I}^{IJ} \left(\ddot{U}^I \delta U^J + \ddot{V}^I \delta V^J + \ddot{W}^I \delta W^J \right) \end{array} \right\} d\Omega \quad (7e)$$

U jednačinama (7), $N_x, N_y, N_{xy}, Q_x, Q_y$ su presečne sile u srednjoj ravni ploče, $N_x^I, N_y^I, N_{xy}^I, Q_x^I, Q_y^I$ su relativne vrednosti presečnih sila u I-tom numeričkom sloju, $\overline{N}_x^I, \overline{N}_y^I, \overline{N}_{xy}^I, \overline{Q}_x^I, \overline{Q}_y^I$ su presečne sile koje razdvojene čvorove u zoni delaminacije u I-toj ravni drže sastavljenim i $I_0, I^I, I^{IJ}, \overline{I}^{IJ}, \tilde{I}^{IJ}$ su faktori inercije dobijeni integracijom gustine materijala po visini ploče. Presečne sile i faktori inercije su dati u [29]. Konstitutivne matrice laminata dobijene su integracijom linearno elastičnih ortotropnih konstitutivnih matrica svakog pojedinačnog sloja. One se označavaju sa [***A***], [$\boldsymbol{B}^I$], [$\boldsymbol{E}^I$], [$\boldsymbol{D}^{IJ}$], [$\boldsymbol{L}^{IJ}$], [$\boldsymbol{F}^{IJ}$], [$\boldsymbol{L}^{IJK}$], [$\boldsymbol{F}^{IJK}$], [$\boldsymbol{F}^{IJKL}$] i date su u radu [29].

3 NUMERIČKI MODEL MKE

3.1 Polje pomeranja

Posle određivanja „weak” forme, numerički model je dobijen prostornom i vremenskom diskretizacijom opisanom u ovom poglavlju. Slojeviti numerički model konačnog elementa baziran na prethodnim razmatranjima sastoji se od srednje ravni, *N* dodirnih površi između materijalnih slojeva po visini laminata (osim srednje ravni, uključujući i spoljne površi) i konačno *ND* numeričkih slojeva u kojima se nalazi delaminacija. Predložena teorija omogućava da se za generalisana pomeranja u čvorovima usvoje samo translacije u tri ortogonalna pravca. Promenljive u čvorovima (stepeni slobode) komponente su pomeranja (u,v,w) u srednjoj ravni, relativna pomeranja (u^I,v^I) u I-tom numeričkom sloju i skokovi u polju pomeranja (U^I,V^I,W^I) u I-tom numeričkom sloju gde postoji delaminacija. Prirodni koordinatni sistem pojedinačnog elementa ξ-η nalazi se u težištu elementa, Slika 2.

S obzirom na to što se proizvoljna geometrija ljuske ne može potpuno diskretizovati primenom četvorougaonih elemenata, primenjuju se trougaoni elementi. Interpolacione funkcije definišu se u prirodnom koordinatnom sistemu (na master elementu), jer se primenjuju trougaoni elementi proizvoljnog oblika i veličine. Prirodne koordinate ξ_i za proizvoljnu materijalnu tačku trougla (x,y,z) predstavljaju površine parcijalnih trouglova A_i, dobijenih povezivanjem tačke (x,y,z) sa uglovima trougla, kao na Slici 2. Zato važe sledeći uslovi:

In Eqs. (7), $N_x, N_y, N_{xy}, Q_x, Q_y$ are mid-plane stress resultants, $N_x^I, N_y^I, N_{xy}^I, Q_x^I, Q_y^I$ are relative values of the stress resultants in the I^{th} numerical layer, $\overline{N}_x^I, \overline{N}_y^I, \overline{N}_{xy}^I, \overline{Q}_x^I, \overline{Q}_y^I$ are the forces to hold the delaminated nodes together in the I^{th} delaminated interface and $I_0, I^I, I^{IJ}, \overline{I}^{IJ}, \tilde{I}^{IJ}$ are inertia terms derived by the integration of mass density through the plate thickness. The force resultants as well as inertia terms can be found in [29]. The constitutive matrices of the laminated plate are obtained by the integration of the linear elastic orthotropic matrices over all layers. They are denoted as [***A***], [$\boldsymbol{B}^I$], [$\boldsymbol{E}^I$], [$\boldsymbol{D}^{IJ}$], [$\boldsymbol{L}^{IJ}$], [$\boldsymbol{F}^{IJ}$], [$\boldsymbol{L}^{IJK}$], [$\boldsymbol{F}^{IJK}$], [$\boldsymbol{F}^{IJKL}$] and can be found in [29].

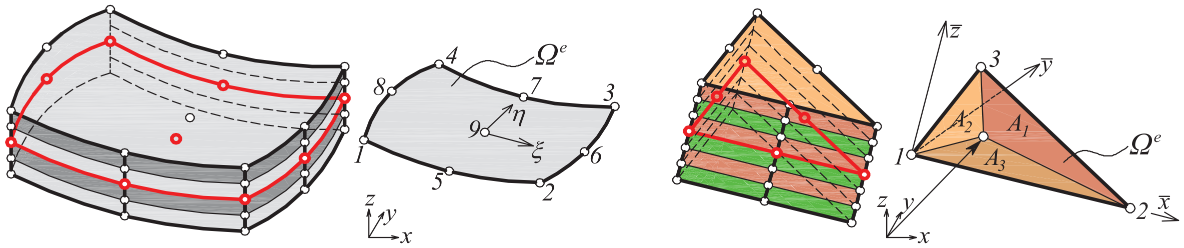
3 FINITE ELEMENT MODEL

3.1 Displacement field

After the derivation of the weak form, the numerical model is obtained by the spatial and temporal discretization described in this section. The layered numerical model of the single element, based on the previous considerations, consists of the middle plane, *N* interfaces between the laminas through the plate thickness (except the middle plane, including the outer surfaces), and finally *ND* interfaces in which delamination is present. The proposed theory allows adopting only translation components in three orthogonal directions as generalized displacements in the nodes. Nodal variables (degrees of freedom) are the displacement components (u,v,w) in the mid-plane, relative displacements (u^I,v^I) in I^{th} numerical layer and displacement jumps (U^I,V^I,W^I) in I^{th} delaminated numerical layer. The natural coordinate system of the single FE is located at its centroid, as shown in Figure 2.

Since the arbitrary shell geometry cannot be fully discretized using quadrilateral elements, triangular layered finite elements are used in this case. The shape functions are formulated in the natural coordinate system (on a master or unit triangle) because we are dealing with the triangular elements of arbitrary shape and size. The natural coordinates ξ_i for an arbitrary material point (x,y,z) of the triangle are the areas of partial triangles A_i, created by connecting the point (x,y,z) with triangle corners, as shown in Figure 2. Since there exist the following conditions:

$$\sum_{i=1}^{3} A_i = \sum_{i=1}^{3} \xi_i A = A \qquad \sum_{i=1}^{3} \xi_i = \xi_1 + \xi_2 + \xi_3 = 1 \qquad \xi_3 = 1 - \xi_1 - \xi_2 \tag{8}$$



Slika 2. Lagrange-ov četvorougaoni konačni element sa devet čvorova (levo) i trougaoni slojeviti konačni elementi sa tri čvora (desno) u prirodnom (ξ-η) i globalnom (xyz) koordinatnom sistemu ($\bar{x}\,\bar{y}\,\bar{z}$ - lokalni koordinatni sistem trougaonog elementa)

Figure 2. Lagrange 9-node quadrilateral (left) and 3-node triangular (right) layered finite elements in natural (ξ-η) and global (xyz) coordinate systems ($\bar{x}\,\bar{y}\,\bar{z}$ - local coordinate system of the triangular element)

Mreža konačnih elemenata generiše se u 2D ravni, a usvojene interpolacione funkcije po visini ploče se koriste za interpolaciju nepoznatih upravno na ravan laminata (čime se iz proračuna eliminiše *z*-koordinata). Ova pretpostavka omogućava da se interpolacija nepoznatih u ravni i upravno na ravan laminata vrši nezavisno. Nepoznate komponente pomeranja interpoliraju se u lokalnoj ravni pojedinačnog konačnog elementa, definisanoj s tri ugla trougla, dok lokalna *x*-osa povezuje čvorove 1–2. Lokalna *y*-osa nalazi se u ravni elementa i upravna je na *x*-osu, dok je lokalna *z*-osa upravna na ravan elementa I formira Dekartov koordinatni sistem ($\bar{x}\ \bar{y}\ \bar{z}$) lociran u čvoru 1. Radi jednostavnosti, za sva generalisana pomeranja koriste se iste interpolacione funkcije:

The FE mesh is generated in the 2D plane, and the adopted interpolation functions through the plate thickness are used for out-of-plane interpolation of the unknown variables (which eliminates the *z*-coordinate from the calculation). This assumption allows interpolating the unknown field variables independently for the in-plane and out-of-plane distribution. The unknown displacement components are interpolated in the local plane of the single finite element, defined by three corner nodes, while the local *x*-axis connects nodes 1-2. The local *y*-axis is positioned in the element plane and it is perpendicular to the local *x*-axis, while the local *z*-axis is perpendicular to the element plane and forms the local Cartesian orthogonal coordinate system ($\bar{x}\ \bar{y}\ \bar{z}$), located in the node 1. For the sake of simplicity, the same interpolation functions are used for the interpolation of all generalized displacements:

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \begin{Bmatrix} \sum_{i=1}^{m} u_i \psi_i \\ \sum_{i=1}^{m} v_i \psi_i \\ \sum_{i=1}^{m} w_i \psi_i \end{Bmatrix} = [\Psi]\{\Delta\}, \quad \begin{Bmatrix} u^I \\ v^I \end{Bmatrix} = \begin{Bmatrix} \sum_{i=1}^{m} u_i^I \psi_i \\ \sum_{i=1}^{m} v_i^I \psi_i \end{Bmatrix} = [\bar{\Psi}]\{\Delta^I\}, \quad \begin{Bmatrix} U^I \\ V^I \\ W^I \end{Bmatrix} = \begin{Bmatrix} \sum_{i=1}^{m} U_i^I \psi_i \\ \sum_{i=1}^{m} V_i^I \psi_i \\ \sum_{i=1}^{m} W_i^I \psi_i \end{Bmatrix} = [\Psi]\{\bar{\Delta}^I\} \tag{9}$$

U jednačinama (9), $\{\Delta\}$, $\{\Delta^I\}$ i $\{\bar{\Delta}^I\}$ predstavljaju vektore pomeranja u srednjoj ravni, *I*-tom numeričkom sloju *I*-tom numeričkom sloju u kome postoji delaminacija, respektivno. Indeks *m* označava broj čvorova konačnog elementa. Primenjeni su pravougaoni Lagrange-ovi konačni elementi sa četiri ili devet čvorova, kao i trougaoni slojeviti konačni elementi s tri čvora. $[\Psi]$ i $[\bar{\Psi}]$ su matrice Lagrange-ovih interpolacionih funkcija:

In Eqs. (9), $\{\Delta\}$, $\{\Delta^I\}$ and $\{\bar{\Delta}^I\}$ denote displacement vectors in the middle plane, the I^{th} numerical layer and the I^{th} delaminated layer, respectively. Index *m* denotes the number of nodes per element. Four- and nine-node Lagrange quadrilateral, as well as three-node triangular layered finite elements are derived. $[\Psi]$ and $[\bar{\Psi}]$ are matrices of Lagrangian interpolation functions:

$$[\Psi]=\begin{bmatrix}\psi_1 & 0 & 0 & \\ 0 & \psi_1 & 0 & \cdots \\ 0 & 0 & \psi_1 & \end{bmatrix}_{3\times 3m} \quad , \quad [\bar{\Psi}]=\begin{bmatrix}\psi_1 & 0 & \\ 0 & \psi_1 & \cdots\end{bmatrix}_{2\times 2m} \tag{10}$$

3.2 Jednačine kretanja

Zamenom interpolacije komponenata pomeranja iz jednačine (9) u princip virtualnih pomeranja (jednačine (7)), dobijamo potpuno diskretizovan numerički model MKE [5, 6, 29]. Na ovaj način dobijamo sistem jednačina kretanja na nivou konstrukcije:

3.2 Equations of motion

When substituting the interpolation of displacement components from Eq. (9) into the principle of virtual displacements (Eqs. (7)), the fully discretized finite element model [5, 6, 29] has been obtained. This leads to the system of equations of motion on the structural level:

$$[\boldsymbol{M}]\{\ddot{\boldsymbol{d}}\}+[\boldsymbol{C}]\{\dot{\boldsymbol{d}}\}+\left[\boldsymbol{K}^{L}+\boldsymbol{K}^{NL}\right]\{\boldsymbol{d}\}=\{\boldsymbol{F}\} \tag{11}$$

Matrica masa [***M***], matrica prigušenja [***C***], linearne i nelinearne matrice krutosti [$\boldsymbol{K}^L$] i [$\boldsymbol{K}^{NL}$] i globalni vektor sila {***F***} dobijaju se sabiranjem odgovarajućih članova u karakterističnim matricama i vektorima pojedinačnih elemenata.

Sve matrice dobijene su primenom Gauss-Legendre-ove integracije na domenu pojedinačnog konačnog elementa, označenog sa Ω^e. Kako bi se iz proračuna eliminisala nepostojeća smičuća krutost (fenomen „shear locking, primenjena je selektivna integracija. Gauss-Legendre-ova integracija na trougaonom domenu sračunava se prema izrazu:

The mass matrix [***M***], the damping matrix [***C***], the linear and nonlinear structural stiffness matrices [$\boldsymbol{K}^L$] and [$\boldsymbol{K}^{NL}$] and the global force vector {***F***} are obtained from the assembly of the respective element matrices and element load vector.

All element matrices are derived using Gauss-Legendre quadrature over single finite element domain, denoted as Ω^e. Selective integration is used for the elimination of spurious shear stiffness from calculation (shear locking phenomenon). The Gauss-Legendre quadrature for triangular domain is written as:

$$\int_{\Omega^e} F(\bar{x},\bar{y})d\Omega^e=\int_0^0\int_0^{1-\xi_2} F(\xi,\eta)d\xi d\eta\cdot\det[J]=\sum_{i=1}^{n_p}W_i f(\xi^i,\eta^i) \tag{12}$$

U jednačini (12), F je funkcija koju treba numerički sračunati, [J] je Jacobi-eva matrica, n_p je broj integracionih tačaka, ξ^i,η^i su koordinate i-te integracione tačke i W_i je odgovarajući težinski koeficijent [43]. Submatrice matrica krutosti i masa pojedinačnog konačnog elementa date su u [29]. Sledeće jednačine opisuju dva problema koji su razmatrani u ovom radu:

1. Linearne slobodne vibracije $\left(\left[\boldsymbol{K}^{L}\right]-\omega^2[\boldsymbol{M}]\right)\{\boldsymbol{d}\}=0$
2. Geometrijski nelinearna dinamička analiza $[\boldsymbol{M}]\{\ddot{\boldsymbol{d}}\}+[\boldsymbol{C}]\{\dot{\boldsymbol{d}}\}+\left[\boldsymbol{K}^{L}+\boldsymbol{K}^{NL}\right]\{\boldsymbol{d}\}=\{\boldsymbol{F}\}$

In Eq. (12), F is the function to be calculated numerically, [J] is the Jacobi matrix, n_p is the number of integration points, ξ^i,η^i are the coordinates of the i^{th} integration point and W_i is the corresponding weighting factor [43]. The submatrices of the element stiffness and mass matrices are derived in [29]. Two problems investigated in this paper are described using the following equations:

1. Linear free vibrations $\left(\left[\boldsymbol{K}^{L}\right]-\omega^2[\boldsymbol{M}]\right)\{\boldsymbol{d}\}=0$
2. Geometrically nonlinear transient analysis $[\boldsymbol{M}]\{\ddot{\boldsymbol{d}}\}+[\boldsymbol{C}]\{\dot{\boldsymbol{d}}\}+\left[\boldsymbol{K}^{L}+\boldsymbol{K}^{NL}\right]\{\boldsymbol{d}\}=\{\boldsymbol{F}\}$

3.3 Transformacija u globalne koordinate i formiranje matrica sistema

Kada se proizvoljna ljuska deli na trougaone elemente, svaki element ima proizvoljnu orijentaciju u globalnom koordinatnom sistemu, pa je iz tog razloga od značaja da pogodno definišemo matrice tranformacije svakog konačnog elementa – potrebno je definisati kosinuse uglova koje lokalne ose zaklapaju s globalnim osama. Uzimajući u obzir ranija razmatranja, broj čvornih stepeni slobode u lokalnom koordinatnom sistemu je: $n_{DOF,LOCAL}$ = 3+2×N+3×ND. Ove lokalne komponente pomeranja transformišu se primenom matrice transformacije konačnog elementa $[\hat{\boldsymbol{T}}]$ u globalne komponente

3.3 Transformation to global coordinates and assembly procedure

When the arbitrary shell is divided into triangular elements, each element has an arbitrary orientation in the global coordinate system, so it is now important to conveniently define the transformation matrices for each element - we need to define the cosines of each finite element. Following the preceding considerations, the number of nodal degrees of freedom in the local coordinate system is: $n_{DOF,LOCAL}$ = 3+2×N+3×ND. These local displacement components are transformed using the element transformation matrix $[\hat{\boldsymbol{T}}]$ into the global pomeranja - čvorne stepene slobode u globalnom koordinatnom sistemu $n_{DOF,GLOBAL}$ = 3+3×N+3×ND. Matrice krutosti ili masa pojedinačnog konačnog elementa u globalnom koordinatnom sistemu sračunavaju se kao:

displacement components – nodal degrees of freedom in global coordinate system $n_{DOF,GLOBAL}$ = 3+3×N+3×ND. The global stiffness/mass matrices of the triangular finite element can be calculated as follows:

$$\begin{aligned}[\boldsymbol{K}]^e &= [\hat{\boldsymbol{T}}]^T [\boldsymbol{K}][\hat{\boldsymbol{T}}] \\ [\boldsymbol{M}]^e &= [\hat{\boldsymbol{T}}]^T [\boldsymbol{M}][\hat{\boldsymbol{T}}]\end{aligned} \tag{13}$$

4 REŠENJE VREMENSKOG PROBLEMA I KONTAKTNI ALGORITAM

Za integraciju u vremenu je primenjena Newmark-ova implicitna integraciona šema [8]. Ubrzanja i brzine su aproksimirani primenom redukovanih Taylor-ovih redova. Pomeranja i brzine određeni su primenom rekurentnih formula [8], a početni granični uslovi su homogeni. S obzirom na to što je matrica [K^{NL}] funkcija nepoznatog pomeranja $\{d\}_{n+1}$, sistem uslovnih jednačina sistema mora se rešavati iterativno sve dok kriterijum konvergencije ne bude zadovoljen. Picard-ov metod [8] primenjuje se sve dok greška ne bude manja ili jednaka vrednosti neke unapred usvojene tolerancije (recimo $\varepsilon \leq$ 1%). Prigušenje je zanemareno.

Tokom dinamičkog odgovora laminatnih kompozitnih ili sendvič-ploča s delaminacijom, može se formirati mali međuprostor između susednih slojeva u zoni delaminacije. Nakon toga razdvojeni slojevi tokom kretanja mogu ponovo da dođu u kontakt i na taj način zatvore postojeći međuprostor. Ovaj fenomen se u literaturi naziva „disanje” delaminacije [36–37], koje se može modelirati primenom kontaktnih uslova između čvorova, bez uzimanja u obzir trenja [6]. Kontaktni algoritam uspešno sprečava međusobno prodiranje sloja u sloj tokom dinamičkog odgovora kompozitnih ploča s delaminacijom. Ovo važi i za linearnu i za geometrijski nelinearnu analizu.

4 SOLUTION OF THE TIME DEPENDENT PROBLEM AND CONTACT ALGORITHM

For integration in time, an implicit Newmark's integration scheme is employed [8]. The accelerations and velocities are approximated using truncated Taylor's series. Displacements and velocities are approximated using recursive formulae [8], while the homogenous initial conditions are prescribed. The assembled equation must be solved iteratively until the convergence criterion is satisfied since the matrix [K^{NL}] is the function of displacements $\{d\}_{n+1}$. The Picard method [8] is employed until the error is less than or equal to some prescribed tolerance (say $\varepsilon \leq$ 1%). The structural damping is neglected.

During the transient response of delaminated composite or sandwich structures, a small gap may be formed between the adjacent layers in delaminated zones of the plate. After that the separated layers may unload and again contact each other at that delaminated interface. This phenomenon is referred to as "breathing" of a delamination [36-37], which can be modelled using the node-to-node frictionless contact conditions [6]. The contact algorithm successfully "corrects" the interlaminar penetration during the transient response of the delaminated composite plate both in the linear and geometrically nonlinear analysis.

5 NUMERIČKI PRIMERI I DISKUSIJA

U ranijim radovima [5, 6, 15, 30] autori su dokazali da ESL teorije precenjuju vrednosti sopstvenih frekvencija i potcenjuju vrednosti ugiba kod pravougaonih kompozitnih i sendvič-ploča bez oštećenja. U ovom radu su proširene mogućnosti primene modela na analizu slobodnih vibracija kružnih kompozitnih ploča s delaminacijama.

5 NUMERICAL EXAMPLES AND DISCUSSION

In previous works [5, 6, 15, 30], authors have proven that ESL theories overestimate the fundamental frequencies and underestimate the transverse deflections of rectangular intact composite and sandwich plates. The applicability of the model is extended here for the free vibrations analysis of circular composite plates with delaminations.

5.1 Analiza linearnih slobodnih vibracija

Primer 5.1.1. U prvom primeru [44] razmatra se neoštećena uklještena (CC) četvoroslojna kružna kompozitna ploča simetrične (θ/-θ/-θ/θ) šeme laminacije. Prečnik ploče označen je sa a, a ukupna debljina ploče sa h. Svi slojevi su jednake debljine h_k. Za sve slojeve su pretpostavljeni ortotropni konstitutivni modeli sa sledećim materijalnim karakteristikama: E_1/E_2 = 40, G_{12}/E_2 = = G_{13}/E_2 = 0.6, G_{23}/E_2 = 0.5, $\upsilon_{12} = \upsilon_{13} = \upsilon_{23}$ = 0.25, ρ = const. Granični u slovi su zadati na uklještenim

5.1 Linear free vibrations analysis

Example 5.1.1. The first benchmark example [44] is concerned with an intact 4-layer clamped (CC) circular composite plate with symmetric (θ/-θ/-θ/θ) stacking sequence. Plate diameter is denoted as a, while the overall plate thickness is denoted as h. All laminas are of equal thickness h_k. The following material parameters are assumed for orthotropic constitutive models of all laminas: E_1/E_2 = 40, $G_{12}/E_2 = G_{13}/E_2$ = 0.6, G_{23}/E_2 = 0.5, $\upsilon_{12} = \upsilon_{13} = \upsilon_{23}$ = 0.25, ρ = const. The boundary conditions ivicama sprečavanjem svih generalisanih pomeranja u čvorovima. U ovom proračunu su zanemareni članovi koji odgovaraju velikim rotacijama. Rezultati su dobijeni primenom nestrukturirane mreže sa 931 slojevitim konačnim elementom sa devet čvorova, s redukovanom integracijom (broj čvorova je 3849). Sračunate su bezdimenzionalne sopstvene frekvencije neoštećenih kružnih laminatnih kompozitnih ploča prema izrazu $\Omega = \omega \cdot a^2/h(\rho/E_2)^{1/2}$ i izvršeno je poređenje s rezultatima dobijenim primenom različitih ESL teorija: smičuće teorije ploča [44] i smičuće teorije ploča prvog reda [45]. Rezultati su objedinjeni u Tabeli 1.

are prescribed along clamped boundaries by constraining all generalized displacements in edge nodes. The terms related to the large rotations in the kinematic equations are omitted in this calculation. The results are obtained using the unstructured FE mesh of 931 9-node layered elements with reduced integration (number of nodes is 3849). The nondimenzionalized fundamental frequencies $\Omega = \omega \cdot a^2/h(\rho/E_2)^{1/2}$ of intact circular laminated composite plates is calculated and compared with results obtained using different ESL theories: transverse shear deformation theory [44] and First-Order Shear Deformation Theory [45]. The results are elaborated in Table 1.

Tabela 1. Bezdimenzionalne sopstvene frekvencije četvoroslojne uklještene kružne kompozitne ploče simetrične angle-ply ($\theta/-\theta/-\theta/\theta$) šeme laminacije

Table 1. The nondimenzionalized fundamental frequencies of the 4-layer clamped circular laminated composite plates with symmetric ($\theta/-\theta/-\theta/\theta$) angle-ply stacking sequence

Numerical model	θ = 0	θ = 30	θ = 45
SDT [36]	23.130	24.063	24.557
FSDT [37]	22.211	24.071	24.752
GLPT, Present	22.913	25.107	25.684

Na osnovu Tabele 1 očigledno je da je predloženi model u stanju da predvidi sopstvene frekvencije kružnih laminatnih kompozitnih ploča, čak i uz korišćenje četvorougaonih elemenata za modeliranje kružne geometrije. Za sve šeme laminacije dobijen je nešto krući odgovor (2–4%). Sopstvene frekvencije očigledno rastu s povećanjem nivoa ortotropije.

Primer 5.1.2. U drugom primeru [13] razmatra se kvadratna kompozitna ploča sa osam slojeva, simetrične $(0/90/45/90)_s$ šeme laminacije. Ivice ploče imaju dužinu $a = 250mm$, dok je ukupna visina ploče $h = 2.12mm$. Svi slojevi su jednake debljine. Za ortotropni konstitutivni model svih slojeva pretpostavljeni su sledeći parametri materiala: $E_1 = 132GPa$, $E_2 = 5.35GPa$, $G_{12} = G_{13} = 2.79GPa$, $\upsilon_{12} = \upsilon_{13} = 0.291$, $\upsilon_{23} = 0.300$, $\rho = 1446.2kg/m^3$. Kvadratna delaminacija, stranice $a_{del} = a/2$ ranije je ubačena u srednjoj ravni (između slojeva 4 i 5), u centru ploče. Granični uslovi zadati su duž ivica ploče na sledeći način:

- slobodno oslonjene (SS_x) ivice: za $x = 0$ i $x = a$: $v = w = v^I = 0$,
- slobodno oslonjene (SS_y) ivice: za $y = 0$ i $y = b$: $u = w = u^I = 0$,
- uklještene (CC) ivice: $u = v = w = u^I = v^I = 0$.

Ploča je analizirana kako bi se ispitao uticaj graničnih uslova na sopstvene frekvencije kompozitnih ploča s prethodno ubačenom delaminacijom konstantne površine. Ploča je diskretizovana pomoću mreže od 6×6 slojevitih konačnih elemenata s devet čvorova, s redukovanom integracijom. Sračunate su sopstvene frekvencije za prva četiri tona oscilovanja neoštećenih i oštećenih ploča i upoređene su s rezultatima iz [13] u Tabeli 2.

From Table 1 it is obvious that the proposed model is capable to predict the fundamental frequencies of circular laminated composite plates, even by using the quadrilateral FE to describe the circular plate geometry. A slightly stiffer response (2-4%) is obtained for all stacking sequences. Natural frequencies obviously increase with the level of orthotropy.

Example 5.1.2. The second benchmark example [13] is concerned with an 8-layer square composite plate with symmetric $(0/90/45/90)_s$ stacking sequence. Side length of the plate is $a = 250mm$, while overall plate thickness is $h = 2.12mm$. All laminas are of equal thickness. The following material parameters are assumed for orthotropic constitutive models of all laminas: $E_1 = 132GPa$, $E_2 = 5.35GPa$, $G_{12} = G_{13} = 2.79GPa$, $\upsilon_{12} = \upsilon_{13} = 0.291$, $\upsilon_{23} = 0.300$, $\rho = 1446.2kg/m^3$. Square delamination of side $a_{del} = a/2$ is prescribed in the mid-plane (between layers 4 and 5) in the centre of the plate. The boundary conditions are prescribed along boundary edges as follows:

- simply supported (SS_x) edges: at $x = 0$ and $x = a$: $v = w = v^I = 0$,
- simply supported (SS_y) edges: at $y = 0$ and $y = b$: $u = w = u^I = 0$,
- clamped (CC) edges: $u = v = w = u^I = v^I = 0$.

The plate is analyzed to check the influence of boundary conditions on fundamental frequencies of composite plates with previously imposed delaminated zone of constant area. The plate is discretized by 6×6 9-node layered finite elements with reduced integration. Natural frequencies for first 4 modes for intact and delaminated plates are calculated and compared with the results from [13] in Table 2.

Tabela 2. Sopstvene frekvencije (Hz) neoštećenih i oštećenih $(0/90/45/90)_s$ kompozitnih ploča s različitim uslovima oslanjanja, za prva četiri tona oscilovanja

Table 2. Natural frequencies (Hz) for intact and delaminated (0/90/45/90)s composite plates with different boundary conditions for first four modes

	Model	State	1	2	3	4
Simply Supported Plate	FSDT	Intact	164.37	404.38	492.29	658.40
		Damaged	161.58	348.27	371.19	637.48
	Present	Intact	169.81	409.78	504.22	672.69
		Damaged	167.04	347.88	374.62	611.08
Clamped Plate	FSDT	Intact	346.59	651.51	781.06	1017.20
		Damaged	334.67	579.43	653.25	851.27
	Present	Intact	346.81	643.44	777.93	982.16
		Damaged	316.88	529.34	554.81	783.80

Rezultati prikazani u Tabeli 2 potvrđuju da je predloženi model u stanju da precizno predvidi sopstvene frekvencije neoštećenih i oštećenih kompozitnih ploča. Redukcija sopstvene frekvencije usled prisustva delaminacija veća je u slučaju viših tonova oscilovanja, za oba razmatrana slučaja.

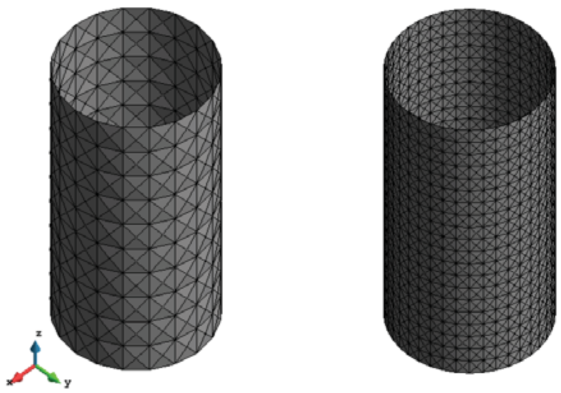
Primer 5.1.3. U trećem primeru razmatraju se cilindrične cross-ply laminatne kompozitne ljuske uklještene na oba kraja. Dužina razmatranih ljuski je L=12m, a poluprečnik R=3m. Ljuske su sačinjene od tri ortotropna sloja, pojedinačne debljine h_k=0.02m, tako da je ukupna debljina ljuske h=0.06m (odnos dužina/poluprečnik je L/R=4, a odnos debljina/poluprečnik je h/R=0.02, što odgovara tankim i umereno dugim ljuskama). Za sve slojeve su pretpostavljeni materijalni parametri koji odgovaraju grafit-epoksidu [27]: $E_1 = 138$ GPa, $E_2 = E_3 = 8.96$ GPa, $G_{12} = G_{13} = 7.1$ GPa, $G_{23} = 3.45$ GPa, $\upsilon_{12} = 0.30$, $\rho = 1645$ kg/m^3. Primenjeni su slojeviti trougaoni konačni elementi s tri čvora. Ljuska je diskretizovana strukturiranom mrežom s dve različite gustine (Mreža 1 – 800 elemenata i Mreža 2 – 3200 elemenata, videti Sliku 3). Granični uslovi su zadati duž uklještenih ivica sprečavanjem svih generalisanih pomeranja u čvorovima. Vrednosti bezdimenzionalnih frekvencija $\Omega = \omega \cdot 100R(\rho/E_2)^{1/2}$ dobijene u analizama poređene su s rezultatima iz [46] dobijenim primenom 2D prstenastih konačnih elemenata, kao i s rezultatima iz [27] dobijenim primenom kontinualnih elemenata baziranih na dinamičkoj matrici krutosti. Vrednosti sopstvenih frekvencija grafički su prikazane na Slici 4, za različite šeme laminacije.

Ovaj primer jasno pokazuje da se progušćenjem mreže dobijaju niže vrednosti sopstvenih frekvencija (konvergencija ka tačnom rešenju). Za **0/90/0** šemu laminacije dobijeno je odlično poklapanje u svim tonovima oscilovanja. Za **90/90/90** šemu laminacije dobijene su nešto niže vrednosti sopstvenih frekvencija u svim tonovima, zbog uticaja deformacije smicanja i idealizacija geometrije ljuske. Uzimanjem ovih napomena u obzir, predloženi model je u stanju da potpuno tačno predvidi sopstvene frekvencije laminatnih kompozitnih ljuski bez oštećenja.

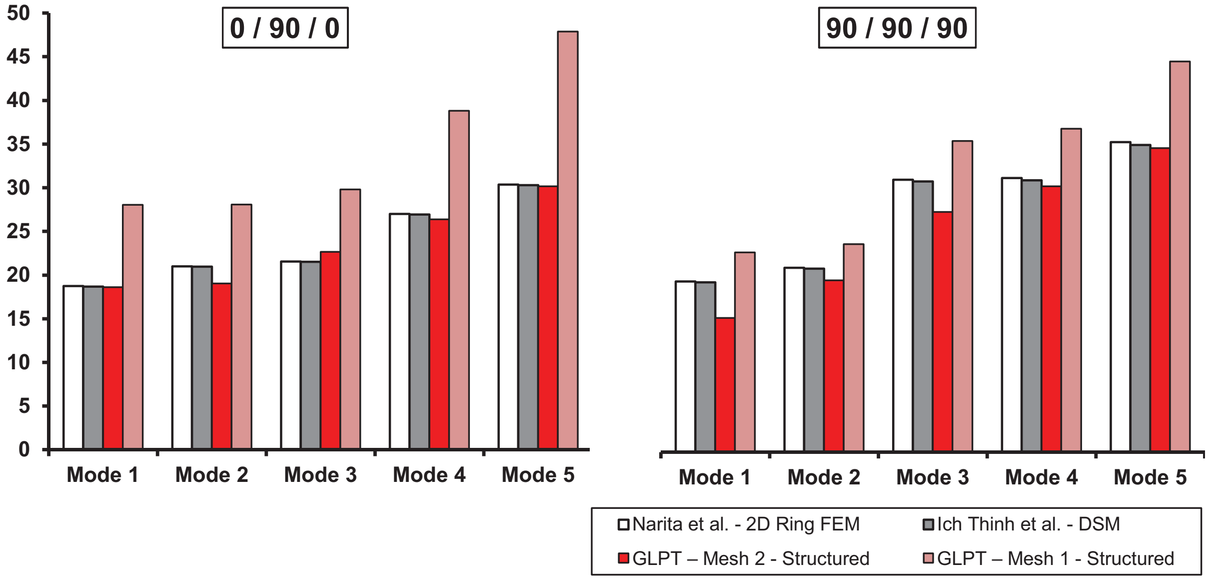
The results presented in Table 2 confirm that the proposed model is capable to accurately predict the fundamental frequencies of intact and delaminated composite plates. The reduction of the fundamental frequency caused by the presence of the delaminated zone is more pronounced for higher modes, for both examined cases.

Example 5.1.3. The third benchmark example is concerned with the cylindrical cross-ply laminated composite shells clamped at both ends. The length of the analyzed shells is L=12m, and the shell radius is R=3m. The shells are composed from three orthotropic layers, each of thickness h_k=0.02m, so the total shell thickness is h=0.06m (length-to-radius ratio L/R=4 and thickness-to-radius ratio h/R=0.02, which is related to thin and moderately long shells). The material parameters (Graphite-Epoxy) for all layers are assumed as [27]: $E_1 = 138$ GPa, $E_2 = E_3 = 8.96$ GPa, $G_{12} = G_{13} = 7.1$ GPa, $G_{23} = 3.45$ GPa, $\upsilon_{12} = 0.30$, $\rho = 1645$ kg/m^3. Layered triangular 3-node elements are used. The shell is discretized using the structured mesh of two different densities (Mesh 1 – 800 elements and Mesh 2 - 3200 elements, see Figure 3). The boundary conditions are prescribed along clamped edges by constraining all generalized displacements in edge nodes. The values of non-dimenzionalized frequency parameters $\Omega = \omega \cdot 100R(\rho/E_2)^{1/2}$ obtained from analyses are compared with the results by Narita et al. [46] using 2D ring FE model and Ich Thinh et al. [27] using continuous element constructed from the dynamic stiffness matrix. The results for fundamental frequencies are graphically interpreted in Figure 4, for different lamination schemes.

This example clearly shows that the mesh refinement leads to the lower values of frequency parameter (convergence to the exact solution). For the **0/90/0** lamination scheme, excellent agreement is obtained for all modes. For the **90/90/90** scheme, the slightly lower frequency parameters are obtained for all modes, because of the influence of the transverse shear deformation and the idealizations regarding the shell geometry. By taking these remarks into account, the presented model is fully capable to accurately predict the fundamental frequencies of intact laminated composite shells.



Slika 3. Strukturirane mreže trougaonih konačnih elemenata
Figure 3. Structured meshes of triangular finite elements



Slika 4. Poređenje bezdimenzionalnih frekvencija $\Omega = \omega \cdot 100R(\rho/E_2)^{1/2}$ cross-ply cilindričnih ljuski uklještenih na oba kraja, dobijenih primenom različitih numeričkih modela
Figure 4. Comparison of frequency parameters $\Omega = \omega \cdot 100R(\rho/E_2)^{1/2}$ of cross-ply cylindrical shells clamped at both ends, obtained using different numerical models

5.2 Geometrijski nelinearna dinamička analiza

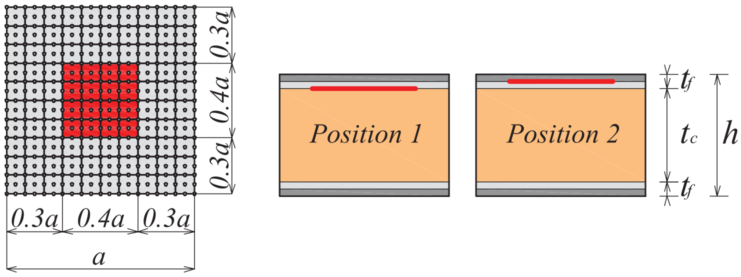
Primer 5.2.1. Poslednji primer ilustruje sposobnost predloženog modela za određivanje nezavisnog kretanja susednih slojeva u zoni delaminacija u sendvič-panelu. Numerički su ispitani linearni i geometrijski nelinearni dinamički odgovori sendvič-ploče s delaminacijom usled naglog eksponencijalnog opterećenja zbog eksplozije. Analizirana je petoslojna (0/90/jezgro/0/90) antisimetrična slobodno oslonjena (SS) kvadratna sendvič-ploča [6, 30]. Panel je napravljen od cross-ply obloge debljine t_f i mekog jezgra debljine t_c, gde je t_c/t_f = 10. Dužina strane ploče je a = 250 *mm*, a njena debljina je h = 2.50 *mm* (a/h = 100). Obloga panela napravljena je od grafit-epoksida T300/934 sa sledećim mehaničkim karakteristikama: $E_{1,f}$ = 131 *GPa*, $E_{2,f}$ = $E_{3,f}$ = 10.34 *GPa*,

5.2 Geometrically nonlinear transient analysis

Example 5.2.1. The final benchmark example illustrates the capability of the proposed model to represent the independent motions of adjacent delaminated interfaces in a sandwich panel. The linear and geometrically nonlinear transient responses of a delaminated sandwich plate under exponential blast pulse loading are investigated numerically. A five layer (0/90/core/0/90) anti-symmetric simply supported (SS) square sandwich plate [6, 30] is analyzed. The plate is composed from cross-ply face sheets, with thickness t_f and a soft core with thickness t_c, where t_c/t_f = 10. The side length of the plate is a = 250 *mm* and its height is h = 2.50 *mm* (a/h = 100). The face sheets are made of Graphite-Epoxy T300/934 with the following mechanical characteristics: $E_{1,f}$ = 131 *GPa*, $E_{2,f}$ = $E_{3,f}$ = 10.34 *GPa*,

$G_{12,f}$ = $G_{23,f}$ = 6.895 *GPa*, $G_{13,f}$ = 6.205 *GPa*, $\upsilon_{12,f}$ = $\upsilon_{13,f}$ = 0.22, $\upsilon_{23,f}$ = 0.49, ρ_f = 1627 kg/m^3. Izotropno meko jezgro napravljeno je od materijala sledećih karakteristika: E_c = 6.89 *MPa*, G_c = 6.895 *MPa*, υ_c = 0, ρ_c = 1550 kg/m^3. Ploča je diskretizovana pomoću mreže od 10×10 slojevitih konačnih elemenata sa devet čvorova s redukovanom integracijom. Jednako podeljeno poprečno opterećenje q_0 = 1.0 kN/m^2 zadato je u vidu eksponencijalnog pulsa $q(t) = q_0 \times e^{-\alpha t}$, trajanja *T = 24 ms*, gde je α = 150 s^{-1} usvojeno kao fiktivni faktor prigušenja. Vremenski inkrement je Δt = *0.8 ms*. Bezdimenzionalni ugib sračunava se kao $w_0 = w \cdot E_{1,f} \cdot h^3/q_0/a^4$. Dinamički odgovor sračunat je za centralno pozicioniranu delaminaciju konstantne površine (videti Sliku 5) na pozicijama 1–2 i prikazan je na Slici 6.

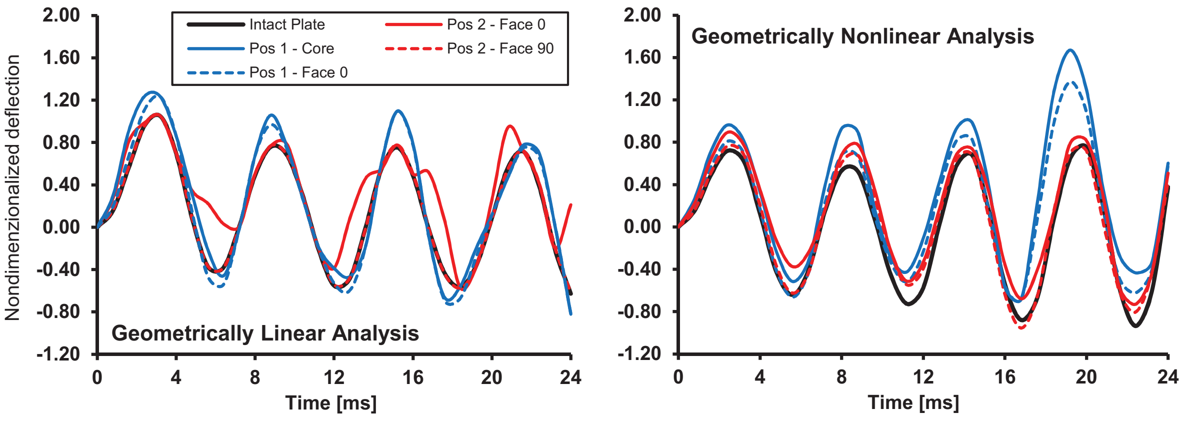
$G_{12,f}$ = $G_{23,f}$ = 6.895 *GPa*, $G_{13,f}$ = 6.205 *GPa*, $\upsilon_{12,f}$ = $\upsilon_{13,f}$ = 0.22, $\upsilon_{23,f}$ = 0.49, ρ_f = 1627 kg/m^3. For the isotropic soft-core the following material parameters are adopted: E_c = 6.89 *MPa*, G_c = 6.895 *MPa*, υ_c = 0, ρ_c = 1550 kg/m^3. The plate is discretized using a 10×10 mesh of 9-node layered finite elements with reduced integration. Uniformly distributed transverse loading q_0 = 1.0 kN/m^2 is prescribed as an exponential pulse $q(t) = q_0 \times e^{-\alpha t}$, with the duration of *T = 24 ms*, using α = 150 s^{-1} as a fictitious damping factor. The time increment is Δt = *0.8 ms*. The normalized centre transverse deflection is calculated as $w_0 = w \cdot E_{1,f} \cdot h^3/q_0/a^4$. The transient response is obtained for centrally located constant-area-delamination (see Figure 5) in positions 1-2 and plotted in Figure 6.



Slika 5. Sendvič-ploča s mekim jezgrom s delaminacijom na različitim pozicijama
Figure 5. Soft-core sandwich plate with different positions of an embedded delamination

Na Slici 6 ilustrovan je uticaj pozicije ranije ubačene delaminacije na rezultate dinamičkog proračuna sendvič-ploče sa oštećenjem. Sendvič-ploča veoma je osetljiva na oštećenje veze između obloge i jezgra, kada je opterećena eksponencijalnim opterećenjem usled eksplozije (plave linije na Slici 6). Ukoliko delaminacija postoji u okviru obloge panela, globalne amplitude pomeranja približno su iste kao i u slučaju neoštećene ploče, jer neoštećen deo ploče ima približno istu krutost na savijanja kao i neoštećena ploča (crvene linije na Slici 6). Razdvojeni segment osciluje lokalno svojom sopstvenom frekvencijom, izazivajući velike otvore prsline. U slučaju geometrijski nelinearne analize, dodatna krutost na savijanje dovodi do redukcije otvaranja prsline u poređenju s linearnom analizom.

Figure 6 illustrates the influence of the position of the previously prescribed delaminated zone on the results of transient analysis of the delaminated sandwich plate. The sandwich plate is highly vulnerable to face-core debonding when subjected to exponential blast pulse loading (blue lines in Figure 6). If the delamination occurs within the face sheets the global amplitudes are nearly the same as for the intact plate because the undamaged part has more or less the same bending stiffness as the intact plate (red lines in Figure 6). The delaminated segment oscillates locally with its local frequency, causing large crack opening displacements. In the geometrically nonlinear case the added bending stiffness leads to the reduction of the crack opening displacements as compared to the linear case.



Slika 6. Promena ugiba u centru dva susedna sloja sendvič-ploče kroz vreme, za različite položaje zone oštećenja
Figure 6. Temporal evolution of the central transverse deflection of two adjacent delaminated interfaces of a sandwich plate considering different positions of the delaminated area

6 ZAKLJUČCI

Na osnovu opšte laminatne teorije ploča izvedeni su slojeviti konačni elementi koji su u stanju da uvedu nezavisno kretanje razdvojenih slojeva. Međusobno prodiranje sloja u sloj sprečeno je uvođenjem kontaktnih uslova između pojedinih slojeva. Geometrijska nelinearnost je uzeta u obzir na osnovu Von Kármán-ovih pretpostavki. Predloženi numerički model primenjen je u numeričkoj analizi slobodnih vibracija i dinamičkog odgovora laminatnih kompozitnih i sendvič-ploča i ljuski s delaminacijama. Mnogim primerima ilustrovano je na koji način delaminacija utiče na fundamentalne dinamičke osobine laminatnih konstrukcija. U narednim radovima predloženi model će biti proširen kako bi se uzela u obzir propagacija delaminacije, pomoću proračuna brzine oslobađanja energije. Iz numeričke analize može se zaključiti:

1. Predloženi model blago (2–4%) precenjuje vrednosti sopstvenih frekvencija kružnih laminatnih kompozitnih ploča, za sve razmatrane šeme laminacije, zbog primene četvorougaonih konačnih elemenata za opisivanje kružne geometrije.

2. Predloženi model je u stanju da precizno predvidi sopstvene frekvencije neoštećenih ili oštećenih kompozitnih ploča. Uvođenjem smičuće deformacije u proračun smanjuju se sopstvene frekvencije neoštećenih i oštećenih kompozitnih ploča. Smanjenje frekvencije zbog prisustva delaminacija izraženije je u višim tonovima, za razmatrane uslove oslanjanja (CC i SS). Sopstvene frekvencije očigledno se povećavaju s porastom stepena ortotropije.

3. Progušćenjem mreže dobijaju se niže vrednosti sopstvenih frekvencija laminatnih kompozitnih cilindričnih ljuski (konvergencija ka tačnom rešenju). Za **0/90/0** šemu laminacije dobijeno je odlično poklapanje u svim tonovima, dok je za **90/90/90** šemu laminacije u svim tonovima dobijena nešto niža sopstvena frekvencija, zbog uticaja deformacije smicanja, kao i zbog idealizacija u pogledu geometrije ljuske.

4. Predloženi model je u stanju da precizno predvidi relativna pomeranja susednih slojeva u oštećenoj zoni. Na dinamički odgovor sendvič-ploča više utiče delaminacija koja se nalazi između mekog jezgra i obloge panela, u poređenju s delaminacijom koja se nalazi između pojedinih slojeva obloge panela. Ovo potvrđuje činjenicu da je čvrsta veza jezgra za oblogu panela od presudnog značaja u projektovanju sendvič-panela.

5. Ukoliko dođe do delaminacija u okviru obloge panela, u geometrijski linearnoj analizi odvojeni segment osciluje lokalno visokom frekvencijom i izaziva kompleksne kontaktne mehanizme između odvojenog sloja i neoštećenog ostatka ploče. U geometrijski nelinearnoj analizi ovaj složeni mehanizam ne postoji zbog prisustva dodatne krutosti na savijanje.

6 CONCLUSIONS

Layered finite plate elements, capable of incorporating the independent motion of delaminated interfaces between layers, have been derived based upon the Generalized Laminated Plate Theory. Interlaminar penetration between delaminated layers was prevented by considering contact conditions between the individual layers. Geometrical nonlinearity is accounted for based upon the Von Kármán assumptions. The proposed numerical model has been applied to the numerical analysis of the free vibrations and the transient response of delaminated composite and sandwich plates and shells. Through the variety of examples it is illustrated how the embedded delamination affect the fundamental dynamic properties of laminated structures. Future work includes the extension of the proposed model to account for propagation of the delamination using Energy Release Rate calculations. From the numerical analyses, the following conclusions are drawn:

1. The proposed model slightly (2-4%) overpredicts the natural frequencies of circular laminated composite plates, for all considered stacking sequences, because of the application of quadrilateral finite elements to describe the circular geometry.

2. The proposed model is capable to accurately predict the fundamental frequencies of intact and delaminated composite plates. The incorporation of the transverse shear deformation reduces the fundamental frequency both for the intact and delaminated composite plates. The reduction caused by the presence of the embedded delamination is more pronounced for higher modes, for examined types of boundary conditions (CC and SS). Natural frequencies obviously increase with the level of orthotropy.

3. The mesh refinement leads to the lower values of natural frequency of laminated composite cylindrical shells. For the **0/90/0** lamination scheme, excellent agreement is obtained for all modes, while for the **90/90/90** scheme, the slightly lower frequency parameters are obtained for all modes, because of the influence of the transverse shear deformation and the idealizations regarding the shell geometry.

4. The proposed model is capable to accurately predict the relative displacements of adjacent laminas in the damaged area. The transient response of sandwich plates is affected more if the delamination is positioned between the soft-core and the rigid face sheets as compared to the delamination within laminas of the face sheet, which confirms that the strong bonding of the soft core to the face sheet is the most critical aspect in the design of sandwich plates.

5. If delamination occurs within the rigid face sheet, when geometrically linear analysis is performed, the delaminated segment oscillates locally with a high frequency, causing complex contact closure and delamination mechanisms between the sheet layer and the intact rest of the plate. In the geometrically nonlinear analysis this complex mechanism is absent due to the added bending stiffness.

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REZIME

PRIMENA SLOJEVITIH KONAČNIH ELEMENATA U NUMERIČKOJ ANALIZI LAMINATNIH KOMPOZITNIH I SENDVIČ-PLOČA I LJUSKI S DELAMINACIJAMA

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Laminatni kompoziti su moderni materijali koji se široko primenjuju u mašinstvu i građevinarstvu. U ovom radu prikazani su odgovarajući moderni pristupi u numeričkoj analizi laminatnih kompozitnih i sendvič-ploča i ljuski s delaminacijom u pojedinim delovima konstrukcije. Za određivanje numeričkog rešenja različitih problema primenjeni su slojeviti konačni elementi bazirani na Reddy-evoj opštoj laminatnoj teoriji ploča. Nakon verifikacije postojećeg modela za konstrukcije bez oštećenja (primenom postojećih podataka iz literature), putem različitih numeričkih primera, analizirani su efekti veličine i položaja delaminacija na odgovor oštećenih laminatnih konstrukcija.

Ključne reči: Laminatni kompozit, Sendvič-ploča, Metod konačnih elemenata, Delaminacija, Kontakt

SUMMARY

APPLICATION OF LAYERED FINITE ELEMENTS IN THE NUMERICAL ANALYSIS OF LAMINATED COMPOSITE AND SANDWICH STRUCTURES WITH DELAMINATIONS

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Laminar composites are modern engineering materials widely used in the mechanical and civil engineering. In the paper, some recent advances in a numerical analysis of laminated composite and sandwich plates and shells of different shapes, with existing zones of partial delamination, are presented. The layered finite elements, based on the extended version of the Generalized Laminated Plate Theory of Reddy, are applied for the numerical solution of several structural problems. After the verification of the proposed model for intact structures using the existing data from the literature, the effects of the size and the position of embedded delamination zones on the structural response of laminated structures are investigated numerically by means of a variety of numerical applications.

Key words: Laminar Composite, Sandwich Plate, Finite Element Method, Delamination, Contact

UPUTSTVO AUTORIMA*

Prihvatanje radova i vrste priloga

U časopisu Materijli i konstrukcije štampaće se neobjavljeni radovi ili članci i konferencijska saopštenja sa određenim dopunama ili bez dopuna. prema odluci Redakcionog odbora. a samo izuzetno uz dozvolu prethodnog izdavača prihvatiće se i objavljeni rad. Vrste priloga autora i saradnika koji će se štampati su: originalni naučni radovi. prethodna saopštenja. pregledni radovi. stručni radovi. konferencijska saopštenja (radovi sa naučno-stručnih skupova). kao i ostali prilozi kao što su: prikazi objekata i iskustava - primeri. diskusije povodom objavljenih radova i pisma uredništvu. prikazi knjiga i zbornika radova. kao i obaveštenja o naučno-stručnim skupovima.

Originalni naučni rad je primarni izvor naučnih informacija i novih ideja i saznanja kao rezultat izvornih istraživanja uz primenu adekvatnih naučnih metoda. Dobijeni rezultati se izlažu kratko. jasno i objektivno. ali tako da poznavalac problema može proceniti rezultate eksperimentalnih ili teorijsko numeričkih analiza i tok razmišljanja. tako da se istraživanje može ponoviti i pri tome dobiti iste ili rezultate u okvirima dopuštenih odstupanja. kako se to u radu navodi.

Prethodno saopštenje sadrži prva kratka obaveštenja o rezultatima istraživanja ali bez podrobnih objašnjenja. tj. kraće je od originalnog naučnog rada. U ovu kategoriju spadaju i diskusije o objavljenim radovima ako one sadrže naučne doprinose.

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Stručni rad predstavlja koristan prilog u kome se iznose poznate spoznaje koje doprinose širenju znanja i prilagođavanja rezultata izvornih istraživanja potrebama teorije i prakse. On sadrži i rezultate razvojnih istraživanja.

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Ostali prilozi su prikazi objekata. tj. njihove konstrukcije i iskustava-primeri u građenju i primeni različitih materijala. diskusije povodom objavljenih radova i pisma uredništvu. prikazi knjiga i zbornika radova. kao i obaveštenja o naučno-stručnim skupovima.

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