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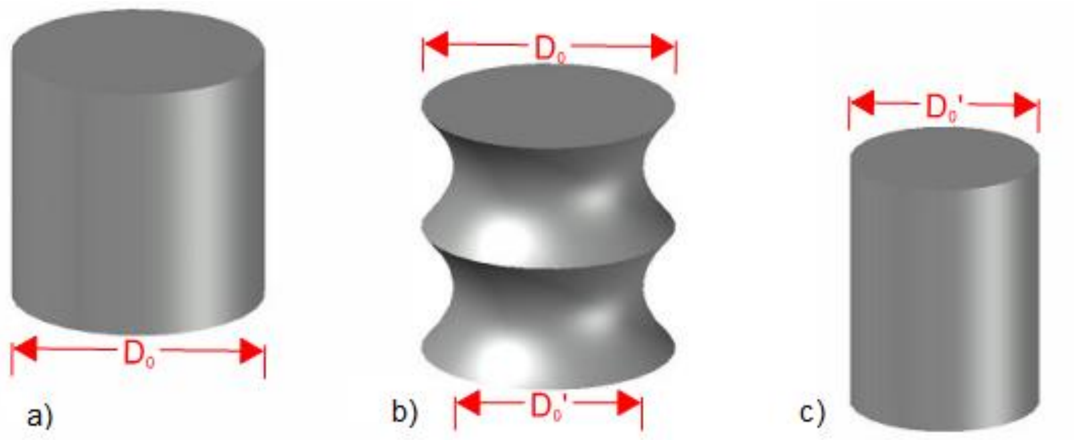

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COVER: Column models: a) Confined volume; b) Effectively confined volume; c) Effectively confined volume by Eurocode 8

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OBEZBEĐENJE LOKALNE DUKTILNOSTI ARMIRANOBETONSKIH ELEMENATA PREMA EVROKODU 8 – KOEFICIJENT UTEZANJA

THE DESIGN OF LOCAL DUCTILITY FOR REINFORCED CONCRETE ELEMENTS BY EUROCODE 8 - CONFINEMENT EFFECTIVENESS FACTOR

Miloš VULINOVIĆ
Ivan MILIĆEVIĆ
Ivan IGNJATOVIĆ

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1 UVOD

Nivo seizmičkog opterećenja, pri elastičnom odgovoru konstrukcije, može biti izuzetno visok i zato ga je veoma teško konstrukcijski prihvatiti. Jedan od načina smanjenja intenziteta seizmičkog opterećenja jeste dopuštanje kontrolisanih neelastičnih deformacija (oštećenja) elemenata konstrukcije, uz zadržavanje integriteta cele konstrukcije, kao i njenih delova. Ovaj tradicionalni koncept prihvatanja seizmičkog opterećenja podrazumeva obezbeđivanje duktilnog ponašanja konstrukcije – globalne duktilnosti, kako bi osnovni zahtev, koji podrazumeva da konstrukcija mora da izdrži pomeranja pri dejstvu zemljotresa, bio ispunjen. Za procenu nelinearnog ponašanja i kapaciteta pomeranja novih i postojećih konstrukcija usled dejstva zemljotresa, moguće je primeniti čitav niz metoda u okvirima linearne i nelinearne analize konstrukcija [1]. Nivo složenosti svake metode zavisi od nivoa aproksimacije uticaja ključnih faktora na ponašanje aproksimacije armiranobetonskih konstrukcija pri dejstvu zemljotresa, što se odnosi, pre svega, na modeliranje opterećenja od zemljotresa, interakcije konstrukcije i tla, nelinearnog ponašanja materijala i prigušenja. Međutim, imajući u vidu jednostavnost i robusnost koje podrazumeva, u praksi se najčešće koristi linearno-elastična analiza, prema kojoj se proračun konstrukcije vrši „prema silama” (*force-based seismic design*).

Miloš Vulinović, mast.inž.građ., vulinovic.milos1@gmail.com
Ivan Milićević, mast.inž.građ., asistent - student doktorskih studija, Građevinski fakultet Univerziteta u Beogradu, Bulevar kralja Aleksandra 73, ivanm@imk.grf.bg.ac.rs
Ivan Ignjatoavić, profesor dr, Građevinski fakultet Univerziteta u Beogradu, Bulevar kralja Aleksandra 73, ivani@imk.grf.bg.ac.rs

1 INTRODUCTION

The level of the seismic load, at an elastic response of the structure, can be extremely high and as such, it can be very difficult for a structure to sustain it. One option for reducing seismic loads on structure is to allow controlled inelastic deformations (damages) to structural elements while maintaining the integrity of both the entire structure and all of its parts. This concept of sustaining seismic loads presumes that the ductile behaviour of the structure i.e. global ductility is provided in order to fulfil the basic requirement in seismic design – the structure must withstand displacements at seismic ground motions. To evaluate the non-linear behaviour and displacement capacity of new and existing structures due to seismic effects, a variety of methods can be applied using linear or non-linear structural analysis [1]. The level of complexity of each method depends on the approximation level of the influence of key factors on the behaviour of reinforced concrete structures during the earthquake. It relates to the modelling of seismic loads, soil-structure interaction, non-linear material behaviour and damping. However, given the simplicity and robustness it entails, linear elastic analysis is most commonly used in practice, with design of structure based on seismic forces (so-called force-based seismic design).

Milos Vulinovic, MSc Civ. Eng., vulinovic.milos1@gmail.com
Ivan Milicevic, Teaching Assistant - PhD student, MSc Civ. Eng., University of Belgrade, Faculty of Civil Engineering, Belgrade,Bulevar kralja Aleksandra 73, ivanm@imk.grf.bg.ac.rs
Ivan Ignjatovic, Associate Prof. Ph.D., University of Belgrade, Faculty of Civil Engineering, Belgrade, Bulevar kralja Aleksandra 73, ivani@imk.grf.bg.ac.rs

Koncept projektovanja novih konstrukcija primenom linearne analize zasniva se na dimenzionisanju elemenata prema proračunskoj (redukovanoj) seizmičkoj sili F_y. Pretpostavlja se linearno ponašanje konstrukcije sve do dostizanja pomeranja na granici tečenja d_y, dok se povećanje pomeranja do pomeranja usled projektnog seizmičkog dejstva d_m realizuje nelinearnim ponašanjem konstruktivnih elemenata – pojavom plastičnih zglobova u elementima, uz nepromenjeni nivo proračunskog seizmičkog opterećenja. Potrebna ili ciljana globalna duktilnost definisana je faktorom duktilnosti pomeranja $\mu_\delta = d_m/d_y$.

Dokaz postignute globalne duktilnosti prema Evrokodu 8 sprovodi se na lokalnom nivou, obezbeđivanjem zahtevanog faktora duktilnosti krivine poprečnih preseka primarnih seizmičkih elemenata [2] i zasnovan je na neelastičnom spektru odgovora sistema s jednim stepenom slobode – predložili su Vidic i ostali [9]. Iz izraza koji su predloženi u [9], očigledno je da globalna duktilnost direktno zavisi od faktora ponašanja. Faktor ponašanja jeste koeficijent kojim se elastičan spektar odgovora deli i koji zavisi od klase duktilnosti konstrukcije (DCL – niska, DCM – srednja, DCH – visoka), tipa konstrukcijskog sistema za prihvatanje seizmičkih uticaja i regularnosti sistema po visini. Klasa duktilnosti, iako se odnosi na globalnu duktilnost, zapravo dominantno zavisi od obezbeđene lokalne duktilnosti, kao i od načina oblikovanja detalja armiranja zona elemenata u kojima se ostvaruju plastične deformacije – plastični zglobovi. Dakle, prema proceduri proračuna saglasno Evrokodu 8, veza između globalne i lokalne duktilnosti ostvaruje se putem koeficijenta q i niza zahteva za armiranje plastičnih zglobova u kojima on figuriše. Plastični zglobovi projektuju se na krajevima horizontalnih elemenata konstrukcije – gredama, kao i u uklještenju vertikalnih elemenata – stubovima i zidovima. Poželjni, pouzdani plastični mehanizam, prema principu programiranog ponašanja, obezbeđuje se pojavom plastičnih zglobova u gredama pre pojave plastičnih zglobova u stubovima i zidovima.

Nekoliko primera armiranja i oblikovanja detalja greda, stubova i zidova za njihovu lokalnu duktilnost prema Evrokodu 8 prikazao je Milev [5]. Milićević i Ignjatović [6] ukazali su na razlike u armiranju AB stubova i greda u slučajevima njihove klasifikacije kao primarnih odnosno sekundarnih seizmičkih elemenata prema Evrokodu 8, sa akcentom na potrebnu količinu poprečne armature za obezbeđivanje duktilnog ponašanja konstrukcije pri dejstvu zemljotresa.

U radu je analiziran koncept obezbeđivanja lokalne duktilnosti vertikalnih armiranobetonskih elemenata prema Evrokodu 8 [2], iz aspekta ostvarivanja zahtevanog faktora duktilnosti krivine poprečnog preseka. Posebna pažnja posvećena je mehanizmu utezanja AB stubova odnosno faktoru efikasnosti utezanja preseka u kritičnim oblastima poprečnom armaturom – uzengijama i poprečnim vezama. Objašnjeno je praktično značenje faktora efikasnosti utezanja i analizirane su različite varijante armiranja iz prakse.

The concept of designing new structures using linear analysis is based on the dimensioning of the elements according to the design (reduced) seismic force F_y. The linear behaviour of the structure is assumed until reaching the displacement at yielding d_y, while the increase of displacement to displacement due to design seismic action d_m is achieved by the non-linear behaviour of structural elements - the appearance of plastic hinges in the elements, with the unchanged level of design seismic load. The required or targeted global ductility is defined by the displacement ductility factor $\mu_\delta = d_m/d_y$.

The proof of achieved global ductility according to Eurocode 8 is conducted locally, by providing the required curvature ductility factor of the cross-sections of primary seismic elements [2] and it is based on the inelastic response spectrum of a single degree of freedom system (SDOF), proposed by Vidic et al. [9]. From the equations proposed in [9] it is obvious that global ductility depends directly on the behaviour factor. The behaviour factor is the coefficient by which the elastic response spectrum is divided and depends on the ductility class of the structure (DCL - low, DCM - medium, DCH - high), the type of structural system for accepting seismic impacts and the regularity of the system in height. The ductility class, although related to global ductility, is in fact predominantly dependent on the provided local ductility, as well as the reinforcement detailing of the zones of elements in which plastic deformations occur - plastic hinges. Thus, according to the calculation procedure in Eurocode 8, the connection between global and local ductility is realized through the coefficient q and a series of requirements for reinforcing the plastic hinges in which it appears. Plastic hinges are designed at the ends of horizontal structural elements - beams, as well as in the base of vertical elements - columns and walls. A desirable, reliable plastic mechanism, according to the principle of capacity design, is provided by the appearance of plastic hinges in beams before the appearance in columns and walls.

Several examples of reinforcement detailing of beams, columns and walls for their local ductility according to Eurocode 8 were presented by Milev [5]. Milicević and Ignjatović [6] pointed out differences in reinforcement of RC columns and beams in cases of their classification as primary or secondary seismic elements according to Eurocode 8, with emphasis on the required amount of transverse reinforcement to ensure ductile structural behaviour under seismic loads.

This paper analyzes the concept of providing local ductility of vertical reinforced concrete elements according to Eurocode 8 [2], from the aspect of achieving the required curvature ductility factor of the cross-section. Special attention was paid to the mechanism of confinement of RC columns, i.e. the confinement effectiveness factor of cross-section in critical areas with transverse reinforcement - stirrups and cross-links. The practical significance of the confinement effectiveness factor was explained and various reinforcement details common in practice were analyzed.

2 LOKALNA DUKTILNOST AB STUBOVA

Da bi se osiguralo duktilno ponašanje u lokalizovanim zonama konstrukcije (plastičnim zglobovima), materijali moraju da budu u stanju da postignu odgovarajuće deformacije. Lokalna duktilnost armiranobetonskih elemenata, na nivou poprečnog preseka, postiže se povećanim izduženjima čelika (ε_s), kao i skraćenjima pritisnutog betona (ε_c), odnosno odgovarajućom duktilnošću krivine preseka. Faktor duktilnosti krivine definisan je kao odnos granične krivine i krivine pri tečenju $\mu_\varphi=\varphi_u/\varphi_y$, gde je φ_y krivina AB preseka pri tečenju (armature), a φ_u granična krivina AB preseka.

Prema [3], krivina preseka pri tečenju AB stubova opterećenih aksijalnom silom pritiska definiše se za sledeća dva moguća slučaja:

a) krivina pri dilataciji na granici razvlačenja zategnute armature ($\varepsilon_s=\varepsilon_{yd}$);

b) krivina pri velikim dilatacijama pritiska na gornjoj (pritisnutoj) ivici betonskog preseka.

Prema Panagiotakosu i Fardisu [3], usled velike normalne sile, može doći do nelinearnog ponašanja pritisnute zone betonskog preseka, pre pojave tečenja zategnute armature. Autori su za proračun krivine pri pojavi tečenja, u slučajevima visokog nivoa normalne sile u stubovima, predložili gornju granicu dilatacije na pritisnutoj ivici betonskog preseka jednaku $1{,}8\cdot f_c/E_c$, gde je f_c čvrstoća betona pri pritisku, a E_c – modul elastičnosti betona.

Granična krivina AB preseka φ_u definisana je odnosom granične dilatacije pritiska utegutog betona i odgovarajuće visine neutralne ose. Određivanje krivine preseka pri lomu zavisi od nivoa opterećenja, količine armature, kao i toga da li je dostignuta granica loma betona ili armature, i tako dalje. U zavisnosti od vrednosti pomenutih parametara, pri određivanju krivine preseka razmatra se ukupni poprečni presek betonskog elementa ili samo utegnuti presek (ukupni presek umanjen za neutegnuti zaštitni sloj betona).

Raznim eksperimentima je ustanovljeno da duktilnost betona znatno raste kada se dovede u stanje triaksijalne kompresije [7]. Ovakvo stanje može se postići utezanjem elementa poprečnom armaturom u vidu zatvorenih uzengija ili spiralne armature. Na taj način, sprečava se bočno širenje elementa usled aksijalne sile. Posledice toga su povećanje čvrstoće betonskog elementa i razvijanje većih graničnih dilatacija $\varepsilon_{cu,c}$, znatno većih od 3,5‰, čime se ostvaruje veća granična krivina preseka φ_u. Parametri koji utiču na stepen utezanja jesu: količina poprečne armature (ρ_w), čvrstoća čelika (oblik dijagrama napon–dilatacija), čvrstoća betona na pritisak (oblik dijagrama napon–dilatacija), razmak, oblik i broj uzengija, kao i podužne (vertikalne) armature.

Bočne sile, koje se javljaju kao posledica sprečenog širenja betonskog elementa, deluju u nivou uzengija. Prema Fardisu [3], smatra se da efekti utezanja dolaze do izražaja pri dostizanju aksijalnog napona pritiska približno jednakom čvrstoći betona pri pritisku, kao i da ne dolazi do ojačanja armature za utezanje nakon dostizanja granice tečenja, već se za graničnu vrednost usvaja napon pri tečenju. Najveći bočni pritisak može se razviti samo na onom delu betonskog elementa gde se nalazi armatura za utezanje. Zbog ovakvog delovanja bočnog pritiska maksimalna vrednost mora biti korigovana koeficijentom utezanja. Ovaj koeficijent utiče

2 LOCAL DUCTILITY OF RC COLUMNS

In order to ensure ductile behaviour in the localized structural zones (plastic hinges), materials must be able to achieve appropriate deformations. Ductility of the reinforced concrete elements, at the cross-sectional level, is achieved by the increased elongation of the steel (ε_s), as well as by corresponding concrete compression deformation (ε_c), i.e. appropriate cross-section ductility curvature. The curvature ductility factor is defined as the ratio of the ultimate curvature and the curvature at yielding $\mu_\varphi=\varphi_u/\varphi_y$, where φ_y is the curve of RC cross-section at yielding (of reinforcement) and φ_u is the ultimate curve of RC cross-section.

According to [3], the yield curvature of cross-section is defined for two possible cases:

a) The curvature with strain at yielding of the tensioned reinforcement ($\varepsilon_s=\varepsilon_{yd}$),

b) The curvature with large pressure strains on the upper (pressed) edge of the concrete cross-section.

According to Panagiotakos and Fardis [3], due to the large normal force, a non-linear behaviour of the compressed zone of the concrete cross-section may occur, before steel yielding. The authors proposed to calculate the curvature at yielding, in cases with large normal forces in columns, by limiting the strain of compressed fibre of the concrete cross-section to a value of $1{,}8\cdot f_c/E_c$, where f_c is the compressive strength of concrete and E_c is the modulus of elasticity of concrete.

The ultimate curvature of the RC cross-section φ_u is defined by the ratio of the ultimate strain of the compressed confined concrete and the corresponding depth of the neutral axis. Determination of the cross-sectional ultimate curvature depends on the load level, the amount of reinforcement, the failure of the section due to rupture tension reinforcement or compressed concrete, etc. Depending on the values of the mentioned parameters, failure of the section can be achieved before spalling of the concrete cover or curvature at the spalling of the concrete cover.

Various experiments have shown that the ductility of the concrete significantly increases when it enters the state of triaxial compression [7]. This condition can be achieved by confining the element with a transverse reinforcement in the form of hoops and ties or spiral reinforcement. This prevents the lateral expansion of the element due to the axial compression force. As a result, the strength of the concrete element increases and the development of higher ultimate stain of cross-section compression fibres $\varepsilon_{cu,c}$, significantly greater than 3.5‰, which results in a larger ultimate curvature of cross-section φ_u. The parameters that affect degree of confinement are: quantity of transversal reinforcement (ρ_w), steel strength (stress-strain diagram), concrete compression strength (stress-strain diagram), distance, shape and number of stirrups as well as longitudinal (vertical) reinforcement.

The lateral forces, which occur as a result of the prevented lateral expansion of the concrete element, act at the level of the stirrups. According to Fardis [3], it is considered that the confinement begins at achieving the approximate compression strength of the concrete, and that the stirrups fail to go into hardening when reaching the ultimate stress and hence the value of stress at yielding is adopted as the limit value. The highest lateral na čvrstoću betona, naravno, u zavisnosti od oblika i količine poprečne armature.

Kako bi se obezbedila minimalna duktilnost kritičnih zona armiranobetonskih elemenata koje prihvataju seizmičko opterećenje, Evrokod 8 propisuje minimalne vrednosti količine poprečne i podužne (vertikalne) armature, njihove prečnike i međusobna rastojanja. Ispunjavanjem ovih uslova, te dobrim oblikovanjem i konstruisanjem položaja plastičnih zglobova, konstrukciji se omogućava da prihvati redukovane seizmičke sile, sa odgovarajućim nelinearnim deformacijama.

pressure can be developed only on the part of the concrete element where the confinement reinforcement is located. Due to this effect of lateral pressure, the maximum value must be reduced by confinement effectiveness factor. This coefficient affects the strength of concrete, depending on the shape and quantity of the transversal reinforcement.

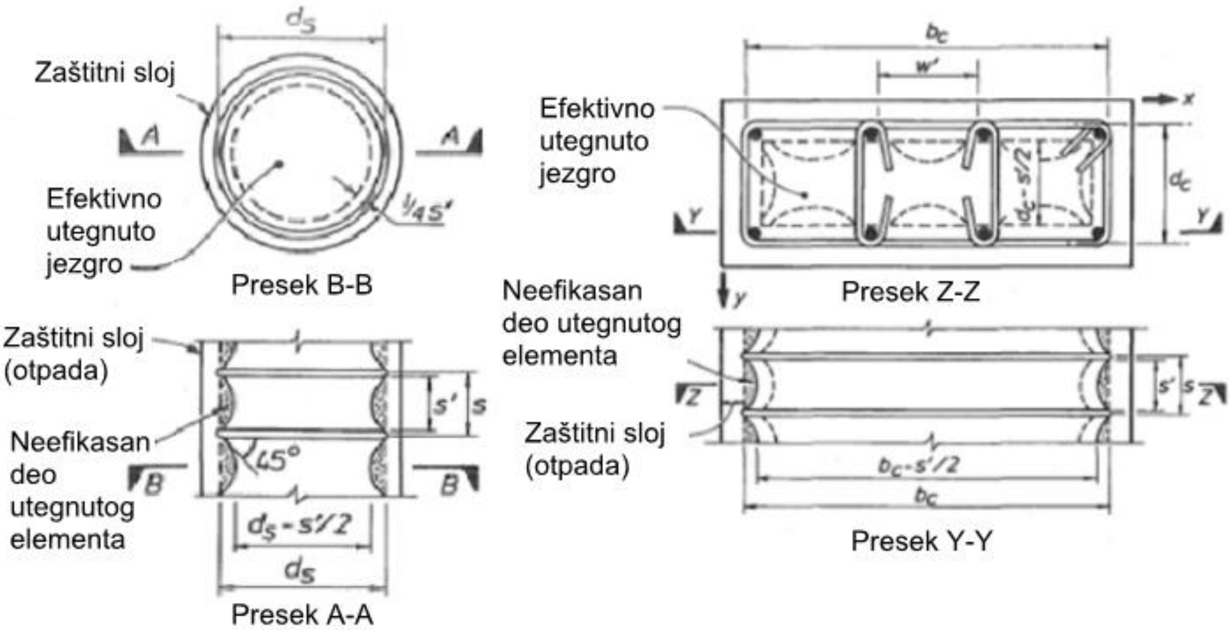
With the aim of the confined zones to be ductile, Eurocode 8 suggests minimum values of the quantity of transversal and longitudinal (vertical) reinforcement, their diameters and their mutual distances. Complying with these conditions, designing good reinforcement details and distinguishing the places of plastic hinges throughout the structure allow the structure to accept seismic forces with certain inelastic deformations.

3 KOEFICIJENT UTEZANJA

Na slici 1 prikazana je teorijska pretpostavka oblika efektivnog dela betonskog elementa, kako pokazuju Sheikh i Uzumeri [8], a kasnije i Mander i ostali [4], u poprečnom preseku (B-B i Z-Z) i duž visine samog elementa (A-A i Y-Y). Pretpostavljeni oblik efektivno utegnutog preseka betona smanjuje se na mestima na kojima nema uzengija. Oblik promene je parabola s tangentama u krajnjim tačkama od 45˚, sa žižom od četvrtine dužine.

3 CONFINEMENT EFFECTIVENESS FACTOR

In Figure 1 the theoretical assumption of the shape of concrete element effective area is shown by Sheikh and Uzumeri [8], and later Mander et al. [4], in the cross-section (B-B and Z-Z) and along the height of the element itself (A-A and Y-Y). The assumed form of the effective cross-section of concrete is reduced in places without hoops or ties. The shape of the assumed volume of effective confined element is a parabola with tangents at the endpoints of 45˚, with apex of a quarter of length between hoops or ties.

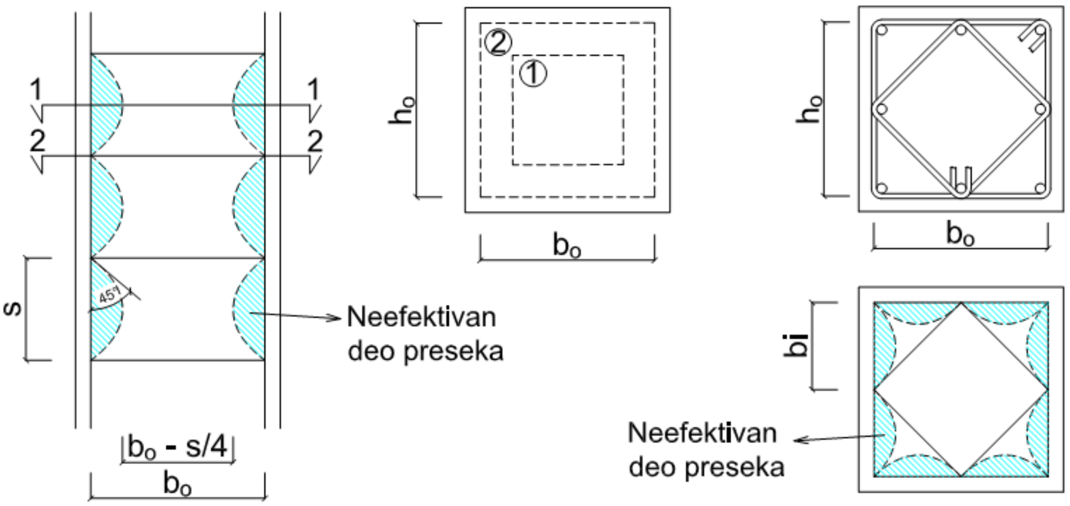


Slika 1. Efektivno utegnut presek s kružnim i pravougaonim uzengijama [4]
Figure 1. Effectively confined cross-section with circular and rectangular stirrups [4]

Koeficijent utezanja (α) predstavlja faktor efikasnosti utezanja poprečnom armaturom. Ovaj faktor, prema propisima Evrokoda 8, sadrži dva činioca α_s i α_n. Prvi član definiše odnos površina preseka 1 i 2 označenih na slici 2 – izrazi (1) i (3). Presek u ravni 1 predstavlja minimalni poprečni presek koji se može javiti prilikom otpadanja neefikasno utegnute zone betonskog elementa, dok drugi predstavlja presek u kojem se nalazi

Confinement effectiveness factor (α) represents the efficiency factor of the transversal reinforcement. This factor, according to Eurocode 8, is defined as a product of two factors α_s and α_n. First one defines the ratio of the surfaces of sections 1 and 2 shown on Figure 2 - equations (1) and (3). The cross-section at level 1 represents the minimum cross-section which can occur after spalling the ineffective area of concrete element, armatura za utezanje. Ovim članom uzima se u obzir efikasnost utezanja po visini elementa, koja zavisi od relativnog odnosa razmaka uzengija (s) i dimenzija utegnutog betonskog preseka (širine i visine označene sa b_o i h_o respektivno). Drugim članom umanjuje se efektivna površina betona za zbir svih neefektivnih delova između podužnih šipki armature prikazanih na slici 2 – izrazi (2) i (4). Ovim članom uzima se u obzir efikasnost utezanja na nivou poprečnog preseka.

while the other is cross-section in which the stirrups are located. First factor takes into account the confinement efficiency along the element that depends on relative ratio of the stirrups distance (*s*) and the dimensions of the concrete cross-section (width and height indicated by $b_o$and h_o respectively).The second factor reduces the effective surface area of concrete for the sum of all ineffective parts between longitudinal rebar shown in Figure 2 - equations (2) and (4). With this factor the efficiency of confinement at the cross-sectional level is taken into account.



Slika 2. Definisanje koeficijenta utezanja
Figure 2. Defining of confinement effectiveness factor

Za pravougaoni poprečni presek:

For rectangular section:

$$\alpha_s = \left(1 - \frac{s}{2 \cdot b_o}\right)\left(1 - \frac{s}{2 \cdot h_o}\right) \tag{1}$$

$$\alpha_n = 1 - \sum_{i=1}^{n} \frac{b_i^2}{6 \cdot b_o \cdot h_o} \tag{2}$$

Za kružni poprečni presek:

For circular section:

$$\alpha_s = \left(1 - \frac{s}{2 \cdot D_o}\right)^2 \tag{3}$$

$$\alpha_n = 1 \tag{4}$$

Prilikom dostizanja graničnih dilatacija, odlama se zaštitni sloj betona, pa – shodno tome – efektivni presek, za takva stanja dilatacija, inicijalno postaje umanjen za debljinu tog sloja, odnosno dobijamo dimenzije utegnutog preseka:

a) Pravougaoni presek

When element is reaching the ultimate strains, the cover of concrete start spalling and, consequently, the effective cross-section for such strains initially becomes smaller for thickness of that layer, i.e. we have dimensions of the smaller, confined, section:

a) For rectangular section:

$$h_o = h_c - 2 \cdot (c - d_{bh}/2) \tag{5}$$

$$b_o = b_c - 2 \cdot (c - d_{bh}/2) \tag{6}$$

b) Kružni presek

b) For circular section:

$$D_o = D_c - 2 \cdot (c - d_{bh}/2) \tag{7}$$

gde su b_c i h_c dimenzije pravougaonog betonskog poprečnog preseka, D_c prečnik kružnog preseka, a d_{bh} prečnik armature za utezanje – uzengija i poprečnih veza.

Redukovanjem površine ograničene spoljnim uzengijama koeficijentima određenim prema propisima Evrokoda 8, došli smo do koeficijenta utezanja, odnosno do efektivno utegnute površine (slika 3). Ako uporedimo interpretacije koeficijenata utezanja prikazane na slikama 1 i 3, tj. prema teorijskoj pretpostavci i izrazima Evrokoda 8, zaključujemo da je veoma teško ustanoviti fizički smisao izraza. Postavlja se pitanje kako izrazi Evrokoda 8 dobijenu efektivnu površinu interpretiraju i po visini elementa, odnosno koji deo stuba se smatra efektivno utegnutim.

where b_c and h_c are dimensions of the rectangular concrete cross-section, D_c is diameter of the circular cross-section and d_{bh} is diameter of the confinement rebar – hoops or ties.

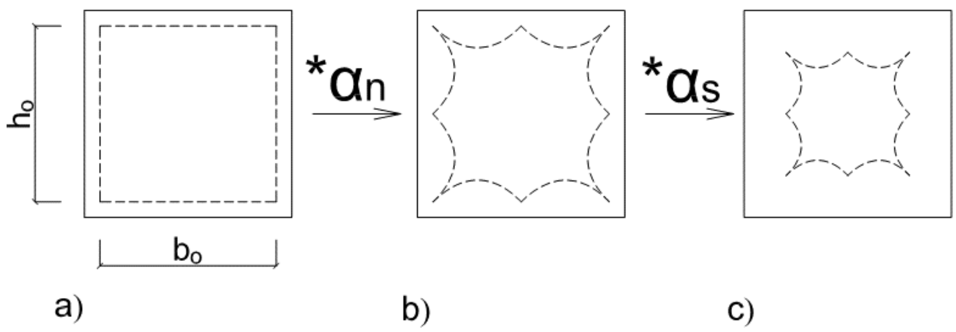
By reducing the area surrounded by external stirrup, according to the Eurocode 8 regulations, we have determined the confinement effectiveness factor, i.e. the effectively confined area (Figure 3). When the interpretations shown on Figure 1 and 3 are compared according to the theoretical assumption and equations of Eurocode 8, it can be concluded that it is very difficult to determine the real meaning of the equations. The question that should be answered is how recommendations of Eurocode 8 interpret the effective area by the height of the element, i.e. which part of the column is considered effective.

4 ANALIZA REALIZOVANOG KOEFICIJENTA UTEZANJA

Kako bismo shvatili oblik efektivno utegnutog elementa duž visine stuba prema izrazima (1)-(4), a imajući u vidu da koeficijent utezanja predstavlja odnos efektivne utegnute površine (slika 3c) i površine utegnutog preseka (slika 3a), pretpostavljamo da to, takođe, može biti odnos zapremina efektivno utegnutog i utegutog dela elementa. Pretpostavljamo da izrazi Evrokoda 8 efektivnu zapreminu interpretiraju kao „prizmu” s bazom površine sa slike 3c, tj. da promene efektivne površine po visini elementa nema.

4 ANALYSIS OF THE ACHIEVED CONFINEMENT EFFECTIVENESS FACTOR

In order to understand the shape of an effectively confined element along the height of the column according to the equations (1)-(4), and taking into account that the confinement effectiveness factor is the ratio of the effective confined area (Figure 3c) and confined area (Figure 3a), it is assumed that this can also be the ratio of the effectively confined and confined volume of the element. It is assumed that the equations of the Eurocode 8 interpret the effective volume as a "prism" with the base shown on Figure 3c, i.e. that there are no changes in the effective volume along the height of element.

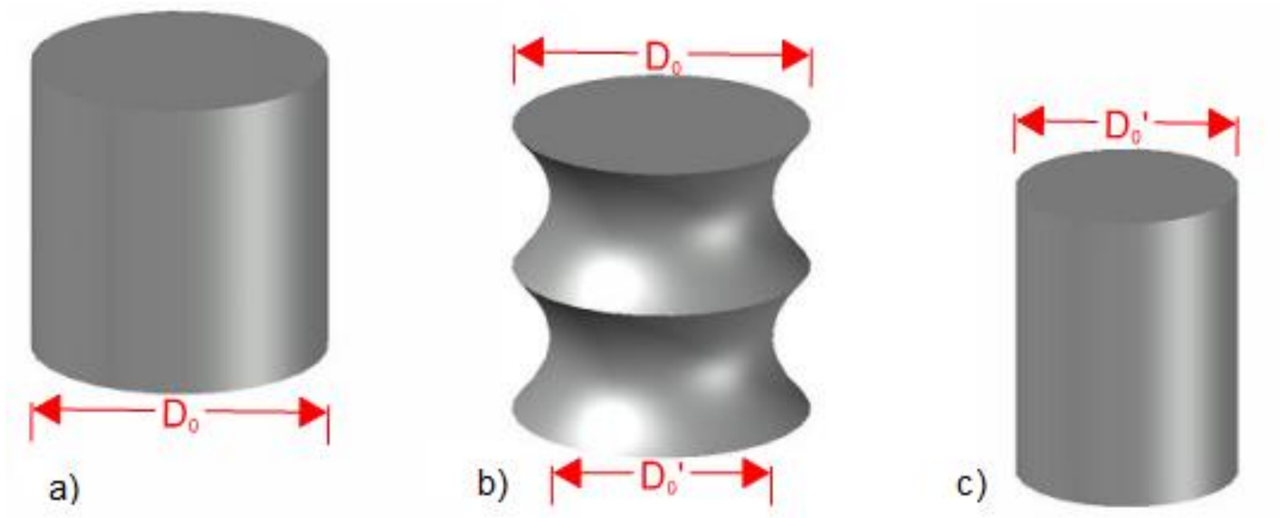


Slika 3. Interpretacija koeficijenta utezanja skaliranjem preseka sa α_n i α_s
Figure 3. Interpretation of the confinement effectiveness factor by scaling cross-section with factors α_n and α_s

Analizu prvo sprovodimo na jednostavnijem obliku stuba, odnosno na stubu kružnog poprečnog preseka, prečnika utegnutog preseka D_o=40 cm i razmaka uzengija s=20 cm. Prvi parametar za analizu predstavlja koeficijent utezanja prema izrazima Evrokoda 8, tj. izrazima (3) i (4), koji nazivamo α[EC8]. Dalje, konstruišemo tri trodimenzionalna elementa, od kojih je prvi stub prečnika D_o (slika 4a). Drugi element predstavlja efektivnu zapreminu prema teorijskoj pretpostavci Mander i ostali [4], s bazom efektivno utegnutog jezgra prikazanog na Preseku B-B (slika 1) i podužnom promenom u svemu prema Preseku A-A. Ovakav model prikazan je na slici 4b. Odnosom zapremina modela sa slike 4b i 4a dobijamo teorijski

The analysis starts with a simpler form of a column, i.e. a circular cross-section. The diameter of the cross-section is D_o=40 cm and stirrup spacing s=20 cm. The first parameter for the analysis is the confinement effectiveness factor according to the assumptions of the Eurocodes 8, i.e. equations (3) and (4), which is named α[EC8]. Subsequently, three three-dimensional elements are designed, where the first is a column with diameter D_o (Figure 4a). The second element represents the effective volume according to the theoretical assumption of Mander et al. [4], with the base of the effectively confined core shown in Section B-B (Figure 1), and a vertical change of shape along the height of element according to Section A-A. This model is shown in Figure koeficijent utezanja preseka i nazivamo ga α[ACAD]. Prema rezultatima iz tabele 1, vidimo da je koeficijent utezanja prema izrazima manji i da nagoveštava da su propisi usvojili nešto jednostavniji, a sigurno konzervativniji oblik efektivno utegnutog elementa. Treći model predstavlja pretpostavljen „cilindar” (slika 4c). U slučaju kružnog stuba, kako je koeficijent α_n=1, imamo da je prečnik baze „cilindra” jednak Do’ = Do-2·s/4 = 30 cm, a koeficijent utezanja koji računamo kao odnos modela sa slike 4c i slike 4a, naziva se α[EC8-ACAD]. Iz tabele 1 vidimo potpuno poklapanje rezultata za α[EC8] i α[EC8-ACAD], što znači da je pretpostavka ostvarena za kružni poprečni presek. Takođe, za kružni presek zaključujemo da je prečnik osnove trećeg modela ustvari jednak najmanjem prečniku teorijskog modela duž visine stuba, odnosno na sredini rastojanja između dve uzengije.

4b. With ratio of the model volume represented on Figures 4b and 4a the theoretical confinement effectiveness factor is obtained, which is named α[ACAD]. According to the results from Table 1, it can be concluded that the confinement effectiveness factor by equations is smaller and suggests that the regulations of Eurocode 8 adopted a simpler, but certainly more conservative form of an effectively confined element. The third model is assumed to be a "cylinder" (Figure 4c). In the case of a circular column, as the coefficient α_n=1, the diameter of the base cylinder is equal to Do’ = Do-2·s/4 = 30 cm, and the confinement effectiveness factor is calculated as the ratio of the model from Figures 4c and 4a and named α[EC8-ACAD]. From Table 1 it can be noticed that there is a complete match of the results for α[EC8] and α[EC8-ACAD], which means that the assumption made for a circular cross-section is fulfilled. In addition, for a circular cross-section, it can be concluded that the base diameter of the third model is actually equal to the smallest diameter of the theoretical model along the height of the column which is in the middle of the two stirrups.



Slika 4. Modeli stuba: a) Utegnut presek; b) Efektivno utegnuto jezgro elementa; c) Efektivno utegnut element prema Evrokodu 8

Figure 4. Column models: a) Confined volume; b) Effectively confined volume; c) Effectively confined volume by Eurocode 8

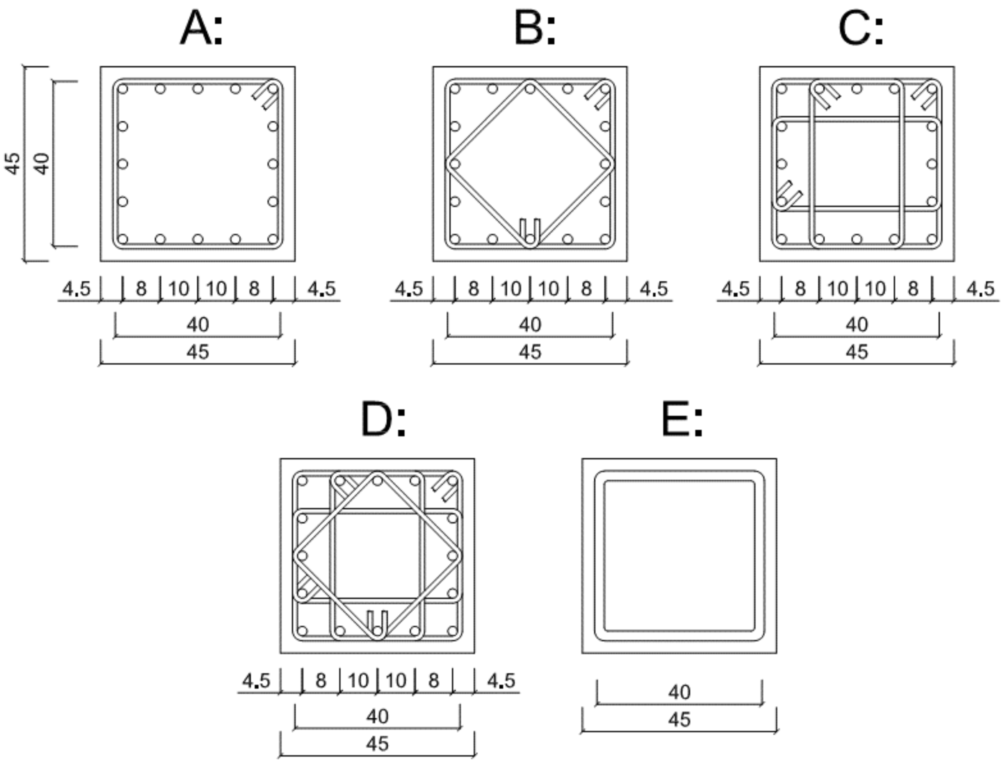
Tabela 1. Koeficijenti utezanja kružnog stuba
Table 1. Confinement effectiveness factor for circular column

Oblik stuba *Column shape*	Prečnik *Diameter* [cm]	Razmak uzengija *Stirrups spacing* [cm]	α [EC8]	α [ACAD]	α [EC8-ACAD]
Kružni *Circular*	40	20	0,5625	0,6974	0,5625

Pošto smo s dovoljnom tačnošću zaključili šta predstavlja bazu „cilindra”, dalje analiziramo kvadratne stubove. Izabrano je nekoliko tipičnih načina armiranja (slika 5). Model A predstavlja presek s najmanjim mogućim stepenom armiranja, koji ne ispunjava minimalne uslove lokalne duktilnosti Evrokoda 8 u

Since it is concluded, with sufficient accuracy, what is the base of "cylinder", square columns are further analyzed. Several typical reinforcement forms have been selected (Figure 5). Model A represents the section with least possible reinforcement, which does not meet the minimum local ductility requirements by Eurocode 8, in pogledu armiranja, ali je pogodan za modeliranje i suštinski bitan – kao početni reper u analizi. Modeli B, C i D česti su slučajevi armiranja u praksi, kod kojih sukcesivno smanjujemo neefektivnu zonu, dok je poslednji presek model E armiran tako da predstavlja teorijski najveći mogući efekat utezanja, koji bi trebalo da zameni kružnu uzengiju i postigne ekvivalentni efekat utezanja. Generalno, za pretpostavljene dimenzije stuba minimalno armiranje je predstavljeno modelom B (slika 5), kako bi se zadovoljio minimalan razmak podužnih pridržanih šipki armature od 20cm, s minimalnim prečnikom armature Ø8. Prema Evrokodu 8, minimalni prečnik uzengije jeste Ø6 na rastojanju koje nije veće od $b_o/2$, 17,5 cm ili 8 minimalnih prečnika podužne (vertikalne) armature u stubu. Broj i prečnici poprečnih šipki mogu biti i veći, što zavisi od intenziteta uticaja u elementu kao i zadovoljenja izraza 5.15 datog u [2], koji treba da obezbedi minimalnu zahtevanu vrednost faktora duktilnosti krivine. Za potrebe analize, usvojene dimenzije utegnutog dela preseka su $b_o=d_o=40$ cm s razmakom uzengija od s=20 cm.

terms of reinforcement, but is suitable for modelling and essentially important as the starting point in the analysis. Models B, C and D are common types of reinforcement details in practice, in which the ineffective zone is reduced one after the other, while the last cross-section, model E, is detailed to represent the highest possible confinement, which should, theoretically, achieve the circular hoops effect of confinement. In general, for the assumed dimensions of the column, the minimal reinforcing provisions are represented by model B (Figure 5), which satisfies the minimum spacing of longitudinal reinforcement with 20 cm and minimum diameter Ø8. According to Eurocode 8, minimum diameter of the stirrup is Ø6 at distance less than $b_o/2$, 17.5 cm or 8 thicknesses of the longitudinal reinforcement. Number and diameter of the rebar can be even higher, which depends on load level and satisfying the equation 5.15 given in [2]. When the second condition is met, the minimum ductile behaviour of the element is achieved. For the purpose of analysis, the dimensions of the cross-section $b_o=d_o=40$ cm with stirrup spacing s = 20 cm were adopted.



Slika 5. Usvojeni modeli za analizu
Figure 5. Adopted models for analysis

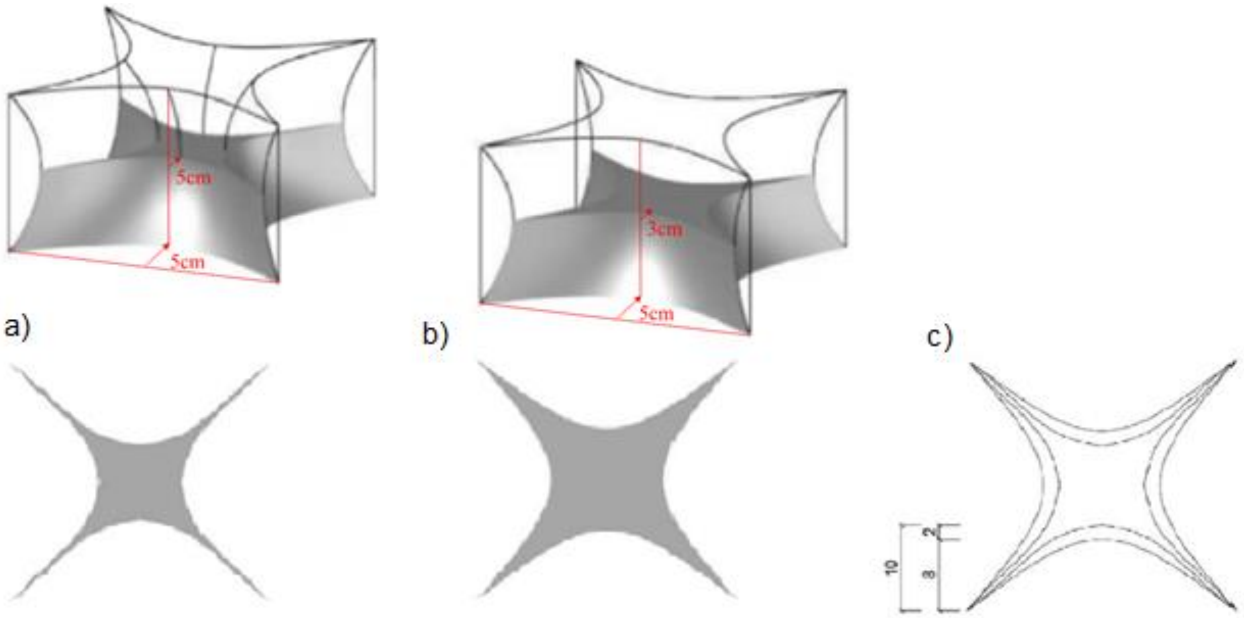
Prilikom modeliranja kvadratnih stubova, nailazimo na nedostatak podataka regulisanih odredbama Evrokoda 8. Reč je o tome da ne znamo koliko maksimalno neefektivna zona ulazi u stub, po visini, između dva reda uzengija, pa su dva razmatrana modela prikazana na slici 6.

Na slici 6a usvojena je funkcija parabole sa žižom od s/4=5 cm, dok je za drugi slučaj (slika 6b) usvojena raspodela konstruisanjem površine ograničene sa četiri parabole u programskom paketu AutoCAD, kod koje se

While modelling the square columns the lack of data, regulated by the provisions of Eurocode 8, is noticed. It is a matter of not knowing how the maximum ineffective zone enters the column between the two rows of the stirrups, along the height of the column, so the two models considered are shown in Figure 6.

In Figure 6a, the parabola function with apex s/4=5 cm is adopted, while for the second case, Figure 6b, surface is designed with bounded four parabolas, using software package AutoCAD, in which the 3 cm apex is dobija žiža u veličini od 3 cm. Na osnovu rezultata analize, prikazanih u tabeli 2, može se zaključiti da model sa slike 6a ima koeficijent utezanja α[EC8-ACAD] mnogo manji u poređenju sa izrazima (1) i (2), tj. α[EC8]. Kako smo pokazali na kružnom stubu da koeficijent α[EC8-ACAD] zadovoljava vrednost koeficijenta utezanja iz propisa α[EC8], to tačniju pretpostavku smatramo modelom sa slike 6b.

obtained. It can be noticed that the model on Figure 6a have confinement effectiveness factor α[EC8-ACAD] much smaller compared to the equations (1) and (2), i.e. α[EC8]. As shown on the circular column that the coefficient α[EC8-ACAD] meets the value of the confinement effectiveness factor from the regulation α[EC8], the model shown on Figure 6b is considered more accurate.



Slika 6. Razlika između dva pretpostavljena modela u prostoru
Figure 6. The difference between two presumed models

Tabela 2. Dve pretpostavke utezanja modela A
Table 2. Two confinement assumptions of model A

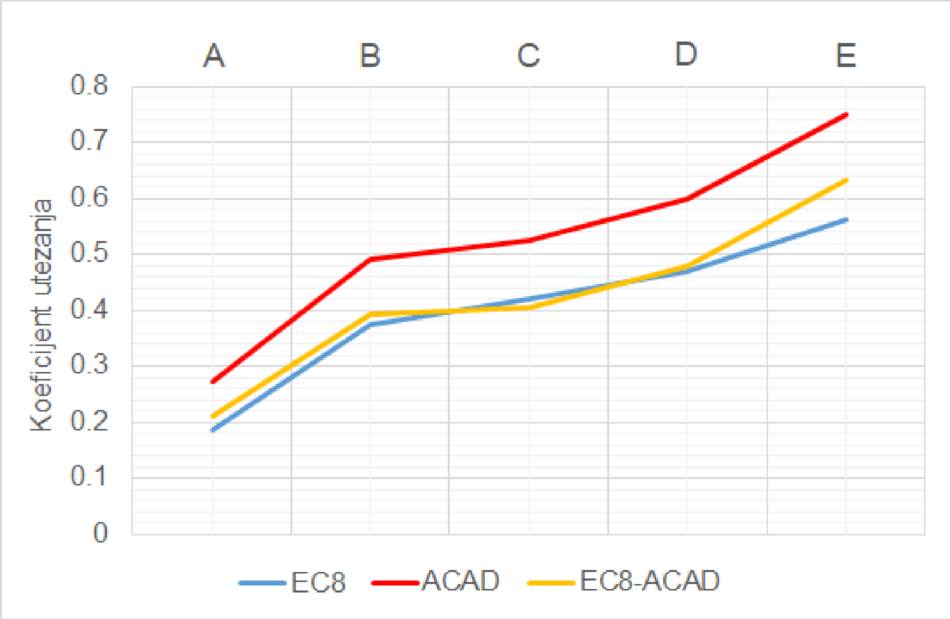
Model *Model*	Dimenzije *Dimensions* [cm]	Razmak uzengija *Stirrups spacing* [cm]	α [EC8]	α [ACAD]	α [EC8-ACAD]
A (Slika 6a) A (*Figure 6a*)	40x40	20	0,1875	0,1997	0,1147
A (Slika 6b) A (*Figure 6b*)	40x40	20	0,1875	0,2726	0,2108

Deo tabele 3, koji je označen kao Teorijski, predstavlja koeficijente utezanja kvadratnog stuba teorijskom pretpostavkom efektivne zone Mander i ostali [4] – α[ACAD] i poređenje dobijenih rezultata s koeficijentima uzezanja dobijenih iz izraza (1) i (2) – α[EC8]. Drugi deo tabele 3 (Prema EC8) predstavlja odnos „prizmatične” pretpostavke efektivno utegnute zone betonskog elementa – α[EC8-ACAD] i izraza (1) i (2) – α[EC8]. Zaključujemo, prema rezultatima tabele 3, da propisi pojednostavljuju oblik efektivno utegnute zone stuba i da je koeficijent utezanja konzervativan. To se uočava u jako maloj razlici (Δ) pretpostavljenog modela i izraza (1) i (2) iz Evrokoda 8, koja su oko 0,02 za klasične slučajeve armiranja.

Part of Table 3, which is named Theoretical, is the square-column confinement effectiveness factor for theoretical assumption of effective zone by Mander et al. [4] - α[ACAD] and a comparison with obtained results for coefficients calculated from equations (1) and (2) - α[EC8]. The second part of Table 3 (According to EC8) is the relation between the "prismatic" assumption of the concrete element effective confinement zone - α[EC8-ACAD] and the equations (1) and (2) - α[EC8]. According to the results shown in Table 3, it is concluded that the regulations simplify the shape of the effectively confined zone of the column and that the confinement effectiveness factor is conservative. This is noticeable in the very small difference (Δ) between the assumed model and equation (1) and (2) from Eurocode 8, which are about 0.02 for usual reinforcement details.

Tabela 3. Koeficijenti utezanja modela
Table 3. Confinement effectiveness factors

Model / *Model*		A	B	C	D	E
Teorijski *Theoretical*	α [EC8]	0,1875	0,3750	0,4219	0,4688	0,5625
	α [ACAD]	0,2726	0,4922	0,5245	0,5989	0,7512
	Δ	0,0851	0,1172	0,1026	0,1301	0,1887
Prema EC8 *According to EC8*	α [EC8]	0,1875	0,3750	0,4219	0,4688	0,5625
	α [EC8-ACAD]	0,2105	0,3929	0,4044	0,4787	0,6331
	Δ	0,0233	0,0179	-0,0175	0,0099	0,0706



Slika 7. Poređenje koeficijenata utezanja razmatranih modela (napomena: veza između modela A-E nije linearna)

Figure 7. Comparison of the confinement effectiveness factors for considered models (note: the relation between models A-E is not linear)

Kod stubova kružnog poprečnog preseka, sila utezanja ravnomerno deluje duž kružne uzengije i nema neefektivnih delova utegnutog poprečnog preseka. Shodno tome, greške pri modeliranju efektivno utegnutog elementa, sa osnovom utegnutog elementa koja je skalirana izrazima (3) i (4), nije bilo i videli smo poklapanja rezultata prema tabeli 1. To nije slučaj i kod kvadratnih preseka, gde postoji komplikovanija geometrija i kod koje se zbog greške modela javljaju određene razlike. Greška se uvećava, takođe, zbog usvajanja površina koje generiše sam program, sa određenom gustinom mreže.

Čest slučaj u praksi jeste da se stubovi dodatno utežu na određenim mestima duž visine stuba (npr. u zoni spoja grede i stuba) postavljanjem spoljašnje uzengije na duplo manjem rastojanju. Prema odredbama Evrokoda 8, utezanje preseka radi se uniformno po celoj visini disipativne zone, postavljanjem svih uzengija preseka na istom rastojanju, pa se postavlja pitanje efikasnosti utezanja preseka progušćenjem samo spoljne uzengije. Pomenuti slučaj iz prakse analizira se dodatnim utezanjem elementa, postavljanjem barem jedne osnovne uzengije na polovini prethodno usvojenog

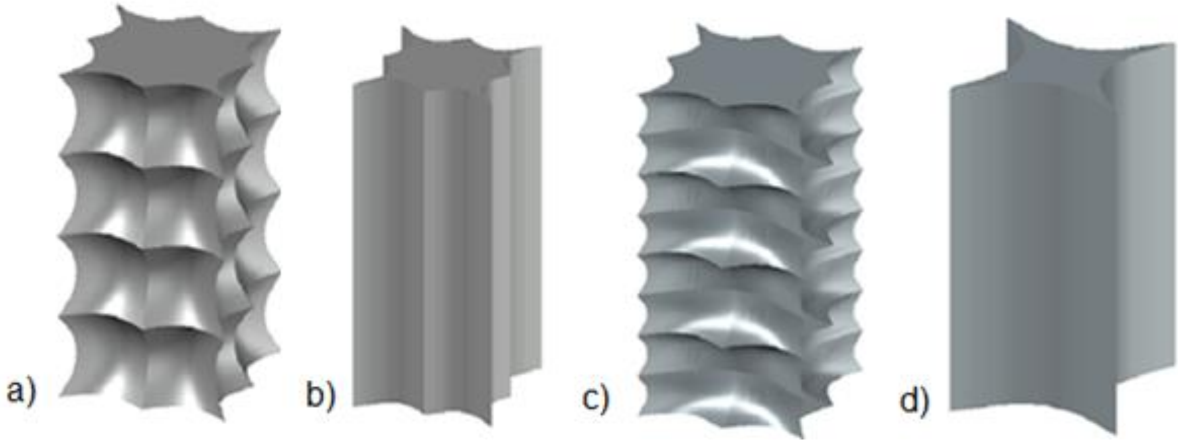
In the case of circular cross-section the confining force acts equally along the circular hoop and there are no ineffective parts of confined cross-section. Consequently, there were no errors in the modelling an effectively confined element, with the basis scaled by the factors calculated from equations (3) and (4), and we noticed the matching of the results in Table 1. This was not the case while designing the square cross-section columns with more complicated geometry and where certain differences occur, due to model errors. The error is also increased by adopting surfaces generated by the software itself, with a certain density of the mesh.

In most cases, in practice, the columns are additionally confined at certain levels along the height of the column (for example, in the zone of beam and column joints) by adding an external stirrup between existing ones. According to the regulations of Eurocode 8, the cross-section confinement is uniform over the entire height of the dissipative zone by placing all stirrups at the same distance, so the question of any extra efficiency on confined element with that external stirrup is to be answered. The mentioned case from the practice is analyzed by additional confinement of the razmaka (s). Osnovnom uzengijom smatra se ona koja pridržava krajnje šipke longitudinalne armature.

Modele s dodatnom osnovnom uzengijom na sredini razmaka (s) nazivamo, respektivno, BA, CA, DA, EA (slika 8). Pri proračunu koeficijenta utezanja ovih modela, korišćenjem izraza Evrokoda 8, sračunata je ista vrednost, jer je u poprečnom preseku na rastojanju s isti način armiranja. Ovo znači da Evrokod 8 ne prepoznaje ovakav princip kao dodatno utezanje, što ga čini konzervativnim, tj. na strani sigurnosti, ali ostaje pitanje da li je dodatno utezanje suštinski ostvareno.

element, adding at least one basic stirrup at half of the previously adopted spacing (*s*). The basic stirrup is the one that wraps edge bars of the longitudinal reinforcement.

Models with additional basic stirrup at the centre of the distance (*s*) are named, respectively, BA, CA, DA, EA (Figure 8). When calculating the confinement effectiveness factor of these models, by using equations given in Eurocode 8, the same value of effectiveness factor is calculated, since the cross-section at distance *s* have the same reinforcement form. This means that the Eurocode 8 fails to recognize this principle as an additional confinement, which makes it conservative, i.e. on the safe side, but the question whether additional confining has been substantially achieved still remains.



Slika 8. Modeli: a) B – teorijski; b) B – prema EC8; c) BA – teorijski; d) BA – prema EC8
Figure 8. Models: a) B - theoretical; b) B - according to EC8; c) BA - theoretical; d) BA - according to EC8

Prema rezultatima iz tabele 3 i tabele 4, za teorijski koeficijent utezanja, zapažamo da s progušćenjem uzengija smanjujemo koeficijent, što nije očekivano i da dobijeni rezultati odstupaju od razmišljanja u praksi, gde se progušćene uzengije smatraju vidom dodatnog utezanja. Greška koja se pravi usvajanjem teorijskog modela jeste ta da parabolu na mestu dodatne uzengije mi teorijski usvajamo. Ona ima dužinu d_0 i žižu s/4.

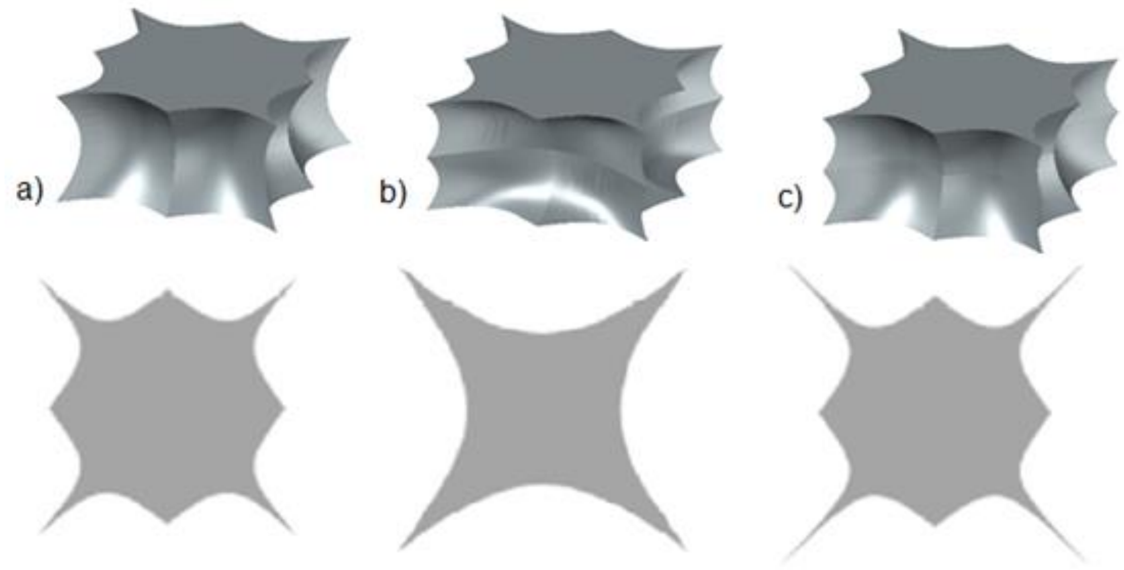
According to the results from Table 3 and Table 4, for the theoretical confinement effectiveness factor, it can be noticed that with additional basic stirrup the coefficient is reduced, which is unexpected and that the obtained results deviate from practice where the additional stirrup is considered as enhanced confinement. The mistake in designing the theoretical model was made because we adopted the parabola at the place of additional stirrup by theory. Parabola have length d_o and apex *s*/4.

Tabela 4. Koeficijenti utezanja modela s dodatnim utezanjem
Table 4. Confinement effectiveness factors with additional confinement

Model / *Model*		A	B	C	D	E
Teorijski *Theoretical*	α [EC8]	/	0,3750	0,4219	0,4688	0,5625
	α [ACAD]	/	0,4128	0,4210	0,440	0,5243
	Δ	/	0,0378	-0,0009	-0,0288	0,0382
Teorijski korigovan *Corrected theoretical*	α [EC8]	/	0,3750	0,4219	0,4688	0,5625
	α [ACAD]	/	0,4901	0,5245	0,5989	0,7420
	Δ	/	0,1151	0,1026	0,1302	0,1795
Prema EC8 *According to EC8*	α [EC8]	/	0,3750	0,4219	0,4688	0,5625
	α [EC8-ACAD]	/	0,4007	0,4042	0,4795	0,6441
	Δ	/	0,0251	-0,0177	0,0107	0,0816

Na modelu kod kog nema progušćavanja uzengija, a na sredini razmaka s, imamo realno mnogo veću efektivnu površinu (slika 9a) u poređenju sa utegnutim modelom (slika 9b) na čijem je mestu postavljena dodatna uzengija. Drugim rečima, dodatnim utezanjem fiktivno smanjujemo efektivan presek kako bismo usvojili pretpostavljenu raspodelu efektivne zone prema preporukama Evrokoda 8. Ovu grešku ispravljamo modeliranjem efektivnog preseka na s/2 sa slike 9a, koji bi se maksimalno mogao pojaviti, tj. kao na modelu B. S tog modela usvajamo istu zavisnost u horizontalnom preseku na visini s/2, samo što je dodatno produžavamo do podužnih šipki armature, jer je na tom mestu armatura pridržana (slika 9c).

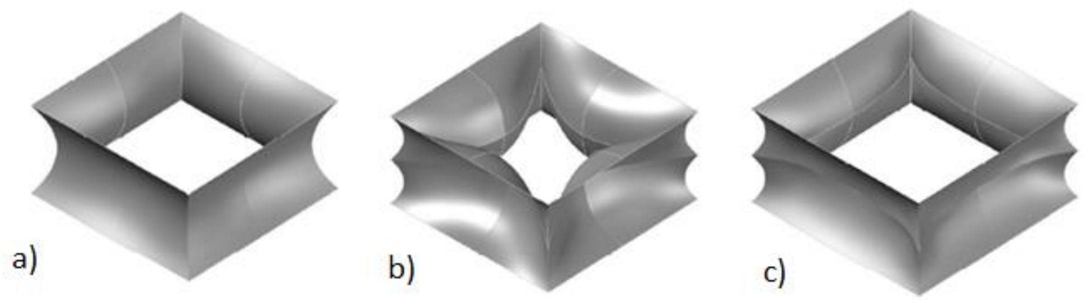
On the model with no additional stirrups, in the middle of the length *s*, there is a much larger effective zone (Figure 9a) than the model in which the additional stirrup is placed (Figure 9b). In other words, by adding basic stirrups, the effective cross-section is fictively reduced to adopt the assumed distribution of the effective zone according to the recommendations of Eurocode 8. This error is corrected by modelling the effective cross-section located at *s*/2 from Figure 9a which could maximally appear, i.e. as on the model B. From this model, the same curve is adopted in the horizontal cross-section at the height *s*/2, but with extending the curve to the edge longitudinal bars, as the reinforcement is retained at those points (Figure 9c).



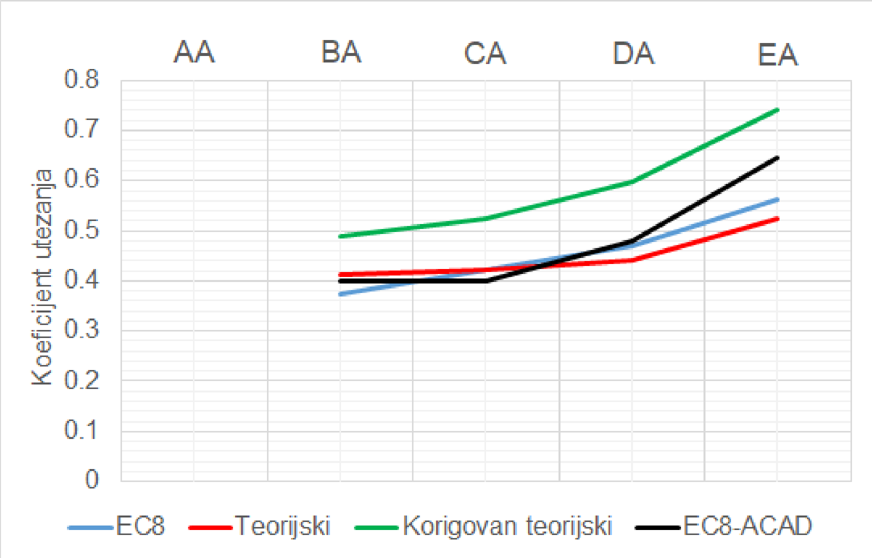
Slika 9. Prikaz razlike modela:a) B; b) BA; c) BA korigovanog; s poprečnim presecima na sredini visine
Figure 9. Model differences: a) B; b) BA; c) BA corrected; with cross-sections in the middle of the height

Na slici 10 prikazan je model sa unutrašnje strane, gde se jasno može uočiti da – zbog ispunjenja preporuka Evrokoda 8 o neefektivnoj zoni između pridržanih šipki podužne armature – činimo grešku koju nadomešćujemo ograničavanjem neefektivne zone u tom preseku.

Figure 10 shows the model from the inside, where it can be clearly noticed that in order to fulfil the recommendations of Eurocode 8 on the ineffective zone between the retained longitudinal reinforcement, an error was made which is corrected by limiting the ineffective zone in that cross-section.



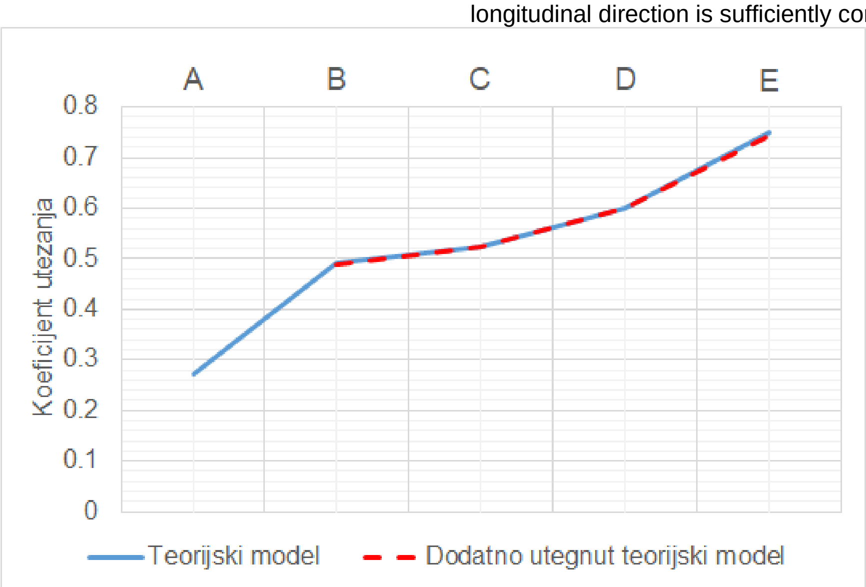
Slika 10. Minimalni poprečni presek po visini stuba modela: a) E; b) EA; c) EA korigovanog
Figure 10. Minimal cross-section along the height of the models: a) E; b) EA; c) EA corrected



Slika 11. Poređenje koeficijenata utezanja za model s dodatnim progušćenjem armature za utezanje iz tabele 4 (napomena: veza između modela A-E nije linearna)
Figure 11. Comparison of confinement effectiveness factors for models with additional basic stirrups from Table 4 (note: the relation between models A-E is not linear)

S dovoljnom tačnošću možemo zaključiti da teorijski pretpostavljen, efektivno utegnut, element, kako su ga dali Mander i ostali [4] (α[ACAD]), daje veće koeficijente utezanja od pretpostavke koju definišu izrazi prema odredbama Evrokoda 8 (α[EC8]). Na slici 11 prikazana je razlika između ovih koeficijenata, s napomenom da veza između modela A do E nije linearna. Prema sumiranim rezultatima, na slici 11, zapažamo veoma mala odstupanja od koeficijenata utezanja prema izrazima (1) i (2) (α[EC8]) u odnosu na pretpostavljenu „prizmu" (α[EC8-*ACAD*]), pa shodno tome smatramo da je pretpostavka o obliku efektivno utegnutog elementa, u podužnom pravcu, dovoljno tačna.

With sufficient accuracy, it can be concluded that the theoretically assumed, effectively confined, element by Mander et al. [4] (α[ACAD]) gives a higher confinement effectiveness factor than the recommendations defined by the equations in Eurocode 8 (α[EC8]). Figure 11 shows the difference of these coefficients, with the note that the relation between the A-E model is not linear. According to the summarized results, in Figure 11, we notice very small deviations from the confinement effectiveness factor by equations (1) and (2) (α[EC8]) in relation to the assumed "prism" (α[EC8-ACAD]), and consequently it is considered that the assumption about the shape of an effectively confined element in the longitudinal direction is sufficiently correct.



Slika 12. Poređenje teorijskog i dodatno utegnutog teorijskog modela – tabele 3 i 4 (napomena: veza između modela A-E nije linearna)
Figure 12. Comparison of the theoretical and additionally confined theoretical model - Table 3 and 4 (note: the relation between models A-E is not linear)

5 ZAKLJUČAK

U radu je predstavljena analiza faktora efikasnosti utezanja armiranobetonskih preseka poprečnom armaturom, kao jednog od ključnih parametara koji utiču na obezbeđivanje zahtevanog faktora efikasnosti krivine preseka, prema Evrokodu 8 [2]. Objašnjeno je fizičko značenje faktora efikasnosti na osnovu grafičkog prikaza utegnutog betona elementa kvadratnog, odnosno kružnog poprečnog preseka. Dokazano je da su izrazi za sračunavanje koeficijenta utezanja prema Evrokodu 8 [2] definisani odnosom: (1) zapremine tela prizmatičnog oblika čija je osnova jednaka najmanjem poprečnom preseku efektivno utegnutog jezgra koji se može javiti duž elementa; (2) zapremine tela prizmatičnog oblika čija je osnova definisana oblikom spoljašnje uzengije. Ovakva definicija daje konzervativne rezultate u odnosu na „realni" faktor efikasnosti utezanja, definisan prema ukupnoj zapremini efikasno utegnutog betona. Takođe, dokazano je da dodatno progušćavanje spoljašnje konturne uzengije na duplo manjem rastojanju ne uvećava bitno vrednost koeficijenta utezanja. Ovaj zaključak odnosi se isključivo na koeficijent utezanja, što ne znači da betonski element, povećanjem poprečne armature, nema povećanje kapaciteta duktilosti.

5 CONCLUSION

The paper presents the analysis of the confinement effectiveness factor for the reinforced concrete cross-sections with stirrups, as one of the key parameters that influence the achievement of the required cross-section curvature ductility factor, according to Eurocode 8 [2]. The physical meaning of the confinement effectiveness factor is graphically explained for confined concrete elements of square and circular cross-sections. Equations for calculating the confinement effectiveness factor according to Eurocode 8 [2] have been shown and defined by the relation: (1) the volume of a prismatic element with basis equal to the smallest cross-section of the effectively confined core that may occur along the element, and (2) the volume of the element of prismatic form with basis defined by the form of external stirrup. This definition gives conservative results with respect to the "real" confinement effectiveness factor, defined by the total volume of effectively confined concrete. In addition, it has been shown that the added external stirrup between existing ones insignificantly increases the value of the confinement effectiveness factor. This conclusion applies only to the confinement effectiveness factor, which does not mean that the concrete element will not increase the ductility capacity with increased transverse reinforcement.

ZAHVALNOST

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REZIME

OBEZBEĐENJE LOKALNE DUKTILNOSTI ARMIRANOBETONSKIH ELEMENATA PREMA EVROKODU 8 – KOEFICIJENT UTEZANJA

Miloš VULINOVIĆ
Ivan MILIĆEVIĆ
Ivan IGNJATOVIĆ

Fokus ovog rada usmeren je na efekte utezanja armiranobetonskih preseka, odnosno na način na koji poprečna armatura utiče na poboljšanje karakteristika – kako materijala, tako i utegnute zone elementa. Pojašnjeno je praktično značenje koeficijenta utezanja iz izraza Evrokoda 8. Izvršena je procena veličine dela elementa koji je efektivno utegnut uzengijama na primerima različito armiranih kružnih i kvadratnih preseka stubova i analizom trodimenzionalnog prikaza efektivno utegnutog betona. Uspostavljena je relacija između koeficijenta utezanja prema izrazima Evrokoda 8 i efektivno utegnutog dela betonskog elementa.

Ključne reči: Evrokod 8, lokalna duktilnost, koeficijent utezanja

SUMMARY

THE DESIGN OF LOCAL DUCTILITY FOR REINFORCED CONCRETE ELEMENTS BY EUROCODE 8 - CONFINEMENT EFFECTIVENESS FACTOR

Milos VULINOVIC
Ivan MILICEVIC
Ivan IGNJATOVIC

This paper is focused on the effects of confinement of the reinforcement reinforced concrete sections, i.e. in the way that the transverse reinforcement affects the improvement of the characteristics of both the material and the affected zone of the element. The practical meaning of the confinement effectiveness factor from the expression of Eurocode 8 was explained. Size of the part of element that is effectively confined by the stirrups is estimated on examples of differently reinforced circular and square sections of the column by analysis of the three-dimensional presentation of effectively confined concrete sections. The connection between confinement effectiveness factor by Eurocode 8 and real effective concrete core is established.

Key words: Eurocode 8, ductility, confinement effectiveness factor

REHABILITATION OF RC BUILDINGS IN SEISMICALLY ACTIVE REGIONS USING TRADITIONAL AND INNOVATIVE MATERIALS

REHABILITACIJA ARMIRANOBETONSKIH (AB) KONSTRUKCIJA U SEIZMIČKIM USLOVIMA KORIŠĆENJEM TRADICIONALNIH I INOVATIVNIH MATERIJALA

Golubka NECHEVSKA-CVETANOVSKA
Artur ROSHI

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1 INTRODUCTION

Behaviour of the structures constructed and built of reinforced concrete during their serviceability period as well as during earthquakes depends on many factors. On one hand, there are the external factors, i.e., loads acting upon the structures (in addition to the main loads, there are also additional loads as well as effects caused by possible explosions, fires, earthquakes), while on the other hand, there are the factors that directly depend on the very structure of the buildings (structural system, type, quality and quantity of material used for the construction of the structure, the number of storeys, the mode of foundation,….). All these factors directly affect the strength and deformation characteristics of the individual structural elements and the structural system as a whole.

The need for repair and strengthening of RC buildings and their structural elements occurs when their elements lack sufficient strength, stiffness and/or ductility out of different reasons or due to slighter or more severe damages most frequently caused by earthquakes.

It has been a usual practice to perform repair and strengthening of structures by application of traditional methods (most frequently, jacketing of elements), but lately, new innovative materials with a special technology of construction and repair have increasingly been applied. The application of these materials is still the subject of a large number of investigations worldwide, particularly in the field of application of these materials in seismically active regions.

Golubka Nechevska-Cvetanovska, Professor Doctor, PhD, Graduate civil engineer, University Ss.Dyril and Metodius, Institute of Earthquake Engineering and Engineering Seismology(IZIIS), Skopje, Macedonia,
email: golubka@pluto.iziis.ukim.edu.mk
Artur Roshi, PhD student-IZIIS-Skopje,Master of science, Graduate civil engineer, Metropolitan university , Tirana Albanija; email: artur.roshi@yahoo.com

2 REPAIR AND STRENGTHENING OF BUILDINGS STRUCTURES

2.1 General

Strengthening of reinforced concrete structural elements is one method to increase the earthquake resistance of damaged or undamaged buildings. The strength of the structures can be moderately or significantly increased and the ductility can be improved, or in other words, it can be said that the concept of strengthening involves: a) increase in strength, b) increase in strength and ductility and c) increase in ductility, (Figure 2.1).

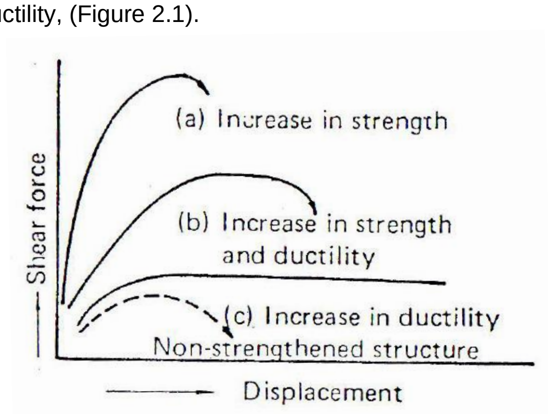


Figure 2.1. Concept of seismic strengthening

The methods for repair and strengthening of buildings may basically be categorized into two main groups: system based repair and strengthening (Global Strengthening) and member based strengthening (Local Strengthening).

In the system based strengthening methods, a structural system is modified by adding members such as reinforced concrete shear walls or additional steel bracing, mainly improving the strength and stiffness characteristics of the system.

A new frame can be introduced to increase the lateral strength and stiffness of a building. Similar to a new wall, integrating a new frame building and providing foundations are critical design issues.

2.2 Global strengthening methods

In the system based strengthening methods, a structural system is modified by adding members such as reinforced concrete shear walls or additional steel bracing, mainly improving the strength and stiffness characteristics of the system.

Most of the strengthening strategies have recently been based on global strengthening schemes as per which the structure is usually strengthened for limiting lateral displacements in order to compensate the low ductility. In these methods causing a change in the global behaviour of the building, as explained above, a behavioural change takes place when new members are added to the building.

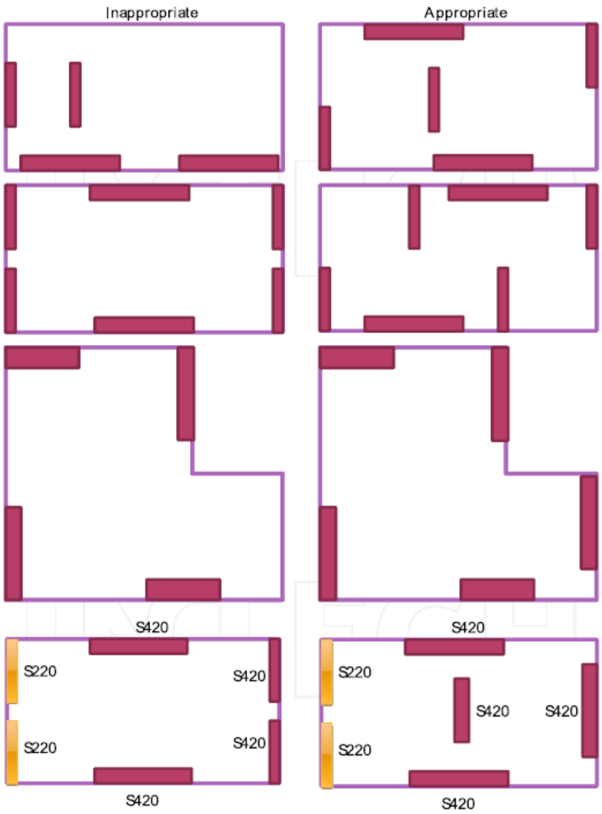


Fig.2.2. Inappropriate and appropriate shear walls layouts (Handbook,[10])

In order to be added to the structure, reinforced concrete walls should be placed in a manner that torsional effects on the structure are prevented and irregularities in the structure are eliminated, as observed in the design of new buildings. Some appropriate and inappropriate shear wall layouts are presented in Figure 2.2.

A steel bracing system can be inserted in a frame to provide lateral stiffness, strength, ductility, hysteretic energy dissipation, or any combination of these. The braces are effective for relatively more flexible frames, such as those without infill walls. The braces can be added to the exterior frames with least disruption of the building use. For an open ground storey, the braces can be placed in appropriate bays while maintaining the functional use. Passive energy dissipation devices may be incorporated in the braces. The connection between the braces and the existing frames is an important consideration of this strategy. One technique of installing braces is to provide a steel frame within the designated RC frame. The steel frame is attached to the RC frame by installing headed anchors. (Figure 2.3).

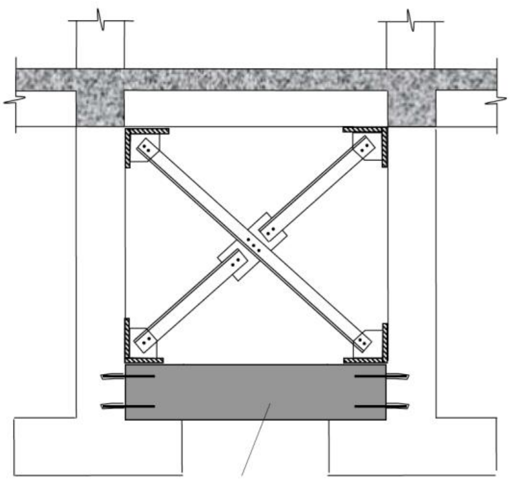


Figure 2.3. Additional steel braces

A new frame can be introduced to increase the lateral strength and stiffness of the building. Similar to a new wall, integrating a new frame building and providing foundations are critical design issues.

2.3 Local strengthening methods

The local strengthening approach involves modification of deficient elements to increase ductility so that the deficient elements will reach their limit states in a ductile manner when subjected to design events. However, this strategy is more expensive and harder to implement in cases of many deficient elements which is the reason that the global strengthening methods have been more popular than element strengthening. Effective results can be obtained by using such methods in buildings with a limited number of deficient elements along with the global strengthening methods.

2.3.1 RC jackets

One of the most frequently used methods for strengthening reinforced concrete columns is reinforced concrete jacketing (Figure 2.4).

Jacketing, which can be defined as the confinement of the column with new and higher quality reinforced concrete elements may be implemented for various purposes based on the type of structural member deficiencies. Columns subjected to brittle damages can be jacketed in order to enhance resistance against shear and/or axial loads. In that case, although the purpose of jacketing is only to increase axial load or shear strength, some changes will also occur in the bending stiffness and moment capacity of the member after the jacketing application. By considering these changes during the jacketing design, the jacketed section is ensured to achieve adequate shear and axial load strength.

Except for such brittle damages, jacketing is applied for elements with inadequate bending capacity or ductility. In this way, strength of the columns displaying a splice failure as a result of bending can also be improved. Jacketing of the columns has the best result when it is implemented at 4 sides of the column. Where necessary, confinement at 3 sides can also provide adequate performance. However, it is not generally recommended to implement the jacketing at 1 or 2 sides. Because, with such jacketing applications, no significant changes take place in the confinement characteristics of the member.

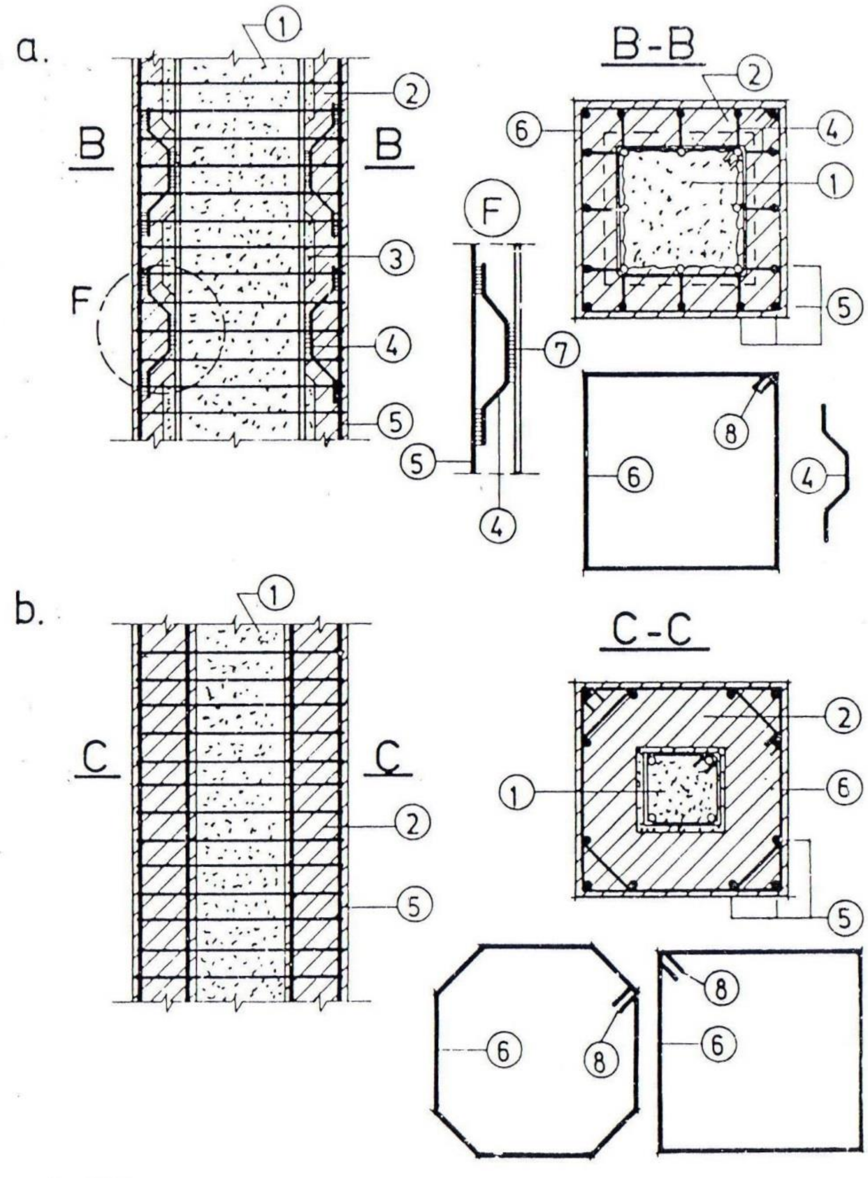


Figure 2.4. Connection of the old to the new reinforcement of the R/C jacket: a) protection of new bar against buckling with welding; b) protection of new bar against buckling with octagonal ties; 1- existing column, 2- jacket, 3-key, 4-bent bars, 5-added reinforcement, 6-ties, 7-welding, 8-alternating corners), (P.Gavrilovic [15])

2.3.2 Steel jackets

Jacketing with steel elements is a practical method used frequently for various applications. A typical steel jacketing application is presented in Figure 2.5.

Fig.2.5. Steel jacketing applied to RC columns(M.N.Fardis, [12])

Steel jacketing can readily be used to especially enhance the shear strength of reinforced concrete elements. Located at the corners of an element, L-profiles are coupled by means of steel plates and confined. With the maintenance of continuity between storeys, steel jacketing can also be used to increase the bending strength. In addition, the maintenance of adequate strength between the steel element and reinforced concrete element is inevitable for the improvement of bending capacity.

3 REPAIR AND STRENGTHENING OF BUILDINGS USING TRADITIONAL MATERIALS

The aim of the repair and strengthening is to modify the seismic demands, and/or the capacities, so that all relevant elements of the strengthened building fulfil the general verification inequality, at all performance levels ("Limit States") under the corresponding seismic action (Figure 3.1) (Folić, R., Zenunović, D. Liolios, A., 2014).

Each strategy may be implemented by using more repair and strengthening techniques. All of them have their own advantages and drawbacks, scope and limitations of use and fit better in one of these strategies

The choice of the technique depends on many factors, such as:

- The locally available materials and technologies
- Cost consideration
- The disruption of use it entails and the duration of the works
- Architectural, functional and aesthetic considerations or restrictions, etc.

3.1 Column strengthening

Usually, the purpose of column strengthening is to improve earthquake resistance of damaged or undamaged buildings. In addition, in the case when, during the construction phase, there is failure of concrete or any other substantial material in reaching the required quality according to the design, strengthening of specific structural members will be applied. Increased resistance of columns means increased column flexural and shear strength, improving column ductility by applying different techniques of their strengthening (Folić, R., and al, 2015).

In the case of damaged columns, depending of the degree and type of damage, different techniques may be applied, such as resin injection, removal and replacement or jacketing.

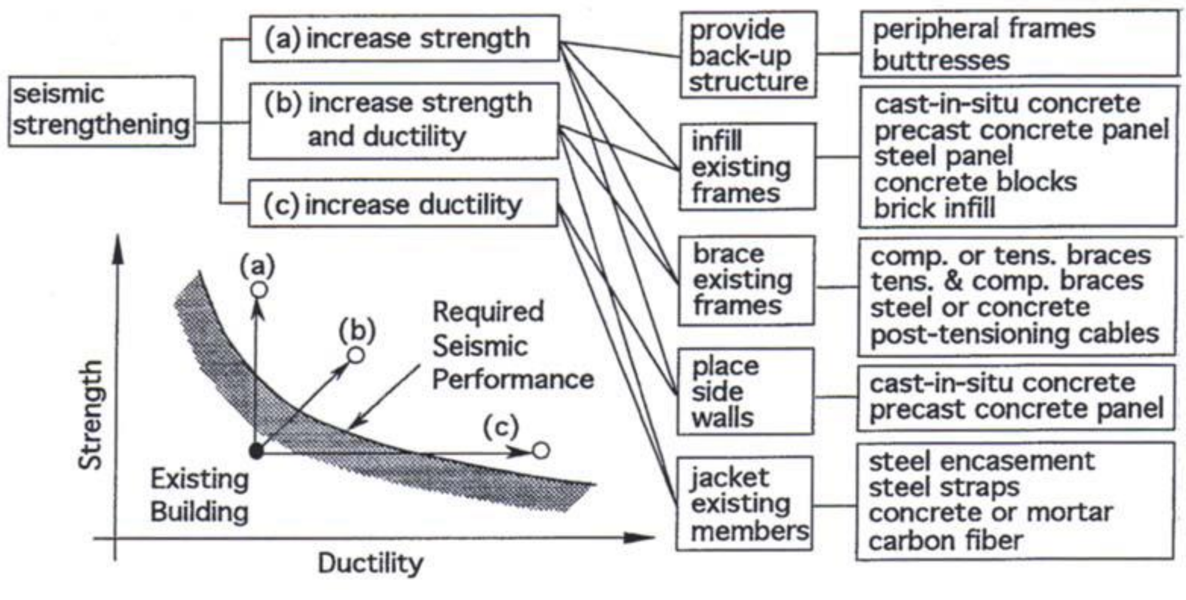


Figure 3.1. Strengthening strategies

3.1.1 Reinforced concrete jacketing of columns

R/C jackets are applied in the case of serious damage or inadequate seismic resistance of the column (including here failure of quality of concrete used on the site during construction). Depending on the existing local conditions, jackets are applied along the perimeter of the column, which is the ideal case, or sometimes on one or more sides.

In the case where the jacket is limited to the storey height, an increase in the axial and shear strength of the column is achieved with no increase in flexural capacity at the joints. Therefore, it is recommended that the jackets protrude through the ceiling and the floor slabs of the storey where column strengthening is necessary (Figure 3.2).

3.1.2 Detailing of RC Jackets

The concrete overlay of the jacket should be at least 75–100 mm, to provide sufficient cover of the new reinforcement and space for 135◦-hooks at the tie ends (Fig. 3.2(a)). For this range of thickness, shotcrete is more convenient. Thicker overlays are normally cast-in-place.

– In order to increase the moment resistance of vertical elements, longitudinal reinforcement should be continued to the adjacent storeys through the holes or slots in the slab. To avoid perforating the beams on all sides of the cross-section, jacket bars continuing through the slab should be concentrated near the corners of the new section, often in bundles (Fig.3.2. (b) and (c)). Jacket vertical bars may be anchored into a foundation element either:

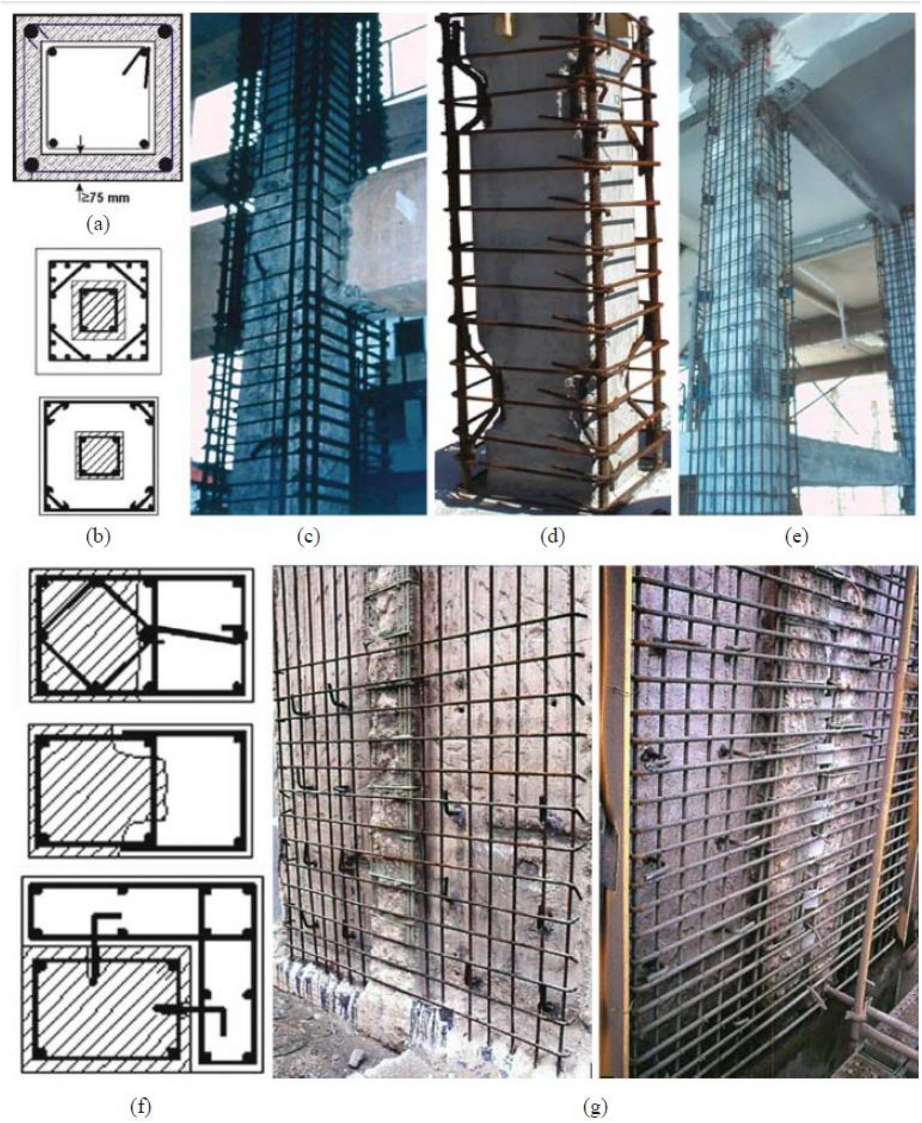


Figure 3.2. Concrete jackets in columns: a) the simplest case b) jacket bars bundled near corners, engaged by cross-ties or orthogonal tie c) jacket bars bundled at corners, dowels at interface with old column d) U-bars welded to corner bars e) steel plates welded to corner bars f) one-or two-sided jackets g) one-sided concrete overlay with single curtain of two way reinforcement at exterior face of perimeter walls, (M,Fardis[12])

– by enlarging the foundation element to accommodate anchorage of the jacket bars in the new concrete there (possibly increasing, at the same time, the capacity of the foundation element to meet the larger moment demands from the jacketed vertical member), or

– by fastening (e.g., through epoxy) starter bars within vertical holes drilled in the foundation element, to be lap-spliced with the jacket vertical bars outside the plastic hinge that may form at the bottom of the retrofitted element.

3.1.3 Strengthening of columns with steel profile skeleton

Steel profile skeleton jacketing consists of four longitudinal angle profiles placed one at each corner of the existing reinforced concrete column and connected together in a skeleton with transverse steel straps (Figure 3.3). In general, an improved ductile behaviour and an increase of the axial load capacity of the strengthened column is achieved. However, the stiffness remains relatively unchanged.

Steel jackets are more expensive than concrete ones. However, their technology is simple, familiar to the construction industry and readily available almost everywhere. So, it is the technique of choice for non-engineered emergency strengthening even hours after a damaging earthquake, to prevent the collapse of heavily damaged buildings or give back to use moderately damaged ones during the aftershock period. Detailed assessment and retrofit design may take place afterwards. The steel jackets may be removed when retrofitting is implemented, or incorporated in a concrete jacket (as in Fig. 3.4 (a)).

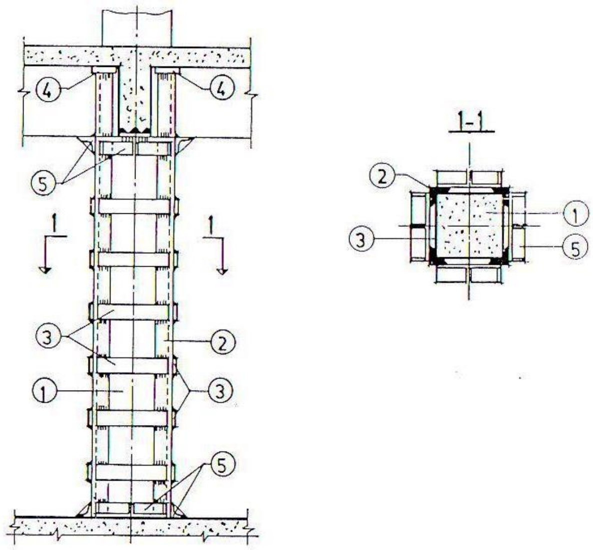


Figure 3.3. Strengthening of column with steel profiles at each corner; 1-existing column, 2-steel angle profile, 3-steel plate, 4-supporting plate, 5-angle profile. (P.Gavrilovic, [15])

3.2 Beam strengthening

The aim of repair and/or strengthening of beams are to provide adequate strength and stiffness of damaged or undamaged beams, which are deficient, to resist gravity and seismic loads. It is very important that the rehabilitation procedure chosen provides proper strength and stiffness of the beams in relation to adjacent columns in order to avoid creating structures of the "strong girder – weak column" type which tend to force seismic hinging and distress into the column, which must also support major gravity loads.

As in the case of columns, depending on the degree of damage in the beams, several techniques are applied, such as resin injections, glued metal or FRP sheets, removal and replacement of R/C jackets.

(a) (b)

Figure 3.4. Steel jackets built-up in situ with corner angles and horizontal straps

3.2.1 Reinforced concrete strengthening and jacketing of beams

Reinforced concrete jackets can be applied by adding new concrete to one, three or four sides of the beam. Within the same technique, one should also include strengthening of the tension or compression zone of a beam through the concrete overlays. In order to enable force transfer between old and new concrete, roughening of the old concrete is required, as well as welding of connecting bars to the existing and new reinforcement bars.(Cvetanovska 2000)

Reinforced overlays on the lower face of the beam (Figure 3.5) can only increase the flexural capacity of the beam. Existing reinforcement is connected to the new one by welding.

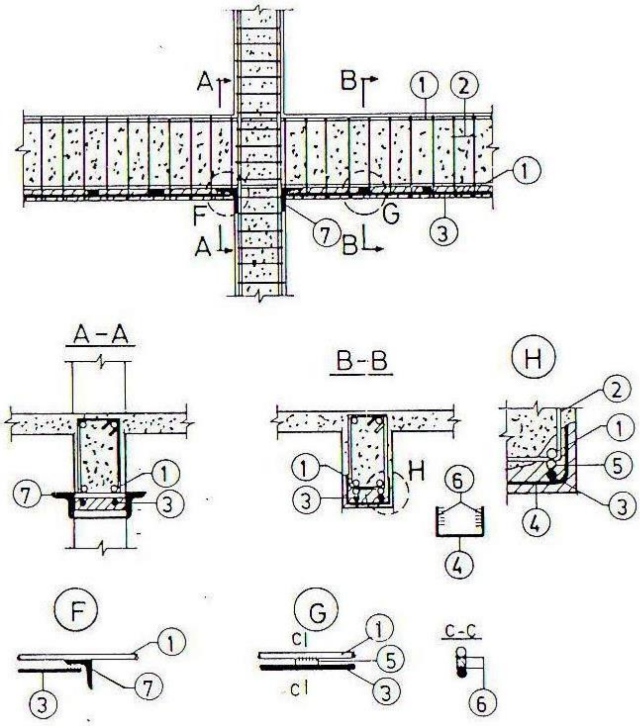


Figure 3.5. Strengthening of a beam on the lower face; 1-existing reinforcement, 2-existing stirrups, 3-added longitudinal reinforcement, 4-added stirrups, 5-welded connecting bar, 6-welding, 7-collar of angle profiles. (P.Gavrilovic,[15])

Jacketing on all four sides of the beams is the most effective solution. The thickness of the concrete which is added to the upper face is such that it can be accommodated within the floor thickness (50-70 mm). The placement of the ties is achieved through holes which are opened in slab at closely spaced distances, which are used for pouring the concrete. The longitudinal reinforcement bars of the jacket are welded to those of the old concrete (Figure 3.6).

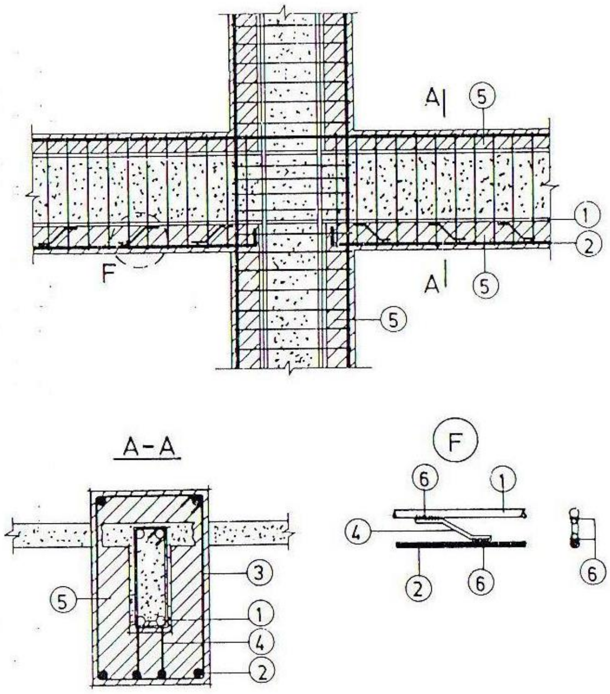


Figure 3.6. Jacket on four sides of a beam; 1-existing reinforcement, 2-added longitudinal reinforcement, 3-added stirrups, 4-welded connecting bar, 5-concrete jacket, 6-welding (P.Gavrilovic, [15])

Jackets on the three sides of the beam are used to increase flexural and shear capacity of the beam for vertical loading, but not for seismic actions, given that strengthening of the load-bearing capacity of the section near the supports is impossible.

3.3 Shear wall strengthening

Due to their great stiffness and lateral strength, shear walls provide the most significant part of the earthquake resistance of the building structure. Therefore, several damaged, poorly designed or constructed shear walls must be repaired or strengthened to significantly improve the structure’s strength for seismic force. As in the case of columns and beams, here, shear wall strengthening can be done by using the epoxy resin and R/C jacketing technique.

3.3.1 Reinforced concrete jacketing of shear walls

When the original strength of the damaged or poorly constructed wall is insufficient, thickening the wall with reinforced concrete should be applied. There are different ways to add strength to an existing concrete shear wall (Figure 3.7). Shotcrete is a frequently used technique in strengthening concrete shear walls.

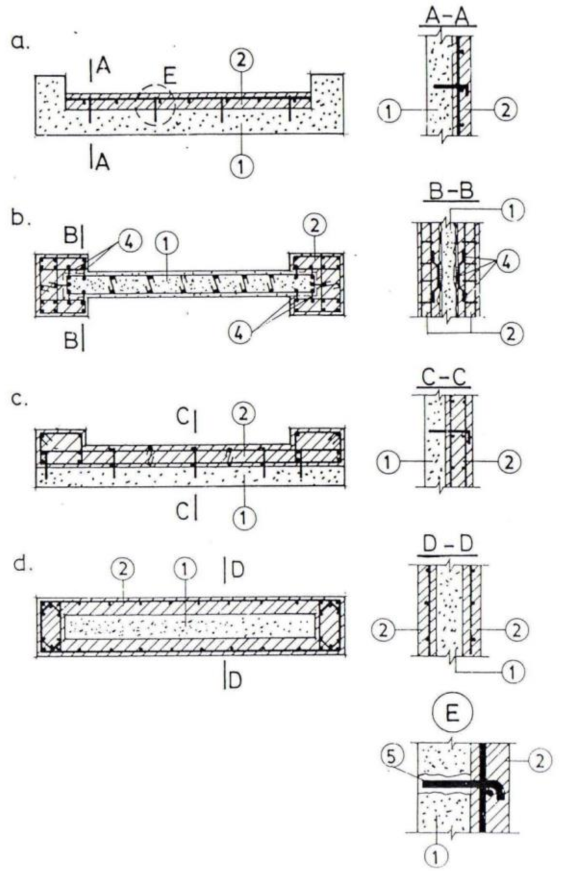


Figure 3.7. Strengthening the shear wall with R/C jacket; 1-existing wall, 2-added wall, 3-added columns, 4-welding, 5-epoxied bar. (P.Gavrilovic [15])

4 REPAIR AND STRENGTHENING BUILDINGS USING INNOVATIVE MATERIALS

4.1 Fibre Reinforced Polymers (FRP)

FRP composites comprise fibres of high tensile strength within a polymer matrix. The fibres are generally carbon or glass, in a matrix such as vinyl ester or epoxy. These materials are manufactured to form plates under factory conditions, generally by a pultrusion process.

The primary materials in the composite are the reinforcement fibre and the polymer matrix. Other materials are incorporated in the composite but they are of less significance in terms of both effect on cost and effect on properties, although the term polymer composites includes both thermosetting and thermoplastic resins.

The most commonly used thermosetting resins in composites are polyester, urethane methacrylate, vinylester, epoxy and phenolic. They are isotropic materials which allow load transfer between fibres, but they perform several other things. The matrix protects notch-sensitive fibres from abrasion and it forms a protective barrier between the fibres and the environment, thus preventing attack from moisture, chemicals and oxidation. It also plays an important role in providing shear, transverse tensile and compression properties. The thermomechanical performance of the composite is also governed by the matrix performance.

Reinforcement fibres are qualified in three main families of glass, aramid and carbon. There are other fibres, but they are relatively insignificant. The most important property of the fibres is their elastic modulus, and the fibres must be significantly stiffer than the matrix which allows them to carry most of the stress. Consequently, they must also be of high strength. Reinforcements are available in a variety of configurations of which there are three main categories:

- Unidirectional, in which all the fibres lie in one direction.
- Bidirectional, in which the fibres lie at 90° to one another. This is achieved either by the use of woven fabric, non-woven fabric or by the use of separate layers of fibres each unidirectional, but successively laid at 90°.
- Random, in which the fibres are randomly distributed and are in-plane.

Stress-strain fibre behaviour is different for every type of fibre. (Fig. 4.1). Different FRP shapes (Fig. 4.2) and Different material properties are given in Table 4.1 [7,8].

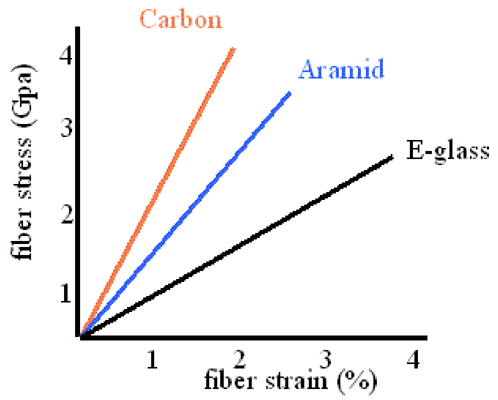
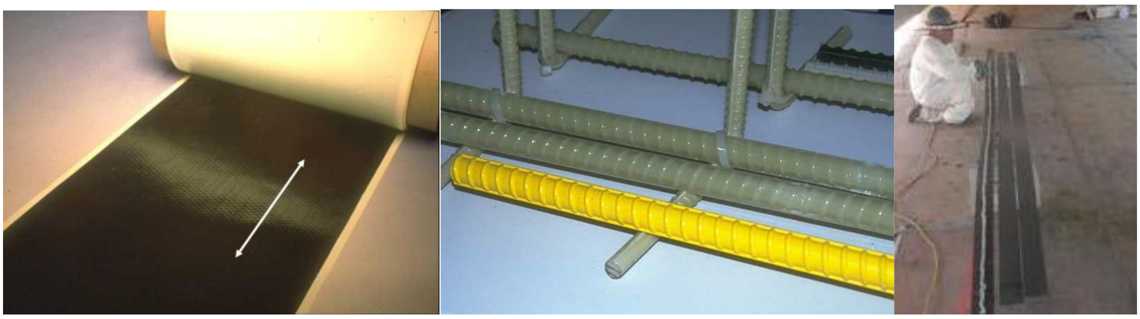


Figure 4.1. Stress- strain fibre behaviour (A. Prota, after [20])

Table 4.1. FRP materials - Fibre comparison

	Strength	Modulus	Moisture and chemical resistance	Cost
Carbon	High	High	Excellent	High
Aramid	High	Intermediate	Good	High
E-Glass	High	Low	Low	Low



a) b) c)

Figure 4.2. Different FRP shapes a) sheet b) bars c) pre cured laminate (A. Prota, [20])

4.2 Confinement strengthening

Confinement strengthening (Figure 4.3) consists of:

(1) Cleaning and repair
(2) Primer
(3) Adhesive
(4) FRP strips
(5) Last adhesive layer

Fibre polymer fabrics that can be used to improve bending, shear and axial capacities of the columns and beams may be manufactured from various materials such as carbon, glass and aramid without an increase in the volume of the strengthened member. In addition, significant improvements can be achieved in the capacity and ductility characteristics of the element. In Figure 4.4, beam strengthening in an existing structure is presented.

These materials may be used for numerous purposes such as enhancement of the flexural capacity of floor slabs and improvement of shear capacity of beams, columns, joints and shear walls (Fig. 4.5 and Fig. 4.6)

Figure 4.3. Confinement strengthening (Di Ludovico M. [21])

Figure 4.4. FRP strengthening of a beam (CNR-DT, [8])

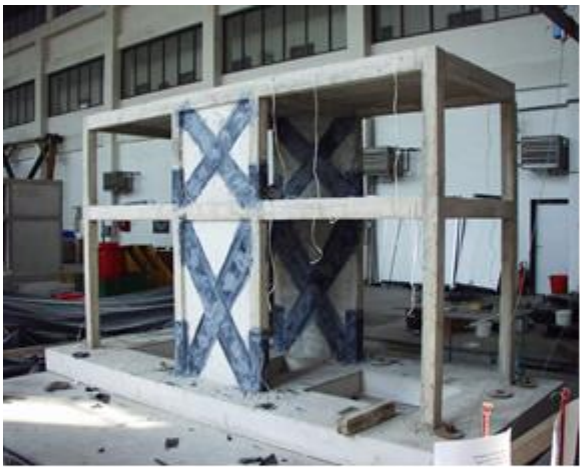


Figure 4.5. Completed model with added carbon fibres (NATO SfP 977231 [29])

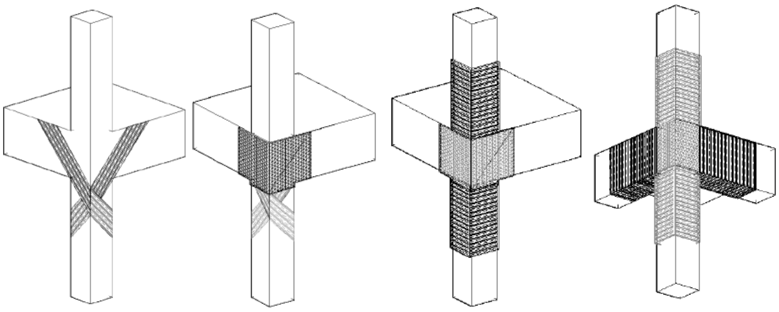


Figure 4.6. Seismic strengthening of external joints using CFRP sheets, (Ozcebe,G.[5])

5 CONCLUSION

The conclusion is given through comparative evaluation of the local retrofit strategies given in table 5.1.

Table.5.1. Comparative evaluation of the local retrofit strategies

Strengthening strategy	Merits	Demerits	Comments
Concrete jacketing	Increases flexural, axial shear strengths and ductility of the member. Easy to analyze. Compatible with original substrate.	Size of member increases. Anchoring of bars for flexural strength; Involves drilling of holes in the existing concrete. Needs preparation of the surface of existing member.	Low cost. High disruption. Experience of traditional RC construction is adequate.
Steel jacketing of columns	Increases shear strength and ductility. Minimal increase in size.	Cannot be used for increasing the flexural strength. Needs protection against corrosion and fire.	Can be used as a temporary measure after an earthquake. Cost can be high. Low description. Needs skilled labour.
Bonding steel plates to beams	Increases either flexural or shear strengths. Minimal increase in size.	Use of bolts involves drilling in the existing concrete. Needs protection against corrosion and fire.	More suitable for strengthening against gravity loads. Cost can be high. Low disruption. Needs skilled labour.
Fiber Reinforced Polymer wrapping	Increases ductility. May increase flexural or shear strength. Minimal increase in size. Rapid installation.	Needs protection against fire.	Cost can be high. Low description. Needs skilled labour.

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SUMMARY

REHABILITATION OF RC BUILDINGS IN SEISMICALLY ACTIVE REGIONS USING TRADITIONAL AND INNOVATIVE MATERIALS

Golubka NECHEVSKA-CVETANOVSKA
Artur ROSHI

The field of research in the frames of this paper will be Application of Traditional and Innovative Materials for Repair and Strengthening of RC Buildings in Seismically Active Regions. The need for repair and strengthening of RC buildings and their structural elements occurs when their elements are insufficiently strong, stiff and/or ductile out of different reasons or due to slighter or more severe damages most frequently caused by earthquakes. Within the frames of this paper, special emphasis will be put on RC buildings where, during construction, the built-in concrete fails to achieve the designed concrete class and/or buildings that cannot satisfy the required strength, stiffness and deformation characteristics particularly in earthquake conditions due to built additional storeys or enlargements. In these cases, it is necessary to take measures for repair and strengthening of both individual structural elements and whole structures using traditional and Innovative Materials.

Key words: Concrete quality, Rehabilitation, Repair and Strengthening, Seismically active regions, Traditional and Innovative Materials, Concrete jacketing, FRP

REZIME

REHABILITACIJA ARMIRANOBETONSKIH (AB) KONSTRUKCIJA U SEIZMIČKIM USLOVIMA KORIŠĆENJEM TRADICIONALNIH I INOVATIVNIH MATERIJALA

Golubka NECHEVSKA-CVETANOVSKA
Artur ROSHI

Predmet ovog rada je primena tradicionalnih i inovativnih materijala za sanacije i pojačavanje AB konstrukcija u seizmički aktivnim regionima. Potreba za izvođenje sanacija i pojačavanja kod zgrada i elemenata i drugih objekata ukoliko elementi nemaju dovoljnu nosivost, krutost i/ili duktilnost usled toga da se u slučaju zemljotresa javljaju umerena ili ozbiljna oštećenja zavisno od snage i učestalosti zemljotresa. U okviru ovog rada, poseban naglasak je na AB zgradama koje ne zadovoljavaju kvalitet ugrađenih materijala i građenja i ne zadovoljavaju nosivost, krutost i karakteristike deformabilnosti bitnih za uslove delovanja zemljotresa ili dodavanje novih spratova. U tim slučajevima potrebno je izvesti radove na sanaciji i pojačavanju na svakom od elemenata korišćenjem tradicionalnih i inovativnih materijala.

Ključne reči: Kvalitet betona, Rehabilitacija, sanacija i pojačavanje, Seizmički aktivna područja, Tradicionalni i Inovativni materijali, Betonska ojačanja preseka, Polimerom modifikovani materijali (FRP)

METHOD FOR DETERMINATION OF LOAD-BEARING CAPACITY OF HAUNCHED ZONES MADE OF IPE-TYPE ROLLED

METOD ODREĐIVANJA NOSIVOSTI ZONE OJAČANJA (VUTA) IZRAĐENIH OD IPE TOPLO VALJANIH PROFILA

Marin VASSILEV

PRETHODNO SAOPŠTENJE
PRELIMINARY REPORT
UDK:692.232.046.3
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1 INTRODUCTION

Despite the extensive application of portal frames for single-storey buildings with steel structures, there are still some aspects of their stability that require additional clarification. No codified practical method is given in EN 1993-1-1 [1] for lateral-torsional stability verification of rafters in the haunched portions loaded by hogging bending moments. It seems that, within the code, there are only two possible approaches: the general method for lateral (clarified in details in [5], [6] and [7]) and lateral torsional buckling (§6.3.4 of [1]) and geometrically and materially nonlinear analysis with imperfections (GMNIA) as regulated by §2.5 and Annex C of EN 1993-1-5 [2]. However, both methods seem quite complicated and cumbersome for practical use.

The lateral-torsional stability of rafters seems an even more complicated problem, taking into account the haunched portions, the negative (hogging) bending moments and the specific restraint conditions with lateral supports at the top (tensile) flange only (the so-called 'fly bracing' is unconventional for Bulgarian practice). Therefore, the author has recently carried out an extensive research and theoretical analyses in the above context. In a recent publication [3] the general method for lateral buckling has been discussed in details with emphasis on the specific issues of its application to the frame lateral stability, namely the complex modelling, the correct identification of the relevant buckling mode and the selection of adequate criterion for load-carrying resistance. The application of the geometrical and material nonlinear analysis with imperfections (GMNIA) is also clarified and discussed in [3]. Some well known simplified methods for out-of-plane stability verification of rafters and haunches are presented as well. However they consider restraints at the bottom flanges too, and thus appear unsuitable for local practice. Nevertheless, some brief description of GMNIA is presented.

The third type of analysis, GMNIA, is also carried out automatically. The model with shell FE is generated and linear buckling analysis is initially performed. The first overall out-of-plane buckling mode is used to obtain the initial imperfections pattern, scaled according to §5.3.4 of EN 1993-1-1 [1]. A revised model is thus generated. Material nonlinearity is based on bilinear constitutive law with isotropic strain hardening. The load-carrying capacity of the frame is assumed to correspond to the ultimate state criterion 'attainment of the maximum load'. The stressed state and the failure mode are also analysed. The software used is ABAQUS nonlinear FE software (Abaqus 2016) [6]. A typical picture at limit state is illustrated in Figure 1.

The primary objective of this study was to adapt, propose and confirm a simplification of widely spread practical method for calculating buckling capacity of haunch. The latter is based on buckling verification of equivalent compressed strut and it is illustrated in Fig. 2.

Marin Vassilev, Department of Steel and Timber Structures, UACEG, Sofia

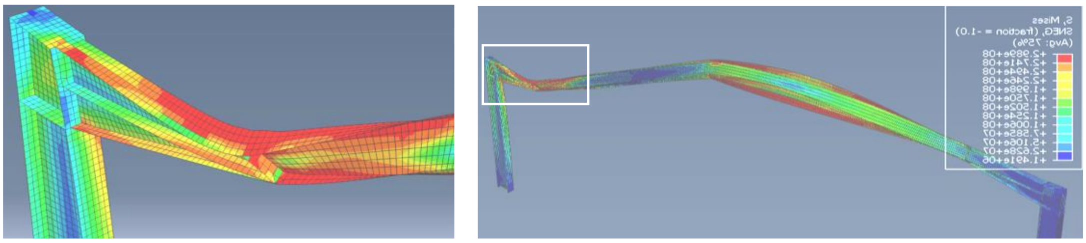

Fig. 1. *Typical frame failure mode obtained by GMNIA.*

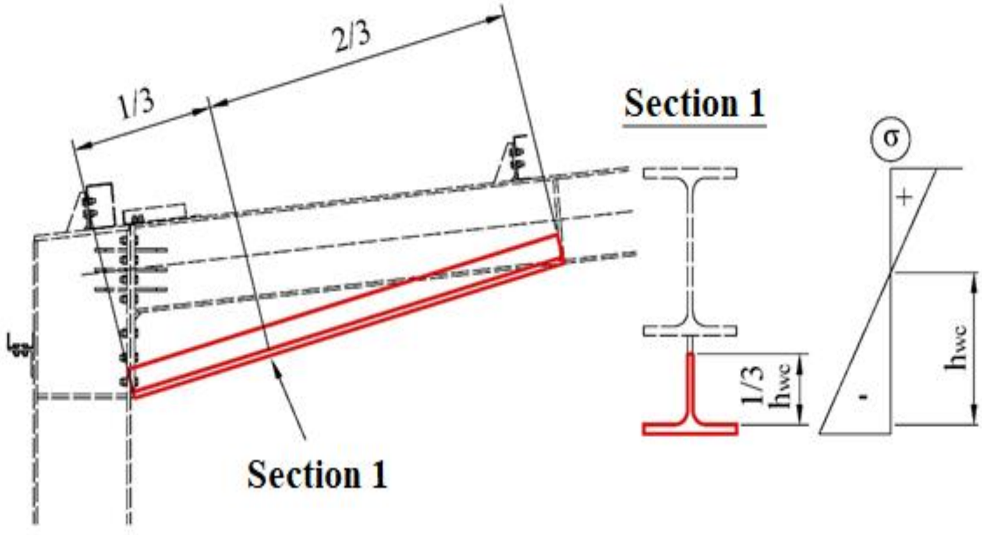

Fig. 2. *Equivalent compressed strut simplified model*

In this well-known simplified model from literature [4], an equivalent compressed strut is defined in section 1 as illustrated in the figure. The axial compression force on the strut is determined in the same section. The lateral buckling verification of the haunched portion is then replaced by out-of-plane flexural buckling check of the strut. Buckling length coincides with the geometric length of the member. The method seems very simple, however requires a fly-brace restraint at the haunch end [4](both flanges at both ends of element must be restraint for out-of-plane movement). Nevertheless, the method is also applied in this study with a view to be eventually adapted to the typical practice in Bulgaria, where fly bracing is absent. Imperfections are considered according to [1] when calculating buckling compression capacity of T-strut. Considered haunches are identical and composed of steel grades – S235, S275 and S355.

2 NUMERICAL ANALYSIS OF METHODOLOGY FOR HAUNCH VERIFICATION

An analysis is made, independently upon the simplified methodology with an equivalent compressed strut, of haunched zones consisting a profile of type *IPE* and a haunch cut from the base profile, with an initial height coinciding with the initial height of the beam projected on the column. Examined lengths for the haunched section are between *1 cm* and *500 cm*. Thus, it can be said that all possible cases are considered in full-wall frames made of rolled profiles (for example, if we decide that the haunch length is 10% of the frame opening and is 4 meters long, it means that the frame should have an opening of*40 meters*– on such an opening a *IPE*-type rolled profile can hardly be applied). The geometry of the options considered is shown schematically in Figure 3.

The purpose of the upcoming analysis is to draw out simplified formulas to apply the simplified method with an equivalent pressed rod, especially for the *IPE*-type beam and the haunch with the same profile described in Figure 3.

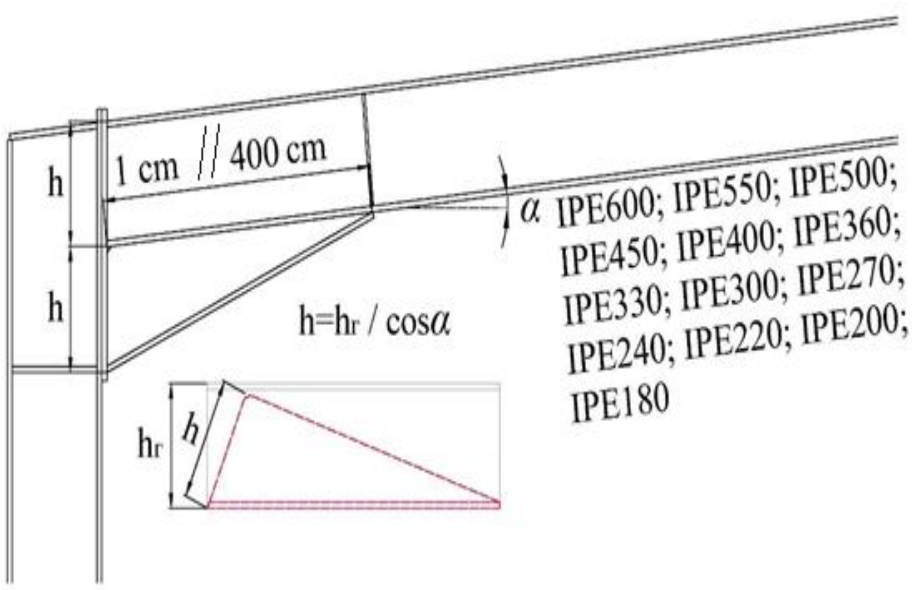

Fig. 3. *Analyzed models*

2.1 Analysis of haunch buckling capacity

We will initially evaluate the effect of the size of the equivalent compressed strut. Its magnitude depends on the compressed part of the stem, respectively the eccentricity of the force, reduced at some distance from the center of gravity of the cross section:

$$e = M / N \ [cm] \qquad (1)$$

Figure 4 illustrates a relationship between the bearing capacity of the *T-section* equivalent profile($N_{b,Rd,z}$) for the various rolled profiles, in function of eccentricity.

In Figure 4, the illustrated dependence is done for a *350 cm* long haunched section, but for practically different lengths, the tendency remains. Only the small eccentricities have some effect on the load bearing capacity of the element – at *e <200*. The typical eccentricity of the frames examined by about *10%* slope is about *300 cm* (eg *1000 kNm bending moment* and approximately *300 kN pressure* in section of the third). Although the eccentricity does not have an enormous importance – about *10%* ($maxN_{b,Rd,z}$ / $minN_{b,Rd,z}$~ *1,1*), in order to be safe for the next reasoning, we will perform a detailed analysis with an eccentricity value of about *300 cm* (this way we will work with the “lower” values of the load bearing capacity).

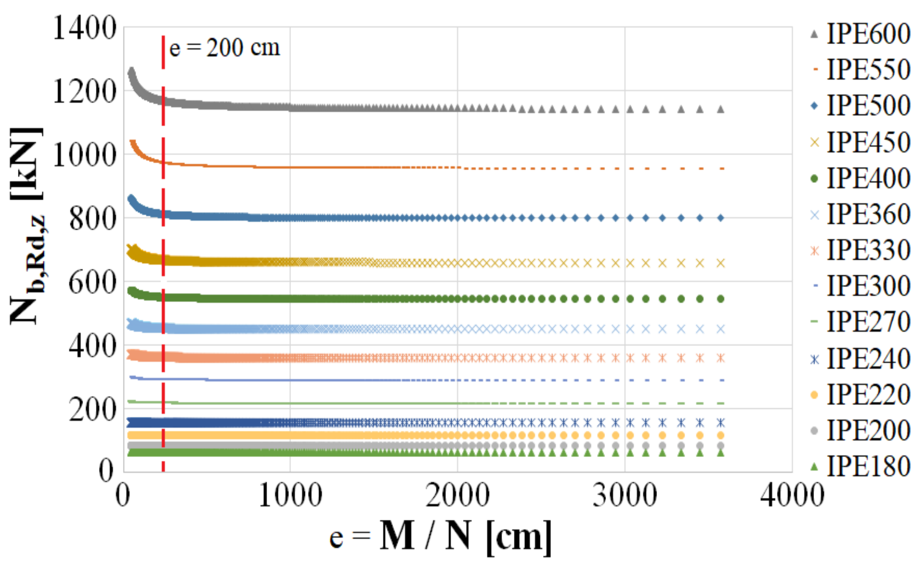

Fig. 4. *Compression capacity of equivalent T-struts in function of eccentricity “e”*

In order to see the load-bearing curves for the different profiles “more generally”, an analysis according to the simplified method for an equivalent compressed *T-profile* for the lengths from *1 cm* to *2000 cm* will be performed. The dependence between the load-bearing capacity of the *equivalent profiles* and the length of the haunch is illustrated in Fig. 5 for various rolled profiles made of *S235* steel grade.

At very small section lengths, the *T-profiles* are so non-slender that they can not buckle. Absolutely identical calculations were made for the relevant profiles, but made up of *S275* steel grade (Figure 6).

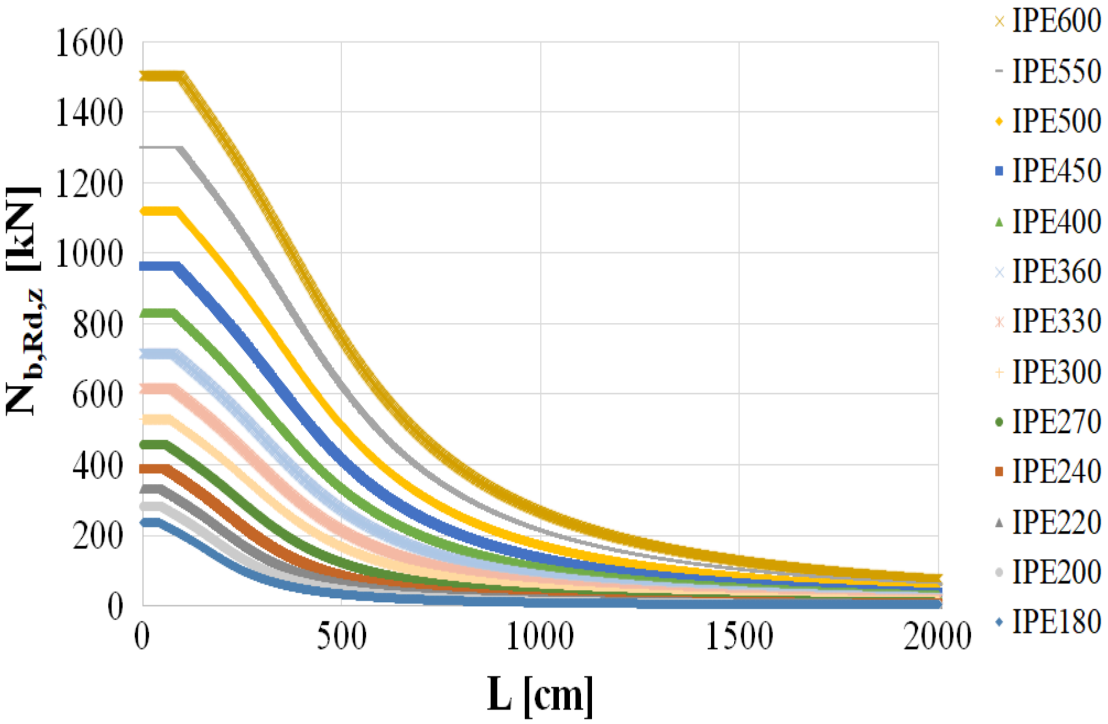

Fig. 5. *Compression capacity of equivalent T-struts with different lengths composed of steel grade S235*

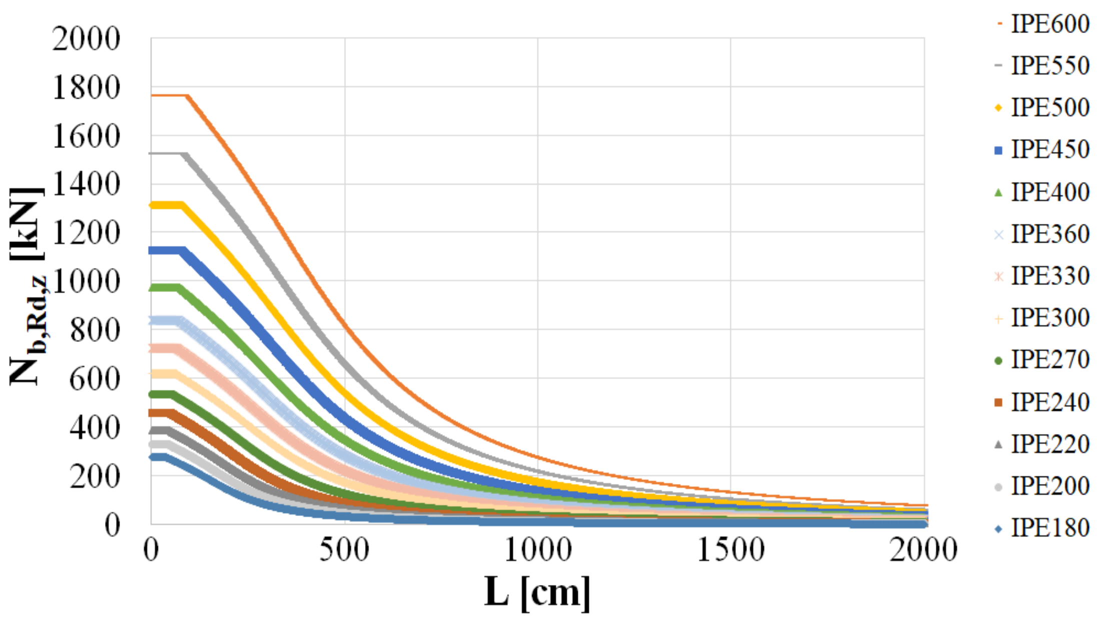

Fig. 6. *Compression capacity of equivalent T-struts with different lengths composed of steel grade S275*

Finally, the analysis is also performed for equivalent bevelled haunched sections, this time the used steel grade is *S355* (Figure7).

Hence, after mathematical operations and transformations for the first ***4 meters***, from these curves and the maximum value limit, formulas were derived for the entire range of *IPE profiles* shown in Figure 5, Figure 6 and Figure 7:

$$N_{b,Rd,z,S235} = -1{,}6\times10^{-4}\times h^{1{,}105}\times L + 0{,}06\times h^{1{,}600} \leq 2{,}95\times h - 330 \ [kN] \quad (2)$$

$$N_{b,Rd,z,S275} = -1{,}3\times10^{-4}\times h^{1{,}175}\times L + 0{,}06\times h^{1{,}630} \leq 3{,}45\times h - 385 \ [kN] \quad (3)$$

$$N_{b,Rd,z,S355} = -1{,}0\times10^{-4}\times h^{1{,}280}\times L + 0{,}06\times h^{1{,}670} \leq 4{,}45\times h - 500 \ [kN] \quad (4)$$

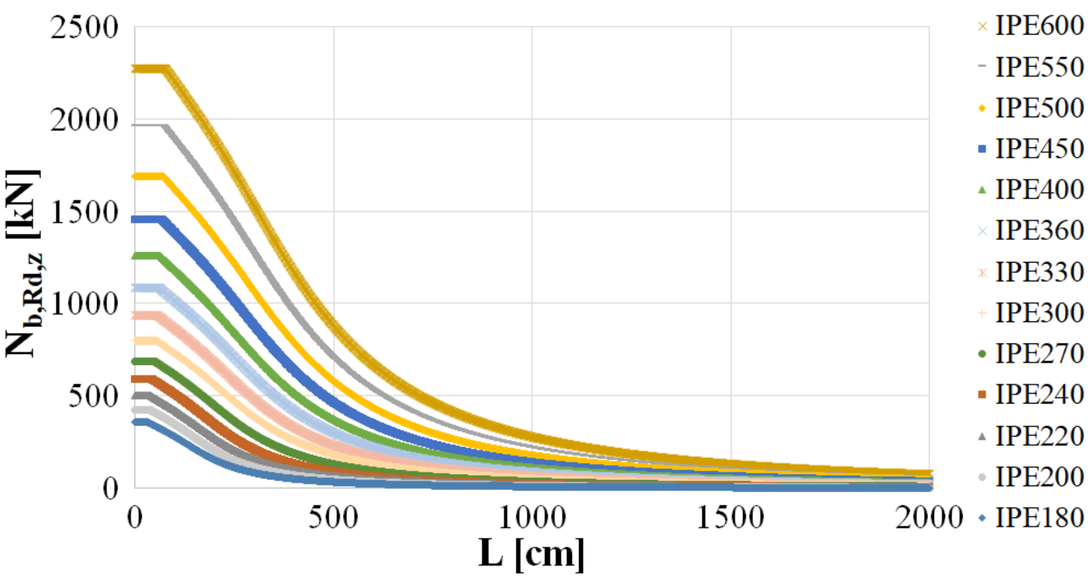

Fig. 7. *Compression capacity of equivalent T-struts with different lengths composed of steel grade S355*

h – height of base profile (e.g.IPE600: h=600 mm) [mm]

L – length of the haunch (formula is valid forL > 0 mmandL ≤ 4000 mm) [mm]

The *three formulas* derived could be combined:

$$N_{b,Rd,z,T\text{-}profile} = -\ \xi_1 \times 10^{-4} \times h^{\alpha} \times L + 0{,}06 \times h^{\beta} \leq \ \xi_2 \times h - \xi_3 \ [kN] \quad (5)$$

$$\xi_1 = 6{,}75 \times\varepsilon^2 - 9{,}05 \times \varepsilon + 3{,}90 \quad (6)$$

$$\xi_2 = 2{,}95 / \varepsilon^2 \quad (7)$$

$$\xi_3 = 330 / \varepsilon^2 \quad (8)$$

$$\alpha = -0{,}85 \times \ln(\varepsilon) + 1{,}105 \ (\alpha \approx -0{,}95 \times\varepsilon + 2{,}055) \quad (9)$$

$$\beta = -0{,}4 \times\varepsilon + 2 \quad (10)$$

$$\varepsilon = (235 / f_y)^{0{,}5} \quad (11)$$

2.2 Compression force in equivalent *T-profile*

Formula (5) is valid for all the haunched zones listed at the beginning of the current subsection (fig.3). Naturally, if it is used in calculations, the compression force which is checked and deducted to this equivalent *T-profile* should be known. Therefore, the different geometric characteristics of the described profiles will be analyzed at the different eccentricities, respectively.

The change of eccentricity defined by *formula (1)* will lead to the changes in the stress diagram in section 1 as illustrated in fig.2, and consequently to the variable compressed part of the stem. This would result in different stem heights (*one-third* of the compressed part of the stem is considered). Figure 8 illustrates the dependence between the eccentricity and the ratio of the geometric characteristics for the case under consideration and Figure 9 illustrates the dependence between the eccentricity and the ratio of the areas of the whole section and the equivalent *T-section*.

Nearly constant values of the geometric relationship are observed in function of the eccentricity of the inner axial force in the section located in the third from the large end of the bevelled section. Only with very small eccentricities (in the presence of a very high normal force compared to a bending moment), which is rather the standard case on a column, an increase in the geometric ratio is observed. This is because, when prevailing pressure, the equivalent *T-profile* has maximum dimensions – the larger part of the stem is compressed or the corresponding strut is bigger. Logically exactly the same is observed in the ratio of the area of the equivalent *T-profile* to the area of the entire cross-section (Fig.9).

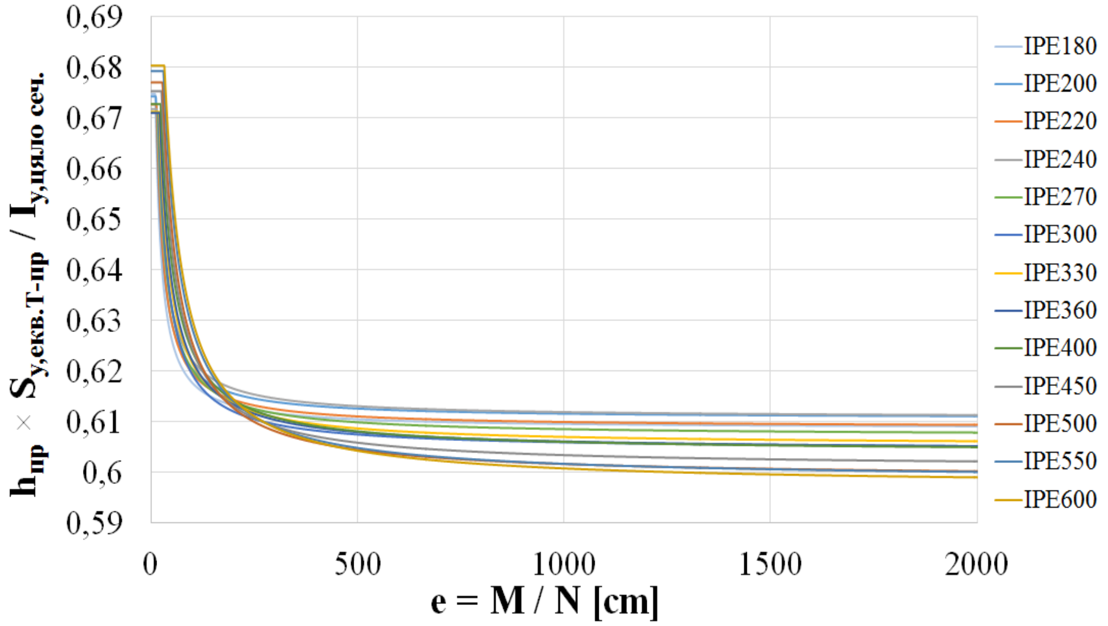

Fig. 8. *Eccentricity in fuction of geometric charachteristics*

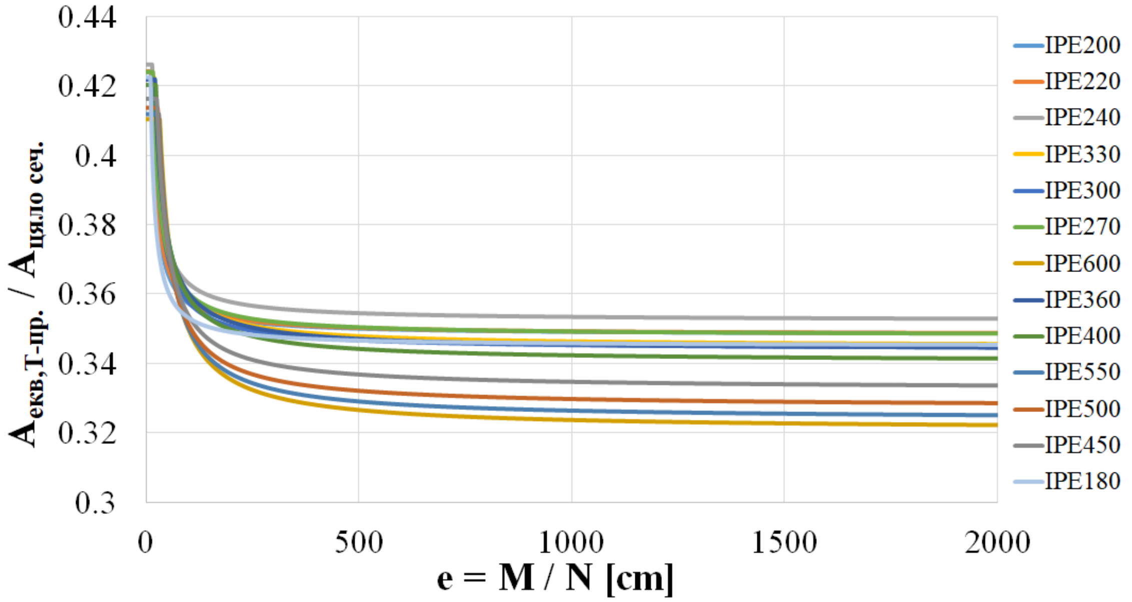

Fig. 9. *Equivalent and base areas ratio in fuction of eccentricity*

From the graphs in Figure 8 it is possible to derive the multiplier for the computation moment in the cross section: *0,6/h* (all values are shown to be between 0.6 and 0.61) and Fig. 9 – the multiplier *0,35* for the deductible normal force. Thus, the final axial force with which to calculate the out of plane buckling of the equivalent *T-profile* results in the following pattern:

$$N_{Ed,eqv.T\text{-}profile} = 0,35 \times N_{Ed} + 0,6 \times M_{Ed} \;/\; h \qquad (12)$$

h – height of base profile (e.g.IPE600: h=600 mm) [mm]

N_{Ed} *– axial compression force in section 1 according to fig.2[kN]*

M_{Ed} *– bending moment in section 1 according to fig.2[kNmm]*

For low eccentricity (e < 200) axial compression force should raise with 15%:

$$N_{Ed,eqv.T\text{-}profile} = 0,4 \times N_{Ed} + 0,7 \times M_{Ed} \;/\; h \qquad (13)$$

3 FINAL VERIFICATION

It would be possible to apply the simplified methodology with the equivalent *T-profile* quickly and practically using these formulas when calculating the haunched segments of the most widely applied type with *IPE*-rolled profiles. The final procedure should be:

$N_{Ed,eqv.T\text{-}profile} = 0,35 \times N_{Ed} + 0,6 \times M_{Ed} \;/\; h$ *[kN] - up with 15% fore = M / N < 200 cm*

$N_{b,Rd,z,T\text{-}profile} = -\xi_1 \times 10^{-4} \times h^{\alpha} \times L + 0,06 \times h^{\beta} \leq \xi_2 \times h - \xi_3$ *[kN]*

$N_{Ed,eqv.T\text{-}profile} / N_{b,Rd,z,T\text{-}profile} \leq 1,00.$

h – height of base profile (e.g.IPE600: h=600 mm) [mm]

L – length of the haunch (formula is valid forL > 0 mmandL ≤ 4000 mm) [mm]

N_{Ed} *– axial compression force in section 1 according to fig.2[kN]*

M_{Ed} *– bending moment in section 1 according to fig.2[kNmm]*

$\xi_1, \xi_2, \xi_3, \alpha, \beta$ *– according formulas (6) to (10).*

4 CONCLUSIONS

There is no practical method for calculating tapered members in Eurocode 3 [1]. In author's opinion the easiest way for solving this problem is the widely spread practical method for calculating buckling capacity of haunch based on buckling verification of equivalent compressed strut, illustrated in Fig. 2. For the application of described method designer must calculate section properties such as second moment of area, buckling reduction factor etc. The simplified equivalent compressed strut model is proved to be suitable and conservative even without restraints to the bottom flange of the rafter.

Therefore simplified formulas are derived for the case of haunches, composed of IPE-profiles – very common case in practice. In this practical approach the only used parameters are height of the beam and material yield strength. Based on this two parameters verification of haunch member could be easily done.

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ABSTRACT

METHOD FOR DETERMINATION OF LOAD-BEARING CAPACITY OF HAUNCHED ZONES MADE OF IPE-TYPE ROLLED

Marin VASSILEV

Recently the author have conducted an extensive theoretical analysis programme on lateral stability of steel portal frames of hot-rolled profiles. Specific software has been developed for automatic modelling and applying the GMNIA method with a view to propose simple and reliable design rules for practical use.

A simplified method with equivalent compressed strut regarding haunched area was proven to be reliable. Therefore the author has analysed and simplified the method to make it easier to use.

Key words: Steel portal frames, Equivalent compressed strut, Haunch

SAŽETAK

METOD ODREĐIVANJA NOSIVOSTI ZONE OJAČANJA (VUTA) IZRAĐENIH OD IPE TOPLO VALJANIH PROFILA

Marin VASSILEV

Autor je sproveo opsežnu teorijsku analizu bočne stabilnosti čeličnih portalnih okvira toplo valjanih profila. Razvijen je poseban softver za automatsko modelovanje i primenu GMNIA metode s ciljem da se predlože jednostavna i pouzdana pravila projektovanja za praktičnu upotrebu. Dokazano je da je pojednostavljena metoda sa ekvivalentnim pritisnutim podupiračima u zoni vute pouzdana. Metod je analiziran i pojednostavljen kako bi bio lakši za primenu.

Ključne reči: Čelični portalni okviri , ekvivalentni pritisnuti podupirač, vuta

ISPITIVANJE INTEGRITETA ŠIPOVA: TESTIRANJE I ANALIZA REZULTATA

PILE INTEGRITY TESTING: TESTING AND RESULTS ANALYSIS

Mladen ĆOSIĆ
Kristina BOŽIĆ-TOMIĆ
Nenad ŠUŠIĆ

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1 UVOD

Problematika ispitivanja integriteta šipova u poslednjih dvadesetak godina doživela je ekspanziju u pogledu: metodologije ispitivanja, tehnike i instrumentalizacije ispitivanja, raznovrsnosti tipova testova ispitivanja, softversko-hardverske podrške ispitivanju i teorije i obrade signala. U tom smislu, biti građevinski inženjer ili inženjer geotehnike sa iskustvom u oblasti projektovanja i izgradnje fundamenata nije dovoljan uslov, već se zahteva multidisciplinarnost u razmatranju problematike ispitivanja šipova. Pored standardnih naučnih disciplina, kao što su teorija elastičnosti, mehanika tla, dinamika tla, mehanika stena, fundiranje, ispitivanje konstrukcija, zahteva se i dobro poznavanje relativno novije naučne tematike interakcija konstrukcija–tlo, ali i drugih naučnih tematika (koje se primarno ne izučavaju u građevinarstvu ili u geotehnici), kao što su: talasna teorija, metoda karakteristika, teorija i obrada signala, termodinamička teorija i slično. U zavisnosti od stepena poznavanja određenih naučnih disciplina, zavisi i stepen pouzdanosti primenjene metodologije i interpretacije rezultata ispitivanja. Iskustva autora ovog rada pokazuju da se neretko nailazi na neadekvatnu interpretaciju standarda ispitivanja šipova, pa i kompletne metodologije ispitivanja. U tom smislu, težišta ovog rada jesu da se predstave određena iskustva autora rada i da se ukaže na potrebu za doslednošću u primeni metodologije ispitivanja šipova, koja je prikazana u radu [6]. S druge strane, primena nekoliko metoda u ispitivanju integriteta šipova omogućava bolje sagledavanje finalnog rešenja ispitivanja. Sve ove metode, primarno, zasnivaju se na talasnoj teoriji, ali i na procesiranju signala i na numeričkim analizama.

Dr Mladen Ćosić, Institut za ispitivanje materijala IMS, Beograd, Srbija, mladen.cosic@institutims.rs
Mr Kristina Božić-Tomić, Institut za ispitivanje materijala IMS, Beograd, Srbija, kristina.tomic@institutims.rs
Dr Nenad Šušić, Institut za ispitivanje materijala IMS, Beograd, Srbija, nenad.susic@institutims.rs

1 INTRODUCTION

The problem of pile integrity testing has expanded over the last twenty years in terms of: test methodology, test technique and instrumentalization, diversity of test types, software-hardware test support, and signal theory and processing. In this sense, being a civil engineer or geotechnical engineer with experience in the field of foundation design and construction is insufficient; a rather multidisciplinary consideration of pile testing is required. In addition to standard scientific disciplines, such as: theory of elasticity, soil mechanics, soil dynamics, rock mechanics, foundations, structural testing requires a good knowledge of relatively recent scientific topics of soil-structure interactions, but also other scientific topics which are not primarily studied in construction or geotechnics, such as: wave theory, method of characteristics, theory and signal processing, thermodynamic theory, etc. The degree of reliability of the applied methodology and interpretation of test results also depends on the degree of knowledge of particular scientific disciplines. The experience of the authors of this paper indicates that there is often an inadequate interpretation of the pile testing standards, even of the complete testing methodology. In this sense, the focus of this paper is to present some of the authors' experiences and to indicate the need for consistency in the implementation of the pile testing methodology presented in [6]. On the other hand, the application of several methods in pile integrity testing allows a better understanding of the final test solution. All of these methods are primarily based on the wave theory, but also on signal processing and numerical analyses.

Dr Mladen Cosic, Institute for testing of materials IMS, Belgrade, Serbia, mladen.cosic@institutims.rs
Mr Kristina Bozic-Tomic, Institute for testing of materials IMS, Belgrade, Serbia, kristina.tomic@institutims.rs
Dr Nenad Susic, Institute for testing of materials IMS, Belgrade, Serbia, nenad.susic@institutims.rs

Upoređivanje rešenja koja se dobijaju analizama reflektograma u vremenskom i frekventnom domenu prikazano je u radu [22], dok su u radovima [21] i [3] prikazane osnove ispitivanja integriteta šipova i procedure za procenu stanja integriteta šipova. U radu [9], razmatrana je analiza propagacije talasa prilikom testa integriteta šipa, dok se u radu [19], primenom teorije talasića, analizira integritet šipa. Numerička analiza defektnih šipova razmatrana je u istraživanjima [28] i [8], a numerička analiza integriteta šipa s promenljivim modulom elastičnosti u radu [26]. Analize 3D efekata, prilikom testa integriteta šipa, prikazane su u radovima [30] i [29]. Interpretacija rezultata testova integriteta šipova sa simuliranim defektima prikazana je u istraživanju [20], dok je interpretacija rezultata ispitivanja integriteta šipova, primenom metode mašinskog učenja, prikazana u istraživanju [5]. Razvoj sveobuhvatne metodologije za analizu integriteta i nosivosti šipova prezentovana je radu [7]. U odnosu na istraživanja koja se sprovode testom integriteta šipa sa senzorom (SIT), primenom testa integriteta šipa sa sondama (CSL) dobija se uočljivo bolji uvid o stanju integralnosti šipa [4], [25]. Pouzdanost testa integriteta šipa sa sondama (CSL), između ostalog, razmatrana je u radu [16].

Tim inženjera i tehničara Centra za puteve i geotehniku Instituta IMS sproveo je nekoliko hiljada ispitivanja testova integriteta šipa sa senzorom (SIT) i više od stotinu ispitivanja testova integriteta šipa sa sondama (CSL). Ispitivanja integriteta sprovedena su za šipove sledećih objekata (izdvojeno): mostovi na koridoru X i XI, Žeželjev most u Novom Sadu, poslovno-komercijalna zgrada-kula Ušće 2, obaloutvrde za projekat *Belgrade Waterfront*, železnička stanica Centar Beograd - Prokop, veći broj mostova na autoputu E 75 Novi Sad - Beograd - Niš, veći broj mostova na autoputu E 763 Beograd - Južni Jadran, mostovi na autoputu E 80 deonica Čiflik - Pirot, mostovi na obilaznici oko Beograda, modernizacija Rafinerije nafte Pančevo, silos pepela u TE Kostolac A, vetrogeneratori u vetroparkovima Kula, Zagajica, Izbište, Malibunar i Alibunar, veći broj objekata na lokaciji ulice Stepa Stepanović u Beogradu, skladište mineralnih đubriva Victoria Zorka, poslovno-stambeni kompleks u ulici Dušana Jovanovića u Beogradu, poslovno-stambeni objekat u Univerzitetskom naselju, kotlarnica toplane na Konjarniku, objekat u naselju dr Ivana Ribara na Novom Beogradu, Klinički centar u Nišu, objekat *dr Oetker* u Šimanovcima, postrojenje za prečišćavanje otpadnih voda u Šapcu i drugo. U ovom radu analiziraće se neki rezultati autorskih ispitivanja integriteta šipova, sprovedeni na velikim i značajnim objektima u Srbiji i u regionu.

2 ISPITIVANJE INTEGRITETA ŠIPOVA TESTOM INTEGRITETA ŠIPA SA SENZOROM (SIT)

Test integriteta šipa sa senzorom (SIT) u praksi se zove i test eha zvuka (SET) ili test eha šipa (PET), a pripada grupi niskodilatacionih testova (LST). Test integriteta šipa sa senzorom (SIT) zasniva se na teoriji jednodimenzionalne propagacije talasa kroz šip, s ciljem utvrđivanja: stvarne dužine šipa, postojanje defekata i diskontinuiteta i redukcije poprečnog preseka šipa [6]. Takođe, analiziraju se: promena signala u domenu glave šipa, kvalitet odziva signala u bazi šipa, promena

The comparison of solutions obtained by the analysis of reflectograms in the time and frequency domains is presented in [22], while in [21] and [3] the basics of pile integrity testing and procedures for pile integrity state assessment were presented. In [9] the analysis of wave propagation in the pile integrity test was considered, while in [19] the pile integrity was analyzed using the wavelet theory. Numerical analysis of defective piles was considered in studies [28] and [8], and numerical analysis of pile integrity with variable modulus of elasticity in operation was considered in [26]. Analyses of 3D effects in pile integrity tests were presented in [30] and [29]. The interpretation of the results of pile integrity tests with simulated defects was presented in the study [20], while the interpretation of the results of pile integrity tests using machine learning method was presented in the study [5]. The development of a comprehensive methodology for analyzing the integrity and load-bearing capacity of piles was presented in [7]. In comparison with the research conducted with SIT, a significantly better insight into the state of integrity of the pile is obtained using CSL [4], [25]. The reliability of the CSL test, among others, was discussed in [16].

A team of engineers and technicians at the *Centre for Roads and Geotechnics of the IMS Institute* conducted several thousand SITs and more than a hundred CSLs. The integrity tests were carried out for piles of the following structures (selected): bridges on *CorridorX* and *XI*, *Žeželj* Bridge in *Novi Sad*, office-commercial building- tower *Ušće 2*, shoreline for the *Belgrade Waterfront* project, *Belgrade Centre - Prokop* railway station, a large number of bridges on the highway *E 75 Novi Sad-Belgrade-Nis*, a number of bridges on the highway *E 763 Belgrade-South Adriatic*, bridges on the highway *E 80* section *Čiflik-Pirot*, bridges on the *bypass around Belgrade*, modernization of the *Pančevo Oil Refinery*, fly ash silo at *Kostolac A TE*, wind turbines in *Kula, Zagajica, Izbište, Malbunar* and *Alibunar* wind farms, a large number of structures on the location of *Stepa Stepanović Street* in *Belgrade*, *Victoria Zorka* mineral fertilizer depot, office and residential complex in *Dušan Jovanović* Street in *Belgrade*, office and residential building in the *University District*, heating plant boiler room on *Konjarnik*, building in *dr Ivan Ribar* district in *New Belgrade*, clinical centre in *Niš*, *dr Oetker* building in *Šimanovci*, sewage treatment plant in *Šabac* et al. This paper analyzes some results of own pile integrity tests conducted on large and significant structures in Serbia and in the region.

2 PILE INTEGRITY TESTING USING SONIC INTEGRITY TEST (SIT)

Sonic Integrity Test (SIT) is in practice also called the Sonic Echo Test (SET) or Pile Echo Test (PET), and it belongs to the group of Low Strain Tests (LST). SIT is based on the theory of one-dimensional wave propagation through the pile, with the aim of determining: the actual length of the pile, existence of defects and discontinuities and reduction of the pile cross-section [6]. In addition, it analyzes variation of signal in the pile head domain, signal response quality at impedance duž stabla šipa, promena slojeva tla u kojima je šip izgrađen i postojanje proširenja poprečnog preseka duž stabla šipa. Ovaj test, zapravo, jeste indirektna metoda analize integriteta šipa, s obzirom na to što se ispitivanje sprovodi analizirajući propagaciju talasa duž šipa, ali indukcijom talasa sa glave šipa. Test je brz, efikasan, sofisticiran i dovoljno pouzdan za praktičnu primenu. Ovim testom se ispituju integriteti svih tipova armiranobetonskih šipova: bušeni, CFA i pobijeni. Takođe, ispituju se i radni (eksploatacioni) i probni (testni) šipovi. Metodologija ispitivanja integriteta šipa sa senzorom (SIT) definisana je standardom ASTM D5882 [1]. Centar za puteve i geotehniku Instituta IMS poseduje licencirane opreme za test integriteta šipa sa senzorom (SIT) holandske firme *Profound* i američke firme *Pile Dynamics*. Obe opreme omogućavaju analizu reflektograma u vremenskom (TDA) i frekventnom domenu (FDA). Takođe, obe opreme imaju integrisane softverske module za: procesiranje, skaliranje (eksponencijalnu amplifikaciju) i filtriranje signala. Oprema SIT^+ [15] za test integriteta šipa sa senzorom (SIT), holandske firme *Profound*, sastoji se iz: mehaničkog čekića, senzora (akcelerometra), hardverskog sistema za konvertovanje i akviziciju podataka i softverskog sistema (SIT i SITWAVE) za procesiranje i vizuelizaciju podataka. Akcelerometar je linearan u opsegu ±50g, rezonantne frekvencije 32kHz i nominalne osetljivosti 10mV/g. Konverzija AD signala se sprovodi primenom 24-bitnog konvertera (>48.6 kHz). Oprema PIT-QFV [12] za test integriteta šipa sa senzorom (SIT), američke firme *Pile Dynamics*, sastoji se iz: mehaničkog čekića povezanog električnim kablom za merenje karakteristika indukovanog signala, senzora (akcelerometra), hardverskog sistema za konvertovanje i akviziciju podataka i softverskog sistema (PIT-W *professional* i PIT-S) za procesiranje i vizuelizaciju podataka. Akcelerometar je linearan u opsegu ±100 g, rezonantne frekvencije 40 kHz i nominalne osetljivosti 50 mV/g. Konverzija AD signala se sprovodi primenom 24-bitnog konvertera (>32 kHz). Na slici 1 prikazane su opreme za ispitivanje integriteta šipova testom integriteta šipa sa senzorom (SIT): SIT^+ oprema holandske firme *Profound* i PIT-QFV oprema američke firme *Pile Dynamics*.

the pile toe, variation of impedance along the pile shaft, variation of layers of soil in which the pile is constructed, and existence of expansions of cross-section along the pile shaft. This test is, in fact, an indirect method of pile integrity analysis, considering that the test is carried out by analyzing the wave propagation along the pile, via induction of waves from the pile head. The test is quick, efficient, sophisticated and sufficiently reliable for practical use. This test is used to test integrities of all types of reinforced concrete piles: bored, CFA and driven piles. It also tests both the service and test piles. The SIT methodology is defined with the ASTM D5882 standard [1]. The *Centre for Roads and Geotechnics of the IMS Institute* possesses the licensed equipment for SIT, manufactured by the Dutch *Profound* company and U.S. *Pile Dynamics* company. Both equipment sets facilitate reflectogram analysis in time (TDA) and frequency domains (FDA). In addition, both equipment sets have integrated software modules: processing, scaling (exponential amplification) and signal filtering. SIT^+ equipment [15] for SIT, of the Dutch *Profound* company consists of: mechanical hammer, sensor (accelerometer), hardware system for data conversion and acquisition and software system (SIT and SITWAVE) for processing and visualization of data. The accelerometer is linear in the ±50g range, of resonant frequency 32kHz and nominal sensitivity 10mV/g. AD signal conversion is conducted using the 24-bit converter (>48.6kHz). PIT-QFV equipment [12] for SIT, by the U.S. *Pile Dynamics* company, consists of: mechanical hammer connected by an electric cable for measuring induced signal characteristics, sensor (accelerometer), hardware system for data conversion and acquisition and the software system (PIT-W *professional* and PIT-S) for data processing and visualization. The accelerometer is linear in the ±100g range, of resonant frequency 40kHz and nominal sensitivity 50mV/g. AD signal conversion is conducted using the 24-bit converter (>32kHz). Equipment sets for pile integrity testing using SIT: SIT^+ equipment by the Dutch *Profound* company and PIT-QFV equipment by the U.S. *Pile Dynamics* company are shown in Figure 1.

a) 

b) 

Slika 1. Opreme za ispitivanje integriteta šipova testom integriteta šipa sa senzorom (SIT): a) SIT^+ oprema holandske firme Profound [15]; b) PIT-QFV oprema američke firme Pile Dynamics [12]

Figure 1. Equipment sets for pile integrity testing using SIT: a) SIT^+ Dutch Profound company equipment [15], b) PIT-QFV U.S. Pile Dynamics company equipment [12]

Institut IMS sproveo je nekoliko hiljada ispitivanja testova integriteta šipa sa senzorom (SIT) na različitim tipovima šipova izgrađenih u različitim geološkim uslovima, tako da poseduje sopstvenu bazu znanja, iskustva i bazu podataka ispitivanja. S obzirom na ovako veliki broj sprovedenih ispitivanja, s vremenom su se definisale karakteristične situacije u kojima su razmatrani aspekti dobijenih reflektograma. U tom smislu, generalno se mogu izdvojiti tri grupe reflektograma: klasični ili standardni reflektogrami koji ukazuju na dobar kvalitet integriteta šipa, reflektogrami koji ukazuju na moguću redukciju integriteta šipa, pa zahtevaju dodatne analize i reflektogrami koji jasno ukazuju na značajniji problem integriteta šipa. Detaljnija klasifikacija reflektograma može se sprovesti prema [17]:

- AA – ispravan šip s pozitivnim refleksijama ili kod koga se pre refleksije od baze šipa identifikuju manje promene brzine i odstupanja brzine propagacije talasa, ne veće od 5% od prosečne brzine propagacije talasa;
- AB – refleksija od baze se jasno ne identifikuje, ali i nema znatnih smanjenja impedance, pri čemu je moguć razlog za nepostojanje refleksije od baze velika krutost tla;
- PF – postoji jedna negativna refleksija ili više njih i/ili postoji bar jedno smanjenje impedance, a s obzirom na to što je refleksija od baze smanjena, impedanca je manja nego kod defekta kod koga nema refleksije od baze;
- PD – brzina propagacije talasa odstupa više od 5% od prosečne brzine propagacije talasa, a što ukazuje na moguć defekat šipa, pri čemu postoji jedna refleksija ili više njih koje maskiraju refleksiju od baze šipa;
- IR – znatno kompleksan signal (odgovor), a što, između ostalog, ukazuje na loš kvalitet betona pri vrhu šipa i/ili na to da je ispitivanje sprovedeno suviše rano da bi beton dostigao potrebnu čvrstoću.

Pre sprovođenja testa, okrajcuje se beton i glava šipa se očisti od prašine i ostataka odlomljenih delova betona. Na slici 2 su prikazani šipovi (glave šipova) pripremljeni za ispitivanje testom integriteta šipa sa senzorom (SIT): adekvanta priprema, neadekvatna priprema, adekvatna priprema, međutim rezultati SIT na ovako pripremljenim glavama šipa sa hidroizolacijom mogu biti diskutabilni i nastavci glava šipova koji mogu biti problematični u smislu interpretacije signala SIT.

The IMS Institute conducted several thousand tests of SIT on various types of piles constructed in different geological conditions, so it possesses its own database of knowledge, experience and testing database. In view of such a large number of tests conducted, over time, characteristic situations were defined in which aspects of the obtained reflectograms were considered. In this sense, three groups of reflectograms can be generally distinguished: classical or standard reflectograms indicating good quality of pile integrity, reflectograms indicating possible reduction of pile integrity, and thus require additional analyses and reflectograms that clearly indicate a more considerable problem of pile integrity. A more detailed classification of reflectograms can be made according to [17]:

- AA - a proper pile with positive reflections or such in which prior to reflection off the pile toe minor variations in velocity and deviations in the wave propagation velocity of not more than 5% of the average propagation velocity of the wave are identified,
- AB - the reflection from the toe is not clearly identified, but there are also no significant impedance reductions, the possible reason for the lack of reflection from the toe being the high stiffness of the ground,
- PF - there is one or more negative reflections and/or there is at least one impedance decrease, and since the reflection from the toe is reduced, the impedance is lower than in the case of a defect when there is no reflection from the toe,
- PD - the wave propagation velocity deviates more than 5% from the average wave propagation velocity, indicating a possible defect in the pile, with one or more reflections masking the reflection from the pile toe,
- IR - considerably complex signal (response), which indicates, among other things, the poor quality of the concrete at the head of the pile and/or the test was conducted too early for the concrete to reach the required strength.

Before the test, the concrete is trimmed and the pile head is cleared of dust and debris from broken concrete. Figure 2 shows the piles (pile heads) prepared for the SIT: adequate preparation, inadequate preparation, adequate preparation, however, the results of SIT on such a pile heads with waterproofing may be debatable and pile head extensions that can be problematic in terms of interpreting the SIT signal.

a) 

b) 

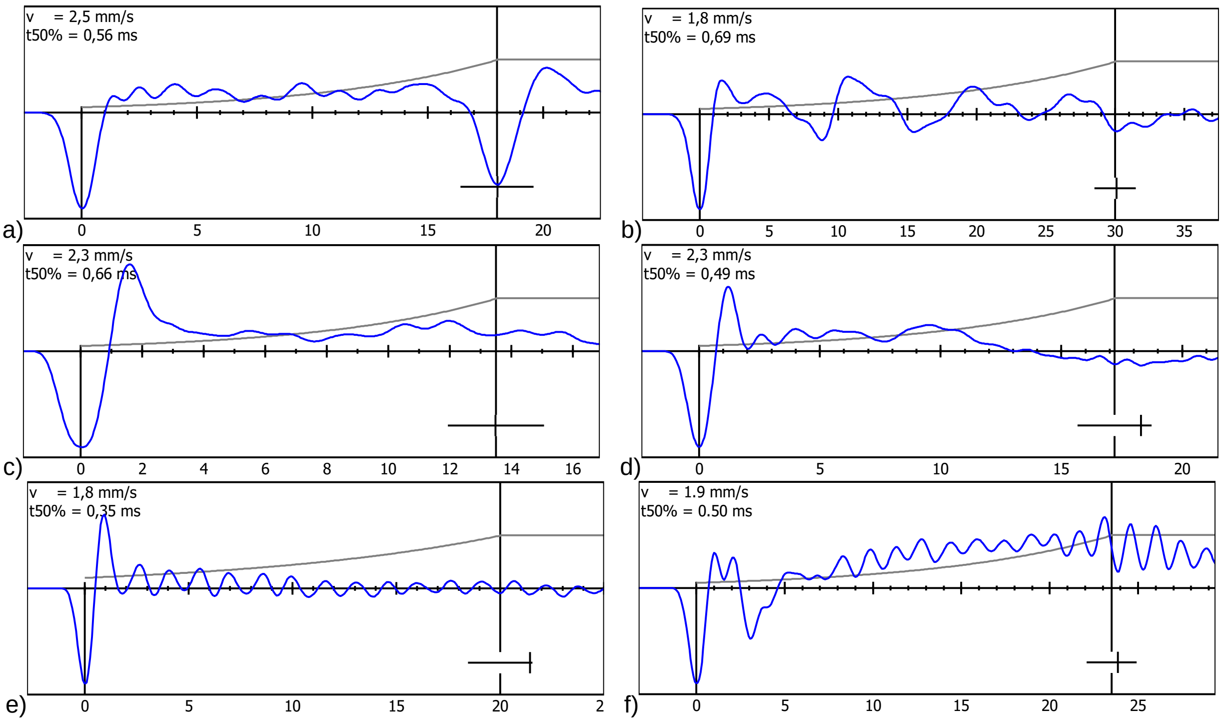
c) d)

Slika 2. Šipovi (glave šipova) pripremljeni za ispitivanje testom integriteta šipa sa senzorom (SIT): a) adekvatna priprema; b) neadekvatna priprema; c) adekvatna priprema, međutim rezultati SIT na ovako pripremljenim glavama šipa sa hidroizolacijom mogu biti diskutabilni; d) nastavci glava šipova koji mogu biti problematični u smislu interpretacije signala SIT

Figure 2. Piles (pile heads) prepared for the SIT: a) adequate preparation, b) inadequate preparation, c) adequate preparation, however the results of SIT on such pile heads with waterproofing may be debatable, d) pile head extensions that can be problematic in terms of interpreting the SIT signal

Na slici 3 prikazani su reflektogrami SIT integriteta šipova dobijeni SIT+ holandskom opremom: regularan šip, šip sa značajnijim redukcijama impedance u određenim presecima, nejasan odziv baze šipa i nakon primene eksponencijalnog filtera, redukcija impedance

Figure 3 shows SIT reflectograms of pile integrity obtained by the Dutch equipment SIT+: regular pile, pile with significant impedance reductions in certain cross-sections, a vague pile toe response even after application of an exponential filter, the impedance reduction



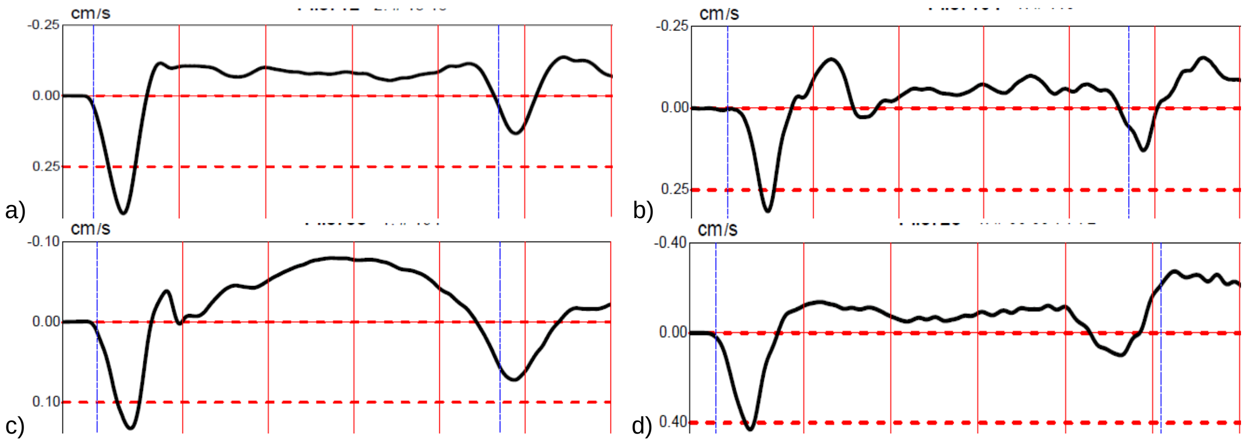
Slika 3. Reflektogrami SIT integriteta šipova dobijeni SIT+ holandskom opremom: a) regularan šip; b) šip sa značajnijim redukcijama impedance u određenim presecima; c) nejasan odziv baze šipa i nakon primene eksponencijalnog filtera; d) redukcija impedance znatnije pre baze šipa; e) varijacija signala iz pozitivne u negativnu vrednost - posledica niskog modula elastičnosti glave šipa; f) značajna redukcija impedance u početnom delu šipa - defekat/diskontinuitet

Figure 3. SIT reflectograms of pile integrity obtained by the Dutch equipment SIT+: a) regular pile, b) pile with significant impedance reductions in certain cross-sections, c) vague pile toe response even after application of an exponential filter, d) impedance reduction significantly before the pile toe, e) signal variation from positive to negative value - consequence of low modulus of elasticity of the pile head, f) significant impedance reduction in the initial part of the pile - defect/discontinuity

znatnije pre baze šipa, varijacija signala iz pozitivne u negativnu vrednost - posledica niskog modula elastičnosti glave šipa i značajna redukcija impedance u početnom delu šipa - defekat/diskontinuitet.
Na slici 4 prikazani su reflektogrami SIT integriteta šipova dobijeni PIT-QFV američkom opremom: regularan šip, šip s redukcijom impedance u početnom delu, efekat povećanja impedance i krutosti tla i šip izgrađen kraći nego što je projektom predviđeno.

significantly before the pile toe, signal variation from positive to negative value - consequence of low modulus of elasticity of the pile head and significant impedance reduction in the initial part of the pile - defect/discontinuity.

Figure 4 shows the SIT reflectograms obtained by the U.S. PIT-QFV equipment: regular pile, pile with impedance reduction in the initial part, an effect of increasing the impedance and soil stiffness, and pile built shorter than designed.



Slika 4. Reflektogrami SIT integriteta šipova dobijeni PIT-QFV američkom opremom: a) regularan šip; b) šip s redukcijom impedance u početnom delu; c) efekat povećanja impedance i krutosti tla; d) šip izgrađen kraći nego što je projektom predviđeno

Figure 4. SIT reflectograms obtained by the U.S. PIT-QFV equipment: a) regular pile, b) pile with impedance reduction in the initial part, c) effect of increasing the impedance and soil stiffness, d) pile built shorter than designed

Prilikom sprovođenja SIT integriteta šipa, kod određenih reflektograma, mogu se pojaviti značajnije redukcije impedance, što može biti jedan od pokazatelja defekta i/ili diskontinuiteta šipa. Da bi se detaljnije analizirao stepen defekta i/ili diskontinuiteta, sprovodi se dodatna analiza koja se zasniva na talasnoj teoriji i metodi karakteristika. Softver SITWAVE ima mogućnost analize promene impedance duž stabla šipa, tako da se efikasno može dobiti oblik šipa izgrađen u tlu, dok softver PIT-S ima mogućnost analize oblika šipa primenom *β* metode. S obzirom na veću pouzdanost rešenja koje se dobija primenom SITWAVE softvera, jer je, između ostalog, matematička analiza promene impedance kompleksnija i naučno utemeljenija, ovaj softver se i češće koristi za ovakve situacije. Jednačina propagacije talasa putem elastičnog medijuma, u opštem slučaju, jeste hiperbolična parcijalna diferencijalna jednačina drugog reda [23]:

During the implementation of pile integrity SIT, in certain reflectograms, considerable impedance reductions may occur, which may be one of the indicators of a defect and/or discontinuity of the pile. In order to analyze in more detail the degree of the defect and/or discontinuity, an additional analysis is conducted, which is based on the wave theory and method of characteristics. The SITWAVE software has the ability to analyze the impedance variations along the pile shaft, so that the pile shape built in the soil can be effectively obtained, while the PIT-S software has the ability to analyze the pile shape using the *β* method. Due to the higher reliability of the solution obtained by the application of SITWAVE software, because, among other things, the mathematical analysis of impedance variation is more complex and scientifically founded, this software is more often used in such situations. The wave propagation equation through an elastic medium is, in the general case, a hyperbolic partial differential equation of the second order [23]:

$$\frac{\partial^2 u}{\partial t^2} = v^2 \nabla^2 u, \tag{1}$$

gde je *v* brzina talasa, *u* pomeranje, *t* vreme. Ukoliko je dužina talasa veća od prečnika šipa ili jednaka prečniku šipa, tada se propagacija talasa u šipu može razmatrati primenom jednodimenzionalne teorije rasprostiranja talasa u čvrstom medijumu [11]. Jednodimenzionalna

where *v* is the wave velocity, *u* displacement, *t* time. If the wavelength is higher than or equal to the pile diameter, then the wave propagation in the pile can be analyzed by applying the one-dimensional theory of wave propagation in a solid medium [11]. The one-talasna jednačina (po *x*) predstavlja specijalan slučaj jednačine (1):

dimensional wave equation (by *x*) is a special case of equation (1):

$$\frac{\partial^2 u}{\partial t^2} = v^2 \frac{\partial^2 u}{\partial x^2}, \tag{2}$$

a opšte rešenje ove jednačine glasi:

and the general solution of this equation is:

$$u(x,t) = u_1(x - vt) + u_2(x + vt). \tag{3}$$

Brzina propagacije longitudinalnih talasa u čvrstom medijumu *v* jeste funkcija karakteristika materijala tog medijuma i određuje se prema:

The velocity of propagation of longitudinal waves in a solid medium *v* is the function of material characteristics of that medium and it is determined according to:

$$v = \sqrt{\frac{E}{\rho}}, \tag{4}$$

gde je *E* *Young*-ov modul elastičnosti, *ρ* zapreminska težina. Sada se jednačina (2) može pisati kao:

where *E* is the *Young* modulus of elasticity, *ρ* is density. Now equation (2) can be written as:

$$\rho \frac{\partial^2 u}{\partial t^2} - E \frac{\partial^2 u}{\partial x^2} = 0, \tag{5}$$

pri čemu se rešenje traži tako da su vreme i pomeranje nezavisne promenljive:

whereby solution is sought so that time and displacement are independent variables:

$$u(x,t) = \Psi(x) g(t), \tag{6}$$

a zatim zamenom izraza (6) u (2) dobija se:

and then, by the substitution of expression (6) in (2) is obtained:

$$\Psi(x) = Ae^{i\alpha x} \quad \text{i / and} \quad g(t) = Ae^{i\omega t}. \tag{7}$$

Rešenje problema (7) moguće je dobiti za jednostavnije sisteme i konturne uslove u zatvorenom obliku, međutim kod kompleksnijeg modeliranja šipa s diskontinuitetima i defektima potrebno je primeniti metodu konačnih elemenata. S druge strane, ukoliko se problem propagacije talasa u šipu razmatra u diskretnim segmentima, tada je rešenje jednačine (2) moguće odrediti metodom karakteristika, pri čemu se izraz (3) može pisati kao [24], [18]:

The solution of the problem (7) can be obtained for simpler systems and contour conditions in a closed form, however, in more complex modelling of a pile with discontinuities and defects, it is necessary to implement the finite element method. On the other hand, if the problem of wave propagation in a pile is considered in discrete segments, then the solution to the equation (2) could be determined using the method of characteristics, whereby expression (3) can be written as [24], [18]:

$$u(x,t) = u^{\downarrow}(x - vt) + u^{\uparrow}(x + vt), \tag{8}$$

gde je ↓ oznaka za talas koji se kreće od glave ka bazi šipa, a ↑ oznaka za talas koji se kreće od baze ka glavi šipa. Odgovarajuća brzina talasa v_p i sila *F* koja se indukuje u šipu, za diskretan element šipa, određuju se iz:

where ↓ is the designation for the wave propagating from the head to the toe of the pile, and ↑ the designation for the wave propagating from the toe to the head of the pile. The corresponding wave velocity v_p and force *F* induced in the pile, for the discrete element of the pile, are determined from:

$$v_p = \frac{\partial u}{\partial t} = \frac{\partial u^{\downarrow}}{\partial (x - vt)}(-v) + \frac{\partial u^{\uparrow}}{\partial (x + vt)}(+v) = v_p^{\downarrow} + v_p^{\uparrow}, \tag{9}$$

$$F = -EA\frac{\partial u}{\partial x} = -EA\frac{\partial u^{\downarrow}}{\partial (x - vt)} + \frac{\partial u^{\uparrow}}{\partial (x + vt)} = F^{\downarrow} + F^{\uparrow}, \tag{10}$$

gde je *A* površina poprečnog preseka šipa. Pošto su $v_p^{\downarrow}$ i $F^{\downarrow}$ samo funkcije od (*x*-*vt*) i $v_p^{\uparrow}$ i $F^{\uparrow}$ samo funkcije od (*x*+*vt*), brzina i sila mogu se pisati kao:

where *A* is the area of the pile cross section. Since $v_p^{\downarrow}$ and $F^{\downarrow}$ are only functions of (*x*-*vt*) and $v_p^{\uparrow}$ and $F^{\uparrow}$ only functions of (*x*+*vt*), the velocity and force can be written as:

$$F^{\downarrow} = Zv_p^{\downarrow} \quad \text{i / and} \quad F^{\uparrow} = -Zv_p^{\uparrow}, \tag{11}$$

gde je *Z* impedanca šipa:

where *Z* is the pile impedance:

$$Z = \frac{EA}{v} = A\sqrt{E\rho}, \tag{12}$$

Bilo koja promena *A*, *E* ili *ρ* parametra generiše promenu u odzivu brzina na reflektogramu. U slučaju diskontinuiteta, kada je na jednom delu prečnik šipa manji, jednačine ravnoteže za granicu dva medijuma glase:

Any variation of *A*, *E* or *ρ* parameters generates a variation in the response of velocities in the reflectogram. In case of a discontinuity, when a section of the pile has a smaller cross section, equilibrium equations for the interface of two media are:

$$F_1^{\downarrow} + F_1^{\uparrow} = F_2^{\downarrow} + F_2^{\uparrow} \quad \text{i / and} \quad v_{p1}^{\downarrow} + v_{p1}^{\uparrow} = v_{p2}^{\downarrow} + v_{p2}^{\uparrow}, \tag{13}$$

gde se indeksi 1 i 2 odnose na medijume. Zamenom (11) u (13) dobija se:

where indices 1 and 2 refer to the media. Substituting (11) for (13) the following is obtained:

$$\frac{F_1^{\downarrow}}{Z_1} - \frac{F_1^{\uparrow}}{Z_1} = \frac{F_2^{\downarrow}}{Z_2} + \frac{F_2^{\uparrow}}{Z_2}, \tag{14}$$

Kada je šip pobuđen na vibracije u tlu postoji kompleksna interakcija šip–tlo, gde se sila trenja po omotaču šipa *W* uzima u razmatranje kao:

When a pile is excited to soil vibrations, there is a complex soil-pile interaction, where the friction force along the pile surface *W* is taken into consideration as:

$$F = F_1^{\downarrow} + F_1^{\uparrow} = F_2^{\downarrow} + F_2^{\uparrow} + W\ , \tag{15}$$

tako da izraz (13) postaje:

so that expression (13) becomes:

$$v_p = \frac{F_1^{\downarrow}}{Z} - \frac{F_1^{\uparrow}}{Z} = \frac{F_2^{\downarrow}}{Z} + \frac{F_2^{\uparrow}}{Z} \quad \text{i / and} \quad Zv_p = F_1^{\downarrow} - F_1^{\uparrow} = F_2^{\downarrow} + F_2^{\uparrow}. \tag{16}$$

Komponente sila za medijume se sada određuju prema:

Force components for media are determined according to:

$$F_2^{\downarrow} = F_1^{\downarrow} - 0.5W \quad \text{i / and} \quad F_1^{\uparrow} = F_2^{\uparrow} + 0.5W. \tag{17}$$

U bazi, na kontaktu šipa i tla, jednačine ravnoteže glase:

At the toe, on the contact of the pile and the soil, equilibrium equations are:

$$F(L,t) = F^{\downarrow}(L,t) + F^{\uparrow}(L,t) = F_g \quad \text{i / and} \quad v_p(L,t) = v_p^{\downarrow}(L,t) + v_p^{\uparrow}(L,t) = \frac{2v_p^{\downarrow} - F_g}{Z}, \tag{18}$$

gde je *L* dužina šipa, a F_g sila reakcije tla. Ukoliko se šip diskretizira po dužini na *n* delova, pri čemu je dužina jednog diskretnog elementa *ΔL=vΔt*, a vreme propagacije talasa kroz šip razmatra se u diskretnim intervalima *Δt*, tada se za sile u diskretnim elementima $f^{\downarrow}_{n,i}$ i $f^{\uparrow}_{n,i}$ može pisati:

where *L* is the pile length, and F_g soil reaction force. If the pile is discretized along its length to *n* sections, whereby the length of one discrete element is *ΔL=vΔt*, and the time of wave propagation through the pile is considered in discrete intervals *Δt*, then, for the forces in the discrete elements $f^{\downarrow}_{n,i}$ and $f^{\uparrow}_{n,i}$ it can be written:

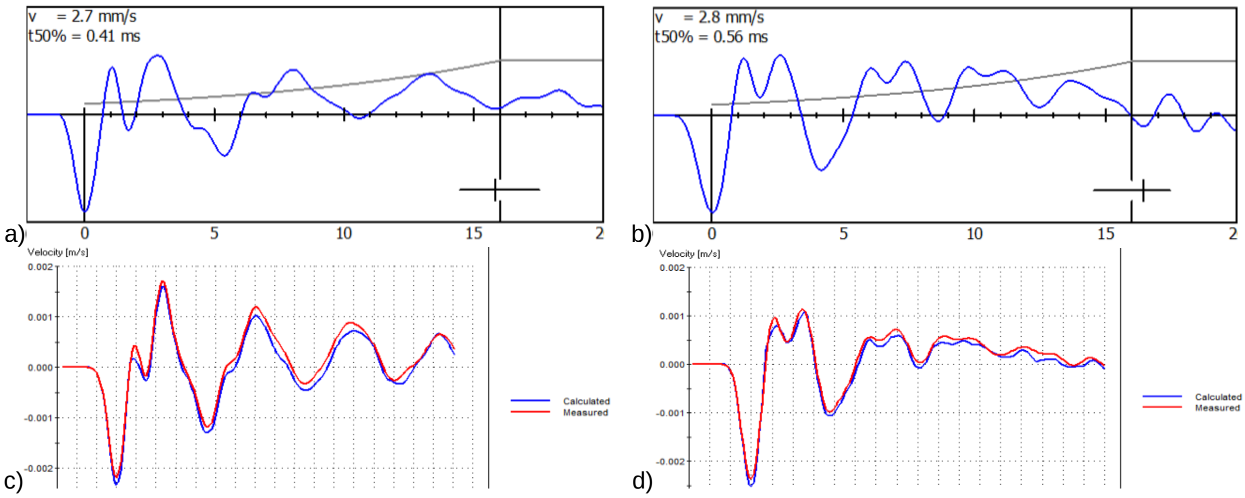
$$f_{n,i}^{\downarrow} = \left(\frac{Z_N - Z_{N+1}}{Z_N + Z_{N+1}}\right) f^{\uparrow} + \left(\frac{Z_{N+1}}{Z_N + Z_{N+1}}\right)\left(2f^{\downarrow} - W_{n,i}\right), \tag{19}$$

$$f_{n,i}^{\uparrow} = \left(-\frac{Z_N - Z_{N+1}}{Z_N + Z_{N+1}}\right) f^{\downarrow} + \left(\frac{Z_N}{Z_N + Z_{N+1}}\right)\left(2f^{\uparrow} + W_{n,i}\right), \tag{20}$$

gde je Z_N impedanca diskretnog *N* elementa šipa, Z_{N+1} impedanca diskretnog *N*+1 elementa šipa. Model interakcije šip-tlo jeste jednodimenzionalni kontinualni diskretan model, kod koga se tlo modelira kontinualno raspodeljenim oprugama duž šipa i koncentrisanom oprugom u bazi šipa. Konstitutivni model ponašanja tla je linearno-elastičan, a dodatno se modelira i prigušenje tla. Usklađivanje signala (odgovora), dobijenog primenom proračunskog modela i reflektograma *in-situ* SIT ispitivanja, sprovodi se iteracijama, a ovaj postupak je poznat kao kompatibilizacija. Prvo se iteriraju parametri tla, a zatim, nakon postizanja konvergencije rešenja putem ovih iteracija, sprovodi se iteriranje geometrijskih parametara (poprečnog preseka) šipa. Takođe, intervencija se sprovodi i korekcijom modula

where Z_N is the impedance of a discrete *N* element of the pile, Z_{N+1} impedance of the discrete *N*+1 element of the pile. The soil-pile interaction model is a one-dimensional continuous discrete model, in which the soil is modelled by continuously distributed springs along the pile and concentrated spring at the pile toe. The constitutive model of soil behaviour is linear-elastic, and soil damping is additionally modelled. When matching the signals (responses) obtained by applying the calculation model and from reflectograms of *in-situ* SIT testing is carried out through iterations, and this procedure is known as signal matching. The soil parameters are first iterated, and then, after achieving the convergence of the solutions through these iterations, iteration of the geometric parameters (cross-elastičnosti betona. Na taj način, direktno se utiče na promenu impedance šipa, gde se putem iteracija utvrđuje njena senzitivnost u domenima defekata i/ili diskontinuiteta. Na osnovu prethodno izložene procedure, primenom softvera SITWAVE, naknadno su analizirani reflektogrami dva šipa (oznake 1 i 2), kod kojih je primenom softvera SIT⁺ ukazano na mogućnosti postojanja defekata i/ili diskontinuiteta. Na slici 5 prikazani su reflektogrami šipova 1 i 2: reflektogram šipa 1, reflektogram šipa 2, kompatibilizovani signal šipa 1 (finalna iteracija), kompatibilizovani signal šipa 2 (finalna iteracija).

section) of the pile is performed. In addition, the intervention is implemented by correcting the modulus of elasticity of concrete. In this way, the variation in the impedance of the pile is directly caused, where its sensitivity in the domains of defects and/or discontinuities is determined through its iterations. Based on the procedure outlined above, the SITWAVE software was used subsequently to analyze reflectograms of two piles (designations 1 and 2), in which by using the SIT⁺ software the possibility of defects and/or discontinuities was indicated. Figure 5 shows the reflectograms of piles 1 and 2: pile 1 reflectogram, pile 2 reflectogram, pile 1 matched signal (final iteration), pile 2 matched signal (final iteration).

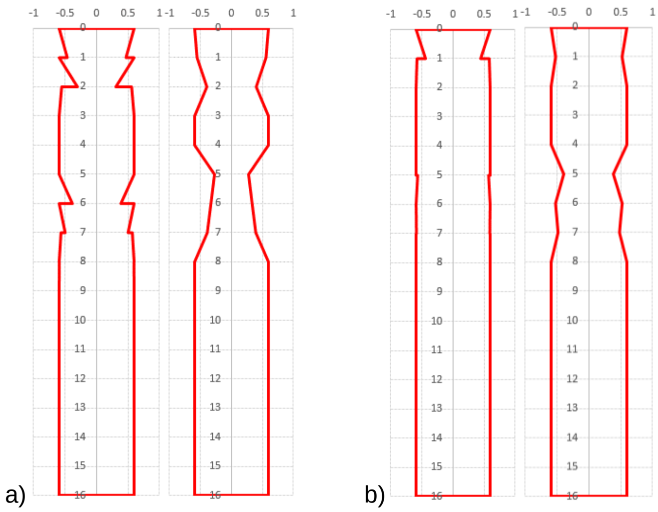


Slika 5. Reflektogrami šipova 1 i 2: a) reflektogram šipa 1; b) reflektogram šipa 2; c) kompatibilizovani signal šipa 1 - finalna iteracija; d) kompatibilizovani signal šipa 2 - finalna iteracija

Figure 5. Piles 1 and 2 reflectograms: a) pile 1 reflectogram 1, b) pile 2 reflectogram, c) pile 1 matched signal (final iteration), d) pile 2 matched signal (final iteration)

Na slici 6 prikazani su oblici defektnih šipova dobijeni primenom softvera SITWAVE: oblik šipa 1 dobijen putem početnih iteracija (slika levo) i oblik šipa 1 dobijen u poslednjoj iteraciji (slika desno), oblik šipa 2 dobijen putem početnih iteracija (slika levo) i oblik šipa 2 dobijen u poslednjoj iteraciji (slika desno). Dobijeni oblici su zapravo funkcija promene impedance, gde – pored promene geometrijskih karakteristika – učestvuju i mehaničke karakteristike šipa. To znači da se redukcija poprečnog preseka odnosi na promenu prečnika šipa i/ili na promenu modula elastičnosti betona. Na osnovu ovako sprovedenih analiza, primenom softvera SITWAVE, naknadno su izvedena bušenja i vađenja uzoraka šipova 1 i 2, tako da su ova ispitivanja potvrdila da postoje defekti u zonama koje su prethodno identifikovane kao domeni redukcije impedance šipova.

Figure 6 shows defective pile shapes obtained using the SITWAVE software: pile shape 1 obtained through initial iterations (figure left) and pile shape 1 obtained in the final iteration (figure right), pile shape 2 obtained through initial iterations (figure left) and shape pile 2 obtained in the final iteration (figure right). The resulting shapes are, in fact, a function of the impedance variation, where in addition to variation of the geometrical characteristics, the mechanical characteristics of the pile also participate. This means that the reduction in cross-section refers to the change in pile diameter and/or the change in modulus of elasticity of concrete. Based on the analyzes performed in this way, by using the SITWAVE software, the drilling and extraction of piles 1 and 2 samples were subsequently performed, and these tests confirmed that there were defects in the zones previously identified as domains of pile impedance reduction.



Slika 6. Oblici defektnih šipova dobijeni primenom softvera SITWAVE: a) oblik šipa 1 dobijen putem početnih iteracija (slika levo) i oblik šipa 1 dobijen u poslednjoj iteraciji (slika desno); b) oblik šipa 2 dobijen putem početnih iteracija (slika levo) i oblik šipa 2 dobijen u poslednjoj iteraciji (slika desno)

Figure 6. Defective pile shapes obtained using SITWAVE software: a) pile shape 1 obtained through initial iterations (figure left) and pile shape 1 obtained in the last iteration (figure right), b) pile shape 2 obtained through initial iterations (figure left) and pile 2 shape obtained in the last iteration (figure right)

3 NUMERIČKE ANALIZE INTEGRITETA ŠIPA SA SENZOROM

Numeričke analize integriteta šipa sprovode se promenom metode konačnih elemenata (FEM – *Finite Element Method*), pri čemu se šip i tlo modeliraju 2D površinskim konačnim elementima ili se koriste konačni elementi za rotacono simetrično stanje. U postupku određivanja ubrzanja, brzine i pomeranja šipa posmatraju se diferencijalne jednačine kretanja:

3 NUMERICAL SIT ANALYSES

Numerical SIT analyses are conducted by varying the finite element method (FEM), whereby the pile and the soil are modelled using 2D surface finite elements or finite elements for rotational symmetry. In the procedure of determining acceleration, velocity and displacement of the pile, differential motion equations are observed:

$$[M]\{A\} + [C]\{V\} + [K]\{U\} = \{Q\}, \tag{21}$$

gde je [*M*] matrica masa, {*A*} vektor ubrzanja, [*C*] matrica prigušenja, {*V*} vektor brzine, [*K*] matrica krutosti, {*U*} vektor pomeranja i {*Q*} vektor spoljašnjeg opterećenja. Rešavanje jednačina (21) se sprovodi numeričkom integracijom korak po korak *Hilber-Hughes-Taylor*-ovim (HHT) postupkom u modifikovanom obliku [10]:

where [*M*] is mass matrix, {*A*} acceleration vector, [*C*] damping matrix, {*V*} velocity vector, [*K*] stiffness matrix, {*U*} displacement vector and {*Q*} external load vector. Solving equations (21) is conducted using step-by-step numerical integrations using the *Hilber-Hughes-Taylor* (HHT) procedure in a modified form [10]:

$$[M]\{A\}_{i+1} + (1+\alpha)[C]\{V\}_{i+1} - \alpha[C]\{V\}_i + (1+\alpha)[K]\{U\}_{i+1} - \alpha[K]\{U\}_i = \{Q\}_{i+\alpha}, \tag{22}$$

za trenutak vremena:

for the time instant:

$$t_{i+1} = t_i + \Delta t\,. \tag{23}$$

Numeričko modeliranje defekata šipa sprovodi se analizom šipa kroz faze oštećenja (SDA). SDA analiza se konstruiše tako da se povezivanjem individualnih analiza generišu i simuliraju uticaji defekata šipa. Ove analize se sukcesivno sprovode korišćenjem matrica krutosti sistema na kraju prethodne analize stanja defekata, kao inicijalne matrice krutosti sistema naredne analize stanja defekata. Matematička formulacija SDA analize izvedena je polazeći od izraza za stanje potpune integralnosti šipa [8]:

Numerical modelling of pile defects is performed by pile stage degradation analysis (SDA). SDA analysis is constructed in such a way that the effects of pile defects are generated and simulated by linking individual analyses. These analyses are successively performed using the system stiffness matrix at the end of the previous defect state analysis as the initial stiffness matrix of the subsequent defect state analysis. The mathematical formulation of SDA was derived from the expression for the state of the complete pile integrity [8]:

$$t = 0: [K_0]\{U_0\} = \{P_0\}, \tag{24}$$

gde je $[K_0]$ matrica krutosti integralnog šipa (bez defekata). Za inicijalnu fazu defekata šipa analiza se sprovodi prema:

where $[K_0]$ is the stiffness matrix of an integral pile (without defects). For the initial phase of pile defects, the analysis is conducted according to:

$$t = 1: [K_1]\{U_1\} = \{P_1\}, \quad [K_1] = [K_0] - [K_0'], [M_1] = [M_0] - [M_0'], \tag{25}$$

gde je $[K_0']$ matrica krutosti eliminisanog domena konačnih elemenata šipa (simulacija defekata), $[M_0]$ matrica masa integralnog šipa (bez defekata), $[M_0']$ matrica masa eliminisanog domena konačnih elemenata šipa (simulacija defekata). U *i*-toj fazi analize defekata šipa, proračun se sprovodi prema:

Where $[K_0']$ is the stiffness matrix of the eliminated domain of finite elements of the pile (defect simulation), $[M_0]$ mass matrix of the integral pile (without defects), $[M_0']$ mass matrix of the eliminated domain of finite pile elements (defect simulation). In *i*-th phase of pile defect analysis, the calculation is conducted according to:

$$t = i: [K_i]\{U_i\} = \{P_i\}, \quad [K_i] = [K_{i-1}] - [K_{i-1}'], [M_i] = [M_{i-1}] - [M_{i-1}'], \tag{26}$$

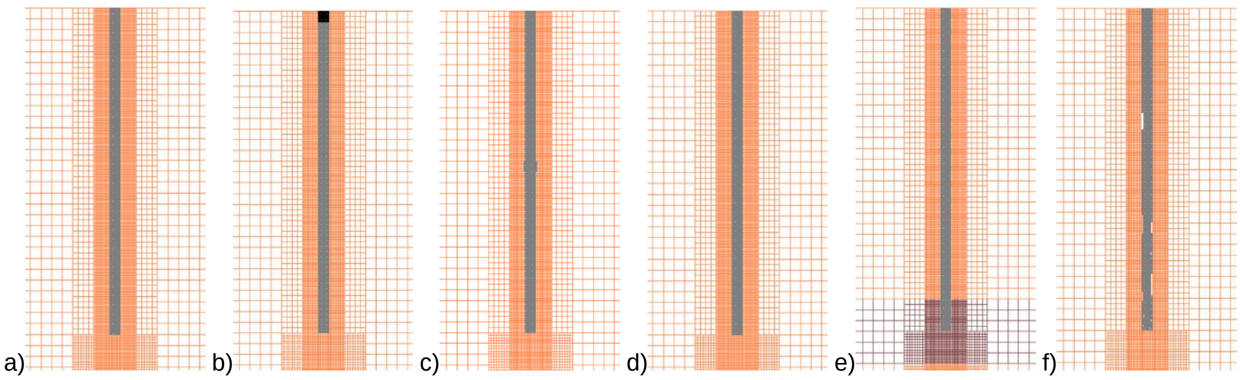
dok za *n*-tu fazu važi:

while for the *n*-th phase, it is:

$$t = n: [K_n]\{U_n\} = \{P_n\}, \quad [K_n] = [K_{n-1}] - [K_{n-1}'], [M_n] = [M_{n-1}] - [M_{n-1}'], \tag{27}$$

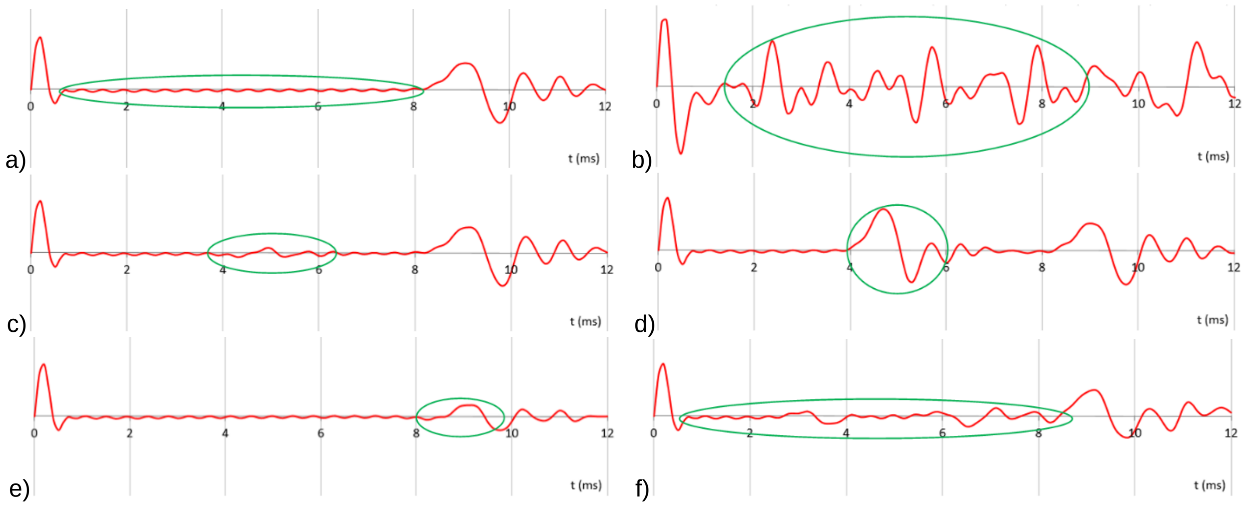
gde je $[K_n]$ matrica krutosti defektnog šipa u finalnoj fazi proračuna, $[M_n]$ matrica masa defektnog šipa u finalnoj fazi proračuna. Na slici 7 prikazani su modeli šipova s defektima i bez njih, dok su na slici 8 prikazani reflektogrami numeričkih modela šipova i tla: integralni šip (bez defekata), šip s redukovanim kvalitetom materijala glave, šip s proširenjem prečnika na polovini dužine stabla, šip s diskontinuitetom na polovini dužine stabla (prslina bez zatvaranja), šip u višeslojnoj sredini (sloj ispod baze šipa je boljih geomehaničkih karakteristika) i šip s randomiziranim diskontinuitetom prečnika duž stabla.

where $[K_n]$ is the stiffness matrix of the defective pile in the final calculation phase, $[M_n]$ the defective pile mass matrix in the final calculation phase. Figure 7 shows pile models with and without defects, while Figure 8 shows reflectograms of the numerical pile and soil models: integral pile (without defects), pile with reduced quality of head material, pile with a diameter expansion at half-length, pile with a discontinuity at half-length (a crack without closure), pile in a multilayered medium (the layer below the pile toe has better geomechanical characteristics) and pile with randomized discontinuity of diameter along the shaft.



Slika 7. Modeli šipova s defektima i bez njih: a) integralni šip (bez defekata); b) šip s redukovanim kvalitetom materijala glave; c) šip s proširenjem prečnika na polovini dužine stabla; d) šip s diskontinuitetom na polovini dužine stabla (prslina bez zatvaranja); e) šip u višeslojnoj sredini (sloj ispod baze šipa je boljih geomehaničkih karakteristika); f) šip s randomiziranim diskontinuitetom prečnika duž stabla

Figure 7. Models of piles with and without defects: a) integral pile (without defects), b) pile with reduced quality of head material, c) pile with a diameter expansion at half-length, d) pile with a discontinuity at half-length (a crack without closure), e) pile in a multilayered medium (the layer below the pile toe has better geomechanical characteristics), f) pile with randomized discontinuity of diameter along the shaft



Slika 8. Reflektogrami numeričkih modela šipova i tla: a) integralni šip (bez defekata); b) šip s redukovanim kvalitetom materijala glave; c) šip s proširenjem prečnika na polovini dužine stabla; d) šip s diskontinuitetom na polovini dužine stabla (prslina bez zatvaranja); e) šip u višeslojnoj sredini (sloj ispod baze šipa je boljih geomehaničkih karakteristika); f) šip s randomiziranim diskontinuitetom prečnika duž stabla

Figure 8. Reflectograms of numerical models of piles and soil: a) integral pile (without defects), b) pile with reduced quality of head material, c) pile with a diameter expansion at half-length, d) pile with a discontinuity at half-length (a crack without closure), e) pile in a multilayered medium (the layer below the pile toe has better geomechanical characteristics), f) pile with randomized discontinuity of diameter along the shaft

S obzirom na to što se prilikom sprovođenja testova integriteta šipa sa senzorom (SIT) i numeričkih analiza integriteta šipova (simulacija) dobijaju originalni (nekorigovani) reflektogrami, to se oni dodatno procesiraju s ciljem sprovođenja određenih korekcija i filtriranja. Najčešće se sprovode procedure filtriranja i skaliranja direktno u vremenskom domenu, međutim koriste se i metode filtriranja u frekventnom domenu. Filtriranjem se koriguje reflektogram radi jasnijeg uočavanja eventualnih defekata u šipu eliminacijom manje bitnih i konzervacijom bitnih diskretnih vrednosti pikova brzina reflektograma, dok se skaliranjem povećava intenzitet refleksije signala, prevashodno u bazi šipa s ciljem lakše identifikacije dužine šipa. Najčešće se primenjuje *n*-tostruki težinski filter kojim se signal direktno filtrira u vremenskom domenu [27]:

Given that when conducting SITs and numerical analyzes of pile integrity (simulations), original (uncorrected) reflectograms are obtained, they are further processed in order to make certain corrections and filtering. Most often, filtering and scaling procedures are performed directly in the time domain, however, frequency filtering methods are also used. Filtration adjusts the reflectogram to more clearly detect possible defects in the pile by eliminating less significant and conserving essential discrete peak velocity values of the reflectograms, while scaling increases the signal reflection intensity, primarily at the pile toe, for an easier identification of the pile length. A *n*-times weight filter is most commonly used to filter the signal directly in the time domain [27]:

$$v_{f,1}(t) = \frac{v_0(t-1)+2v_0(t)+v_0(t+1)}{4}, \tag{28}$$

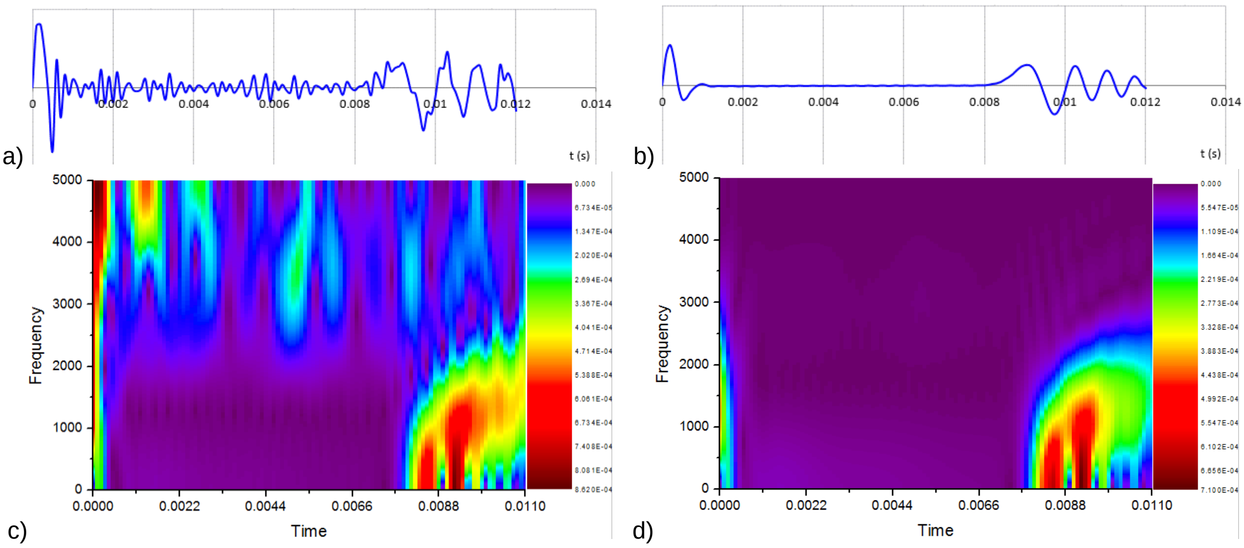
$$v_{f,i}(t) = \frac{v_{f,i-1}(t-1)+2v_{f,i-1}(t)+v_{f,i-1}(t+1)}{4}, \tag{29}$$

$$v_{f,n}(t) = \frac{v_{f,n-1}(t-1)+2v_{f,n-1}(t)+v_{f,n-1}(t+1)}{4}, \tag{30}$$

gde je $v_o(t)$ brzina originalnog (nefiltriranog) reflektograma u vremenu (t), dok su $v_{f,1}(t)$, $v_{f,i-1}(t)$, $v_{f,i}(t)$, $v_{f,n-1}(t)$, $v_{f,n}(t)$ brzine korigovanog (filtriranog) reflektograma u vremenu (t). Na slikama 9 i 10 prikazani su karakteristični primeri reflektograma i 2D spektrograma šipova s manjim diskontinuitetima i većim defektom u sredini šipa: bez primenjenog filtera i s primenjenim filterom. Spektrogrami su konstruisani primenom kratkotrajne *Fourier*-ove transformacije (STFT), tako da se u frekventnom domenu jasno može

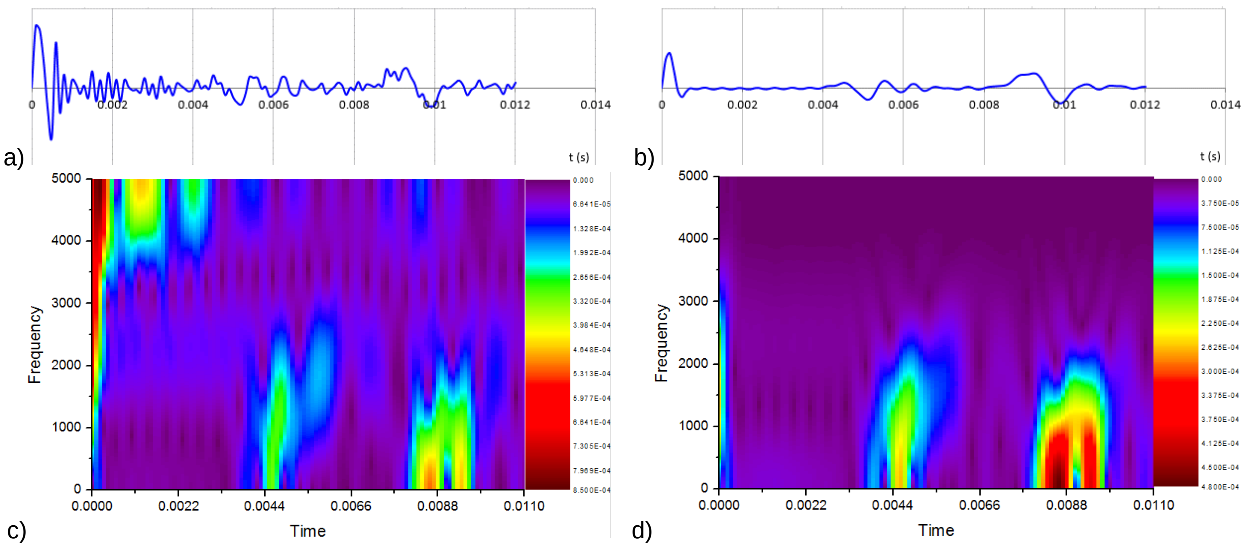
where $v_o(t)$ is the velocity of the original (unfiltered) reflectogram in time (t), while $v_{f,1}(t)$, $v_{f,i-1}(t)$, $v_{f,i}(t)$, $v_{f,n-1}(t)$, $v_{f,n}(t)$ are velocities of corrected (filtered) reflectogram in time (t). Figures 9 and 10 show characteristic examples of reflectograms and 2D spectrograms of piles with smaller discontinuities and larger defects in the middle of the pile: with no filter applied and with a filter applied. Spectrograms are constructed using the Short Time Fourier transform (STFT), so that in the frequency domain one can clearly observe the variation in sagledati promena amplituda u funkciji frekvencija odgovarajućeg signala (reflektograma), eliminacija i konzervacija određenih amplituda.

amplitudes as a function of the corresponding signal (reflectograms) frequencies, the elimination and conservation of certain amplitudes.



Slika 9. Reflektogrami i 2D spektrogrami šipa s manjim diskontinuitetima: a) reflektogram šipa bez primenjenog filtera; b) reflektogram šipa s primenjenim filterom; c) 2D spektrogram šipa bez primenjenog filtera; d) 2D spektrogram šipa s primenjenim filterom

Figure 9. Reflectograms and 2D spectrograms of a pile with smaller discontinuities: a) pile reflectogram without applied filter, b) pile reflectogram with applied filter, c) 2D pile spectrogram without applied filter, d) 2D pile spectrogram with applied filter



Slika 10. Reflektogrami i 2D spektrogrami šipa s većim defektom u sredini šipa: a) reflektogram šipa bez primenjenog filtera; b) reflektogram šipa s primenjenim filterom; c) 2D spektrogram šipa bez primenjenog filtera; d) 2D spektrogram šipa s primenjenim filterom

Figure 10. Reflectograms and 2D spectrograms of a pile with larger defects in the middle of the pile: a) pile reflectogram without applied filter, b) pile reflectogram with applied filter, c) 2D pile spectrogram without applied filter, d) 2D pile spectrogram with applied filter

4 ISPITIVANJE INTEGRITETA ŠIPOVA TESTOM INTEGRITETA ŠIPA SA SONDAMA (CSL)

Test integriteta šipa sa sondama (CSL) zasniva se na propagaciji talasa, primenom sondi s razdvojenim transmiterom i risiverom. Ovim testom se interaktivno i simultano, između instaliranih cevi u šipu, detaljno može ispitati integritet šipa celom dužinom po svim poprečnim presecima [6]. Ispitivanje integriteta sprovodi se kod svih tipova armiranobetonskih bušenih šipova. Metodologija ispitivanja integriteta šipa sa sondama (CSL) definisana je standardom ASTM D6760 [2]. Centar za puteve i geotehniku Instituta IMS poseduje licenciranu opremu za test integriteta šipa sa sondama američke firme *Pile Dynamics*. Korišćenjem ove opreme moguće je sprovesti analizu ultrazvučnih profila u vremenskom domenu (TDA), ali i dodatnu tomografsku analizu integriteta šipa (CSLT). Oprema poseduje integrisane softverske module za: procesiranje, skaliranje, korekciju i filtriranje signala. CHAMP-Q oprema [14] za test integriteta šipa sa sondama (CSL), američke firme *Pile Dynamics*, sastoji se iz: metra s tegom za preliminarnu proveru dužine i nezapušenosti instaliranih cevi, sondi - transmitera (generišu ultrazvučni signal nominalne frekvencije 45 kHz), sondi - risivera (nominalne frekvencije 45 kHz), četiri seta kablova za povezivanje četiri sonde, tripoda za kablove sa senzorima za analizu pozicije sondi u cevima, hardverskog sistema za akviziciju, memorisanje, procesiranje i vizuelizaciju podataka i softvera CHA-S, CHA-W i PDI-Tomo. Konverzija AD signala sprovodi se primenom 12-bitnog konvertera (frekvencija semplovanja je od 500 kHz do 2 MHz). Na slici 11 prikazana je CHAMP-Q oprema za ispitivanje integriteta šipova testom integriteta šipa sa sondama (CSL) američke firme *Pile Dynamics*.

4 PILE INTEGRITY TESTING USING CROSSHOLE SONIC LOGGING (CSL)

Crosshole Sonic Logging (CSL) is based on wave propagation using separate transmitter and receiver sensor. With this test, the integrity of the pile can be thoroughly examined interactively and simultaneously, between the installed pipes in the pile, along entire length and across all cross sections [6]. Integrity testing is performed on all types of bored reinforced concrete piles. The testing methodology of CSL is defined by ASTM D6760 [2]. The *Centre for Roads and Geotechnics of the IMS Institute* possesses the licensed CSL equipment manufactured by the US *Pile Dynamics* company. Using this equipment, it is possible to perform ultrasonic time domain analysis (TDA), as well as additional Crosshole Sonic Logging Tomography (CSLT). The equipment has integrated software modules for: signal processing, scaling, correction and filtering. The CHAMP-Q equipment [14] for CSL, of the U.S. *Pile Dynamics* company, consists of: a meter with a weight for preliminary checking of the length and possibility of installed pipes, probes - transmitters (generating ultrasonic signal of 45kHz nominal frequency), probes - receivers (nominal frequencies 45kHz), 4 sets of cables for connecting 4 probes, tripods for cables with sensors for analyzing the position of probes in the pipes, hardware system for acquisition, storage, processing and visualization of data and software CHA-S, CHA-W and PDI-Tomo. AD signal conversion is conducted using the 12-bit converter (sampling frequency is from 500kHz to 2MHz). Figure 11 shows the CHAMP-Q equipment for CSL by the U.S. *Pile Dynamics* company.


Slika 11. CHAMP-Q oprema za ispitivanje integriteta šipova testom integriteta šipa sa sondama (CSL) američke firme Pile Dynamics [14]

Figure 11. CHAMP-Q CSL equipment of the U.S. company Pile Dynamics [14]

Pravilno sprovođenje testa integriteta šipa sa sondama (CSL) zahteva prethodnu pripremu cevi u koje se spuštaju sonde za ispitivanje. Ove cevi se ugrađuju u telo šipa, a naknadno se mogu injektirati nakon sprovedenog ispitivanja. Na slici 12 prikazane su čelične cevi spojene i zavarene za unutrašnju stranu armaturnog koša šipa i krajevi cevi koji vire nakon betoniranja.

A proper procedure of CSL requires the preliminary preparation of pipes into which test probes are lowered. These tubes are embedded in the body of the pile and they can be subsequently injected after testing. Figure 12 shows the steel pipes connected and welded to the inside of the pile reinforcement cage and the ends of the pipes protruding after concreting.

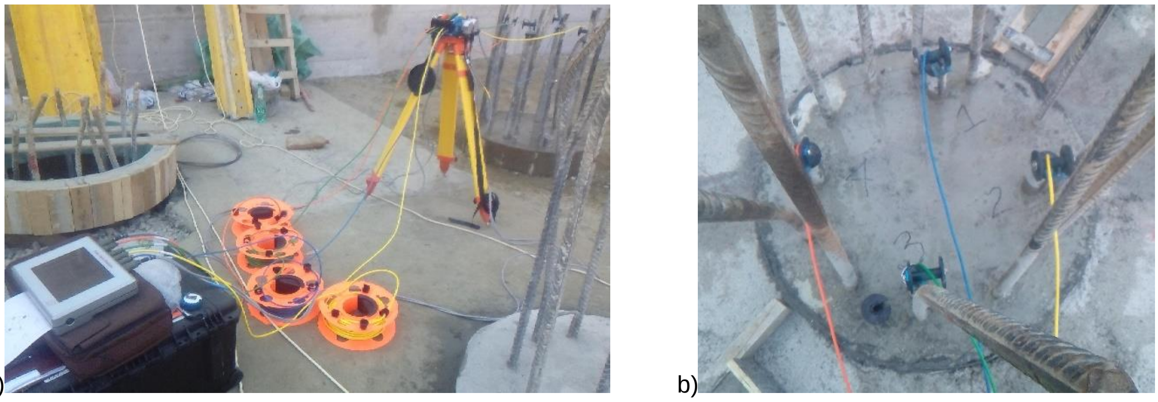
a) b) c)

Slika 12. a) i b) čelične cevi spojene i zavarene za unutrašnju stranu armaturnog koša šipa; c) krajevi cevi koji vire nakon betoniranja

Figure 12. a) and b) steel pipes joined and welded to the inside of the pile reinforcement cage, c) pipes ends protruding after concreting

Na slici 13 prikazani su: tripod za kablove sa senzorima, uređaj za akviziciju, memorisanje, procesiranje i vizuelizaciju podataka i povezane i postavljene sonde u cevima. Sonde na svojim krajevima imaju tegove, tako da je ukupna dužina sondi i tegova nešto veća od 30 cm. U tom smislu, da bi se adekvatno sprovela analiza integriteta glave šipa, potrebno je ispustiti cevi dovoljno izvan glave šipa, kako bi se i sonde izvukle izvan glave šipa, a ostale u cevima. Budući da prilikom krajcovanja glave šipa vrlo često nastupi oštećenje cevi za ispitivanje integriteta šipa sa sondama (CSL), to je gotovo nemoguće sprovesti adekvatnu analizu integriteta glave šipa.

Figure 13 shows: tripod for sensor cables, acquisition, storage, processing and data visualization device and connected and placed probes in tubes. The probes have weights at their ends, so the total length of the probes and weights is a little over 30 cm. In this sense, in order to adequately carry out the analysis of the integrity of the pile head, it is necessary to make the pipes sufficiently protrude outside the pile head to allow the probes to be pulled out of the pile head and remain in the pipes. Since during the trimming of the pile head the pipe for CSL is very often damaged, it is almost impossible to perform an adequate analysis of the integrity of the pile head.



a) b)

Slika 13. a) tripod za kablove sa senzorima, uređaj za akviziciju, memorisanje, procesiranje i vizuelizaciju podataka povezan sa sondama; b) povezane i postavljene sonde u cevima

Figure 13. a) tripod for sensor cables, device for acquisition, storage, processing and visualization of data connected to probes, b) probes connected and placed in pipes

Na slici 14 prikazani su specifični slučajevi pozicija i dužina cevi izvan glave šipa: cevi su adekvatne dužine, čak je i beton nedovoljno okrajcovan, što je povoljno u smislu ispitivanja integriteta glave šipa, cevi nisu adekvatne dužine i krajevi cevi se završavaju na različitim visinama, cevi su adekvatne dužine, glava šipa je dobro okrajcovana i naknadno obrađena (najpovoljnija situacija) i krajevi cevi se završavaju u ravni glave šipa, što je nepovoljno, jer se sonde ne mogu izvući kompletno, pa se samim tim ne može sprovesti adekvatna analiza integriteta glave šipa.

Figure 14 shows specific cases of positions and lengths of pipes outside the pile head: the pipes are adequate in length, even the concrete is insufficiently trimmed, which is advantageous in terms of testing the integrity of the pile head, the pipes are inadequate in length and the ends of the pipes end at different heights, the pipes are of adequate length, the head of the pile is well-trimmed and finished (the most favourable situation) and the ends of the pipe end flush with the pile head, which is unfavourable, since the probes cannot be pulled out completely, and thus, it is impossible to carry out an adequate analysis of pile head integrity.

Slika 14. Specifični slučajevi pozicija i dužina cevi izvan glave šipa: a) cevi su adekvatne dužine, čak je i beton nedovoljno okrajcovan, što je povoljno u smislu ispitivanja integriteta glave šipa; b) cevi nisu adekvatne dužine i krajevi cevi se završavaju na različitim visinama; c) cevi su adekvatne dužine, glava šipa je dobro okrajcovana i naknadno obrađena (najpovoljnija situacija); d) krajevi cevi se završavaju u ravni glave šipa, što je nepovoljno, jer se sonde ne mogu izvući kompletno, pa se samim tim ne može sprovesti adekvatna analiza integriteta glave šipa

Figure 14. Specific cases of positions and lengths of pipes outside the pile head: a) the pipes are adequate in length, even the concrete is insufficiently trimmed, which is advantageous in terms of testing the integrity of the pile head, b) the pipes are not adequate in length and the ends of the pipes end at different heights, c) the pipes are of adequate length, the head of the pile is well-trimmed and finished (the most favourable situation), d) the ends of the pipe end flush with the pile head, which is unfavourable, since the probes cannot be pulled out completely, and thus, it is impossible to carry out an adequate analysis of pile head integrity.

Transmiterom se emituju talasi kroz telo šipa, a s obzirom na to što su transverzalni talasi znatno sporiji, od interesa za ispitivanje su samo longitudinalni talasi, koji su dosta brži i nose u sebi informaciju o stanju šipa. Merenje se zasniva, zapravo, na analizi promene: vremena (FAT) ili brzine propagacije talasa od transmitera do risivera, a za poznato rastojanje između cevi po dubini šipa i količine relativne energije po dubini šipa. Signali primljeni risiverom sempluju se i beleže kao promene amplitude u funkciji vremena, a zatim procesiraju po dužini ispitanog šipa. Dobijeni podaci koriste se za potvrdu kvaliteta betona i za identifikaciju zona lošeg kvaliteta. Kompletna obrada (procesiranje) signala sprovodi se primenom teorije i obrade signala, pri čemu se zapis signala prikazuje u digitalizovanom formatu, a sam signal prikazuje u vremenskom domenu. Merenje se sprovodi za vertikalni interval od 2 cm do 5 cm. Kriterijumi za analizu oštećenja šipa definisani su prema [13]:

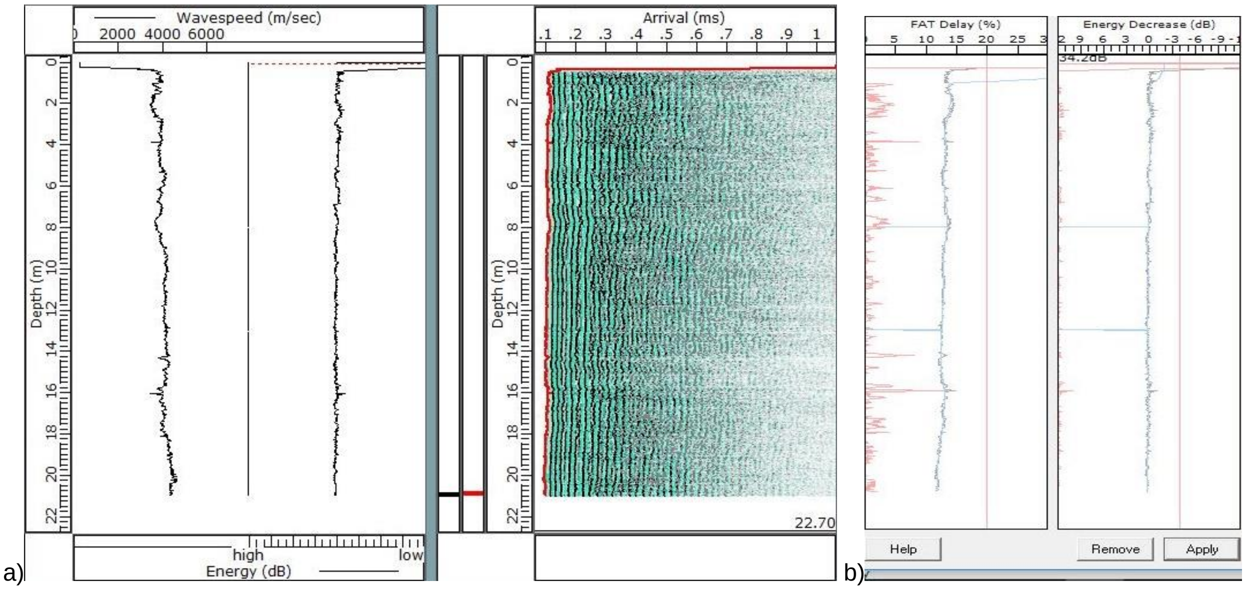
- zadovoljavajuće (G), (odlično): povećanje FAT od 0 do 10% (mada se može tolerisati i do 15%) i/ili redukcija energije < 6 db (mada se može tolerisati i do 7.5 db);
- odstupanje (Q), (devijantno): povećanje FAT od 11% do 20% i/ili redukcija energije od 6 db do 9 db;
- prslina/pukotina (P/F), (lošije): povećanje FAT od 21% do 30% i/ili redukcija energije od 9 db do 12 db;
- defekat (P/D), (defekat/diskontinuitet): povećanje FAT > 31% i/ili redukcija energije > 12 db.

S obzirom na to što se ispitivanje integriteta šipova, testom integriteta šipa sa sondama (CSL), sprovodi s četiri sonde, simultano se u šest pravaca dobijaju ultrazvučni profili. Na slikama 15, 16 i 17, za jedan pravac, prikazani su ultrazvučni profili integralnog šipa (bez defekata), šipa s diskontinuitetom u domenu baze i defektnog šipa - dijagrami promena: brzina propagacije talasa, relativne energije, vremena dolaska signala

Transmitters emit waves through the body of the pile, and since transversal waves are considerably slower, only longitudinal waves, which are much faster and carry information about the state of the pile, are interesting for testing. In fact, the measurement is based on an analysis of variation: of time (FAT) or the wave propagation speed from the transmitter to the receiver, for the known distance between the pipes along the depth of the pile and the quantity of relative energy along the depth of the pile. The signals received by the receiver are sampled and recorded as variation in amplitude as a function of time and then processed along the length of the test pile. The data obtained are used to confirm the quality of concrete and identify poor quality zones. Complete signal processing is performed by applying theory and signal processing, whereby the signal record is displayed in a digitized format and the signal itself is displayed in the time domain. The measurement is carried out for a vertical interval of 2cm to 5cm. Criteria for pile damage analysis are defined according to [13]:

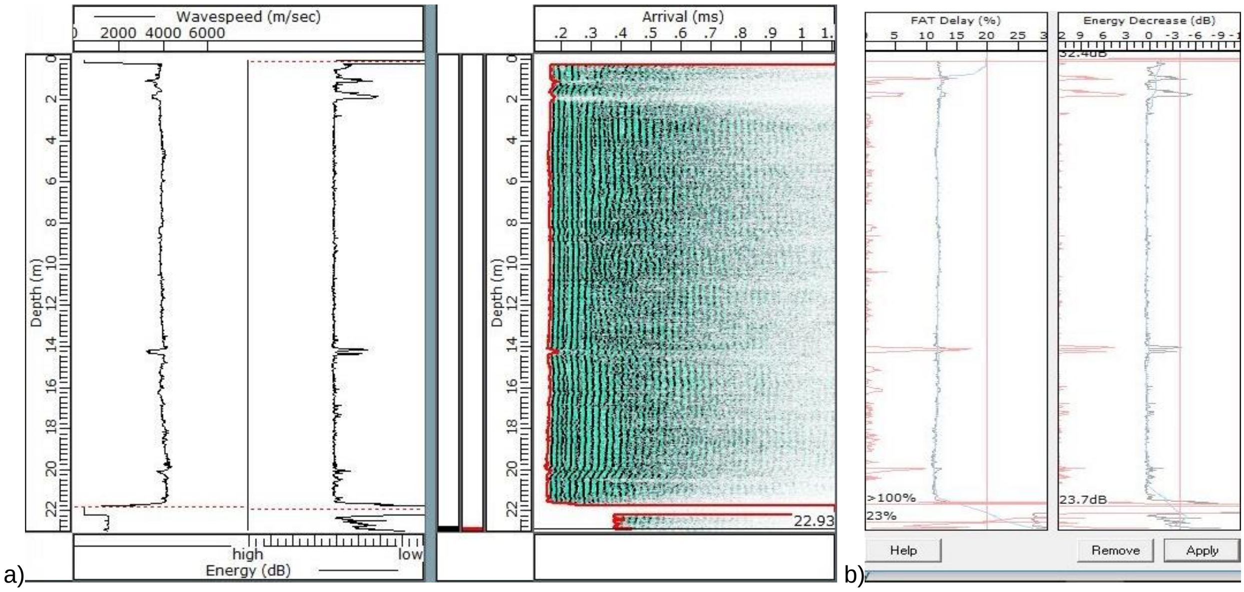
- satisfactory (G) (good): increase of FAT from 0 to 10% (even though up to 15% can be tolerated) and/or energy reduction < 6db (even though up to 7.5db can be tolerated),
- deviation (Q) (questionable): increase of FAT from 11% to 20% and/or energy reduction from 6db to 9db,
- flaw (P/F) (poor/flaw): increase of FAT from 21% to 30% and/or energy reduction 9db to 12db,
- defect (P/D) (poor/defect): increase of FAT > 31% and/or energy reduction > 12db.

Since the pile integrity test, CSL, is performed with 4 probes, ultrasonic profiles are obtained simultaneously in 6 directions. For one direction, Figures 15, 16 and 17, show ultrasonic profiles of an integral pile (without defects), a pile with discontinuity at the toe and a defective pile – variation diagrams: of wave propagation



Slika 15. Ultrazvučni profili integralnog šipa (bez defekata): a) dijagrami promena brzina propagacije talasa, relativne energije i vremena dolaska signala (FAT); b) dijagrami povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa

Figure 15. Ultrasonic profiles of an integral pile (without defects): a) diagrams of variations in wave propagation velocities, relative energy and signal first arrival time (FAT), b) diagrams of increase of time of signal first arrival time (FAT) and reduction of relative energy along the pile shaft



Slika 16. Ultrazvučni profili šipa s diskontinuitetom u domenu baze: a) dijagrami promena brzina propagacije talasa, relativne energije i vremena dolaska signala (FAT); b) dijagrami povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa

Figure 16. Ultrasonic profiles of a pile with a discontinuity at the toe: a) diagrams of variations in wave propagation velocities, relative energy and signal first arrival time (FAT), b) diagrams of increase of time of signal first arrival time (FAT) and reduction of relative energy along the pile shaft

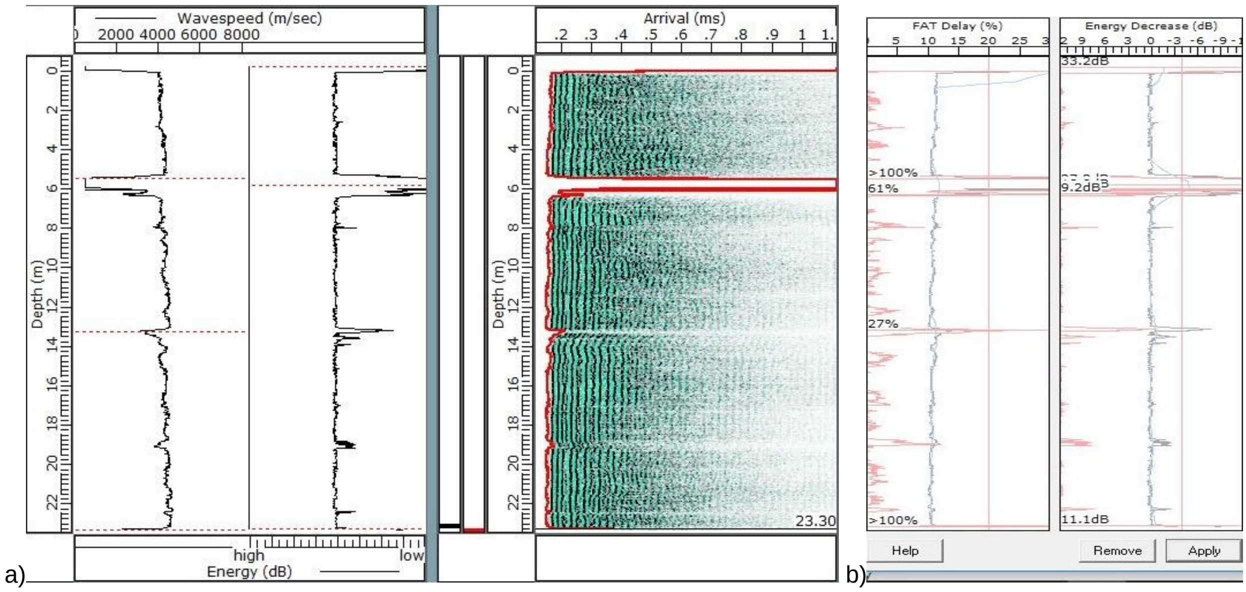
(FAT), povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa, respektivno. U konkretnom slučaju, kod integralnog šipa, analizom ultrazvučnih profila za sve pravce (nisu svi prikazani, s obzirom na obimnost ispitivanja), može se konstatovati

velocity, relative energy, first arrival time (FAT) increases in first arrival time (FAT) and reductions in relative energy along the pile shaft, respectively. In the specific case of the integral pile by analyzing the ultrasonic profiles for all directions (not all of them are shown, da je šip u pogledu integriteta zadovoljavajućeg kvaliteta. Kod integralnog šipa (bez defekata) nije bilo moguće detaljno snimiti bazu šipa, jer su određene cevi bile zapušene, dok su kod šipa s diskontinuitetom u domenu baze, za sve pravce, konstatovana povećanja FAT i redukcija energije.

U slučaju defektnog šipa, za sve pravce, konstatovana su značajnija povećanja FAT i redukcija energije na određenom intervalu dužine šipa. Snimanje je još dva puta ponovljeno i dobijeni su gotovo identični rezultati.

given the scope of the test), it can be concluded that the pile has satisfactory quality in terms of integrity. In the case of the integral pile (without defects) it was impossible to record the pile toe in detail because certain pipes were obstructed, while in the case of piles with a discontinuity at the toe, for all directions, FAT increases and energy reductions were observed.

In the case of defective pile, for all directions, significant increases in FAT and energy reduction of certain pile length interval were observed. Recording was repeated two times more and almost identical results were obtained.

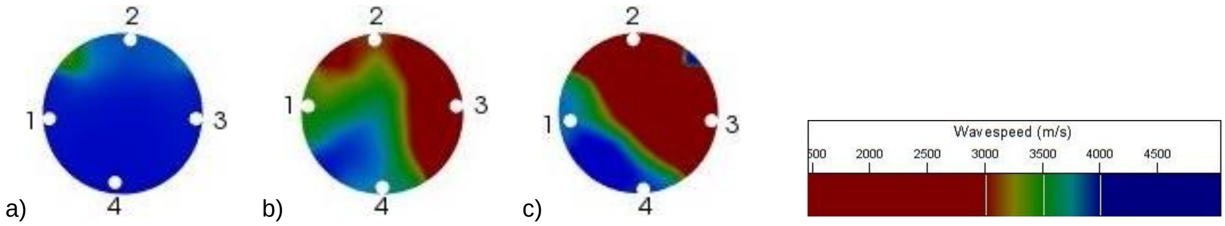


Slika 17. Ultrazvučni profili defektnog šipa: a) dijagrami promena brzina propagacije talasa, relativne energije i vremena dolaska signala (FAT); b) dijagrami povećanja vremena dolaska signala (FAT) i redukcije relativne energije duž stabla šipa

Figure 17. Ultrasonic profiles of a defective pile: a) diagrams of variations in wave propagation velocities, relative energy and signal first arrival time (FAT), b) diagrams of increase of time of signal first arrival time (FAT) and reduction of relative energy along the pile shaft

Na osnovu sprovedenih ispitivanja i prikazanih ultrazvučnih profila integralnog šipa (bez defekata), šipa s diskontinuitetom u domenu baze i defektnog šipa, primenom softvera PDI-Tomo za tomografiju, dodatno su analizirane identifikovane karakteristične zone promena povećanja i smanjenja brzina propagacije talasa u betonu. Ove zone prikazane su primenom izopovrši, čije boje odgovaraju brzinama propagacije talasa u betonu. Na slici 18 prikazani su poprečni preseci za integralni šip (bez defekata), šip sa diskontinuitetom u domenu baze i defektni šip, kod kojih se najviše identifikuju povećanja FAT i redukcije energije, a prikazane su takođe i odgovarajuće proračunate efektivne površine ovih poprečnih preseka šipova. Efektivna površina poprečnog preseka proračunata je kao odgovarajući procenat površine poprečnog preseka šipa, kod kojeg je brzina propagacije talasa u betonu veća od 3600 m/s.

Using PDI-Tomo tomography software, the identified characteristic zones of variation of increase and decrease of wave propagation velocity in concrete were additionally analyzed based on the performed tests and presented ultrasonic profiles of an integral pile (without defects), pile with a discontinuity at the toe and defective pile. These zones are shown using isosurface, the colours which correspond to the wave propagation rates in concrete. Figure 18 shows the cross sections for the integral pile (without defects), the pile with the discontinuity at the toe, and the defective pile, where FAT increases and energy reductions are mostly identified. In addition, the corresponding calculated effective surfaces of these pile cross sections are shown as well. The effective cross-sectional area was calculated as the corresponding percentage of the pile cross-sectional area where the wave propagation velocity in concrete is higher than 3600m/s



Slika 18. Poprečni preseci kod kojih se najviše identifikuju povećanja FAT i redukcije energije, a takođe prikazane su i odgovarajuće proračunate efektivne površine ovih poprečnih preseka šipova: a) integralni šip (bez defekata) - efektivna površina je 95%; b) šip s diskontinuitetom u domenu baze - efektivna površina je 52%, c) defektni šip - efektivna površina je 31%

Figure 18. Cross-sections where FAT increases and energy reductions are identified the most, and corresponding calculated effective surfaces of these cross-sections of piles are also shown: a) integral pile (without defects) - effective surface is 95%, b) pile with discontinuity at the toe - effective area is 52%, c) defective pile - effective area is 31%

5 ZAVRŠNE NAPOMENE I ZAKLJUČCI

Ispitivanje integriteta šipova metodološki se može prikazati u nekoliko faza: priprema ispitivanja, *in-situ* ispitivanje šipova na gradilištu, analiza i odlučivanje tokom ispitivanja, analiza, interpretacija i prezentacija rezultata ispitivanja, dodatne numeričke analize integriteta, donošenje odluke o integralnom stanju šipa i pisanje izveštaja o integritetu šipa. S obzirom na troškove ispitivanja, najčešće se za ispitivanje integriteta šipova koristi test integriteta šipa sa senzorom (SIT). Međutim, u zavisnosti od stepena važnosti objekta, pa i pouzdanost rešenja na raspolaganju je ispitivanje integriteta šipova testom integriteta šipa sa sondama (CSL). U praksi, za gotovo sve šipove objekata, primenjuje se test integriteta šipa sa senzorom (SIT), s obzirom na efikasnost i brzinu ispitivanja, ali se često i zanemaruje to da je ovo indirektna metoda. Istraživanjem su pokazani karakteristični modeli reflektograma, na osnovu kojih se lako mogu doneti odluke o stanju integriteta šipa. Međutim, veoma često se u praksi pojavljuju diskutabilne situacije u kojima nije moguće odmah dati odgovor o stanju integriteta šipa, pa je preporuka da se koriste dodatne metode koje se zasnivaju na talasnoj teoriji, kompatibilizaciji signala i numeričkim analizama.

Kada je u pitanju veliki broj šipova objekta, pouzdanije je napraviti plan ispitivanja pre izgradnje šipova. Kvalitetnim planom ispitivanja, mogu se definisati probni (testni) šipovi na kojima će se sprovesti testovi integriteta šipa sa sondama (CSL) i uticati na korekciju tehnologije izgradnje i/ili dispozicije i/ili broja šipova. Naknadno se svi radni (eksploatacioni) šipovi mogu ispitati testom integriteta šipa sa senzorom (SIT). Najveći problem pojavljuje se kada se svi šipovi objekta izgrade, pa se nakon toga zahteva sprovođenje ispitivanja integriteta šipova, jer se stvara ograničen prostor za korekcije – kako na konstruktivnom nivou, tako i na nivou dinamičkog plana izgradnje objekta. U velikom broju slučajeva, kada naručioci ispitivanja interpretiraju rezultate ispitivanja prikazane u izveštajima, kriterijumi integriteta i nosivosti šipova razmatraju se nezavisno. Takođe, vrlo često se jedan kriterijum favorizuje ili se potpuno isključuje drugi kriterijum. Jedino i inženjerski ispravno rešenje jeste da se oba kriterijuma poštuju i da se uvažavaju uslovi pod kojima se ispunjavaju ovi kriterijumi. Sve to, pored

5 CLOSING REMARKS AND CONCLUSIONS

Pile integrity testing can be methodologically presented in several stages: test preparation, *in-situ* pile testing at the construction site, analysis and decision-making during testing, analysis, interpretation and presentation of test results, additional numerical integrity analysis, decision on the integral condition of a pile and pile integrity report writing. Given the cost of testing, SIT is the most commonly used pile integrity test. However, CSL pile integrity test is also available depending on the degree of importance of the structure and even the reliability of the solution. In practice, SIT is applied for almost all structural piles given the efficiency and speed of testing, but it is often neglected that it is an indirect method. The research has shown characteristic models of reflectograms on the basis of which it is possible to make decisions on the state of pile integrity. However, there are often debatable situations in practice where it is impossible to immediately provide an answer concerning the pile integrity state, so it is recommended to use additional methods based on wave theory, signal matching, and numerical analyses.

When there is a large number of piles in a structure, it is more reliable to make a test plan before building the piles. A quality test plan can define the test piles on which CSL will be conducted and the construction technology and/or the arrangement and/or number of piles can be corrected. Subsequently, all working (service) piles can be tested with SIT. The biggest problem arises when all the piles of a structure are built, and then subsequently the pile integrity test is applied. In that case the space for corrections is limited, both in terms of the structural level and the dynamical construction plan of the structure. In many cases the integrity and load-bearing criteria of piles are considered independently when test results presented in the reports are interpreted by the contracting party. In addition, very often one criterion is favoured or another criterion is completely excluded. The only correct engineering solution is that both criteria are observed and the conditions under which these criteria are met are considered. All this, in addition to knowledge and experience, requires continuous improvement in this multidisciplinary pile testing problem which goes beyond the usual domains of construction and geotechnical practice.

znanja i iskustva, zahteva i kontinualno usavršavanje iz ove multidisciplinarne problematike ispitivanja šipova, koje pravazilazi uobičajene domene građevinske i geotehničke prakse.

ZAHVALNICA

Ovaj rad je deo istraživanja u okviru projekta TR 36014, koje finansira Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije.

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REZIME

ISPITIVANJE INTEGRITETA ŠIPOVA: TESTIRANJE I ANALIZA REZULTATA

Mladen ĆOSIĆ
Kristina BOŽIĆ-TOMIĆ
Nenad ŠUŠIĆ

U radu su prikazani karakteristični primeri ispitivanja integriteta šipova sa analizom rezultata, pri čemu se metodologija ispitivanja oslanja na postojeće ASTM standarde, ali i na metodologiju ispitivanja prikazanu u naučnom radu „Ispitivanje integriteta i nosivosti šipova: metodologija i klasifikacija", koji je publikovan u ovom časopisu. Ispitivanja šipova sprovedena su primenom licenciranih oprema za test integriteta šipa sa senzorom (SIT) i test integriteta šipa sa sondama (CSL). Ispitivanjima su prikazane korektne i problematične situacije, koje se pojavljuju prilikom analize integriteta šipova. Ukazano je na aspekte primene talasne teorije, ali i na procesiranja signala i numeričke analize. Takođe, posebno je skrenuta pažnja na potrebu izrade plana ispitivanja integriteta šipova kod objekata s velikim brojem šipova.

Ključne reči: šip, ispitivanje, integritet, reflektogram, SIT, ultrazvučni profil, CSL

SUMMARY

PILE INTEGRITY TESTING: TESTING AND RESULTS ANALYSIS

Mladen COSIC
Kristina BOZIC-TOMIC
Nenad SUSIC

The paper presents typical examples of pile integrity testing and the results analysis, whereby the testing methodology relies on existing ASTM standards, as well as on the testing methodology presented in the scientific paper *Pile Integrity and Load Testing: Methodology and Classification*, published in this journal. The pile tests were conducted using licensed equipment for Sonic Integrity Test (SIT) and Crosshole Sonic Logging (CSL). The tests have shown the correct and problematic situations that arise when analyzing pile integrity. Some aspects of the wave theory implementation, but also of signal processing and numerical analysis have been indicated. Also, the need to develop a plan for testing the integrity of piles in structures with a large number of piles has been emphasized.

Key words: pile, testing, integrity, reflectogram, SIT, ultrasonic profile, CSL

IN MEMORIAM

Akademik profesor dr **NIKOLA HAJDIN**, dipl.inž.građ.
Academician, Professor Dr. **NIKOLA HAJDIN**, B.Sc. Eng.Civ.

(1923 – 2019)

Ovog leta, 17. jula, preminuo je akademik Nikola Hajdin, doktor tehničkih nauka, diplomirani građevinski inženjer, redovni profesor (u penziji) Građevinskog fakulteta Univerziteta u Beogradu. Pored predmeta na osnovnim studijama – Teorije konstrukcija, Otpornosti materijala i Teorije površinskih nosača na Građevinskom fakultetu u Beogradu, predavao je i na poslediplomskim studijama – Teoriju plastičnosti, Nelinearnu elastičnost i Teoriju tankozidnih nosača. Dekan Građevinskog fakulteta bio je u mandatu 1975/76 – 1976/77. godine. Za dopisnog člana SANU izabran je 1970. godine, a za redovnog člana – 1976. godine. Potpredsednik SANU bio je od 1994. do 2003. godine, a predsednik SANU – od 2003. do 2015. godine.

Tokom svoje profesionalne karijere, Nikola Hajdin obavljao je naučne i stručne funkcije u različitim domaćim i stranim društvima. Između ostalog, bio je predsednik Jugoslovenske grupe Međunarodnog udruženja za mostove i visokogradnju, predsednik Jugoslovenskog komiteta Međunarodne unije za teorijsku i primenjenu mehaniku i predsednik Jugoslovenskog društva građevinskih konstruktera.

Nikola Hajdin bio je član Atinske akademije nauka,

Academician Nikola Hajdin, Doctor of Technical Sciences, Bachelor of Civil Engineering, full professor (retired) at the Faculty of Civil Engineering, University of Belgrade passed away this summer, on July 17. In addition to the subjects in basic studies: Structural Mechanics, Strength of Materials, and Theory of Plates and Shells at the Faculty of Civil Engineering in Belgrade, he also delivered lectures at postgraduate studies in subjects Theory of Plasticity, Nonlinear Elasticity, and Theory of Thin-Walled Members. Within the period 1975/76 - 1976/77, he held the position of the Dean of the Faculty of Civil Engineering. He was elected a corresponding member of Serbian Academy of Science and Arts (SANU) in 1970 and a full-time member in 1976. From 1994 to 2003 he was the vice-president of SANU, and its president from 2003 to 2015.

During his professional career, Nikola Hajdin held scientific and professional positions in various domestic and foreign associations, including president of the Yugoslav Group of the International Association for Bridges and Structural Engineering, president of the Yugoslav Committee of the International Union for Theoretical and Applied Mechanics and president of the

Slovenačke akademije znanosti i umetnosti (Ljubljana), Evropske akademije nauka, umetnosti i literature (Pariz), Evropske akademije nauka i umetnosti (Salcburg), kao i Evropske akademije nauka (Lijež). Izabran je 2000. godine za počasnog doktora Nacionalnog tehničkog univerziteta u Atini. Takođe, bio je član Grčkog udruženja za naučna istraživanja metalnih konstrukcija, Naučnog komiteta italijanskog časopisa za metalne konstrukcije, Švajcarskog udruženja za čelične konstrukcije, Međunarodnog udruženja za mostove i visokogradnju (Cirih) i Naučnog komiteta međunarodnog udruženja za čelične konstrukcije; pritom, bio je i počasni član Jugoslovenskog društva za mehaniku, Jugoslovenskog društva građevinskih konstruktera i Grčkog nacionalnog društva za teorijsku i primenjenu mehaniku.

Nikola Hajdin je sedam decenija bio aktivan na naučnom i stručnom polju u našoj zemlji i u inostranstvu.

Naučni rad Nikole Hajdina odnosio se najvećim delom na radove iz oblasti primenjene mehanike, posebno iz teorije konstrukcija. Međutim, ubrzo je došao do uverenja da rad u oblasti teorije konstrukcija dodatno dobija na značaju i na vrednosti ako je prožet, pored svoje teorijske osnove, i poznavanjem realnih konstrukcija – koje tehnološkim razvojem utiču na naučni rad u ovoj oblasti; jer su u pitanju simultani procesi teorije i primene, koji utiču jedan na drugi. Usled ovakvog shvatanja, kao i zbog potrebe privrede da se ljudi iz nauke pozabave praktičnim problemima, Nikola Hajdin zainteresovao se za projektovanje – kao paralelnu aktivnost. Upravo ta primenjena, visokokvalitetna sprega teorije i prakse predstavlja krunu naučnostručnog rada Nikole Hajdina.

Pored izuzetno bogatog naučnog rada, Nikola Hajdin istakao se kao autor i veoma cenjeni projektant čeličnih, betonskih i spregnutih konstrukcija.

Stvaralački opus profesora Hajdina može se okvirno podeliti na šest perioda, odnosno šest oblasti u kojima je dao svoj doprinos nauci i njenim primenama, a može se slobodno reći – i prilog opštem napretku. Te oblasti jesu: metod integralnih jednačina, spregnute konstrukcije, tankozidni štapovi, mostovi s kosim kablovima, udar saobraćajnih sredstava na građevinske objekte, stabilnost i nosivost čeličnih nosača.

Prvi period odnosno prva oblast – metod integralnih jednačina

Nikola Hajdin je predložio (1954) i razradio jedan metod za numeričko rešavanje graničnih zadataka teorije elastičnosti, koji se pokazao prikladnim – kako u teoriji linijskih nosača, tako i u teoriji površinskih nosača. Metod je zasnovan na osnovnim diferencijalnim jednačinama teorije elastičnosti, primenjenim na dvodimenzionalne probleme. Pretvarajući osnovne diferencijalne jednačine u integralne, duž usvojenih linija mreže i njihovim približnim rešavanjem numeričkim putem, dobija se sistem linearnih jednačina, koji vodi ka rešenju problema. Metod je našao široku primenu u različitim granama tehnike, posebno u građevinskom konstrukterstvu, hidrotehnici, analizi saobraćajnih vozila, analizi

Yugoslav Society of Structural Engineers.

Nikola Hajdin was a member of the Athens Academy of Sciences, the Slovenian Academy of Sciences and Arts (Ljubljana), the European Academy of Sciences, Arts and Literature (Paris), the European Academy of Sciences and Arts (Salzburg), and the European Academy of Sciences (Liege). In 2000, he was elected Honorary Doctor of the National Technical University of Athens. He was also a member of the Greek Society of the Scientific Research of Metal Structures, the Scientific Committee of the Italian Journal of Metal Structures, the Swiss Association for Steel Structures, the International Association for Bridges and Structural Engineering (Zurich), the Scientific Committee of the International Association for Steel Structures; and was an honorary member of the Yugoslav Society for Mechanics, the Yugoslav Society of Structural Engineers, and the Greek National Society for Theoretical and Applied Mechanics.

Nikola Hajdin was involved in the scientific and professional research in civil engineering in our country and abroad for seven decades.

Nikola Hajdin's scientific work was mostly related to the research and papers in the field of applied mechanics, especially Theory of Structures. However, he soon realized that the work in the field of Theory of Structures gains in importance and value when permeated (in addition to its theoretical basis) with knowledge of actual structures, the technological development which affects the scientific work in this field, so that they are simultaneous processes of theory and application that affect one another. This understanding, as well as the need of the economy for people in science to address practical problems, makes the basis of Nikola Hajdin's interest in designing as a parallel activity. This applied high quality combination of theory and practice is the crown of Nikola Hajdin's scientific and professional work.

In addition to his extremely rich scientific work, Nikola Hajdin was a distinguished author and a highly respected designer of steel, concrete, and composite structures.

Professor Hajdin's creative oeuvre can be roughly divided into six periods, or six fields in which he contributed to science and its applications, and thereby to the general progress: integral equations method, composite structures, thin-walled members, cable-stayed bridges, vehicle impact on structures, stability and bearing capacity of steel girders.

First period - first field: the integral equations method.

In 1954, Nikola Hajdin proposed and developed a method for numerically solving boundary problems of Theory of Elasticity, which proved to be suitable in both Linear Beam Theory and Theory of Plates and Shells. The method is based on basic differential equations of the Theory of Elasticity applied on two-dimensional problems. By converting the basic differential equations in integral equations along the adopted lines of the net and their approximate solving by numerical means, a system of linear equations is obtained which leads to the solution of the problem. The method found widespread application in various branches of engineering, particularly in civil engineering, hydraulic engineering, zvuka, kao i u nekim drugim problemima slične matematičke prirode. Višestruko je citiran i korišćen u radovima stranih autora. Iz ove oblasti, izdvaja se rad *Integral Equation Method for Solution of Boundary Value Problems of Structural Mechanics*, objavljen u međunarodnom časopisu *Numerical Methods in Engineering*. Izuzetno je vredna primena ovog postupka u proračunu hidrotehničkih konstrukcija. Velike lučne brane, kao što su Grančarevo, Mratinje i Glažnja, analizirane su primenom ovog metoda. Baveći se u početku svoje karijere teorijom lučnih brana, profesor Hajdin učestvovao je kao konsultant na čitavom nizu hidrotehničkih konstrukcija. Kao svoj prilog realizaciji lučnih brana, projektovao je branu Glažnja u Makedoniji, jednu od najvećih lučnih brana (treću po visini u bivšoj Jugoslaviji).

Drugi period odnosno druga oblast – spregnute konstrukcije

Nikola Hajdin posvetio je jedan deo svoje aktivnosti spregnutim konstrukcijama od betona i čelika. Osnovni naučni problem – koji je počeo ozbiljnije da se proučava posle Drugog svetskog rata – bio je izučavanje fenomena puženja i skupljanja betona, koji dovodi tokom vremena do preraspodele naprezanja u spregnutoj konstrukciji. Pored više naučnih radova iz oblasti spregnutih konstrukcija, Nikola Hajdin je i projektovao spregnute mostove, od kojih se izdvaja most Orašje preko reke Save, na kome je prvi put u svetu primenjeno tzv. dvostruko sprezanje, gde je kod kontinualnog nosača mosta, pored betonske kolovozne ploče gore, primenjena i betonska ploča u donjoj zoni nosača iznad oslonaca. Most Orašje, osim toga, imao je najveći raspon za spregnute mostove u to vreme u svetu. Ovde treba dodati i izvedene projekte nadvožnjaka u Ljubljani, sa originalnim načinom sprezanja u donjoj zoni na celoj dužini nadvožnjaka, kao i most preko reke Ibar kod Rožaja i most preko akumulacije za hidroelektranu Špilje. Sve ove konstrukcije mostova imale su poneku svojevrsnu inovaciju u našem građevinskom konstrukterstvu, upravo zahvaljujući autoru-projektantu – Nikoli Hajdinu.

Treći period odnosno treća oblast – tankozidni štapovi

Naučna oblast Teorije konstrukcija, u kojoj je Nikola Hajdin takođe dao izuzetan doprinos, jesu tankozidne konstrukcije koje se zbog svojih osobina upotrebljavaju u više grana tehnike, kao što su: građevinarstvo, mašinstvo, brodogradnja, aeronautika i druge. Radovi Nikole Hajdina iz ove oblasti objavljeni su uglavnom u inostranstvu u više časopisa i stručnih publikacija; a citirani su i korišćeni u brojnim objavljenim radovima stranih i domaćih naučnih radnika. Izuzetnu vrednost iz ovog opusa predstavljaju dve monografije – *Dünnwandige Stäbe*, *Bd. 1* i *2* (s koautorom Kurtom Kolbrunerom), objavljene u prestižnoj izdavačkoj kući *Springer* (1972. i 1975). Prema sadržaju, te monografije su jedinstveno delo i na originalan način, sa čitavim nizom priloga, izlažu oblast kojom se Nikola Hajdin bavio više od 20 godina. Kako su ovi radovi bili među prvima koji su se na širokom planu bavili ovom problematikom,

analysis of traffic vehicles, sound analysis and in some other problems of similar mathematical nature. It was repeatedly cited and used in papers of foreign authors. The paper "Integral Equation Method for Solution of Limit Value Problems of Structural Mechanics" published in the international journal "Numerical Methods in Engineering" is the most important one. The application of this approach on hydro engineering structures is highly valuable. Large arch dams, like Grancarevo, Mratinje, and Glaznja were analyzed using this method. Dealing with the theory of arch dams at the beginning of his career, professor Hajdin participated as a consultant on a series of hydro engineering structures. As a contribution to the field of arch dams, he designed the Glaznja dam in Macedonia, one of the largest arch dams and the third highest dam in the former Yugoslavia.

Second period – second field: composite structures.

Nikola Hajdin dedicated a part of his activity to composite structures of concrete and steel. The basic scientific problem that attracted the attention of engineers in the field after the World War II was the phenomenon of creep and shrinkage of concrete, which over time leads to the redistribution of stresses in composite structures. In addition to several scientific papers in the field of composite structures, Nikola Hajdin also designed composite bridges. The Orašje Bridge over the Sava River is the most important one. What makes this bridge outstanding is the first application of the so-called double composite action, where in the case of a continuous girder, in addition of the surface concrete slab, a concrete slab was also applied in the bottom zone of the girder above the supports. Moreover, the Orašje Bridge had the largest span in the world for composite bridges at the time. Here, we should mention the overpass projects in Ljubljana, with the original method of composite action in the bottom zone along the entire length of the overpass, as well as the bridge over the Ibar River near Rožaje and the bridge over the reservoir for the Špilje hydroelectric power plant. All these bridge structures contained some kind of innovation in our structure engineering thanks to the author-designer Nikola Hajdin.

Third period – third field: thin-walled members.

The scientific field of Theory of Structures in which Nikola Hajdin made a remarkable contribution is thin-walled structures that, due to their properties, are used in many branches of engineering, such as civil engineering, mechanical engineering, shipbuilding, aeronautics and others. Nikola Hajdin's papers in this field were published, for the most part abroad, in a number of journals and professional publications, and were cited and used in many published papers by foreign and domestic scholars. Two monographs: "Dünnwandige Stäbe", Bd. 1 and 2 (with C.F. Kollbrunner) published by the prestigious Springer Publishing House (1972 and 1975) have exceptional value in this opus. The monographs are unique in their contents, presenting in an original way the scientific fields on which Nikola Hajdin was focused for more than 20 years with a series of contributions. As these papers veoma važnom u konstrukterstvu, a i s obzirom na novine u oblikovanju konstrukcija, izazvane širokom primenom tehnologije zavarivanja, interes za radove ove vrste bio je znatan među inženjerima i projektantima, većinom u oblasti čeličnih konstrukcija.

Četvrti period odnosno četvrta oblast – mostovi s kosim kablovima

Nikola Hajdin dao je značajan doprinos – u naučnom i stručnom pogledu – analizirajući i projektujući mostove s kosim kablovima, koji su se pojavili kao novost u mostogradnji početkom šezdesetih godina dvadesetog veka.

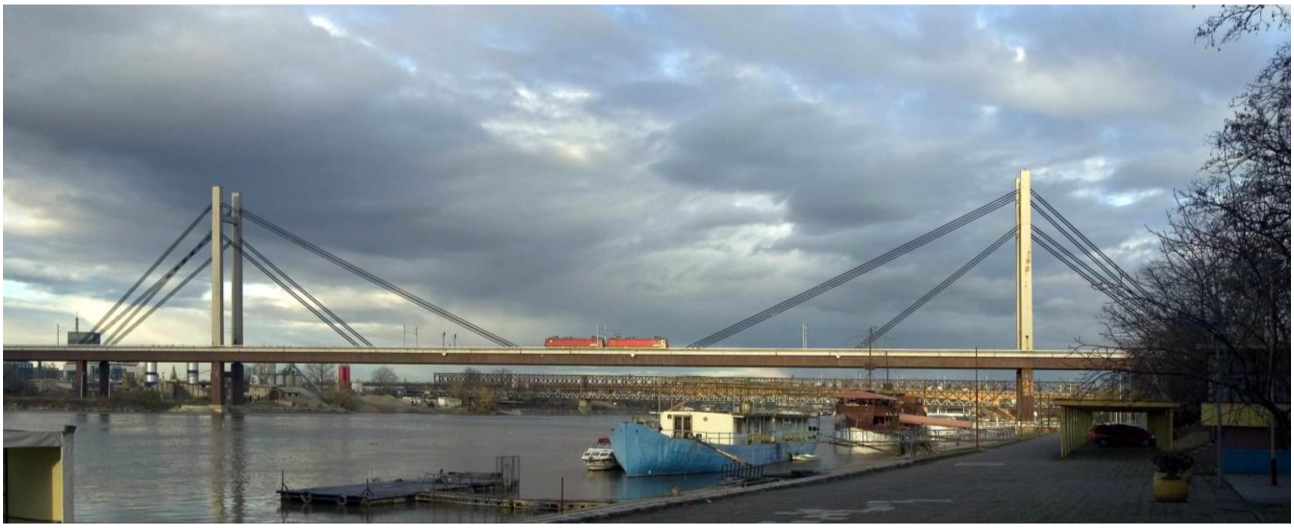
U vreme kada je Nikola Hajdin projektovao beogradski železnički most s kosima kablovima, u svetu je bilo izgrađeno samo dvadesetak mostova s kosim kablovima za drumske mostove. Nikola Hajdin (sa koautorom Ljubomirom Jevtovićem), prvi u svetu, isprojektovao je most s kosim kablovima samo za železnički saobraćaj, iako je tada vladalo mišljenje među stručnjacima u svetu da takav relativno fleksibilan konstrukcijski sistem nije primenjiv za železnički saobraćaj. Kosi kablovi, raspoređeni u dve vertikalne ravni, prihvataju mostovsku gredu na petinama raspona od 254 metara. Primenjena su užad s paralelnim žicama sistema *BBR* sa izuzetno otpornim na zamor *Hi-Am* ankernim glavama, uz mere za povećanje mase mosta s kolovozom u zastoru, dobijeni su izvanredno iskorišćenje napona (uključivo i na zamor), dobra napetost užadi za stalno opterećenje i mali uticaj izduženja užadi na ugib konstrukcije. Treba napomenuti i to da je ovo prva primena ove vrste užadi u Evropi. Most je završen 1979. godine (slika 1).

were among the first to deal extensively with this issue, which is very important in structure engineering from the aspect of novelties in the design of structures caused by the widespread use of welding technology, there was a considerable interest in papers of this kind among engineers and designers, mostly in the field of steel structures.

Fourth period – fourth field: cable-stayed bridges.

Nikola Hajdin made significant scientific and professional contribution by analyzing and designing cable-stayed bridges, which emerged as a novelty in bridge construction in the early 1960s.

At the time when Nikola Hajdin was designing the Belgrade railway cable-stayed bridge with inclined cables, only about twenty bridges with inclined cables for road bridges were in existence in the world. Nikola Hajdin (with co-author Ljubomir Jevtovic) was the first in the world to design a bridge for railway traffic only, although at that time it was believed among experts in the world that such a relatively flexible structural system was inapplicable in railway traffic. The stay cables are arranged in two vertical planes, holding the bridge girder in fifths of the 254 m span. It was applied the BBR system of parallel wires with extremely fatigue resistant Hi-Am anchor heads, with measures for increasing the mass of the bridge by application of carriageway in gravel, an extraordinary stress utilization was obtained (including fatigue), good cable tension for permanent load and low influence of rope elongation on structural deflection. It should be noted that this is the first application of this type of cables in Europe. The bridge was completed in 1979 (Figure 1).



Slika 1. Železnički most preko Save u Beogradu (autori – projektanti: Nikola Hajdin i Ljubomir Jevtović)
Figure 1. Railway Bridge over the Sava River in Belgrade (authors-designers: Nikola Hajdin and Ljubomir Jevtović)

Posle ovog beogradskog mosta, Nikola Hajdin je isprojektovao Most slobode preko Dunava u Novom Sadu. S rasponom od 351 metar, ova mostovska konstrukcija, u trenutku građenja, predstavljala je svetski rekord za mostove s kosim kablovima, kod kojih su piloni i kosi kablovi u srednjoj ravni mosta. Most je završen i

After this bridge in Belgrade, Nikola Hajdin designed the Liberty Bridge over the Danube in Novi Sad. With its span of 351 m, at the time of construction this bridge structure represented a world record for cable-stayed bridges, with the pylons and stay cables being situated in the central plane of the bridge. The bridge was pušten u saobraćaj 1981. godine, ali je porušen projektilima, aprila 1999. godine. Objekat je u potpunosti obnovljen u prvobitnom obliku, te je završen i ponovo pušten u saobraćaj 2005. godine (slika 2).

completed and put into service in 1981. The bridge was destroyed by missiles in April 1999. It was completely renovated in its original form and was completed and re-launched for traffic in 2005 (Figure 2).

Slika 2. Most slobode preko Dunava u Novom Sadu (autor – projektant Nikola Hajdin)
Figure 2. Liberty Bridge over the Danube River (author-designer: Nikola Hajdin)

Nikola Hajdin (s koautorom Bratislavom Stipanićem) isprojektovao je most preko reke Visle u poljskom gradu Plocku, koji je nagrađen prvom nagradom na međunarodnom konkursu za projekat. S rekordnim rasponom od 375 metara, za mostove s kosim kablovima (s kablovima u srednjoj ravni i pilonima uklještenim u gredu), predstavlja napredak u odnosu na most u Novom Sadu. Ukupna dužina mosta jeste 1.200 metara, od čega je 615 metara dužina glavnog dela mosta nad koritom reke Visle, a 585 metara je dužina prilaznog dela spregnutog mosta nad inundacijom. Glavna mostovska konstrukcija je simetrična konstrukcija od čelika – most s kosim kablovima, koji čine: kontinualna greda, kosi kablovi i dva pilona. Ovo je most s najvećim rasponom u Poljskoj i predstavlja korak dalje u razvoju mostova s kosim kablovima. Most je završen 2005, a sa pristupnim vijaduktom otvoren je za saobraćaj 2007. godine (slika 3).

Nikola Hajdin (co-authored with Bratislav Stipanić) designed the bridge over the Wisla River in the Polish city of Plock, which was awarded the first prize in the international design competition. With the record range of 375 meters for cable-stayed bridges (with cables in the central plane and pylons fixed in beam), it represented a further improvement in relation to the bridge in Novi Sad. The total length of the bridge is 1200 m, of which 615 m accounts for the length of the main part of the bridge over the riverbed of the Vistula River, and 585 m is the length of the access part of the composite bridge over the inundation. The main bridge structure is a symmetrical steel structure, a cable-stayed consisting of a continuous girder, stay cables, and two pylons. The bridge represents a step further in the development of cable-stayed bridges. It is the bridge with the largest span in Poland. The bridge was completed in 2005 and open for traffic with the approach viaduct in 2007 (Figure 3).

Slika 3. Most solidarnosti preko Visle u Plocku (autori – projektanti: Nikola Hajdin i Bratislav Stipanić)
Figure 3. Solidarity Bridge in Plock over the Vistula River (authors-designers: Nikola Hajdin and Bratislav Stipanic)

Peti period odnosno peta oblast – udar saobraćajnih sredstava na objekte

Nikola Hajdin, krajem devedesetih godina, naučno se posvetio nelinearnim dinamičkim problemima mehanike, posebno izučavanju udara (impakta) saobraćajnih sredstava na građevinske konstrukcije, kao što su udari od železničkih kompozicija i plovnih objekata. Ovi radovi, između ostalog, nastali su iz praktičnih potreba da se zaštite građevinski objekti izloženi mogućnosti udara saobraćajnih sredstava, prvenstveno u Švajcarskoj, tako da su ih delimično finansirale zainteresovane državne institucije zadužene za ovu problematiku. Na osnovu tih radova, objavljenih u časopisima, izrađene su zvanične preporuke za proračun mostova, posebno mostovskih stubova na udar.

Šesti period odnosno šesta oblast – stabilnost i nosivost čeličnih nosača

Sredinom sedamdesetih godina prošlog veka, Nikola Hajdin objavio je niz radova koji se bave problemima stabilnosti i granične nosivosti limenih nosača odnosno problemima izbočavanja ploča. U to vreme, posle niza havarija mostova, u svetu su intenzivirana i teorijska, kao i eksperimentalna istraživanja raznih aspekata stabilnosti i nosivosti čeličnih nosača. U radovima profesora Hajdina analizirana su najnovija saznanja, kao i njihova primena u okviru naših propisa za proračun čeličnih konstrukcija.

Krajem sedamdesetih godina, posebna pažnja u svetu počinje da se posvećuje problemu takozvanog *patch loading*, opterećenja pojaseva limenih nosača koncentrisanim ili opterećenjem raspodeljenim na maloj dužini u ravni rebra, koje može da dovede prvo do lokalnog izbočavanja u zoni unošenja opterećenja, a – u zavisnosti od ostalih uslova – i do progresivnog loma nosača. Ovaj problem posebno je važan prilikom montaže čeličnih mostova prevlačenjem preko privremenih ili stalnih oslonaca. Krajem sedamdesetih i početkom osamdesetih godina, profesor Hajdin je u Beogradu rukovodio istraživanjima u ovoj oblasti. Njegovi saradnici s Građevinskog fakulteta u Beogradu dobijaju priliku da na *University College Cardiff* u Velikoj Britaniji, veoma važnom istraživačkom centru u tom periodu, učestvuju u istraživanjima koja se duži niz godina sprovode u svetu u ovoj oblasti. Oni nadalje nastavljaju sopstvena istraživanja u zemlji. U tom periodu, istraživanja se sprovode u okviru saradnje sa Institutom za mehaniku Čehoslovačke akademije nauka. Iz tih istraživanja proizašao je veći broj radova publikovanih u međunarodnim časopisima i na međunarodnim naučnim skupovima, koje su kasnije citirali autori iz različitih zemalja, koji se bave ovim problemima. Između ostalog, u okviru ovog problema, analiziran je uticaj podužnih ukrućenja u zoni unošenja opterećenja na izbočavanje limenih nosača i dat je predlog izraza kojim se taj uticaj uzima u obzir. Ovaj predlog Nikole Hajdina (sa koautorom Nenadom Markovićem), u 2000. godini, prihvaćen je u celosti u novoj verziji britanskih propisa za čelične mostove, u kojima je ranije bio obuhvaćen samo proračun za nosače bez podužnih ukrućenja. Tako da je to prvi propis u svetu koji je direktno uključio uticaj podužnih ukrućenja na nosivost limenih nosača pod dejstvom

Fifth period – fifth field: vehicle impact on structures.

In the late 1990s, Nikola Hajdin was scientifically devoted to nonlinear dynamic problems in mechanics, particularly to studying the impact of vehicles on structures, such as impacts from railway compositions and floating vessels. These papers were created, among the other things, from the practical need to protect the structures exposed to the possibility of traffic collisions, primarily in Switzerland, and therefore they were partially funded by the interested state institutions in charge of this issue. Due to these papers published in the journals, official recommendations were made for the calculation of bridges, especially bridge piers, against the impact.

Sixth period – sixth field: stability and bearing capacity of steel girders

In the mid-1970s, Nikola Hajdin published a series of papers dealing with the problems of stability and limit bearing capacity of plate girders, i.e. the problems of plate buckling. At that time, after a series of bridge failures, theoretical and experimental research into various aspects of stability and ultimate bearing capacity of steel girders intensified in the world. In his papers, professor Hajdin analyzed the latest findings and their application within the framework of our regulations for the calculation of steel structures.

In the late 1970s, the attention in the world was specifically focused on the problem of so-called "patch loading", loading subjected to flanges of plate girders with concentrated or distributed load over a small length in the web plane, which may first lead to local buckling in the loading zone and, depending on other conditions, even to progressive failure of the girder. This problem is especially important when installing steel bridges by launching over temporary or permanent supports. In the late 1970s and early 1980s, professor Hajdin was the head of the research in this area in Belgrade. His associates from the Faculty of Civil Engineering in Belgrade were given the opportunity to participate in research at the University College Cardiff in the UK, a very important research center at that time, a research that was conducted in the field worldwide for many years. They further continue their own research in the country. During this period, the research was conducted in cooperation with the Institute of Mechanics of the Czechoslovak Academy of Sciences. These studies resulted in a large number of papers published in international journals and presented at international scientific conferences, which were later cited by authors from different countries involved in these issues. Among other things, effects of longitudinal stiffeners in the loading zone on the buckling of plate girders were analyzed within the framework of this issue, and a term was proposed to take these effects into account. This proposal by Nikola Hajdin (co-authored with Nenad Marković) was fully accepted in 2000 in a new version of the British regulations for steel bridges, which previously covered only the calculation for girders without longitudinal stiffeners. Thus, this is the first regulation in the world that directly included the effect of longitudinal stiffeners on the bearing capacity of plate girders under the action of concentrated load on flange of plate girder. In recent decades, research into this issue has been koncentrisanog opterećenja po pojasu limenih nosača. Poslednjih decenija nastavljaju se u svetu intenzivna istraživanja ovog problema i publikovan je znatan broj radova, doktorskih i magistarskih disertacija, a u mnogima je citiran doprinos rada Nikole Hajdina.

Naučni opus Nikole Hajdina čini više od 230 radova, od čega je približno polovina objavljena u inostranstvu, u najuglednijim časopisima ili na značajnim naučnim konferencijama. Prema podacima iz časopisa koji su nam dostupni, citiran je više od 300 puta u inostranoj literaturi i više od 500 puta u domaćoj, dok su njegova projektantska ostvarenja, posebno kada je reč o Mostu Slobode u Novom Sadu, citirani nekoliko stotina puta.

U kineskoj enciklopediji *Yingliang Wang*, iz 2007 godine, najznačajnijih mostova Evrope i Amerike za poslednjih 200 godina, navode se četiri mosta autora-projektanta Nikole Hajdina (most Orašje, železnički most u Beogradu, Most Sloboda u Novom Sadu i novi most u Plocku).

Nikola Hajdin, kao međunarodno priznati ekspert, učestvovao je kao konsultant više svetski poznatih organizacija iz oblasti projektovanja i izvođenja raznih građevinskih konstrukcija.

Nikola Hajdin bio je gostujući profesor za predmet Tankozidni štapovi na Saveznoj visokoj školi (*ETH*) u Cirihu, od 1971. do 1973. godine, gost-naučnik Švajcarskog udruženja za čelične konstrukcije. U više navrata, boravio je u Švajcarskoj, gde je učestvovao u istraživanju iz oblasti Teorije tankozidnih štapova. Pored toga, održao je čitav niz predavanja na naučnim skupovima, na stranim univerzitetima, na naučnim i stručnim institucijama u Velikoj Britaniji, Švajcarskoj, Češkoj, Slovačkoj, Nemačkoj, Kini, Indiji, Austriji, Iraku, Grčkoj, Rumuniji, Italiji... Učestvovao je u radu više različitih naučnih komiteta internacionalnih simpozijuma i konferencija.

Kao profesor posebnih naučnih oblasti, Nikola Hajdin održao je više predavanja i kurseva na poslediplomskim studijama na Prirodno-matematičkom fakultetu u Beogradu, na Građevinskom fakultetu i Mašinskom fakultetu u Skoplju, na Građevinskom fakultetu u Zagrebu i Fakultetu za arhitekturu, građevinarstvo i geodeziju u Ljubljani. Sarađivao je s Društvom građevinskih konstruktera Slovenije i 3. razredom SAZU (Slovenačke akademije nauka i umetnosti).

Rukovodio je izradom odnosno bio je član komisija za 52 magistarske i 42 doktorske disertacije na matičnom fakultetu, kao i za mnogobrojne disertacije na različitim fakultetima bivše Jugoslavije, te na Atinskom i Helsinškom univerzitetu. Rukovodio je projektom „Teorijska i eksperimentalna istraživanja metalnih konstrukcija i njihov uticaj na savremeno projektovanje i izvođenje" u SANU. Rukovodio je nizom naučnoistraživačkih projekata na Građevinskom fakultetu u Beogradu.

Za svoj izuzetni doprinos nauci i struci, Nikola Hajdin dobio je brojna priznanja i više nagrada, od koji se izdvajaju: Oktobarska nagrada Beograda za 1959. godinu, Oktobarska nagrada Novog Sada za 1981. godinu, Nagrada AVNOJ-a za 1987. godinu, nekoliko nagrada na anonimnim konkursima za projekte mostove u Jugoslaviji i prva nagrada na međunarodnom konkursu za most preko reke Visle u Poljskoj.

intensified in the world, and a considerable number of papers, doctoral and master's theses have been published with the contribution of Nikola Hajdin being widely cited in many of them.

Nikola Hajdin's scientific contribution consists of more than 230 papers, of which approximately half were published abroad in the most reputable journals or presented at important scientific conferences. According to data from journals available to us, he has been cited more than 300 times in foreign literature and more than 500 times in domestic literature. Nikola Hajdin's achievements in bridge design, especially the Liberty Bridge in Novi Sad, have been cited several hundred times.

The Chinese encyclopedia Yingliang Wang (2007) lists four bridges of Nikola Hajdin among the most important bridges in Europe and America for the last 200 years (Orašje Bridge, Belgrade Railway Bridge, Liberty Bridge in Novi Sad and new Plock Bridge).

As internationally recognized expert, Nikola Hajdin participated as a consultant to several world-renowned organizations in the field of design and construction of various structures of civil engineering.

Nikola Hajdin was a visiting professor for the subject of thin-walled members at the Federal High School (ETH) in Zurich from 1971 to 1973, and a visiting scholar at the Swiss Association for Steel Structures. He repeatedly visited Switzerland where he participated in research in the field of Theory of Thin-Walled Members. In addition, he delivered a whole series of lectures at scientific conferences, foreign universities, scientific and professional institutions in the United Kingdom, Switzerland, Czech Republic, Slovakia, Germany, China, India, Austria, Iraq, Greece, Romania, Italy, etc. He participated in the work of several different scientific committees, international symposia and conferences.

As a professor of specific scientific fields, Nikola Hajdin delivered lectures and courses at postgraduate studies at the Faculty of Natural Sciences and Mathematics in Belgrade, the Faculty of Civil Engineering and Mechanical Engineering in Skopje, the Faculty of Civil Engineering in Zagreb and the Faculty of Architecture, Civil Engineering and Geodesy in Ljubljana. He collaborated with the Society of Slovenian Structural Engineers and the 3. class of SAZU (Slovenian Academy of Sciences and Arts).

He led the preparation or was a committee member for 52 masters and 42 doctoral theses at the parent faculty, and for a large number of them at various faculties from the former Yugoslavia, as well as at the University of Athens and the University of Helsinki. He was the head of the project called "Theoretical and Experimental Research of Metal Structures and Their Effect on Contemporary Design and Construction" at the SANU (Serbian Academy of Sciences and Arts). He was the head of a number of research projects at the Faculty of Civil Engineering in Belgrade.

Nikola Hajdin received numerous awards for his outstanding contribution to the science and profession, including: October Award of the city of Belgrade in 1959, October Award of the city of Novi Sad in 1981, AVNOJ Award in 1987, several awards at anonymous contests for bridge designs in former Yugoslavia, and the first prize at the international contest for the bridge over the Wisla River in Poland.

Na onovu svega iznetog, može se zaključiti da je Nikola Hajdin bio izuzetna ličnost, koja je ne samo svojim bogatim opusom naučnih radova i projektima građevinskih konstrukcija, već i svojim uticajem i delovanjem u akademskom i javnom životu u našoj zemlji, aktivno obeležila protekli period od sedam decenija; što je nadasve teško dostižan fenomen.

Prof. dr Bratislav Stipanić, dipl.inž.građ.

It can be concluded from the above that Nikola Hajdin was an extraordinary person who actively marked a period within last seven decades both with his rich oeuvre of scientific work and designs of structures in civil engineering, as well as his influence and activity in the academic and public life in our country. A truly hard-to-reach phenomenon.

Professor Bratislav Stipanic, Ph.D. M.Sc. B.C.Eng.

UPUTSTVO AUTORIMA*

Prihvatanje radova i vrste priloga

U časopisu Materijli i konstrukcije štampaće se neobjavljeni radovi ili članci i konferencijska saopštenja sa određenim dopunama, iz oblasti građevinarstva i srodnih disciplina (geodezija i arhitektura). Vrste priloga autora i saradnika koji će se štampati su: originalni naučni radovi, prethodna saopštenja, pregledni radovi, stručni radovi, prikazi objekata i iskustava (studija slučaja), kao i diskusije povodom objavljenih radova.

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 sažeto, ali tako da poznavalac problema može proceniti rezultate eksperimentalnih ili teorijsko numeričkih analiza, 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.

Pregledni rad je naučni rad koji prikazuje stanje nauke u određenoj oblasti kao plod analize, kritike i komentara i zaključaka publikovanih radova o kojima se daju svi neophodni podaci pregledno i kritički uključujući i sopstvene radove. Navode se sve bibliografske jedinice korišćene u obradi tematike, kao i radovi koji mogu doprineti rezultatima daljih istraživanja. Ukoliko su bibliografski podaci metodski sistematizovani, ali ne i analizirani i raspravljeni, takvi pregledni radovi se klasifikuju kao stručni radovi.

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

Ostali prilozi su prikazi objekata, tj. njihove konstrukcije i iskustava-primeri u građenju i primeni različitih materijala (studije slučaja).

Da bi se ubrzao postupak prihvatanja radova za publikovanje, potrebno je da autori uvažavaju Uputstva za pripremu radova koja su navedena u daljem tekstu.

Uputstva za pripremu rukopisa

Rukopis otkucati jednostrano na listovima A-4 sa marginama od 31 mm (gore i dole) a 20 mm (levo i desno), u Wordu fontom Arial sa 12 pt. Potrebno je uz jednu kopiju svih delova rada i priloga, dostaviti i elektronsku verziju na navedene E-mail adrese, ili na CD-u. Autor je obavezan da čuva jednu kopiju rukopisa kod sebe.

Od broja 1/2010, prema odluci Upravnog odbora Društva i Redakcionog odbora, radovi sa pozitivnim recenzijama i prihvaćeni za štampu, publikovaće se na srpskom i engleskom jeziku, a za inostrane autore na engleskom (izuzev autora sa govornog područja srpskog I hrvatskog jezika).

Svaka stranica treba da bude numerisana, a optimalni obim članka na jednom jeziku, je oko 16 stranica (30000 slovnih mesta) uključujući slike, fotografije, tabele i popis literature. Za radove većeg obima potrebna je saglasnost Redakcionog odbora.

* **Uputstvo autorima je modifikovano i treba ga, u pripremi radova, slediti.**

GUIDELINES TO AUTHORS

Acceptance and types of contributions

The Building Materials and Structures journal will publish unpublished papers, articles and conference reports with modifications in the field of Civil Engineering and similar areas (Geodesy and Architecture).The following types of contributions will be published: original scientific papers, preliminary reports, review papers, professional papers, objects describe / presentations and experiences (case studies), as well as discussions on published papers.

Original scientific paper is the primary source of scientific information and new ideas and insights as a result of original research using appropriate scientific methods. The achieved results are presented briefly, but in a way to enable proficient readers to assess the results of experimental or theoretical numerical analyses, so that the research can be repeated and yield with the same or results within the limits of tolerable deviations, as stated in the paper.

Preliminary report contains the first short notifications on the results of research but without detailed explanation, i.e. it is shorter than the original scientific paper.

Review paper is a scientific work that presents the state of science in a particular area as a result of analysis, review and comments, and conclusions of published papers, on which the necessary data are presented clearly and critically, including the own papers. Any reference units used in the analysis of the topic are indicated, as well as papers that may contribute to the results of further research. If the reference data are methodically systematized, but not analyzed and discussed, such review papers are classified as technical papers.

Technical paper is a useful contribution which outlines the known insights that contribute to the dissemination of knowledge and adaptation of the results of original research to the needs of theory and practice.

Other contributions are presentations of objects, i.e. their structures and experiences (examples) in the construction and application of various materials (case studies).

In order to speed up the acceptance of papers for publication, authors need to take into account the Instructions for the preparation of papers which can be found in the text below.

Instructions for writing manuscripts

The manuscript should be typed one-sided on A-4 sheets with margins of 31 mm (top and bottom) and 20 mm (left and right) in Word, font Arial 12 pt. The entire paper should be submitted also in electronic format to e-mail address provided here, or on CD. The author is obliged to keep one copy of the manuscript.

As of issue 1/2010, in line with the decision of the **Management Board of the Society and the Board of Editors, papers with positive reviews, accepted for publication, will be published in Serbian and English, and in English for foreign authors (except for authors coming from the Serbian and Croatian speaking area).**

Each page should be numbered, and the optimal length of the paper in one language is about 16 pages (30.000 characters) including pictures, images, tables and references. Larger scale works require the approval of the Board of Editors.

Naslov rada treba sa što manje reči (poželjno osam, a najviše do jedanaeset) da opiše sadržaj članka. U naslovu ne koristiti skraćenice ni formule. U radu se iza naslova daju ime i prezime autora, a titule i zvanja, kao i ime institucije u podnožnoj napomeni. Autor za kontakt daje telefon, adresu elektronske pošte I poštansku adresu.

Uz sažetak (rezime) od oko 150-250 na srpskom i engleskom jeziku daju se ključne reči (do sedam). To je jezgrovit prikaz celog članka i čitaocima omogućuje uvid u njegove bitne elemente.

Rukopis se deli na poglavlja i potpoglovlja uz numeraciju, po hijerarhiji, arapskim brojevima. Svaki rad ima uvod, sadržinu rada sa rezultatima, analizom i zaključcima. Na kraju rada se daje popis literature.

Kod svih dimenzionalnih veličina obavezna je primena međunarodnih SI mernih jedinica.

Formule i jednačine treba pisati pažljivo vodeći računa o indeksima i eksponentima. Autori uz izraze u tekstu definšu simbole redom kako se pojavljuju, ali se može dati i posebna lista simbola u prilogu.

Prilozi (tabele, grafikoni, sheme i fotografije) rade se u crno-beloj tehnici, u formatu koji obezbeđuje da pri smanjenju na razmere za štampu, po širini jedan do dva stupca (8 cm ili 16,5 cm), a po visini najviše 24,5 cm, ostanu jasni i čitljivi, tj. da veličine slova i brojeva budu najmanje 1,5 mm. Originalni crteži treba da budu kvalitetni i u potpunosti pripremljeni za presnimavanje. Mogu biti i dobre, oštre i kontrastne fotokopije. Koristiti fotogrfije, u crno-beloj tehnici, na kvalitetnoj hartiji sa oštrim konturama, koje omogućuju jasnu reprodukciju.

U popisu literature na kraju rada daju se samo oni radovi koji se pominju u tekstu. Citirane radove treba prikazati po abecednom redu prezimena prvog autora. Literaturu u tekstu označiti arapskim brojevima u uglastim zagradama, kako se navodi i u Popisu citirane literature, napr [1]. Svaki citat u tekstu mora se naći u Popisu citirane literature i obrnuto svaki podatak iz Popisa se mora citirati u tekstu.

U Popisu literature se navode prezime i inicijali imena autora, zatim potpuni naslov citiranog članka, iza toga sledi ime časopisa, godina izdavanja i početna i završna stranica (od - do). Za knjige iza naslova upisuje se ime urednika (ako ih ima), broj izdanja, prva i poslednja stranica poglavlja ili dela knjige, ime izdavača i mesto objavljivanja, ako je navedeno više gradova navodi se samo prvi po redu. Kada autor citirane podatke ne uzima iz izvornog rada, već ih je pronašao u drugom delu, uz citat se dodaje «citirano prema...».

Autori su odgovorni za izneseni sadržaj i moraju sami obezbediti eventualno potrebne saglasnosti za objavljivanje nekih podataka i priloga koji se koriste u radu.

Ukoliko rad bude prihvaćen za štampu, autori su dužni da, po uputstvu Redakcije, unesu sve ispravke i dopune u tekstu i prilozima.

Rukopisi i prilozi objavljenih radova se ne vraćaju. Sva eventualna objašnjenja i uputstva mogu se dobiti od Redakcionog odbora.

Radovi se mogu slati i na e-mail: folic@uns.ac.rs ili miram@uns.ac.rs

Veb sajt Društva I časopisa: www.dimk.rs

The title should describe the content of the paper using a few words (preferably eight, and up to eleven). Abbreviations and formulas should be omitted in the title. The name and surname of the author should be provided after the title of the paper, while authors' title and position, as well as affiliation in the footnote. The author should provide his/her phone number, e-mail address and mailing address.

The abstract (summary) of about 150-250 words in Serbian and English should be followed by key words (up to seven). This is a concise presentation of the entire article and provides the readers with insight into the essential elements of the paper.

The manuscript is divided into chapters and subchapters, which are hierarchically numbered with Arabic numerals. The paper consists of introduction and content with results, analysis and conclusions. The paper ends with the list of references. All dimensional units must be presented in international SI measurement units. The formulas and equations should be written carefully taking into account the indexes and exponents. Symbols in formulas should be defined in the order they appear, or alternatively, symbols may be explained in a specific list in the appendix. Illustrations (tables, charts, diagrams and photos) should be in black and white, in a format that enables them to remain clear and legible when downscaled for printing: one to two columns (8 cm or 16.5 cm) in height, and maximum of 24.5 cm high, i.e. the size of the letters and numbers should be at least 1.5 mm. Original drawings should be of high quality and fully prepared for copying. They also can be high-quality, sharp and contrasting photocopies. Photos should be in black and white, on quality paper with sharp contours, which enable clear reproduction.

The list of references provided at the end of the paper should contain only papers mentioned in the text. The cited papers should be presented in alphabetical order of the authors' first name. References in the text should be numbered with Arabic numerals in square brackets, as provided in the list of references, e.g. [1]. Each citation in the text must be contained in the list of references and vice versa, each entry from the list of references must be cited in the text.

Entries in the list of references contain the author's last name and initials of his first name, followed by the full title of the cited article, the name of the journal, year of publication and the initial and final pages cited (from - to). If the doi code exists it is necessary to enter it in the references. For books, the title should be followed by the name of the editor (if any), the number of issue, the first and last pages of the book's chapter or part, the name of the publisher and the place of publication, if there are several cities, only the first in the order should be provided. When the cited information is not taken from the original work, but found in some other source, the citation should be added, "cited after ..."

Authors are responsible for the content presented and must themselves provide any necessary consent for specific information and illustrations used in the work to be published.

If the manuscript is accepted for publication, the authors shall implement all the corrections and improvements to the text and illustrations as instructed by the Editor.

Writings and illustrations contained in published papers will not be returned. All explanations and instructions can be obtained from the Board of Editors.

Contributions can be submitted to the following e-mails: folic@uns.ac.rs or miram@uns.ac.rs

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Izdavanje časopisa "Građevinski materijali i konstrukcije" finansijski su pomogli:

REPUBLIKA SRBIJA
MINISTARSTVO PROSVETE, NAUKE I TEHNOLOŠKOG RAZVOJA

UNIVERZITET U BEOGRADU
GRAĐEVINSKI FAKULTET

DEPARTMAN ZA GRAĐEVINARSTVO I GEODEZIJU
FAKULTET TEHNIČKIH NAUKA NOVI SAD

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MATEST "iT TECH" KONTROLNA JEDINICA

JEDNA TEHNOLOGIJA MNOGO REŠENJA

IT Touch Techlogy je Matestov najnoviji koncept koji ima za cilj da ponudi inovativna i user-friendly tehnologiju za kontrolu i upravljanje najmodernijom opremom u domenu testiranja građevinskih materijala

Ova tehnologija je srž Matestove kontrolne jedinice, software baziran na Windows platformi i touch screen sistem koji je modularan, fleksibilan i obavlja mnoge opcije

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| INTERFEJS SA IKONICAMA
| INDUSTRIJALNA TEHNOLOGIJA

SISTEM JEDNOG RAZMIŠLJANJA JEDNOM SHVATIŠ - SVE TESTIRAŠ

NAPREDNA TEHNOLOGIJA ISPITIVANJA ASFALTA

| GYROTRONIC - Gyratory Compactor
| ARC - Electromechanical Asphalt Roller Compactor
| ASC - Asphalt Shear Box Compactor
| SMARTRACKER^{tm} - Multiwheels Hamburg Wheel Tracker, DRY + WET test environment
| SOFTMATIC - Automatic Digital Ring & Ball Apparatus
| Ductilometers with data acquisition system

MULTIFUNKCIONALNI RAMOVI ZA TESTIRANJE

| CBR/Marshall digital machines
| Universal multispeed load frames
| UNITRONIC 50kN or 200kN Universal multipurpose compression/flexural and tensile frames

OPREMA ZA GEOMEHANIČKO ISPITIVANJE

| EDOTRONIC - Automatic Consolidation Apparatus
| SHEARLAB - AUTOSHEARLAB - SHEARTRONIC Direct / Residual shear testing systems
| Triaxial Load Frame 50kN

MIXMATIC - Automatic Programmable Mortar Mixer

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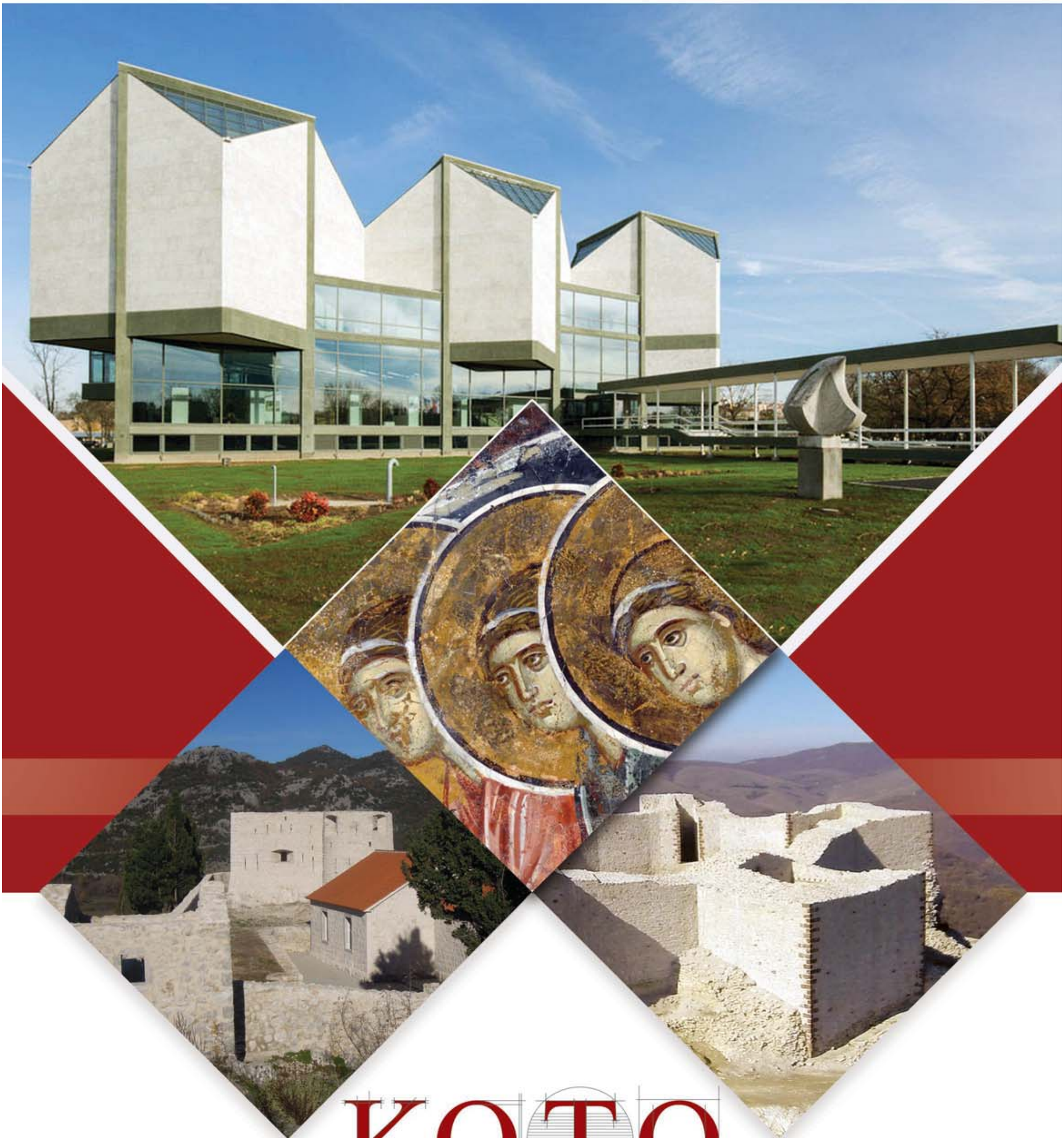

Institut za ispitivanje materijala IMS, sa tradicijom od 1929. godine, predstavlja najstariju naučno-istraživačku instituciju u Srbiji. Osnovna ideja prilikom osnivanja bila je potreba za jedinstvenom institucijom koja bi se osim istraživanja bavila i kontrolom građevinske industrije.

Delatnost Instituta IMS obuhvata laboratorijska ispitivanja građevinskih materijala, sertifikaciju proizvoda, nadzor nad izvođenjem radova i ispitivanje različitih tipova konstrukcija, izradu projektne dokumentacije, kao i naučno - istraživački rad u svim oblastima građevinarstva.

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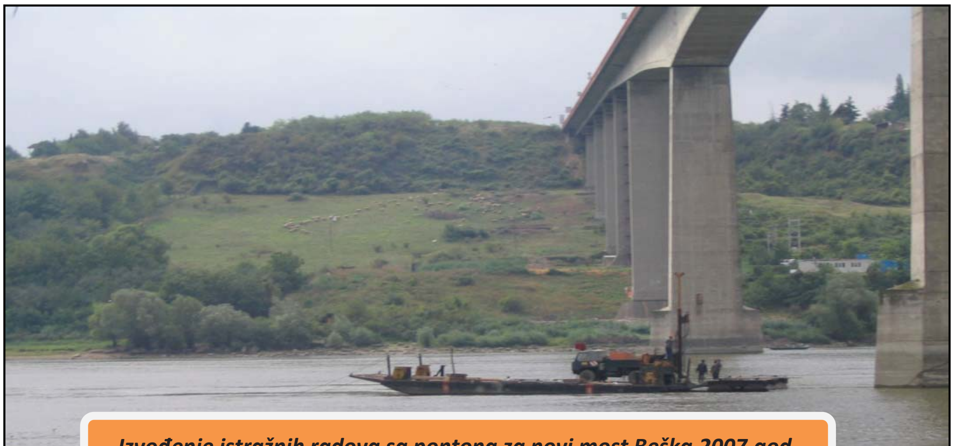


Izvođenje istražnih radova sa pontona za novi most Beška,2007.god.

Geotehnička istraživanja i ispitivanja – in situ

Od terenskih istražnih radova izdvajamo izvođenje istražnih bušotina (IB), standardnih penetracionih opita (SPT), statičkih penetracionih opita (CPT i CPTU), opita dilatometarskom sondom (DMT i SDMT), ispitivanja vodopropustljivosti tla različitim terenskim metodama (VDP), ugradnja pijezometara i dr.
Terenske metode ispitivanja šipova zauzimaju značajno mesto u našoj delatnosti, a na tržištu se izdvajamo kao lideri u toj oblasti u protekloj deceniji.

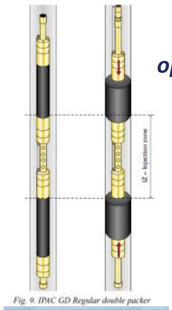
DLT-dinamičko ispitivanje šipova

Ispitivanje šipova

SLT metoda (Static load test) ispitivanje nosivosti šipova statičkim opterećenjem;
DLT metoda (Dynamic load test) ispitivanje nosivosti šipova dinamičkim opterećenjem;
PDA metoda (Pile driving analysis) omogućava praćenje i optimizaciju procesa pobijanja prefabrikovanih betonskih i čeličnih šipova u tlo;
PIT (SIT) metoda (Pile(Sonic) integrity testing) koristi se za ispitivanje integriteta izvedenih šipova (dužine, prekida, suženja ili proširenja).

CPT/CPTU opiti

Aktivno klizište



oprema za ispitivanje vodopropusnosti stena pod pritiskom do 10 bar-a metodom LIŽONA

Laboratorija za puteve i geotehniku

Laboratorija za puteve i geotehniku akreditovana je kod Akreditacionog tela Srbije – ATS prema SRPS ISO/IEC 17025:2006. U njoj se vrše ispitivanja tla (identifikaciono–klasifikaciona ispitivanja, fizičko–mehanička modelska ispitivanja), kamenog agregata i brašna, bitumena i bitumenskih emulzija, asfaltnih mešavina. U okviru laboratorijskih ispitivanja na terenu vrši se kontrola kvaliteta ugrađenog materijala i izvedenih radova (prethodna, tekuća, kontrolna ispitivanja i izvođenja opita in situ).

Projektovanje puteva i sanacija klizišta

U okviru projektovanja značajno mesto u radu zauzimaju geotehnička istraživanja terena i projekti sanacije klizišta - nestabilnih kosina useka i nasipa puteva i prirodno nestabilnih padina . Značajna su i projekovanja svih vrsta fundiranja specijalnih geotehničkih konstrukcija. Ističe se i iskustvo u oblasti putarstva, na projektovanju novih, rehabilitacija i rekonstrukcija postojećih puteva svih rangova sa pratećim objektima i dimenzionisanjem kolovoznih konstrukcija.

Nadzor

Naši inženjeri imaju veliko iskustvo u kontroli i proveri kvaliteta izvođenja svih vrsta radova, kontroli građevinske dokumentacije i praćenju radova u skladu sa njom, kao i rešavanju novonastalih situacija tokom izvođenja radova.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BUILDING TRUST

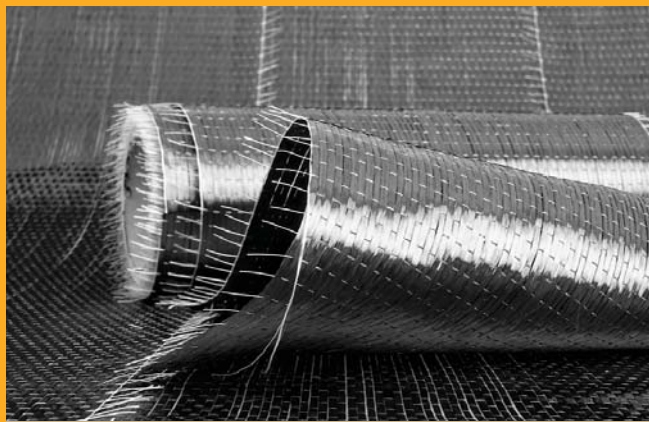
NAPREDNA SIKA REŠENJA U OBLASTI STRUKTURALNIH OJAČANJA

Kompanija Sika pruža trajnu dodatnu vrednost vlasnicima građevinskih objekata, njihovim konsultantima i izvođačima, kao i tehničku podršku tokom svih faza projekta, od ispitivanja uslova i razvoja inicijalnog koncepta ojačanja pa sve do uspešnog završetka i primopredaje projekta

SIKA – VAŠ PARTNER NA GRADILIŠTU

- Globalni lider na tržištu građevine i građevinske hemije
- Najbolja tehnička ekspertiza i praksa za sanaciju betona i strukturalna ojačanja
- Odlična reputacija kod vodećih izvođača i ugovarača posla

SIKA VREDNOSTI I INOVACIJE U GRAĐEVINI



- Integrisani proizvodi i sistemi visokih performansi koji mogu da povećaju i poboljšaju kapacitet, efikasnost, trajnost i estetiku zgrada i drugih objekata – u korist naših klijenata i boljeg održivog razvoja
- Sika mreža obučenih i iskusnih građevinskih stručnjaka

JEDINSTVENA SIKA REŠENJA U ZAHTEVNIM USLOVIMA

- Rešenja za gotovo sve uslove apliciranja
- Kontrolisano vreme rada, vreme sazrevanja i očvršćavanja za različite vremenske uslove
- Posebna rešenja završnih ojačanja za korišćenje kod betona slabije jačine i drugih podloga

POTVRĐENI SIKA SISTEMI I TEHNIKE APLICIRANJA

- Preko 40 godina iskustva u strukturalnim ojačanjima, sistemima i tehnikama
- Proizvodi i sistemi sa brojnim testovima i procenama kako internim tako i eksternim
- Najviši međunarodni standardi proizvodnje i kontrole kvaliteta

PUT INŽENJERING

Put inženjering d.o.o punih 25 godina radi kao specijalizovano preduzeće za izgradnju infrastrukture u niskogradnji i visokogradnji, kao i proizvodnjom kamenog agregata i betona. Preduzeće se bavi i transportom, uslugama građevinske mehanizacije i specijalne opreme.

Za spravljanje betona koristimo drobljeni krečnjački agregat sa našeg kamenoloma, deklarisanih frakcija, kontrolisane vlažnosti. Kompletan proces proizvodnje i kontrole kvaliteta vršimo prema važećim standardima.

Kao generalni izvođač radova, vršimo koordinaciju svih učesnika na projektu, planiranje, praćenje i nabavku materijala, kontrolu kvaliteta izvedenih radova, poštujući zadate vremenske rokove i finansijski okvir investitora.

Obradu armature vršimo brzo, stručno i kvalitetno, sa kompjuterskom preciznošću i dimenzijama po projektu.

Osnovi princip našeg poslovanja zasniva se na individualnom pristupu svakom klijentu i pronalaženje najoptimalnijeg rešenja za njegove transportne i logističke potrebe.

Koristeći inovativne tehnike i kvalitetan građevinski materijal iz sopstvenih resursa, spremni smo da odgovorimo na mnoge zahteve naših klijenata iz oblasti niskogradnje.

Naša kompanija u oblasti visokogradnje primenjuje sistem prefabrikovnih betonskih elemenata koji u odnosu na klasičnu gradnju ima brojne prednosti.

Usluge građevinskom mehanizacijom vršimo tehnički ispravnim mašinama, sa potrebnim sertifikatima kako za rukovaoce građevinskim mašinama tako i za same mašine.

Osnovna prednost prefabrikovane konstrukcije jeste brzina kojom konstrukcija može biti projektovana, proizvedena, transportovana i namontirana.

Prednapregnute šuplje ploče su konstruktivni elementi visokog kvaliteta, proizvedeni u fabrički kontrolisanim uslovima.

Raspolažemo opremom i mašinama za sve zemljane radove, kipere i dampere za rad u teškim terenskim uslovima, automiksere i pumpe za beton, autodizalice, podizne platforme.

Izvodimo hidrograđevinske radove u izgradnji kanalizacionih mreža za odvođenje atmosferskih, otpadnih i upotrebljenih voda, izvođenjem hidrograđevinskih radova u okviru regulacije rečnih tokova, kao i izvođenjem hidrotehničkih objekata.

Izrađujemo betonske "New Jersey profile" koji se u svetu koriste za preusmeravanje saobraćaja i zaštitu pešaka u toku izgradnje puta, kao i Betonblock sistem betonskih blokova.

Sakupljanje i privremeno skladištenje otpada vršimo našim specijalizovanim vozilima i deponujemo na našu lokaciju sa odgovarajućom dozvolom. Kapacitet mašine je 250 t/h građevinskog neopasnog otpada.

Površinski kop udaljen je 35 km od Niša. Savremene drobilice, postrojenje za separaciju i sejalica efikasno usitnjavaju i razdvajaju kamene agregate po veličinama. Tehnički kapacitet trenutne primarne drobilice je 300 t/h.

Uslugu transporta vršimo automikserima, kapaciteta bubnja od 7 m^3 do 10 m^3 betonske mase. Za ugradnju betona posedujemo auto-pumpu za beton, radnog učinka 150 m^3/h, sa dužinom strele od 36 m.

NIŠ
Knjaževačka bb, 18000 Niš - Srbija
+381 18 215 355
office@putinzenjering.com

BEOGRAD
Jugoslovenska 2a, 11250 Beograd – Železnik
+381 11 25 81 111
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