ISSN 2217-8139 (Print)
ISSN 2334-0229 (Online)

UDK: 06.055.2:62-03+620.1+624.001.5(497.1)=861

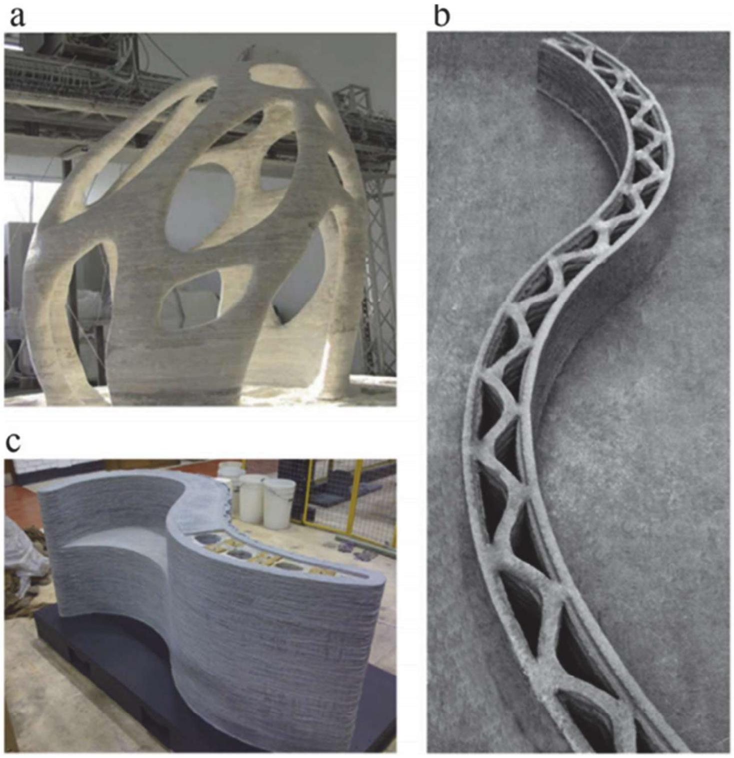
2020.
GODINA
LXIII

GRAĐEVINSKI MATERIJALI I KONSTRUKCIJE

4

BUILDING MATERIALS AND STRUCTURES

ČASOPIS ZA ISTRAŽIVANJA U OBLASTI MATERIJALA I KONSTRUKCIJA
JOURNAL FOR RESEARCH OF MATERIALS AND STRUCTURES



DRUŠTVO ZA ISPITIVANJE I ISTRAŽIVANJE MATERIJALA I KONSTRUKCIJA SRBIJE
SOCIETY FOR MATERIALS AND STRUCTURES TESTING OF SERBIA

ТЕХНИЧАРСКА
ДРУЖИНА
1868 2018

САВЕЗ ИНЖЕЊЕРА И ТЕХНИЧАРА СРБИЈЕ

ПОВЕЉА

Часопис
"Грађевински материјали
и конструкције"
издавач Друштво за грађевинске материјале
и конструкције Србије

ЗА НАЈБОЉУ ПУБЛИКАЦИЈУ
СРБИЈЕ

БЕОГРАД,
02. фебруар 2018.

ПРЕДСЕДНИК
др Игор Марић

DRUŠTVO ZA ISPITIVANJE I ISTRAŽIVANJE MATERIJALA I KONSTRUKCIJA SRBIJE
SOCIETY FOR MATERIALS AND STRUCTURES TESTING OF SERBIA

GRAĐEVINSKI MATERIJALI I KONSTRUKCIJE

BUILDING MATERIALS AND STRUCTURES

ČASOPIS ZA ISTRAŽIVANJA U OBLASTI MATERIJALA I KONSTRUKCIJA
JOURNAL FOR RESEARCH IN THE FIELD OF MATERIALS AND STRUCTURES

INTERNATIONAL EDITORIAL BOARD

Professor **Radomir Folić**, Editor in-Chief
Faculty of Technical Sciences, University of Novi Sad, Serbia
Fakultet tehničkih nauka, Univerzitet u Novom Sadu, Srbija
e-mail:folic@uns.ac.rs

Professor **Mirjana Malešev**, Deputy editor
Faculty of Technical Sciences, University of Novi Sad, Serbia - Fakultet tehničkih nauka, Univerzitet u Novom Sadu, Srbija, e-mail: miram@uns.ac.rs

Dr **Ksenija Janković**
Institute for Testing Materials, Belgrade, Serbia
Institut za ispitivanje materijala, Beograd, Srbija

Dr **Jose Adam, ICITECH**
Department of Construction Engineering, Valencia, Spain.

Dr. Ing. **Anamaria Feier**
Universitatea Politehnica Timișoara
Departamentul Ingineria Materialelor și Fabricației

Professor **Dubravka Bjegović**
University of Zagreb, Faculty of Civil Engineering, Department of Materials, Zagreb, Croatia

Professor **Meri Cvetkovska**
Faculty of Civil Eng. University "St Kiril and Metodij", Skopje, Macedonia

Professor **Michael Forde**
University of Edinburgh, Dep. of Environmental Eng. UK

Dr **Vladimir Gocevski**
Hydro-Quebec, Montreal, Canada

Acad. Professor **Yachko Ivanov**
Bulgarian Academy of Sciences, Sofia, Bulgaria

Dr. Habil. **Miklos M. Ivanyi**
UVATERV, Budapest, Hungary

Professor Asterios Liolios
Democritus University of Thrace, Faculty of Civil Eng., Greece

Professor **Doncho Partov**
University of Construction and Architecture - VSU "LJ.Karavelov" Sofia, Bulgaria

Predrag Popović
Wiss, Janney, Elstner Associates, Northbrook, Illinois, USA.

Professor **Rüdiger Höffer**
Ruhr University of Bochum, Bochum, Germany

Professor **Valeriu Stoin**
Dep. of Civil Eng. „Poloitehnica“ University of Temisoara, Romania

Acad. Professor **Miha Tomaževič**, SNB and CEI, Slovenian Academy of Sciences and Arts,

Professor **Mihailo Trifunac**,Civil Eng. Department University of Southern California, Los Angeles, USA

Sekretar redakcije: **Slavica Živković**, mast.ekon.
Lektori za srpski jezik: Dr **Miloš Zubac**, profesor
Aleksandra Borojev, profesor
Proofreader: Prof. **Jelisaveta Šafranj**, Ph D
Technical editor: Stoja Todorovic, e-mail: saska@imk.grf.bg.ac.rs

PUBLISHER

Society for Materials and Structures Testing of Serbia, 11000 Belgrade, Kneza Milosa 9
Telephone: 381 11/3242-589; e-mail:dimk@ptt.rs, veb sajt: www.dimk.rs

REVIEWERS: All papers were reviewed

KORICE: Tehnologije 3D štampanja: D-shape (a), Contour Crafting (b) i 3D štampanje betona (c)
COVER: 3D printing technologies: "D-shape" (a), Contour Crafting (b) and 3D concrete printing (c)

Štampa/Print: Razvojno istraživački centar grafičkog inženjerstva, Beograd

Publikacija: tromesečno
Edition: quarterly

Financial supports: Ministry of Scientific and Technological Development of the Republic of Serbia

ISSN 2217-8139 (Print)
ISSN 2334-0229 (Online)
GODINA LXIII - 2020.

DRUŠTVO ZA ISPITIVANJE I ISTRAŽIVANJE MATERIJALA I KONSTRUKCIJA SRBIJE
SOCIETY FOR MATERIALS AND STRUCTURES TESTING OF SERBIA

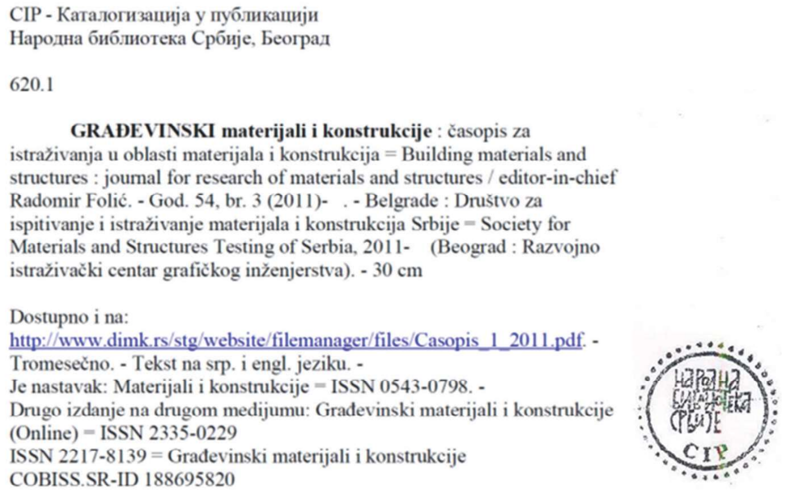
GRAĐEVINSKI MATERIJALI I KONSTRUKCIJE

BUILDING MATERIALS AND STRUCTURES

ČASOPIS ZA ISTRAŽIVANJA U OBLASTI MATERIJALA I KONSTRUKCIJA
JOURNAL FOR RESEARCH IN THE FIELD OF MATERIALS AND STRUCTURES

SADRŽAJ

CONTENTS



CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

620.1

GRAĐEVINSKI materijali i konstrukcije : časopis za istraživanja u oblasti materijala i konstrukcija = Building materials and structures : journal for research of materials and structures / editor-in-chief Radomir Folić. - God. 54, br. 3 (2011)- . - Belgrade : Društvo za ispitivanje i istraživanje materijala i konstrukcija Srbije = Society for Materials and Structures Testing of Serbia, 2011- (Beograd : Razvojno istraživački centar grafičkog inženjerstva). - 30 cm

Dostupno i na:
http://www.dimk.rs/stg/website/filemanager/files/Casopis_1_2011.pdf. -
Tromesečno. - Tekst na srp. i engl. jeziku. -
Je nastavak: Materijali i konstrukcije = ISSN 0543-0798. -
Drugo izdanje na drugom medijumu: Građevinski materijali i konstrukcije (Online) = ISSN 2335-0229
ISSN 2217-8139 = Građevinski materijali i konstrukcije
COBISS.SR-ID 188695820

UVODNIK
EDITORIAL

Ovim brojem časopisa koji predajemo čitaocima, ja završavam njegovo uređivanje započeto s brojem 3–4, davne 2002. godine. U njemu sam zahvalio prethodnom uredniku prof. dr Borislavu Zakiću, dopisnom članu SANU, koji je časopis strpljivo i uspešno uređivao dugi niz godina (1988–2002) savlađujući pri tome mnogobrojne probleme. Poslednjih godina, tražio sam zamenu na mestu glavnog i odgovornog urednika, sa željom podmlađivanja. Tek sada (posle nešto više od 18 godina) pred održavanje Skupštine Društva za istraživanje materijala i konstrukcija (DIMK), održane 7. decembra 2020. godine, stekli su se uslovi za to. Na njoj je doneta odluka da od januara 2021. godine glavni i odgovorni urednik bude dr Snežana Marinković, redovni profesor Građevinskog fakulteta Univerziteta u Beogradu, veoma aktivna na svim poljima rada i stvaralaštva. Zbog toga delim uverenje predlagača da će časopis nastaviti s redovnim publikovanjem i njegovim unapređivanjem.

Na početku, ime časopisa bilo je Materijali i konstrukcije (orijentacija i ime preuzeti od RILEM-ovog časopisa „Materials and Structures”). Ovo ime je promenjeno odlukom Skupštine DIMK-a, od 19. aprila 2011. godine i od tada se objavljuje pod imenom Građevinski materijali i konstrukcije (GMiK). Ova promena je bila uslovljena proceduralnim razlozima, tj. radi praćenja njegove citiranosti, jer su do tada citati pripisivani pomenutom časopisu koji i sada publikuje RILEM. Tada je formiran Međunarodni redakcioni odbor (MRO) sastavljen od uglednih istraživača iz 12 zemalja, što je pospešilo regionalnu i međunarodnu saradnju i doprinelo unapređivanju i ugledu časopisa. Nažalost, dva ugledna profesora i člana Redakcionog odbora (RO) dr Miklos Ivanyi i dr Tom Schanz su preminuli, pa su na upražnjena mesta izabrani novi članovi. S još jednom dopunom u RO zastupljeno je 13 država. Članke recenziraju naučnici iz Srbije i susednih zemalja, a osigurana je tajnost recenzija.

Časopis je od 23. novembra 2014. godine (po Ugovoru sa Centrom za evaluaciju u obrazovanju i nauci – CEON) pretplaćen na ASEESTANT – Servis za uređivanje časopisa, kojim je obezbeđena bolja vidljivost i podrška DOI broja. Iste godine je prijavljen za praćenje citatnog indeksa Tomasa Rojtersa (Science Citation Index by Thomas Routers), uz uslov redovnog publikovanja. U 2016. godini časopis je uvršten u Emerging Sources Citation Index list što je detaljno dato u Izveštaju uz ovaj broj. Našem časopisu je Savez

With this issue of the Journal that we are handing out to our readers, I am finishing its editing, which started with issue 3-4, back in 2002. Then, I thanked the previous editor, prof. Borislav Zakić, Ph.D. a corresponding member of SANU, who patiently and successfully edited the Journal for many years (1988–2002), overcoming numerous problems. In recent years, I have been looking for a replacement as editor-in-chief, with a desire to rejuvenate. Only now (after more than 18 years) before the Assembly of the Society for Research of Materials and Structures (DIMK), held on December 7, 2020, the conditions for that have been met. It was decided that from January 2021, the editor-in-chief will be prof. Snežana Marinković, Ph.D. a full professor at the Faculty of Civil Engineering, University of Belgrade, very active in all fields of work and creativity. Therefore, I share the belief of the proposer that the Journal will continue to be published regularly and improved.

At the beginning, the name of the Journal was Materials and Structures (orientation and name taken from RILEM's journal "Materials and Structures"). This name was changed by the decision of the Assembly of DIMK, from April 19, 2011 and since then it has been published under the name **Building Materials and Structures (BMaS)**. This change was conditioned by procedural reasons, i.e. in order to follow its citations, because until then the citations were attributed to the mentioned journal, which is still published by RILEM. At that time, the International Editorial Board (IRO) was formed, composed of eminent researchers from 12 countries, which fostered regional and international cooperation and contributed to the improvement and reputation of the journal. Unfortunately, two distinguished professors and members of the Editorial Board (RO), Miklos Ivanyi, Ph.D. and Tom Schanz, Ph.D. passed away, so new members were elected to the vacant positions. With another addition, 13 countries are represented in the RO. The articles are reviewed by scientists from Serbia and neighbouring countries, and the secrecy of the reviews is ensured.

The journal has been subscribed to ASEESTANT - Journal Editing Service since November 23, 2014 (according to the Agreement with the Center for Evaluation in Education and Science - CEON), which provides better visibility and support of the DOI number. In the same year, it was reported for monitoring the Science Citation Index by Thomas Routers, provided inženjera i tehničara Srbije 2. februara 2018. godine dodelio Povelju kojom je proglašen za najbolju IT publikaciju te godine. Časopis je menjao status na osnovu kriterijuma za određivanje kategorije naučnih publikacija i dosegao do M24, ali je sada u kategoriji „vodeći nacionalni časopis” kategorije M51.

Period mog uređivanja časopisa pratile su mnoge teškoće vezane za oseku u građevinarstvu i opštu krizu izazvanu tranzicijom, ali smo uspeli da održimo redovno publikovanje, za šta su posebno zaslužni predsednici DIMK-a, profesori dr Mihailo Muravljov, dr Vlastimir Radonjanin, dr Zoran Grdić i dr Dragica Jevtić, na čemu im svesrdno zahvaljujem. Zahvalnost dugujem i sekretarima Društva, pokojnom dipl. inž. Vladimiru Deniću, koji je ovu dužnost obavljao od 2002. do 2011. godine od kada je sekretar dipl. ecc. Slavica Živković. Oni su pravovremeno obavljali sve poslove i bili su mi značajna podrška u radu. Zahvalan sam i većini članova Upravnog odbora DIMK-a za ispoljen interes za časopis i podršku u radu.

Zahvalnost dugujem svim autorima koji su objavljivali svoje radove, članovima RO koji su svojim uglednim imenima, ostvarenim rezultatima i dometima doprineli ugledu i statusu časopisa. Oni su davali korisne sugestije, a neki od njih su se angažovali na pisanju radova i animiranju drugih autora. Na tom planu su se istakli akademik Jačko (Yachko) Ivanov i prof. dr Dončo (Doncho) Partov, obojica iz Bugarske.

Veoma uspešnu saradnju imao sam s lektorima prof. dr Jelisavetom Šafranj i dr Milošem Zupcem, kao i s tehničkim urednikom časopisa Stojom-Saškom Todorović, koje svesrdno preporučujem i koleginici S. Marinković za dalju saradnju.

Novom glavnom i odgovornom uredniku, dr Snežani Marinković, svim članovima Redakcionog odbora i svim budućim saradnicima koji će svoje radove objavljivati u Građevinskim materijalima i konstrukcijama – želim puno uspeha.

Decembra 2020. godine

Glavni i odgovorni urednik
Profesor emeritus dr Radomir Folić

regular publication. In 2016, the journal was included in the Emerging Sources Citation Index list, which is given in details in the Report with that issue. On February 2, 2018, the Association of Engineers and Technicians of Serbia awarded our Journal a Charter which declared it the best IT publication of that year. The journal changed its status based on the criteria for determining the category of scientific publications and reached M24, but now it is in the category of "leading national journal" of the M51 category.

The period of my editing of the Journal was accompanied with many difficulties related to the low tide in construction and the general crisis caused by the transition, but we managed to maintain regular publication, for which the presidents of DIMK are especially credited, professors Mihailo Muravljov, Ph.D., Vlastimir Radonjanin, Ph.D., Zoran Grdić, Ph.D. and Dragica Jevtić, Ph.D. for which I wholeheartedly thank them. I also owe gratitude to the secretaries of the Society, the late Vladimir Denić, B.Sc. eng. who performed this duty from 2002 to 2011, when Slavica Zivković, B.Sc. ecc. has become the secretary. They did all the work on time and were a significant support in my work. I am also grateful to the majority of the members of the Board of Directors of DIMK for their interest in the Journal and support in my work.

I owe gratitude to all the authors who published their research papers, to the members of the RO who contributed to the reputation and status of the Journal with their respectable names, accomplished results and achievements. They gave useful suggestions, and some of them were engaged in writing papers and animating other authors. Academician Jačko (Yachko) Ivanov and prof. Doncho Partov, Ph.D., both from Bulgaria were noticed in that work.

I had a very successful cooperation with the proofreaders prof. Jelisaveta Šafranj, Ph.D. and Miloš Zupac, Ph.D., as well as with the technical editor of the Journal Stoja-Saška Todorović, which I wholeheartedly recommend to my colleague S. Marinković for further cooperation.

I wish a lot of success to the new editor-in-chief, prof. Snežana Marinković, Ph.D., all the members of the Editorial Board and all future associates who will publish their research papers in Building Materials and Structures.

December 2020

Editor-in-Chief
Professor Emeritus Dr.-Ing. Radomir Folić, Dr. h.c.

IZVEŠTAJ O RADU NA UREĐIVANJU ČASOPISA GRAĐEVINSKI MATERIJALI I KONSTRUKCIJE ZA PERIOD OD OKTOBRA 2017. DO KRAJA 2020. GODINE

Oktobra 2017. godine održan je XXVII kongres i Skupština DIMK-a, gde sam u svojstvu glavnog i odgovornog urednika časopisa Građevinski materijali i konstrukcije podneo Izveštaj o radu od oktobra 2014. do oktobra 2017. godine. Taj izveštaj objavljen je u časopisu broj 4 iz 2017. godine. U istom broju časopisa koji je štampan na 68 strana, objavljen je Izveštaj predsednice prof. Dragice Jevtić o radu Društva u periodu 2014–2017. godine i četiri članka-rada. Dva rada su iz inostranstva, a dva su napisali autori iz Srbije. Tri rada su recenzenti ocenili kao originalni naučni rad, a jedan kao prethodno saopštenje. Prvi rad tretira visko-plastičnost i tečenje u poliedarskim ljuskama,a drugi oštećenja nearmiranih zidanih konstrukcija. Upravljanje-održavanje ulica prikazano je na slučaju Kragujevca. Analizirane su prsline u AB gredi armiranoj metalnim vlaknima. U ovom periodu su blagovremeno štampana sva četiri broja kvartalno, tako da nije bilo kašnjenja.

U br**. 1/ 2018.** godine, koji je bio posvećen akademiku Dušanu Miloviću, povodom 150 godina od formiranja Saveza inženjera i tehničara Srbije, publikovano je devet radova, na 186 stranica. Svi radovi su bili iz geotehničkog inženjerstva. Četiri rada su klasifikovana kao originalni naučni rad, dva rada kao stručni, a tri rada iz kategorije pregledni radovi. Analizirana je nosivost šipova na osnovu terenskih i teorijskih metoda. Tečenje se odnosi na veoma stišljiva tla i talog. Opisana je upotreba probnog tunela za prevazilaženje teških terenskih uslova. Upoređeno je vrednovanje peska iz Sofije i Tojoura-Japan triaksijalnim opitom. Analizirani su rezultati nelinearne analize interakcije šip–tlo 2D AB rama. Prikazana je metoda validacije HASP konstitutivnog modela za prekonsolidovane gline. Analizirana je bočna nosivost i pomeranje vertikalnih šipova, bočno opterećenih. Sistematizovane su metode proračuna klizišta. Prikazan je primer zaštite temeljne jame i susednih objekata u urbanoj sredini. U ovom broju, objavljeni su In memoriam za prof. dr Vladimira Simočea sa GF Skoplje, koji je objavljivao radove i u našem časopisu, te In memoriam za člana Redakcionog odbora prof. dr Toma Šanca (Tom Schanz) sa Univerziteta u Bohumu – Nemačka.

U broju **2/2018.** godine štampano je pet radova 84 strane. Od toga jedan rad inostranih autora, a četiri rada autora iz Srbije. Četiri rada su iz kategorije originalni naučni rad, a jedan je pregledni rad. Analizirana je granična nosivost pritisnute grede sa imperfekcijama. Razmatrani su železnički mostovi sa interakcijom mosta i koloseka. Analizirane su poprečne slobodne vibracije prizmatičnih greda opterećenih aksijalnom silom. Prikazan je proračun vitkih AB stubova CFT centrično pritisnutih stubova. Analizirano je vrednovanje tvrdog drveta u građevinarstvu. Umesto pokojnog prof. dr Toma Šanca, od ovog broja je u Redakcioni odbor uključen prof. dr Ridiger Hefer (Rüdiger Höffer) sa Univerziteta u Bohumu – Nemačka.

U broju **3/2018.** godine, sa 83 strane, objavljeno je pet radova, jedan iz inostranstva i tri sa autorima iz Srbije, a u jednom radu sa po jednim autorom iz Srbije i iz inostranstva. Tri rada su iz kategorije stručnih radova, a jedan je originalni naučni rad. Analiziran je razvoj beskonačnih elemenata za simulaciju neograničenih medija. Prikazan je sistem za monitoring Novog drumsko-železničkog mosta u Novom Sadu. Ekonomska analiza pojačanog održavanja primenjena je na jednom primeru puta Ruma–Irig. Procena čvrstoće betona pri pritisku, korišćenjem funkcije zrelosti, prikazana je na jednom konkretnom primeru. Analizirana je mogućnost primene zgure iz visoke peći kao agregata za beton.

Broj **4/2018.** štampan je na 75 stranica. U njemu su objavljena četiri rada. Jedan rad je iz inostranstva, a tri iz Srbije. Sva četiri rada su klasifikovana kao originalni naučni rad. U prvom radu je nelinearna statička nasuprot inkrementalne dinamičke analize okvira sa ispunom sa otvorenom prvom etažom. U drugom su analizirani eksperimentalni rezultati ispitivanja drvenih lepljenih nosača, a u trećem primena numeričkih metoda u analizi spregnutih konstrukcija drvo–beton. Analizirana je elastična kritična sila ploča i limenih nosača pod dejstvom lokalizovanog opterećenja (4. rad). Objavljen je In memoriam za akademika Dušana Milovića.

U časopisu broj **1/2019.** godine, na 70 strana, štampana su četiri rada. Dva rada su iz inostranstva, a dva iz Srbije. Po jedan rad je iz kategorije originalni naučni rad i pregledni rad, a dva rada su klasifikovana kao prethodno saopštenje. Analiziran je raspored ukrućenja, ukrućenje čvorova i veza s krajnjim osloncima čeličnih cevastih lučnih mostova pri projektovanu. Razmatrana je nelinearna seizmička analiza AB okvirnih konstrukcija sa zidnom ispunom. Upoređeno je ponašanje tankih cilindričnih i konusnih ljuski od ugljeničnog i nerđajućeg čelika. Prikazani su rezultati ispitivanja integriteta i nosivosti šipova: metodologija i klasifikacija. U ovom broju objavljena je i Povelja Saveza inženjera i tehničara Srbije, u kojoj je našem časopisu dodeljena Povelja za najbolju

IT publikaciju. Ova povelja dodeljena je 2. februara 2018. godine.

Broj **2/2019.** štampan je na 57 strana, s tri rada. Sva tri rada su klasifikovana kao originalni naučni. U prvom radu analizirana je verovatnoća i determinizam u upravljanju mostovima svetski poznatog eksperta B. Janeva iz Njujorka. U drugom radu tematika je fleksiono izvijanje naknadno termički obrađenih i hladno-oblikovanih stubova elipsastog poprečnog preseka: numerička uporedna analiza. Detaljno je prikazan Interaktivni algoritam za geometrijsko modeliranje dvojno zakrivljenih brana s primenama. Objavljena su i dva In memoriama za akademika Boška Petrovića i prof. dr Sekulu živkovića.

Broj **3/2019.** godine sadrži 70 strana, s četiri rada. Dva rada su iz inostranstva, a dva iz Srbije . Jedan rad je iz kategorije originalni naučni rad, jedan je stručni rad, a dva rada pripadaju kategoriji preglednih radova. U prvom radu razmatra se obezbeđenje lokalne duktilnosti AB elemenata prema Evrokodu 8 – koeficijent utezanja. Rehabilitacija armiranobetonskih (AB) konstrukcija u seizmičkim uslovima korišćenjem tradicionalnih i inovativnih materijala, predmet je drugog rada. Opisane su metode određivanja nosivosti zone ojačanja (vuta) izrađenih od IPE toplo valjanih profila. Prikazano je ispitivanje integriteta šipova testiranjem i analizom rezultata. U ovom broju objavljen je In memoriam za akademika Nikolu Hajdina.

U broju **4/2019.** godine štampana su četiri rada na 54 strane. Tri rada su iz inostranstva, a jedan iz Srbije. Sva četiri rada su klasifikovana kao originalni naučni radovi. Nelinearna analiza okvirnog AB mosta fundiranog na plitkim temeljima i na šipovima predmet je prvog rada. Prikazana je i komparativna analiza modela interakcije tla i lučnog mosta sa zemljanom ispunom, zasnovanih na MKE, a u drugom radu jedinjenja za sprečavanje korozije i za povećanje trajnosti prethodno izolovanih cevi. Analizirana je numerička simulacija ponašanja uzoraka od lakoagregatnog betona u slučajevima laboratorijskog ispitivanja.

Broj **1/2020.** godine sadrži 45 strana, s četiri rada. Dva su iz inostranstva i dva iz Srbije. Tri rada su klasifikovani kao originalni naučni radovi, a jedan rad kao stručni. Prvi rad je naslovljen: o multivalnom elasto-dinamičkom kvadri-lateralnom beskonačnom elementu za obuhvatanje interakcije konstrukcije i tla s primerima. Analizirano je pojačanje temeljne ploče postojeće AB zgrade primenom džet-grouting metode (mlazno injektiranje). Prikazana je, detaljno, izgradnja drumskog mosta preko reke Save kod Ostružnice. Zavisnost sila zatezanja membranskih konstrukcija od različitih parametara pod dejstvom koncentrisane sile analizirana je iz praktičnog aspekta.

U broju **2/2020.** godine štampana su tri rada na 69 strana. Jedan rad je iz inostranstva, a dva su iz Srbije. Dva rada su klasifikovana kao originalni naučni, a jedan kao pregledni. Aktuelni problemi čeličnih mostova, kao što je procena zamora saniranih šavova, predmet su prvog rada. Prikazana je obimna analiza oštećenja fasada zgrada lakog montažnog sistema nakon dugogodišnje eksploatacije. Opširno je prikazan istorijat razvoja graditeljstva iz aspekta zaštite od zemljotresa s naglaskom na objekte graditeljskog nasleđa. Analizirani su primeri iz različitih epoha.

Broj **3/2020.** godine štampan je na 37 strana i sadrži tri rada. Dva rada su iz inostranstva, a u trećem je jedan autor iz Srbije, a drugi iz Bugarske. Dva rada su iz kategorije originalni naučni rad, a treći je pregledni rad. Slično radu objavljenom u broju 2, rad A. Tesra tretira zamor šavova za sanaciju čeličnih mostova, uz analizu vrednih eksperimentalnih rezultata. Autori iz Indije su na osnovu obimnih eksperimenata pokazali vredenovanje pepela od ljuske jajeta kao potencijalne zamene kreča u stabilizaciji ekspanzivnih zemljišta/tla. Predmet trećeg rada je uporedna analiza nekih sistema za upravljanje mostovima. U njemu je kritički analizirano mnoštvo sistema BMS-a uz formulisanje niza preporuka.

U broju **4/2020.** godine, bilo je 120 strana, s četiri rada iz inostranstva, a u dva rada autori su iz Srbije. Tri rada su klasifikovana kao originalni naučni radovi, a po jedan kao pregledni rad i jedan je prethodno saopštenje. U prvom radu je sprovedena detaljna numerička analiza armiranobetonskih okvirnih zgrada sa izolovanom zidanom ispunom. Numeričko i eksperimentalno ispitivanje bilo je osnova za određivanje opterećenja vetra na sklopove fotonaponske ploče. Razmatrani su i specifični aspekti projektovanja rehabilitacije i seizmičke procene pešačkog mosta koji se tretira kao graditeljsko nasleđe. Na osnovu eksperimentalnih rezultata prikazan je metod predviđanja mehaničke čvrstoće betona ojačanog polipropilenskim vlaknima za korišćenje veštačkih neuronskih mreža. Prikazana je uporedna analiza ponašanja betonskih greda armiranih šipkama i tekstilom, zasnovana na eksperimentalnim istraživanjima. Pregled osnovnih svojstava trodimenzionalnog (3D) štampanog betona u svežem stanju, štampanog procesom ekstrudiranja, korišćen je da bi se objasnila specifična svojstva ove tehnologije građenja. Pored navedenih radova objavljena su dva In memoriama – za prof. dr Vladimira Kristeka, sa Univerziteta u Pragu, koji je nedavno publikovao rad u našem časopisu i za dipl. inž. Vladimira Denića, dugogodišnjeg sekretara DIMK-a.

Tematika objavljenih radova, u periodu na koji se ovaj izveštaj odnosi, obuhvatila je eksperimentalna ispitivanja građevinskih materijala, pretežno konstrukcijskih i proučavanje njihovih svojstava i nekih primena. Obuhvaćena je i reologija različitih materijala, tla i betona, zemljotresno inženjerstvo, geotehnički problemi, održivi razvoj, intervencije na konstrukcijama uz primenu savremenih materijala, zaštita graditeljskog nasleđa i drugi problemi u vezi s građevinskim materijalima i konstrukcijama. Svi objavljeni radovi imali su po dve pozitivne recenzije. Veći broj radova je klasifikovan kao originalni naučni rad, a manje ih je klasifikovano kao stručni rad, pregledni rad i prethodno saopštenje.

Pored toga, vredno je pomenuti da smo ličnim kontaktima i kontaktima dva člana Redakcionog odbora (J. Ivanov, i naročito D. Partov iz Bugarske) postigli da odziv kolega iz susednih zemalja bude zadovoljavajući, što se iz navedenog prikaza može sagledati. Nedavno su počeli da pristižu radovi iz inostranstva, putem sajta, ali neki od njih su posle negativnih recenzija morali biti odbijeni, iako je „ponuda” radova skromna.

Prilikom uređivanja časopisa, sretao sam se s problemom nedostatka radova jer naši autori malo pišu, a oni koji pišu – orijentisani su na časopise koji su na Sci listi. Nažalost, **autori retko citiraju naš časopis** pa ga to dovodi u podređen položaj i umesto napretka, prošle godine je lošije ocenjen. U više navrata inovirali smo

Uputstvo – smernice (Guidelines) za autore, pa smo 2017. godine iz pomenutih razloga, pored polja građevinarstva uveli i slične discipline (geodezija i arhitektura). Na svakom Kongresu DIMK-a insistirali smo na većoj citiranosti, ali se stanje nije popravilo. Pored problema sa autorima, teškoće predstavljaju i recenzenti, jer se to obavlja volonterski, i veoma često kasne, a neki profesori s fakulteta gde imam manji uticaj ne odgovore ni posle nekoliko meseci. To usporava publikovanje i obeshrabruje autore. Nažalost, skoro redovno nastavnici fakulteta šalju radove pred izbore, kada im je važno objaviti rad u najkraćem roku, a kasnije gube interes, što nije dobro.

Društvo je 23. novembra 2014. godine sklopilo ugovor s Centrom za evaluaciju u obrazovanju i nauci, koji zastupa prof. dr Pero Šipka, a u vezi s korišćenjem servisa Assistant za elektronsko uređivanje časopisa Građevinski materijali i konstrukcije. Osnovni cilj pokretanja servisa jeste unapređivanje efikasnosti rada uredništva, poboljšanje kvaliteta i regularnosti recenzentskog postupka, zaštita od objavljivanja duplikata ili plagiranih radova, poboljšanje opremljenosti radova i – na osnovu svega toga – poboljšanje kvaliteta i uticajnosti časopisa, a time i baze SCI indeksa – Srpski citatni indeks u celini. Zahvaljujući ovoj podršci, očekuje se i internacionalizacija radova, časopisa i baze, uključujući napredak u poštovanju međunarodnih etičkih i publicističkih normi.

O vrednovanju časopisa

Od 2013. godine, časopis se odlukom Matičnog odbora Ministarstva za obrazovanje, nauku i tehnološki razvoj, vrednuje kategorijom M24=3 poena, sve do 2019. godine. Časopis je od 2014. godine prijavljen za praćenje kod Thomson Routers-a pa je to uslovljavalo da sveske časopisa (četiri godišnje) ne smeju kasniti s publikovanjem, do kraja svakog kvartala za odgovarajuće sveske (1 do 4). To je i pored problema u kojima smo radili – uspešno ispunjeno.

U 2016. godini, naš časopis je uvršten u Emerging Sources Citation Index list i vodi se pod slovom G kao Gradevinski (sa d umesto đ) ali je naslov na engleskom adekvatan – Building Materials and Structures. Sajt na kome je lista **Emergin sources citation index je**: http://ip-science.thomsonreuters.com/mjl/?utm_source=false&utm_medium=false&utm_campaign=false; Journal Gradevinski materijali i konstrukcije – Building materials and structures, Quarterly ISSN: 2217-8139; SOC MATERIALS & STRUCTURES TESTING SERBIA. I dalje je na istoj listi i adresi, što ga svrstava u internacionalne časopise. Kada se otvori Web of Science Master Journal List-WoS MJL by Clavirate, ukuca se Građevinski materijali i konstrukcije, ne Građevinski. Dobijaju se podaci o njemu. To je šansa da bude vidljiv. Javljao sam da se ovo Gredevinski popravi u Građevinski i da pored ISSN 2217-8139 uvedu i broj za on line, tj. ISSN 2334-0229 (Online). To ostaje zadatak i novom glavnom uredniku, da im ponovo piše.

Za 2019. godinu imali smo problema s vrednovanjem. Umesto CEONA koji je to radio veoma profesionalno, pojavio se Matematički institut (koji je angažovalo Ministarstvo) i već marta meseca (a CEON i drugi ne mogu da završe vrednovanja do juna meseca i vrednovan je kao M52) oni daju klasifikaciju M53, posle koje ju je Matični odbor podigao za jedan nivo na M52, a da je uvaženo vrednovanje CEON-a, bio bi M51 kao i FACTA. Već sledeće godine, kada sam u julu imao uvid u vrednovanje CEON-a, naš časopis je dobio kategoriju M51 kao i Spacium i Arhitektura i urbanizam i njima je shodno prošloj godini ostalo M42 (što je dobro za ovu struku), a nas su **ostavili na M51 vodeći nacionalni časopis**. Lično sam pokušao u dva navrata s M. Nikolić, zaduženom za vrednovanje, pisao u tri navrata (slao neke podatke o citiranosti, uključio i jedan rad sa Sci liste), ali uzaludno jer je ona tražila da nađem citate i da ih joj dostavim pa će ih uvažiti. Nisam imao vremena za to, jer bih morao da radim manuelno budući da nije bilo pretraživača. Ostaje da budemo aktivni i da se izborimo za povoljnije vrednovanje. Ipak, najveći problem su autori koji nemaju naviku – da ne kažem neku tešku reč – „kulturu citiranja". Ostaje da se zajedno sa autorima i recenzentima borimo za što veću citiranost našeg časopisa.

Pri uređivanju, podršku i pomoć mi je pružala predsednica DIMK-a prof. dr Dragica Jevtić, a imao sam veliku pomoć i veoma uspešnu saradnju s lektorima prof. dr Jelisavetom Šafranj, dr Milošem Zupcem, tehničkim urednikom časopisa Stojom-Saškom Todorović i sekretarom Društva i Redakcionog odbora Slavicom Živković, na čemu im srdačno zahvaljujem.

Decembra 2020. godine

Glavni i odgovorni urednik
Profesor emeritus dr Radomir Folić

IZVEŠTAJ O RADU DIMK SRBIJE OD 2017. DO 2020. GODINE

U 2017. godini najznačajnija aktivnost Društva je organizovanje XXVII Kongresa i Međunarodnog simpozijuma o istraživanjima i primeni savremenih dostignuća u građevinarstvu u oblasti materijala i konstrukcija. Skup je održan u hotelu ,,Srbija" u Vršcu, od 18.10.2017. do 20.10.2017. godine pod pokroviteljstvom Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije, u saradnji sa Institutom za ispitivanje materijala AD Beograd. Uočen je značajan napredak u istraživanju, koji je postignut u vremenskom periodu od prošlog Kongresa, pre svega zbog nove opreme koju su u prethodnom periodu dobile laboratorije – na taj način je u mnogim radovima zastupljena mikrostruktura materijala primenom savremenih metoda ispitivanja. Vidljivo je osvajanje novih metoda i tehnologija ispitivanja materijala, proisteklih iz međunarodnih i nacionalnih projekata. Takođe je zaključeno da učešće u međunarodnim i nacionalnim projektima, kao i novi uslovi za izbore u viša zvanja na univerzitetima u zemlji i okruženju, daju značajan napredak u procesu istraživanja. S obzirom na savremenu i aktuelnu problematiku održivog razvoja, to jest održivog graditeljstva i na količine i problem postojanja otpadnih materijala u Srbiji, prikazanih u velikom broju radova, zaključak je da ova oblast zbog svoje važnosti treba da i dalje bude predmet interesovanja i istraživanja stručnjaka i naučnika. Značajan zaključak je da treba obezbediti racionalno i održivo upravljanje otpadom na nivou Republike Srbije. Posebno važan zaključak koji se može izvesti jeste da Republika Srbija u polju naučnih oblasti koje su na ovom simpozijumu obrađene, ne kasni s naučnim dostignućima već ide u korak sa zemljama u svom okruženju, što je i najveći značaj ovog kongresa. Izveštaj o časopisu „Građevinski materijali i konstrukcije" takođe je štampan u broju 4. Konstatovan je uspešan rad na uređivanju i izdavanju časopisa u prethodnoj godini. Od 2018. godine, časopis je – zahvaljujući dr Zagorki Radojević na finansijskoj pomoći – dobio i svoj sajt koji će obezbediti bolju vidljivost, što je od presudne važnosti za dalje napredovanje.

Planom rada za 2018. godinu Društva za ispitivanje i istraživanje materijala i konstrukcija Srbije nije predviđena organizacija stručnih skupova tako da je osnovna aktivnost bila da se obezbedi finansiranje časopisa „Građevinski materijali i konstrukcije". Zahvaljujući sponzorima koji su se oglašavali u časopisu i doprinosu za sufinansiranje časopisa koje su nastavili da uplaćuju Građevinski fakultet iz Beograda, FTN iz Novog Sada i IMS Beograd, ispoštovana je kvartalnost u izdavanju časopisa. Ministarstvo prosvete, nauke i tehnološkog razvoja podržalo je sufinansiranje časopisa sa 300.000 dinara. Predsednica je zahvalila članovima upravnog odbora koji su obezbedili sponzore i apelovala da se i u narednom periodu nastavi s radom na stvaranju stabilnih uslova finansiranja u smislu potvrđivanja sponzorstva i za ovu godinu, s obzirom na to što su pozivna pisma upućena svima.

U septembru 2018. godine, na 8. Kongresu Udruženja savremene industrije glinenih proizvoda Srbije, Društvu za ispitivanje i istraživanje materijala i konstrukcija Srbije dodeljena je Povelja u znak zahvalnosti za uspešnu saradnju, a povodom 50 godina postojanja Udruženja SIGP. Takođe, u prethodnoj godini, Savez inženjera i tehničara Srbije dodelio je Povelju časopisu „Građevinski materijali i konstrukcije" za najbolju IT publikaciju Srbije.

Na sastancima Upravnog odbora i Skupštine naglašavan je problem citiranosti časopisa „Građevinski materijali i konstrukcije", koji traje već duže i organi upravljanja Društva su upoznati sa ranijom odlukom Matičnog odbora da će ukoliko se citiranost ne uveća – časopis biti nepovoljnije vrednovan. U tom slučaju, nema više motiva da se finasira i izdaje takav časopis, te se svi napori moraju usmeriti u narednoj godini ka uvećanju broja citata.

U izveštaju o časopisu „Građevinski materijali i konstrukcije", prof. dr Radomir Folić istakao je da su u prethodnoj godini izdata četiri broja sa ukupno 23 rada, a poseban akcenat je na broju 1 koji je bio posvećen akademiku Miloviću, gde je štampano devet radova vrhunskih stručnjaka iz oblasti geotehnike. Kao veliki problem istakao je recenzente i komunikaciju koja oduzima dosta vremena, a problematična je motivacija recenzenata. Društvo je finansiralo časopis zahvaljujući sredstvima od sponzora i doprinosima za sufinasiranje časopisa, kao i podršci Ministarstva prosvete, nauke i tehnološkog razvoja. Jedini trošak koji Društvo ima u vezi je s časopisom, održavanje, struju i grejanje a knjigovođu plaća Udruženje SIGP na ime zakupa. U junu 2018. godine uvećani su honorari za Glavnog i odgovornog urednika, lektore i tehničkog urednika za 30%, honorar za tehničkog sekretara se nije menjao i nije isplaćen za drugu polovinu 2018. godine. To je bio jedini način da se obezbedi nesmetano finansijsko poslovanje. Predlogom finansijskog plana predviđena su sredstva od sponzora, ali sredstva koja bi bila eventualno obezbeđena na ime Stručnog skupa koji se planira za april nisu ušla u plan, s obzirom na to što još uvek nisu utvrđeni detalji. Predlog finansijskog plana je realan i ukoliko se članovi upravnog odbora budu angažovali kao i u prethodnoj godini, moguće je obezbediti sredstva za redovno finansijsko poslovanje u 2019. godini. Iznos članarina nije se menjao – kolektivne 20.000 dinara, a individualne 2000 dinara godišnje. Za fakultete se iznos članarine uvećava budući da više nisu u mogućnosti da uplaćuju sredstva za sufinansiranje časopisa, te će se zbog novih finansijskih propisa taj iznos uplaćivati kroz članarinu – 50.000 dinara za časopis i 20.000 dinara članarina, ukupno 70.000. Ova odluka se nije menjala do danas.

U aprilu mesecu 2019. godine, održan je jednodnevni stručni skup u IMS-u pod nazivom „Nove tendencije u proizvodnji i kontroli kvaliteta betona". U konsultacijama između članova Upravnog odbora, definisan je naziv skupa, kao i predlog tema:

1.Ocenjivanje in-situ čvrstoće pri pritisku betona ugrađenog u konstrukcije i prefabrikovane betonske elemente prema odredbama standarda SRPS EN 13791, prof.dr Zoran Grdić, Građevinsko-arhitektonski fakultet Niš;

2. Metode za ocenjivanje čvrstoće pri pritisku betona in-situ prema odredbama serije standarda SRPS EN 12504, docent dr Nenad Ristić, Građevinsko-arhitektonski fakultet Niš;

3. Ispitivanje betonskih prefabrikovanih elemenata prema EN standardima, dr Ksenija Janković, Institut IMS Beograd;

4. Sertifikacija fabričke kontrole proizvodnje betona u skladu sa SRPS EN 206, dr Biljana Ilić, Institut IMS Beograd;

6. Sanacija i zaštita betonskih konstrukcija u skladu sa evropskim standardom EN 1504, prof. dr Vlastimir Radonjanin, prof. dr Mirjana Malešev, Fakultet tehničkih nauka Novi Sad;

7. Projektovanje betonskih konstrukcija – stanje i perspektive, prof. dr Radomir Folić, i prof. dr Zoran Brujić, Fakultet tehničkih nauka Novi Sad;

8. Metode ispitivanja svežeg betona prema odredbama serije standarda SRPS EN12350, prof. dr Dragica Jevtić, v. prof. dr Dimitrije Zakić, doc dr Aleksandar Savić, doc dr Aleksandar Radević, Marina Aškrabić, mast. inž. građ.,Univerzitet u Beogradu, Građevinski fakultet;

9. Metode ispitivanja očvrslog betona prema odredbama serije standarda SRPS EN12390, prof. dr Dragica Jevtić, v. prof. dr Dimitrije Zakić, doc. dr Aleksandar Savić, doc. dr Aleksandar Radević, Marina Aškrabić, mast. inž. građ., Univerzitet u Beogradu, Građevinski fakultet.

Profesor Grdić je tada predložio da se isti skup održi i na Građevinsko-arhitektonskom fakultetu u Nišu početkom septembra, gde bi polaznici popunili određene upitnike – ispitna pitanja, na osnovu kojih će dobiti uverenja o stečenom znanju. Dr Dragan Bojović predložio je da se uključe i sponzori i predvidi vreme i za njihova izlaganja za šta bi, naravno, platili određen iznos, što bi doprinelo uspešnijoj finansijskoj realizaciji skupa.

Skup u IMS-u bio je izuzetno posećen i doneo je Društvu značajna finansijska sredstva koja su omogućila rad i izdavanje časopisa. Drugi deo skupa održan je u Nišu s nešto pomerenim rokom, u februaru 2020. godine, sa istim temama. I ovaj skup je bio veoma lepo organizovan, s dosta učesnika i spozora. Društvo je izdalo 160 sertifikata o učešću za sve prisutne koji su ispunili uslove.

Kongres i Međunarodni simpozijum o savremenim tendencijama u ispitivanju i istraživanju materijala i konstrukcija nije bilo moguće realizovati u toku 2020. godine, tačnije kako je planirano, u oktobru ove godine, zbog pandemije.

Plan rada Društva za narednu godinu nije moguće jasno definisati zbog vanrednih okolnosti izazvanih pandemijom. Simpozijum bi trebalo planirati za 2021. godinu ukoliko uslovi takve skupove budu dozvoljavali, prvenstveno zbog mera Vlade Republike Srbije. Ono što se sa sigurnošću može planirati jeste publikovanje časopisa „Građevinski materijali i konstrukcije" i zajednički rad svih članova upravnog odbora na obezbeđivanju sredstava za njegovo redovno izlaženje. Vrlo je važno da se i dalje radi na obezbeđivanju sponzora, jer je to jedini siguran izvor finansiranja, s obzirom na to što skupove ne možemo planirati.

U Beogradu, 4.12.2020.

Predsednik DIMK Srbije
Prof. dr Dragica Jevtić

NUMERIČKA ANALIZA ARMIRANOBETONSKIH OKVIRNIH ZGRADA SA IZOLOVANOM ZIDANOM ISPUNOM

NUMERICAL ANALYSIS OF REINFORCED CONCRETE FRAME BUILDINGS WITH DECOUPLED INFILL WALLS

Marko MARINKOVIĆ
Santiago FLORES CALVINISTI
Christoph BUTENWEG

ORIGINALNI NAUČNI RAD
ORIGINAL SCIENTIFIC PAPER
UDK:624.012.45
doi:10.5937/GRMK2004013M

1 UVOD

Značajan deo konstrukcija na svetu predstavljaju AB okvirne zgrade sa zidanom ispunom. Jednostavan razlog za to je potreba da se razdvoje prostorije unutar zgrade kao i da se razdvoji unutrašnjost zgrade od spoljašnje sredine. Pored toga, zidana ispuna je pokazala dobre performanse i trajnost u pogledu zvučne izolacije, vlage i požara kao i dobre termičke karakteristike. Zbog svega navedenog, upotreba zidane ispune u AB okvirnim zgradama česta je u mnogim zemljama, kao i u seizmički aktivnim oblastima. Međutim, kada su izložene dejstvu zemljotresa, AB okvirne zgrade sa zidanom ispunom pokazale su loše ponašanje, često praćeno značajnim oštećenjima zidane ispune. Ovo je potvrđeno u brojnim izveštajima koji prikazuju oštećenja AB okvirnih zgrada sa ispunom usled skorašnjih zemljotresa u: L'Aquila (Italija) 2009. godine [1], Lorca (Španija) 2011. godine [2], Van (Turska) 2011. godine [3] i Centralna Italija 2016. godine [4]. Velika i rasprostranjena oštećenja zidane ispune praćena kolapsima celih zidanih panela na nižim spratovima zgrada (slika 1a) prikazana su u izveštaju [5]

1 INTRODUCTION

Significant portion of structures in the world goes to RC frame buildings with the masonry infill walls. The simple reason for that is need for separating space inside the building and between internal space of buildings and external environment. Furthermore, masonry infills demonstrated reasonable performance and durability with respect to noise, moisture and fire as well as good heat and sound insulation properties. Due to this, the use of masonry infill walls in RC frame buildings is common in many countries, as well as in the seismic active regions too. However, when subjected to an earthquake excitation, masonry infilled RC frame buildings behave rather poor experiencing very often severe damage of infill walls. This is confirmed with several reports presenting damage to RC frame buildings with masonry infill walls during the recent earthquake events in L'Aquila (Italy) in 2009 [1], in Lorca (Spain) in 2011 [2], in Van (Turkey) in 2011 [3] and Central Italy in 2016 [4]. Heavy and widespread damage of masonry infills with the collapse of infill panels at the lower stories of the buildings

---

Marko Marinkovic, docent, dr, Katedra za tehničku mehanikku i teoriju konstrukcije, Univerzitet u Beogradu Građevinski fakultet, Bulevar kralja Aleksandra 73, 11000 Beograd, Srbija. (E-mail address: mmarinkovic@grf.bg.ac.rs)
Santiago Flores Calvinisti, Master student, Politecnico Di Milano, School of Civil, Environmental and Land Management Engineering, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy.
(E-mail address:santiago.flores@mail.polimi.it)
Christoph Butenweg, Full Professor, CWE – Center for Wind and Earthquake Engineering, RWTH Aachen University, Mies-van-der Rohe-Straße 1, 52074 Aachen, Germany. (E-mail address: butenweg@lbb.rwth-aachen.de)

Marko Marinkovic, Assistant Professor, Department of engineering mechanics and theory of structures, Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia. (E-mail address: mmarinkovic@grf.bg.ac.rs)
Santiago Flores Calvinisti, Master student, Politecnico Di Milano, School of Civil, Environmental and Land Management Engineering, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy.
(E-mail address: santiago.flores@mail.polimi.it)
Christoph Butenweg, Full Professor, CWE – Center for Wind and Earthquake Engineering, RWTH Aachen University, Mies-van-der Rohe-Straße 1, 52074 Aachen, Germany. (E-mail address: butenweg@lbb.rwth-aachen.de)

o poslednjem zemljotresu koji se dogodio u Albaniji u novembru 2019. godine. Brojne studije su pokazale da oštećenja zidane ispune predstavljaju značajan deo ukupnih troškova i gubitaka AB zgrada usled zemljotresa [6,7].

(Figure 1a) during the recent earthquake in Albania, was reported in [5]. Studies showed that damage of infill walls considerably affects overall seismic losses of RC buildings [6,7].

a) b)

Slika 1. Novembarski zemljotres 2019. u Albaniji: a) kolaps zidova ispune; b) pojava „fleksibilnog prizemlja" AB okvirne konstrukcije sa zidanom ispunom [5]

Figure 1. November 2019 earthquake in Albania: a) failure of masonry infill walls and b) soft storey collapse of RC frame building with masonry infills [5]

Jedan od razloga za tako loše ponašanje jeste činjenica da zidana ispuna značajno povećava krutost AB okvirne zgrade i time menja njene dinamičke karakteristike. Međutim, ovo nije uzeto u obzir u svakodnevnoj inženjerskoj praksi. Umesto toga, zidana ispuna se smatra nekonstruktivnim elementom. Zapažanja nakon zemljotresa u Nepalu, koji se dogodio 25.4.2015. godine, pokazuju da je zidana ispuna dovela do značajnog povećanja krutosti koja je uticala na sopstvene frekvencije konstrukcije [8]. Takođe, dinamički odgovor oštećene dvospratne AB okvirne zgrade, koji potvrđuje doprinos zidane ispune horizontalnoj nosivosti konstrukcije, ispitivan je u [9] uz to da je potencijalno oštećenje zidane ispune moglo da se odredi korišćenjem sofisticiranih numeričkih modela. Nekoliko autora [10–12] bavilo se istraživanjem promene perioda konstrukcije usled prisustva ispune. U zavisnosti od predominantnog perioda zemljotresa, smanjenje perioda konstrukcije usled ispune može dovesti do povećanja ili smanjenja očekivanog nivoa seizmičkog opterećenja.

Za vreme zemljotresa, zidovi ispune su izloženi dejstvu opterećenja u ravni, koje se javlja usled deformacije okvira. Visoko deformabilni AB okviri dovode do krtog odgovora krute ispune, što uzrokuje značajna oštećenja. Ponašanje zidane ispune pri takvom opterećenju istraživali su mnogi [13–17]. Pored opterećenja u ravni, ispuna je izložena i opterećenju upravno na ravan zida forces, koje se javlja usled ubrzanja i same mase zida. Optrećenje van ravni zida deluje upravno ne njegovu ravan i ponašanje ispune pri ovakvim uslovima, između ostalih, ispitivali su autori [18–20]. Sveobuhvatni pregled literature u vezi sa

One of the reasons for such a poor behaviour is that infill walls significantly increase the stiffness of RC frame buildings and thus change their dynamic characteristics. However, in everyday design this is not taken into account. Instead, infills are considered as non-structural elements. Field observation after the April 25th earthquake in Nepal showed that infills produced significant increase of stiffness that influenced the natural frequencies of the structure [8]. In addition, dynamic response of a damaged two-story infilled RC building confirming contribution of the infills to the lateral resistance of this structure was investigated in [9] adding that the potential damage in the infills should be accounted with the use of sophisticated numerical models. Several researchers [10-12] investigated change of period of structure due to the infill presence. Depending on the predominant periods of the earthquake, decrease in the natural period due to infill may produce increase or decrease of the expected seismic response.

During the earthquakes infill walls are subjected to in-plane (IP) loading that comes from the deformation of the frame. High deformable RC frames produce brittle response of stiff masonry infills causing severe damage. Behaviour of infill walls under such conditions was investigated by many researchers [13-17]. Besides in-plane loading, infills are subjected to out-of-plane (OOP) forces coming from the floor accelerations and mass of the wall itself. Out-of-plane load acts perpendicular to the wall panel and the behaviour of infills under these conditions was studied by [18-20], among others. Comprehensive literature review about out-of-plane experimental tests is given in [21], concluding that the eksperimentalnim ispitivanjima ispune na dejstvo opterećenja van ravni dato je u [21], sa zaključkom da kvalitet izvođenja može značajno uticati na ponašanje zida upravno na svoju ravan time što bi se narušili granični uslovi zida. Uticaj interakcije opterećenja u ravni i van ravni zida je prikazan u [22] gde je rečeno da opterećenje u ravni može da dovede do odvajanja ispune od okolnog AB okvira i time spreči razvoj efekta luka bitnog za nosivost van ravni zida. U ovom radu su autori takođe pokazali da okvirna konstrukcija sa zidanom ispunom ima mnogo manja relativna međuspratna pomeranja u poređenju sa okvirnom konstrukcijom, ali kada se interakcija opterećenja u ravni i van ravni uzme u obzir, relativno međuspratno pomeranje konstrukcije sa ispunom bilo je čak veće od okvirne konstrukcije bez ispune. Drugi autori [23–26] takođe su naglasili neophodnost uzimanja u obzir interakcije opterećenja u ravni i van ravni. Samo nekoliko autora [26–28] istraživalo je uticaj istovremenog dejstva opterećenja u ravni i van ravni ispune, iako je očekivano da da u toku zemljotresa oba pravca opterećenja deluju na zid ispune. Eksperimentalna ispitivanja prikazana u [26] pokazala su značajno smanjenje kapaciteta deformacije u ravni i kapaciteta nosivosti van ravni, objašnjavajući da deformacija okvira dovodi do gubitka veze između okvira i ispune i time čini zidanu ispunu ranjivu na opterećenje van ravni.

Ukoliko ispuna nije uzeta u obzir u toku projektovanja kao noseći element, problemi kao što su dodatni uticaji na AB okviru mogu se zanemariti. Najčešći tipovi oštećenja uzrokovani neregularnim rasporedom ispune jesu efekti torzije, fleksibilno prizemlje/sprat i efekat kratkog stuba. Zgrade koje se nalaze na uglu ulice obično nemaju ispunu na strani do ulice a na druge dve ispuna je ozidana, što može dovesti do torzije konstrukcije u toku dejstva zemljotresa koja može biti pogubna za globalno ponašanje zgrade. Kao što je opisano u [29] nejednak raspored zidane ispune može da prouzrokuje globalnu torziju konstrukcije, koja može da dovede do velikih zahteva na stubovima što nije uzeto u obzir u originalnom proračunu. Uticaji nejednakog rasporeda ispune na oštećenja AB zgrada usled zemljotresa ispitani su u [30], uz zaključak da su ovi uticaji manje izraženi kod zgrada s jakim AB zidovima. Rušenje konstrukcije usled torzije i pojave fleksibilnog sprata (slika 1b) mogu da se pojave čak i u slučaju kada Evrokod 8 [31] ne zahteva amplifikaciju seizmičkih uticaja [32]. U [33] zaključeno je da će torzioni uticaji usled nejednakog rasporeda ispune verovatno dovesti do rušenja zidova ispune ispadanjem van ravni.

Uobičajeni problem dispozicije jeste fleksibilni sprat uzrokovan odsustvom zidova ispune ili postojanjem značajno manje zidova ispune na spratu iznad ili ispod. Ovakva konfiguracija javlja se usled funkcionalnih zahteva kao što su radnje i potreba za parking mestima. U [34] pokazano je da čak i kada se koriste zahtevi dati u propisima za ojačanje nosećih elemenata okvira, projektanti moraju modelirati zidanu ispunu i treba da verifikuju da se fleksibilni sprat neće javiti. Uticaji fleksibilnog sprata numerički su ispitivani u [35] primenom 3D modela, dok je u [36] pokazano da čak ni seizmička izolacija ponekad ne može da pomogne u slučaju nejednakog rasporeda ispune i formiranja fleksibilnog sprata, uz zaključak da se značajna oštećenja mogu

workmanship could significantly affect the panel OOP behaviour by disturbing their boundary conditions. The influence of in-plane/out-of-plane interaction was studied in [22] saying that in-plane loading can disable development of out-of-plane arching effect due to the detachment of infill walls from the surrounding RC frames. In this paper authors also show that the frame structure with infill has much lower IP drifts when compared to the bare frame structure, but when IP/OOP interaction is taken into account the drifts with infill walls are even higher than in the case of bare frame structure. Other researchers [23-26] also pointed out the necessity to take into account IP/OOP interaction. Just a few researchers [26-28] studied in-plane and out-of-plane loading acting simultaneously on the infill walls, although it is expected that during the earthquake infills are loaded in both directions. Experimental tests performed and presented in [26]showed high decrease of both in-plane and out-of-plane capacity, explaining that deformation of the frame causes loss of connection between frame and infill, thus making infill walls vulnerable to out-of-plane loads.

If infills are not considered during the design as load carrying elements, problems such as additional demands to the RC frame components can be missed. Most common damage configurations caused by irregular distribution of infill walls are torsion, weak and/or soft stories and short columns. Buildings located on the street corners usually have infill panels on the non-street sides, which can result in a torsional response during an earthquake that might be detrimental to the global performance of the building. As described in [29] the unbalanced distribution of infill walls can introduce global torsion in buildings, which can induce larger demands in columns that were not considered in the original design. Effects of the irregular placement of the infills on the seismic damage of RC buildings was investigated in [30], concluding that these effects are less pronounced for the buildings with strong RC shear walls. Structural failure due to torsion and soft-storey effects may occur even in cases where Eurocode 8 [31] does not require the amplification of the action effects [32]. In [33] it was concluded that torsional effects due to the irregular infill distribution would probably result in failure of the infill wall through out-of-plane collapse.

Very common configuration problem is a weak and/or soft story caused by the absence of infill walls or the presence of many fewer infill walls than the story above and/or below. This configuration appears due to the functional demands such as parking and shops. In [34] it was shown that even when using code provisions for strengthening open-story frame members, designers must model the infill walls and should verify that a weak story will not form. Soft story effect using numerical model on a 3D building was investigated in [35], whereas [36] showed that even base isolation sometimes cannot help with the irregular infill distribution and creation of soft storey effect, concluding that heavy damage is to be expected in the base isolated structures subjected to near-fault earthquakes.

Short column can appear in a case of non-structural partial-height masonry infills that are in a rigid contact with the columns causing high demand that even strong columns cannot take. In [37] it was reported that the presence of the partial height wall decreases the ultimate lateral load capacity of the system by 47%. As solution for očekivati u slučaju seizmički izolovanih konstrukcija koje se nalaze blizu epicentra.

Efekat kratkog stuba može se javiti u slučaju zidane ispune koja nije u punoj visini u kontaktu sa okvirom kada je kontakt sa stubom krt, što ima za posledicu tako visoke zahteve da ih čak i jaki stubovi ne mogu prihvatiti. U [37] prikazano je da je prisustvo zidova koji se ne protežu celom visinom stuba dovelo do pada kapaciteta konstrukcije za 47%. Kao rešenje za efekat kratkog stuba, u [38] predloženo je da se ispuna razdvoji od okvira tako što će se ostaviti prostor između njih. U [39] savetuje se da se efekat kratkog stuba izbegne u toku rada na arhitektonskom konceptu konstrukcije, i dodaje da zidana ispuna u kontaktu sa stubom treba da se izoluje razdvajanjem od okvira.

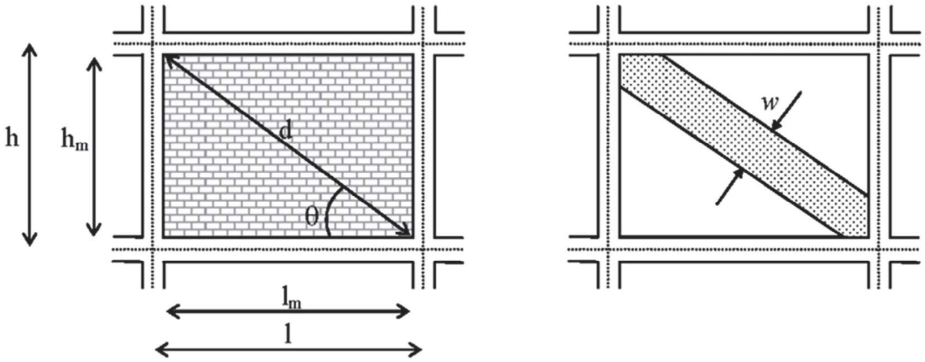
Jedna opcija da se unapredi ponašanje AB okvirnih konstrukcija sa zidanom ispunom jeste da se ispuna modelira u toku projektovanja. Za ovu svrhu najpogodniji je pristup makro modeliranja. Na ovaj način se mogu opisati uticaji zidane ispune na globalno ponašanje AB zgrada u toku zemljotresa. U toku dugog perioda istraživanja ponašanja okvira sa zidanom ispunom, predloženo je više pristupa za makro modeliranje. Upotreba ekvivalentne pritisnute dijagonale, bez sumnje, najviše je prihvaćen i najviše izučavan pristup. Međutim, njena primena nije jednostavna i za sada ne postoji opšti konsenzus oko jedinstvenog pristupa.

Prva istraživanja [40–41] na okvirima sa ispunom bazirana su na konceptu ekvivalentne dijagonale. Navedeni autori pretpostavili su da se ispuna ponaša kao pritisnuta dijagonala, kao što je pokazano na slici 2.

short column, [38] proposed an application of separation gap between infill and frame. In [39] it was suggested that the short column effect should be avoided during the architectural design stage itself adding that the infills in the short column region should be isolated from adjoining columns.

One option to improve the behaviour of masonry infilled RC frame buildings is to model the infills during the design phase. For this purpose the macro-modelling approach is the most convenient. This approach is used to describe the effect of the masonry infill walls to the global seismic behaviour of RC buildings. During the long period of studying the behaviour of infilled frames, there have been different proposals for macro-modelling approach. Using the strut to model the infill is undoubtedly the mostly accepted and the mostly studied approach. However, its application is also a difficult task and so far there is no overall consensus about the unique approach.

First studies [40-41] on infilled frames were based on the equivalent diagonal strut concept. They assumed that the infill wall acts as a diagonal compression strut, as shown in Figure 2.



Slika 2. Pritisnuta dijagonala i ekvivalentna dijagonala [42]
Figure 2. Diagonal compression strut and equivalent strut [42]

Pristupom ekvivalentne dijagonale može se modelirati globalno ponašanje okvira sa ispunom, ali model sa samo jednim elementom po dijagonali ne može da uzme u obzir promenu momenata savijanja i smičućih sila po dužini stuba koja se javlja usled panela ispune [43] i zbog toga je neefikasna u modeliranju kompleksnog ponašanja okvirnih konstrukcija [44]. Kako bi se prevazišlo ovo ograničenje, nekoliko autora [45–47] razvilo je modele s različitom orijentacijom i brojem dijagonalnih elemenata. Kako bi se koristila pritisnuta dijagonala za predstavljanje ispune, karakteristike kao što su širina dijagonale, krutost i veza sila–pomeranje moraju se definisati. Neki autori [29, 41, 48] definisali su širinu dijagonale kao procenat dužine dijagonale, dok su drugi [49–54] zaključili da

The equivalent diagonal strut approach can model the global force-displacement behaviour of the infilled frame, but model of the infill wall with just one single strut element is incapable of properly taking into account the change in the bending moment and shear diagram along the column length due to the presence of the panel [43] and therefore it is ineffective in modelling the complex behaviour of infilled frames as reported in [44]. To overpass this limit, several researchers [45-47] developed models with different orientations and number of struts. In order to use the strut for representing an infill, characteristics such as strut width, stiffness and force-displacement relation have to be defined. Some authors [29, 41, 48] defined the width of the strut as percentage of the diagonal length, whereas efektivna širina dijagonale zavisi od dužine kontakta okvira i ispune i parametra koji uzima u obzir relativni odnos krutosti okvira i ispune, λh, definisan u [55].

Kao što je slučaj sa širinom dijagonale, puno predloga je dato za definisanje nosivosti i određivanje kapaciteta različitih tipova loma ispune. Jednačine za neke od tipova loma ispune u ravni date su u [41, 49, 56], pri čemu su autori smatrali nerelevantnim one tipove loma koji nisu obuhvaćeni. Jedna od bitnih prednosti pristupa predloženog u [51, 52] jeste sposobnost da se pri određivanju nosivosti uzmu u obzir svi tipovi loma. Ovo je takođe predloženo u [57]. Definicija konstitutivnog zakona za pritisnutu dijagonalu neophodna je kako bi se model pritisnute dijagonale implementirao u program za proračun konstrukcija. Tipovi konstitutivnih modela neophodnih da se definiše pritisnuta dijagonala zavise od tipa analize (linearno-elastična ili nelinearna) i od tipa opterećenja (monotono, ciklično ili dinamičko). U [52] među prvima je predložena relacija sila–pomeranje za ekvivalentnu dijagonalu, definišući početnu krutost, granu ojačanja i omekšanja praćenu rezidualnom nosivošću. Slično, u [58] predložena je nelinearna zavisnost sila–pomeranje kako bi se opisao odgovor pritisnute dijagonale. Slična relacija s tri-linearnim odgovorom predložena je u [59, 60]. Kako bi se sprovela dinamička nelinearna analiza, potrebno je definisati histerezisno ponašanje materijala. U literaturi je dato samo par modela histerezisa za definiciju pritisnute dijagonale, zato što je većina istraživanja ispitivala ponašanje zidane ispune pri monotonom opterećenju, ali i zbog činjenice da uzimanje u obzir histerezisnog ponašanja u modelu povećava ne samo kompleksnost već i nepouzdanost modela. Jedan od prvih pokušaja prikazan je u [61], a jedan od najčešće korišćenih modela predložen je u [43, 62]. Nešto skorije, u [63] prikazan je unapređeni histerezisni model predložen prvo u [64] uviđanjem detaljne veze sila–pomeranje koja uzima u obzir ciklično i monotono ponašanje ekvivalentne dijagonale, kalibrisane uz pomoć eksperimentalnih rezultata. Iako eksperimentalna istraživanja pokazuju neophodnost uzimanja u obzir interakcije opterećenja u ravni i van ravni, njeno obuhvatanje u numeričkom modelu izuzetno je kompleksan zadatak koji se trenutno nalazi u početnoj fazi razvijanja i verifikacije.

Druga opcija za unapređivanje ponašanja zidane ispune u AB ovirnim zgradama sa zidanom ispunom jeste da se primene konstruktivne mere na samoj ispuni. Ovo se može uraditi povećanjem nosivosti ispune dodavanjem armature u zidno platno [65, 66] ili primenom maltera armiranih tekstilnim mrežicama [67–69]. Unapređivanje ponašanja ispune podelom zida na horizontalne delove sa specijalnim klizajućim površinama između njih predložilo je nekoliko autora [70–73]. Na ovaj način povećava se deformabilnost zida ispune.

Treća opcija podrazumeva kompletnu izolaciju u ravni ispune u odnosu na okolni okvir, tako da se okviru dozvoli deformacija i time odloži aktivacija ispune. Najjednostavniji način da se razdvoji ispuna od okvira jeste ostavljanjem prostora između njih. A ovaj prostor se može popuniti mekim materijalom [29, 74, 75]. Dodatna korist razdvajanja ispune i okvira jeste smanjenje napona u stubovima usled mekog kontakta okvira i ispune. U ovom pristupu bitno je obezbediti adekvatnu vezu okvira i ispune koja može da prihvati opterećenje van ravni kako se zid ispune ne bi srušio. Za ovu svrhu, veza ispune i

others [49-54] found that effective width is dependent on the length of contact between the infill and the frame and relative panel to frame stiffness parameter, λh, defined by [55].

As it is the case for the width of the strut, many proposals for the strength are given in order to determine the capacities for the various failure modes that infill walls can experience. The equations for some of the in-plane failure modes are given by [41, 49, 56], considering the omitted ones as negligible. One of the important advantages of the approach proposed by [51, 52] for the calculation of strut strength is its ability to account for all failure mechanisms. This was also done by [57]. Definition of constitutive relations for the strut is necessary in order to implement a strut model in software for structural calculations. The types of constitutive models required to set the strut models depend on the type of analysis (linear elastic or nonlinear) and the type of loading (monotonic, cyclic or dynamic).One of the first to propose force-displacement relationship for the equivalent strut defining initial stiffness, hardening and softening branch followed with the residual strength was [52]. Similarly, [58] proposed a nonlinear force-displacement relationship to describe the response of equivalent strut. Similar relation with the tri-linear response for the strut was proposed in [59, 60]. In order to run dynamic nonlinear analysis the hysteretic behaviour of the material must be established. In literature just a few hysteretic models for diagonal strut can be found, because most researchers studied the behaviour of infill masonry under monotonic loading, but also due to the fact that the modelling of hysteretic behaviour increases not only the computational complexity but also the uncertainties of the problem. One of the early attempts was conducted by [61]. One of the most commonly used models was proposed by [43, 62]. More recently, [63] improved the hysteresis law proposed in [64] by introducing a detailed force–displacement law accounting for cyclic or monotonic behaviour of an equivalent strut, calibrated against experimental results. Although, experimental studies show necessity for taking into account in-plane/out-of-plane interaction, incorporating it in the numerical models is highly complex task being at the starting phase of development and verification.

Second option for improvement of the behaviour of masonry infilled RC frame buildings is to apply some construction measures to the infills itself. This can be done by increasing the infill strength with addition of reinforcement to the infill wall [65, 66] or by applying textile reinforced mortars for plastering [67-69]. Improving the behaviour of the infills by subdividing the wall in horizontal sections with special sliding surfaces between them was proposed by several authors [70-73]. In this way deformability of the infill panel is increased.

The third approach considers the complete in-plane isolation of non-structural elements from the surrounding frame, so to allow frame deformation and thus delayed infill activation. The simplest way to separate infill from the frame is by creating the gaps between them. This can be done by filling the gap with soft material [29, 74, 75]. Additional benefit of infill/frame decoupling is reduction of stresses induced to the frame because of the soft contact. Important aspect which should be covered in this approach is adequate out-of-plane restrain to prevent the infill wall to collapse due to the perpendicular loads.

okvira preko čeličnih ankera ispitivana je u [76, 77]. Izolacija ispune takođe je data kao jedno od rešenja u međunarodnim preporukama i propisima [78–80].

Problem je što ima puno pristupa i procedura, koji nisu standardizovani kako bi se primenili u inženjerskoj praksi. Štaviše, mnoga rešenja donose korist ispuni, ali za sada nije predloženo kompletno rešenje koje može da reši probleme ponašanja zidane ispune pri zemljotresnom dejstvu. Nedostaci su razni, od komplikovanih do praktično neprimenjivih rešenja i onih koja nisu efikasna u rešavanju istovremenog dejstva opterećenja u ravni i van ravni. Za neka od njih primena je problematična u smislu ostavljanja mogućnosti i fleksibilnosti za korišćenje prostorija, a neka nisu primenjiva za sve tipove cigli. Jedno od rešenja koje je pokazalo obećavajuće rezultate opisano je u [81]. To je sistem pod imenom INODIS (Innovative Decoupled Infill System) koji omogućava efikasnu izolaciju zida ispune u ravni i time odlaže aktivaciju ispune, čime smanjuje interakciju okvira i ispune i njene neželjene efekte. Zbog osobina i oblika koji pruža vezu koja može da prihvati opterećenje van ravni, ovaj sistem je izabran za detaljnu numeričku analizu prikazanu u ovom radu.

Kako bi se utvrdilo da li je sistem izolacije bolje rešenje u odnosu da tradicionalnu ispunu, niz numeričkih linearnih i nelinearnih analiza je sproveden. Novina ovog rada ogleda se u istraživanju ponašanja AB okvirnih konstrukcija sa izolovanom ispunom na nivou konstrukcije. Slična istraživanja su sprovedena s tradicionalnom ispunom ali nijedno sa izolovanom ispunom. S obzirom na to što INODIS sistem obezbeđuje izolaciju ispune u ravni, time uklanja interakciju opterećenja u ravni i van ravni, kao što je i eksperimentalno prikazano [81]. Stoga, u prikazanim numeričkim analizama uzeto je u obzir samo ponašanje ispune u ravni.

2 SISTEM IZOLACIJE ISPUNE

U ovom poglavlju je ukratko predstavljen sistem INODIS. Njegovi detalji i osobine su detaljno dati u [81, 82]. Osnovna ideja INODIS sistema (slika 3) jeste razdvajanje zidane ispune i AB okvira u ravni ispune u kombinaciji sa njihovom vezom duž ivica panela ispune koja može da prihvati opterećenje van ravni. Cilj ove veze je da poveća kapacitet i u ravni i van ravni putem konstruktivne veze koja omogućava klizanje na kontaktu rama i ispune. INODIS sistem razdvaja zidanu ispunu od AB okvira putem elastomera u obliku latiničkog slova „U" koji je postavljen duž vertikalnih ivica ispune i na vrhu zida ispune. Elastomeri u obliku latiničkog slova „U" projektovani su tako da dozvoljavaju relativno međuspratno pomeranje AB okvira tako da se ne ošteti zidana ispuna.

Osim toga, viskoelastično ponašanje elastomera povećava ukupno prigušenje zgrade. Plastični profili su ekserima ili zavrtnjima vezani za AB okvir dok su elastomeri u obliku latiničkog slova „U" zalepljeni za zid ispune s jedne strane i postavljeni oko plastičnih profila s druge strane (slika 3), sprečavajući time lom van ravni ispune. Flanše „U" elastomera na slici 3 napravljene su od mekog elastomera dok je krući elastomer iskorišćen za rebra „U" profila. Najkrući elastomer postavljen je na dno zida u vidu tri trake.

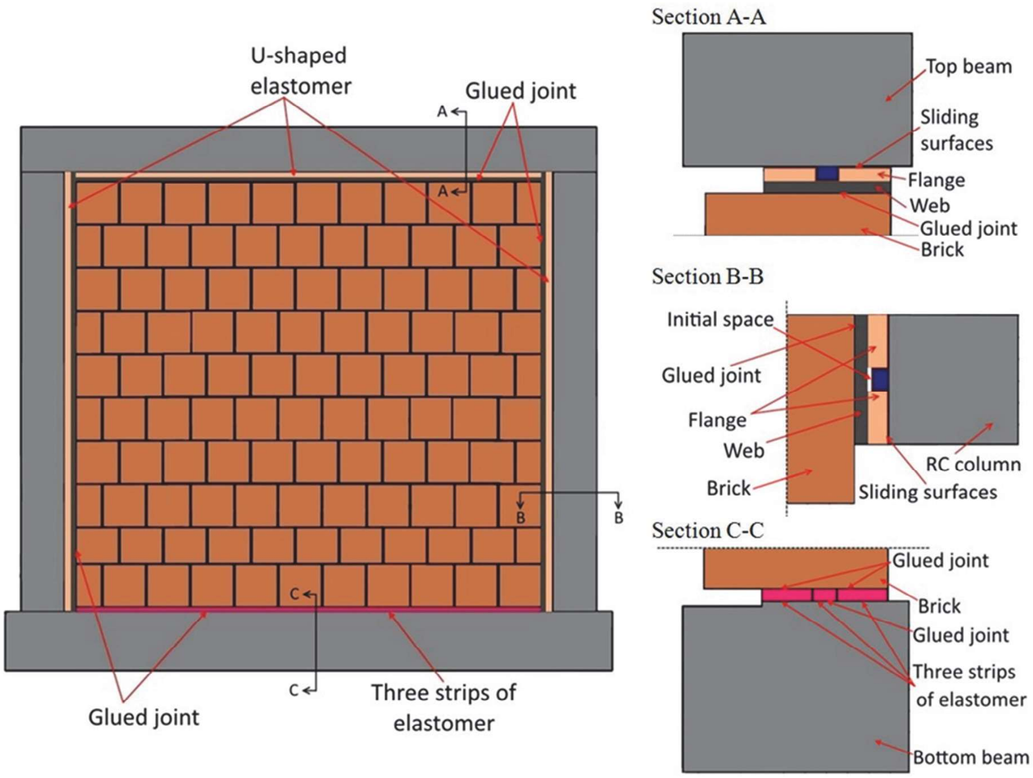
Therefore, the use of steel anchors connecting infills to the frame was studied by [76, 77]. Decoupling approach is also given as one of the options in some international guidelines [78-80].

The problem that can be found is that there are many approaches and the process has not been standardized in order to be used by the practical engineering community. Furthermore, many solutions bring the benefit to the infills, but so far no complete solution is proposed that solves the problems of the behaviour of the masonry infill walls under earthquake excitations. Shortcomings are different, from complicated to practically inapplicable solutions and solutions not effective for simultaneous in-plane and out-of-plane load. For some of them the application is problematic with respect to flexible room use and they are inapplicable to all types of bricks. One solution that has shown promising results is the decoupling system described in [81]. This system called INODIS (Innovative Decoupled Infill System) is able to effectively decouple and delay the activation of the infill walls, thus reducing the infill/frame interaction and the undesirable effects of it. Due to its features and the shape providing sufficient out-of-plane connection for infill walls, this system is chosen for detailed numerical study presented in this paper.

In order to determine whether the decoupling system is a better solution compared to traditional unreinforced masonry walls, a series of numerical linear and non-linear analyses were performed. The novelty of the paper is study of the behaviour of the RC frame buildings with decoupled infill walls at the structural level. Similar studies were done for traditional infills but none is performed on decoupled infills. Since the INODIS system provides in-plane decoupling it removes in-plane/out-of-plane interaction, as shown experimentally [81]. Therefore, in the numerical analyses just in-plane behaviour of the infill walls was considered.

2 DECOUPLING SYSTEM

In this section the decoupling system INODIS is briefly described. Its details and features are thoroughly given in [81, 82]. The basic idea of the INODIS system (Figure 3) is decoupling of infill masonry and RC frame in in-plane direction combined with the out-of-plane connection measures along the edges of the infill panel. It aims to raise the in- and out-of-plane resistance by means of dissipative and sliding connections along the contact areas of the infill to the RC frame. INODIS decouples the infill wall and RC frame with the U-shaped elastomers placed at the top and along the vertical edges of an infill, together with the elastomer divided in three strips at the bottom of the infill. The U-shaped elastomers are designed to allow the design drift of the reinforced concrete frame without inducing damages to the infill wall. Furthermore, the viscoelastic bearings enhance the overall damping capacity of the building. Plastic profiles are attached by metal nails or screws to the surrounding frame while U-shaped elastomers are glued to the masonry infill on one side and placed around plastic profiles on the other side (Figure 3), thus preventing the out-of plane failure. Flanges of the U-shaped elastomers shown on Figure 3 are made of soft elastomer while stiffer elastomers are used for the webs. The stiffest elastomer is applied at the bottom in a form of three strips.



Slika 3. Izgled i postavka INODIS sistema [81]
Figure 3. Layout of the INODIS system [81]

3 NUMERIČKI MODELI

U ovom poglavlju, predstavljeni su pristupi modeliranja svih komponenti AB okvira sa izolovanom ispunom. Budući da su tema istraživanja AB okviri sa zidanom ispunom, modeliranje se može podeliti na tri dela, jedan vezan za AB okvir, drugi se odnosi na zidanu ispunu i treći na elemente izolacije ispune. Tri različita modela su razvijena: prazan okvir, okvir sa ispunom i okvir sa izolovanom ispunom. Softverski paket SAP2000 [83] izabran je zbog široke upotrebe u projektantskoj praksi.

3.1 Modeliranje AB okvira

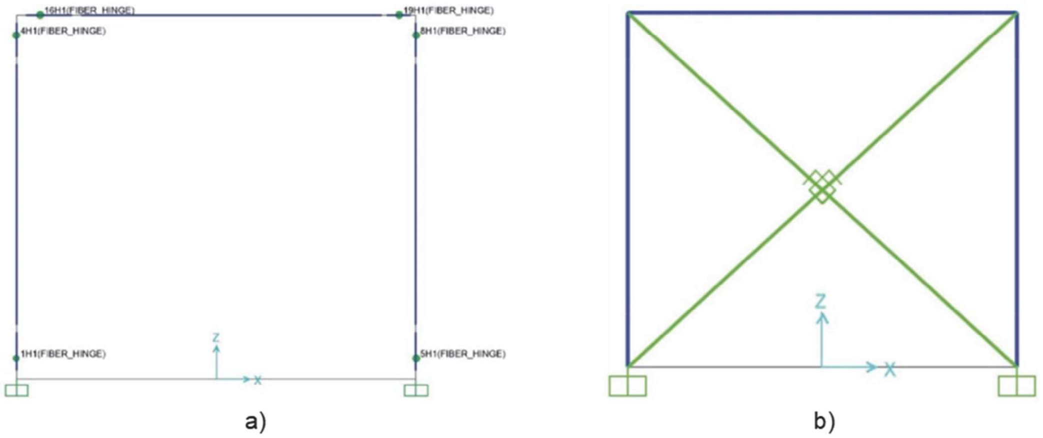
Grede i stubovi modelirani su linijskim konačnim elementima, pretpostavljajući uklještenje na dnu stubova (slika 4a). Kako bi se sprovela nelinearna analiza, u modelima je uzeta u obzir nelinearnost materijala i preseka, uvođenjem plastifikacije preseka. Tačnije, na kraju elementa definisani su plastični zglobovi (slika 4a). Za betonske elemente, karakteristike zglobova uzete su prema Tabeli 6–7 za grede i prema Tabeli 6–8 za stubove iz FEMA-356 [84]. Kriva sila ili moment-deformacija zasniva se na krivoj prikazanoj na slici 5, gde je dato pet različitih tačaka (A do E) koje treba definisati. Tačke predstavljaju početak, tečenje, maksimalnu nosivost, zaostalu nosivost i lom [83].

3 NUMERICAL MODELS

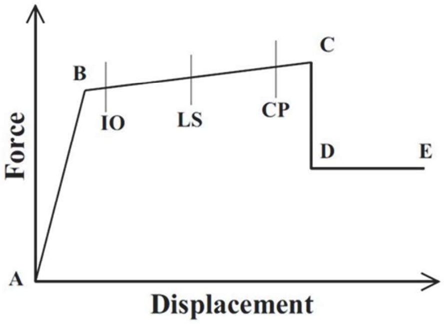
In this section, modelling approaches for all parts of the RC frames with decoupled infills are presented. Since the topic of the investigation are masonry infilled RC frames, the modelling approaches can be divided into three sections, one related to the RC frame, second to the infill wall and third to the decoupling elements. Three different models have been developed: the bare frame model, the infilled model and model of the frame with the decoupled infills. The software SAP2000 [83] was chosen because it is a widely used commercial program in design practices.

3.1 Modelling of the concrete frame

Beams and columns are modelled as one-dimensional frame elements, assuming fixed end restraints at the base of the columns (Figure 4a). In order to perform nonlinear analysis, models include non-linearity properties of materials and section, through a distributed plasticity approach. In particular, at the end section of the elements plastic hinges are placed (Figure 4a). For concrete elements, the hinge properties are taken from Tables 6-7 for beams and 6-8 for columns from FEMA-356 [84]. The force or moment-deformation curve is based, on the curve shown in Figure 5, where five different points (A to E) must be defined. The points represent the place of origin, yielding, ultimate capacity, residual strength and failure, respectively [83].



Slika 4. a) Model praznog okvira s položajem „fiber" zglobova i b) makro model okvira s tradicionalnom ispunom
Figure 4. a) Bare frame model with location of fibre hinges and b) macro model of traditionally infilled frame

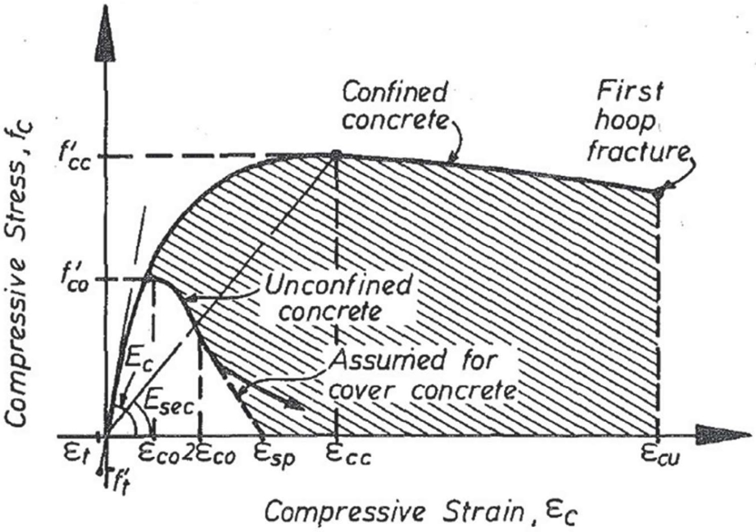


Slika 5. Ponašanje plastičnog zgloba prema FEMA 356 [84]
Figure 5. Plastic hinge behaviour according to FEMA 356 [84]

Za definisanje poprečnog preseka betonskih elemenata upotrebljena je posebna opcija dostupna u programu SAP2000 koja se zove „Section Designer". Uz pomoć nje je moguće definisati proizvoljnu geometriju preseka i kreirati kombinaciju materijala. U opciji „Section Designer" moguće je definisati presek betona s različitim karakteristikama materijala kao i tačan raspored armature. Za zaštitni sloj betona definisan je neutegnuti beton dok je za ostali deo preseka zadat utegnuti beton. Glavna razlika je da pri niskom nivou napona, poprečna armatura je slabo opterećena i beton se ponaša kao neutegnut. Dok pri naponima bliskim jednoaksijalnoj nosivosti betona, pojava pukotina u betonu dovodi do značajne aktivacije uzengija koje onda pružaju utezanje betonskom elementu. Na ovaj način se obezbeđuje značajno povećanje nosivosti i duktilnosti betonskog elementa [85]. Kriva napon–dilatacija za utegnuti i neutegnuti beton (slika 6) zasniva se na modelu predloženom u [86]. Prema njoj, nosivost na pritisak i granična dilatacija određuje se u funkciji poprečne armature. Bitne karakteristike Manderove krive su da se može koristiti i za statička i dinamička opterećenja, kada su ona zadata monotono ili ciklično [86, 87]. Upotrebnom

For creating specific frame section properties separate utility built into SAP2000 called "Section Designer" is used. It allows sections of arbitrary geometry and combinations of materials to be created. In Section Designer it is possible to create a section with different concrete material properties and precise disposition of reinforcement. For the concrete cover unconfined concrete was assigned and confined for the rest of the section. The main difference is that under the low levels of stress, transverse reinforcement is barely stressed and the concrete behaves like unconfined concrete. At stresses close to the uniaxial strength of concrete, fracturing causes the concrete to stress the stirrups which then provide confining action in concrete element. In this way, a significant increase of strength and ductility of concrete is present [85]. The stress-strain curve used for the confined and unconfined concrete(Figure 6) is based on the concrete model proposed [86]. It derives the compressive strength and ultimate strain values as a function of the transverse reinforcement. Important characteristic is that Mander's curve can be used for both static and dynamic loadings, when they are applied monotonically or cyclically [86, 87]. With the use of automatskog definisanja karakteristika plastičnih zglobova, program određuje krivu moment–rotacija i ostale karakteristike plastičnog zgloba prema FEMA 356 [84] kriterijumu koristeći preciznu geometriju i definiciju materijala datu u „Section Designer” [85].

automatic hinge properties, program calculates the moment-rotation curve and other hinge properties according to FEMA 356 [84] criteria using precise geometry and material defined in Section Designer [85].



Slika 6. Kriva napon–dilatacija za utegnut i neutegnut beton [86]
Figure 6. Stress-strain curves for unconfined and confined concrete [86]

Kako bi se modelirala plastifikacija duž elementa i po širini poprečnog preseka korišćen je takozvani „fiber” presek. Upotrebom „fiber” zglobova moguće je definisati uvezano ponašanje aksijalne sile i momenta savijanja. Poprečni presek diskretizuje se u niz aksijalnih vlakana koja se protežu podužno kroz celu dužinu plastičnog zgloba. Ovi plastični zglobovi su elastoplastični i sastoje se od seta materijalnih tačaka, gde svaka predstavlja deo poprečnog preseka i ima njegove materijalne karakteristike. Krive sila–deformacija i moment–rotacija nisu definisane, već se određuju u toku analize na osnovu krive napon–dilatacija za svaku materijalnu tačku [83].

3.2 Modeliranje zidane ispune

Kako bi se modeliralo ponašanje zida ispune u ravni, korišćen je makro model, primenom link-elementa za modeliranje ekvivalentne dijagonale. Link-element se može koristiti da spoji dva čvora konačnih elemenata i njima se može prikazati nelinearno ponašanje. Zbog toga su oni pogodan izbor za modeliranje ponašanja ispune u ravni. Link-element predstavlja šest opruga za svaki od šest stepeni slobode. Za svaku oprugu je moguće definisati različite tipove linearnog i nelinearnog ponašanja. Između više vrsta link-elemenata koji postoje u programu SAP 2000 *multi-linear plastic* link-element je izabran zbog sposobnosti da predstavi nelinearno ponašanje ispune. Unutar svakog rama su postavljena dva link-elementa, po jedan na svaku dijagonalu (Figure 4b).

Definisane su samo karakteristike u pravcu U1 nelinearnom krivom sila pomeranja. Za definisanje ove

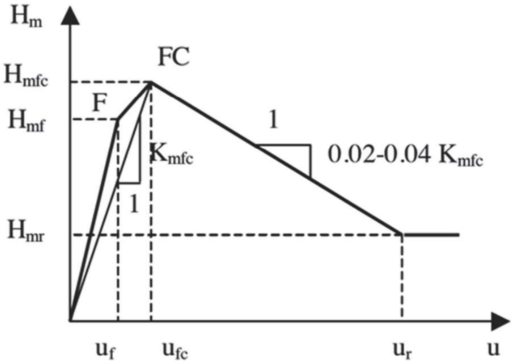
To model distributed plasticity along the member length and across the section so-called fibre section models are used. With the employment of fibre hinges it is possible to define coupled axial force and bending behaviour. The cross section is discretized into a series of representative axial fibres which extend longitudinally along the hinge length. These hinges are elastic-plastic and consist of a set of material points, each representing a portion of the cross-section having the same material. Force-deflection and moment-rotation curves are unspecified, but computed during the analysis from the stress-strain curves of the material points [83].

3.2 Modelling of the infill wall

In order to model the in-plane behaviour of the infill walls, a macro modelling approach was employed, using link element to model equivalent strut. Link elements can be used to connect two joints together and they are able to capture a nonlinear behaviour. Therefore, they are a suitable choice for modelling in-plane behaviour of infill panel. A link element is assumed that is made of six springs for each of the six degrees of freedom. For each spring it is possible to assign different types of linear or nonlinear properties. Between several types of link elements available in SAP 2000 the multi-linear plastic link element was chosen due to its ability to present nonlinear behaviour of infill wall. Two link elements are placed inside the frame connecting diagonal opposite corners (Figure 4b).

Only the properties in the U1 direction were defined with the nonlinear force-deformation curve. For the krive iskorišćen je pristup dat u [51, 52]. Tu je predložena kriva s četiri dela koja opisuje: (i) linearno-elastičnu fazu do H_{mf}; (ii) fazu nakon prvih pukotina do dostizanja maksimalne nosivosti H_{mfc}; (iii) silaznu granu do H_{mr}; i (iv) rezidualnu nosivost definisanu horizontalnom linijom kao što se može videti na slici 7.

definition of this curve approach from [51, 52] was used. They proposed a four branched backbone curve that describe: (i) the linear elastic phase up to H_{mf}; (ii) the post-cracking stage until reaching the maximum strength H_{mfc}; (iii) the deterioration descending branch until H_{mr}; and (iv) the residual stress characterized by a horizontal line as seen in Figure 7.



Slika 7. Veza sila–pomeranje zadata pritisnutoj dijagonali [88]
Figure 7. Force-displacement relationship for diagonal strut [88]

Za definiciju širine pritisnute dijagonale, navedeni autori su koristili parametar relativnog odnosa krutosti, λ_h, predložen u [55] i dve konstante K_1 i K_2 prema sledećim jednačinama:

For the definition of the equivalent strut width, the relative stiffness parameter was used, λ_h, proposed by [55] and two constants K_1 and K_2 according to the following equations:

$$\omega=\left(\frac{K_1}{\lambda_h}+K_2\right)d \tag{1}$$

$$\lambda_h=h\sqrt[4]{\frac{E_m t_m \sin 2\theta}{4 E_c I_c h_m}} \tag{2}$$

gde K_1 i K_2 uzimaju vrednosti iz Tabele 1 i gde E_m predstavlja modul elastičnosti zida; $E_c I_c$ je fleksiona krutost stuba, t_m je debljina zida ispune; h je visina stuba između osa greda; h_m je visina ispune; Θ je ugao između horizontale i dijagonale zida kao što je prikazano na slici 2.

where K_1 and K_2 take the values from Table 1 and where E_m is the masonry panel's modulus of elasticity; $E_c I_c$ is the column's flexural rigidity, t_m is panel thickness of the infill panel; h is the column's height between beams' centre lines; h_m is the height of the infill; Θ is the angle between the horizontal and the diagonal of the wall as seen in Figure 2.

Tabela 1. Vrednosti za koeficijente K_1 i K_2
Table 1. Values for coefficients K_1 and K_2

	$\lambda_h < 3.14$	$3.14 < \lambda_h < 7.85$	$\lambda_h > 7.85$
K_1	1.3	*0.707*	0.47
K_2	-0.178	*0.01*	0.04

Nosivost dijagonalog elementa na pritisak definisana je uzimajući u obzir četiri tipa loma ispune: (i) zatezanje po dijagonali $\sigma_{br(1)}$; (ii) klizanje po horizontalnim malterskim spojnicama $\sigma_{br(2)}$; (iii) lom u uglu zida $\sigma_{br(3)}$; i (iv) lom po dijagonali usled pritiska $\sigma_{br(4)}$, definisanog prema sledećim jednačinama:

The compression failure stress of the strut is defined so that it takes into account four different failure modes: (i) diagonal tension $\sigma_{br(1)}$; (ii) bed joint sliding shear $\sigma_{br(2)}$; (iii) corner crushing $\sigma_{br(3)}$; and (iv) diagonal compression failure $\sigma_{br(4)}$, defined according to the following equations:

$$\sigma_{br(1)} = \frac{0.6\tau_{m0} + 0.3\sigma_0}{\omega / d} \tag{3}$$

$$\sigma_{br(2)} = \frac{\left(1.2\sin\theta + 0.45\cos\theta\right) f_{sr} + 0.3\sigma_0}{\omega / d} \tag{4}$$

$$\sigma_{br(3)} = \frac{\left(1.12\sin\theta\cos\theta\right)}{K_1\left(\lambda_h\right)^{-0.12} + K_2\left(\lambda_h\right)^{0.88}}\sigma_{m0} \tag{5}$$

$$\sigma_{br(4)} = \frac{1.16\sigma_{m0} tg\theta}{K_1 + K_2\lambda_h} \tag{6}$$

gde je σ_{m0} nosivot zidarije na pritisak, τ_{m0} je smičuća nosivost određena iz testa pritiska po dijagonali, f_{sr} nosivost spojnice na klizanje i σ_0 je napon usled vertikalnog opterećenja.

Nosivost ekvivalentne pritisnute dijagonale računa se korišćenjem minimalnog napona od navedena četiri, kao i sledeće jednačine:

where σ_{m0} is the compression strength, τ_{m0} is the shear strength measured taken from the diagonal compression test, f_{sr} is the joint slide resistance, and σ_0 is the vertical stress of the applied loads.

Lateral strength of the equivalent diagonal strut is calculated using minimal stress and following equation:

$$H_{mfc} = \sigma_{br,\min} t\omega\cos\theta \tag{7}$$

Proračun elastične krutosti, K_0, uzima u obzir elastičnu krutost okvira, K_{t0}, i krutosti zidane ispune kada je dostigla maksimalnu nosivost i ispucala, K_{mfc}, određene prema [89]:

The calculation of the elastic stiffness, K_0, takes into account the elastic stiffness of the frame, K_{t0}, and the infill wall stiffness when it is completely cracked, K_{mfc}, calculated according to [89]:

$$K_0 = 3K_{t0} + 4K_{mfc} \tag{8}$$

gde je

where

$$K_{t0} = \frac{1+6\phi}{2+3\phi}\frac{12E_c I_p}{h^3} \tag{9}$$

$$\phi = \frac{I_{beam}}{I_{column}}\frac{h}{l} \tag{10}$$

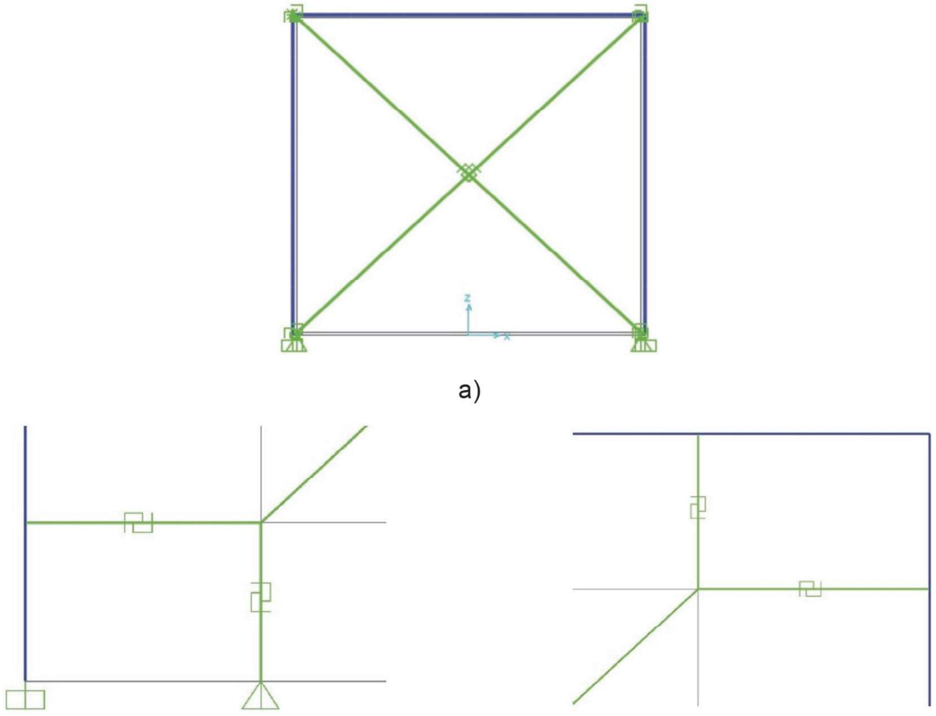
$$K_{mfc} = \frac{E_m t\omega}{d}\cos^2\theta \tag{11}$$

3.3 Modeliranje elastomera

S obzirom na to što se elastomeri koriste za razdvajanje okvira i ispune, treba izabrati element koji može da predstavi hiperelastično ponašanje elastomera. U tu svrhu takođe je izabran *multi linear plastic* link-element. Link-elementi koji predstavljaju elastomere postavljeni su u uglovima, povezujući link-element koji predstavlja ispunu sa okvirom (slika 8).

3.3 Modelling of the decoupling elastomer

Since elastomers are used for decoupling of frame and infill wall, an element that can present hyperelastic behaviour of elastomer should be chosen. For that purpose also multi linear plastic link element was employed. Link elements presenting elastomers are placed in the corners connecting infill's link element and frame (Figure 8).



a)

b)

c)

Slika 8. a) Model okvira sa izolovanom ispunom; b) i c) detalj u uglu koji prikazuje link-element koji predstavlja elastomere

Figure 8. a) Decoupled infilled frame model; b) and c) corner details of link elements presenting elastomers

4 VALIDACIJA PREMA EKSPERIMENTALNIM REZULTATIMA

U ovom poglavlju prikazana je kalibracija i validacija numeričkih modela s ciljem da se razvije numerički model koji može da predstavi eksperimentalne testove na praznim AB okvirima, AB okvirima s tradicionalnom ispunom i AB okvirima sa izolovanom ispunom. Cilj je da se nakon toga validirani modeli iskoriste za parametarsku analizu na 2D ramovima konstrukcije i na 3D modelu zgrade.

Za validaciju numeričkih modela, iskorišćeni su rezultati testova za opterećenje u ravni iz [81]. Eksperimentalna ispitivanja sastojala su se od opterećenja u ravni zadatog na prazan okvir, okvir s tradicionalnom ispunom i okvir sa izolovanom ispunom. Eksperimentalna kampanja i svi detalji dati su u [81]. Prvo je urađena kalibracija numeričkih modela primenom statičke nelinearne analize (*pushover*) poređenjem rezultata sa anvelopom histerezisne krive dobijene u eksperimentu. Nakon toga je sprovedena dinamička nelinearna analiza (*time history*) za kalibraciju modela prema histerezisnoj krivoj dobijenoj usled cikličnog opterećenja.

4 VALIDATION WITH THE EXPERIMENTAL RESULTS

In this section the calibration and validation of the different models will be presented, the goal is to develop a numerical model to simulate tests on RC bare frame, traditionally infilled RC frame and RC frame with decoupled infills. The purpose is to later use this calibrated frame models to simulate the behaviour of the 2D structural frames and 3D building.

For the validation of the numerical model, test results for in-plane loading conditions from [81] will be used. Test campaign consisted of in-plane cyclic loading on full scale bare frame, traditionally infilled frame and frame with decoupled infills. Experimental campaign and all the details are given in [81]. Here, the calibration of the numerical models is first performed using pushover analysis and comparing the results with the envelope of the hysteretic curve and then the time history analysis is employed for calibrating the model to match the hysteretic curve from the cyclic loading.

4.1 Prazan okvir

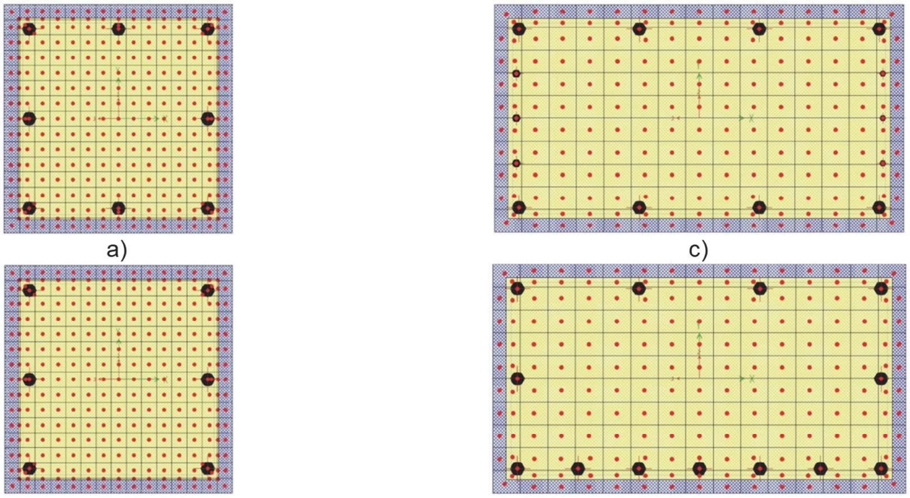
Kako bi se validirao numerički pristup korišćen za modeliranje AB okvira, iskorišćeni su testovi na neskaliranim uzorcima. Okvir je projektovan prema [90, 91] uzimajući u obzir nemački nacionalni aneks i klasu duktilnosti L. Stubovi su kvadratnog poprečnog preseka 25x25 cm sa 1.48% podužne armature, 0.63% poprečne armature na početku i kraju stuba, kao i 0.42% uzengija u sredini. S druge strane greda je projektovana na dimenzije 25x45 cm (visina x širina) sa 1.05% podužne armature i 0.35% poprečne armature na početku/kraju grede i 0.23% u sredini.

Relativno rastojanje od 0.05 i 0.95 uzeto je u obzir za lokaciju „fiber” plastičnih zglobova (slika 4a). Tačne dimenzije i raspored armature definisani su za poprečne preseke. Koristeći *Section Designer*, armiranobetonski elementi se mogu modelirati prilično precizno (slika 9). Kao što se može videti, tačna lokacija armature zadata je, kao i dva različita materijala za beton (utegnut – žuta boja; neutegnut – plava). Dva različita poprečna preseka generisana su za grede, takođe i za stubove, kako bi se uzela u obzir promena podužne armature i razmaka uzengija. Grede i stubovi preseka A zadati su na krajevima, a presek B je korišćen za središnje delove elemenata (slika 9). Slika 9 takođe pokazuje distribuciju mreže konačnih elemenata i poziciju vlakana (fiber). Svaki presek ima tri tipa vlakana korišćenih za različite materijale. Za beton je korišćen Manderov model [86] za definiciju krive napon–dilatacija, koja se automatski definiše u programu (slika 10). Za armaturu je korišćena kriva napon–dilatacija, ručno definisana prema materijalnim karakteristikama datim u [82].

4.1 Bare frame

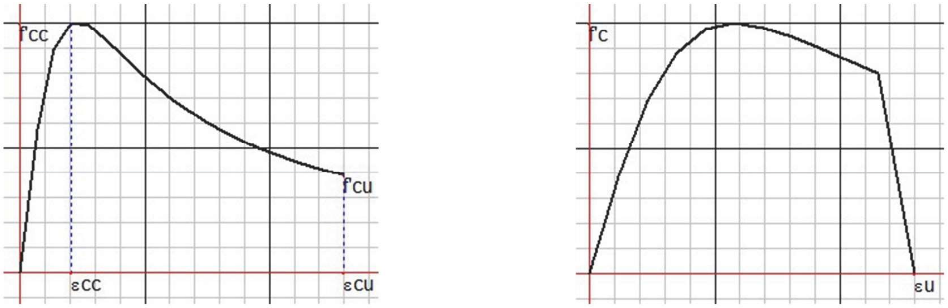
To validate the numerical approach used for the concrete frame modelling, the test onfull-scale RC frame is used. The frame was designed according to [90, 91] considering the German national annexes for ductility class L. Columns have a square cross section of 25x25cm with a 1.48% longitudinal reinforcement, 0.63% transverse reinforcement at the start and end of the column, as well as 0.42% middle section stirrups. On the other hand, the beam was designed with a size of 25x45cm (height x width) with a 1.05% of longitudinal reinforcement and 0.35% and 0.23% of transverse reinforcement at beam start/end and in middle section, respectively.

A relative distance of 0.05 and 0.95 was considered for the location of fibre hinges in the model (Figure 4a). Exact dimensions and reinforcement distribution was defined in the cross sections. With the use of Section Designer reinforced concrete elements can be modelled quite precise (Figure9). As it can be seen, the exact location of the rebars is obtained as well as two different material properties of concrete (confined - yellow colour; unconfined - blue colour). Two different cross sections were generated for beams and also for columns, as there is a change in longitudinal reinforcement and spacing of stirrups. Beam and columns cross section A is the ones used near the edges while cross section B is used in the mid-section (Figure 9). Figure 9 also shows mesh distribution and fibre position. Each section was divided into three types of fibres for different kind of materials. For concrete material, the Mander model [86] was used for the definition of the stress-strain curves, which are auto defined by the program (Figure 10). For the rebars, a user defined stress-strain curve was defined, with the material characteristics described in [82].


a) b) c) d)

Slika 9. a) Presek stuba A, 250 x 250 mm (mreža = 15x15); b) presek stuba B, 250 x 250 mm (mreža = 15x15); c) presek grede A, 250 x 450 mm (mreža = 15x15); i d) presek grede B, 250 x 450 mm (mreža = 15x15)

Figure 9. a) column section A, 250 x 250mm (mesh = 15x15); b) column section B, 250 x 250mm (mesh = 15x15); c) beam section A, 250 x 450mm (mesh = 15x15); and d) beam section B, 250 x 450mm (mesh = 15x15)



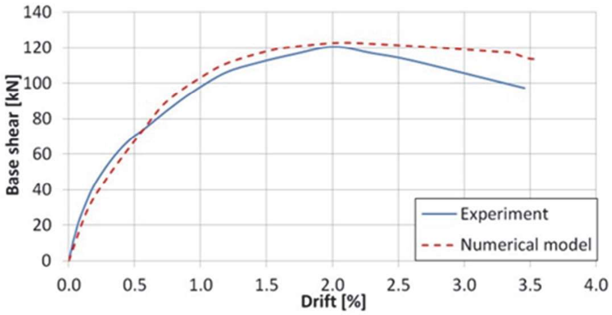
a)

b)

Slika 10. Krive napon–dilatacija za a) utegnut beton b) neutegnut beton
Figure 10. Stress-strain curves for a) confined concrete and b) unconfined concrete

Numerički rezultati statičke nelinearne analize (*pushover*) upoređeni su sa anvelopom histerezisne krive iz eksperimentalnih rezultata (slika 11). Iz rezultata se može primetiti da je kriva dobijena iz numeričkog modela prilično blizu eksperimentalne krive. I degradacija krutosti i kapacitet nosivosti praznog okvira dobro se poklapaju. Numerički rezultati pokazuju skoro isti kapacitet do trenutka dostizanja maksimalne nosivosti i treba istaći da i numerički model i eksperimentalni rezultati pokazuju da je maksimalna nosivost dostignuta pri 2% relativnog međuspratnog pomeranja. Nakon toga postoji blago razilaženje ove dve krive, ali u granicama zadovoljavajućeg.

The results from the numerical pushover analysis were compared to the envelope curve of the hysteresis experimental results (Figure 11). From the results obtained it is possible to notice that, in general, the pushover curves from the numerical model are pretty close to one obtained in experimental test. Both stiffness degradation and strength capacity of the bare frame are matched very well. The numerical results follow almost the same capacity curve until it reaches a peak load capacity; it should be pointed out that both numerical and experimental results reach the peak at 2% of inter storey drift. After the peak there is a small and tolerable diversion between both curves.



Slika 11. Poređenje između numerički dobijene pushover krive i anvelope eksperimentalne histerezisne krive
Figure 11. Comparison between pushover curve from numerical model and the envelope of experimental hysteresis

Kako bi se uhvatilo histerezisno ponašanje materijala, histerezisni model je definisan za beton i za čelik definisan za armaturu. Za model betona, uzet je faktor degradacije energije s = 0. Za model armature, parametri korišćeni za kalibraciju dati su u Tabeli 2.

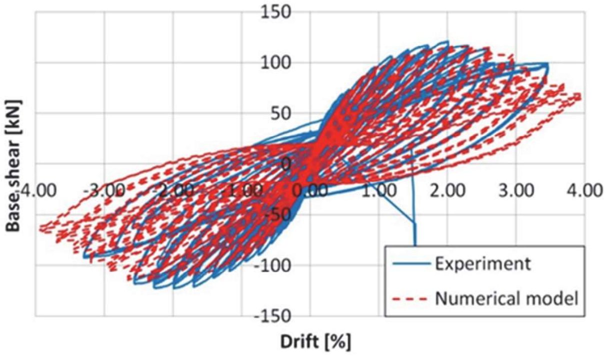
Rezultati dinamičke nelinearne analize prikazani su na slici 12, i može se videti jako dobro poklapanje u smislu krutosti i maksimalnog kapaciteta nosivosti. Takođe, histerezisne petlje su slične, što potvrđuje validnost modela praznog okvira.

In order to capture the hysteretic behaviour of the materials, the concrete hysteresis model was defined for concrete and for steel material of rebars degrading hysteresis model. For the concrete model, an energy degradation factor s = 0, was assigned. For the rebar model, the parameters used after calibration can be found in the Table 2.

From the results of the time history analysis shown in Figure 12, it can be seen a very good matching of the stiffness and maximum load capacity. In addition, hysteresis loops are very similar, confirming the validity of the bare frame model.

Tabela 2. Vrednosti korišćene za model armature
Table 2. Values used for rebar model

Faktor degradacije energije / *Energy degradation factor, f_0*	1.0
Faktor energije pri umerenim deformacijama / *Energy factor at moderate deformation, f_1*	1.5
Faktor energije pri maksimalnim deformacijama / *Energy factor at maximum deformation, f_2*	0.2
Umereni nivo deformacije u odnosu na nivo tečenja / *Moderate deformation level as a ratio of yield, x_1*	1.0
Maksimalni nivo deformacije u odnosu na nivo tečenja / *Maximum deformation level as a ratio of yield, x_2*	2.0
Akumulacioni deformacioni težinski faktor / *Accumulation deformation weighting factor*	0
Težinski faktor za krutost / *Stiffness weighting factor*	0.2
Veći-manji težinski faktor / *Larger-smaller weighting factor*	0.4



Slika 12. Poređenje rezultata numeričkog modela dinamičke nelinearne analize i eksperimentalnog histerezisa praznog okvira

Figure 12. Comparison between the numerical model time history results and the experimental hysteresis of the bare frame

4.2 AB okvir s tradicionalnom ispunom

Okvir s tradicionalnom ispunom iz eksperimenata prikazanih u [81] sastoji se od istog praznog AB okvira ispunjenog zidom od šupljih blokova od opeke povezanih tankoslojnim malterom. Detaljne materijalne karakteristike blokova i zidarije date su u [81, 82]. Za definisanje krive sila–pomeranje za link-element, iskorišćen je pristup zasnovan na četiri grane krive, definisan u [51, 52]. Kako bi se definisala kriva potrebno je da se odredi bezdimenzioni koeficijent λ_h korišćenjem Jednačine 2. U Tabeli 3 prikazane su korišćene vrednosti:

4.2 RC frame with traditional infills

The traditional infilled frame, used in the experimental tests performed by [81], was composed of the same frame that was infilled with masonry wall made of hollow clay bricks with thin-layer mortar connection. Detailed material characteristics of the bricks and masonry are given in [81, 82]. For the force-displacement curve defined for the link element, a four branch model based on [51, 52] was used. In order to define it, the calculation of the dimensionless parameter λ_h was performed using Equation 2. The following Table 3 shows the values used:

Tabela 3. Određivanje parametra λ_h
Table 3. Calculation of parameter λ_h

E_m	*4870*	N/mm^2
t_m	365	mm
Θ	0.738	rad
$sin2\Theta$	0.996	-
E_c	32559	N/mm^2
h_m	2520	mm
h	2750	mm
λ_h	**5.54**	-

Za određivanje širine dijagonale korišćena je Jednačina 1. Kao što se može videti u Tabeli 3 λ_h vrednost je između 3.14 i 7.85, K_1 i K_2 su onda 0.707 i 0.010, što daje širinu dijagonale od 514.93 mm.

S obzirom na to što test pritiska u pravcu dijagonale zida nije sproveden eksperimentalno, nosivost zida na smicanje je određena prema Jednačini 12, uzimajući nosivost na pritisak, f'_m, da iznosi 3.1 N/mm^2. Nosivost horizontalne malterske spojnice na smicanje takođe je određena prema Jednačini 13:

For the calculation of the strut width, Equation 1 was used. As seen in Table 3, for λ_h values in between 3.14 and 7.85, K_1 and K_2 are equal to 0.707 and 0.010 respectively, which gives the strut width equal 514.93 mm.

Since the diagonal compression test was not performed in the experiments, the masonry shear strength was calculated using Equation 12 with a compressive strength, f'_m, equal to 3.1 N/mm^2. The bed joint shear strength was also calculated, using Equation 13 as shown below:

$$\tau_{m0} = 0.285\sqrt{f'_m} \tag{12}$$

$$\tau_0 = 2/3\tau_{m0} = 0.211\sqrt{f'_m} \tag{13}$$

Obe jednačine predložene su u [92] i daju nosivost od 0.707 MPa za τ_{m0} i 0.01 MPa za τ_0.

Za određivanje nosivosti dijagonale na pritisak upotrebljene su Jednačine 3–6 i rezultati su prikazni u Tabeli 4.

Both equations are proposed by [92] and they derive 0.707 MPa for τ_{m0} and 0.01 MPa for τ_0.

For calculating the compression failure stress of the strut Equations 3-6 were used and results are shown in the Table 4.

Tabela 4. Naponi nosivosti na pritisak
Table 4. Compression failure stresses

$\sigma_{br(1)}$	*2.19*	N/mm^2
$\sigma_{br(2)}$	6.72	N/mm^2
$\sigma_{br(3)}$	2.78	N/mm^2
$\sigma_{br(4)}$	4.29	N/mm^2

Minimalna vrednost, $\sigma_{br(1)}$, i Jednačina 7 daju minimalnu nosivost pritisnute dijagonale H_{mfc} u iznosu od 303.77kN.

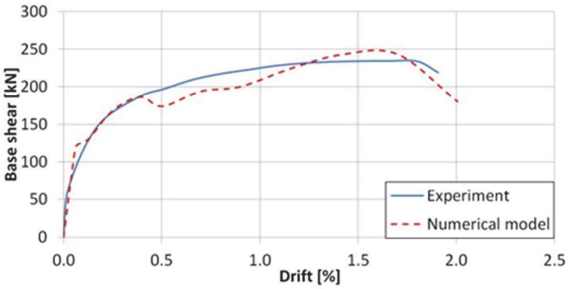
Kako bi se dobilo zadovoljavajuće poklapanje rezultata, neke vrednosti su morale da se kalibriraju. Minimalna nosivost je smanjena na 45% dajući H_{mfc} = 136.68kN. Linearna elastična sila H_{mf} je uzeta kao 80% od H_{mfc} a H_{mr} kao 87.5% od H_{mfc}. Za određivanje elastične krutosti, K_0 (Jednačina 8), elastična krutost okvira, K_{t0} (Jednačina 9), i krutost ispune pri maksimalnoj nosivosti, K_{mfc} (Jednačina 11), iskorišćeni su za dobijanje K_0 = 299.8 kN/mm. Takođe, predložena je modifikacija za elastičnu krutost i krutost ispune uzimajući samo 15% vrednosti, čime je dobijeno K_{mfc} = 13.04 kN/mm. A za elastičnu krutost je uzeto 60% od vrednosti dajući K_0 = 63.34 kN/mm. Završna grana definisana sa K_{mr} uzeta je kao negativna krutost u iznosu od 35% krutosti ispune.

Slika 13 pokazuje rezultate dobijene numeričkim modelom i eksperimentalno. Može se uočiti dobro poklapanje krutosti i maksimalne nosivosti. Ovo pokazuje uspešnost kalibracije i validnost modela okvira sa ispunom.

The minimum value, $\sigma_{br(1)}$, and Equation 7 derive the minimum lateral strength H_{mfc} having the value of 303.77kN.

In order to match the experimental results better, some values had to be calibrated. The minimum lateral strength was considered to be only 45% of the lateral strength previously calculated, obtaining H_{mfc}= 136.68kN. The linear elastic force H_{mf} was assumed as 80% of H_{mfc} and H_{mr}as 87.5% of H_{mfc}. For the calculation of the elastic stiffness, K_0 (Equation 8), the elastic stiffness of the frame, K_{t0}(Equation 9), and the infill wall stiffness when it is completely cracked, K_{mfc} (Equation 11), were used obtaining K_0 = 299.8 kN/mm. Also a modification is proposed for the elastic stiffness and the infill stiffness taking only 15% of the infill stiffness, giving a value of K_{mfc} = 13.04 kN/mm, and 60% of the elastic stiffness, giving a value of K_0 = 63.34 kN/mm. The final branch defined with K_{mr} is considered to have negative slope equal to 35% of the infill stiffness.

Figure 13 shows the results obtained with the numerical model and experimental test. A good matching of stiffness and maximal load capacity can be seen. This demonstrates a good calibration and validates the infill frame model.

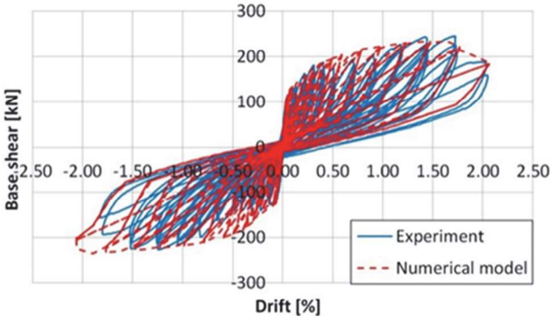


Slika 13. Poređenje pushover krive dobijene numerički i anvelope eksperimentalne histerezisne krive za okvir s tradicionalnom ispunom

Figure 13. Comparison between pushover curve from numerical model and the envelope of experimental hysteresis for traditionally infilled frame

Za definisanje histerezisnog modela ispune izabran je pivot model. Ovaj model podešava uzlaznu i silaznu granu parametrima α_1, α_2, β_1 i β_2. Uzlazna grana podešava se parametrom α dok β parametar podešava silaznu granu. S obzirom na to što nosivost ispune na zatezanje nije uzeta u obzir, parametri α_1 i β_1 su 0, dok α_2 ima vrednost 5 [83]. Rezultati dinamičke nelinearne analize prikazani na slici 14 pokazuju dobro poklapanje numeričkih rezultata (crveno) i eksperimentalnih rezultata (plava), potvrđujući time validnost korišćenja numeričkog modela za dinamičku nelinearnu analizu.

For the definition of the hysteresis model for the infill wall a pivot model was chosen. This model is defined by adjusting the loading and unloading branches, with the parameters α_1, α_2, β_1 and β_2. The α parameters adjust the unloading zone while the β parameters adjust the loading zone. Since the tension strength of the infill panel is unconsidered, parameters α_1 and β_1 are set to 0, while α_2 is set to 5 [83]. Results of the time history analysis in Figure 14 show a good resemblance between the numerical results (red) and the experimental results (blue), confirming the validity of using the model for nonlinear time history analysis.



Slika 14. Poređenje rezultata dinamičke nelinearne analize dobijene numeričkim modelom i eksperimentalno dobijene histerezisne krive za okvir s tradicionalnom ispunom

Figure 14. Comparison between the numerical model time history results and the experimental hysteresis of the traditionally infilled frame

4.3 AB okvir sa izolovanom ispunom

Kako bi se uzelo u obzir razdvajanje ispune od okvira primenom elastomera u sistemu INODIS, nelinearni link element je dodat u uglove zidnog panela povezujući dijagonale sa okvirom (slika 8). Koristeći širinu dijagonale ispune (ω) i njen ugao Θ, kontaktna dužina između pritisnute dijagonale i stuba, L_c, i grede, L_b, jeste određena:

4.3 RC frame with decoupled infills

In order to take into account decoupling with the elastomers that are applied in the INODIS system, nonlinear link elements are added to the corners of the infill panel connecting the diagonal links with the frame (Figure 8). Using the strut width of the infill (ω) and its angle Θ, contact length between the diagonal strut and the column, L_c, and beam, L_b, are determined:

$$L_c = \omega \cos\theta = 380.89 mm \tag{14}$$

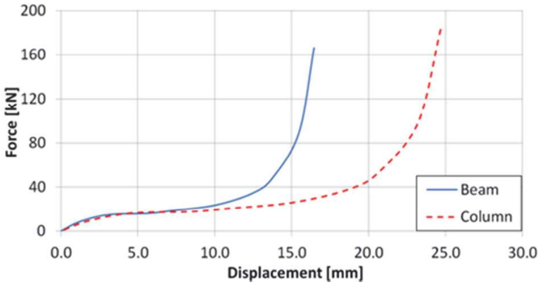
$$L_c = \omega \sin\theta = 346.51 mm \tag{15}$$

Uzimajući širinu elastomera od 250 mm, kotaktna površina je određena kao A_c = 95222.52 mm^2 i A_b = 86628.43 mm^2.

Debljina elastomera do stuba je 37.5 mm a za grede 25 mm. Koristeći ove podatke, krive sila–pomeranje su definisane (slika 15) i zadate link-elementima koji predstavljaju elastomer. Takeda model je korišćen za definiciju histerezisnog modela za elastomere. Ovo je najjednostavniji histerezisni model jer ne zahteva definiciju nijednog parametra.

Using the width of the elastomers of 250 mm, the contact area is calculated giving a value of A_c = 95222.52 mm^2 and A_b = 86628.43 mm^2.

Thickness of the column elastomers is of 37.5mm and for the beams 25 mm. Using this data, the force-displacement curves were defined (Figure 15) and assigned to the links presenting the elastomers. The Takeda model was used for the definition of the hysteretic model for the elastomers. This is the simplest model as it does not require definition of any parameter.



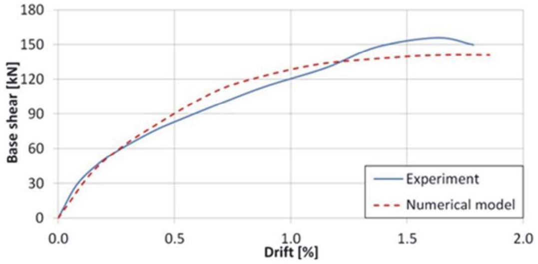
Slika 15. Krive sila–pomeranje primenjene za definiciju ponašanja link-elemenata koji predstavljaju elastomere
Figure 15. Force-displacement curves applied to the links presenting elastomers

Test na okviru sa izolovanom ispunom, izloženom opterećenju u ravni upotrebljen je za validaciju numeričkog modela i rezultati (slika 16) pokazuju dobro poklapanje. Rezultati dinamičke nelinearne analize (*time history*) za test opterećenja u ravni (slika 17) i za kombinovano opterećenje u ravni i van ravni zida (slika 18) pokazuju takođe dobro poklapanje, sa blago užim histerezisnim petljama u poređenju sa eksperimentalnim. Ovo takođe potvrđuje da ponašanje u ravni ispune nije u zavisnosti sa opterećenjem van ravni u slučaju kada je primenjena izolacija ispune od okvira.

Nakon validacije sva tri modela uz pomoć eksperimentalnih rezultata, moguće je analizirati uticaj izolacije ispune na ponašanje višespratnih zgrada uz pomoć dvodimenzionalnih i trodimenzionalnih modela s različitim konfiguracijama ispune.

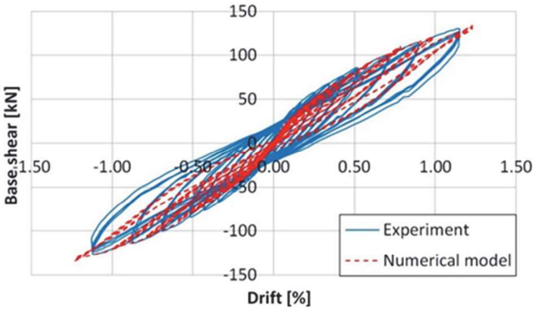
In-plane test on the decoupled infilled frame was used for validation of the numerical model and results (Figure 16) show a good resemblance between the numerical model (red) and the experimental results (blue). The time history results for the pure in-plane test (Figure 17) and for the combined in-plane and out-of-plane loading phase (Figure 18) show a good matching as well, with slightly narrower loops compared with the experimental ones. This also confirms that in-plane behaviour is independent on the out-of-plane load when decoupling is applied.

After validating all three models with the experimental results, it is possible to study and analyse the influence of decoupling on the behaviour of multi storey buildings in two and three dimensions with different configurations of infill walls



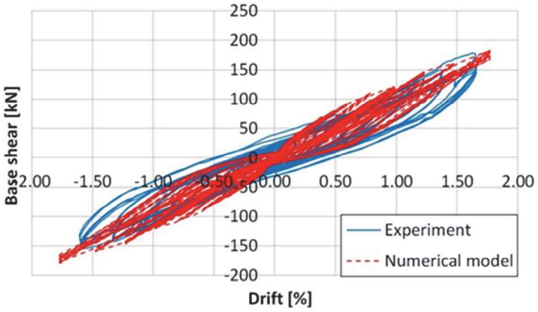
Slika 16. Kriva dobijena statičkom nelinearnom analizom (pushover) i kriva koja predstavlja anvelopu eksperimentalno dobijene histerezisne krive za okvir sa izolovanom ispunom

Figure 16. Pushover curve of the numerical model and experimental hysteresis envelope for the infilled frame with elastomers



Slika 17. Poređenje rezultata numeričkog modela i eksperimentalno dobijene histerezisne krive za okvir sa izolovanom ispunom pri opterećenju u ravni

Figure 17. Comparison between the numerical model time history results and the experimental hysteresis of the infilled frame with elastomers for pure in-plane loading



Slika 18. Poređenje rezultata numeričkog modela i eksperimentalno dobijene histerezisne krive za okvir sa izolovanom ispunom pri kombinaciji opterećenja u ravni i van ravni

Figure 18. Comparison between the numerical model time history results and the experimental hysteresis of the infilled frame with elastomers for combined in-plane and out-of-plane loading

5 ANALIZA 2D OKVIRA KONSTRUKCIJE

Nakon validacije numeričkih modela, korišćenjem eksperimentalnih rezultata, mogu se sprovesti naredne analize ponašanja AB okvirnih konstrukcija sa izolovanom ispunom. Dvodimenzionalni okvir konstrukcije analiziran je primenom statičke nelinearne analize i dinamičke nelinearne analize. Kako bi se modelirao okvir konstrukcije s više spratova i brodova, prethodno validirani numerički modeli jednospratnih i jednobrodnih okvira multiplicirani su u visinu i širinu. Svi poprečni preseci i karakteristike greda, stubova, ispune i elastomera zadržani su isti.

U tu svrhu, analizirana je višespratnica srednje visine (M) koja ima šest spratova. Primenjujući pristup iz [93], analizirane su različite konfiguracije ispune uključujući: prazan okvir, okvir sasvim popunjen ispunom, okvir sa otvorenim prizemljem i okvir s delimično otvorenim prizemljem. U svim ovim konfiguracijama, i tradicionalna i izolovana ispuna je ispitana. To znači da je sedam različitih konfiguracija analizirano (slika 19) – prazan okvir (1); okvir sasvim popunjen tradicionalnom ispunom i sa INODIS sistemom (2 i 5); okvir s delimično otvorenim prizemljem, popunjen tradicionalnom ispunom i sa INODIS sistemom (3 i 6) i okvir sa otvorenim prizemljem, popunjen tradicionalnom ispunom i sa INODIS sistemom (4 i 7).

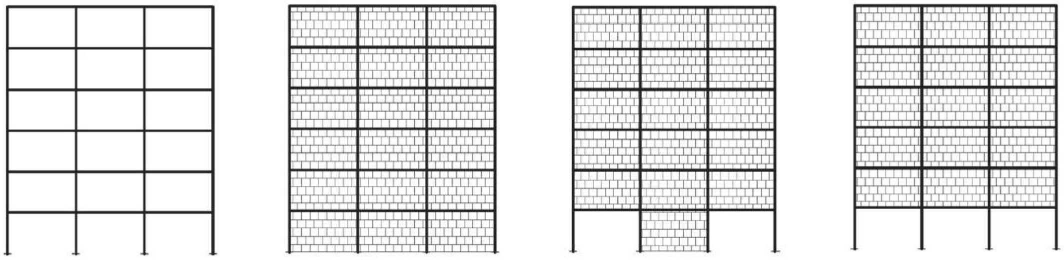
5 ANALYSIS OF 2D STRUCTURAL FRAMES

After validating numerical models using experimental results further analysis of the behaviour of RC frame structures with decoupled infills can be done. Two dimensional structural frames were analysed using pushover and dynamic time-history analysis. In order to model structural frames with several floors and bays, the previously validated models of one-bay and one-storey frame were multiplied in height and width. All cross-section and properties of beams, columns, infills and elastomers were kept the same.

For this purpose a medium (M) rise six story building was analysed. Following the approach by [93], different infill configurations were studied including: bare frame, fully infilled frame, open ground storey frame and partially open ground storey frame. For all these configurations, both traditional and decoupling approaches were studied. That means seven different configurations were analysed (Figure 19) - bare frame (1); fully infilled frame with traditional infill and INODIS system (2 and 5, respectively); partially open ground storey frame with traditional infill and INODIS system (3 with traditional infill and 6 with the INODIS system); and open ground storey frame with traditional infill and INODIS system (4 and 7, respectively).

Dodatno opterećenje je uzeto u obzir u iznosu od 2.0 kN/m^2 za slojeve podova i pregradne zidove i 2.0 kN/m^2 za korisno opterećenje. Sopstvena težina konstrukcije uzeta je u obzir u samom numeričkom modelu. Za težinu ispune uzeto je linijsko opterećenje u iznosu od 6.0 kN/m.

Additional loads were considered taken as 2.0 kN/m^2 for floor finishes and partitions and 2.0 kN/m^2 for the live load. The self-weight of the structure is taken into account in the numerical model. For the weight of the infills, a line load of 6.0 kN/m was used.



a) M1 b) M2 and M5 c) M3 and M6 d) M4 and M7

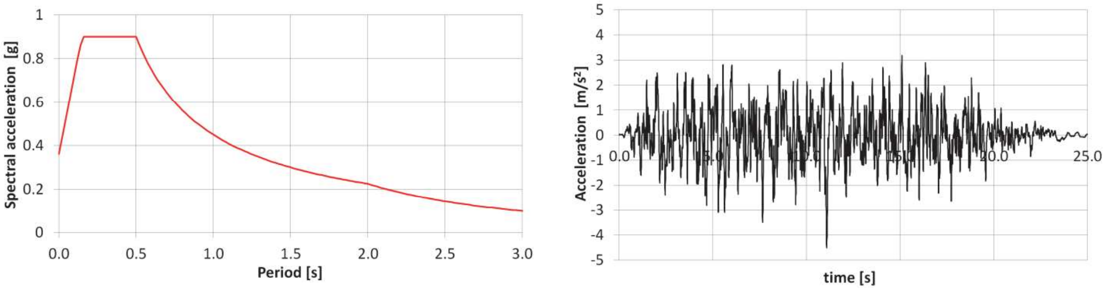
Slika 19. Dispozicija zidova ispune u zgradi srednje visine [93]
Figure 19. Disposition of infill walls for medium rise building [93]

5.1 Tipovi analize

Prvo je sprovedena modalna analiza kako bi se uporedile dinamičke karakteristike različitih konfiguracija i proverio uticaj zidova ispune na okvir konstrukcije. Nakon toga, statička nelinearna analiza (*pushover*) upotrebljena je da se dobije kapacitet sila–pomeranje i ukupne smičuće sile. Na kraju je sprovedena nelinearna dinamička analiza (*time history*) kako bi se poredila apsolutna pomeranja i relativno međuspratno pomeranje. Akcelerogrami korišćeni u nelinearnoj dinamičkoj analizi veštački su generisani na osnovu linearnog spektra Tipa 1 datog u Evrokodu [31], sa uslovima tla B, i za dva nivoa ubrzanja PGA=0.1g i PGA=0.3 g, korišćenjem relativnog prigušenja u iznosu od 5%. Generisanje akcelerograma sprovedeno je uz pomoć softverskog paketa SeismoArtif [94] uz korak od 256 Hz i ukupno trajanje od 25s s korekcijom osnovne funkcije. slika 20 prikazuje spektar odgovora za ubrzanje PGA=0.3g i odgovarajući akcelerogram.

5.1 Types of analysis

First, a modal analysis was performed to compare the dynamic characteristics of different configurations and check the influence of the infill walls on the structural frame. Then static nonlinear (pushover) analysis is used to check force-displacement capacity and base shear forces. At last, nonlinear time history analysis is employed to compare the displacements and inter storey drifts. Accelerogram used in time history analysis is generated artificially based on a Eurocode 8 [31] linear elastic response spectrum Type 1, with soil condition B, for two different PGA values, PGA=0.1g and PGA=0.3g, and damping ratio of 5 %. Generation of accelerogram is done using software SeismoArtif [94] with the sampling rate of 256 Hz and total duration of 25s with the base line correction. Figure 20 shows response spectrum for PGA=0.3g and corresponding accelerogram.



a) b)

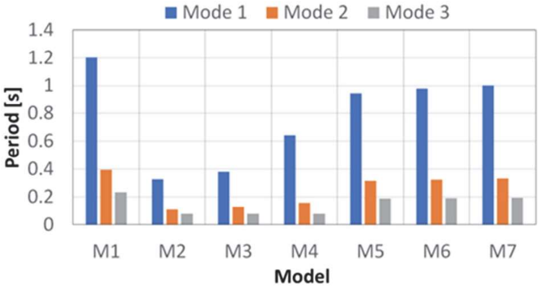
Slika 20. a) Spektar odgovora i b) akcelerogram za PGA=0.3g
Figure 20. a) Response spectrum and b) time history signal for PGA=0.3g

5.2 Rezultati za 2D okvire konstrukcije

Slika 21 pokazuje sopstvene periode za prva tri tona za sve konfiguracije. Iz poređenja praznog okvira i okvira s tradicionalnom ispunom može se uočiti značajan pad, oko četiri puta, u sopstvenim periodima konstrukcije od 1.2 s za prazan okvir na 0.33 s za okvir s tradicionalnom ispunom. Malo manji efekat smanjenja je kod konfiguracije sa otvorenim prizemljem, ali je i tu smanjenje perioda dva puta. S druge strane, smanjenje perioda u slučaju okvira sa izolovanom ispunom u odnosu na prazan okvir je mnogo manje. Sasvim popunjen ram sa izolovanom ispunom ima osnovni period 0.95 s, što predstavlja umanjenje od 21%. Ta razlika je još manja u slučaju okvira s delimično ili potpuno otvorenim prizemljem i iznosi 17%.

5.2 Results for 2D structural frames

Figure 21 shows fundamental periods for the first three modes for all configurations studied. Comparing the bare frame and the traditionally infilled, it can be seen a significant drop in natural period from the bare frame to the other configurations. Looking at the first natural period natural period being 1.20s for the bare frame and 0.33s for the frame with traditional infills, a four times reduction can be seen. Slightly lower effect is for open ground configuration, but again being almost twice smaller. On the other hand, the reduction on the natural period of the frames with decoupled infills with respect to the bare frame is much lower. The fully infilled frame with decoupling system gave a natural period of 0.95s. This represents a reduction of 21%. This is even lower for partially open ground and open ground where difference is 17%.



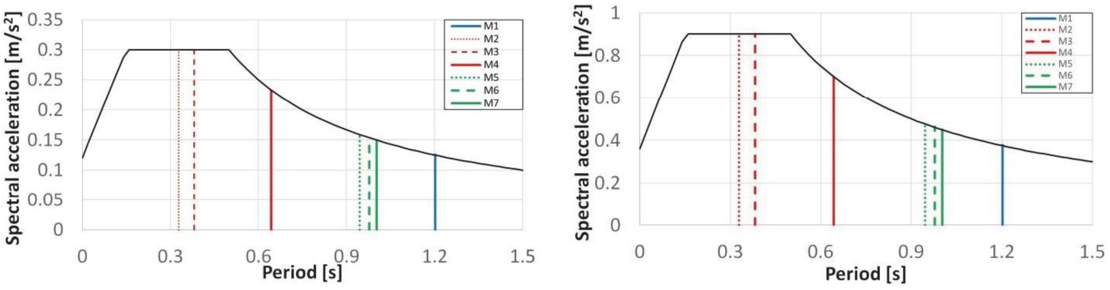
Slika 21. Sopstveni periodi za prvi, drugi i treći ton za različite konfiguracije
Figure 21. Natural periods of the first, second and third mode for different configurations

Kada se postave periodi na krivu spektra odgovora (Slika 22), može se videti jasna razlika između praznog okvira (plava boja) i okvira s tradicionalnom ispunom (crvena boja), pokazujući značajno potcenjivanje nivoa seizmičkog opterećenja ukoliko ispuna nije uzeta u obzir u toku proračuna. Period okvira s tradicionalnom ispunom nalazi se na platou spektralnog ubrzanja imajući skoro tri puta veće opterećenje od praznog okvira. Kod okvira sa izolovanom ispunom (zelena), ne samo da su im periodi blizu za sve tri konfiguracije već su i blizu perioda praznog okvira. Razlika u nivou seizmičkog opterećenja manja je od 12%, što pokazuje da se model praznog okvira može koristiti za projektovanje AB okvira sa izolovanom zidanom ispunom.

Okvir s tradicionalnom ispunom (crvena) aktivira ukupnu horizontalnu silu (Slika 23) skoro dva puta veću od praznog okvira. Ova horizontalna sila dostiže se mnogo ranije u odnosu na sistem sa izolovanom ispunom. Bitno je napomenuti da postoji značajno smanjenje sile u slučaju okvira s tradicionalnom ispunom i otvorenim prizemljem, dok to nije slučaj za okvir sa izolovanom ispunom. Ali je ta sila malo veća od sile za prazan okvir.

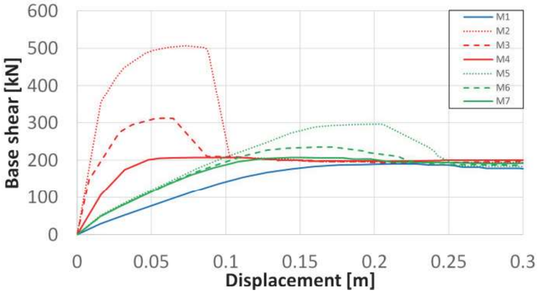
When locating the periods on the response spectrum curve (Figure 22), it can be seen a clear difference between the bare frame (blue) and the traditionally infilled frames (red), showing significant underestimation of the seismic load if infill walls are not taken into account during the design. Traditional infills fall into the plateau with the spectral acceleration almost three times higher than for bare frame. For the frames with decoupled infills instead (green), not only the periods remain close in between each other, but also are much closer to the ones of the bare frame. The difference in the seismic load level is less than 12%, showing that bare frame model can be used for the design of RC frames with decoupled infill walls.

The traditionally infilled structural frame(red) activates base shear (Figure 23) almost double than the bare frame (blue). This base shear, however is achieved at a much earlier stage compared to the decoupled system. It is important to notice significant reduction in base shear force in the case of open ground story of traditionally infilled frame whereas for the case of decoupled frame there is no significant change in the base shear force level. However it is slightly higher than for the bare frame.



a) b)

Slika 22. Prvi period oscilovanja na spektru odgovora za a) PGA=0.1g and b) PGA=0.3g
Figure 22. First natural periods on the response spectrum curves for a) PGA=0.1g and b) PGA=0.3g



Slika 23. Krive dobijene pushover analizom
Figure 23. Pushover analysis curves

Relativno međuspratno pomeranje okvira s tradicionalnom ispunom i otvorenim prizemljem pokazuje pojavu fleksibilnog sprata (slika 24). Gledajući u rezultate nelinearne dinamičke analize za PGA=0.1g maksimalno relativno međuspratno pomeranje na prvom nivou je 0.93%. Uočava se da postoji značajan skok na prelazu prvog i drugog nivoa, na kome dolazi do pada relativnog međuspratnog pomeranja na 0.07% i 0.04%. Za PGA=0.3g okvir sasvim popunjen tradicionalnom ispunom i sa otvorenim prizemljem ima relativno međuspratno pomeranje 0.15% i 0.11% na prvom i drugom spratu, ostajući u granicama malih vrednosti i na višim spratovima; dok se 3.85% relativnog međuspratnog pomeranja javilo u prizemlju. Ovo relativno međuspratno pomeranje tri puta je veće u odnosu na ono za slučaj delimično ispunjenog prizemlja i četiri puta veće od sasvim popunjenog okvira.

Kao što je i očekivano, usled povećanja krutosti, uzrokovanog zidanom ispunom, pomeranje poslednjeg sprata okvira s tradicionalnom ispunom je značajno manje od ostalih okvira. Takođe, u slučaju oba sistema uočava se povećanje apsolutnog pomeranja kako se broj zidova ispune smanjuje u prizemlju. Za slučaj tradicionalne ispune, za delimično ili potpuno otvoreno prizemlje, apsolutna pomeranja su 0.307 m i 0.351m, dok su ona za izolovanu ispunu 0.616 m i 0.635 m. Isto ponašanje je za oba nivoa ubrzanja. Uočava se da su za okvire s tradicionalnom ispunom, apsolutna pomeranja nekoliko puta manja od praznih okvira i okvira sa izolovanom ispunom. Ovo jeste slučaj za konfiguraciju s delimično otvorenim prizemljem ili sa sasvim popunjenom ispunom.

The inter storey drifts of the fully open ground storey for frame with traditional infills, show that a soft storey behaviour occurred (Figure 24). Looking at the results of the nonlinear time history analysis for PGA=0.1g the maximum inter story drift at the first level is 0.93%. It can be observed that for the first floor and second floor, there was a significant and abrupt reduction in the drift, 0.07% and 0.04%. For PGA=0.3g fully open ground storey frame with traditional infills had inter storey drift of 0.15% and 0.11% at first and second floor, remaining small and almost constant for the rest of the floors; whereas 3.85% of drift occurred at the ground floor. This drift is three times higher than for the case of partially open ground floor and four times higher than fully infilled frame.

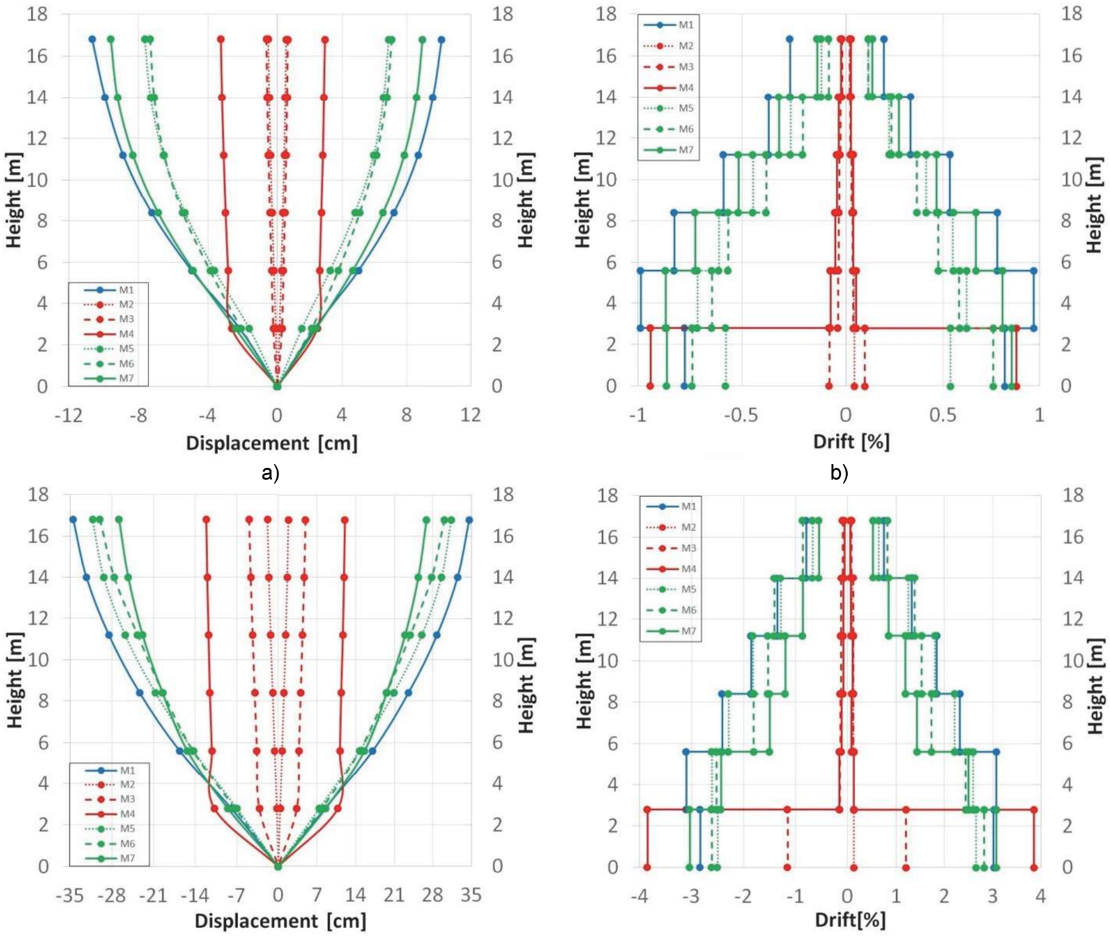
As it was expected due to the increase in stiffness caused by the infill walls, the top floor displacement of the frames with traditional infills are significantly lower than for the other frames. Also for both systems, it can be noticed an increase in absolute displacements as the amount of infilled frames in the ground floor is reduced. For the traditional infill, for the partial and fully open ground floor the absolute displacements were 0.307m and 0.351m, respectively; while with the decoupling system, they were 0.616m and 0.635m respectively. The same behaviour can be seen for both PGA levels. It can be observed that for the traditional infilled systems, the absolute displacements are several times smaller than the bare frame and the decoupled system. This is true for the structural frame fully infilled with traditional infills and also for the partially open ground floor configuration. However, fully open ground floor configuration with

Ali za potpuno otvoreno prizemlje s tradicionalnom ispunom, apsolutna pomeranja u prizemlju su najveća. Apsolutna pomeranja okvira sa izolovanom ispunom nalaze se između pomeranja za prazan okvir i okvir s tradicionalnom ispunom, ali su bliža pomeranjima praznog okvira.

S druge strane, u slučaju sa izolovanim ispunama, postoji ujednačen prelaz u relativnim međuspratnim pomeranjima između spratova, gde je najveća vrednost u prizemlju a najmanja na poslednjem spratu. Ono što je još bitnije jeste da je za sve konfiguracije sa izolovanom zidanom ispunom nelinearna dinamička analiza kao rezultat dala relativna međuspratna pomeranja bliska onima kod praznog okvira. Pored toga, efekat fleksibilnog sprata se nije javio u slučaju okvira sa izolovanom ispunom niti postoji nagli prelaz u vrednostima relativnog međuspratnog pomeranja između spratova.

traditional infills experienced highest displacement in the ground floor. The displacements of the decoupled frame fall in between the displacements of the bare frame and the traditional one, but they resemble more and are closer to the values of the bare frames.

On the contrary, for the decoupling system, there is a smooth reduction of inter storey drift from its maximum along the first floors up to its minimum at the top floor. What is more important is that all infill configurations for nonlinear time history analysis, frames with decoupled infills had drifts in a range of bare frame model distributed in the same manner along the frame height. Furthermore, soft storey effect is absent in the case of decoupled infills and there is no sudden increase of drift between the floors.



a) b)

c) d)

Slika 24. Rezultati nelinearne dinamičke analize za svaki sprat: a) maksimalna apsolutna pomeranja (za PGA=0.1g); b) maksimalna relativna međuspratna pomeranja (za PGA=0.1g); c) maksimalna apsolutna pomeranja (za PGA=0.3g) i d) maksimalna relativna međuspratna pomeranja (za PGA=0.3g)

Figure 24. Nonlinear time history results at each storey: a) max absolute displacement (for a PGA=0.1g); b) max inter storey drift (for a PGA=0.1g); c) max absolute displacement (for a PGA=0.3g) and d) max inter storey drift (for a PGA=0.3g)

6 ANALIZA 3D ZGRADE

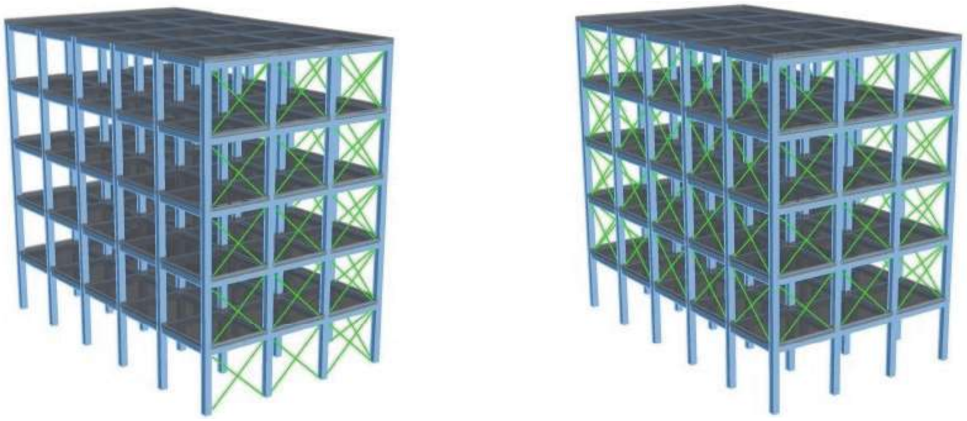
Za trodimenzionalnu zgradu, analizirane su tri konfiguracije zidane ispune, pored praznog okvira (slika 25a). Analizirana je petospratnica s tri polja u poprečnom pravcu i pet polja u podužnom pravcu. U prvoj konfiguraciji zidana ispuna se nalazi samo u spoljašnjim okvirima praveći tako jezgro od ispune (slika 25b). Druga konfiguracija predstavlja zgradu lociranu na uglu ulice koja sa te dve strane nema ispunu a sasvim su popunjeni okviri s druge dve strane (slika 25c). Ova konfiguracija je uobičajena u praksi i bitno je da se analizira jer nesimetričan raspored zidane ispune dovodi do nepoklapanja centra mase i centra krutosti što dovodi do pojave torzije cele zgrade. Kao što je navedeno u uvodu, analiza efekata fleksibilnog prizemlja takođe je jako bitna zbog prakse da se zidana ispuna ukloni iz nivoa prizemlja zbog funkcionalnih zahteva za garaže i radnje. Prema tome, ova konfiguracija je takođe analizirana (slika 25d). Sve konfiguracije su analizirane za slučaj s tradicionalnom ispunom i sa izolovanom ispunom. Analizirani modeli su: Model br. 1: Zgrada s praznim AB okvirima; Model br. 2: zgrada sa okvirima sa sasvim punom tradicionalnom ispunom; Model br. 3: zgrada na uglu s tradicionalnom ispunom; Model br. 4: zgrada sa otvorenim prizemljem s tradicionalnom ispunom; Model br. 5: zgrada sa ovirima sa sasvim punom izolovanom ispunom; Model br. 6: zgrada na uglu sa izolovanom ispunom; Model br. 7: zgrada sa otvorenim prizemljem sa izolovanom ispunom; i Modeli 8, 9 i 10 koji su kao Modeli 5, 6 i 7, samo bez elemenata na dijagonali, koji predstavljaju zidanu ispunu. Umesto toga, oni imaju samo masu predstavljenu kao linijsko opterećenje na poziciji zidova ispune. Poslednje tri konfiguracije su bitne kako bi se istražio potencijal upotrebe modela praznog okvira za proračun AB zgrada sa izolovanom zidanom ispunom. Ploča je modelirana s debljinom 0.2 m i opterećenja prethodno definisana za 2D okvire konstrukcije takođe su uzeta u obzir. Dispozicija u osnovi kao i raspored zidane ispune prikazan je na slici 26.

6 ANALYSIS OF A 3D BUILDING

For the three-dimensional building, three infill configurations were studied, besides a bare frame (Figure 25a). A five-storey high building consisting of 3 bays in the transversal direction and 5 bays in the longitudinal direction was analysed. In the first configuration infills are located in the most outer frames creating an infill core (Figure 25b). Second configuration represents the buildings located in a corner where two adjacent sides are without infill walls, whereas the other two are infilled (Figure 25c). This configuration is common in practice and important to be studied because if the walls are not symmetrically placed along the whole plan of the building, the position of the centre of stiffness and mass could be mismatch creating a torsional effect on the building. As discussed in introduction, the study of the soft storey mechanism is important due to the common practice to remove infill walls in the ground storey because of the functional requirement for shops or garages. Therefore, this configuration is also investigated (Figure 25d). All configurations were studied for the case of traditional infills and decoupled infills. The models analysed were: Model No. 1: bare frame building; Model No. 2: fully traditionally infilled frames; Model No. 3: corner building with traditionally infilled frames; Model No. 4: open ground floor with traditionally infilled frames; Model No. 5: fully infilled frame building with decoupled system; Model No. 6: corner building with decoupled infill system; Model No. 7: open ground floor building with decoupled infills; and Models 8, 9 and 10 made as Models 5, 6 and 7 just without struts presenting decoupled infill walls. Instead they have just mass at the position of infill walls assigned as line loads. Last three configurations are important to investigate the potential of the use of bare frame model for the design of RC buildings with decoupled infill walls. The slab was modelled with a 0.20m thickness and the loads previously defined for 2D structural frames were also taken into account. Ground plan configuration and distribution of infills is given on Figure 26.


a)

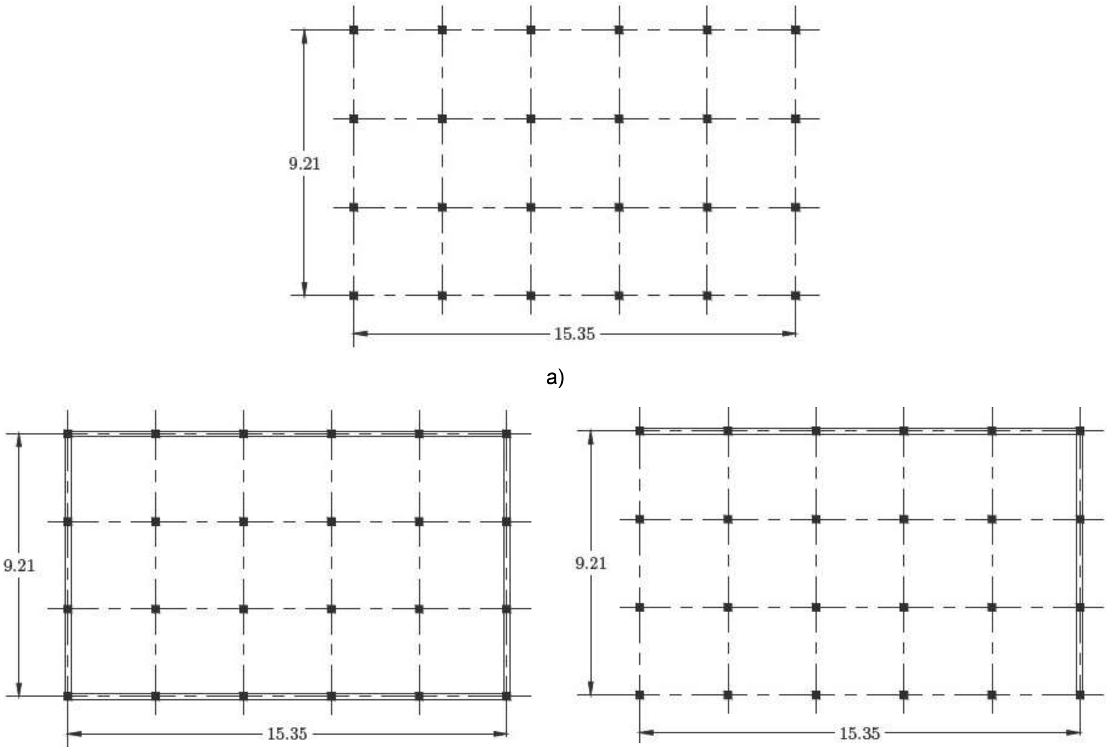
b)



c) d)

Slika 25. a) zgrada s praznim okvirima; b) zgrada sa okvirima sa sasvim punom ispunom; c) zgrada na uglu; i d) zgrada sa otvorenim prizemljem

Figure 25. a) bare frame building; b) fully infilled frames; c) corner building; and d) open ground floor building



a)

b) c)

Slika 26. Prikaz osnove: a) prazni okviri i zgrada sa otvorenim prizemljem; b) okviri sasvim popunjeni ispunom; i c) zgrada na uglu

Figure 26. Ground plan of: a) bare frame and open ground floor building; b) fully infilled frames; and c) corner building

6.1 Tipovi analize

Za 3D model zgrade, korišćene su iste analize (modalna, *pushover* i nelinearna dinamička) kao za 2D okvire konstrukcije. Za nelinearnu dinamičku analizu (*time history*) veštački generisani akcelerogrami korišćeni za analizu 2D okvira konstrukcije i ovde su upotrebljeni.

6.2 Rezultati za 3D zgradu

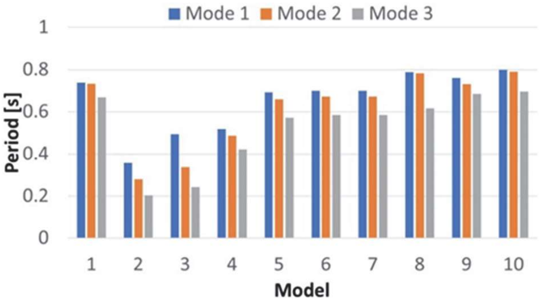
Krenuvši od modalne analize, može se uočiti da zgrade s tradicionalnom zidanom ispunom imaju značajno veću krutost u poređenju sa zgradama sa izolovanom ispunom. Rezultati (slika 27) pokazuju da zgrada sa sasvim popunjenom tradicionalnom ispunom ima dva puta manji prvi period oscilovanja u odnosu na zgradu s praznim okvirima. Za razliku od njih, zgrade sa izolovanom ispunom imaju periode koji su samo 6% manji. Za njih su takođe i druga dva perioda beznačajno manja za 10 i 14%. Suprotno od njih, zgrade s tradicionalnom ispunom imaju periode manje za 62 i 69% za drugi i treći ton. Ova razlika je manja za zgradu na uglu i zgradu sa otvorenim prizemljem, dok je za zgrade sa izolovanom ispunom period skoro isti za sve tri konfiguracije. Ono što je još važnije jeste da zgrade s masom koja predstavlja izolovanu ispunu imaju iste periode kao one s dijagonalnim elementima koji predstavljaju izolovanu ispunu.

6.1 Types of analysis

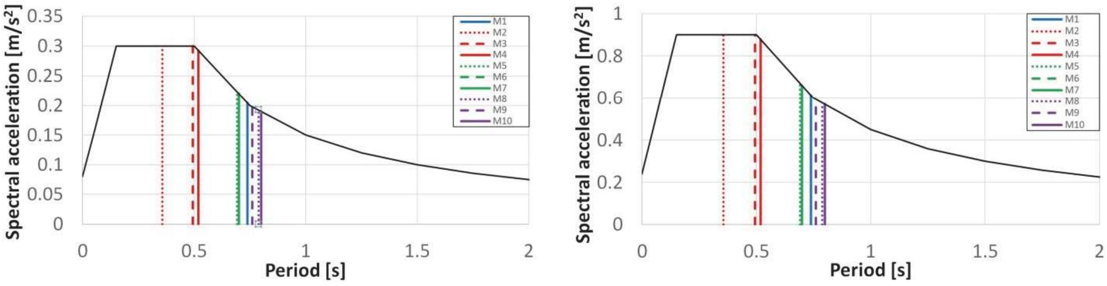
For the 3D building model, the same analyses (modal, pushover and nonlinear time history) as for 2D structural frames were used. Artificial accelerograms created for 2D structural frames are also used for the nonlinear time history calculations.

6.2 Results for 3D building

Starting from the modal analysis, it can be observed that the building which uses a traditional infills, presents a much stiffer behaviour in comparison with the one with decoupled infills. From the results (Figure 27), the completely infilled building with traditional infills has a two times smaller first period with respect to the bare frame building. Instead, for the building fully infilled with the decoupled walls, the reduction was of only 6% for the first period. For this building with decoupling system, the other two periods also presented a lower decrease in the period, with 10% and 14% representing the second and third mode period, respectively. In contrast, the traditional infilled system had a reduction of 62% and 69% of the second and third mode period. This difference is slightly smaller in the case of corner and open ground building for traditional infill, whereas it is almost the same for the decoupled infills in all three configurations. What is even more important that the buildings with the mass presenting decoupled infills have almost the same periods as the one with struts used for decoupled infills.



Slika 27. Sopstveni periodi za prvi, drugi i treći ton za različite konfiguracije
Figure 27. Natural periods of the first, second and third mode for different configurations



a) b)

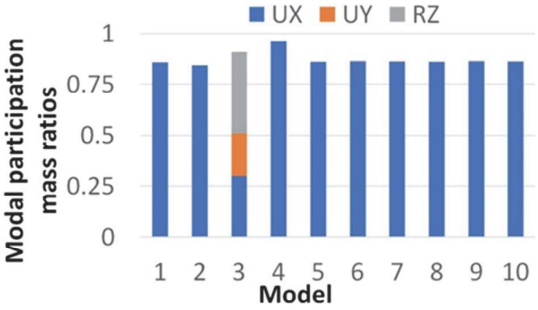
Slika 28. Prvi ton oscilovanja 3D zgrade na spektru odgovora za a) PGA=0.1g i b) PGA=0.3g
Figure 28. First natural periods of a 3D buildings on the response spectrum curves for a) PGA=0.1g and b) PGA=0.3g

Kada se periodi postave na spektar odgovora (slika 28), može se videti da zgrada sa izolovanom ispunom ima nivo opterećenja koji je blizak za sve konfiguracije, i on je blizak i s vrednošću za zgradu s praznim okvirima. S druge strane, zgrade s tradicionalnom ispunom nalaze se na platou spektra odgovora, daleko od vrednosti koja odgovara zgradi s praznim okvirima. Ukoliko se zgrade s tradicionalnom ispunom projektuju prema modelima praznih okvira, slično kao i za 2D okvire, potcenjuje se nivo spektralnog ubrzanja za više od 50%, dok je za zgrade sa izolovanom ispunom ta razlika zanemarljiva (manja od 10%). Rezultati pokazuju da se AB okvirne zgrade sa izolovanom ispunom, kada je ona predstavljena samo preko mase prikazane linijskim opterećenjem, poklapaju s nivoom seizmičkog opterećenja sa zgradama u kojima je ispuna modelirana pritisnutim dijagonalama. Stoga, jednostavan model s praznim okvirima s masom umesto pritisnutih dijagonala može biti iskorišćen za projektovanje AB ramovskih konstrukcija sa izolovanom ispunom.

Faktori participacije (slika 29) na najbolji način prikazuju efekat neujednačenog rasporeda tradicionalne ispune na slučaju zgrade na uglu. Od svih konfiguracija, jedino zgrada s tradicionalnom ispunom ima u odgovoru kombinaciju tonova. Zgrada na uglu s tradicionalnom ispunom ima 40% participacije torzionog tona u odgovoru konstrukcije. Suprotno od toga, zgrada sa izolovanom ispunom ima samo 0.5% participacije mase u rotaciji oko Z ose.

When the periods are located on the response spectrum curve (Figure 28), it can be seen that the buildings with the decoupling system are close together for all configurations, and also very close to the position of the bare frame period. On the other hand, it can be seen that the periods of the traditional infilled building are all located at the plateau of the response spectrum, far away from the bare frame. If buildings with traditional infills are designed with the bare frame model, similar to 2D structural frames, underestimation of the spectral acceleration would be more than 50%, whereas for the decoupled infills it is negligible (less than 10%). The results show that RC frame buildings where decoupled infills are taken into account as a line load presenting their mass match the seismic load level of the building with the struts presenting decoupled infills and bare frame building. Therefore, simple bare frame model with the mass instead of struts can be used for the design of RC frame buildings with decoupled infills.

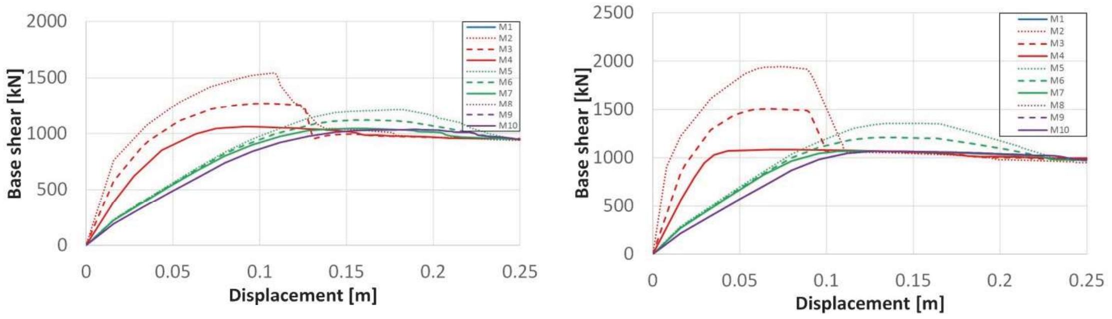
The modal participation mass ratios (Figure 29) in the best way presents the effect of traditional infill irregular arrangement in the case of corner building. Only, the corner building with traditional infills had mixed modes. The traditional corner building presented a 40% of mass participation in the rotational Z direction in the first mode. In contrast, the corner building with the decoupled infills presented only a 0.5% mass participation in the rotational Z direction.



Slika 29. Faktori participacije za prvi ton za različite konfiguracije
Figure 29. Modal participation mass ratios for the first mode for different configurations

Slično rezultatima na 2D okvirima, zgrade s tradicionalnom ispunom aktiviraju najveće horizontalne sile i u X i u Y pravcu (slika 30). Tradicionalni sistem takođe pokazuje nagli pad sile kada se dostigne maksimalna nosivost nakon čega kriva prati krivu kapaciteta praznog okvira. Takođe, uklanjanje tradicionalne ispune iz prizemlja smanjuje maksimalnu silu koju konstrukcija može da prihvati za 50%. Zgrada sa otvorenim prizemljem i tradicionalnom ispunom dolazi do kapaciteta pri mnogo manjim deformacijama u odnosu na ostale konfiguracije. Suprotno od toga, zgrada sa izolovanom ispunom ponaša se skoro identično u svim konfiguracijama, bez pokazivanja naglog pada sile i dostižući mnogo veći kapacitet deformacije.

Similar to the results from the 2D frames, the traditionally infilled frame buildings activate higher maximum base shear force in both X and Y direction than the building with decoupled infills and bare frame building (Figure 30). The traditional system also experiences a fast or sudden drop in load when the maximum was reached followed by a curve that follows the capacity curve of the bare frame. It can also be noticed that removing traditional infill walls in the ground floor reduces by 50% the maximum base shear attained by the structure. Building with open ground floor with traditional infills has reached its deformation capacity much sooner than all other configurations. In contrast, buildings with decoupled infills behave almost the same for all configurations, not experiencing sudden drop in the base shear force and providing higher deformation capacity.



a) b)

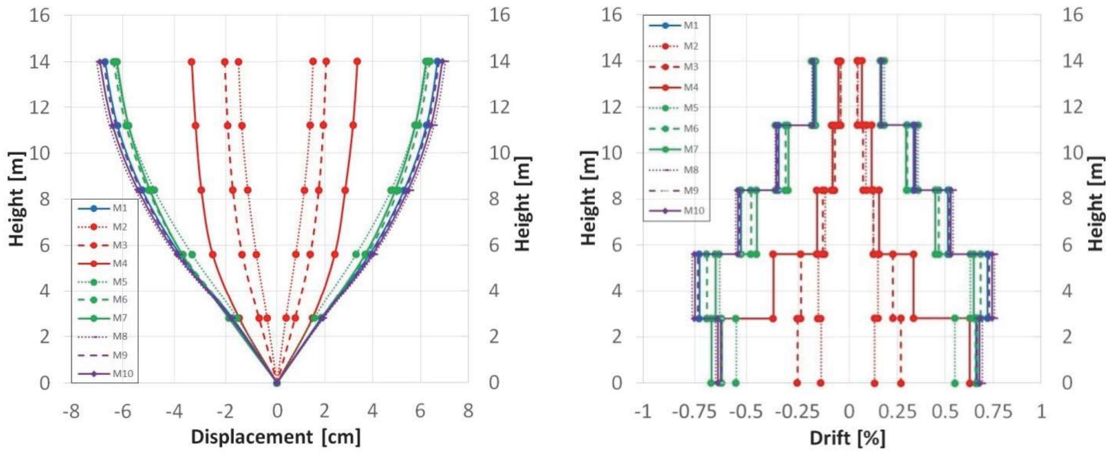
Slika 30. Pushover krive za zgradu za a) X pravac i b) Y pravac
Figure 30. Three-dimensional building pushover curves for a) X direction and b) Y direction

Rezultati nelinearne dinamičke analize (slike 31 i 32) pokazuju da zgrada s tradicionalnom ispunom ima generalno manja apsolutna pomeranja ali mnogo veće relativno međuspratno pomeranje, osim u slučaju otvorenog prizemlja. U ovoj konfiguraciji postoji ogromna razlika u relativnom međuspratnom pomeranju između prizemlja i prvog sprata. Ovo je više izraženo u Y pravcu a još više za slučaj ubrzanja PGA = 0.3g, dok je u X pravcu promena relativnog međuspratnog pomeranja postepena ali ponovo sa značajno većom promenom nego u ostalim konfiguracijama. Za zgradu na uglu s tradicionalnom ispunom, slično ponašanje se može uočiti ali s manjim relativnim međuspratnim pomeranjem u prizemlju.

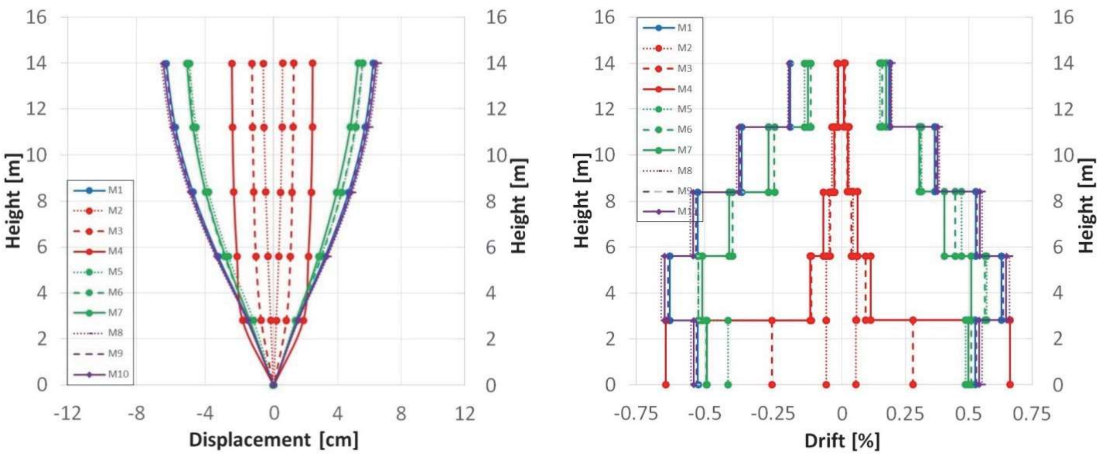
Što se tiče konfiguracija sa izolovanom ispunom, apsolutna pomeranja za sasvim pune okvire, zgradu na uglu i zgradu sa otvorenim prizemljem u granicama su vrednosti zgrade s praznim okvirima. Pojava fleksibilnog sprata nije prisutna ni u jednoj od konfiguracija sa izolovanom ispunom. Ovo je značajno unapređivanje koje dolazi kao rezultat toga da izolacija ispune uklanja efekat povećanja krutosti usled zidova ispune i usled toga nema skokova u nivou krutosti između različitih spratova.

Results of nonlinear time history analyses (Figure 31 and 32) show that buildings with traditional infills have in overall a lower absolute displacements and a much smaller inter storey drift, except for the case of the open ground configuration. For this situation huge difference in the inter storey drift between ground floor and first floor can be seen. This is more pronounced in Y direction and even higher for the case of PGA = 0.3g, whereas in X direction the change in inter storey drift is much smoother but with a noticeable higher change in the values compared with the rest of the models. For the corner building with traditional infills, a similar behaviour can be seen but with a smaller inter storey drifts in the ground floor.

For the decoupled infills, the absolute displacements for the fully infilled building, the corner building and the open ground floor building are in the range of the values of the bare frame model. The soft story effect cannot be observed in any of the configurations having decoupled infills. This is significant improvement coming from the decoupling measure that diminishes increase of stiffness coming from the infill walls and thus there are no jumps in stiffness between the floors.



a) b)



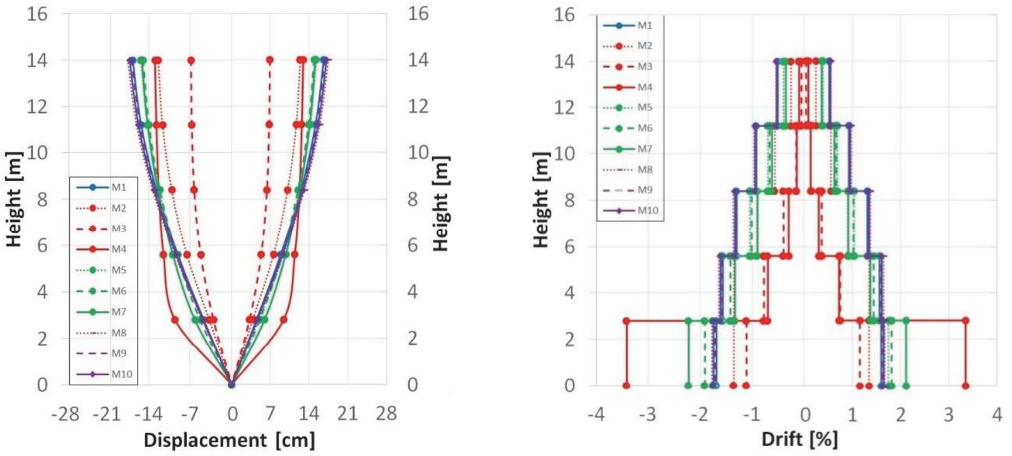
c) d)

Slika 31. Rezultati nelinearne dinamičke analize za PGA=0.1g: a) maksimalna apsolutna pomeranja i b) maksimalno relativno međuspratno pomeranje u X pravcu i c) maksimalna apsolutna pomeranja i d) maksimalno relativno međuspratno pomeranje u Y pravcu

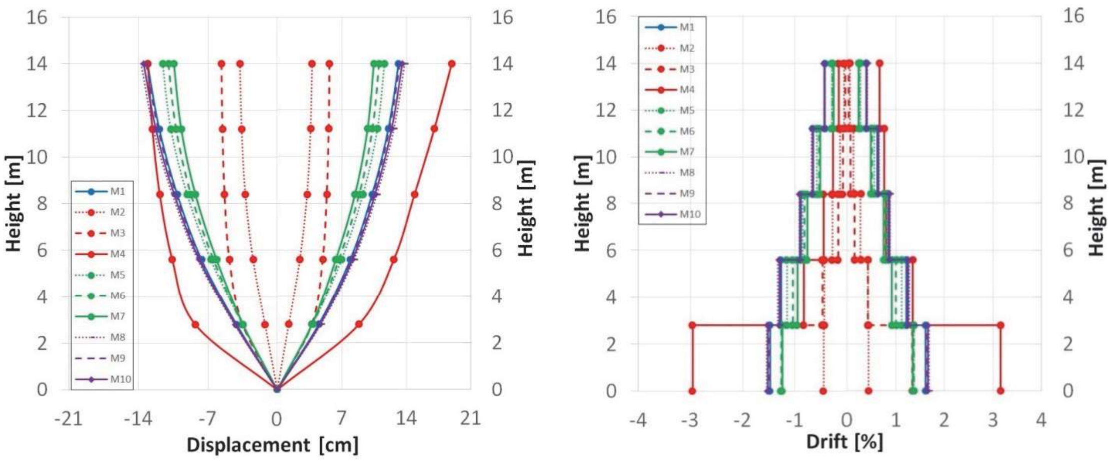
Figure 31. Nonlinear time history results for PGA=0.1g:a) max absolute displacements and b) max inter storey drift along X direction and c) max absolute displacements and d) max inter storey drift along Y direction

Usled nejednakog rasporeda ispune u slučaju zgrade na uglu, interesantno je analizirati rezultate u pravcu upravno na pravac nanetog opterećenja. Za tradicionalnu ispunu, neujednačen raspored apsolutnih pomeranja i relativnog međuspratnog pomeranja može se uočiti u ovom slučaju. Ovi uticaji koji dolaze od aktiviranja torzionog ponašanja zgrade nisu prisutni u zgradi sa izolovanom ispunom, čime pokazuju da se izolovanje ispune može koristiti kao mera za rešavanje problema torzije u slučaju nejednakog rasporeda zidane ispune, posebno kod zgrada na uglu.

Due to the irregular distribution of the infill walls in the corner building configuration, it is interesting to analyse the results in the perpendicular direction of the applied load. For the traditional infill, a prominent and uneven distribution of absolute displacements and inter storey drift can be observed in this case. These effects coming from the activation of the torsional displacements are absent in the case of buildings with decoupled infill walls, showing that decoupling can be used as measure to solve torsional problems in the case of irregular distribution of infill walls, specifically corner building.



a) b)



c) d)

Slika 32. Rezultati nelinearne dinamičke analize za PGA=0.3g: a) maksimalna apsolutna pomeranja i b) maksimalno relativno međuspratno pomeranje u X pravcu i c) maksimalna apsolutna pomeranja i d) maksimalno relativno međuspratno pomeranje u Y pravcu

Figure 32. Nonlinear time history results for PGA=0.3g: a) max absolute displacements and b) max inter storey drift along X direction and c)max absolute displacements and d) max inter storey drift along Y direction

7 ZAKLJUČAK

Ovaj rad predstavlja istraživanje ponašanja AB okvirnih zgrada sa izolovanom ispunom. Istraživanje je sprovedeno kako bi se ispitao uticaj izolacije ispune na nivou zgrade. Kao rešenje za izolaciju ispune korišćen je sistem INODIS. On pruža izolaciju u ravni i stabilnu vezu za opterećenje van ravni. S obzirom na to što pristup izolacije omogućava da se opterećenje u ravni i van ravni mogu razmatrati razdvojeno, za razliku od tradicionalne ispune, fokus istraživanja je ponašanje zidane ispune u ravni.

Prvo je sprovedena kalibracija i validacija numeričkih modela na jednospratnim okvirima s jednim brodom, koji su prethodno ispitani eksperimentalno. Zatim su analizirani 2D okviri s različitim rasporedom ispune. Tri različite konfiguracije koje su istraživane su: sasvim ispunjen okvir, okvir s delimično praznim prizemljem i okvir sa otvorenim prizemljem i njihovo ponašanje je poređeno s praznim okvirom. Za sve ove konfiguracije su istražene i tradicionalna i izolovana ispuna. Rezultati pokazuju da tradicionalna ispuna značajno smanjuje sopstvene periode okvira, i time značajno menja nivo seizmičkog opterećenja koje deluje na konstrukciju. To nije slučaj sa izolovanom ispunom, gde je promena perioda beznačajna. Krive sila–pomeranje dobijene *pushover* analizom potvrđuju nizak kapacitet deformacije okvira s tradicionalnom ispunom u poređenju s praznim okvirima i okvirima sa izolovanom ispunom. Nelinearna dinamička analiza je na najbolji način pokazala negativne efekte tradicionalne ispune na ponašanje okvira. U slučaju otvorenog prizemlja veliki skok u relativnom međuspratnom pomeranju javlja se u prizemlju u odnosu na ostale spratove. Suprotno od toga, AB okviri sa izolovanom ispunom ponašaju se slično kao prazni okviri imajući malo niže relativno međuspratno pomeranje i postepen porast apsolutnih pomeranja duž visine okvira.

7 SUMMARY

The paper presents investigation on the behaviour of RC frame buildings with decoupled infill walls. Research was performed in order to study the effects of infill decoupling on the building level. As a solution for decoupling the INODIS system was used. It provides in-plane decoupling and stable out-of-plane connection. Since the decoupling approach enables in-plane and out-of-plane loads to be studied separately, in contrast to the traditional infills, here the focus was on the numerical modelling of in-plane behaviour of infill walls. For that purpose equivalent strut model was employed.

First, calibration and validation of the numerical model was done on one-bay frames with one storey, previously tested experimentally. Then, 2D structural frames with different infill distribution were analysed. Three different infill configurations were studied including: fully infilled frame, open ground storey frame and partially open ground storey frame and its behaviour was compared with the bare frame. For all these configurations, both traditional and decoupling approaches were studied. Results show that traditional infill walls significantly reduce natural period of the frame, thus considerably change the level of seismic loading acting on the structure. This is not the case with decoupled infills, where the change of period is insignificant. Force-displacement curves obtained in pushover analysis confirm low deformation capability of traditionally infilled frames in comparison with the bare frames and frames with decoupled infills. Nonlinear time history analysis showed in the best way negative effects of traditional infills on the behaviour of structural frames. In the case of open ground floor configuration huge jump in the inter storey drift can be noticed on the ground floor in comparison with the other storeys. In contrast, RC frames with decoupled infill walls behaved similarly as the bare frame configuration

Za 3D zgradu analizirana je petospratnica s pet spratova i tri polja u poprečnom pravcu i pet polja u podužnom pravcu. Konfiguracija sa ispunom u spoljašnjim okvirima ispitivana je zajedno sa zgradom na uglu i zgradom sa otvorenim prizemljem. Pored zgrade sa praznim okvirima, ove tri konfiguracije su istražene za slučaj tradicionalne i izolovane ispune. Pored toga, dodatna tri modela su napravljena koji su imali masu zadatu kao linijsko opterećenje na mestima izolovane ispune. Rezultati jasno pokazuju veliku razliku u periodima oscilovanja između zgrade s praznim okvirima i zgrade s tradicionalnom ispunom. Ovo nije slučaj sa zgradama sa izolovanom ispunom kod kojih se periodi oscilovanja razlikuju za 10% u odnosu na zgradu s praznim okvirima. To značajno utiče na nivo sizmičkog opterećenja koje deluje na zgradu, koji je u slučaju s tradicionalnom ispunom 50% veći u odnosu na zgradu s praznim okvirima koja se uobičajeno koristi danas u praksi u toku proračuna. Međutim, razlika u slučaju izolovane ispune je zanemarljiva. Ovo jasno pokazuje prednosti pristupa izolacije, koji pruža jasan i jednostavan postupak proračuna, s obzirom na to što eventualna primena izolacije ispune beznačajno menja trenutnu građevinsku praksu. Pored toga, rezultati oblika odgovora zgrade na uglu pokazuju značajne torzione efekte u slučaju tradicionalne ispune, što nije slučaj kada se primeni izolovana ispuna. Razlog za to je činjenica da izolovanje ispune uklanja efekat povećanja krutosti koja dolazi od zidane ispune.

Slično rezultatima na 2D okvirima, okviri s tradicionalnom ispunom aktiviraju najveću horizontalnu silu i u X i u Y pravcu. Takođe, zgrada sa otvorenim prizemljem i tradicionalnom ispunom dostigla je kapacitet deformacije mnogo ranije od svih ostalih konfiguracija.

Nelinearna dinamička analiza pokazala je katastrofalne efekte tradicionalne ispune na celokupno ponašanje zgrade. Krta veza okvira i ispune dovodi do značajne promene krutosti cele zgrade što za rezultat ima smanjenje pomeranja i pojavu torzije u slučaju zgrade na uglu kao i pojave fleksibilnog sprata u slučaju zgrade sa otvorenim prizemljem. Rezultati pokazuju da je zgrada s tradicionalnom ispunom imala značajno manja apsolutna pomeranja i relativno međuspratno pomeranje u odnosu na druge konfiguracije, osim u slučaju zgrade sa otvorenim prizemljem gde se javlja veliko relativno međuspratno pomeranje. Apsolutno pomeranje koje se javlja duž visine zgrade potvrđuje pojavu fleksibilnog sprata u slučaju tradicionalne ispune kao rezultat velikih pomeranja u odnosu na sve ostale konfiguracije iako su relativna međuspratna pomeranja mala. Ovo se javlja usled velikih pomeranja na nivou prizemlja, koja dovode do toga da se cela zgrada značajno pomera. Ovi negativni efekti mogu biti uklonjeni primenom izolacije ispune koja za rezultat ima blagu promenu pomeranja i relativnog međuspratnog pomeranja. Pojava fleksibilnog sprata u ovom slučaju nije prisutna zato što izolacija ispune uklanja promenu krutosti između spratova, koja dolazi od zidane ispune. I apsolutna pomeranja i relativno međuspratno pomeranje zgrade sa izolovanom ispunom su u granicama zgrade s praznim okvirima. Ovo potvrđuje da model s praznim okvirima može da predstavi realno situaciju zgrade sa izolovanom ispunom, umesto da bude daleko od pravog ponašanja što je slučaj s tradicionalnom ispunom. To pokazuje potencijal primene modela s with slightly lower inter storey drifts and having smooth rise in absolute displacements along the height.

For the three-dimensional building a five-storey building was analysed, consisting of 3 bays in the transversal direction and 5 bays in the longitudinal direction. Configuration with outer frames completely filled with masonry walls was studied, together with the case of corner and open ground floor building. Besides bare frame building, these three configurations were studied in the case of traditional infills as well as decoupled infills. Furthermore, additional three models were investigated with only mass as line load presenting decoupled infill walls. The results clearly show huge difference in natural period between bare frame configuration and building with traditional infill walls. This is not the case with buildings having decoupled infills, where natural periods defer from the bare frame ones less than 10%. This affects a lot the level of seismic load actually acting on the building, which in the case of traditional infill can be even 50% higher than in the case of bare frame configuration that is usually used in the design today. However, the difference in the case of decoupled infills is negligible. This shows the advantage of decoupling approach having clear and simple design process, since the eventual implementation of decoupling system alter only marginally the current design practice. Furthermore, results for the mode shapes of corner building configuration show significant torsional effects in the case of traditional infills, which is not the case for the decoupled infill walls. This is due to the fact that decoupling diminishes increase of stiffness coming from the infill walls.

Similar to the results from the 2D frames, the traditionally infilled frames presented a higher maximum base shear in both X and Y direction than the decoupled and bare frame structures. In addition, building with open ground floor and traditional infills has reached its deformation capacity much sooner than all other configurations.

Nonlinear time history analysis show disastrous effects of traditional infill walls on the overall building behaviour. Rigid connection between infills and frame produce significant change in the stiffness of the overall building, resulting in reduction of displacements but producing torsional behaviour in the case of corner building and soft storey effect in the case of open ground floor. Results show that buildings with traditional infills have lower absolute displacements and inter storey drifts than other configurations, except in the case of open ground floor configuration where a huge inter storey drifts are present at the ground floor. The absolute displacements along the building height confirm appearance of soft storey in the case of traditional infills, resulting in the highest displacements of all configuration even the inter storey drifts at higher floors are low. This is due to the very high displacement in the ground floor producing whole building to move significantly. These negative effects are removed with the application of decoupling resulting in smooth change of displacement and inter storey drift. The soft storey effect is absent in the case of decoupled infill because the decoupling diminishes change of stiffness between the floors that comes from the infill walls. Both absolute displacements and inter storey drifts of the buildings with decoupled infills are in the range of the bare frame configuration. This praznim okvirima u proračunu AB okvirnih konstrukcija sa izolovanom ispunom.

Treba napomenuti da interakcija uticaja u ravni i van ravni ispune nije uzeta u obzir u modelima, što je opravdano za slučaj izolovane ispune. Međutim, za slučaj tradicionalne ispune ova interakcija ne može biti zanemarena i tada bi numerički modeli predstavili još lošije ponašanje. Pored toga, model ispune predstavljene elementom po dijagonali ne može da predstavi efekte ispune na stubove i povećanje momenata i smičuće sile, što ponovo nije problem za slučaj izolovane ispune zbog eliminisane interakcije okvira i ispune, ali u slučaju tradicionalne ispune to bi dovelo do još gorih rezultata.

Na osnovu prikazanih rezultata može se zaključiti da tradicionalna ispuna vezana za ram preko maltera značajno menja ponašanje AB zgrada i to je neophodno uzeti u obzir u toku projektovanja. Jedini način da se to uradi jeste da se zidana ispuna modelira, što je prilično kompleksan, praktično neprimenjiv zadatak za svakodnevnu praksu. Pogotovo kada taj numerički model treba da uzme u obzir interakciju uticaja van ravni i u ravni, što je neophodno. Tada je proračun AB okvirnih konstrukcija s tradicionalnom ispunom praktično nemoguć. Prema tome, koncept proračuna AB zgrada sa zidanom ispunom mora se unaprediti tako da ponudi inženjerima pouzdano i stabilno rešenje zasnovano na konstruktivnim merama a ne na detaljnim numeričkim modelima. Jedno od obećavajućih rešenja jeste izolacija ispune od okolnog okvira. Ova konstruktivna mera pruža značajna poboljšanja u poređenju s tradicionalnom ispunom. Korist postupka izolacije ogleda se u odloženoj aktivaciji zidane ispune i time se značajno povećava kapacitet deformacije, kao i uklanjanje interakcije uticaja u ravni i van ravni, čime se značajno poboljšava ponašanje AB zgrade sa zidanom ispunom. Dodatni doprinos izolacije ispune vidi se u slučaju bilo kakve promene u konstrukciji ili tradicionalnoj ispuni za vreme izvođenja ili u toku upotrebe objekta, svaka ta promena mora se adekvatno opravdati i verifikovati, što nije slučaj sa izolovanom ispunom. Pored toga, jednostavan numerički model koji uzima u obzir izolovanu zidanu ispunu samo kao masu atraktivan je za aplikaciju u inženjerskoj praksi, što pristupu izolacije ispune pruža veliki potencijal za primenu.

ZAHVALNICA

Autori srdačno uvažavaju finansijsku podršku „Arbeitsgemeinschaft Mauerziegel im Bundesverband der Deutschen Ziegelindustrie e.V” i iskazuju posebnu zahvalnost dr Udu Mejeru (Udo Meyer) za njegove vredne savete i podršku u toku sprovođenja Evropskog projekta INSYSME.

confirms that bare frame model will present a real situation in the case of decoupled infills, instead of being far from the real behaviour for the case of traditional infills. This shows the potential of use of bare frame model in the design of RC frame buildings with decoupled infills.

It should be pointed out that in-plane/out-of-plane interaction is not taken into account in these models, which is justified when decoupling approach is applied. However, for the case of traditional infill this interaction cannot be neglected and even worse behaviour than the one presented in these models can be expected. Furthermore, infill model with one diagonal strut cannot present the effects of infill wall to the columns and increase of moment and shear force, which again is not the problem for decoupled due to the eliminated infill/frame interaction, but in the case of traditional infill it would lead to much worse results.

Based on the results it can be concluded that traditionally connected infill walls using mortar to fill the gaps between frame and infill wall are significantly changing the behaviour of the RC buildings and they should be appropriately designed. The only way to correctly design traditional infills is to model infill walls, which is rather complex and inapplicable for everyday engineering works. Especially, when numerical model should take into account IP/OOP interaction, which is necessary. Then the design of RC frame buildings with traditional infills is practically impossible. Therefore, the design concept of infilled frame buildings should be improved in the sense that offers engineers to apply reliable and stable solution based on constructional improvements and not detailed numerical models. One of the promising options is decoupling infill walls from the frame. This construction measure shows significant improvements when compared to the traditional infills. Benefits of decoupling approach such as delayed infill activation and thus significant deformation capacity, as well as removal of in-plane/out-of-plane interaction, significantly improve overall behaviour of the RC buildings with infill walls. Additional benefit of decoupling can be seen in the case of any change in the structure or in the traditional infills during the construction phase or during the subsequent life of the structure, this change should be properly justified and verified, which is not the case for decoupled infills. Furthermore, simple numerical model that considers decoupled infill walls with their mass is attractive for application in the engineering practice, thus the approach of infill decoupling shows huge potential for application.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support from the “Arbeitsgemeinschaft Mauerziegelim Bundesverband der Deutschen Ziegelindustriee.V” and express their special thanks to Dr.Udo Meyer for his valuable suggestions and support during the execution of the European project INSYSME.

8 LITERATURA
REFERENCES

[1] Braga, F., Manfredi, V., Masi, A., Salvatori, A., & Vona, M. (2011). Performance of non-structural elements in RC buildings during the L'Aquila, 2009 earthquake. Bulletin of Earthquake Engineering, 9(1), 307-324.

[2] Hermanns, L., Fraile, A., Alarcón, E., &Álvarez, R. (2014). Performance of buildings with masonry infill walls during the 2011 Lorca earthquake. Bulletin of Earthquake Engineering, 12(5), 1977-1997.

[3] Yazgan, U., Oyguç, R., Ergüven, M. E., &Celep, Z. (2016). Seismic performance of buildings during 2011 Van earthquakes and rebuilding efforts. Earthquake Engineering and Engineering Vibration, 15(3), 591-606.

[4] Masi, A., Chiauzzi, L., Santarsiero, G., Manfredi, V., Biondi, S., Spacone, E., ...&Verderame, G. M. (2017). Seismic response of RC buildings during the M w 6.0 August 24, 2016 Central Italy earthquake: The Amatrice case study. Bulletin of Earthquake Engineering, 17(10), 5631-5654.

[5] Nikolić-Brzev, S., Marinković, M., Milicević, I. i Blagojević, N. (2020). Posledicezemljotresa u Albanijiod 26.11.2019. naobjekte i infrastrukturu (Consequences of the November 26, 2019 Albania earthquake on the buildings and infrastructure), Serbian Association for earthquake engineering (SUZI-SAEE), Belgrade, Serbia (in Serbian), 80 p.

[6] Miranda, E., Mosqueda, G., Retamales, R., &Pekcan, G. (2012). Performance of nonstructural components during the 27 February 2010 Chile earthquake. Earthquake Spectra, 28(S1), S453-S471.

[7] Rossi, A., Morandi, P., Milanesi, R.R., Magenes, G., (2019). Economic and Technical advantages of an innovative infill solution in the seismic response of RC buildings, 4th International Workshop on the Seismic Performance of Non-Structural Elements (SPONSE), May 22-23, 2019 – Pavia, Italy

[8] Varum, H., Furtado, A., Rodrigues, H., Dias-Oliveira, J., Vila-Pouca, N. and Arêde, A. (2017). Seismic performance of the infill masonry walls and ambient vibration tests after the Ghorka 2015, Nepal earthquake. Bulletin of Earthquake Engineering, 15(3), 1185-1212.

[9] Yousefianmoghadam, S., Song, M., Mohammadi, M. E., Packard, B., Stavridis, A., Moaveni, B., & Wood, R. L. (2020). Nonlinear dynamic tests of a reinforced concrete frame building at different damage levels. Earthquake Engineering & Structural Dynamics.

[10] Ricci, P., Verderame, G. M., & Manfredi, G. (2011). Analytical investigation of elastic period of infilled RC MRF buildings. Engineering structures, 33(2), 308-319.

[11] Asteris, P. G., Repapis, C. C., Tsaris, A. K., Di Trapani, F., &Cavaleri, L. (2015). Parameters affecting the fundamental period of infilled RC frame structures. Earthquakes and Structures, 9(5), 999-1028.

[12] Perrone, D., Brunesi, E., Filiatrault, A., &Nascimbene, R. (2020). Probabilistic estimation of floor response spectra in masonry infilled reinforced concrete building portfolio. Engineering Structures, 202, 109842.

[13] Mehrabi, A. B., Benson Shing, P., Schuller, M. P., & Noland, J. L. (1996). Experimental evaluation of masonry-infilled RC frames. Journal of Structural engineering, 122(3), 228-237.

[14] Al-Chaar, G., Issa, M., & Sweeney, S. (2002). Behavior of masonry-infillednonductile reinforced concrete frames. Journal of Structural Engineering, 128(8), 1055-1063.

[15] Stavridis, A., &Shing, P. B. (2010). Finite-element modeling of nonlinear behavior of masonry-infilled RC frames. Journal of structural engineering, 136(3), 285-296.

[16] Zhai, C., Kong, J., Wang, X., & Chen, Z. (2016). Experimental and finite element analytical investigation of seismic behavior of full-scale masonry infilled RC frames. Journal of Earthquake Engineering, 20(7), 1171-1198.

[17] Hak, S., Morandi, P., and Magenes, G. (2017). Prediction of inter-storey drifts for regular RC structures with masonry infills based on bare frame modelling. Bulletin of Earthquake Engineering, 1-29.

[18] McDowell, E. L., McKee, K., &Sevin, E. (1956). Arching action theory of masonry walls. Journal of the Structural Division, 82(2), 1-8.

[19] Dawe, J. L., &Seah, C. K. (1989). Out-of-plane resistance of concrete masonry infilled panels. Canadian Journal of Civil Engineering, 16(6), 854-864.

[20] Asteris, P. G., Cavaleri, L., Di Trapani, F., &Tsaris, A. K. (2017). Numerical modelling of out-of-plane response of infilled frames: State of the art and future challenges for the equivalent strutmacromodels. Engineering Structures, 132, 110-122.

[21] Furtado, A., Rodrigues, H., Arêde, A., &Varum, H. (2018). Out-of-plane behavior of masonry infilled RC frames based on the experimental tests available: A systematic review. Construction and Building Materials, 168, 831-848.

[22] Furtado, A., Rodrigues, H., Arêde, A., &Varum, H. (2017). Assessment of the mainshock-aftershock collapse vulnerability of RC structures considering the infills in-plane and out-of-plane behaviour. Procedia engineering, 199, 619-624.:

[23] Da Porto, F., Guidi, G., DallaBenetta, M., &Verlato, N. (2013, June). Combined in-plane/out-of-plane experimental behaviour of reinforced and strengthened infill masonry walls. In Proceedings of the 12th Canadian Masonry Symposium (pp. 2-5).

[24] Morandi, P., Hak, S., &Magenes, G. (2014, January). In-plane experimental response of strong masonry infills. In 9th international masonry conference.

[25] De Risi, M. T., Di Domenico, M., Ricci, P., Verderame, G. M., &Manfredi, G. (2019). Experimental investigation on the influence of the aspect ratio on the in-plane/out-of-plane interaction for masonry infills in RC frames. Engineering Structures, 189, 523-540.

[26] Butenweg, C., Marinković, M., &Salatić, R. (2019). Experimental results of reinforced concrete frames with masonry infills under combined quasi-static in-plane and out-of-plane seismic loading. Bulletin of Earthquake Engineering, 17(6), 3397-3422.
[27] Flanagan, R. D., & Bennett, R. M. (1999). Bidirectional behavior of structural clay tile infilled frames. Journal of structural engineering, 125(3), 236-244.
[28] Yuen, T. Y., Kuang, J. S., & Ali, B. S. M. (2016). Assessing the effect of bi-directional loading on nonlinear static and dynamic behaviour of masonry-infilled frames with openings. Bulletin of Earthquake Engineering, 14(6), 1721-1755.
[29] Paulay, T. and Priestley, M. J. N. (1992). Seismic Design of Reinforced Concrete and Masonry Buildings. John Wiley and Sons, Inc., New York, NY, USA.
[30] Kostinakis, K., &Athanatopoulou, A. (2020). Effects of in-plan irregularities caused by masonry infills on the seismic behavior of R/C buildings. Soil Dynamics and Earthquake Engineering, 129.
[31] EN 1998-1 (2004). Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings (EN 1998-1). CEN, Brussels, Belgium.
[32] Ferraioli, M., &Lavino, A. (2020). Irregularity Effects of Masonry Infills on Nonlinear Seismic Behaviour of RC Buildings. Mathematical Problems in Engineering, 2020.
[33] Onat, O., Correia, A. A., Lourenço, P. B., &Koçak, A. (2018). Assessment of the combined in-plane and out-of-plane behavior of brick infill walls within reinforced concrete frames under seismic loading. Earthquake Engineering & Structural Dynamics, 47(14), 2821-2839.
[34] Padhy, T.K., Prasad, A.M., Menon, D., Robin, D.P. (2012). Seismic Performance Assessment of Open Ground StoreyBuildings, Proceedings, 15th World Conference on Earthquake Engineering, Lisbon
[35] Pokhrel, A., Gautam, D., &Chaulagain, H. (2019). Effect of variation on infill masonry walls in the seismic performance of soft story RC building. Australian Journal of Structural Engineering, 20(1), 1-9.
[36] Mazza, F., Mazza, M., &Vulcano, A. (2018). Base-isolation systems for the seismic retrofitting of rc framed buildings with soft-storey subjected to near-fault earthquakes. Soil Dynamics and Earthquake Engineering, 109, 209-221.
[37] Chiou, Y. J., Tzeng, J. C., &Liou, Y. W. (1999). Experimental and analytical study of masonry infilled frames. Journal of Structural Engineering, 125(10), 1109-1117.
[38] Charleson, A. (2012). Seismic design for architects. Routledge.
[39] Murty, C. V. R., Brzev, S., Faison, H., Irfanoglu, A., &Comartin, C. D. (2001). The seismic performance of reinforced concrete frame buildings with masonry infill walls.
[40] Polyakov S.V., (1963). Masonry in framed buildings. National Lending Library for Science and Technology, Yorkshire, U.K.
[41] Holmes, M. (1961). Steel frames with brickwork and concrete infilling. Proceedings of the Institution of Civil Engineers, 19(4), pp.473–478.
[42] Liberatore, L., and Mollaioli, F. (2015). Influence of masonry infill modelling on the seismic response of reinforced concrete frames. Civil-Comp Proceedings, 108.
[43] Crisafulli, F. J., (1997). Seismic behaviour of reinforced concrete structures with masonry infills. Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
[44] Asteris, P. G. (2008). Finite element micro-modelling of infilled frames. Electronic Journal of Structural Engineering, 8 1-11.
[45] Syrmakezis C. A. and Vratsanou V. Y. (1986). Influence of Infill Walls to RC Frames Response. Proceedings of the 8th European Conference on Earthquake Engineering, Lisbon, Portugal, Vol. 3, pp. 6.5/47-53.
[46] Žarnić R. and Tomaževič M. (1988). An Experimentally Obtained Method for Evaluation of the Behaviour of Masonry Infilled R/C Frames. Proceedings of the 9th World Conference on Earthquake Engineering, Tokyo, Japan, Vol. VI, pp. 163-168.
[47] Chrysostomou, C. Z., Gergely, P., and Abel, J. F. (2002). A six-strut model for nonlinear dynamic analysis of steel infilled frames. International Journal of Structural Stability and Dynamics, 2(03), 335-353
[48] Smith, B. S. (1962). Lateral stiffness of infilled frames. Journal of the Structural Division, 88(6), 183-226.
[49] Mainstone, R. J. (1971). On the stiffnesses and strengths of infilled frames. Institution of Civil Engineers, Proceedings, Vol. iv 57-90.
[50] Mainstone, R. J. (1974). On the Stiffness and Strength of In-filled Frames. Proc. Supplement, Trans. of Inst. Of Civil Eng. State Univ. of New York.
[51] Decanini, L.D. and Fantin, G.E. (1987). Modelossimplificados de la mamposteríaincluida en porticos. Características de rigidez y resistencia lateral en astadolímite. In: Jornadas Argentinas de Ingenierìa Estructural; 1987. p. 81736 [in Spanish].
[52] Bertoldi, S. H. Decanini, L. D., and Gavarini, C. (1993). Telaitamponatisoggettiadazionesismica, unmodellosemplificato: Confrontosperimentale e numerico (in Italian). Atti Del 6 Convegno Nazionale ANIDIS, pp. 815–824.
[53] Al-Chaar, G. (2002). Evaluating strength and stiffness of unreinforced masonry infill structures (No. ERDC/CERL-TR-02-1). Engineer research and development center champaignil construction engineering research lab.
[54] Chrysostomou, C. Z., and Asteris, P. G. (2012). On the in-plane properties and capacities of infilled frames. Engineering structures, 41, 385-402.
[55] Stafford Smith, B., and Carter, C. (1969). A method of analysis for infilled frames. Proceedings of the institution of civil engineers, 44(1), 31-48.
[56] Hendry, A. (1981). Structural Brickwork. Macmillan, London.
[57] Stafford-Smith, B., and Coull, H. (1991). Chapter 8: Infilled-Frame Structures. Tall Building Structures: Analysis and Design, John Wiley and sons. Inc, New York, USA, 168-183.

[58] Panagiotakos, T.B. and Fardis, M.N., (1996). Seismic response of infilledrc frames structures. 11th World Conference on Earthquake Engineering, paper 225, (pp. 23-28).

[59] Dolšek, M. and Fajfar, P. (2008). The effect of masonry infills on the seismic response of a four-storey reinforced concrete frame - a deterministic assessment. Eng Struct;30(7):1991–2001.

[60] Shing, P. B., and Stavridis, A. (2014). Analysis of seismic response of masonry-infilled RC frames through collapse. ACI Struct. J., 297, 1–20.

[61] Klingner, R.E. and Bertero,V.V. (1976). Infilled frames in earthquake resistant construction. Report No. EERC 76-32, University of California, Berkely.

[62] Crisafulli, F.J. and Carr, A.J. (2007). Proposed macro-model for the analysis of infilled frame structures. Bull NZ Soc Earthq Eng 40(2):69–77.

[63] Cavaleri, L., Fossetti, M., and Papia, M. (2005). Infilled frames: developments in the evaluation of cyclic behaviour under lateral loads. Structural Engineering and Mechanics, 21(4), 469-494.

[64] Klingner R. and Bertero, V. (1978). Earthquake resistance of infilled frames. J Struct Div 104:973–989.

[65] Calvi, G. M., &Bolognini, D. (2001). Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panels. Journal of Earthquake Engineering, 5(02), 153-185.

[66] Furtado, A., Rodrigues, H., Arêde, A., &Varum, H. (2020). Experimental tests on strengthening strategies for masonry infill walls: A literature review. Construction and Building Materials, 263, 120520.

[67] da Porto, F., Guidi, G., Verlato, N., & Modena, C. (2015). Effectiveness of plasters and textile reinforced mortars for strengthening clay masonry infill walls subjected to combined in-plane/out-of-plane actions/Wirksamkeit von Putz und textilbewehrtem Mörtel bei der Verstärkung von Ausfachungswänden aus Ziegelmauerwerk, die kombinierter Scheiben-und Plattenbeanspruchung ausgesetzt sind. Mauerwerk, 19(5), 334-354.

[68] Akhoundi, F., Vasconcelos, G., Lourenço, P., Silva, L. M., Cunha, F., &Fangueiro, R. (2018). In-plane behavior of cavity masonry infills and strengthening with textile reinforced mortar. Engineering Structures, 156, 145-160.

[69] Pohoryles, D. A., &Bournas, D. A. (2020). Seismic retrofit of infilled RC frames with textile reinforced mortars: State-of-the-art review and analytical modelling. Composites Part B: Engineering, 183, 107702.

[70] Preti, M., Bettini, N., &Plizzari, G. (2012). Infill walls with sliding joints to limit infill-frame seismic interaction: large-scale experimental test. Journal of Earthquake Engineering, 16(1), 125-141.

[71] Preti, M., Migliorati, L., &Giuriani, E. (2015). Experimental testing of engineered masonry infill walls for post-earthquake structural damage control. Bulletin of Earthquake Engineering, 13(7), 2029-2049.

[72] Verlato, N., Guidi, G., Da Porto, F., & Modena, C. (2016). Innovative systems for masonry infill walls based on the use of deformable joints: combined in-plane/out-of-plane tests. In Brick and Block Masonry (pp. 1359-1366). CRC Press.

[73] Morandi, P., Milanesi, R. R., &Magenes, G. (2018). Innovative solution for seismic-resistant masonry infills with sliding joints: in-plane experimental performance. Engineering Structures, 176, 719-733.

[74] Peng, Q., Zhou, X., & Yang, C. (2018). Influence of connection and constructional details on masonry-infilled RC frames under cyclic loading. Soil Dynamics and Earthquake Engineering, 108, 96-110.

[75] Tsantilis, A. V., & Triantafillou, T. C. (2018). Innovative seismic isolation of masonry infills using cellular materials at the interface with the surrounding RC frames. Engineering Structures, 155, 279-297.

[76] Kuang, J. S., & Wang, Z. (2014, August). Cyclic load tests of rc frame with column-isolated masonry infills. In Second European Conference on Earthquake Engineering and Seismology, Istanbul (pp. 25-29).

[77] Facconi, L., &Minelli, F. (2020). Retrofitting RC infills by a glass fiber mesh reinforced overlay and steel dowels: experimental and numerical study. Construction and Building Materials, 231, 117133.

[78] FEMA (1998). FEMA 306: Evaluation of earthquake damaged concrete and masonry wall buildings.

[79] FEMA. (2011). FEMA E-74 Reducing the risks of nonstructural earthquake damage—A practical guide.

[80] MSJC (2013) - ACI 530-13/ASCE 5-13/TMS 402-13. Building Code Requirements for Masonry Structures. United States: Masonry Standards Joint Committee.

[81] Marinković, M., &Butenweg, C. (2019). Innovative decoupling system for the seismic protection of masonry infill walls in reinforced concrete frames. Engineering Structures, 197, 109435.

[82] Marinković, M., (2018). Innovative system for seismic resistant masonry infills in reinforced concrete frame structures (PhD Thesis), University of Belgrade – Faculty of Civil Engineering.

[83] Computers & Structures, Inc. (2016), CSI Analysis Reference Manual for SAP2000, ETABS, SAFE and CSIBridge, Berkeley, California, U.S.A.

[84] FEMA 356. (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency, Washington, D.C., U.S.A.

[85] Salihović, A., &Ademović, N. (2017). Nonlinear analysis of reinforced concrete frame under lateral load. Coupled systems mechanics, 6(4), 523-537.

[86] Mander, J. B., Priestley, M. J., & Park, R. (1988). Theoretical stress-strain model for confined concrete. Journal of structural engineering, 114(8), 1804-1826

[87] Nastri, E., & Palese, M. I. (2017). Preliminary comparison between different software modeling of confined concrete. In 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering. Rodos Adası, Yunanistan.

[88] Decanini, L., Mollaioli, F., Mura, A., &Saragoni, R. (2004). Seismic performance of masonry infilled R/C frames. In 13th world conference on earthquake engineering (No. 165).

[89] Noh, N. M., Liberatore, L., Mollaioli, F., &Tesfamariam, S. (2017). Modelling of masonry infilled RC frames subjected to cyclic loads: State of the art review and modelling with OpenSees. Engineering Structures, 150, 599-621.

[90] DIN EN 1992-1-1 (2011) Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau; Deutsche Fassung EN 1992-1-1:2004 + AC:2010

[91] DIN EN 1998-1 (2010) Eurocode 8: Auslegung von Bauwerken gegen Erdbeben – Teil 1: Grundlagen, Erdbebeneinwirkungen und Regeln für Hochbauten; Deutsche Fassung EN 1998-1:2004 + AC:2009.

[92] Liberatore, L., Noto, F., Mollaioli, F., &Franchin, P. (2018). In-plane response of masonry infill walls: Comprehensive experimentally-based equivalent strut model for deterministic and probabilistic analysis. Engineering Structures, 167, 533-548.

[93] Abdelaziz, Mohamed &Gomaa, Mohamed & El-Ghazaly, Hany. (2019). Seismic evaluation of reinforced concrete structures infilled with masonry infill walls. Asian Journal of Civil Engineering.

[94] Seismosoft (2019) "SeismoArtif - A computer program for generation of artificial accelerograms".

REZIME

NUMERIČKA ANALIZA ARMIRANOBETONSKIH OKVIRNIHZGRADASA IZOLOVANOM ZIDANOM ISPUNOM

Marko MARINKOVIĆ
Santiago FLORES CALVINISTI
Christoph BUTENWEG

Armiranobetonske (AB) zgrade sa zidanom ispunom se izvode u mnogim zemljama širom sveta. Iako se zidana ispuna posmatra kao nekonstruktivni element, ona značajno utiče na promenu dinamičkih karakteristika AB ramovskih konstrukcija u toku zemljotresnog dejstva. Odskora, značajan napor je utrošen na istraživanje izolovanih ispuna, koje su odvojene od okolnog rama obično ostavljanjem prostora između rama i ispune. U ovom slučaju deformacija rama ne aktivira ispunu i na taj način ispuna ne utiče na ponašanje rama. Ovaj rad predstavlja rezultate istraživanja ponašanja AB ramovskih zgrada sa INODIS sistemom koji izoluje ispunu u odnosu na okolni ram. Uticaj izolovane ispune je prvo ispitan na jednospratnim i jednobrodnim ramovima. Ovo je iskorišćeno kao osnova za parametarsku analizu na višespratnim i višebrodnim ramovima, kao i na primeru zgrade. Promena krutosti i dinamičkih karakteristika je analizirano kao i odgovor pri zemljotresnom dejstvu. Izvršeno je poređenje sa praznom ramovskom konstrukcijom kao i ramovima ispunjenim ispunom na tradicionalni način. Rezultati pokazuju da je ponašanje ramova sa izolovanom ispunom slično ponašanju praznih ramova, dok je ponašanje ramova sa tradicionalnom ispunom daleko drugačije i zahteva kompleksne numeričke modele. Ovo znači da ukoliko se primeni adekvatna konstruktivna mera izolacije ispune, proračun ramovskim zgrada sa zidanom ispunom se može značajno pojednostaviti.

Ključne reči: zidana ispuna, seizmika, INODIS, ponašanje u ravni; ponašanje van ravni, izolovana ispuna, zemljotres.

ABSTRACT

NUMERICAL ANALYSIS OF REINFORCED CONCRETE FRAME BUILDINGS WITH DECOUPLED INFILL WALLS

Marko MARINKOVIĆ
Santiago FLORES CALVINISTI
Christoph BUTENWEG

Reinforced concrete (RC) buildings with masonry infill walls are widely used in many countries all over the world. Although infills are considered as non-structural elements, they significantly change dynamic characteristics of RC frame structures during earthquake excitation. Recently, significant effort was spent on studying decoupled infills, which are isolated from the surrounding frame usually by adding a gap between frame and infill. In this case, the frame deformation does not activate infill wall, thus infills are not influencing the behaviour of the frame. This paper presents the results of the investigation of the behaviour of RC frame buildings with the INODIS system that decouples masonry infills from the surrounding frame. Effect of masonry infill decoupling was investigated first on the one-bay one-storey frame. This was used as a base for parametric study on the frames with more bays and storeys, as well as on the building level. Change of stiffness and dynamic characteristics was analysed as well as response under earthquake loading. Comparison with the bare frame and traditionally infilled frame was performed. The results show that behaviour of the decoupled infilled frames is similar to the bare frame, whereas behaviour of frames with traditional infills is significantly different and demands complex numerical models. This means that if adequate decoupling is applied, design of infilled frame buildings can be significantly simplified.

Keywords: masonry infill, seismic, INODIS, in-plane behaviour, out-of-plane behaviour, decoupled infill, earthquake.

NUMERICAL AND EXPERIMENTAL DETERMINATION OF WIND LOAD ON PHOTOVOLTAIC PANEL ASSEMBLIES

NUMERIČKO I EKSPERIMENTALNO ODREĐIVANJE OPTEREĆENJA KOJE VETAR VRŠI NA SKLOPOVE FOTONAPONSKE PLOČE

Oľga HUBOVÁ
Michal FRANEK
Marek MACÁK

ORIGINALNI NAUČNI RAD
ORIGINAL SCIENTIFIC PAPER
UDK:621.383.51
doi:10.5937/GRMK2004049H

1 INTRODUCTION

Presently, solar panels represent one of the possible alternative energy sources in our climate zone. They can be located on the roofs of buildings, but also on the ground as solar power plants. Depending on the shape of the terrain, various geometric panel assemblies have been designed to obtain maximum energy from the sun and to use the available lands. Design and arrangement of photovoltaic (PV) and photothermal (PT) panels, generally called the solar collectors, is mainly affected by the electric and thermal efficiency of collectors. Only a limited research was done on the wind loads of panels and their supporting structures so far. Designers of PV panels often use applicable standards, in our region the STN EN 1991-1-4 [18, 19] in which the panel is considered as a monopitch canopy. Early wind studies describing the experimental investigation of ground mounted solar collectors and their supporting systems were published by Miller and Zimmerman [14]. They focused on the techniques to predict dynamic response and the structural dynamic loads of PV panels due to the wind turbulence. They identified, that the largest response and dynamic magnification factor occurred at mid chord location on an array and near the trailing edge. A significant decrease of wind loads was observed on interior to the array field.

Franklin [10] performed a dynamic analysis on a panel assembly. His conclusions show that the array of panels can be divided into two zones. The edges of the field reach the value of the wind force coefficient higher than 0.30, the maximum is around 0.8 and the wind force coefficient of the inner zone is lower than 0.30. The torque is also higher only in the area of the field edges. Radu and Axinte [16] performed experimental wind pressure measurements to evaluate suction factor on a panel support system. Recent works by Strobel and Banks [20] have shown that panels placed on the ground are prone to oscillations with frequencies above 1 Hz, which is contrary to the regulations in ASCE 7. Warsido et al. [22] investigated a group of panels placed on the terrain and the effect of the distance between rows of panels on the wind load. They found that the coefficient of force and moment from the wind for a group of panels decreases along the rows of panels, which is caused by the shielding effect of the front panels. The largest reduction in wind load was measured in the second row of panels; load reductions after the fourth row were minimal.

Detailed research of wind load on solar panels located on the ground is provided by technical report no. 64 by Bodhinayake, Ginger and Ingham [6]. This report determines the net pressure factor for the design of PV modules. The highest values of the net pressure coefficient were measured at the upper edge of the panel when the wind flowed towards the lower surface of the inclined panels. The increasing use of PV panel assemblies on the roofs of residential buildings leads to wind load research for this type of panel placement [16, 7, 12, 15]. Advanced numerical methods with computer simulation of fluid flow were used in work Bitsumlak et al. [4], where the assembly of three free-standing panels in tandem arrangement only for one wind direction (180°)

Oľga Hubová, Associate Professor, Slovak University of Technology, Department of Structural Mechanics, 810 05 Bratislava, Slovakia, e-mail: olga.hubova@stuba.sk
Michal Franek, Assistant Professor, Slovak University of Technology, Department of Building Construction, 810 05 Bratislava, Slovakia, e-mail: michal.franek@stuba.sk
Marek Macák, Assistant Professor, Slovak University of Technology, Department of Mathematics and Descriptive Geometry, 810 05 Bratislava, Slovakia, e-mail: marek.macak@stuba.sk

was analyzed. As a result of the CFD simulation using Large Eddy Simulation (LES), it was found that by placing another panel in front of the examined panel, the wind load is significantly reduced. Meroney and Neft [13] used CFD simulation of roof panels to compare with experimental results from a wind tunnel. Shademan et al. [17] investigated for the 0° wind direction the effect of the distance between rows of panels placed on the ground, at an angle of 45 °. They used the turbulent Shear Stress Transport (SST) model k-ω. It was found that the distance between the rows has insignificant effect on the load of the first row of panels in the windward part. However, for the rest of the rows, increasing the distance between the rows increased the drag coefficient and decreased the buoyancy coefficient. Jubayer and Hangan [11] used a 3D Reynolds-Averaged Navier–Stokes (RANS) simulation with an unsteady solver and Shear Stress Transport (SST) k-ω turbulence model. This article provides a detailed analysis of the wind load on a group of solar panels for the direct (0° and 180°) but also for the oblique (45° and 135°) wind directions. Wind speeds and wind pressure distributions for all panel assemblies are listed here.

The aim of our research - numerical simulation and experimental measurements - was to determine the wind load for a rectangular panel assembly and to determine the wind load values of the upper and lower surfaces of individual solar panels in different rows. Slovak national standard STN EN 1991-1-4 [18, 19] fails to include groups of panels or open roofs arranged in rows and exposed to wind, and therefore the values for the design of an open roof are based on the provisions of Table 7.6 in [18]. The resulting wind force coefficients c_f and net pressure coefficients $c_{p,net}$ take into account the combined effect of wind on the upper and lower surface of the canopies for all wind directions.

Since existing standards consider wind loads only for typical object shapes, wind tunnel tests on models were used for a better understanding of the wind effects on a particular objects arrangement in a given location and also determine local extreme loads on individual surfaces. The wind flow in Boundary Layer Wind Tunnel (BLWT) represents with technical accuracy the wind flow in the lower part of the atmosphere up to about 200 m above the ground, where the objects are located. BLWT STU tunnel with modelled boundary layer allows repeated measurements for different wind directions and speeds. Wind effect on structures can be observed in model reduction experimentally, and the most unfavourable effects of wind on the objects can be determined.

2 NET PRESSURE COEFFICIENT

STN EN 1991-1-4 [18] provides a procedure for determination of the net pressure coefficient $c_{p,net}$, which is defined as the difference between the pressures on the opposite surfaces for monopitch canopies. The force coefficient and the net pressure coefficients after interpolation (Figure 1 and Table 1) for free-standing canopy with inclination 27° can be found in [18].

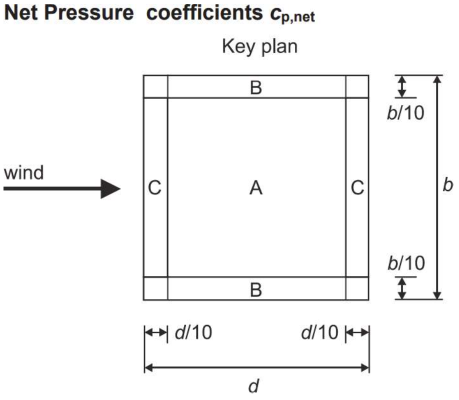


Figure 1. Key plan of zones for monopitch canopies [18]

Table 1. Interpolated values of net pressure coefficient for monopitch canopies

Roof angle α [°]	Zone	Downward wind action $c_{p,net}$ [-]	Upward wind action $c_{p,net}$ [-]
27	A	2.08	- 2.76
	B	3.14	- 3.44
	C	2.34	- 3.36

Wind pressure coefficients for the upper and lower table surfaces were experimentally obtained from the values of wind pressure in the form as follows:

$$c_p = \frac{\Delta p}{p_{\mathrm{dyn}}(z_{\mathrm{ref}})} = \frac{p(t) - p_0}{\frac{1}{2} \cdot \rho \cdot v_m{}^2(z_{\mathrm{ref}})} \tag{1}$$

where Δp is difference pressure [Pa], $p(t)$ is the wind pressure in measuring point on the surface of the model [Pa] and $p0$ is static pressure of undisturbed flow [Pa]. Dynamic pressure of the mean wind velocity p_{dyn} was considered in reference height $z\mathrm{ref}$ (in our case, reference height was equalled to the height of the top of examined panel), ρ is air density [kg/m^3], v_{m} (z_{ref}) is mean wind velocity in reference height (m/s).

The resulting net wind pressure coefficient $c\mathrm{p,net}$ was calculated as the difference between the values from the upper and lower table surfaces according to the relation:

$$c_{\mathrm{p,net}} = c_{\mathrm{p,upper}} - c_{\mathrm{p,lower}} \tag{2}$$

If the resulting pressure is negative, the table is loaded by suction, at a positive value it is the wind pressure. The evaluation of the results of the experimental and numerical approach for the rectangular assembly was plotted as resulting net wind pressure coefficients.

3 GEOMETRY OF PHOTOVOLTAIC PANNEL ASSEMBLIES

External wind pressures corresponding to the reference wind speed at the top of the model were measured at two altitude levels along the panel. The location of the sampling points was selected based on the results of CFD simulation. One panel had 40 × 4 m (length × width) with tilt angle 27°, which represented one table. The total number of sampling points on one solar table was 43 on upper and 43 on lower part. Panels were placed in series of 3 without gap, which represented one row. There were 8 rows with rectangular assembly. Gap between rows was 4.536 m (Figure 2).

4 NUMERICAL SIMULATION (CFD)

The aim of the numerical simulation was to pre-define the wind pressure distribution for the panel assemblies for different wind directions with a step of 22.5°. The results from the simulation helped to place the pressure taps on the model and the numerical results were used for comparison with the experimental measurements.

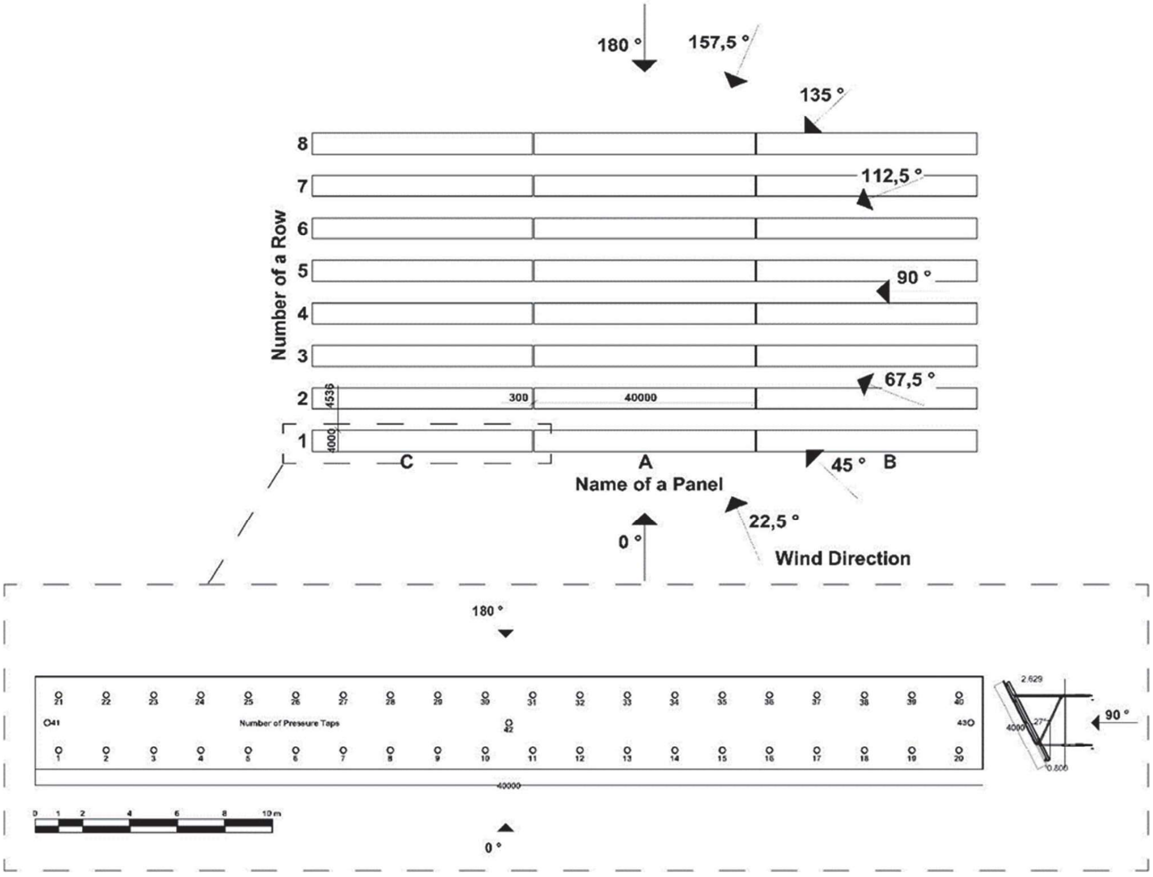


Figure 2. Arrangement of panel assembly with layout of pressure taps

4.1 Numerical model

Numerical simulation was solved in the program ANSYS Fluent [2, 3], which allows a detailed definition of the problem and its solution and contains the most comprehensive set of mathematical models used in many applications.

The Realizable *k*-*ε* model was used in numerical simulations. It is a two-equation model in which the calculation of the turbulent dynamic viscosity in the equation for the Bussinesque's hypothesis is solved using two separate transport equations and allows to determine the turbulent kinetic energy *k* and the dissipation of turbulent kinetic energy *ε*. The chosen Realizable *k*-*ε* model solves the transport equation for the transfer of turbulent kinetic energy *k* in the form as follows

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k. \tag{3}$$

Dissipation of turbulent kinetic energy *ε* is calculated by the equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_{2\varepsilon}\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon, \tag{4}$$

where *u* is wind speed [m/s], *t* is time [s], *k* is turbulent kinetic energy [m^2/s^2], *ε* is dissipation of turbulence kinetic energy [m^2/s^3], *v* is kinematic viscosity [m^2/s], μ_t is turbulent dynamic viscosity, *σ* is turbulent Prandtl number [-], G_k expresses the change in turbulent kinetic energy due to the change in velocity gradient, $\rho C_1 S_\varepsilon$ is the productive member, C_2 is the model constant and *ρ* is the air density [kg/m^3].

This turbulent model is characterized by high accuracy near the walls, while the accuracy in the open terrain is average.

4.2 Computational domain

The size of the computation domain was chosen 600 × 400 × 50 m^3 (length × width × height) taking into account the recommendations in [9, 21], so that the block ratio between the size of objects and the computational area is less than 3 %, which guarantees that the results will not be affected by the boundary of the computational domain (Figure 3).

4.3 Computational mesh

The computational mesh was generated using an adaptive function and polyhedral elements. The size of the elements on the examined object was set to 0.2 m using the distance and curvature function. An inflatable function with five layers and the first layer size of 0.02 m was used for the investigated solar panel system. The generated mesh had 18 087 614 computing nodes (Figure 4).

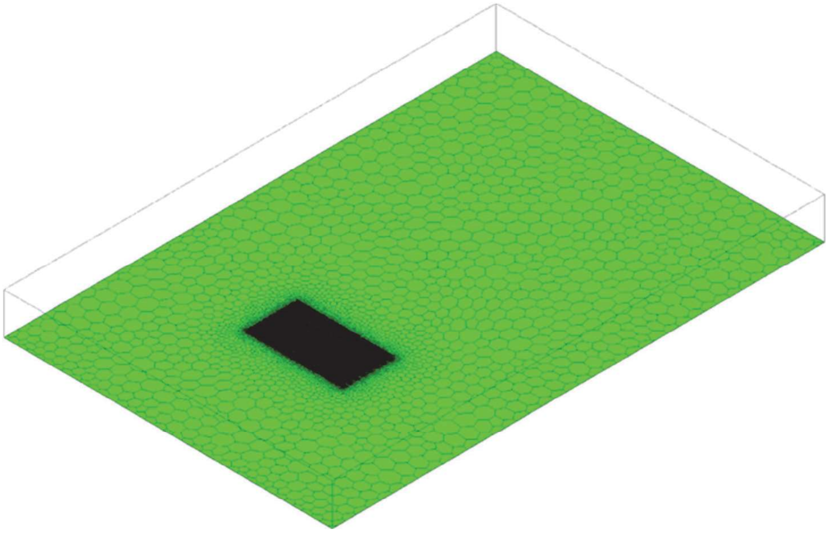


Figure 3. Computational domain with mesh

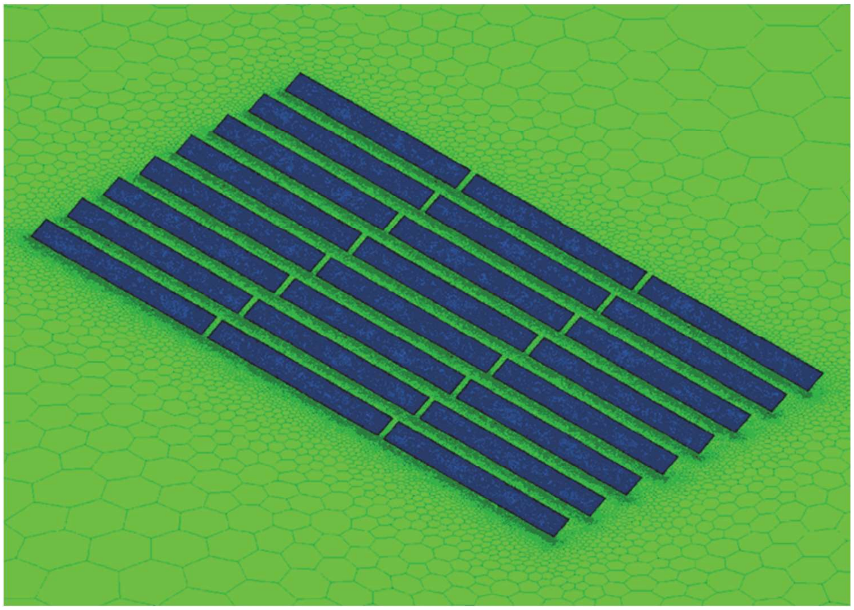


Figure 4. Detail of computational mesh

4.4 Boundary conditions

The input to the calculation area was set as Inlet using the logarithmic function of the wind profile as follows:

$$v(z) = \frac{v^*}{\kappa} \ln \frac{z + z_0}{z_0} \tag{5}$$

$$v^* = \frac{v_{ref}\kappa}{\ln \frac{z_{ref} + z_0}{z_0}} \tag{6}$$

where $v(z)$ is the mean wind speed at height z, v^* is the friction speed, z_0 is the aerodynamic roughness length (for smooth terrain it is 0.005), κ is von Karman constant ($\kappa = 0.42$), vref is the reference wind speed, which had a value of 8.15 m/s at a reference height at the level of the upper edge of the panel.

Turbulence at the entrance to the computational domain was modelled using the relations:

$$k = \frac{v^{*2}}{\sqrt{C_\mu}} \tag{7}$$

$$\varepsilon = \frac{v^{*3}}{\kappa(z + z_0)} \tag{8}$$

where $C_\mu = 0.09$. These boundary conditions guaranteed a wind profile and turbulence of wind profile identical to the wind tunnel.

The outlet boundary is defined as pressure outflow and the side and upper boundary as zero gradient (symmetry).

4.5 Setting up the computing environment

All calculations were run as pressure-based and the task was solved stationary. The numerical scheme was set up as a simple pressure-velocity coupling with second-order discretization without relaxation. Solutions were initialized using hybrid initialization. Due to the used modelling approach RANS and Realizable k-ε model, the output were the average values of wind pressures in the calculation points of the mesh, which were transformed to the dimensionless coefficient of the resulting wind pressure $c_{p,net}$.

5 EXPERIMENTAL MEASUREMENT IN BLWT

The existing standards consider wind loads only for typical object shapes and do not consider surrounding objects modifying wind flow, therefore wind tunnel tests on the models provide a better understanding of the effects of wind on the specific arrangement of objects in a given location and also determine local extreme wind loads on individual areas. Flow in wind tunnels BLWT (Boundary layer wind tunnel) represents with technical accuracy the wind flow in the lower part of the atmosphere up to about 200 m above the ground, where the objects are located.

The solar panels can be arranged in different formations with gaps between them and therefore it is necessary to obtain experimentally the coefficients of the resulting wind pressure for individual areas and assuming all wind directions. The rear solar collectors are less stressed than those standing in front or on the side. In the BLWT wind tunnel in Bratislava (Figure 5), we tested according to the ASCE recommendation [8], solar panels grouped in the shape of a rectangle with gaps between them at different wind speeds and wind directions.

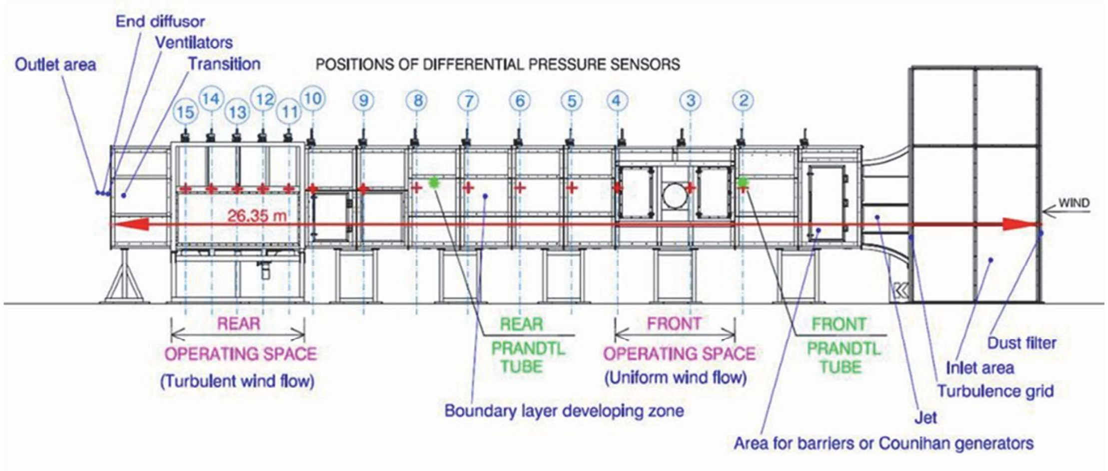


Figure 5. Scheme of BLWT Bratislava

5.1 Characteristics of Atmospheric Boundary Layer (ABL)

The solar panel models at a scale of 1 : 200 were placed behind the modelled and experimentally verified boundary layer of smooth terrain (terrain category between I - II). The boundary layer representing the open terrain was modelled using smooth plates and a barrier. Mean wind velocity and turbulence intensity profiles were compared with Eurocode categorization (Figure 6). The wind flow velocities were set using LabVIEW, which

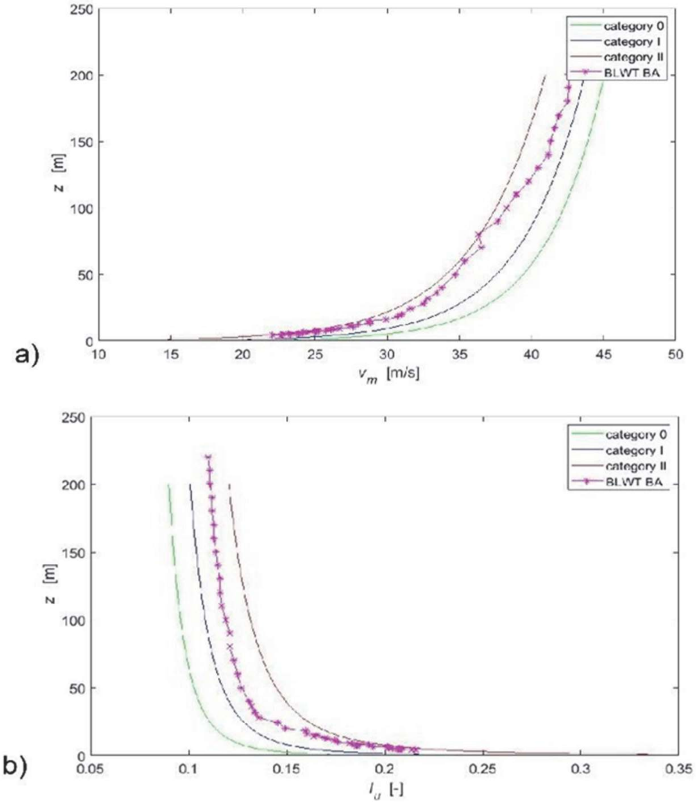


Figure 6. Atmospheric Boundary Layer: a) mean wind velocity profile, b) turbulence intensity profile

controlled the tunnel depending on the frequency of the inverters and had values of 24 and 28 Hz, which corresponded to the mean values of the reference wind speeds at the top of the photovoltaic panel of 6.965 and 8.15 m/s depending on barometric pressure, temperature and air density.

5.2 Instrumentation

Pressure sampling points with tubing system and pneumatic connectors were designed for a reduced rigid model of solar panels (Figure 7). Tubing system was conducted to the pressure scanner Scanivalve DSA 3217. Scanner had 16 temperature compensated piezoresistive pressure transducers with a pneumatic calibration valve. 500 samples per one measurement were recorded. It corresponded to sampling frequency for each tap equal to 25 Hz. Lengths of the tubing system and connectors prescribed by the manufacturer were used to eliminate the low pass noise. The duration of one measurement was 20 s. For each measurement it was recorded the time series of difference pressure between the reference tap in Prandtl tube and taps on the model.

6 RESULTS AND DISCUSSION

Determination of net pressure coefficients or/and suction on panel assemblies was performed by:

1/ CFD simulation in ANSYS Fluent program

2/ experimental measurements in the BLWT STU tunnel on models of panel assemblies at a scale of 1 :200.

6.1 Net pressure coefficients distribution

A rectangular assembly of 8 rows of solar panels was placed on a horizontal smooth terrain, with wind turbulence less than 20 %. The dimensionless coefficients of the resulting wind pressure $c_{p,net}$ as the difference of the values on the upper and lower surface were determined on the basis of the reference wind speed at the level of the upper edge of the panel. Extreme values of wind effects occurred in both solutions in the same wind direction.

Because the RANS modelling approach and Realizable k-ε model were chosen to solve the CFD simulation, the output are the average values of wind pressures at the calculation points of the network, which were transformed into a dimensionless resulting wind pressure coefficient $c_{p,net}$. For a large number of simulations and measurements, which were solved for all wind directions with a step of 22.5°, the values of the net wind pressure and suction coefficients on the solar panels are depicted for the decisive and critical wind directions 0°; 22.5°; 135°; 157.5° and 180° (Figures 8 – 12). The values of the net pressure coefficient have a + sign and the resulting net suction coefficient has a - sign. The colour range in the figures shows significantly increased loads on the front and side panels and less stress on the inner rows of the photovoltaic panels.

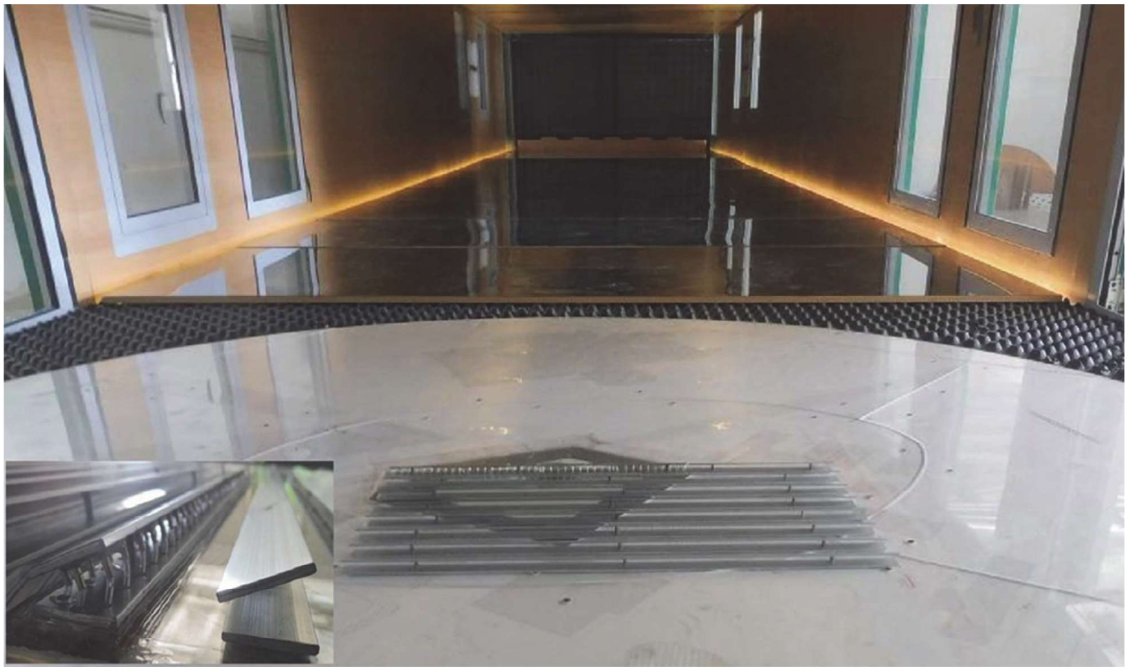


Figure 7. Solar panel assemblies during experiment in BLWT

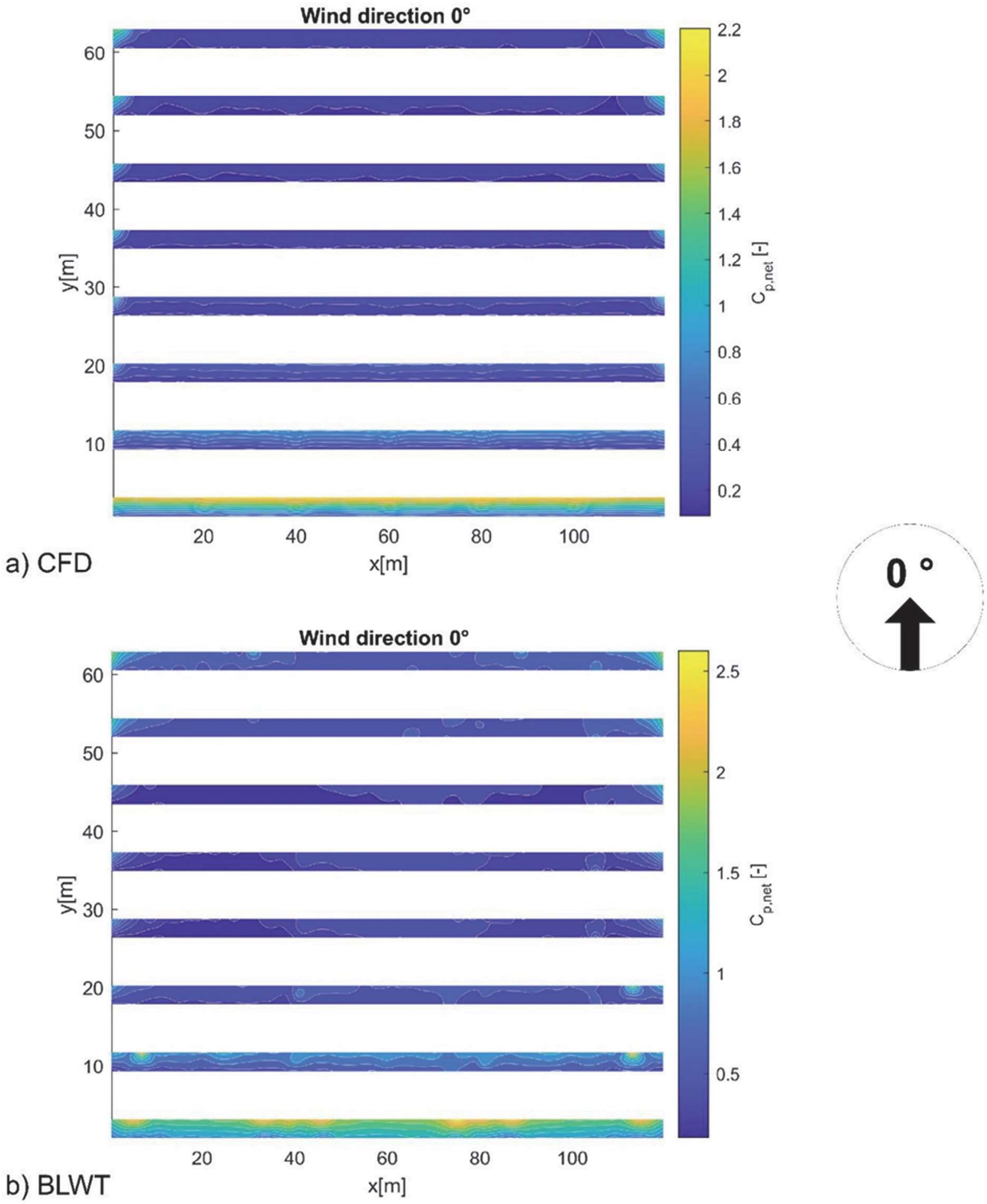
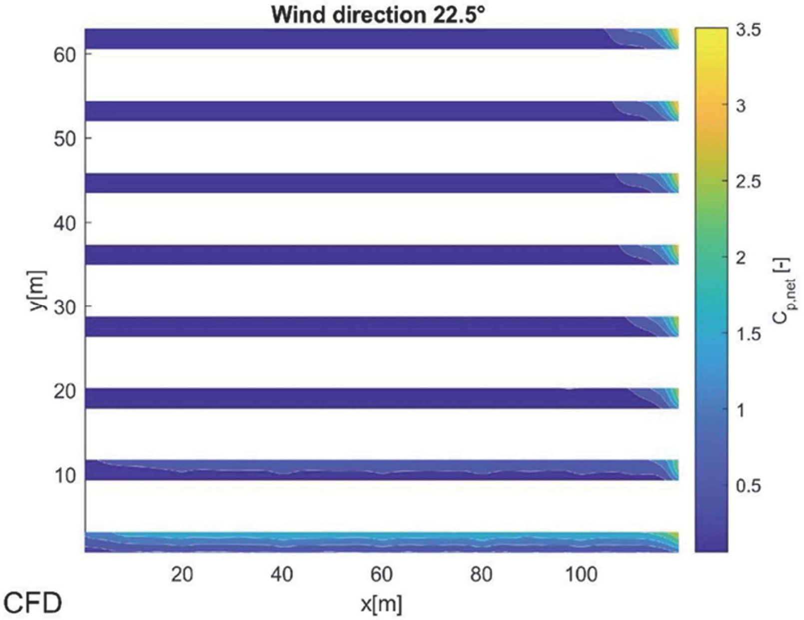
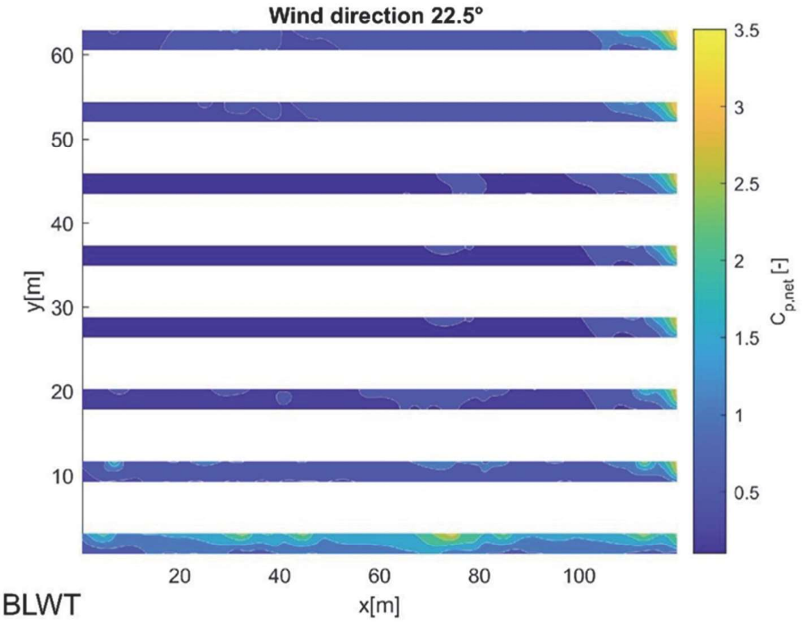


Figure 8. Net pressure coefficients distribution for wind direction 0°: a) results from simulation, b) results from wind tunnel



a) CFD



b) BLWT

Figure 9. Net pressure coefficients distribution for wind direction 22.5°: a) results from simulation, b) results from wind tunnel

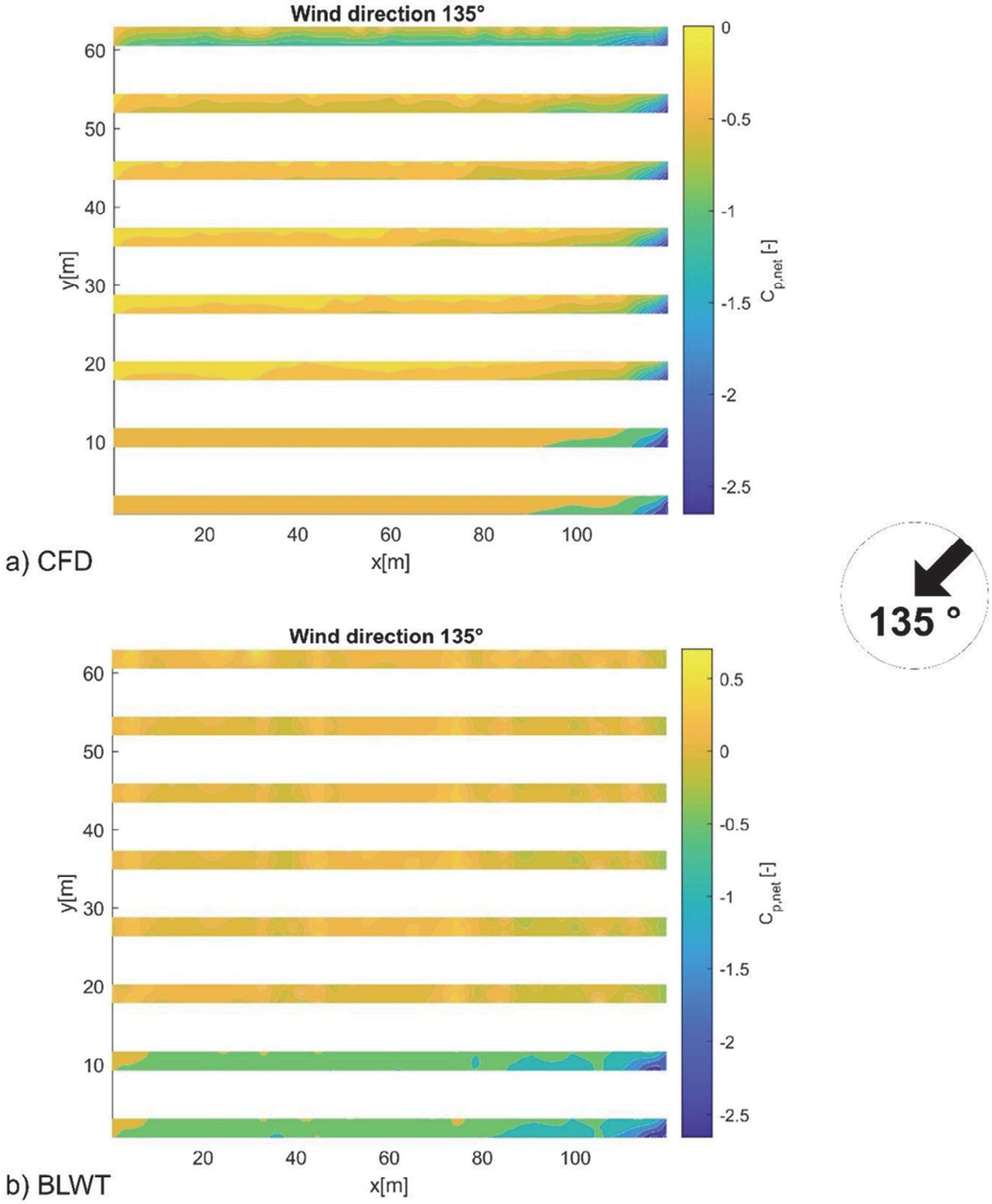
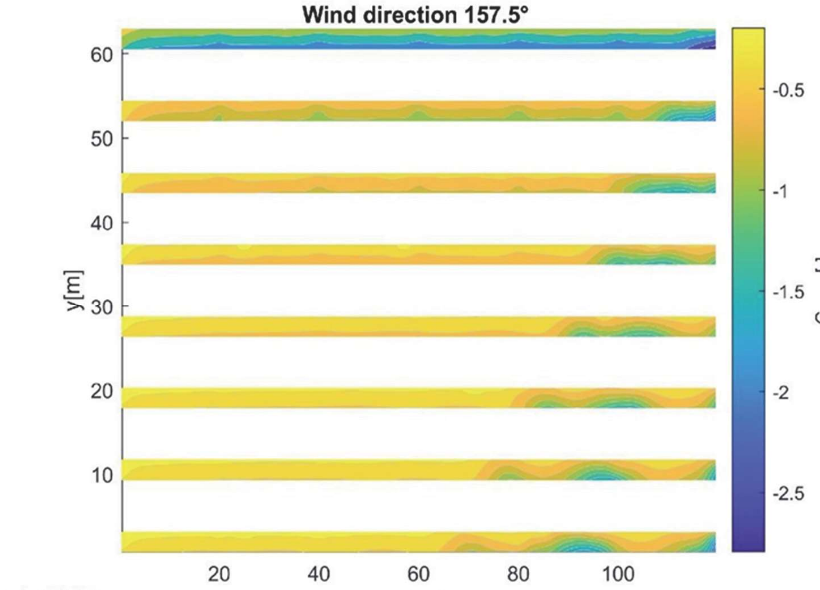
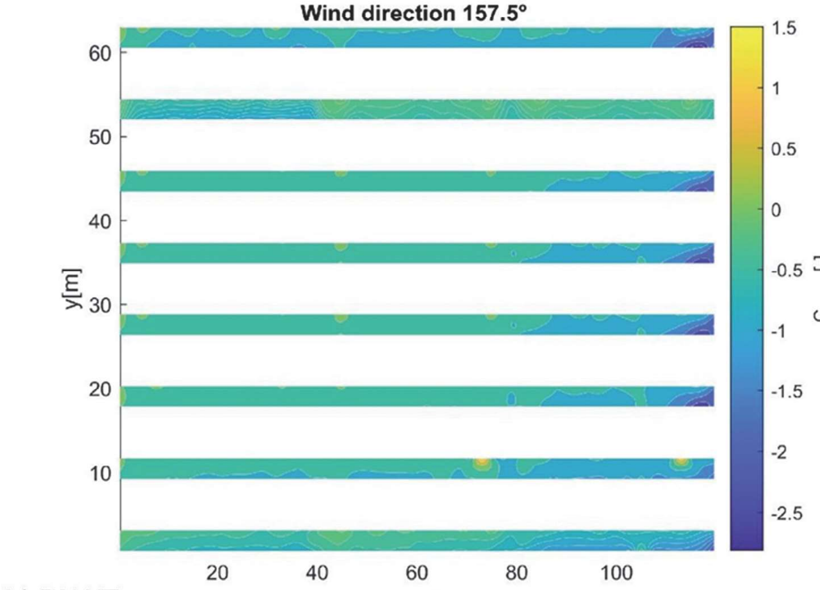


Figure 10. Net pressure coefficients distribution for wind direction 135°: a) results from simulation, b) results from wind tunnel

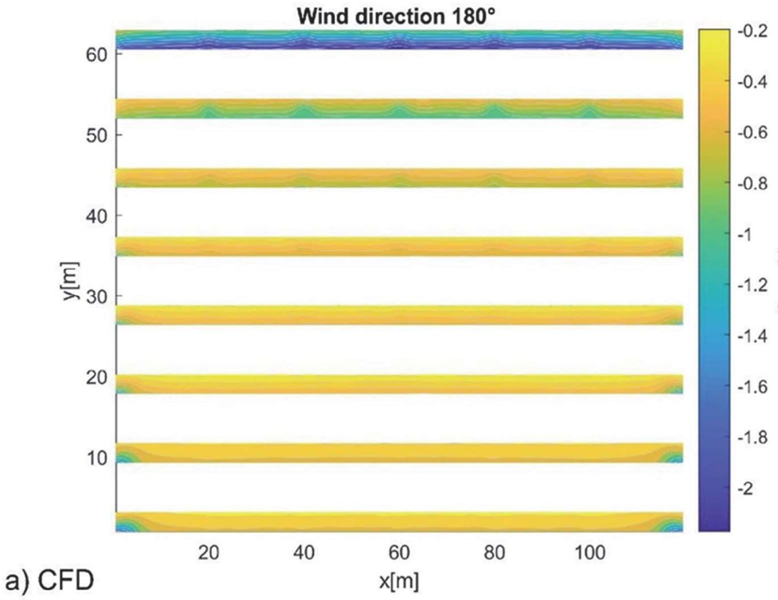


a) CFD

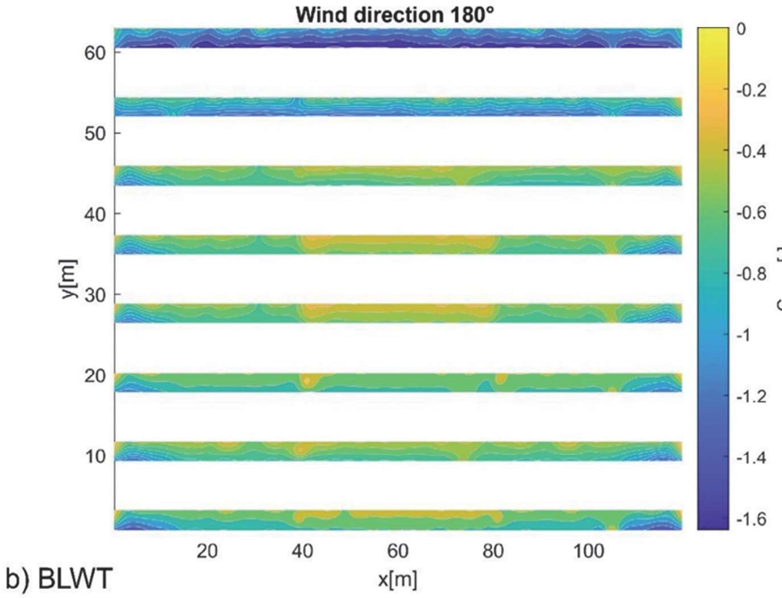


b) BLWT

Figure 11. Net pressure coefficients distribution for wind direction 157.5°: a) results from simulation, b) results from wind tunnel



a) CFD



b) BLWT

Figure 12. Net pressure coefficients distribution for wind direction 180°: a) results from simulation, b) results from wind tunnel

7 CONCLUSIONS

The highest values of pressures occurred at wind flows of 22.5 ° or 0 ° and the highest suction was observed at wind directions 135 °, 157.5 ° and 180 °. The 0 ° wind direction represents the south wind flow of the site. The results of experimental measurements are processed according to the methodology given in EN1991-1-4 [18], which determines the coefficients of net pressure in individual zones, considering areas loaded by pressure or suction and determines both values in individual zones.

Tab. 2 and Tab. 3 show a comparison of the extreme values of the coefficients of net pressure and suction obtained by CFD simulation, experimental measurements and STN EN 1991-1-4 for open shelters, where the designation of the row and position of panels A, B, C in the assembly are shown in Figure 2.

1.

Table 2. Comparison of extreme values of wind pressure coefficients $c_{p,net}$

row	wind direction	CFD		Experimental measurements in BLWT		EN 1991-1-4 open canopies
		point	$c_{p,net}$ pressure	point	$c_{p,net}$ pressure	$c_{p,net}$ pressure
1	22.5°	B20	2.934	B20	2.5	3.14
2	22.5°	B43	2.844	B43	2.795	3.14
3	22.5°	B43	2.869	B43	2.87	3.14
4	22.5°	B43	2.875	B43	2.83	3.14
7	22.5°	B20	3.26	B20	3.249	3.14
8	0°	B20	3.52	B20	3.6	3.14

Table 3. Comparison of extreme values of wind suction coefficients $c_{p,net}$

row	wind direction	CFD		Experimental measurements in BLWT		EN 1991-1-4 open canopies
		point	$c_{p,net}$ pressure	poin t	$c_{p,net}$ pressure	$c_{p,net}$ pressure
1	135°	B43	-2.523	B39	-2.659	-3.44
2	135°	B43	-2.482	B39	-2.544	-3.44
3	135°	B40	-2.234	B39	-2.497	-3,44
4	135°	B40	-2.25	B39	-2.496	-3.44
7	135°	B40	-2.26	B39	-2.415	-3.44
8	157.5°	B40	-2.77	B39	-2.764	-3.44

The aim of the CFD simulation and experimental research was to determine the coefficients of the resulting wind pressure on the solar panel system, since it is impossible to use the values from the standard. It can be seen that the inner panels are considerably less loaded than areas A for canopy roofs. The panels placed on the side of the assembly or on the edge of the aisle are loaded significantly more than parts B. Frontal panels are also less loaded by wind than areas C in standard (see Tab. 1). The obtained values of wind effects on solar panels allow to optimize the design of supports of the whole set of panels and show the extremes of pressures and suction in the corners, which should be taken into account in the design. The inner parts of the panel assembly, where the wind load is significantly lower, can be designed more economically.

ACKNOWLEDGEMENTS

This work was supported by the Slovak Research and Development Agency under the contract no. APVV-16-0126 and by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences in the project VEGA 1/0113/19. Presented results have been arranged due to the research supported by the Slovak Scientific Grant Agency, projects VEGA No. 1/0412/18 and No. 1/0453/20.

8 REFERENCES

[1] Adrian, R., Axinte, E., Theohari, Ch. Steady wind pressures on solar collectors on flat-roofed buildings, Journal of Wind Engineering and Industrial Aerodynamics, Volume 23, 1986, Pages 249-258, ISSN 0167-6105, https://doi.org/10.1016/0167- 6105(86)90046-2.

[2] [7]ANSYS Inc., ANSYS Fluent Theory Guide, Release 18.1, 2017.

[3] [8]ANSYS Inc., ANSYS Fluent User's Guide, Release 19.1, 2018.

[4] Bitsuamlak, G.T., Dagnew, A.K., Erwin, J. Evaluation of wind loads on solar panel modules using CFD. In: Proceedings of the Fifth International Symposium on Computational Wind Engineering, Chapel Hill, North Carolina, USA, May 23–27, 2010.

[5] Blocken, B., STATHOPOULOS, T., CARMELIET, J., CFD simulation of the atmospheric boundary layer–wall function problems. Atmospheric Environment Volume 41(2), 2007, Pages 238-252. Elsevier.

[6] Bodhinayake, G. G., Ginger, J. D. & Ingham, S. REPORT - Wind Loads on Ground Mounted Solar Panels, Issue April 2019.

[7] Browne, M. T. L., Gibbons, M. P. M., Gamble, S., & Galsworthy, J. Wind loading on tilted roof-top solar arrays: The parapet effect. Journal of Wind Engineering and Industrial Aerodynamics, Volume 123, 2013, Pages 202–213. https://doi.org/10.1016/j.jweia.2013.08.013

[8] Cermak, J. E. et al. Wind Tunnel Studies of Buildings and Structures : ASCE Manuals and Reports on Engineering Practice, 1999. Virginia: American Society of Civil Engineers. ISBN 0-7844-0319-8.

[9] Franke, J. et al. Best practice guideline for the CFD simulation of flows in the urban environment, COST Office Brussels, 2007.

[10] Franklin, H.A., 1983. Integrated Structure Designs for Photovoltaic Arrays, Report SAND81-7191. Bechtel Group, Inc., San Francisco, California, April 1983.

[11] Jubayer, C. M., & Hangan, H. A numerical approach to the investigation of wind loading on an array of ground mounted solar photovoltaic (PV) panels. Journal of Wind Engineering and Industrial Aerodynamics, Volume 153, 2016, Pages 60–70. https://doi.org/10.1016/j.jweia.2016.03.009

[12] Kopp, G. A., Farquhar, S., & Morrison, M. J. Aerodynamic mechanisms for wind loads on tilted, roof-mounted, solar arrays. Journal of Wind Engineering and Industrial Aerodynamics, Volume 111, 2012, Pages 40–52. https://doi.org/10.1016/j.jweia.2012.08.004

[13] Meroney, R.N., Neft, D.E. Wind effects on roof-mounted solar photovoltaic arrays: CFD and wind-tunnel evaluation. In: Proceedings of the Fifth International Symposium on Computational Wind Engineering, 2010, Chapel Hill, North Carolina, USA.

[14] Miller, R.D., Zimmerman, D.K. Wind Loads on Flat Plate Photovoltaic Array Fields. Boeing Engineering and Construction Company, 1981, Seattle, Washington, USA.

[15] Naeiji, A., Raji, F., & Zisis, I. Wind loads on residential scale rooftop photovoltaic panels. Journal of Wind Engineering and Industrial Aerodynamics, Volume 168(October 2016), Pages 228–246. https://doi.org/10.1016/j.jweia.2017.06.006

[16] Radu, A., Axinte, E. Wind forces on structures supporting solar collectors. Journal of Wind Engineering and Industrial Aerodynamics, Volume 32,1989, Pages 93–100.

[17] Shademan, M., Barron, R.M., Balachandar, R., Hangan, H. Numerical simulation of wind loading on ground-mounted solar panels at different flow configurations. Can.J. Civ. Eng. Volume 41, 2014, Pages 728–738.

[18] STN EN 1991-1-4 (2007) Eurocode 1. Actions on structures. Part 1-4: General actions. Wind actions.

[19] STN EN 1991-1-4/NA (2008) Eurocode 1. Actions on structures. Part 1-4: General actions. Wind actions. National Annex.

[20] Strobel, K., & Banks, D. Effects of vortex shedding in arrays of long inclined flat plates and ramifications for ground-mounted photovoltaic arrays. Journal of Wind Engineering and Industrial Aerodynamics, Volume 133, 2014, Pages 146–149. https://doi.org/10.1016/j.jweia.2014.06.013

[21] Tominaga, Y. AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, J Wind Eng Ind Aerod, Volueme 96, (10-11) 2008, Pages 1749-1761.

[22] Warsido, W. P., Bitsuamlak, G. T., Barata, J., & Gan Chowdhury, A. Influence of spacing parameters on the wind loading of solar array. Journal of Fluids and Structures, Volume 48, 2014, Pages 295–315. https://doi.org/10.1016/j.jfluidstructs.2014.03.005

ABSTRACT

NUMERICAL AND EXPERIMENTAL DETERMINATION OF WIND LOAD ON PHOTOVOLTAIC PANEL ASSEMBLIES

Oľga HUBOVÁ
Michal FRANEK
Marek MACÁK

The article presents the aerodynamic study of solar panel assemblies and determination of wind load. In the first part, the task is solved by computer simulation of the wind flow around the proposed rectangular assembly in the scale of 1:1 using the FLUENT ANSYS program; realization of experimental measurements in the wind tunnel with a boundary layer (BLWT) in Bratislava is presented subsequently. The aim of the solution was to determine the maximum pressure and suction wind load on top and bottom surfaces of panels. The resulting net pressure coefficient represents the maximum local pressure in each panel row as maximum values from all wind directions. The experimentally obtained net pressure coefficient values were compared with computer simulation and the procedures mentioned in standard STN EN 1991-1-4. It can be seen that the inner panels are loaded considerably less than the standard defines. The panels placed on the side of the assembly or on the edge of the aisle are loaded significantly more than the standard defines. Frontal panels are also less wind stressed than in the standard defines.

Key words: Photovoltaic Panel, Wind Tunnel, Computational Fluid Dynamics, Net Pressure Coefficient, Wind Load

APSTRAKT

NUMERIČKO I EKSPERIMENTALNO ODREĐIVANJE OPTEREĆENJA KOJE VETAR VRŠI NA SKLOPOVE FOTONAPONSKE PLOČE

Oľga HUBOVÁ
Michal FRANEK
Marek MACÁK

Rad predstavlja prikaz aerodinamičke studije na sklopovima solarnih ploča i određivanje opterećenja koje vetar vrši na njih. U prvom delu istraživanje je obavljeno računarskom simulacijom protoka vetra oko predloženog pravougaonog sklopa u odnosu 1:1 primenom programa FLUENT ANSYS. Nakon toga predstavljena su eksperimentalna merenja iz aerodinamičkog tunela sa graničnim slojem (BLWT) u Bratislavi. Cilj je bio da se odredi maksimalni pritisak i usisno opterećenje vetra na svakom nizu panela iz svakog pravca duvanja vetra. Eksperimentalno dobijene ukupne vrednosti za koeficijent pritiska upoređene su sa vrednostima dobijenim iz računarske simulacije i procedurama iz standarda STN EN 1991-1-4. Može se videti da su unutrašnji paneli znatno manje opterećeni od onoga kako je u standardu definisano. Paneli smešteni na bočnim stranama ili po ivici znatno su više opterećeni od onoga kako je u standardu definisano. Frontalni paneli su takođe manje opterećeni delovanjem vetra nego što standard definiše.

Ključne reči: solarni panel, aerodinamički tunel, računarska dinamika fluida, ukupni koeficijent pritiska, opterećenje vetra

SPECIFIC ASPECTS OF THE RETROFITTING DESIGN AND SEISMIC ASSESSMENT OF A HERITAGE PEDESTRIAN BRIDGE

SPECIFIČNI ASPEKTI PROJEKOTVANJA REHABILITACIJE I SEIZMIČKE PROCENE PEŠAČKOG MOSTA KAO GRADITELJSKO NASLEĐE

Emil YANEV

PREGLEDNI RAD
REVIEW PAPER
UDK:625.745.11
doi:10.5937/GRMK2004065Y

1 INTRODUCTION

The River Arda's Cascade is the only system of large dams in Bulgaria created along a single river basin. In the upper course of the river, near the town of Ardino, the "Byalizvor" Hydroelectric Power Plant (HPP) is situated, which has been in operation since 1952. To provide a waterfall for the power plant a catch-water dam along the river had been constructed, consisting of a dam wall and a floodgate tower with exhaust panels.

Access to the service of the gates is carried out by a pedestrian bridge consisting of two structures: a steel platform on stone pillars at the beginning of the approach from the left bank of the river and a reinforced concrete platform on the same type of pillars to the end of the approach at the floodgate tower. The reinforced concrete part of the bridge, together with the pillars, was destroyed after enormous floods in January 2016 when the river came.

Figure 1. Plan view of the river and catch-water dam

Emil Yanev, Chief Expert, "Construction and Renewable Energy" Directorate at Risk Engineering Ltd, Sofia, Bulgaria, emil.yanev@riskeng.bg

Figure 2. Existing situation after accident. The destroyed part of the pedestrian bridge

As a result a project for restoration of the related part was made with appropriate structural planning and an optimal number of supports to prevent the river from backwatering.

2 INFORMATION RECEIVED FROM THE ASSIGNOR. FEASIBILITY STUDY

In the original form of the bridge, the pillars in the section of the dam wall are at a light distance of 4.0 m and it doubles to 8.0 m in the last three openings. According to the original project which the Client provided to our team the existing construction of the pillars is made of stone masonry, built of cement-sand mortar, filled with a core of non-reinforced concrete. The overall dimensions of the pillars section is 100/140 cm. Above the masonry part of the pillars there is a concrete hat, on which the structure of the existing steel footbridge sits. The pillars height above the dam wall edge is 3,0 m, they enter 1.5 m into the body of the dam wall without being anchored in it.

Figure 3. Comparison of the bridge in its original form (up)and now (down)

As a result of their construction with non-reinforced concrete, the columns have insufficient bending capacity due to which under the action of horizontal loads during the flood they collapsed primarily by shear in cross section at their connection with the dam wall, as evidenced by the remains. The part with the narrower wheelbases of the pillars was mainly destroyed.

3 BASICS OF DESIGN. STRUCTURAL CONCEPT

3.1 Basic requirements of the assignor. Durability adjustment

The same levels of reliability for load-bearing capacity and serviceability are accepted according to the section 2 of EN1990.

The degree of responsibility of the facility with the accepted reliability is CC2 (Table B 1, EN1990). The significance class corresponding to the accepted degree of responsibility is class II (average significance) according to item 2 (4) P of EN 1998-2: 2006.

According to Table 2.1 of EN 1990 the construction corresponds to category S5 with a design service life of 100 years.

3.2 Project solution

The facility will consist of stone-lined reinforced concrete pillars, anchored in the body of the spillway wall on which is seated a top steel structure, equipped with safety railings and steel pavement. The pillars form five intermediate axes (axes 3-8) of 9.0 m each, identical to the original openings remaining after the accident (axes 1-3) (Figure 4). Over the pillars the steel footbridge is seated on the newly designed foundation over the existing floodgate tower on the right along the river and on a stone masonry pillar on the existing part of the footbridge along axis "3". The stone masonry pillar at the connection of old and new structure will be replaced with reinforced concrete. The existing pillar near the floodgate tower falls between axes "6" and "7" of the new footbridge and will be removed.

The number of new supports is halved compared to the original solution and has been adopted so as to satisfy the passage and non-retention of solid debris. The overflow fields are larger than the existing ones, which is a prerequisite for the better operation of the overflow (the overflow front has been increased by about 5 meters), reducing the overflow height, compared to the original solution. At the same time, with the solution thus adopted, the wheelbases of the columns become commensurate, thus their response to seismic impact will be equivalent due to the regularity of the structure in plan compared to the original solution.

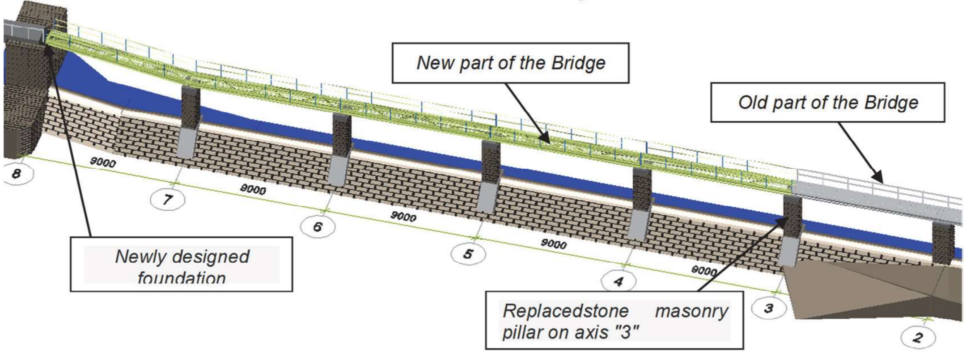


Figure 4. Structural concept. General view of the facility from axes 2-8

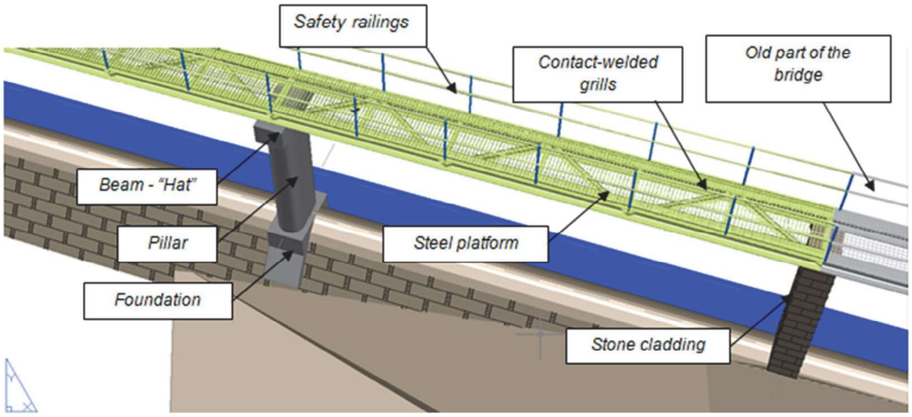


Figure 5. Project solution. Structural elements of the bridge

In its upper part the pillars end with a crossbar (coussinet), on which, by means of supporting devices, the structure of the superstructure is seated. The body of the pillars is lined with row stone masonry of granite blocks with a thickness of 15 cm and a row height of 20 cm, a multiple of the height of the rows of existing stone masonry pillars. The cladding will be performed before concreting, with pre-fixing of the stone blocks with steel fastening to the reinforcement from the body of the pillars.

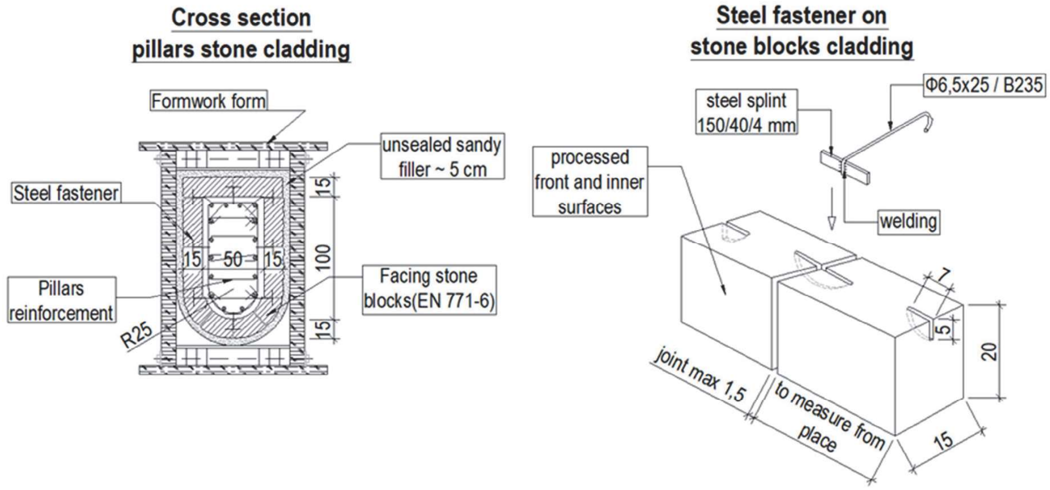


Figure 6. Stone cladding. Cross section with formwork and steel fastener on stone blocks

The foundations are anchored in the wall with injection of adhesive anchor chemical paste and reinforcing steel rods, the holes for which are drilled by pneumatic impact drilling. Additionally, in the geometry of the foundation, a front indentation has been added along the contours of the wall, which reduces the stresses in the main plane by increasing its area.

The foundations are anchored in the wall with injection of adhesive anchor chemical paste and reinforcing steel rods, the holes for which are drilled by pneumatic impact drilling. Additionally, in the geometry of the foundation, a front indentation has been added along the contours of the wall, which reduces the stresses in the main plane by increasing its area.

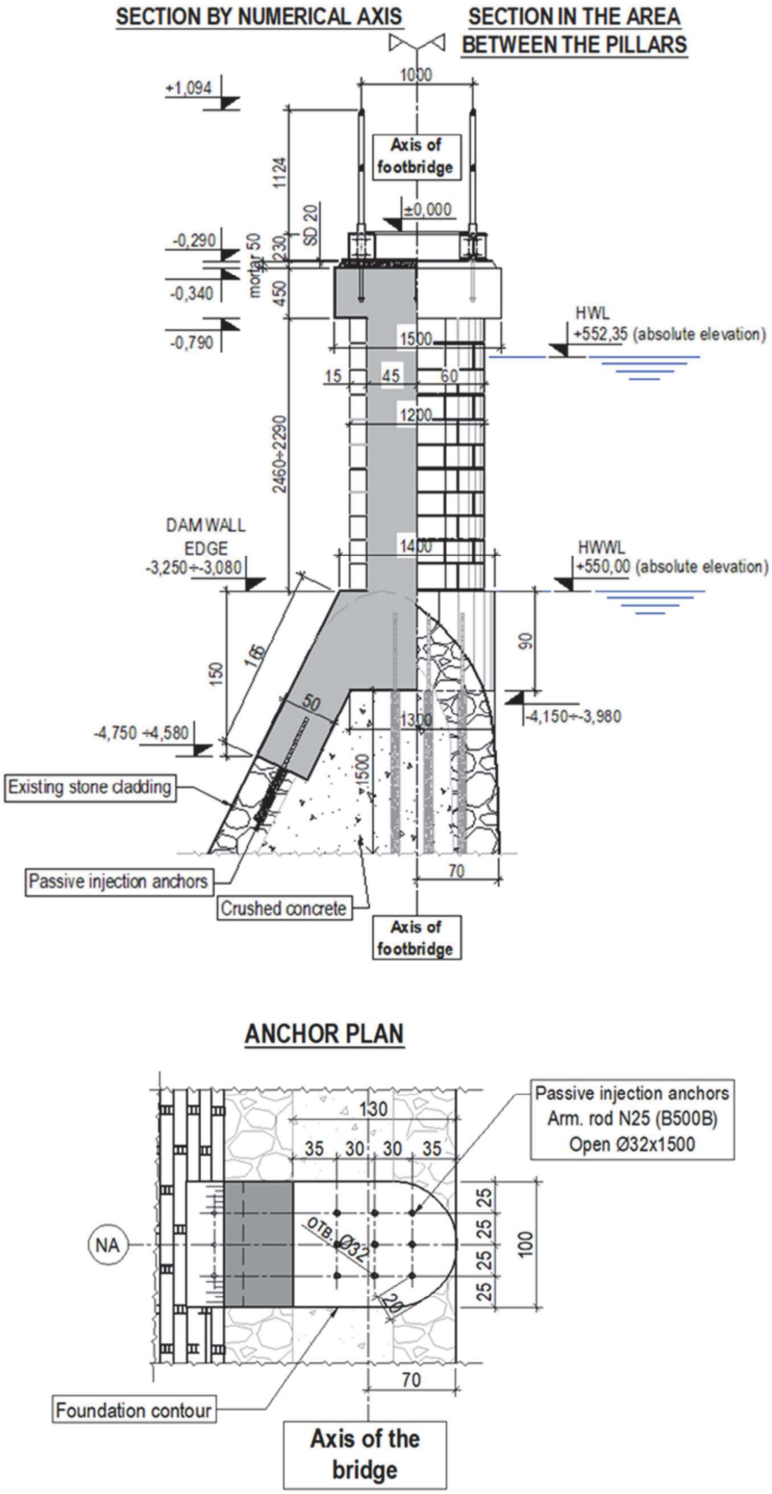


Figure 7. Project solution. Sections (up) and anchor plan (down)

To prove the bearing capacity of the anchors in the foundation, a test is performed according to BDS EN 1537 ("Pool-out" test) on a test site, under conditions identical to the operational ones. Additionally, a test for acceptance is performed up to a test load Pp = 50 kN of at least 1 pc. foundation anchor.

3.3 BEARING SYSTEM

According to the original project - for a static scheme of the three fields of the existing part of the footbridge three single-opening fixed frames are adopted. In the design of the new superstructure a static scheme of individual articulated simply supported beam, is adapted, laterally fixed, fixed at one end and longitudinally free at the other end.

The connection with the existing and the new part is movable. The movement is carried out by means of friction surfaces of the lower flange of the main beams and supporting steel devices (SD1), pre-set as embedded parts in the crossbars of the columns. The movable connection is realized in deformation joints provided for this purpose, which also serve to absorb the temperature expansions of the elements. In addition to the joints, in the geometry of the node between two adjacent sections are provided bushings on the transverse end plates of the main beams, which compensate for the movement in the opposite direction - in case of temperature shrinkage of the structural elements. The space of the joints and bushings is filled with elastic polyurethane-based sealant.

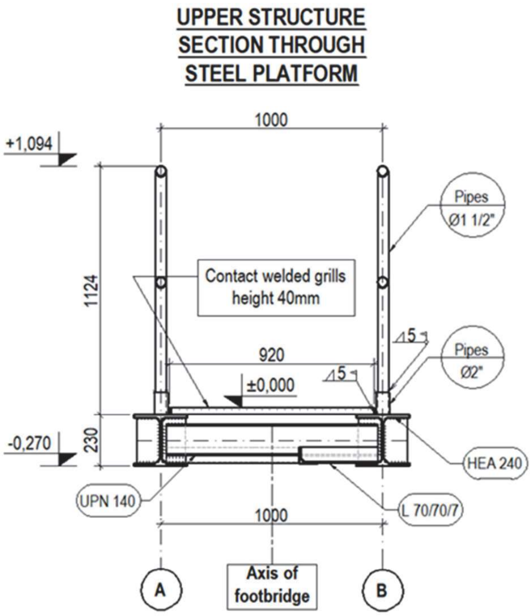


Figure 8. Upper structure. Section through steel platform

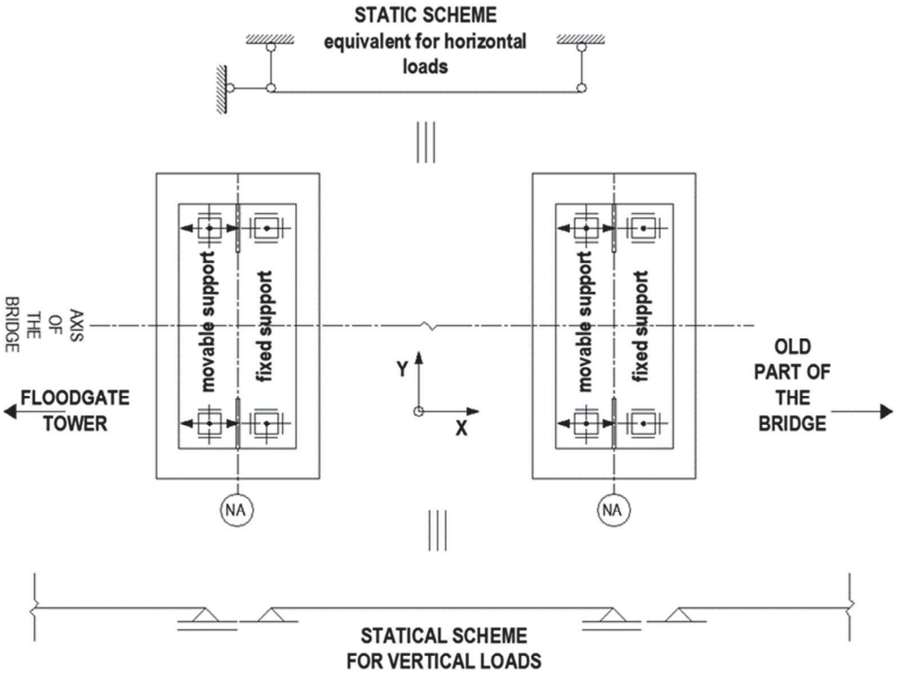


Figure 9. Bearing system. Static scheme for lateral and longitudinal movement

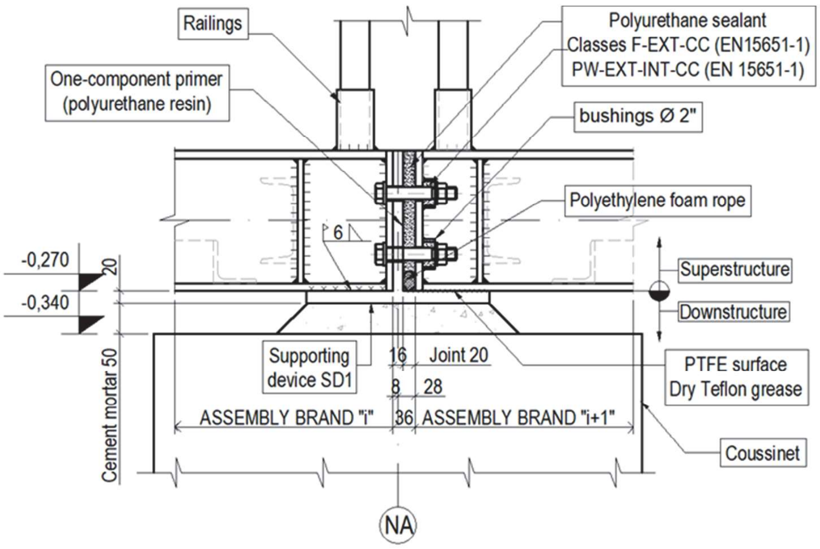


Figure 10. Detail of the node between the sections of the superstructure

4 MATERIALS

4.1 Existing pillars

The masonry pillars of the existing part of the footbridge are taken into account with a volume weight of 24 kN/m^{3}and a modulus of elasticity E = 10000MPa [3].

4.2 New foundations and pillars

Ordinary concrete with a dense structure and dense aggregates will be used for the elements of the substructure. For the specific case, a risk of corrosion caused by carbonization (classes XC) and one caused by thawing and freezing (classes XF) is accepted. The waters of the Arda River are fresh, soft, slightly aggressive towards the Portland cement concrete. The selected compressive strength class is C30/37 (EN 206-1).

- Density of reinforced concrete - 25kN/m3;
- Environmental impact class - XC4, XF3;
- Medium (cutting) modulus of elasticity – E0=33 000 MPa.

4.3 Steel structure

The selected structural steel for sheet and linear products is non-alloy, hot rolled and weldable from class S235J2, according to BDS EN 10025-2. The full designation of steel grade according to EN10027-1 is S235J2 + AR.

5 COMPUTATIONAL MODEL AND STRUCTURAL ANALYSIS METHOD

A computational three-dimensional model with finite elements in the software environment of "SAP2000" v.14 has been generated. The pillars and the superstructure are modelled with beam "frame" elements, and "shell" elements defined for the pavement. The supports of the main beams are introduced eccentrically with respect to the axis of the columns and are connected to them by "link" elements with corresponding degrees of freedom to simulate the bearing system of the superstructure. For the stepping on the floodgate tower and on the stand at the left bank, movable and immovable supports were introduced, respectively. Permanent modal damping 5% for the whole structure is accepted.

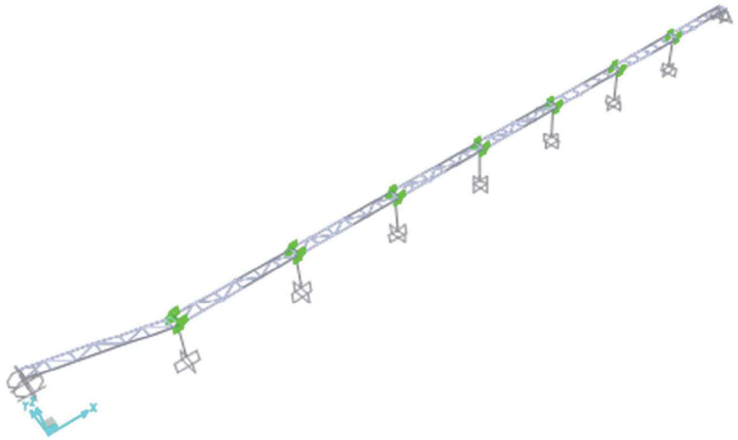


Figure 11. General view of the finite elements model

6 LOADS AND IMPACTS

The main points of the loads and impacts essential for the behaviour of the structure are cited.

6.1 Variable loads

- **Loads, caused by water**

The calculations are in accordance with the requirement of the Assignor to determine the hydrodynamic force when passing a high wave with a probability of exceedance 5%, as well as checking with a high wave with a probability of exceedance 3%.The data on the high wave values that were provided are as follows:

- High wave with probability **50%**.............477,5 m^3/s;
- High wave with probability **5%**................1186 m^3/s;
- High wave with probability **1%**.............1630,2 m^3/s.

With the available data, a water quantity was calculated for the high wave with a probability of exceedance 3%, by means of approximation with two probability distributions, selected as representative - lognormal and Gumbel maxima I, and the higher obtained value was accepted as authoritative.

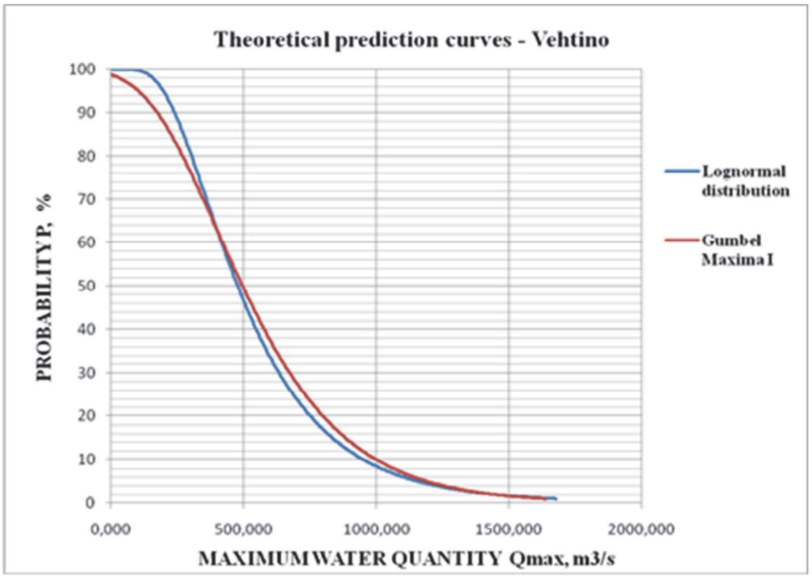


Figure 12. Theoretical prediction curves calculated from the data for the nearest hydrometric point - Vehtino

– High wave with probability **3%** ....1331,0m^3/s.

The appropriate water speed **v$_0$** is determined by the dependence:

$$v_0 = \frac{Q}{(H_{\text{пр}} + P).B_{\text{пр}}} Q = \varepsilon.m.B_{\text{пр}}\sqrt{2g}.H_{\text{пр}}{}^{3/2}$$

$\varepsilon = 1 - 0{,}2\frac{\xi_{\text{уст}}+(n-1).\xi_{\text{ст}}}{B_{\text{пр}}}.H_{\text{пр}}$ - Lateral contraction coefficient;

$\xi_{\text{уст}} = 1{,}0$ - Coefficient of resistance according to the shape of the side pillar;

$\xi_{\text{ст}} = 0{,}45$ - Resistance according to the shape of the intermediate pillar;

$n = 10$ - number of overflow openings;

$m = 0.48$ - Coefficient of water quantity according to the shape of the dam wall.

The approach flow speed thus obtained determines the forces acting on the structure.

– **Hydrodynamic force.** According to BDS EN 1991-1-6: 2005 the magnitude of the total horizontal force from the main flow on a vertical surface is determined by the dependence:

$$F_{wa} = \frac{1}{2}k.\rho_{wa}.h.b.v_{wa}^2$$

– **Load from waste accumulation.** According to BDS EN 1991-1-6: 2005 the magnitude of the total horizontal force from possible waste accumulation is determined by the dependence:

$F_{deb} = k_{deb}A_{deb}v_{wa}^2$, where k_{deb} is a parameter for volume of waste. The recommended value according to BDS EN 1991 was accepted: $k_{deb} = 666\ kg/m^3$

6.2 SEISMIC IMPACT AND ANALYSIS

To represent the seismic motion an elastic response spectrum Type 1 was used with identical components in the directions "X" and "Y" and parameters for the vertical component "Z" - $a_{vg}/a_g = 0.85$, according to BDS EN 1998-1: NA.

The body of the dam wall is built on a rock base, for which a ground base type A is accepted. The behaviour of the dam wall structure is considered to be an infinitely rigid body with equal accelerations along the height of the wall, because of which the columns of the bridge will receive the same accelerations as this at the base without signal amplification.

The value of the return period of repeatability for the requirement for non-destruction of the bridge T_{NCR} = 475 years is accepted (corresponding to probability of exceeding P_{NCR} = 0.19 for design service life of 100 years) A.1 (2) BDS EN 1998-1: NA.

To reflect the seismic response of the bridge the reference procedure for linear dynamic analysis using a spectral method was adopted. For the lower structure at average of moderate seismicity of the site, the perceived behaviour is ductile limited (q=1,5) so far as the deviation from the ideal elastic behaviour provides a certain dissipation of hysteresis energy without the need for plasticization in the range of the coefficient of behaviour 1,0<q<1,5.

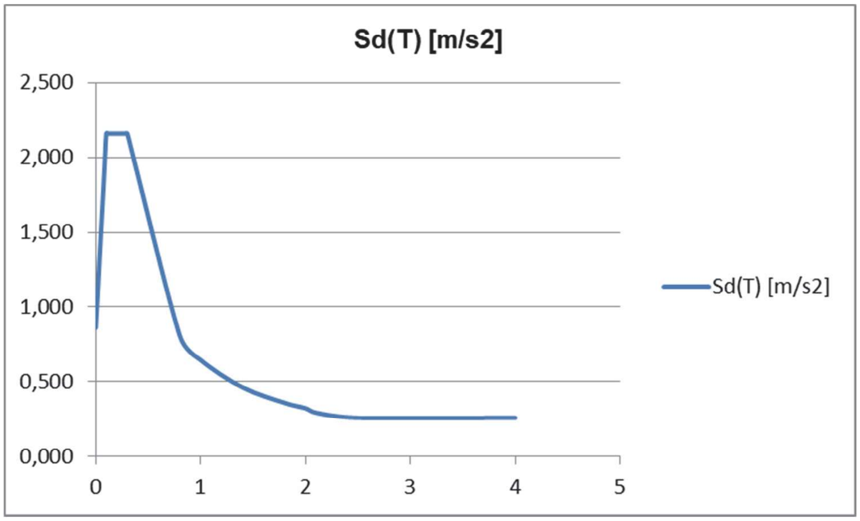


Figure 13. Computational response spectra for horizontal components at q = 1.5, Ground type A, according to BDS EN 1998-1 / NA

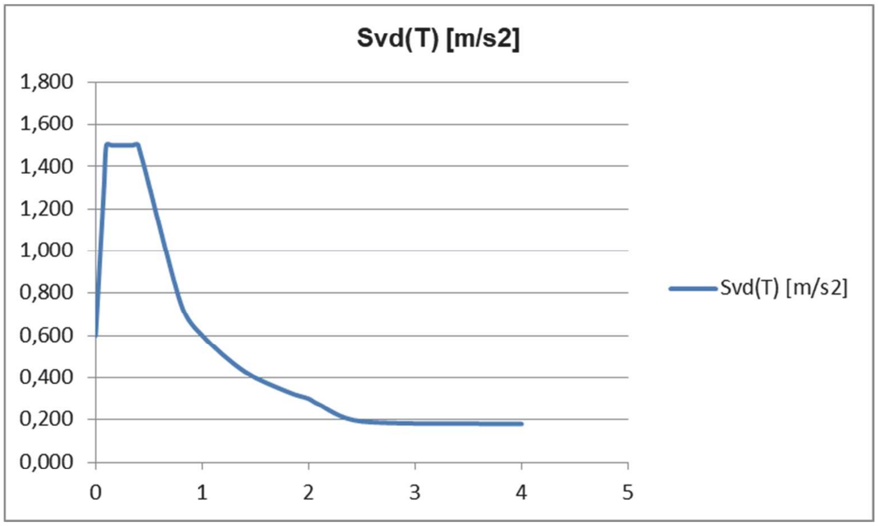


Figure 14. Computational response spectra for vertical components at q = 1.5, Ground type A, according to BDS EN 1998-1 / NA

6.3 Accidential impacts - strike from traffic on the river

The impact is presented according to BDS EN 1991-1-7, by means of two mutually incompatible forces:

– Front force: $F_{dx} = F_{dyn} = F_{impact} \cdot \varphi$

– Lateral force with one component acting perpendicular to the frontal force and one component of friction parallel to: $F_{dv} = 0{,}5 . F_{dx}$,

$F_R = \mu . F_{dv} = 0{,}4 . 0{,}5 . F_{d}$

The magnitude of the frontal impact force is determined by reference to a simplified formula (2-1) for determining the equivalent static force from a hard impact according to Annex C (BDS EN 1991-1-7: 2008):

$F_{impact} = V_r \sqrt{k . m}$, where

"k"- equivalent static stiffness of the impact object (the ratio between the force F_{impact} and the total deformation). For inland waterway vessels, according to ISO DIS 10252, a stiffness *k* = 5 MN / m' is accepted.

To take into account the pulse nature of the load and the caused dynamic effects inside the structure, a dynamic gain coefficient has been adopted $\varphi_{dvn} = 2{,}0$, according to App. C (3) (BDS EN 1991-1-7: 2008).

7 MODAL SPECTRAL ANALYSIS

The constant impacts with their characteristic values and the quasi-constant values of the variable impacts with coefficient $\psi_{2,1}$ = 0,2 (according to item 4.1.2. EN 1998-2-NA) are taken as masses.

The connected mass of water acting in the horizontal direction per unit length of the submerged column with dimensions $2a_x/2a_y$ determined according to Annex F of EN 1998-2 with the expression:

$m_a = k \rho \pi a_y^2$, where k is a function of a_x/a_y.

The value of $\mathbf{m_a}$ is entered as a linearly distributed load assigned along the height of the pillars up to the elevation highest water level (HWL) which provided by the Assignor.

The dynamic effect of the impact from pedestrians varies in the range of 0.5 to 3 Hz (according to item 5.7., EN 1991-2) and is outside the frequency response range of the bridge, whose first natural frequency is ≈ 5 Hz.

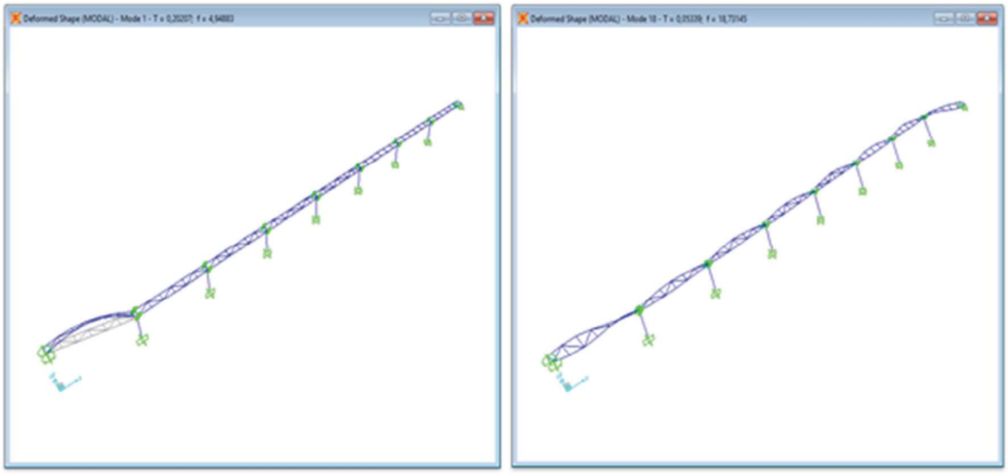


Figure 15. First modal form (T1 = 0.20 sec). First global translation form along the Y axis (T18 = 0.05 sec

8 METHOD STATEMENT

The construction of the footbridge will be carried out from the dry slope of the dam wall and the flooding of the river must be taken into account during the annual period chosen for the construction. The peculiarities of the climate on the territory of Kardzhali district and in particular the area of the site are typical for the continental-Mediterranean climatic region: hot summer and mild winter, summer minimum and winter maximum rainfall, pronounced summer-autumn drought, episodic and non-permanent snow cover. In view of the climatic characteristics of the area and the distribution of run-off, the most suitable periods for rehabilitation are August - November.

8.1 Definition of individual stages

The stage of temporary construction and mobilization of the construction site is commented.

1) *Construction of a temporary access road incl. temporary ford for crossing the riverbed and construction of an embankment for technological berm in front of a dry slope*

The temporary access road will be filled with ordinary gravel pavement at least 0.20 m thick, laid on a layer of crushed stone 0.25 m thick and compacted with a roller. The width of the lane in one-way traffic is assumed to be 4.0 m. The transverse slope of the road should be in the range of 1.5 - 4.0%. The construction of the ford begins with the laying of tubular reinforced concrete culverts across the direction of the flowing waters (deviation 15 ° from the perpendicular is allowed) with diameter Φ1000 and a number sufficient to conduct water quantities necessary for the normal functioning of ecosystems in the Arda riverbed. After laying the pipes, the embankment sections are formed with frontal barrier of the river waters, by means of intensive free embankment of unsorted crushed stone for "pressing" of the water flow to form a stone prism with a thickness of at least 0.40 m above the top of the gutter slope of the upper slope 1: 1.25 (1.0).

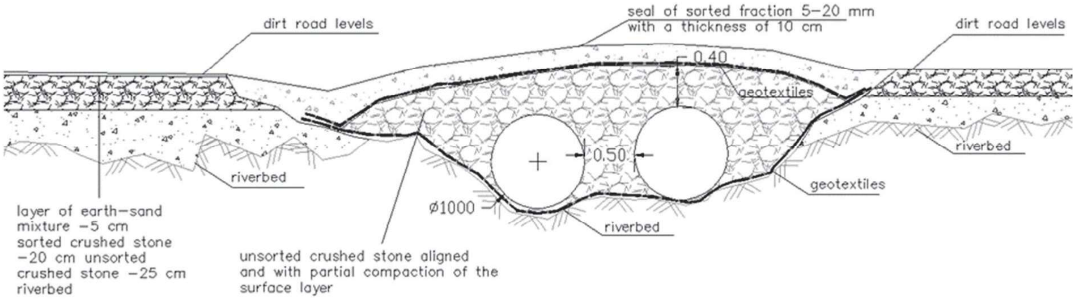


Figure 16. Typical longitudinal section of dirt road (ford) through the riverbed in a section above culverts

2) *Securing the site and installation / construction of scaffolding to the overflow wall, incl. delineation of storage areas*

It is planned a self-supporting volumetric tubular metal scaffolding to be build in stages in four measures in order to provide work sites at the level of the crown of the wall. For a pillar in axis 3, which is at the connection with the existing footbridge, the volumetric tubular scaffolding is not provided due to the very small free height to the crown, providing for the installation of a standard facade scaffolding (Hramar type) anchored in the rock massif and freely resting on the crown. The support towers are mounted above the rock massif by anchoring in it. A truss of universal tubular scaffolding elements develops between the support towers and the crown of the wall.

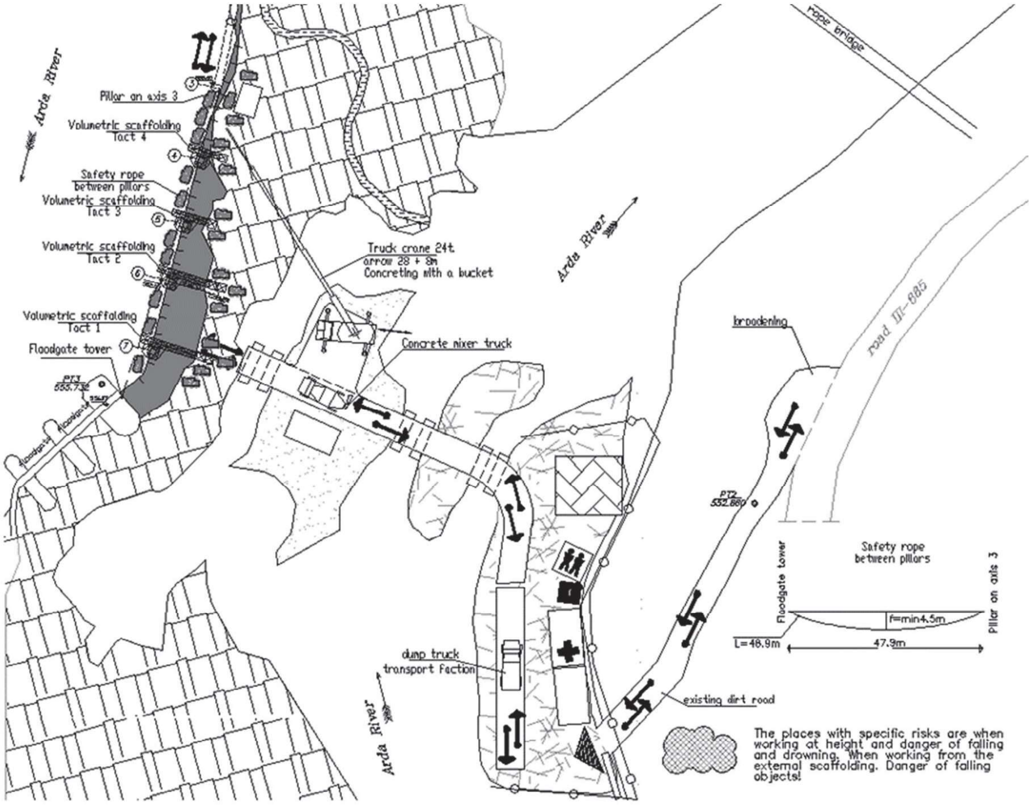


Figure 17. Construction situation plan

9 CONCLUSIONS

– With the measures adopted for reinforcement of the pillars and their anchoring in the body of the wall, their bearing capacity is significantly increased and they are able to absorb the design seismic impact for the site;

– With the increase of the wheelbase of the columns, in addition to the raster unity of the structure, an equal contribution of each of the columns in the control of the seismic energy is achieved, as the cutting forces will be commensurate along the entire length of the bridge;

– While preserving the material unity of the new and existing pillars, the goal is to evenly distribute the masses and stiffness in the plan of the facility. The stiffness of the new pillars is increased due to the reinforcement and this relieves the existing ones, as the pillar is the most loaded where the new and old part connect.

10 REFERENCES

[1] Eurocodes 1990-1998 and National Annexes for Bulgaria
[2] "Гидравлика", Энергоиздат Ленинград, 1982, P.P. Чугаев;
[3] „Masonry structures. Eurocode 6“, 2014, N. Barakova, T. Barakov;
[4] “Standards for design of hydraulic structures. Basics principles, BSA 11, 1985”;
[5] “Standards for design of concrete and reinforced concrete structures of hydraulic structures” 24.02.1992.

SUMMARY

SPECIFIC ASPECTS OF THE RETROFITTING DESIGN AND SEISMIC ASSESSMENT OF A HERITAGE PEDESTRIAN BRIDGE

Emil Yanev

The purpose of this study is to establish a suitable structural system for the restoration of the destroyed part of the pedestrian bridge, which is a part of a hydro-complex built along the Arda River (Bulgaria), and to improve the vulnerable details in the original structure, taking into account the seismic hazard on the site. The decision is also dictated by the choice of a construction method that does not interfere the Hydroelectric Power Plant (HPP) that is built along the river with the normal operation of which the subject is connected. The appropriate selection of materials and modelling of the overall behaviour of the old and new parts of the bridge are the basis of the optimal solution for interference with the structure and the possibility of extending its service life. It is also important to preserve the visual unity of the whole structural complex, thus preserving the original appearance and good construction practice from the time they have been built during the middle of the 20th century This design solution is part of an investment project of "Risk Engineering" Ltd..

Key words: Retrofitting of bridges, Maintenance of bridges, Seismic assessment

REZIME

SPECIFIČNI ASPEKTI PROJEKOTVANJA REHABILITACIJE I SEIZMIČKE PROCENE PEŠAČKOG MOSTA KAO GRADITELJSKO NASLEĐE

Emil YANEV

Svrha ovog istraživanja je da uspostavi odgovarajući konstruktivni sistem za obnovu uništenog dela pešačkog mosta, koji je deo hidro-kompleksa izgrađenog duž reke Arde (Bugarska), i da poboljša povredljive detalje u originalnoj konstrukcijii, uzimajući u obzir seizmičku opasnost na lokalitetu. Odluka je takođe uslovljena/diktirana izborom načina gradnje koji ne ometa Hidroelektranu (HE) koja je izgrađena duž reke čiji je normalan rad povezan sa tim. Odgovarajući izbor materijala i modeliranje celokupnog ponašanja starih i novih delova mosta osnova su optimalnog rešenja vezano za ometanje i mogućnost produženja njenog životnog veka konstrukcije. Takođe je važno sačuvati vizuelno jedinstvo celog konstruktivnog sklopa, čime se zadržava prvobitni izgled i dobra građevinska praksa iz vremena kada su objekti građeni sredinom 20. veka. Ovo dizajnersko (projektno) rešenje je deo investicionog projekta „Risk Engineering“ Ltd.

Ključne reči: dogradnja mostova, održavanje mostova, seizmička procena

PREDICTION OF MECHANICAL STRENGTH OF POLYPROPYLENE FIBRE REINFORCED CONCRETE USING ARTIFICIAL NEURAL NETWORK

PREDVIĐANJE MEHANIČKE ČVRSTOĆE BETONA OJAČANOG POLIPROPILENSKIM VLAKNIMA KORIŠĆENJEM VEŠTAČKE NEURONSKE MREŽE

P. SANGEETHA
M. SHANMUGAPRIYA

ORIGINALNI NAUČNI RAD
ORIGINAL SCIENTIFIC PAPER
UDK:624.971.012.45:004.032.26
doi:10.5937/GRMK2004079S

1 INTRODUCTION

The Polypropylene fibre reinforced concrete (PFRC) contains randomly distributed concrete and it acts as internal reinforcement so as to enhance the properties of the cementitious composite (concrete). The principal reason for incorporating the Polypropylene fibres into a cement matrix is to reduce cracking in the elastic range, and to increase the tensile strength and deformation capacity and increase the flexural strength of the resultant concrete. These properties of PFRC primarily depend upon the length and volume of propylene fibres (PPF) used in the concrete mixture. The strength properties of the concrete reinforced with polypropylene fibre and alkali resistant glass fibres was predicted by Regression modelling and found near to the experimental results of all the specimens [1]. The predicted compressive strength of concrete form the different batching plants for fresh concrete and early strength using artificial neural network [2]. The Intelligent Prediction system of concrete strength was developed, to provide strength information for removal of form work and scheduling the construction [3]. The split tensile strength and percentage of water absorption of concrete containing TiO_2 nanoparticles were predicted by using ANN and genetic programming and also concluded that ANN prediction is better than genetic programming [4]. The application of the Artificial neural network for predicting drying shrinkage of concrete was performed and found that prediction was in good agreement with the experimental strength [5].

The strength predictions of high performance steel fibre concrete with different volume of fibres were established using regression models and its second order regression model gives better predictions when compared to actual strength [6]. In the recent years an Artificial Neural Network (ANN) has been used to predict the behaviour of the mechanical properties of the concrete and various civil engineering structures. The compressive stress of the FRP confined and unconfined concrete column was predicted from the experimental and analytical results using ANN [7]. Previous studies [8–10] have developed the concrete compressive strength prediction model using ANN and Genetic Programming. This paper discusses the experimental study on the polypropylene fibre reinforced concrete to find the mechanical properties for different volume of fibre at 7 days and 28 days of curing. The prediction of strength using ANN approach was also discussed and compared.

2 EXPERIMENTAL STUDY

The ingredients of concrete were studied properly to identify its properties of the ingredients. Table 1 presents the properties of the polypropylene fibres. Concrete preparation was done by mixing constitute materials with different percentage of fibre thoroughly to avoid the segregation of fibres. Figure 1 shows the batching of ingredients of the polypropylene concrete. All the specimens casted with different proportion were cured under room temperature in the water tank. Figure 2 and 3 shows the cube, cylinder and prism specimens in order to find the compressive strength, split tensile strength and flexural strength of the specimen respectively. After 7 and 28 days of curing, the specimens were tested under compression testing machine of capacity 2000 kN and universal testing machine of capacity 600 kN to measure compressive strength, split tensile strength and flexural

---

P. Sangeetha, Department of Civil Engineering, Sri Sivasubramaniya Nadar College of Engineering , Chennai, Tamilnadu, India, sangeethap@ssn.edu.in
M. Shanmugapriya, Department of Mathematics, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamilnadu, India, shanmugapriyam@ssn.edu.in

strength of the specimens respectively. Figure 4 shows the loading position of the specimens.

Table 1. Properties of Polypropylene fibre

Fibre	Tensile Strength (gf/den)	Elongation (%)	Relative density	L (mm)	D (mm)	Aspect Ratio
Polypropylene	4.5	60	0.91	12	0.03	400

Figure 1. Polypropylene fibre and ingredients of concrete

Figure 2. Test Specimens to measure compressive strength

Figure 3. Test specimens to measure flexural and split tensile strength

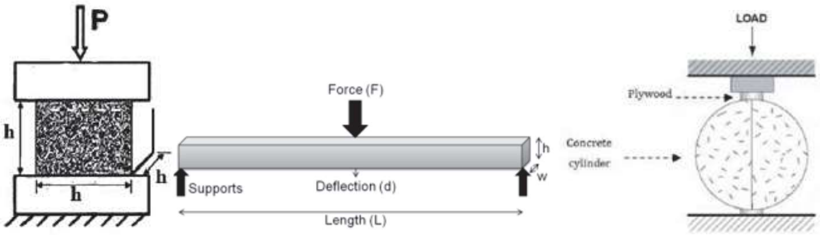


Figure 4. Test set up of the specimens

The increase in the percentage of fibres in the concrete increases the compressive strength, flexural strength and split tensile strength by 8 %, 20 % and 40 % respectively for change in the percentage of fibre from 0.5 % to 2.0 % by volume of cement. Figure 5 shows the comparison between the strength and % of fibre content for two curing period 7 days and 28 days.

3 ARTIFICIAL NEURAL NETWORK

The ANN prediction model is performed using MATLAB with one hidden layer of twenty-five hidden neurons and one output layer of dependent variables like compressive strength, flexural strength and split tensile strength. 70%, 15 % and 15 % of the date has been used for training, testing and validation respectively. The layered feed-forward networks have been used to predict the mechanical strength of concrete in Levenberg-Marquardt algorithm. In this network the signals are sent forward and errors are propagated backwards. The performance of ANN model to predict the mechanical strength of the concrete was measured using some statistical methods. The tests involved are coefficient of determination (R^2), Mean Squared Error (MSE), Mean Absolute Error (MAE) and Sum of Squared Errors (SSE).

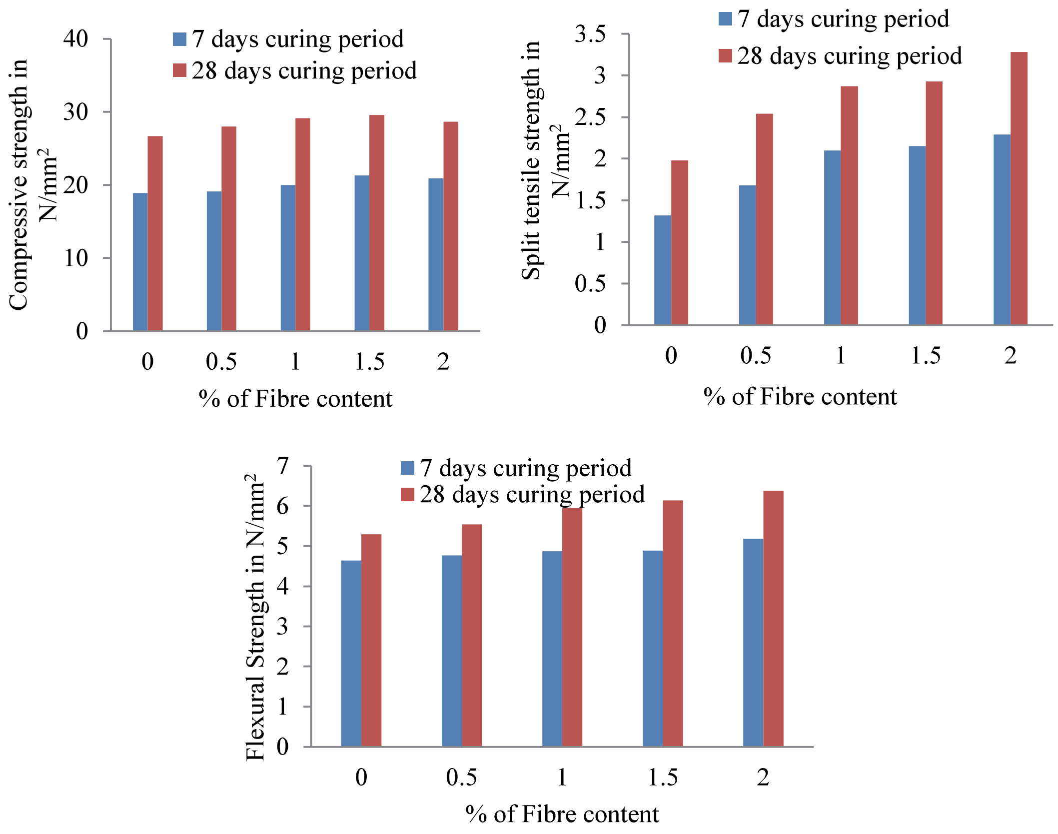


Figure 5. Effect of Polypropylene Fibre on the mechanical properties of concrete

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(E_i - P_i)^2}{\sum_{i=1}^{N}(E_i - \bar{E})^2} \quad (1)$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(E_i - P_i)^2 \quad (2)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|(E_i - P_i)| \quad (3)$$

$$SSE = \sum_{i=1}^{N}(E_i - P_i)^2 \quad (4)$$

whereE_i, P_i and N denote the experimental value, predicted value and the number of data points, respectively.

Figure 6 demonstrates the test errors for compressive strength, flexural strength and split tensile strength of the polypropylene fibre reinforced concrete. The MSE, MAE and SSE values are obtained by varying the number of hidden neurons and found that the test errors attained minimum for 11 neurons in compressive strength, 23 neurons in flexural strength and 12 neurons in split tensile strength. The optimum hidden neurons are employed to predict the mechanical strength of fibre reinforced concrete with three different neural networks. In addition, the comparison of R^2, MSE, MAE and SSE with the curing period days of 7 and 28 for all specimens is presented in table 2.

The experimental and predicted values for training, validation and testing obtained from MATLAB programme for compressive strength, flexural strength and split tensile strength are shown in figure 7 to 9 respectively. From figure 7 to 9 it is observed that the distribution of the network outputs verses the target values for all data sets are distributed along the optimal agreeable line. The correlation between the predicted and target components was found to be (0.99785,0.99495, 0.99865) for compressive strength, (0.98618, 0.98739, 0.99944) for flexural strength and (0.9959, 0.99423, 0.99595) for split tensile strength in the training, validation and testing process of the network and it is found to be satisfactory.

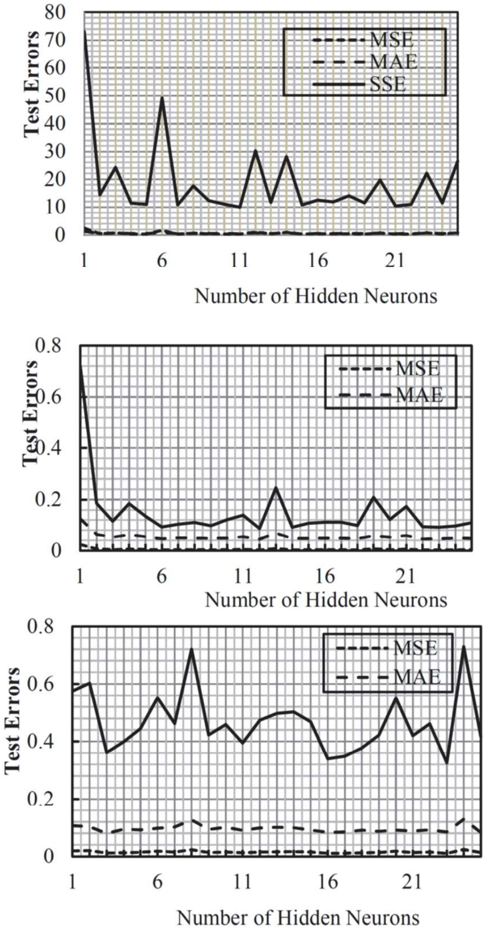


Figure 6. Test errors of fibre reinforced concrete against hidden neurons

Table 2. Comparison between the R^2, MSE, MAE and SSE for all specimens

Model	Period of Curing(days)	Coefficient of Determination (R^2)	Mean Squared Error (MSE)	Mean Absolute Error (MAE)	Sum of Squared Errors (SSE)
Compressive strength	7	0.733934	0.278883	0.430889	4.183241
	28	0.853518	0.288364	0.416	4.325458
Flexural strength	7	0.793707	0.013431	0.087035	0.201460
	28	0.956548	0.007614	0.067962	0.114208
Split tensile strength	7	0.978643	0.002563	0.042321	0.038442
	28	0.984468	0.013609	0.042755	0.040851

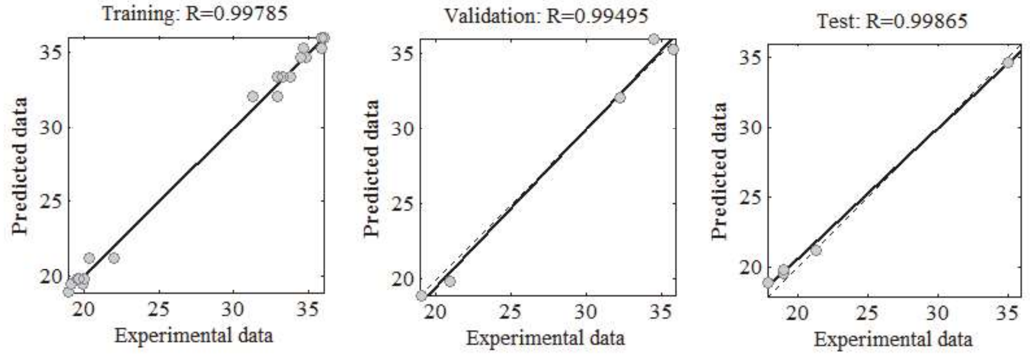


Figure 7. ANN graph for Compressive strength of the fibre reinforced concrete

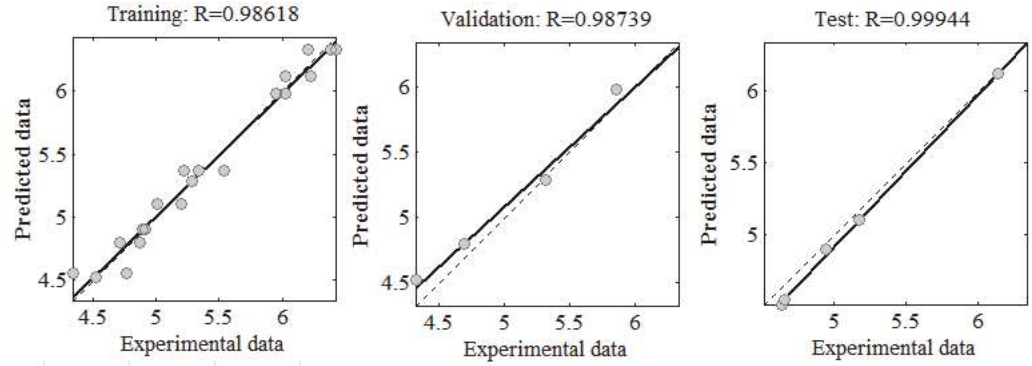


Figure 8. ANN graph for Flexural strength of the fibre reinforced concrete

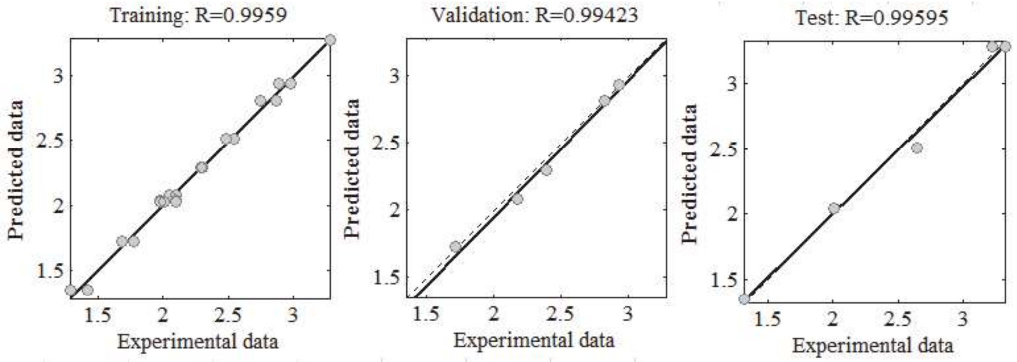


Figure 9. ANN graph for Split Tensile strength of the fibre reinforced concrete

Figure 10 shows convergence characteristics of the ANN model during the training, validation and testing phases respectively and the Table 3 gives the comparison of the test conducted on the predicted models. In addition, it shows the number of epochs (4, 4 & 6 iterations) and the best validation performance, which is 0.71201 at 2 iterations, 0.01369 at 4 iterations and 0.00404 at 5 iterations for compressive strength, flexural strength and split tensile strength respectively.

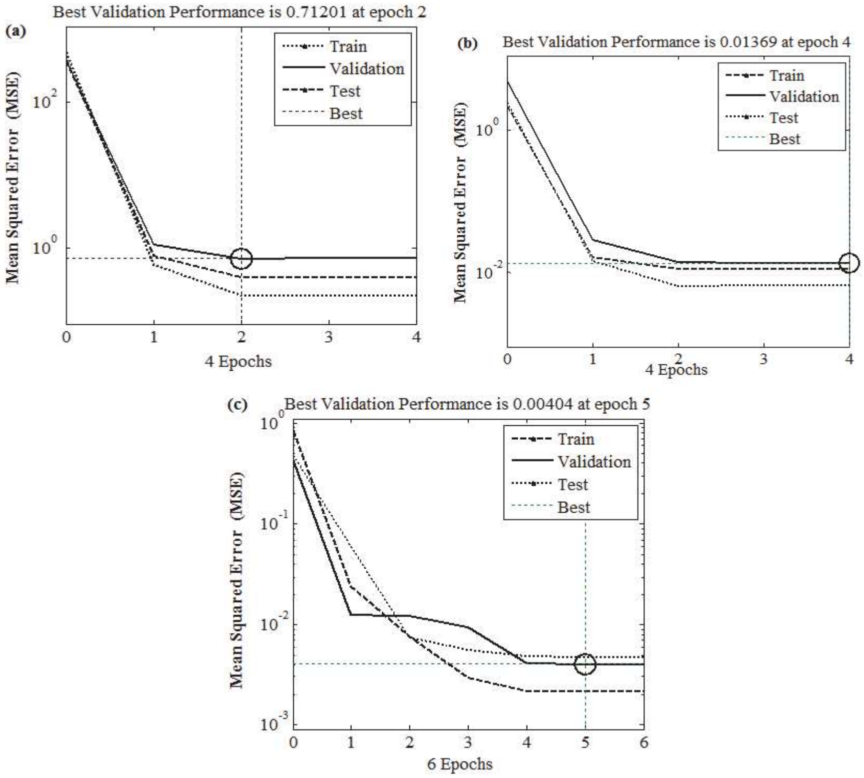


Figure 10. Performance plot for Polypropylene fibre Reinforced Concrete

Table 3. Comparison between the experimental and predicted strength of PFRC

% of Fibre	Compressive Strength (N/mm^2)			Flexural Strength (N/mm^2)			Split Tensile Strength (N/mm^2)		
	Exp. Value	**Predicted Value**	**Prediction Error (%)**	**Exp. Value**	**Predicted Value**	**Prediction Error (%)**	**Exp. Value**	**Predicted Value**	**Prediction Error (%)**
7 days									
0	18.89	18.8917	0.0017	4.64	4.52	-0.12	1.28	1.3500	0.0700
0.5	19.11	19.4900	0.3800	4.77	4.555	-0.215	1.77	1.7250	-0.0450
1	20	19.7788	-0.2212	4.87	4.795	-0.075	2.01	2.0400	0.0300
1.5	21.33	21.2050	-0.1250	4.89	4.905	0.015	2.05	2.0750	0.0250
2	19.98	19.8312	-0.1488	5.2	5.105	-0.095	2.39	2.2950	-0.0950
28 days									
0	32.29	32.0901	-0.1999	5.29	5.29	0.0000	1.98	2.0300	0.0500
0.5	33.82	33.3179	-0.5021	5.54	5.3667	-0.1733	2.54	2.5100	-0.0300
1	34.8	34.6469	-0.1531	5.95	5.985	0.035	2.87	2.8100	-0.0600
1.5	34.62	35.2519	0.6319	6.14	6.12	-0.02	2.98	2.9350	-0.0450
2	36	35.9438	-0.0562	6.42	6.3333	-0.0867	3.22	3.2800	0.0600

4 CONCLUSIONS

This study is aimed to find the best model to predict the compressive strength, flexural strength and split tensile strength at 7 days and 28 days curing using ANN. A total of 90 values were trained to predict the mechanical strength of polypropylene fibre Reinforced Concrete by 3 ANN models. All the outputs are compared using the coefficients of determination calculated for the highest R^2 values. The following conclusions are obtained from the study.

- From the predicted results of mechanical properties of the polypropylene fibre reinforced concrete, it is concluded that ANN models are more suitable and accurate for prediction of 28 days strength based on the R^2 values obtained from the ANN model.
- The Mean Squared Error (MSE) for all three models for predicting the compressive, split tensile and flexural strength are very low and nearly equal to zero. The correction coefficient (R) for all three models are greater than 0.85 and it is acceptable.
- ANN model with $R^2 = 0.9844$, MSE = 0.0136 and SSE = 0.03844 are found to be capable of predicting the 28 days split tensile strength.
- The increase in the number of independent variables leads to the increase in the accuracy of the ANN model.

5 REFERENCES

[1] A.W.Otunyo&A.J.Odebiyi, “Regression Modeling of the Strength Properties of Concrete Reinforced with Polypropylene Fibre and Alkali Resistant Glass Fibre”, Nigerian Journal of Technology, vol. 37, no.4, (**2018)**, pp.898-906.

[2] MeltemOzturan, BirgulKutlu&TuranOzturan, “Comparison of concrete strength prediction techniques with artificial neural network approach”, Building Research Journal, vol. 56, no.1, (**2008**), pp.23 – 36.

[3] Seung – Chang Lee, “Prediction of concrete strength using artificial neural network”, Engineering Structures, vol. 25, (**2003**), pp.849 – 587.

[4] Ali Nazari &ShadiRiahi, “Prediction of split tensile strength and water permeability of high strength concrete containing TiO_2 nanoparticles by artificial neural network and genetic programming”, Composites: Part B, vol. 42, (**2011**), pp.473-488.

[5] Lyes Bal & Francois Buyle-Bodin, “Artificial neural network for predicting drying shrinkage of concrete”, Construction and Building Materials, vol.38, (**2013**), pp.248-254.

[6] Sumathi A & Saravana Raja Mohan, “Strength Predictions of Admixed High Performance Steel Fiber Concrete”, International Journal of ChemTech Research, vol.6, no.11, (**2014**), pp.4729 - 4736.

[7] Sangeetha P &Shanmugapriya M, “Numerical study on FRP wrapped concrete columns under compression”, Indian Journal of Science and Technology, vol.12, no.15, (**2019**), pp. 1 – 7.

[8] FaezehossadatKhademi,SayedMohammadmehdi Jamal, Neela Deshpande &ShreenivasLondhe “Predicting strength of recycled aggragate using Artificial neural network, Adaptive neuro-fuzzy inference system and Multiple Linear Regression” International Journal of Sustainable Built Environment , vol. 5, (**2016**) ,pp. 355 – 369.

[9] Osama A. Hodhod, Mohamed S.Khalafalla&MohanedS.M.Osman, “ANN models for nano silica/silica fume concrete strength prediction”, Water Science, vol. 33, no. 1, (**2019**), pp.118-127.

[10] Palika Chopra, Rajendra Kumar Sharma &Maneek Kumar “Prediction of compressive strength of concrete using artificial neural network and genetic programming”, Advances in Materials Science and Engineering, vol. 2016, (**2016**), pp. 1-10.

ABSTRACT

PREDICTION OF MECHANICAL STRENGTH OF POLYPROPYLENE FIBRE REINFORCED CONCRETE USING ARTIFICIAL NEURAL NETWORK

P. SANGEETHA
M. SHANMUGAPRIYA

The usefulness of fibre reinforced concrete (FRC) in various civil engineering applications is indisputable. Fibre reinforced concrete has been successfully used so far in construction of structures like bridges, industrial structures, concrete, architectural panels, precast products, offshore structures and many other applications. This paper presents the study on the mechanical properties of the polypropylene fibre reinforced concrete. The parameters varied in the study include volume of fibre (0%, 0.5%, 1.0%, 1.5% & 2.0%) and the curing period (7 days and 14 days). From the study it is concluded that the further increases in the volume of fibre reduces the water cement ratio. The mechanical properties of the polypropylene fibre reinforced concrete were also predicted by using Artificial Neural Network (ANN) and found to have minimal error when compared to actual experimental results.

Keywords: Polypropylene fibre, fibre content, curing period, strength prediction, ANN

APSTRAKT

PREDVIĐANJE MEHANIČKE ČVRSTOĆE BETONA OJAČANOG POLIPROPILENSKIM VLAKNIMA KORIŠĆENJEM VEŠTAČKE NEURONSKE MREŽE

P. SANGEETHA
M. SHANMUGAPRIYA

Upotrebljivost betona ojačanog vlaknima (FRC) u različitim građevinarskim primenama je nesporna. Armirani beton ojačan vlaknima do sada se uspešno koristi u izgradnji objekata kao što su mostovi, industrijske konstrukcije-objekti, betonski arhitektonski paneli, gotovi proizvodi, morske konstrukcije i mnoge druge. U ovom radu je predstavljeno istraživanje mehaničkih svojstvima armiranog betona od polipropilenskih vlakana. Parametri koji su varirali u istraživanju uključuju zapreminu vlakana (0%, 0,5%, 1,0%, 1,5% i 2,0%) i period očvršćavanja (7 dana i 14 dana). Iz analize istraživanja je zaključeno da dalje povećanje zapremine vlakana smanjuje odnos vodo – cementnog faktora. Mehanička svojstva betona ojačanog sa polipropilenskim vlakanima takođe su predviđena korišćenjem veštačke neuronske mreže (ANN) i utvrđeno je da imaju minimalnu grešku u poređenju sa stvarnim eksperimentalnim rezultatima.

Ključne reči: Polipropilenska vlakna, sadržaj vlakana, period očvršćavanja, predviđanje čvrstoće, ANN

UPOREDNA ANALIZA PONAŠANJA BETONSKIH GREDA ARMIRANIH ŠIPKAMA I TEKSTILOM – EKSPERIMENTALNO ISTRAŽIVANJE

COMPARATIVE ANALYSIS OF BEHAVIOUR OF REINFORCED CONCRETE BEAMS USING BARS AND TEXTIL – EXPERIMENTAL RESEARCH

Damir ZENUNOVIĆ
Danijel RUŽIĆ

PRETHODNO SAOPŠTENJE
PRELIMINARY REPORT
UDK:624.012.45:66.017/.018
doi:10.5937/GRMK2004087Z

1 UVOD

Dinamičan razvoj tehnologije materijala doveo je do primjene različitih novih materijala za poboljšanje svojstava nosivosti i trajnosti betonskih nosača. Jedan od pristupa jeste primjena sistema zaštite obložnog dijela betonskog nosača (zaštitni sloj betona). U ovu svrhu, razvijeni su polimerni materijali armirani karbonskim, staklenim ili aramidnim vlaknima (FRP – Fiber Reinfored Polymer). Novi pravac razvoja ovih sistema jeste primjena tekstilom armiranih sitnozrnih betona, gdje se koriste tekstili s vlaknima u više pravaca. Fabrički proizvedena ravninska tekstilna struktura sačinjena je od vlakana upletenih na razne načine, kao što su tkanje, pletenje, filcovanje ili štrikanje. Za potrebe istraživanja i razvoja ovog sistema ojačanja betonskih greda, formirana su dva istraživačka centra u kojima se sprovode projekti pod nazivom „Textile Reinforced Concrete (TRC) -Technical Basis for the Development of a New Technology” (SFB 532) RWTH Aachen University i „Textile Reinforcements for Structural Strengthening and Repair” (SFB 528) Technische Universitat Dresden. U ovim istraživačkim centrima sprovode se istraživanja mehanizama trajnosti, prionljivosti i kapaciteta nosivosti. Pored dva navedena velika projekta, postoji i niz projekata koji se odnose na tekstilom armirani beton, a sprovedeni su u Izraelu, Sjedinjenim Državama, Grčkoj, Belgiji, Ujedinjenom Kraljevstvu i Kanadi [3]. Utvrđeno je da količina i raspored tesktilne strukture imaju značajan uticaj na ponašanje tekstilom armiranog betona. Istraživanja su posvećena:

1 INTRODUCTION

The dynamic development of material technology has led to the application of various new materials for the purpose of improving the load-bearing properties and durability of concrete girders. One of the approaches is the application of the protection system at the surface layer of the concrete girders(protective layer of concrete). Polymer materials reinforced with carbon, glass or aramid fibres (FRP - Fibre Reinforced Polymer) have been developed for this purpose, A new direction of development of these systems is the use of textile reinforced fine-grained concrete, where textiles with fibres have been used in several directions. The factory-produced flat textile structure is formed of interlocking fibres in various ways such as weaving, knitting, felting or knitting. Two research centres were formed for the purpose of a research and development of this system where projects entitled ‘Textile Reinforced Concrete (TRC) -Technical Basis for the Development of a New Technology’ (SFB 532) RWTH Aachen University and ‘Textile Reinforcements for Structural Strengthening and Repair’(SFB 528) Technical University of Dresden. These research centres have carried out a research about the durability mechanisms, adhesion and load-bearing capacity. In addition to these two major projects, there are a number of projects related to textile reinforced concrete, which have been implemented in Israel, USA, Greece, Belgium, the UK and Canada [3]. It was determined that the amount and arrangement of the textile structure have

---

Damir Zenunović, profesor, Univerzitet u Tuzli, Univerzitetska 2, 75000 Tuzla, damir.zenunovic@untz.ba
Danijel Ružić, magistar, Univerzitet u Tuzli

Damir Zenunovic, Professor, University of Tuzla, Univerzitetska 2, 75000 Tuzla, damir.zenunovic@untz.ba
Danijel Ruzic, Master of Science, University of Tuzla, danijelr@hotmail.com

primjeni tekstilnih materijala znatno većeg modula elastičnosti u odnosu na beton, kako otvaranje pukotina u betonu ne bi uzrokovalo značajnu redukciju krutosti konstruktivnog elementa, trajnosti tekstilnog materijala, ponašanju tekstilnog materijala pod dugotrajnim opterećenjem, prionljivosti s betonom, te smanjenju troškova izrade tekstilnih mreža. Istraživanjima je utvrđeno da alkalno otporna staklena vlakna, karbonska i aramidna vlakna ispunjavaju potrebne zahtjeve. U radu [13] dat je pregled fizičko-mehaničkih i deformacionih karakteristika pojedinih vlakana.

Korištenje alkalno-otpornog stakla u građevinarstvu započinje sedamdesetih godina prošlog vijeka [3]. U zavisnosti od finoće vlakana, čvrstoće su do 1.400 N/mm^2, linearno elastično izduženje – do 2%, a modul elastičnosti – od 70 do 80 kN/mm^2. U eksperimentalnom programu, predstavljenom u ovom radu, korištene su tekstilne mreže sa alkalno-otpornim, staklenim vlaknima.

Da bi se postigla stabilna forma za armiranje betona tekstilom, započeta je proizvodnja tekstilnih mreža. U radu [3] opisuje se ideja armiranja za vrijeme procesa proizvodnje tekstilnih mreža, te postizanje stabilnosti tekstilne mreže impregnacijom i ubacivanjem dodatnih oslonaca, odnosno dodatnih elemenata za ukrućenje.

U radovima [3], [7] i [12] daju se preporuke za recepture betona kako bi se osigurala prionljivost tekstilne mreže i betona, kao i ugradljivost betona kroz tekstilnu teksturu. Istraživanja pokazuju da je pogodan sitnozrni beton tečne konzistencije, te da su neophodni dodaci plastifikatora.

U radovima [15] i [16] dat je pregled utvrđenih fizičko-mehaničkih i deformacionih svojstava tekstilnih mreža, te dosadašnja iskustva primjene u građevinarstvu.

Tekstilne mreže se uglavnom koriste za spoljna ojačanja armiranobetonskih nosača. Efekti ojačanja istraženi su i prezentovani u radovima [1], [2], [4], [5], [7], [9], [10], [12] i [13]. Istraživanja su pokazala da efekti ojačanja tekstilnim mrežama zavise od orijentacije glavnih vlakana tekstilnih mreža, broja slojeva tekstilnih mreža, postupka ugradnje, u smislu ostvarenja prionljivosti tekstilne mreže i podloge, kao i adekvatnog utezanja nosača tekstilnom mrežom. Dobijena su povećanja kapaciteta nosivosti armiranobetonskih greda na smicanje i savijanje, s tim što procenat povećanja zavisi od prethodno navedenih efekata.

Numerički modeli za proračun armiranobetonskih elemenata ojačanih tekstilnim mrežama predstavljeni su u radovima [6], [8], [11], [10] i [14].

U ovom radu predstavljen je program istraživanja s ciljem utvrđivanja mogućnosti primjene tekstilnih mreža za armiranje unutar poprečnog presjeka, što bi omogućilo razvoj poluprefabrikovane armiranobetonske grede sa spregnutim poprečnim presjekom. Istraživanje sa sličnom idejom predstavljeno je u radu [9].

2 PROGRAM EKSPERIMENTA (EXPERIMENTAL PROGRAM)

S ciljem utvrđivanja mehanizma nosivosti greda armiranih armaturnim šipkama i tekstilom, eksperimen-

a significant influence on the behaviour of textile reinforced concrete. Researchers are dedicated to the application of textile materials with significantly higher modulus of elasticity compared to the concrete, so that openings of the cracks in the concrete are unlikely to cause a significant reduction in stiffness of structural element, durability of textile material, behaviour of textile material under long-term load, adhesion with the concrete and reduced costs of textile meshes production. Studies have shown that alkali-resistant glass fibres, carbon and aramid fibres meet the necessary requirements. In the paper [13], physical-mechanical and deformation characteristics of individual fibres have been presented.

The use of alkali-resistant glass in civil engineering began in the 1970s [3]. Depending on the fineness of the fibres, the strengths are up to 1400 N/mm^2, the linear elastic elongation is up to 2%, and the modulus of elasticity ranges from 70 to 80 kN/mm^2. In the experimental program presented in the paper textile meshes with alkali-resistant glass fibres were used. A production of textile meshes has begun for the purpose of achieving a stable form of reinforced concrete with textile. In the paper [3] has been described an idea of reinforcing textile meshes during production, and achieving stability of textile mesh through impregnation and adding additional support and elements for stiffening. In papers [3], [7] and [12], have been presented recommendations for concrete recipes in order to ensure the adhesion of textile mesh and concrete, as well as to embed ability of concrete through textile texture. Research demonstrated that fine-grained concrete of liquid consistency is suitable but it is necessary to add plastizers. In papers [15] and [16] have been presented physical-mechanical and deformation properties of textile meshes, as well as previous experiences of application in construction.

Textile meshes are generally used for external reinforcements of reinforced concrete structures. The effects of reinforcement were presented in papers [1], [2], [4], [5], [7], [9], [10], [12] and [13]. Research have shown that the reinforcement effects of using textile meshes depends on the main fibre orientation of the textile meshes, the number of textile layers of the meshes, the installation process when it comes to achieving adhesion textile mesh or basis and an adequate shrinkage of the textile mesh girder. Increases have been obtained when it comes to the bearing capacity of reinforced concrete beams for shearing and bending, bearing in mind that the percentage of increase depends on the previously mentioned effects. In the papers [6], [8], [10], [11] and [14] have been presented numerical models for the calculation of reinforced concrete elements reinforced with textile mesh.

This paper presents a research program with the aim of determining possible applications of textile mesh reinforcement within the cross section, which would allow the development of semi-prefabricated reinforced concrete beams with a composite cross-section. Research with a similar idea has been presented in the paper [9].

2 EXPERIMENTAL PROGRAM

In order to determine the load-bearing mechanism of reinforced beams using reinforced bars and textiles, the talnim programom predviđeno je uporedno ispitivanje tri tipa modela:

- model grede armirane armaturnim šipkama (RC – Reinforced Concrete);
- model grede armirane armaturnim šipkama i tekstilom (CRC – Combined Reinforced Concrete);
- model grede armiran tekstilom (TRC – Textile Reinforced Concrete).

Urađeno je devet modela (3 RC + 3 CRC + 3 TRC) (slika 1).

experimental program provides comparative research of three types of models:

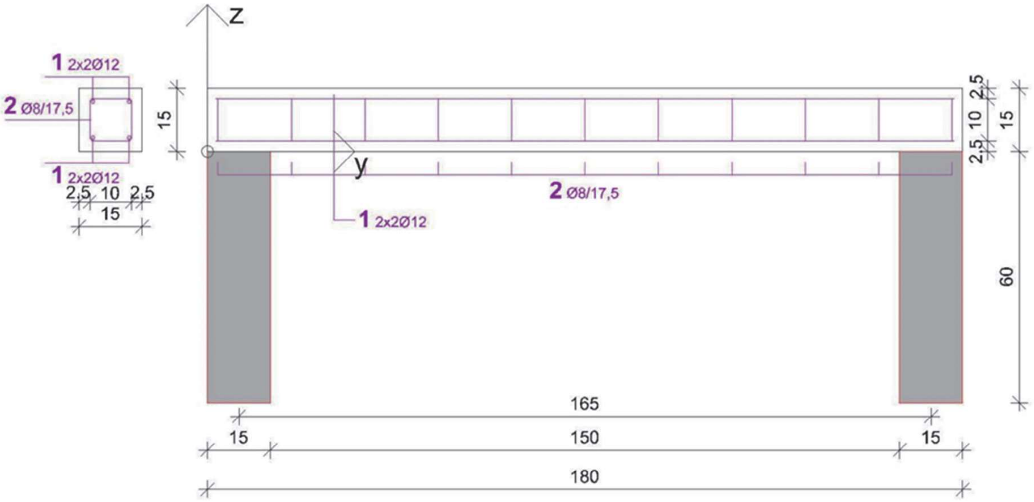
- model of reinforced beams using reinforced bars (RC - Reinforced Concrete),
- model of reinforced beams using reinforced bars and textiles (CRC - Combined Reinforced Concrete),
- textile-reinforced beam model (TRC - Textile Reinforced Concrete).

In the research participated nine (9) models (3 RC + 3 CRC + 3 TRC) (Figure 1).

Slika 1. Izrada modela
Figure 1. Model setup

Modeli greda su dimenzija 15/15/180 cm. Svi modeli urađeni su od betona iste recepture klase čvrstoće C 25/30, armirani armaturnim šipkama S500N. Na slici 2 prikazan je način armiranja RC modela.

Dimensions of model beams are 15/15/180 cm. All models are made of concrete with the same recipe of strength class C25/30. All models are reinforced with S500N reinforcing bars. Figure 2 shows the method of reinforcing the RC model.



Slika 2. Način armiranja RC modela
Figure 2. The method of reinforcing the RC model

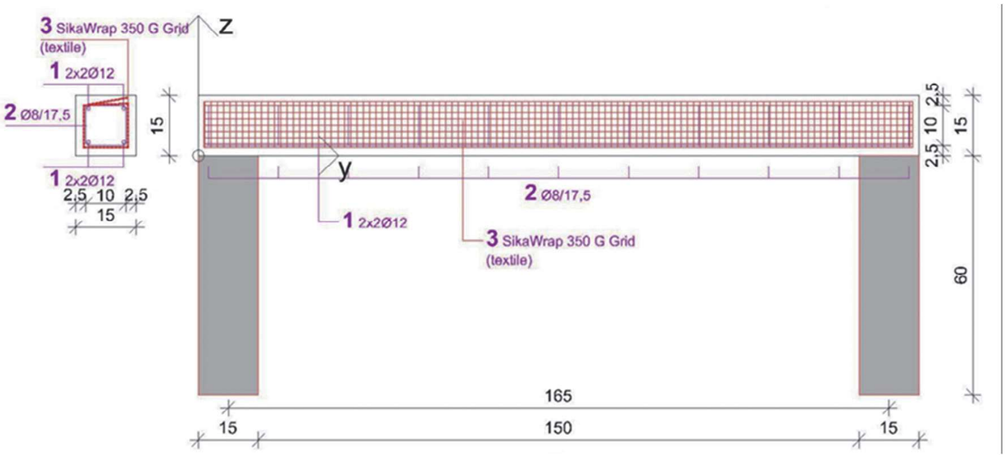
Podužna armatura jeste 4Ø12, a poprečna - RØ8/17,5 cm. Za CRC modele korištena je tekstilna mreža od alkalno-otpornih staklenih vlakana proizvođača SIKA AG, komercijalnog naziva SikaWrap – 350 G Grid.

Čvrstoća na zatezanje vlakana je f_{yt} = 2600MPa, a modul elastičnosti E = 80000MPa. Kako su ispitivanja prezentovana u radovima [1], [6], [8] i [9] pokazala da je

The longitudinal reinforcement is 4Ø12, while the transverse reinforcement is RØ8 / 17.5 cm. A textile mesh used for CRC models is made of alkali-resistant glass fibres manufactured by SIKA AG, commercial name is SikaWrap - 350 G Grid. The tensile strength of the fibres is f_{yt} = 2600MPa, and the modulus of elasticity E = 80000MPa.

orijentacija tekstila značajna za konačne rezultate u pogledu nosivosti i mehanizma otvaranja pukotina, tekstilne mreže ugrađene su tako da su glavne nosive trake mreže u pravcu podužne ose modela grede, što je povoljna orijentacija iz aspekta nosivosti na savijanje. Kako bi se ostvarila što bolja prionljivost betona i tekstilne mreže, prilikom ugradnje betona, mreže su ostavljene otvorene s gornje strane. Konačan izgled armature CRC modela prikazan je na slici 1. Način armiranja CRC modela predstavljen je na slici 3. Prilikom izrade TRC modela, tekstilna mreža ojačana je uzengijama od žice prečnika 3 mm, kako bi se osigurala stabilnost tekstilne mreže tokom ugradnje betona.

Testing presented in [1], [6], [8] and [9] showed that the orientation of textiles is important for the final results in terms of load-bearing capacity and crack opening mechanism. Therefore, textile meshes were installed in such way that the main load-bearing fibres in the mesh are placed in the direction of the longitudinal axis of the beam model, which is a favourable orientation from the aspect of bearing capacity to bending. In order to achieve the best possible adhesion of concrete and textile mesh, during the installation of concrete meshes were left open from the top. The final arrangement of CRC model reinforcement is shown in Figure 1. The method of reinforcing the CRC model is presented in Figure 3.During the creation of the TRC model, textile mesh is reinforced with stirrup made out of wire diameter of 3 mm for the purpose of ensuring the stability of the textile mesh during installation of concrete.



Slika 3. Model CRC
Figure 3. The method of reinforcing the CRC model

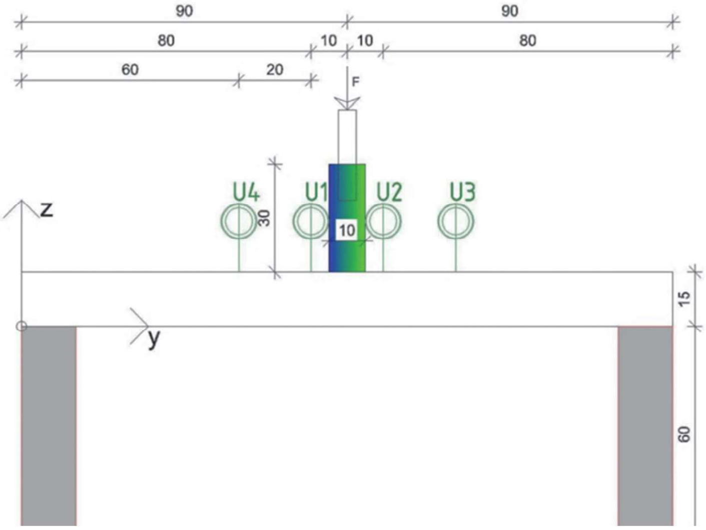
Tokom ispitivanja, mjereni su ugibi, dilatacije (izduženja i skraćenja) gornjeg i donjeg površinskog sloja grede i širine pukotina. Raspored mjernih mjesta prikazan je na slikama 4 i 5.

Mjerenje ugiba rađeno je sa ugibomjerima tačnosti mjerenja 0,01 mm, a dilatacije deformaterima s tačnošču mjerenja 0,01 mm i mjernim bazama 100 i 300 mm.

Intenziteti opterećenja usvojeni su na osnovu proračuna proste armiranobetonske grede datih geometrijskih karakteristika i raspona (prezentovanih na slikama 2 i 3). Puno opterećenje grede, pri kojem se dostiže kapacitet nosivosti s faktorom sigurnosti 1.0, jeste F = 27kN. Modeli su opterećeni u 12 faza, sa opterećenjima intenziteta F = 2, 4, 6, 8, 14, 21, 27, 36, 45, 51, 54 kN. Nakon dostizanja opterećenja F = 8 Kn, rađeno je rasterećenje modela nakon svake faze opterećenja kako bi se pratilo područje razvijanja plastičnih deformacija. Opterećenje modela vršeno je hidrauličkom presom. Postavka ispitivanja modela prikazana je na slici 6.

During the testing, deflections, dilatations (elongation and shortening) of the upper and lower surface layer of the beam and the width of cracks were measured. The layout of the measuring points is shown in Figures 4 and 5. Measurement of deflection is done with the measurement accuracy of 0.01 mm, with a dilatation of deformation of 0.01 mm measuring accuracy and measuring bases 100 and 300 mm.

The load intensities of the beams were adopted on the basis of the calculation of a simple reinforced concrete beam of geometrical characteristics and spans presented in Figures 2 and 3. The full load of the beam, at which the bearing capacity is reached with a safety factor of 1.0, is F = 27kN. The models were loaded in 12 phases with load intensities of F = 2, 4, 6, 8, 14, 21, 27, 36, 45, 51, 54 kN. After reaching the load of F = 8 kN, the model was unloaded after each phase of the load in order to monitor the area of development of plastic deformations. The model was loaded with a hydraulic press. The model test setup is presented in Figure 6.



Slika 4. Raspored mjernih mjesta za mjerenje ugiba
Figure 4. Disposition of deflection measurement points

Slika 5. Raspored mjernih mjesta za mjerenje dilatacija
Figure 5. Disposition of dilatation measurement points

Slika 6. Postavka ispitivanja
Figure 6. Test setup

3 REZULTATI ISPITIVANJA

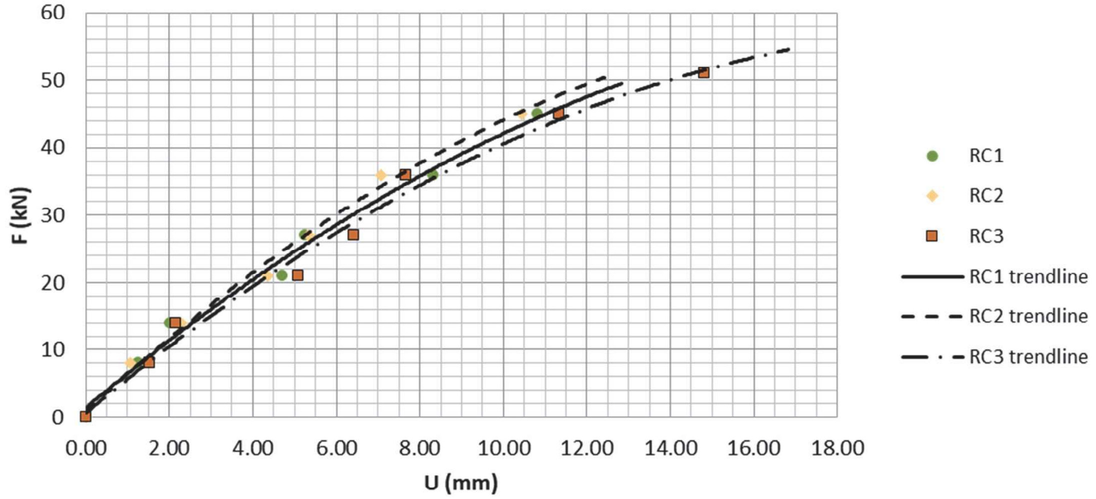
U radu se predstavljaju rezultati mjerenja ugiba i praćenja mehanizma otvaranja pukotina. Na osnovu tih rezultata, moguće je donijeti zaključak o ponašanju betonskih greda armiranih armaturnim šipkama i tekstilnim mrežama.

Na slikama 7 i 8 prikazani su radni dijagrami sila–progib ispitanih RC modela za mjerna mjesta U2 i U4

3 TEST RESULTS

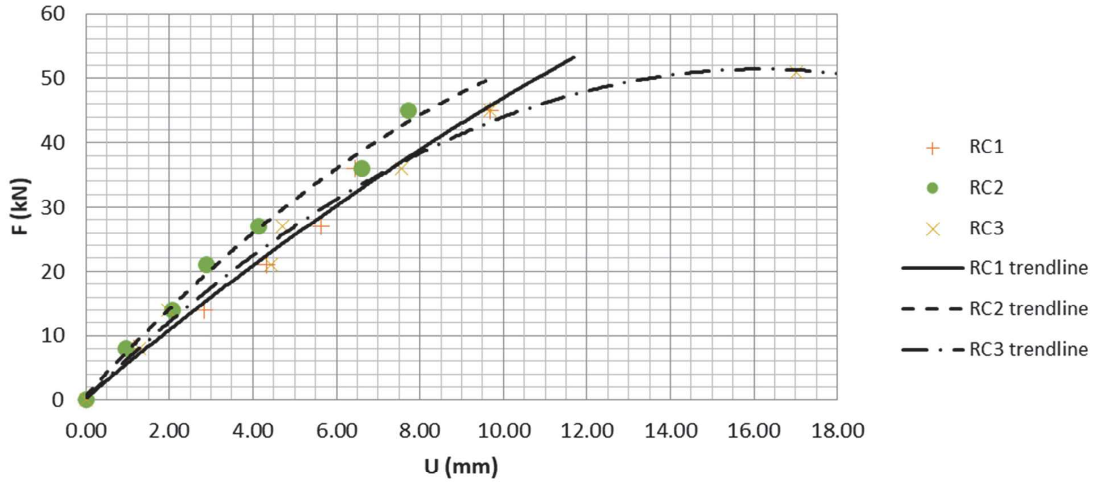
The paper presents the results of measuring deflection and monitors the crack opening mechanism. Based on these results, it is possible to draw a conclusion about the behaviour of reinforced concrete beams using reinforced bars and textile meshes.

In figures 7 and 8 are presented the force-displacement diagrams of the tested RC models for measuring points U2 and U4.



RC1 trendline *y = -0.1144x2 + 5.2169x + 1.3932 (R² = 0.9884)*
RC2 trendline *y = -0.1396x2 + 5.7282x + 0.7925 (R² = 0.9934)*
RC3 trendline *y = -0.1163x2 + 5.1578x + 0.6395 (R² = 0.9876)*

Slika 7. RC modeli, mjerno mjesto U2
Figure 7. RC models, measurement point U2

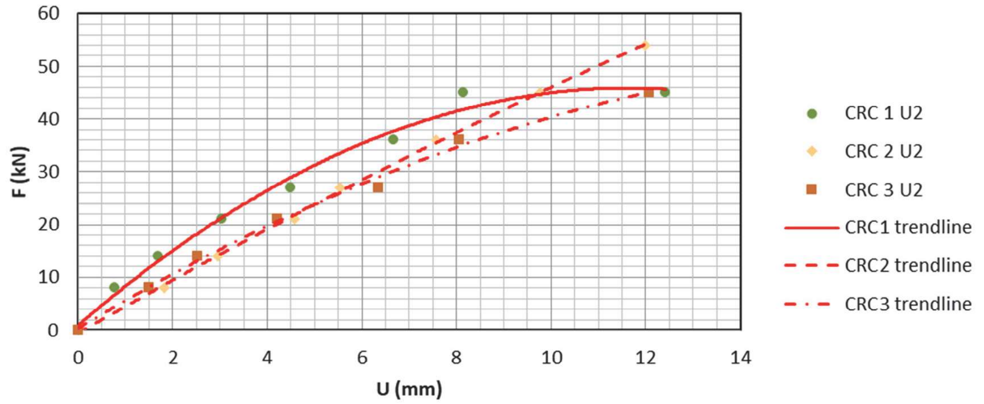


RC1 trendline *y = -0.0796x2 + 5.4604x + 0.3137 (R² = 0.9842)*
RC2 trendline *y = -0.2157x2 + 7.1769x + 0.68 (R² = 0.9908)*
RC3 trendline *y = -0.1953x2 + 6.3209x + 0.3012 (R² = 0.9902)*

Slika 8. RC modeli, mjerno mjesto U4
Figure 8. RC models, measurement point U4

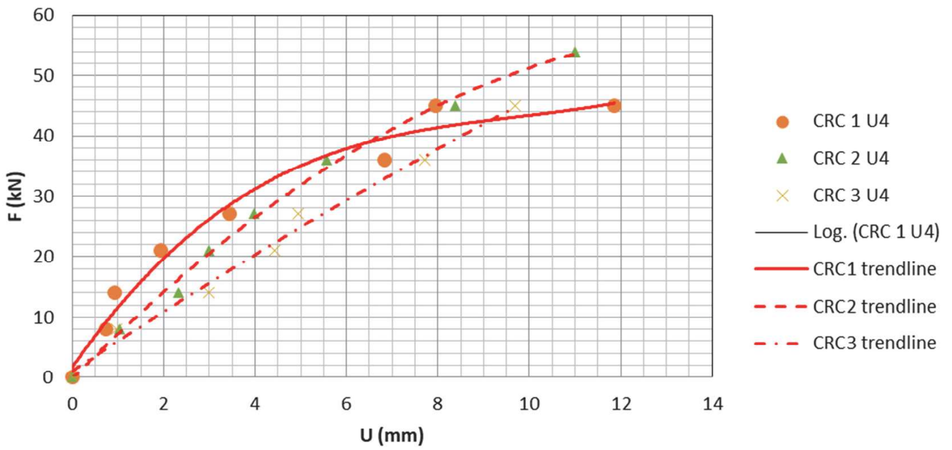
Efikasnost provlačenja (fitovanja) radnih dijagrama određena je koeficijentom determinacije R^2. Koeficijenti determinacije imaju zadovoljavajuće vrijednosti. Iz priloženih radnih dijagrama vidljivo je da je nešto veće rasipanje rezultata pri mjerenju ugiba na mjernim mjestima koja su u trećini raspona (mjerno mjesto U4), odnosno mjernim mjestima udaljenim od mjesta nanošenja opterećenja, u odnosu na mjerna mjesta u blizini nanošenja sile na polovini raspona (mjerno mjesto U2). Ovdje je vidljiv efekat heterogenosti strukture betona, odnosno stohastički promjenljivog odnosa zapremine zrna i zapremine cementnog kamena duž grede. Ujednačenost ponašanja RC modela vidljiva na slici 7. Na slikama 9 i 10 prikazani su radni dijagrami sila–progib ispitanih CRC modela za ista mjerna mjesta U2 i U4.

The fitting efficiency of the working diagrams is determined by the coefficient of determination R2. The coefficients of determination have satisfactory values. It is evident, as shown in diagrams, that there is a slightly higher scattering of the results during measuring the deflection at the measuring points which are in one third of the span (measuring point U4), measuring points far from the place of application of the load, compared to the measuring points near the application of force at half the span (measuring point U2). Here, the effect of heterogeneity of concrete structure, i.e. stochastically variable ratio of aggregate volume and cement stone volume along the beam is visible. The uniformity of the RC model behaviour can be seen in Figure 7. Figures 9 and 10 show the working force-displacement diagrams of the tested CRC models for the same measuring points U2 and U4.



CRC1 trendline $y = -0.5178x^2 + 9.8375x + 0.3343$ ($R^2 = 0.9803$)
CRC2 trendline $y = -0.0284x^2 + 4.9683x - 0.4273$ ($R^2 = 0.9987$)
CRC3 trendline $y = -0.0886x^2 + 4.5451x + 3.3714$ ($R^2 = 0.9786$)

Slika 9. CRC modeli, mjerno mjesto U2
Figure 9. CRC models, measurement point U2



CRC1 trendliney = *0.0349x3 - 1.0234x2 + 10.915x + 1.6715* ($R^2 = 0.977$)
CRC2 trendline *y = -0.2535x2 + 7.68x - 0.2135* ($R^2 = 0.9958$)
CRC3 trendline *y = -0.053x2 + 5.0249x + 1.0493* ($R^2 = 0.9893$)

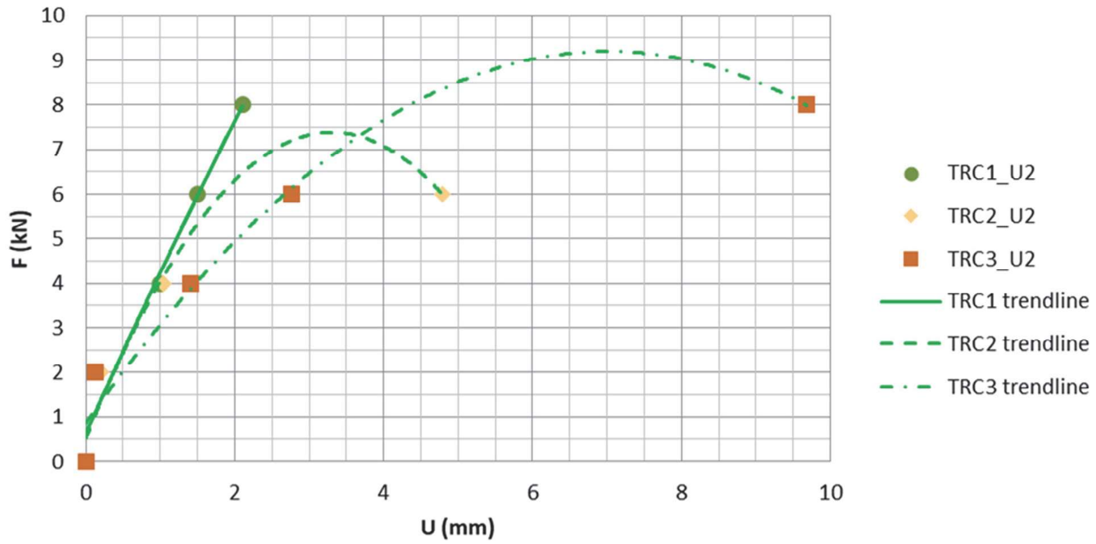
Slika 10. CRC modeli, mjerno mjesto U4
Figure 10. CRC models, measurement point U4

Iz radnih dijagrama na slikama 9 i 10 vidljivo je da je kod CRC modela veće rasipanje rezultata, što je posljedica kompozitnosti presjeka, otežanih uslova ugradnje betona i stepena prionljivosti tekstila i betona duž grede.

Ispitivanjem TRC modela dobila se nosivost grede na savijanje približno 50% veća u odnosu na nearmiranu betonsku gredu. Na slici 11 predstavljeni su radni dijagrami TRC modela.

The working diagrams in Figures 9 and 10 show that the CRC model has a higher scattering of results, which is the consequence of the cross-sectional composition, difficult conditions for concrete installation and the degree of adhesion of textiles and concrete along the beam.

By testing the TRC model, the load-bearing capacity of the beam was approximately 50% higher compared to the non-reinforced concrete beam. Figure 11 presents the working diagrams of the TRC model.



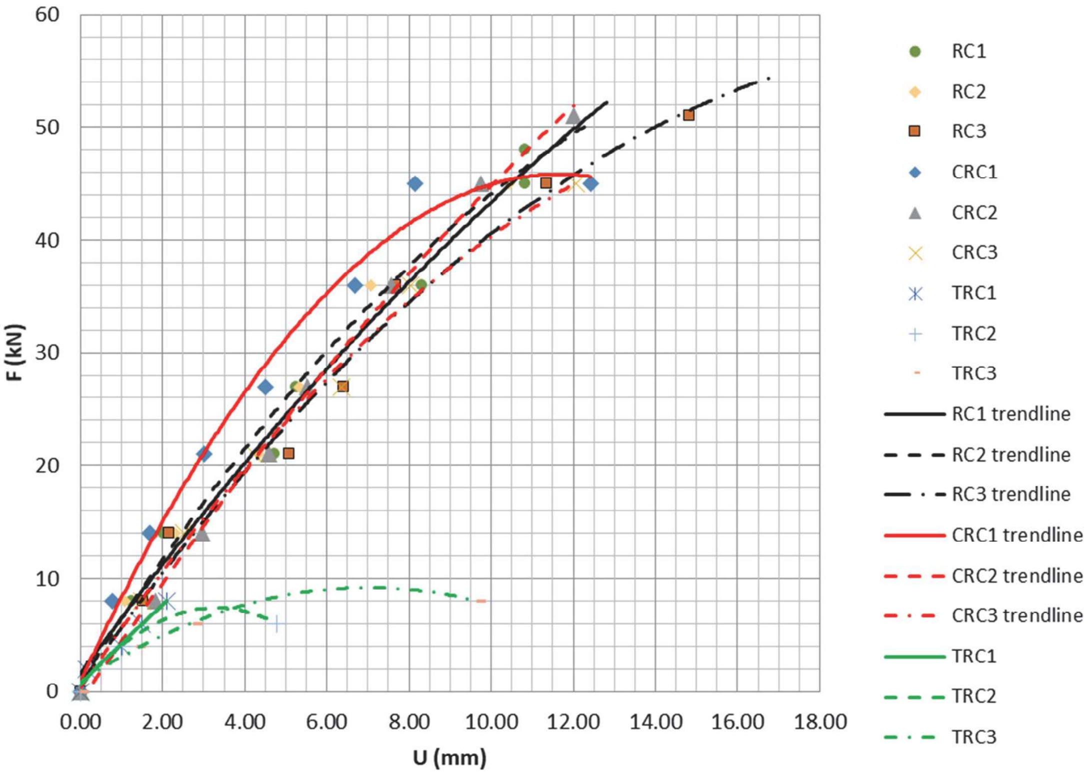
Slika 11. Dijagrami sila–progib RC i CRC modela, mjerno mjesto U2
Figure 11. TRC models, measurement point U2

Poređenje radnih dijagrama sila–progib RC, CRC i TRC modela prikazano je na slici 12. Iz prezentovanih radnih dijagrama RC i CRC modela vidljivo je slično ponašanje klasično armiranih greda (RC) i greda armiranih armaturnim šipkama i tekstilom (CRC). Utvrđeni prosječni intenzitet sile loma isti je kod CRC modela i RC modela.

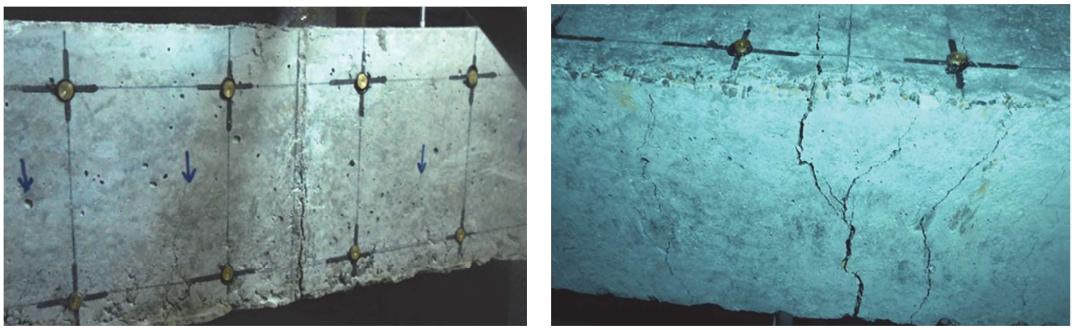
Pored mjerenja ugiba i dilatacija, praćen je mehanizam otvaranja pukotina i način otkaza ispitanih modela. Kod RC i CRC modela, prve pukotine otvorile su se pri istom intenzitetu sile (F=21kN). Međutim, kod RC modela i CRC modela, registrovani su različiti mehanizmi loma (otkaza). Kod RC modela lom se desio otvaranjem dominantne vertikalne pukotine u sredini raspona, odnosno otkazom na savijanje (sl. 13), dok se kod CRC modela lom desio otvaranjem dominantne kose pukotine (sl.14).

The comparison of the force-displacement diagrams of the RC, CRC and TRC models is shown in Figure 12. The presented working diagrams of the RC and CRC models show similar behaviour of conventionally reinforced beams (RC) and beams reinforced with reinforcing bars and textiles (CRC). The determined average fracture force intensity is the same for CRC models and RC models.

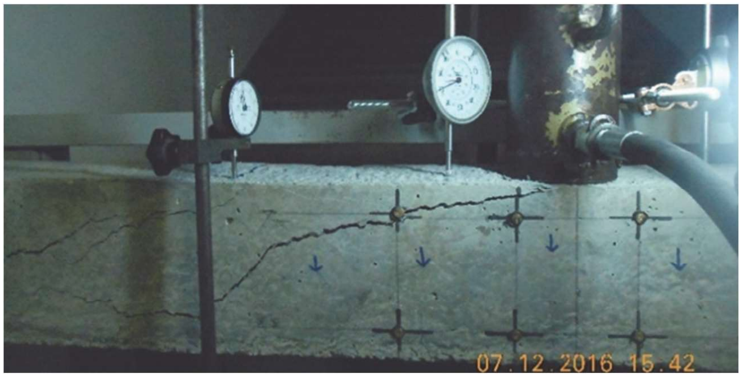
Besides measuring deflection and dilatation, it has been monitored the mechanism of crack opening and the failure mode of the tested models. In the RC and CRC models, the first cracks opened at the same force intensity (F = 21kN). However, different fracture (failure) mechanisms have been registered in the RC model and the CRC model. In the RC model, the fracture occurred through the opening of a dominant vertical crack in the middle of the span, or by failure at the bending (Fig. 13), while in the CRC model the fracture occurred through the opening of the dominant oblique crack (Fig. 14).



Slika 12. Dijagrami sila–progib RC i CRC modela, mjerno mjesto U4
Figure 12. Force-displacement diagrams of the RC, CRC and TRC models, measurement point U4



Slika 13. Mehanizam otkaza RC modela
Figure 13. Mechanism of RC model failure



Slika 14. Mehanizam otkaza CRC modela
Figure 14. Mechanism of CRC model failure

Do intenziteta sile F = 40kN registrovane su jednake širine vertikalnih pukotina u sredini raspona na RC i CRC modelu (širina 0,3 mm). S povećanjem intenziteta sile, povećavale su se širine vertikalnih pukotina na RC modelu do registrovane širine 1 mm neposredno prije loma. Na CRC modelima, s povećanjem intenziteta sile nije došlo do povećanja širine pukotine. Dakle, kod CRC modela lom se desio otkazom na smicanje. Tekstilna mreža povećala je nosivost na savijanje grede, ali orijentacija glavnih vlakana mreže u smjeru podužne osi nosača nije dala doprinos nosivosti na smicanje, što je zaključak istraživanja u radu [1], gdje se navodi da je iz aspekta nosivosti na smicanje povoljna orijentacija glavnih vlakana mreže uspravno na podužnu os.

4 ZAKLJUČAK

Ispitivanjem RC modela i CRC modela dobijena je sila loma jednakog intenziteta. Međutim, razlika u mehanizmu otkaza RC modela i CRC modela ukazuje na to da je upotrebom tekstila došlo do povećanja nosivosti na savijanje grede u odnosu na klasično armirane betonske grede. Ovo povećanje nije kvantifikovano zbog obima eksperimentalnog programa, koji je bio ograničen na određeni broj modela za inicijalna ispitivanja. Naime, nije rađena kombinacija tekstilnih mreža s različitim pravcima glavnih tekstilnih vlakana i različitim procentima armiranja poprečnom armaturom s ciljem povećanja nosivosti na smicanje. Međutim, jasna je mogućnost primjene tekstilnih mreža za istovremeno povećanje trajnosti i nosivosti.

Za intenzivniju primjenu tekstilnih mreža za armiranje unutar poprečnog presjeka betonske grede, iskustva istraživača u ovoj oblasti eksperimenta pokazuju da je potrebno riješiti tri ključna problema:

- tehnologiju ugradnje betona unutar tekstilne mreže;
- stabilnost tekstilne matrice (tekstilne mreže) tokom opterećenja;
- prionljivost betona i tekstilne mreže.

Jedan od pristupa za ostvarenje adekvatnog mehanizma nosivosti betonskih greda armiranih armaturnim šipkama i tekstilnim mrežama, promovisan i u radu [9], jeste izvođenje poluprefabrikovanih betonskih greda s prefabrikovanim obložnim dijelom grede

Equal widths of vertical cracks in the middle of the range were registered on the RC and CRC model (width 0.3 mm)by the intensity of force F = 40kN.As intensity of the forces increased, at the same time increased the width of the vertical cracks on RC model up to registered width of 1 mm before the fracture. On CRC models with increasing force intensity, there was no increase in crack width. Thus, in the CRC model, the fracture occurred by shear failure. Textile mesh increased the bending load of the beam, but the orientation of the main fibres of the mesh in the direction of the longitudinal axis of the girder did not contribute to shear load, which is the conclusion of the research in [1], where it is stated that the mesh is perpendicular to the longitudinal axis.

4 CONCLUSION

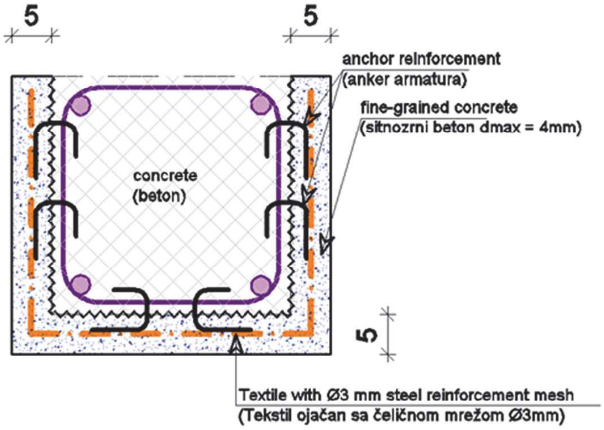
By testing the RC model and the CRC model, a fracture force of equal intensity was obtained. However, the difference in the failure mechanism of the RC model and the CRC model indicates that the use of textiles has increased the load-bearing capacity of the beam compared to classically reinforced concrete beams. This increase was not quantified due to the scope of the experimental program, which was limited to a number of models for initial testing. Namely, no combination of textile nets with different directions of the main textile fibres and different percentages of reinforcement with transverse reinforcement was made in order to increase the shear capacity. However, the possibility of applying textile nets to simultaneously increase durability and load-bearing capacity is clear.

For more intensive application of textile reinforcement nets within the cross section of the concrete beam, the experience of researchers in this field shows that it is necessary to solve three key problems,

- concrete placing technology within the textile mesh,
- stability of the textile matrix (textile mesh) during loading and
- adhesion of concrete and textile mesh.

One of the approaches for achieving an adequate load-bearing mechanism of reinforced concrete beams using reinforced bars and textile meshes is presented in the paper [9], and that is the construction of semiarmiranim tekstilnom mrežom, ojačanom mrežom od čelične žice i unutrašnjim dijelom grede koji se izvodi na licu mjesta. Prijedlog poprečnog presjeka poluprefabrikovane betonske grede prikazan je na slici 15.

prefabricated concrete beams with prefabricated beam cladding reinforced with textile mesh, reinforced steel wire mesh and inner part on the site. The cross-sectional proposal of the semi-prefabricated concrete beam is shown in Figure 15.



Slika 15. Prijedlog poluprefabrikovane betonske grede armirane armaturnim šipkama i tekstilom
Figure 15. Proposal of semi-prefabricated reinforced concrete beams using reinforced bars and textiles

U nastavku istraživanja uradiće se eksperimentalni program za razvoj tehnologije izvođenja i adekvatnog sprezanja prefabrikovanog i monolitnog dijela betonske grede, te verifikovanje fizičko-mehaničkih i deformacionih karakteristika grede poprečnog presjeka na slici 15.

U savremenom građevinarstvu, tekstilne mreže primjenjuju se za povećanje trajnosti obložnog dijela armiranobetonskih greda i naknadno ojačanje greda spoljnom primjenom, oblaganjem (umotavanjem) greda. Iskustva predstavljena u radovima, pobrojanim u referencama i prezentovana ispitivanja u ovom radu pokazala su da je, uz razvoj tehnologije ugradnje, moguća primjena tekstilnih mreža unutar poprečnog presjeka.

The following studies will be carried out for the purpose of developing an experimental program, and technology of adequate coupling of the prefabricated and monolithic part of the concrete beam and the verification of the physical and mechanical characteristics and deformation parts of the beam cross-section in Figure 15.

In modern civil engineering, textile meshes are used to increase the durability of the cladding part of reinforced concrete beams and subsequent reinforcement of beams through external application, coating (wrapping) of beams. Experiences presented in the papers are listed in the references. In addition, the tests presented in this paper have shown that it is possible to use textile meshes within the cross section with the development of installation technology.

5 LITERATURA
REFERENCES

[1] Akhil A., Prabhakaran P., EXPERIMENTAL STUDY ON SHEAR STRENGTHENING OF RC BEAMS USING NYLON TEXTILE-REINFORCED MORTAR; International Journal of Innovative Research in Science, Engineering and Technology, Vol.5, Issue 8, August 2016;

[2] Giorgia Colombo I., Colombo M., DiPrisco M., BENDING BEHAVIOUR OF TEXTILE REINFORCED CONCRETE SANDWICH BEAMS; Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 2013;

[3] Gries T., Roye A., Offermann P., T Engler., Peled A., TEXTILE REINFORCED CONCRETE, State-of-the-Art Report of RILEM Technical Committee 201-TRC, Report 36, RILEM Publications S.A.R.L. 2006,

[4] Hashemi S., INVESTIGATION OF FLEXURAL PERFORMANCE OF RC BEAMS STRENGTHENED WITH CFRP TEXTILE AND CEMENT BASED ADHESIVES; Hokkaido University Japan; APFIS 2012.;

[5] Hegger J., Zell M. &Horstmann M., TEXTILE REINFORCED CONCRETE – REALIZATION IN APPLICATIONS, Taylor & Francis Group, London, ISBN 978-0-415-47535-8, 2008,

[6] Hegger J., Zell M., Voss S., DIMENSIONING OF TRC STRUCTURES, Institute of Structural Concrete, RWTH Aachen University, Germany,

[7] Kok M., MASTER'S THESIS - TEXTILE REINFORCED DOUBLE CURVED CONCRETE ELEMENTS, TU Delft, Faculty of Civil Engineering and Geosciences, Department of Structural and Building Engineering, July 2013;

[8] Mobasher B., DEVELOPMENT OF DESIGN PROCEDURES FOR FLEXURAL APPLICATIONS OF TEXTILE COMPOSITE SYSTEMS BASED ON TENSION STIFFENING MODELS, 6th Colloquium on Textile Reinforced Structures (CTRS6),

[9] Papantoniou I.C., Papanicolaou C.G., TEXTILE REINFORCED CONCRETE (TRC) FOR PRECAST STAY-IN-PLACE FORMWORK ELEMENTS; Tailor Made Concrete Structures – Walraven&Stoelhorst (eds), 2008 Taylor & Francis Group, London, ISBN 978-0-415-47535-8;

[10] Schladitz F., Curbach M., INCREASE IN THE TORSIONAL RESISTANCE OF REINFORCED CONCRETE MEMBERS USING TEXTILE REINFORCED CONCRETE (TRC); Concrete Repair, Rehabilitation and Retrofitting II – Alexander et al (eds), 2009 Taylor & Francis Group, London;

[11] Voss S., Hegger J.; DIMENSIONING OF TEXTILE REINFORCED CONCRETE STRUCTURES; 1st International Conference Textile Reinforced Concrete (ICTRC);

[12] Williams Portal N., NyholmThrane L., Lundgren K., FLEXURAL BEHAVIOUR OF TEXTILE REINFORCED CONCRETE COMPOSITES: EXPERIMENTAL AND NUMERICAL EVALUATION; Department of Civil and Environmental Engineering, Division of Structural Engineering Concrete Structures, CHALMERS UNIVERSITY OF TECHNOLOGY, Gothenburg, Sweden;

[13] Williams Portal N., SUSTAINABILITY AND FLEXURAL BEHAVIOUR OF TEXTILE REINFORCED CONCRETE; Department of Civil and Environmental Engineering, Division of Structural Engineering Concrete Structures, CHALMERS UNIVERSITY OF TECHNOLOGY, Gothenburg, Sweden 2013;

[14] Worner J.-D., Deuβer S., OBERFLACHENNAHE TEXTILBEWEHRUNG IM STAHLBETONBAU, BauenmitTextilien Heft, Masivbau 1998;

[15] Zenunović D., Folić R.: Tekstilom armirani beton – materijali, ponašanje i osnove projektovanja, 13. DGKS Kongres, Zbornik radova, septembar 2010., str. 243-252.

[16] Zenunović D., Folić R.: Tekstilom armirani beton – primjeri primjene u konstrukcijama, 13. DGKS Kongres, Zbornik radova, septembar 2010., str. 253-262.

REZIME

UPOREDNA ANALIZA PONAŠANJA BETONSKIH GREDA ARMIRANIH ŠIPKAMA I TEKSTILOM – EKSPERIMENTALNO ISTRAŽIVANJE

Damir ZENUNOVIĆ
Danijel RUŽIĆ

U ovom radu prezentovan je eksperimentalni program inicijalnih ispitivanja betonskih greda armiranih šipkama i tekstilom, koji je sproveden s ciljem uporedne analize ponašanja betonskih greda armiranih tekstilom u odnosu na klasično armirane grede. Za potrebe eksperimenta, korišćene su tekstilne mreže od alkalno-otpornih staklenih vlakana. Opisana je postavka eksperimenta. Predstavljeni su dobijeni rezultati ispitivanja. Na kraju rada, data je analiza dobijenih rezultata, sa zaključcima. Sprovedeni eksperimentalni pogram pokazao je da dodatak tekstilnih mreža, pored poboljšanja trajnosti zaštitnog sloja betona, može poboljšati nosivost i duktilnost armiranobetonskih greda. Ostaje otvoreno pitanje ugradljivosti betona u tekstilom armirane grede i ostvarenja potpune prionljivosti tekstilne mreže i betona. Na kraju rada, dat je prijedlog poluprefabrikovane betonske grede armirane armaturnim šipkama i tekstilom.

Ključne reči: armiranobetonska greda, tekstilne mreže, ugradljivost, nosivost, duktilnost, mehanizam loma

ABSTRACT

INTRODUCING EUROCODES AND THE CALCULATION OF SEISMIC RESISTANCE OF THE MASONRY CONSTRUCTIONS

Damir ZENUNOVIC
Danijel RUZIC

This paper presents an experimental program of initial testing of reinforced concrete beams using bars and textiles carried out with an aim of comparative analysis of the behaviour of reinforced concrete beams using textiles in relation to conventional reinforced beams. Alkaline-resistant glass fibre textile meshes were used for the purposes of the experiment. An experiment setting is described and obtained test results are presented in this paper. An analysis of the obtained results is presented at the end of the paper. The experimental program demonstrated that adding textile mesh, besides improvement of the durability of the protective layer of concrete, can improve the load-bearing capacity and ductility of reinforced concrete beams. There is still an issue related to workability of concrete in textile reinforced beams and achievement of full adhesion between textile mesh and concrete. At the end of the paper, a suggestion was given about semi-prefabricated reinforced concrete beams using reinforced bars and textiles.

Key Words: reinforced concrete beam, textile mesh, workability, bearing capacity, ductility, fracture mechanism

OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU

BASIC FRESH-STATE PROPERTIES OF EXTRUSION-BASED 3D PRINTED CONCRETE

Olivera BUKVIĆ
Vlastimir RADONJANIN
Mirjana MALEŠEV
Mirjana LABAN

PRETHODNO SAOPŠTENJE
PRELIMINARY REPORT
UDK:624.012.45
666.982
doi:10.5937/GRMK2004099B

1 UVOD

Trodimenzionalno štampanje (3D štampanje) ili aditivna proizvodnja u opštem smislu predstavlja sukcesivno dodavanje slojeva materijala kako bi se formirao željeni model iz 3D digitalnog geometrijskog modela. Važno je napomenuti da se, iako postoje različite vrste aditivnih tehnologija (deponovanje istopljenog filamenta, vezivna 3D štampa, stereolitografija, selektivno lasersko sinterovanje itd.), vrste materijala (materijali u čvrstom, tečnom, gasovitom stanju, praškasti materijali, laminati) i primene (za izradu prototipova ili proizvodnju), izraz 3D štampanje koristi kao opšti termin za sve aditivne tehnološke procese. Drugi termini koji su takođe u upotrebi jesu digitalna fabrikacija, tehnologija brze izrade prototipa ili CAD dizajn [27].

Proces 3D štampanja sastoji se od kreiranja 3D modela u computer-aided-design (CAD) formatu i njegovom eksportovanju u stereolitografski (STL) format,

1 INTRODUCTION

Three - dimensional printing (3D printing) or additive manufacturing is in general defined as successive assembling of the material layers in order to make objects or structures from a 3D data model. It is important to notice that, although there are several types of additive technologies (material extrusion, binder jetting, vat photo polymerization, powder bed fusion, etc.), materials used (i.e. materials in solid, liquid, gas state, powders or sheets)and application (for making of prototypes or for production), the term 3D printing is usually used as an umbrella term for all additive manufacturing processes. Other terms used as a synonym for additive manufacturing are digital fabrication, rapid prototyping or computer-aided design [27].

The process of 3D printing consists of creating the 3D model in computer-aided-design (CAD) format and exporting it to stereo lithography (STL) format with a specific

---

Olivera Bukvić, Asistent-master, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, olivera.bukvic@uns.ac.rs
Vlastimir Radonjanin, Redovni profesor, dr, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, radonjanin.vlastimir@gmail.com
Mirjana Malešev, Redovni profesor, dr, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, miram@uns.ac.rs
Mirjana Laban, Vanredni profesor, dr, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Departman za građevinarstvo i geodeziju, Trg Dositeja Obradovica 6, Novi Sad, Serbia, mlaban@uns.ac.rs

Olivera Bukvic, MSc, teaching assistant, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, olivera.bukvic@uns.ac.rs
Vlastimir Radonjanin, PhD, full professor, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, radonv@uns.ac.rs
Mirjana Malesev, PhD, full professor, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, miram@uns.ac.rs
Mirjana Laban, PhD, associate professor, University of Novi Sad Faculty of Technical Sciences, Department of Civil Engineering and Geodesy, Trg Dositeja Obradovica 6, Novi Sad, Serbia, mlaban@uns.ac.rs

pomoću specijalizovanog softvera. Digitalni format se zatim konvertuje u listu komandi koje treba da izvrši 3D štampač. Tip 3D štampača i njegova priprema za štampanje zavise od odabrane tehnologije štampanja [27].

Prema Američkom udruženju za testiranje i materijale (engl. American Society for Testing and Materials), postoji sedam kategorija aditivnih tehnoloških procesa: ubrizgavanje vezivnog sredstva, direktno energetsko taloženje, ekstrudiranje materijala, ubrizgavanje materijala, sjedinjavanje praha, laminacija listova i fotopolimerizacija [7].

Dve najviše istraživane i razvijane aditivne tehnologije za 3D štampanje betona jesu proces ekstrudiranja i ubrizgavanje vezivnog sredstva [27,42]. Ekstrudiranje materijala se zasniva na istiskivanju materijala kroz diznu, pravljenjem višeslojnih modela, bez upotrebe oplate [27]. Zbog prirode procesa, armatura se ne primenjuje, iako je pokušano da se armatura inkorporira u 3D štampu betona procesom ekstrudiranja [1,2,35]. U okviru štampanja betona procesom ekstrudiranja, vremenom su razvijene dve tehnologije: Contour Crafting („izrada kontura”) i štampanje betona [27,42]. Contour Crafting (slika 1b) podrazumeva istiskivanje maltera, ili drugih materijala koji imaju vezivna svojstva, u slojevima, uz mistriju koja omogućava završnu obradu površine materijala, čineći je glatkom [12,17]. Štampanje betona je takođe proces ekstrudiranja, ali s manjom rezolucijom deponovanja i tri ose kretanja štampača (slika 1c) [16,17]. Tehnika ekstrudiranja koristi se za izvođenje konstrukcija „in-situ”, dok je 3D štampanje na praškastoj podlozi (tj. Ubrizgavanje vezivnog sredstva) pogodno za primenu u prefabrikaciji konstruktivnih elemenata. Ova tehnologija štampanja je bazirana na selektivnom ubrizgavanju veziva u podlogu od praškastog materijala, čime se formira željeni 3D oblik očvršćavanjem materijala, na mestima gde je ciljano ubrizgano vezivo [42]. Proces je razvijen na principu aditivne proizvodnje polimera i metala, prilagođene betonu – praškasta podloga može biti agregat u koji se ubrizgava cementna pasta visokoplastične konzistencije, ili vezivo na bazi cementa ili geopolimera, u koje se ubrizgava [27]. Ova tehnologija aditivne proizvodnje koja se primenjuje u građevinarstvu poznata je i kao D-shape proces štampanja betona (slika 1a) [4,27].

Materijali koji se koriste u procesu ekstrudiranja

Sastav betona za 3D štampanje ekstrudiranjem i konvencionalnih cementnih betona značajno se razlikuju. Beton za 3D štampu sadrži veću količinu Portland cementa i posledično manju količinu agregata. Takođe, da bi se postiglo štampanje betona, krupan agregat se izostavlja iz ovog kompozita. Najčešće korišćena nominalna maksimalna veličina zrna agregata u literaturi je 1–2 mm [13,20,24,25,33,37,40,41] ali su objavljena i eksperimentalna istraživanja s nominalnom maksimalnom veličinom i do 4,75 mm [1,3,5,36]. Ipak, postoje i nedavne studije o uticaju krupnog agregata (maksimalna veličina 10 mm) na osnovna svojstva 3D betona u svežem stanju [32]. Krupan agregat je korišćen i za izgradnju kuće pomoću specifičnog masivnog 3D štampača za proces ekstrudiranja [35].

Nezaobilazne komponente 3D štampanih betona jesu dodaci reduktori vode, ubrzivači i obično modifikatori viskoznosti [11,39]. Mešavine 3D štampanih betona sadrže i leteći pepeo, silikatnu prašinu i nano-glinu, kako

software. The digital model is then converted to a list of commands for 3D printer to conduct. The type of 3D printer and its preparation for printing depends on chosen printing technology [27].

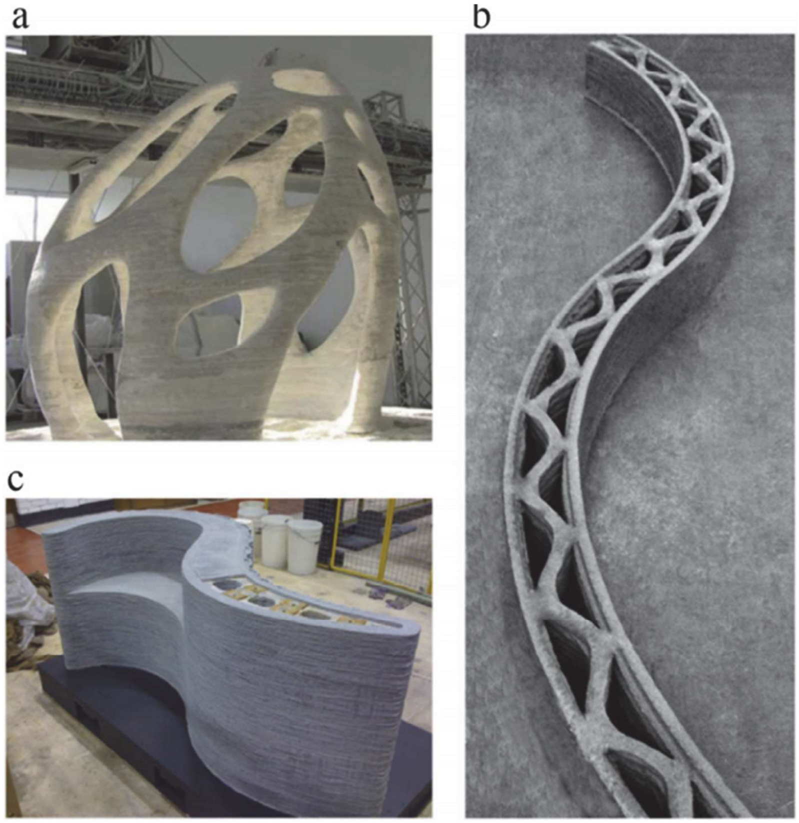
According to the American Society for Testing and Materials, there are seven categories of additive manufacturing technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photo polymerization [7].

The two most researched and developed additive manufacturing technologies used for 3D printing of concrete are material extrusion and binder jetting [27,42]. Material extrusion is based on selective dispensing of the material through a nozzle, making a multi-layer objects, with no need for formwork use [27]. Given the nature process, reinforcement is not used, although there have been attempts to incorporate it in extrusion-based 3D printing [1,2,35]. Under the extrusion-based concrete printing, two technologies have been eventually developed: Contour Crafting and concrete printing [27,42]. Contour Crafting (Figure 1b) is based on extrusion of a mortar or cementitious materials in layers, against a trowel which forms the smooth surface of the printed object [12,17]. Concrete printing is extrusion process as well, but with smaller deposition resolution and retained 3-dimensional freedom (Figure 1c) [16,17]. The extrusion-based processes are used for ”in-situ” construction, while powder based 3D concrete printing(i.e. binder jetting)is suitable for making a precast structure elements. This printing technology is based on selective deposition of a liquid binder into a powder bed, creating the 3D object at the targeted areas where the powder is bound [42]. Powder-based 3D concrete printing is developed on the basis of methods for polymers and metals additive manufacturing, adjusted to concrete – powder bed can be made of aggregate in which a fluid cement paste is jetted, or the powder bed can be a cement-based or geopolymer-based binder in which the water is jetted [27]. This additive manufacturing technology applied in construction is also known as „D-shape“ process (Figure 1a) [4,27].

Materials used for extrusion based process

The compositions of concrete for extrusion-based 3D printing and conventional cement concrete are significantly different. Concrete for 3D printing has larger amount of Portland cement and consequently, smaller amount of aggregate. In addition, to achieve printability of concrete, the coarse aggregate is omitted from this composite. The most commonly found nominal maximum aggregate size in literature is 1-2mm [13,20,24,25,33, 37,40,41], but nominal maximum sizes up to 4,75 mm is reported in experimental research as well [1,3,5,36]. However, there has been a recent study on the impact of coarse aggregate (maximum size 10mm) on basic 3D concrete fresh-state properties [32]. Coarse aggregate has been used for constructing a house with specific huge 3D extrusion-based printer [35].

The inevitable component of 3D printing concretes are water reducing admixtures, accelerators and, usually, viscosity modifying agents [11,39]. 3D printing concrete mixtures also contain fly ash, silica fume and nanoclay, to



Slika 1. Tehnologije 3D štampanja: D-shape (a), Contour Crafting (b) i 3D štampanje betona (c) [44]
Figure 1. 3D printing technologies: "D-shape" (a), Contour Crafting (b) and 3D concrete printing (c) [44]

bi se poboljšale performanse mešavina za štampu. Izazovi u projektovanju sastava 3D betonskih mešavina na koje treba odgovoriti jesu uspostavljanje veze između reoloških i tehnoloških svojstava s mogućnosti štampanja 3D betona i smanjenje ranog skupljanja usled sušenja, koje se javlja usled odsustva oplate i velikih količina cementa – više od 500 kg/m^3, zbog čega je uobičajena primena polipropilenskih vlakana pri projektovanju mešavina [11,19,29,33,34,37,38]. Prema nekim istraživanjima, Portland cement je, za sada, najpouzdanije vezivo u pogledu postizanja zahtevanih svojstava 3D betona [11,29]. Međutim, velike količine cementa koje se koriste imaju negativan uticaj na okolinu, povećavaju eksploataciju prirodnih sirovina i cenu 3D štampanja [8]. Kako bi se rešili ovi problemi, prethodna iskustva s betonima koji se ugrađuju na tradicionalan način, u pogledu primene recikliranog lakog agregata i materijala s vezivnim svojstvima kojima se može zameniti deo cementa [18,30,31] mogu biti prilagođena i primenjena na 3D štampane betone. Istražuje se primena lakih krupnih agregata [32] i alternativnih veziva, kako bi se postigla svojstva eko-betona i betona povoljnih po okolinu i potrebna svojstva za 3D štampanje betona (npr. alternativni materijali koji imaju vezivna svojstva i geopolimerna veziva) [23,25].

improve the performance of printing mixtures. The challenges of 3D concrete mix design that need to be addressed to are establishing relation between the rheological and technological properties with printability of 3D printed concrete and, early age drying shrinkage reduction, due to the absence of formwork and large quantities of cement - more than 500 kg/m^3 which is why polypropylene fibres are commonly used in mixture design [11,19,29,33,34,37,38]. According to some studies, Portland cement is, for now, the most reliable binder that can ensure achieving the required 3D concrete properties [11,29]. However, large amount of cement used has a negative impact on environment, enlarges consumption of natural raw materials and increases cost of 3D concrete printing [8]. In order to resolve these problems, the previous experience in using recycled lightweight aggregates and supplementary cementitious materials in traditionally casted concrete mixtures [18,30,31] can be adjusted and applied for 3D printed concretes. The use of lightweight coarse aggregate [32] and alternative binders are investigated, in order to meet the needs of an eco and environmental friendly concrete and required properties for 3D concrete printing (e.g. supplementary cementitious materials and geopolymer binder) [23,25].

Istorija i primena

Prvi zvaničan patent, kao pokušaj da se automatizuje proces betoniranja, patentirao je Tomas Edison (engl. Thomas Edison), 1917. godine. Proces se sastojao od sipanja betona s Portland cementom u jednodelan kalup od livenog gvožđa, pomoću pumpe i sistema creva, od vrha do dna kalupa. Oblik kalupa bi, nakon sklapanja njegovih delova, odgovarao obliku objekta (npr. kuće ili zgrade), praveći jedinstvenu konstrukciju nakon očvršćavanja betona. Zbog nemogućnosti savladavanja kompleksnosti svojstava sveže betonske mešavine, kao i visoke cene opisanog kalupa, patent je primenjen samo nekoliko puta [2,6,39,47].

Značajan razvoj automatizacije izvođenja betonskih konstrukcija, nastavlja se 1990-ih godina. U prvoj polovini ove decenije, automatizacija se ogledala u procesu sklapanja prefabrikovanih elemenata, primenom specijalizovanih robota [39]. Istraživanje mogućnosti primene aditivne proizvodnje u izvođenju betonskih konstrukcija počinje tehnologijom sjedinjavanja praha, gde je pionir u objavljivanju ovih istraživanja Džozef Penja (Joseph Pegna - Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, Rensselaer Polytechnic Institute, Troy, New York, USA), 1997. godine. 3D štampanje betona ekstrudiranjem, primenom Contour Crafting procesa, predstavljeno je 1998. godine, od strane profesora Beroka Košnevisa (Berokh Khoshnevis, University of Southern California). Godine 2004. Predstavljen je zid odštampan u razmeri 1:1, a ovaj proces 3D štampanja je dalje razvijan kao tehnologija građenja „in-situ" [2,12,39].

Od tada, 3D štampanje betona istražuje se mnogo šire, naročito od 2012. godine. Slobodna forma građenja je od velikog interesa za arhitekte, omogućavajući im veću slobodu pri projektovanju. Korišćenje oplate i kalupa za tradicionalno betoniranje ograničava kreativni izraz arhitekata, s obzirom na to što je oplata kompleksne geometrije veoma skupa i izrada ovakve oplate nije racionalna. Procenjeno je da su troškovi oplate 35%–65% ukupne cene betonske konstrukcije, dok je višestruka upotreba oplate ograničena ili nije moguća [2]. Izvođenje betonskih konstrukcija bez oplate smanjilo bi troškove izvođenja, kao i količinu građevinskog otpada i povećalo nizak godišnji rast produktivnosti, karakterističan za građevinsku industriju [2,27,35].

Iako su istraživanja u oblasti 3D štampanja betona u ranoj fazi i i dalje se unapređuju, iako još uvek ne postoje standardizovane metode za projektovanje sastava mešavina i ispitivanje 3D štampanog betona, u svetu postoje impresivni primeri mogućnosti uspešne primene ove tehnologije. Neki od njih prikazani su na slikama u nastavku.

Cilj ovog rada jeste objašnjenje najbitnijih svojstava ekstrudiranog 3D štampanog betona, kako bi se naglasile specifičnosti ove relativno nove i obećavajuće tehnologije građenja. Iako je terminologija za osnovna svojstva 3D štampanih betonskih mešavina (npr. obradljivost, tiksotropija, granica tečenja) ista kao i za mešavine za tradicionalno betoniranje, postoje dodatni zahtevi i osobine koje nijansiraju osnovne i prave suštinsku razliku u projektovanju sastava mešavina 3D štampanog betona.

History and application

The first officially patented attempt to automatize concrete casting was made by Thomas Edison in 1917. The process consisted of single-pouring a Portland cement mixture into the single-piece mould made of cast iron, through a pump and a hose system, from the top to the bottom of the mould. The mould is supposed to be in shape of entire structure (e.g. a house or a building) after assembling, making an integral construction after hardening of the cement mixture. However, due to inability to overcome the complexity of concrete mixture properties and high cost of described mould, this patent was implemented only a few times [2,6,39,47].

Significant increase in automation of in-situ construction of concrete structures started in 1990s. In the first part of the decade, this reflected in Japanese automized assembling of prefabricated elements using specialized robots [39]. Research on possibilities of the additive manufacturing application in construction of concrete structures begun with powder bed fusion technology published by Joseph Pegna (Department of Mechanical Engineering, Aeronautical Engineering and Mechanics, Rensselaer Polytechnic Institute, Troy, New York, USA) in 1997. Extrusion-based 3D concrete printing using Contour Crafting process was introduced in 1998 by Berokh Khoshnevis, Professor of Engineering at the University of Southern California. In 2004, the 1:1 scale printed wall was shown, and this 3D printing process further developed to large scale on-site construction technology [2,12,39].

Since then, 3D concrete printing has been researched more extensively, especially since 2012. The freeform construction is of great interest for architects, giving them more design freedom. The use of formwork and moulds for traditional concrete casting limits the creative expression of architects, since the complex geometry formwork is very expensive and irrational to make. Furthermore, it is estimated that formwork costs are 35%-65% of total concrete construction costs, while formwork has limited or no possibility for re-use [2]. Making concrete structures without formwork would decrease the construction cost as well as construction waste and increase the low annual growth in productivity common for construction industry [2,27,35].

Although the research in the field of 3D concrete printing is at its early stage and still improving and the standardized methods for 3D printed concrete mixtures design and testing still do not exist, there have been impressive examples world-wide of potential successful application of this technology. Some of them are illustrated in the following figures.

The aim of this paper is to explain the most important fresh properties of extrusion-based 3D printed concrete in order to emphasize specificities of this relatively new and promising construction technology. Although the terminology for basic properties of 3D printed concrete mixtures (e.g. workability, thixotropy, yield stress) is the same as for traditionally casted concrete mixtures, there are additional requirements and properties that give nuances to the basic ones, making the crucial difference in design of 3D printable concrete mixtures.

Slika 2. Petospratni stambeni kompleks kineske kompanije WinSun, 2015 (1100m^2) [14]
Figure 2. A five-story residential complex by Chinese company WinSun, 2015 (1100m^2) [14]

Slika 3. Hotel Suite, Filipini, 2015 (12.5x10.5x4.0m) [2]
Figure 3. Hotel Suite, Philippines, 2015 (12.5x10.5x4.0m) [2]

Slika 4. Stub proizveden od strane XtreeE kompanije [28]
Figure 4. Support column produced by XtreeE company [28]

Slika 5. The Y-Box Paviljon, "21st-century Cave" - Supermachine Studio i Siam Cement Group - 3 m visoka konstrukcija [35]
Figure 5. The Y-Box Pavilion, 21st-century Cave by Supermachine Studio and Siam Cement Group – 3m tall structure [35]

Slika 6. Prvi 3D štampani pešački most, "Institute of Advanced Architecture of Catalonia", 2017 (raspon – 12 m, širina – 1.75 m) [44]

Figure 6. The first 3D printed pedestrian bridge, by Institute of Advanced Architecture of Catalonia, 2017 (span – 12m, width – 1.75m) [44]

Primenjeni metod za prikupljanje podataka o svojstvima u svežem stanju uključuje pristup „odozdo na gore". Pregledana je aktuelna literatura u oblasti 3D štampanja betona i proširena je pregledom referenci iz prvobitno uključene literature. Na osnovu kriterijuma za inkluziju, u pregled literature uključeni su pregledni i eksperimentalni radovi o 3D betonu štampanom procesom ekstrudiranja. Radovi koji se tiču isključivo svojstava očvrslog 3D štampanog betona nisu uzeti u obzir.

2 OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU

Termini u literaturi na engleskom jeziku koji se koriste za opis svojstava 3D štampanog betona u svežem stanju, uglavnom, jesu izvedenice glagola i često je prevod na srpski jezik otežan. Zbog toga je potrebno opisno definisati pojedina svojstva.

Svojstva 3D štampanog betona u svežem stanju su kompleksna, preklapaju se i veoma su zavisna od vremena. Mogu se podeliti na reološka (granica tečenja, plastična viskoznost i tiksotropija), tehnološka (pumpabilnost i sposobnost tečenja) i na svojstva koja određuju sposobnost štampanja (sposobnost ekstrudiranja, kvalitet štampe i buildability svojstvo). Sposobnost štampanja 3D betona (engl. printability) najvažnije je svojstvo za proces 3D štampe. Nije striktno definisano, ali se odnosi na svojstva u svežem stanju koja je potrebno postići kako bi

Method used for gathering data on fresh-state properties include bottom-up research approach. The recent literature in the field of 3D concrete printing was reviewed and was extended by reference screening of the included papers. Based on the inclusion criteria, a review and experimental papers about extrusion-based 3D concrete printing were included. Papers containing only hardened properties of 3D printed concrete were excluded.

2 BASIC FRESH-STATE PROPERTIES OF EXTRUSION-BASED 3D PRINTED CONCRETE

Fresh-state properties of 3D printed concrete are complex, overlapping and highly time-dependent. They can be divided into rheological (yield stress, plastic viscosity and thixotropy), technological properties (pumpability and flowability) and printability properties (extrudability, print quality and buildability). The printability of the 3D concrete is the most important property for 3D printing process. It is not strictly defined, but it refers to fresh-state properties needed to successfully conduct the printing process, from extrusion to the end of the process [39].

Since there are no standardized methods and procedure for defining and evaluating these complex 3D concrete properties, the terminology found in the body of se sprovelo štampanje, od ekstrudiranja do kraja procesa [39].

Kako ne postoje standardne metode i procedure za definisanje i ocenu ovih kompleksnih svojstava 3D betona, terminologija u literaturi nije uvek konzistentna, u smislu objedinjavanja ili jasnog razdvajanja određenih svojstava.

Pumpabilnost (engl. pumpability ili deliverability) jeste sposobnost betonske mešavine da se transportuje od mešalice, kroz cev, do dizne. Povezana je s plastičnom viskoznošću i granicom tečenja betonske mešavine (tj. reološkim svojstvima), kao i sa snagom pumpe i tehnologijom pumpanja mešavine, koje moraju biti odabrane u skladu s reološkim svojstvima [27]. Složenost pumpanja 3D betonske mešavine ogleda se u vremenski zavisnim svojstvima betona u svežem stanju, pojavi „krvarenja" betona i segregacije. Dovoljna količina cementne paste neophodna je kako bi se formirao sloj oko čestica agregata, smanjilo trenje, a time smanjio i napon smicanja između njih. Ovim dolazi do porasta obradljivosti 3D mešavine u smislu pumpabilnosti/transporta kroz sistem za pumpanje [37]. U jednom istraživanju opsega u kome se kreće sposobnost štampanja, odnosno, printability svojstvo 3D štampanog betona [37], autori uvode indeks pumpabilnosti kako bi kvantifikovali pumpabilnost mešavine za štampu. Kako bi se dobili rezultati, za svaku probnu mešavinu, indeks pumpabilnosti je računat kao odnos brzina tečenja mešavine i tečenja vode (ml/s), za konstantnu brzinu pumpanja, u odabranom vremenskom intervalu. Veće vrednosti indeksa pumpabilnosti ukazuju na lakše pumpanje mešavine [37].

Sposobnost tečenja (engl. flowability) predstavlja lakoću s kojom beton teče pod određenim uslovima i uglavnom se ispituje metodom rasprostiranja [19]. Uticaj optimalne količine agregata na sposobnost tečenja ispitivali su Zhang i dr. [43].

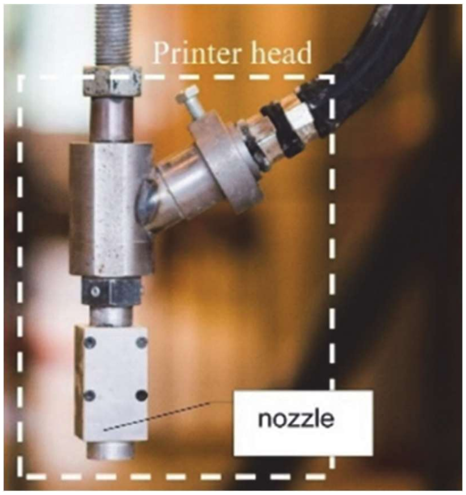
Sposobnost ekstrudiranja ili ekstrudabilnost (engl. extrudability) definiše se kao sposobnost betonske mešavine da bude kontinualno istiskivana kroz diznu štampača [19,33]. Različiti tipovi dizni prikazani su na slikama 7 i 8. S porastom sposobnosti tečenja, raste i sposobnost

literature is sometimes not fully consistent, in terms of joining or separating properties one from another.

Pumpability (or deliverability) is the ability of concrete mixture to be transported from mixer, through a hose, to a nozzle. It is related to plastic viscosity and yield stress of the concrete mixture (i.e. rheology properties) and power of the pump as well as its technology must be chosen in accordance with them [27]. The challenges of pumping 3D concrete mixtures reflect in the time-dependent fresh-state properties, bleeding and segregation. The sufficient amount of cement paste is necessary so it could form a coat around aggregate particles and reduce the friction between them and reduce the shear stress. This will lead to increase of the 3D mixture workability in terms of pumpability/in terms of transporting through the pumping system [37]. In the study on printability region for 3D printed concrete [37], authors introduce the pumpability index to quantify the pumpability of the printing mixture. For each trial mixture, pumpability index is calculated as ratio of the mixture flow rate and water flow rate (ml/s) for constant pumping speed, in a selected time interval, to obtain the results. Higher pumpability index indicates easier mixture pumping [37].

Flowability is the ease with which concrete flows under given conditions, and is usually tested by the slump flow test [19].The impact of an optimum aggregate content on flowability is investigated by Zhang et al. [43].

Extrudability is defined as ability of the printing mixture to be continuously extruded out of the printer nozzle [19,33]. Different nozzle types are shown at the Figure 8 and Figure 9. With the increase of flowability, extrudability increases as well. Therefore, extrudability depends on the quantity of dry constituents/components in the concrete mixture, properties of the used materials, delivery system (i.e. printer/printer nozzle), water content, conditions during printing, etc. However, the mixture proportions will have the biggest impact, which is why several authors recommend, as a guideline, to design the initial printing mixtures with properties similar to the self-compacting concretes [19,39].



Slika 7. Kružna dizna [2]
Figure 7. Round nozzle [2]

Slika 8. Kvadratna dizna s bočnim mistrijama [45]
Figure 8. Squared nozzle with side trowels [45]

ekstrudiranja. Zbog toga će značajan uticaj na ovo svojstvo imati sadržaj suvih komponenti u betonskoj mešavini, svojstva komponentnih materijala, sistem za dovođenje mešavine (tj. štampač/dizna štampača) sadržaj vode, trenutni uslovi prilikom štampanja, i tako dalje. Najveći uticaj će ipak imati odnos komponentnih materijala, zbog čega neki autori predlažu, kao smernicu, projektovanje sastava betonskih mešavina sa svojstvima sličnim svojstvima samougrađujućeg betona [19,39].

Sposobnost ekstrudiranja može biti narušena usled isušivanja vode i segregacije – slično kao kod toka pumpanja, iako je ekstrudiranje proces s manjim brzinama protoka [39]. Pumpabilnost i sposobnost ekstrudiranja takođe su slične zbog smicanja mešavina tokom procesa, iako se, tokom ekstrudiranja, mešavina smiče u dizni, pod različitim uslovima u odnosu na smicanje u cevi prilikom pumpanja [34]. Sposobnost ekstrudiranja štampanog betona ispituje se vizuelno, najčešće na sloju ekstrudiranom u unapred definisanom vremenskom intervalu. Ne postoje preporuke za pouzdanije metode ispitivanja sposobnosti ekstrudiranja [15,33]. Prema nekim autorima, može biti procenjena preko svojstava kvaliteta štampanja [33], koja su objašnjena u narednom paragrafu.

Kvalitet štampanja (engl. *print quality*) u literaturi se odnosi na tri zahteva u pogledu štampane mešavine. Prvi je kvalitet površine odštampanog sloja (engl. *surface quality*) koja treba da bude bez defekata, odnosno diskontinuiteta. Odvajanje delova slojeva (slika 9) često je opisano u različitim istraživanjima, a pojavljuje se usled prekomerne krutosti i slabe kohezije mešavine za štampanje – loše obradljivosti. Sledeći zahtev za kvalitet štampanja jeste da ivice moraju biti pravougaone (engl. *squared edges*), što podrazumeva da ivice nanetog sloja moraju biti izražene. Izraz „pravougaone ivice” predložili su naučnici koji su istraživanje sproveli na štampaču s diznama kvadratnog oblika, ali se izraz odnosi na konzistentnost oblika nanetog sloja u odnosu na oblik dizne [11].

Extrudability can be compromised by water drainage and phase separation – similar as with pumping flow, although extrusion is a process with slower flow velocities [39]. In addition, pumpability and extrudability are similar due to shearing of the mixture, although during extrusion, the mixture is sheared in the nozzle, under different condition than shearing in the pipes during pumping [34]. It is examined visually, usually on the layer extruded in predefined time period. There has been no recommendations for more reliable extrudability testing method [15,33]. According to some authors, extrudability can be assessed through the print quality properties [33], which are explained in the following paragraph.

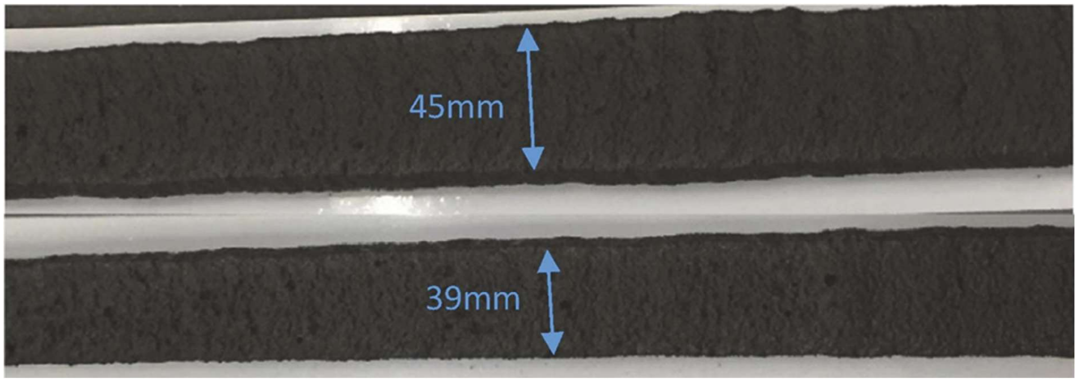
Print quality in the literature refers to three printing mixture requirements. The first one is surface quality of the deposited layers, which has to be free of defects, i.e. discontinuities. The tearing of the layers (Figure 9) is often reported in different studies and it appears due to the excessive stiffness and low cohesion of the printing mixture – poor workability. Next requirement for the print quality is squared edges, which means that the edges of the deposited layer must be visible. The term squared edges is proposed by the researchers that conducted studies using squared printer nozzles, but it refers to the consistency of the deposited layer's shape with the shape of the nozzle, in general/regardless of the nozzle type [11].

Slika 9. Kvalitet površine – odvajanje odštampanog sloja usled slabe kohezije i prekomerne krutosti mešavine za štampanje [10]

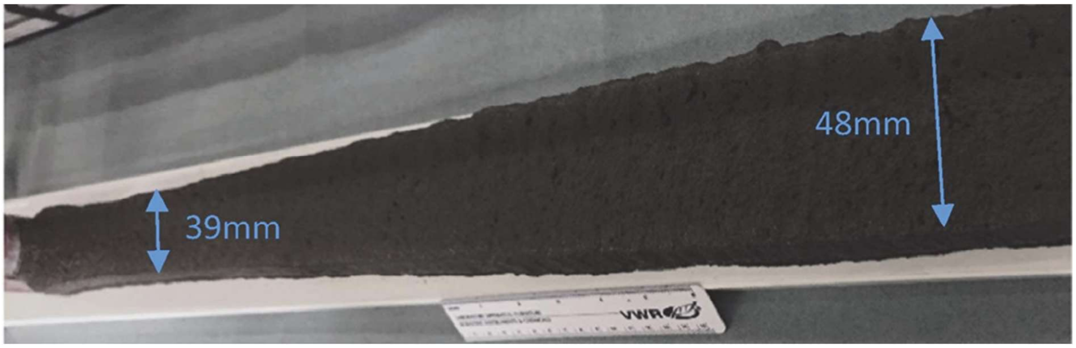
Figure 9. Surface quality – tearing of the printed layer due to low cohesion and excessive stiffness of the printing mixture [10]

Treći zahtev je dimenziona usaglašenost i konzistentnost dimenzija. Da bi ovaj kriterijum bio ispunjen, potrebno je definisati prihvatljiv raspon dimenzija sloja. Ukoliko su dimenzije odštampanog sloja u okviru predviđenog raspona, dimenziona usaglašenost je postignuta. Dimenziona usaglašenost se odnosi na sposobnost mešavine da bude odštampana u slojevima s prihvatljivim rasponom ciljanih dimenzija. Konzistentnost dimenzija odnosi se na variranje širine odštampanog sloja. U studiji o svojstvima mešavine za štampanje u svežem stanju, Kazemian i dr. objavili su da variranje prethodno definisane širine sloja do 10% daje prihvatljiv kvalitet štampanja. Ova variranja odnose se samo na sloj u svežem stanju, odmah nakon deponovanja i ne uzimaju u obzir promene u dimenzijama usled skupljanja betona [10,11]. Dimenziona usaglašenost ispitivana u Kazemian i dr. eksperimentu prikazana je na slici 10, a rezultati merenja konzistentnosti dimenzija na slici 11. Svojstva kvaliteta štampanja ispituju se vizuelno i preporučeno je da se podešavaju kroz više proba s nekoliko ponovljenih mešavina, jer ne postoje predložene metode za ispitivanje i ocenu ovih svojstava [7].

The third requirement is dimension conformity and dimension consistency. For fulfilling this requirement, the acceptable range of the layer dimensions must be defined. If the dimensions of the printed layer are within the range, the dimension conformity is achieved. The dimension conformity is the ability of printing mixture to be printed as layers with acceptable range of targeted dimensions. The dimension consistency refers to variations in printed width of a single layer. In the study on fresh-state printing mixture properties, Kazemian et al. reported that 10% variation of the pre defined layer width is acceptable printing quality. These variations only refer to fresh concrete layer, right after its deposition and do not consider the dimensional changes caused by concrete shrinkage [10,11]. Dimension conformity investigated in Kazemian et al. experiment is shown in Figure 10, and results of measuring dimensional consistency on Figure 11. Print quality properties are examined visually and it is recommended to tune them through several trials with several mixture replicates, since there are no suggested methods for testing and evaluating these properties [7].



Slika 10. Dimenziona usaglašenost odštampanih slojeva [10]
Figure 10. Dimension conformity of the printed layers [10]



Slika 11. Konzistentnost dimenzija – variranje širine odštampanog sloja [10]
Figure 11. Dimension consistency - variations in width of the printed layer [10]

Svojstvo *printability window* se u literaturi definiše kao „vremenski period tokom kog mešavina za štampanje može biti ekstrudirana s prihvatljivim kvalitetom, kroz diznu, razmatrajući gubitak obradljivosti tokom vremena". Ovo svojstvo se naziva i otvoreno vreme za rad (engl. *open time*) i može se meriti metodom rasprostiranja kako bi se procenio gubitak obradljivosti preko sposobnosti tečenja [19]. Imajući u vidu tehnologiju 3D štampanja, neki autori predlažu definisanje dva parametra povezana sa ovim svojstvom: najkraće vreme nakon kog kvalitet štampanja počinje da opada, usled gubitka obradljivosti (engl. *printability limit*) i najkraće vreme nakon kog mešavina za štampanje ne može biti ekstrudirana kroz diznu, odnosno blokada dizne usled procesa očvršćavanja betona (engl. *blockage limit*). Primećeno je da blokada dizne usled očvršćavanja može nastupiti mnogo pre početnog vremena vezivanja betona. Stoga je preporučeno da se vreme za koje mešavina može biti ekstrudirana ispita za svaku mešavinu, tokom projektovanja sastava. Ovo ukazuje na to da gubitak obradljivosti i početak vremena vezivanja ne mogu biti pouzdana zamena za direktno merenje ovih parametara. Dodatni izazov u uspostavljanju veze između obradljivosti i svojstva *printability window* i predlaganju adekvatnih metoda ispitivanja jeste zavisnost vremena nakon kog kvalitet štampanja počinje da opada i vremena nakon kog mešavina za štampanje ne može biti ekstrudirana od svojstava štampača tj. mehanizma ekstrudiranja [11].

Svojstvo *buildability* (sposobnost deponovanja slojeva jedan na drugi) predstavlja sposobnost odštampanog betonskog sloja da prihvati opterećenje i sposobnost da se odupre deformacijama tokom štampanja u slojevima [9,11,19,24]. Usko je povezano i može se smatrati istim svojstvom kao i stabilnost oblika (engl. *shape stability*, *shape retention* ili *green strength*) jer oba svojstva zavise od brzine strukturiranja (porasta granice tečenja s vremenom), a kriterijum za ocenu ovog svojstva se u eksperimentalnim istraživanjima često zasniva na ranoj čvrstoći (engl. *green strength*) [9,11,39]. Stabilnost obika može biti definisana kao sposobnost deponovanog sloja da zadrži konzistentan oblik dizne [25], dok se svojstvo *buildability* uglavnom izražava brojem slojeva sukcesivno štampanih jedan na drugi [19]. Deformacije odštampanih slojeva mogu nastati usled sopstvene težine, težine narednih slojeva i pritiska ekstrudiranja. Zadovoljavajući kvalitet štampe mešavine (engl. *print quality*) ukazuje na to da će odštampani sloj moći da se odupre deformacijama uzrokovanim sopstvenom težinom, dok otpornost na ostale vrste deformacija mora biti potvrđena laboratorijskim ispitivanjem tokom projektovanja sastava mešavine [11]. Naponi pritiska u donjim slojevima, indukovani sopstvenom težinom i težinom narednih slojeva, rastu tokom sukcesivnog deponovanja slojeva. Kada ovaj napon pređe granicu tečenja materijala, dolazi do obrušavanja odštampanih slojeva. Osnovni parametri koji određuju svojstvo *buildability* jesu granica tečenja, plastična viskoznost i tiksotropija. Usled procesa očvršćavanja, *buildability* svojstvo odštampane mešavine će rasti vremenom, zajedno s granicom tečenja materijala i modulom elastičnosti [39]. Napon smicanja kojem je izložena mešavina koja se štampa tokom procesa pumpanja i ekstrudiranja indukuje tiksotropiju mešavine. Unutršnja struktura betona će se narušavati i izgrađivati, utičući na viskoznost i, posledično, na stabilnost oblika [11]. Stoga će brzina štampanja modela zavisiti od brzine

Printability window is defined in literature as "the period of time during which the printing mixture could be extruded by the nozzle with acceptable quality, considering the workability loss that occurs over time". This property is also referred to as an "open time" and can be measured using the slump flow test in order to assess the workability loss by flowability [19]. Considering the technology of 3D printing, some authors suggest defining two parameters related to the printability window: printability limit and blockage limit. The printability limit is the earliest time when print quality starts to decrease due to workability loss. The blockage limit is the earliest time when the printing mixture cannot be extruded out of the nozzle, due to its hardening. It is noted that blockage could occur long before the initial time setting of concrete. Therefore, it is recommended to test blockage limit during mixture design, for each mixture. Furthermore, this indicates that workability loss and setting time cannot be reliable alternatives for direct measuring of printability window parameters. Additional challenge for establishing the relationship between workability and printability window and proposing adequate testing methods is the dependency of printability limit and blockage limit on the printer properties, i.e. extrusion mechanism [11].

Buildability is the load carrying capacity of printed concrete layer and its ability to resist deformations during the layer wise printing [9,11,19,24]. It is closely linked to and can be considered to be almost the same property as shape stability (shape retention or green strength) since both depend on structuration rate (i.e. yield stress increase with time), and buildability criteria is often based on the green strength in experimental research [9,11,39]. Shape stability can be defined as the ability of the deposited layer to retain its shape consistent with the nozzle shape[25], while buildability is usually expressed through the number of layers that can be successively deposited [19].The deformation of printed layers can occur due to self-weight, weight of the next layers and extrusion pressure. Satisfactory printing quality of the mixture indicates that the printed layers will resist self-weight deformations, while the resistance to other two deformation types must be confirmed with laboratory testing during the mix design [11]. The compressive stress induced by self-weight and weight of other layers in bottom layers increase during successive layer deposition. When this stress becomes higher than yield stress of the material, the failure occurs. The main parameters that determine buildability are yield stress, plastic viscosity and thixotropy. Buildability of the printing mixture increases with time, along with the material yield stress and elastic modulus, due to the hardening process [39]. The shear stress applied to the printing mixture during the pumping and extrusion induces the thixotropic behaviour of the mixture. Therefore, internal concrete's structure will break-down and build-up, influencing on viscosity and consequently, on the shape stability[11]. Hence, the building rate of the printed model depends on the structuration rate/structural build-up (i.e. yield stress increase with time), but also on nozzle velocity and length and thickness of the printed layers[11,29]. This means that structuration rate could be considered as a printing process dependent parameter, to account the variability of the mentioned printing properties, which imposes additional complexity to this material requirement [39]. Initial material yield stress and structuration rate are strukturiranja (porasta granice tečenja s vremenom), ali i od brzine dizne i dužine i debljine sloja koji se štampa [11,29]. To znači da se brzina strukturiranja može smatrati parametrom koji zavisi od procesa štampanja, kako bi se uzele u obzir varijacije navedenih karakteristika štampača, što doprinosi dodatnoj složenosti zahteva u pogledu ovog svojstva [39]. Početna granica tečenja i brzina strukturiranja jesu najbitnija reološka svojstva koja se suprotstavljaju naponima pritiska u slojevima, indukovanim gravitacionim opterećenjem [34]. Čak i ako napon ne premašuje napon na granici tečenja, usled kumulativnog napona u slojevima, može doći do pojave značajnih deformacija i narušavanja geometrije odštampanih slojeva. Dodatno, vitki vertikalni štampani modeli izloženi su izvijanju nakon određenog broja odštampanih slojeva modela, zbog čega štampani beton mora, relativno rano, razviti visoke vrednosti modula elastičnosti. Dokazano je da, s porastom visine odštampanog modela, napon tečenja potreban za savladavanje napona pritiska raste linearno, dok modul elastičnosti potreban za odupiranje izvijanju raste sa eksponentom 3. Kao posledica navedenog, do određene visine štampanog elementa (odnosno broja odštampanih slojeva), kritično za svojstvo *buildability* biće obrušavanje usled napona pritiska u donjim slojevima, uzrokovanog težinom viših slojeva. Nakon te visine, najveći uticaj na *buildability* svojstvo štampanog betona će imati izvijanje [39]. Iako se svi naučnici slažu da su neophodna dalja istraživanja i dodatni eksperimentalni rezultati za bolje razumevanje mehanizma formiranja stabilnosti oblika, pokazano je da primena nano-gline u mešavinama doprinosi porastu brzine strukturiranja u periodu mirovanja (engl. *structuration at rest*) betonske mešavine za štampanje [11,22,23,46].

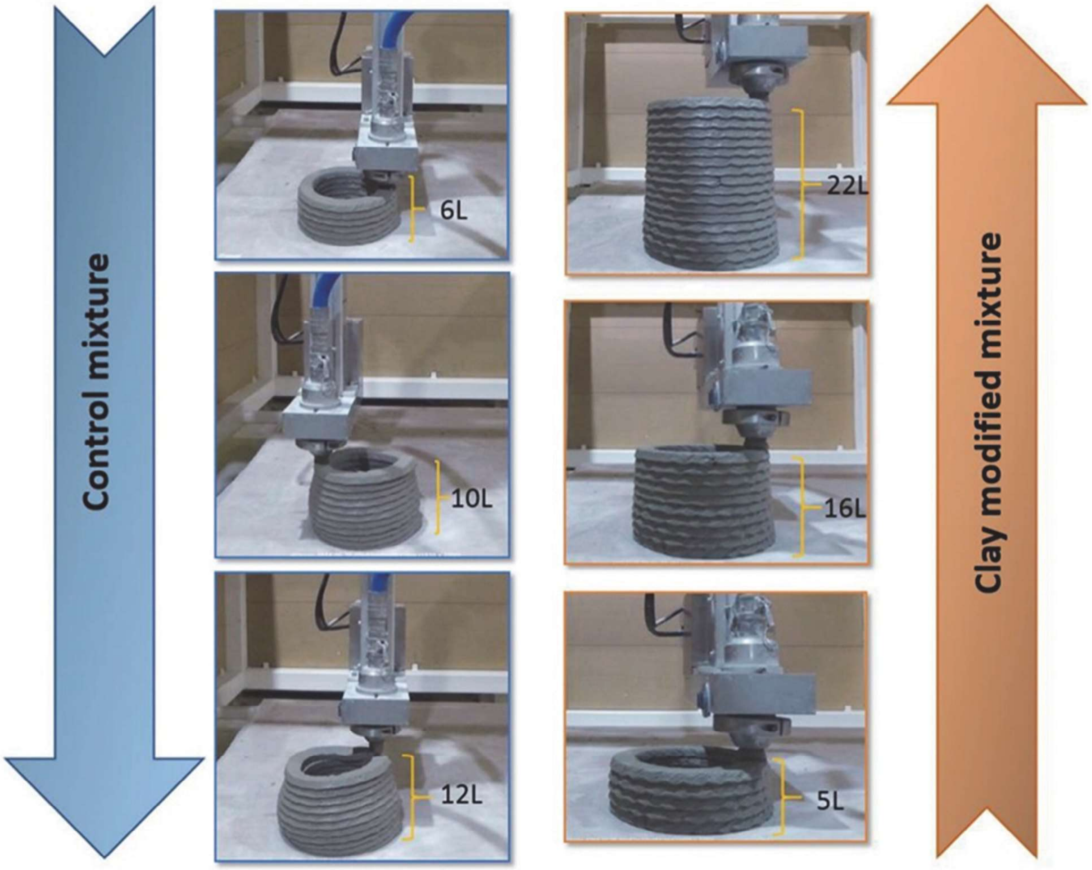
Slika 12 prikazuje analizu *buildability* svojstva u eksperimetalnom istraživanju koje su sproveli Panda i dr. Pored broja deponovanih slojeva pre pojave plastičnih deformacija (odnosno obrušavanja), elastične deformacije slojeva ispitane su na kontrolnoj mešavini i na mešavini modifikovanoj glinom, koja je pokazala bolje *buildability* svojstvo [22]. Slika 13 pokazuje posledice veze između *buildability* svojstva i pumpabilnosti, sposobnosti tečenja i stabilnosti oblika prikazanih u Tay i dr. [37].

Kao kvantitativni parametar za stabilnost oblika, Panda i dr. koriste faktor stabilnosti oblika, izračunat kao odnos poprečnog preseka ekstrudiranog materijala i poprečnog preseka dizne [26]. Prema eksperimentalnim istraživanjima, napon na granici tečenja raste linearno tokom perioda mirovanja, uzrokujući linearan porast stabilnosti oblika s vremenom. Stabilnost oblika utiče na očvrsla svojstva štampanog betona, preko povezanosti s vremenskim razmakom štampanja između sukcesivnih slojeva (engl. *printing time gap*). Kraći vremenski razmak uzrokovaće jaču mehaničku vezu dva odštampana sloja nakon očvršćavanja i obrnuto. Ipak, štampanje u kratkom vremenskom razmaku izvodljivo je samo za mešavine s visokom stabilnosti oblika, jer odštampani sloj mora imati sposobnost da izdrži težinu narednih slojeva odmah nakon ekstrudiranja. Dalje, vremenski razmak štampanja će zavisiti od rastojanja koje prelazi dizna tokom štampanja sloja (tj. dužine sloja) i brzine štampanja [11]. Ovo naglašava složenost i zavisnost više svojstava štampanih betona u svežem i očvrslom stanju od karakteristika štampača.

rheological properties of the highest importance for withstanding the gravity-induced compressive stresses in single and multiple layers [34]. Even if this stress does not exceed the yield stress, significant deformation can occur, due to the cumulative stress in layers, and it can impact the geometry of the printed layers. Additionally, slender vertical printed models are exposed to the buckling, after a certain number of printed layers/model height is achieved, which is why printing concrete must develop high elastic modulus relatively early. It is proven that, with the height increase of the printed object, yield stress needed to resist compressive stress increases linearly, while the elastic modulus needed to resist the buckling increases with the power of 3 of the printed object height. This means that below certain object height (number of printed layers) compressive stress failure will be critical for the buildability. Above this height, the buckling will have most impact on the buildability of the printing concrete [39]. Although all researchers agree that the further research and experimental data is needed for better understanding the mechanisms of forming the shape stability, the use of nanoclay in mixtures is reported to increase the build-up or "structuration at rest" of the printing mixtures [11,22,23,46].

Figure 12 shows the buildability analysis in the experimental study by Panda et al. Besides the number of deposited layers before plastic deformation (i.e. collapsing), elastic deformation of layers is examined on the control mixture and clay modified mixture, which showed higher buildability [22]. Figure 13 shows the consequences of the relations between buildability and pumpability, flowability and shape retention, presented by Tay et al. [37].

As a quantitative parameter for shape stability, Panda et al. use shape retention factor, calculated as ratio between cross section area of extrudate and cross section area of the nozzle [26]. According to the experimental research, yield stress increases linearly during the dormant period, causing linear increase of shape stability with time. The shape stability impacts the hardened properties of printed concrete through the linkage with printing time gap between successive layers. The shorter printing time gap will result in higher mechanical bond between layers and vice versa. However, printing with short time gaps can be feasible only if the mixture has high shape stability, meaning that the printed layer must be capable of withstanding the weight of the following layer right after extrusion. Furthermore, printing time gap will depend on nozzle travelling distance during layer printing (i.e. the layer length) and printing speed [11]. This emphasizes the complexity and dependence of multiple fresh and hardened printing concrete properties and printer properties.



Slika 12. Laboratorijsko ispitivanje "buildability" svojstva odštampane mešavine, opisano preko broja deponovanih slojeva pre obrušavanja [22]

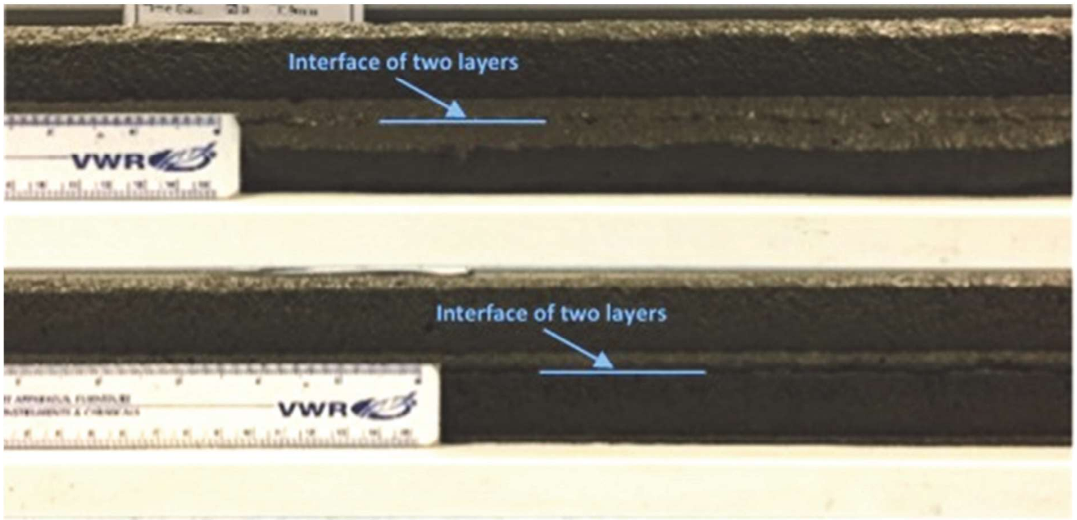
Figure 12. Laboratory testing of buildability of the printing mixtures describe through number of deposited layers before the structure collapsed [22]

Imajući na umu navedeno, većina naučnika predlaže kombinovano ispitivanje stabilnosti oblika. Kazemian i dr. procenjivali su stabilnost oblika preko sleganja slojeva i ispitivanja cilindrom, za vremenski razmak štampanja slojeva od 0 i 19 minuta. Sleganje slojeva ispitano je na dva odštampana sloja, jedan preko drugog, i merenjem sleganja analizom fotografija u program za obradu fotografija. Ispitivanje za vremenski razmak od 19 minuta pokazalo je da nema deformacija u donjem sloju za mešavinu s dodatkom silikatne prašine, polipropilenskih vlakana i nano-gline, dok je prosečna vrednost deformacija za pet merenja na mešavinama s Portland cementom bila 1,5 mm [11]. Ovo ispitivanje prikazano je na slici 14, a uzorak od pet sukcesivnih slojeva prikazan je na slici 15.

Having in mind all the above, a vast majority of the researches propose combined testing of the shape stability. Kazemian et al. assessed shape stability with layer settlement and cylinder stability test, for zero and 19 minutes time gap. Layer settlement test was performed by printing two layers on top of each other and measuring settlement by analyzing photos with image processing program. The test for 19 minutes time gap showed there were no deformations of the bottom layer for mixtures with silica fume, polypropylene fibres and nanoclay, while the average deformation for 5 measuring of Portland cement mixture was 1.5mm [11]. This test is shown at Figure 14, while five layer specimen is shown at Figure 15.

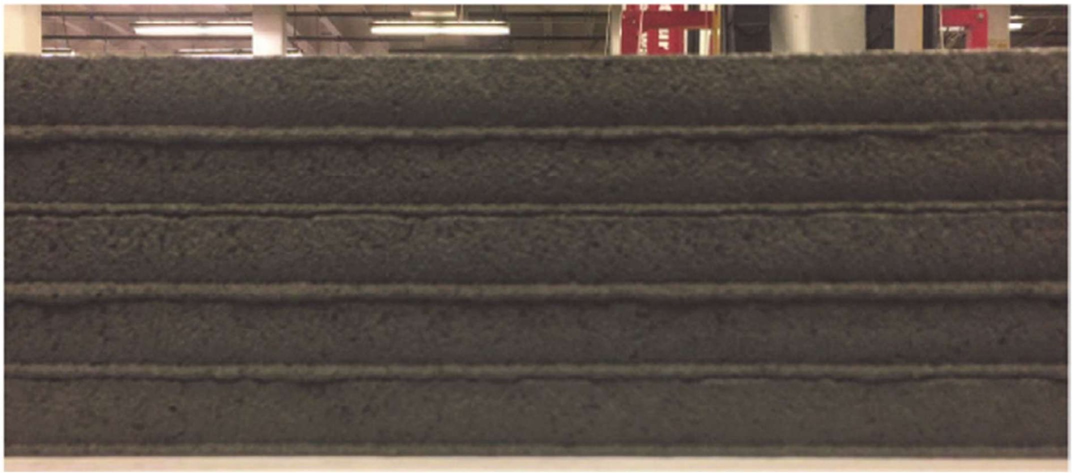
Slika 13. Maksimalan broj odštampanih slojeva – "buildability" svojstvo u zavisnosti od pumpabilnosti, sleganja i sleganje rasprostiranjem: mešavine a-c imaju nizak indeks pumpabilnosti, visoku stabilnost oblika, male vrednosti sleganja i sleganja rasprostiranjem, dok mešavine d-f imaju viši indeks pumpabilnosti, nisku stabilnost oblika i veće vrednosti sleganja i sleganja rasprostiranjem [37]

Figure 13. Maximum number of layers printed - buildability, depending on pumpability, slump and slump flow: mixtures a-c have low pumpability index, high shape retention and low slump and slump-flow values, while mixtures d-f have higher pumpability index, low shape retention and higher slump and slump flow values [37]



Slika 14. Ispitivanje sleganja slojeva – obrušavanje prilikom vremenskog razmaka u štampanju od 0 minuta (gore) i 19 minuta (dole) [10]

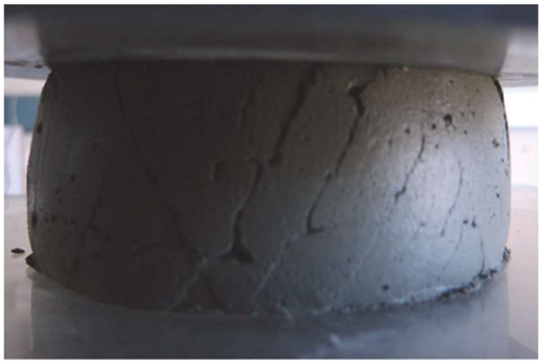
Figure 14. Layer settlement test – collapse with zero time gap (top) and 19 minute time gap (bottom) [10]



Slika 15. Stabilnost oblika sukcesivno odštampanih slojeva s vremenskim razmakom od 19 min [10]
Figure 15. Shape stability of successively printed layers with interlayer time gap of 19 minutes [10]

Dodatno, u ovoj eksperimentalnoj studiji, stabilnost oblika merena je ispitivanjem na cilindričnim uzorcima, a slično su predložili i Perrot i dr. [10,29]. Kazemian i dr. predlažu nanošenje konstantnog opterećenja od 5.5 kg i merenje promene visine uzorka, Perrot i dr. su povećavali opterećenje u inkrementima od 1.5N, kako bi se dobio maksimalan napon pre pojave plastične deformacije [10,29]. Na primer, za vremenski razmak štampanja slojeva od 17 sekundi, prosečno vreme loma četiri uzorka bilo je 656 sekundi nakon nanošenja opterećenja, pri naponu od 4,76 kPa, prosečno. Za vremenski razmak od 60 sekundi, nije uočena plastična deformacija. [29]. Uzorci ispitani u Perrot i dr. za različite vremenske razmake štampanja prikazani su na slici 16 i slici 17.

Additionally, in this experimental study, shape stability was measured by cylinder stability test, while the similar was proposed by Perrot et al. [10,29]. While Kazemian et al. proposed imposing a constant load of 5.5kg and measuring the change in specimen height, Perrot et al. increased the load in 1.5N increments, in order to obtain the maximum stress before the plastic deformation [10,29]. For example, for 17 seconds printing time gap, the 4 specimens average failure time was 656 seconds after load imposing, at 4,76 kPa, average. For 60 second time gap, no plastic deformation was detected [29]. The specimens tested by Perrot et al. for different printing time gaps are shown at Figure 16 and Figure 17.



Slika 16. Pukotine usled plastične deformacije prilikom ispitivanja cilindričnog uzorka – vremenski razmak štampanja 17 s

Figure16. Fractures on cylinder stability test specimen, due to plastic deformation – 17s time gap

Slika 17. Ispitivanje na cilindričnom uzorku – vremenski razmak štampanja 60 s

Figure17. Cylinder stability test specimen – 60s time gap

3 ZAKLJUČAK

U ovom radu prikazana su osnovna svojstva ekstrudiranog 3D štampanog betona u svežem stanju – pumpabilnost, sposobnost tečenja (tehnološka svojstva), sposobnost ekstrudiranja, kvalitet štampanja i buildability svojstvo (svojstva koja određuju mogućnost štampanja). Analizirana svojstva su veoma vremenski zavisna i zavisna od karakteristika štampača. Njihove definicije često se preklapaju i njihova kompleksnost predstavlja izazov za pronalaženje opšteg rešenja i procedura za projektovanje sastava mešavine za štampanje zadovoljavajućih karakteristika.

Iako se oblast 3D štampanja betona obimno istražuje, rezultati daljih eksperimentalnih istraživanja potrebni su kako bi bili predloženi pouzdani modeli za uspostavljanje veze između tehnoloških i reoloških svojstava štampanih betona sa svojstvima koja određuju sposobnost štampanja. Teoretska znanja su i dalje potrebna da bi se moglo, kvantitativno i kvalitativno, izraziti koja su to željena svojstva betonske mešavine za 3D štampu. Specifičnost svojstava 3D štampanog betona u svežem stanju stvara potrebu za uspostavljanjm nove terminologije, u poređenju s terminologijom koja se odnosi na betone koji se ugrađuju na tradicionalan način. Jedno od osnovnih svojstava betona u svežem stanju, obradljivost (engl. workability) ne može biti definisana i opisana na isti način za 3D betone kao i za tradicionalne [11]. Obradljivost se smatra „sposobnošću betonske mešavine u svežem stanju za transport, ugradnju i dorađivanje, bez pojave segregacije", ili, preciznije „količinom korisnog unutrašnjeg rada ili energije koja je potrebna da se prevaziđe unutrašnje trenje između betona i oplate ili armature" [21]. Na primer, bitno svojstvo 3D štampanog betona jeste buildability, to jest njegova veza s brzinom strukturiranja koja je zavisna od vremena. Konzistencija i vreme vezivanja mešavine za štampanje mora biti u određenom intervalu, kako bi zadovoljila zahteve procesa ekstrudiranja, ali s druge strane, odštampani slojevi moraju razviti rane čvrstoće gotovo odmah nakon ekstrudiranja, kako bi prihvatili težinu narednih slojeva. Stoga uobičajena definicija obradljivosti

3 CONCLUSIONS

This paper presents the basic fresh-state properties of extrusion-based 3D printed concrete –pumpability, flowability (technological properties), extrudability, print quality and buildability (printability properties). All analyzed properties are highly time-dependent and printer-dependent as well. Their definitions are often overlapping and their complexity is challenging for finding general solutions and procedures for designing the printable mixtures with satisfying performance.

Although the field of 3D concrete printing is recently extensively researched, further experimental results are needed in order to propose reliable models for linking technological and rheological properties of printing concrete with printability properties. There is still a great need for theoretical knowledge to express, quantitatively and qualitatively, the desirable printing mixture properties. Specific fresh - state properties of 3D printing concretes required establishing the new terminology compared to the traditionally casted concretes. For example, one of the basic properties of the fresh concrete – workability – cannot be defined and described in the same way for 3D concrete as for traditional concrete [11]. Workability is considered as the ability of concrete to "be properly compacted and also transported, placed and finished sufficiently easily without segregation", or, more strictly, as "the amount of useful internal work or energy required to overcome the internal friction between concrete and the formwork or reinforcement" [21]. For example, the important property of 3D concrete is buildability, i.e. its correlation with structuration rate, which is time dependent. The consistency and setting time of the printing mixture must be in certain interval to meet the needs of extrusion, but on the other hand, printed layers must obtain green strengths almost immediately after extruding, in order to bare the load of the following layers. Therefore, the usual definition of workability should be adjusted, since this term in 3D printing process combines a whole set of inter-dependable factors. It is recommended to evaluate the workability of 3D printing mixtures by investigating fresh-state concrete properties relevant mora biti prilagođena, jer ovaj termin u procesu 3D štampanja obuhvata širok spektar međuzavisnih faktora. Preporučeno je da se obradljivost 3D mešavina za štampanje ocenjuje ispitivanjem svojstava betona u svežem stanju koja su relevantna za 3D štampane betone – kvalitet štampe, stabilnost oblika i svojstvo printability window [11].

S obzirom na to što ne postoje standardizovane metode za ispitivanje i ocenu svojstva 3D štampanih betona, većina istraživanja se i dalje zasniva na eksperimentalnim probama (engl. trial-and-error). Zbog toga će svi rezultati istraživanja u oblasti 3D štampanih betona doprineti daljem razvoju i napretku ove tehnologije.

Zahvalnost

Istraživanja u ovom radu realizovana su u okviru projekta Departmana za građevinarstvo i geodeziju Fakulteta tehničkih nauka u Novom Sadu: „Multidisciplinarna teorijska i eksperimentalna istraživanja u obrazovanju i nauci u oblastima građevinarstva, upravljanja rizikom od katastrofalnih događaja i požara i geodezije."

for 3D printed concretes – print quality, shape stability and printability window [11].

Since there are no standardized methods for testing and evaluation of 3D printed concrete properties, most of the research is still based on trial-and-error experimental approach. That is why every research result in the field of 3D concrete printing contributes to further development and improvement of this technology.

Acknowledgement

The paper presents the part of the research realized within the project "Multidisciplinary theoretical and experimental research in education and science in the fields of civil engineering, risk management and fire safety and geodesy" conducted by the Department of Civil Engineering and Geodesy, Faculty of Technical Sciences, University of Novi Sad.

4 LITERATURA
REFERENCES

[1] Asprone D, Auricchio F, Menna C, Mercuri V. 3D printing of reinforced concrete elements: Technology and design approach. Construction and Building Materials. 2018 Mar;165, pp. 218–231.

[2] Bos F, Wolfs R, Ahmed Z, Salet T. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping. 2016 Jul 2;11(3), pp. 209–225.

[3] Casagrande L, Esposito L, Menna C, Asprone D, Auricchio F. Effect of testing procedures on buildability properties of 3D-printable concrete. Construction and Building Materials. 2020 Jun;245:118286.

[4] Cesaretti G, Dini E, De Kestelier X, Colla V, Pambaguian L. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. Acta Astronautica. 2014 Jan;93, pp. 430–450.

[5] Cicione A, Kruger J, Walls RS, Van Zijl G. An experimental study of the behavior of 3D printed concrete at elevated temperatures. 2020 May 4;10.

[6] Edison TA. Process of constructing concrete buildings. 1917 Mar 13;(US44829308A).

[7] F42 Committee. Terminology for Additive Manufacturing Technologies, [Internet]. ASTM International; [cited 2020 Sep 2]. Available from: http://www.astm.org/cgi-bin/resolver.cgi?F2792-12A

[8] Han Y, Yang Z, Ding T, Xiao J. Environmental and economic assessment on 3D printed buildings with recycled concrete. Journal of Cleaner Production. 2021 Jan;278:123884.

[9] Jayathilakage R, Rajeev P, Sanjayan JG. Yield stress criteria to assess the buildability of 3D concrete printing. Construction and Building Materials. 2020 Apr;240:117989.

[10] Kazemian A, Yuan X, Cochran E, Khoshnevis B. Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. Construction and Building Materials. 2017 Aug;145, pp. 639–647.

[11] Kazemian A, Yuan X, Meier R, Khoshnevis B. Chapter 2. Performance-Based Testing of Portland Cement Concrete for Construction-Scale 3D Printing. In: 3D Concrete Printing Technology - Construction and Building Applications. Oxford: Elsevier; 2019., pp. 13–35.

[12] Khoshnevis B, Hwang D, Yao KT, Yeh Z. Mega-scale fabrication by Contour Crafting. IJISE. 2006;1(3):301.

[13] Kloft H, Krauss H-W, Hack N, Herrmann E, Neudecker S, Varady PA, et al. Influence of process parameters on the interlayer bond strength of concrete elements additive manufactured by Shotcrete 3D Printing (SC3DP). Cement and Concrete Research. 2020 Aug;134:106078.

[14] Labonnote N, Rønnquist A, Manum B, Rüther P. Additive construction: State-of-the-art, challenges and opportunities. Automation in Construction. 2016 Dec;72, pp. 347–366.

[15] Le TT, Austin SA, Lim S, Buswell RA, Gibb AGF, Thorpe T. Mix design and fresh properties for high-performance printing concrete. Mater Struct. 2012 Aug;45(8):1221–1232.

[16] Lim S, Buswell R, Le T, Wackrow R, Austin S, Gibb A, et al. Development of a Viable Concrete Printing Process [Internet]. Seoul, Korea: 2011 [cited 2020 Sep 1]. Available from: http://www.iaarc.org/publications/proceedings_of_the_28th_isarc/development_of_a_viable_concrete_printing_process.html
[17] Lim S, Buswell RA, Le TT, Austin SA, Gibb AGF, Thorpe T. Developments in construction-scale additive manufacturing processes. Automation in Construction. 2012 Jan;21, pp. 262–268.
[18] Lukić I, Malešev M, Radonjanin V, Bulatović V, Dražić J. Comparative LCA analysis of ordinary concrete beams and structural lightweight concrete beams. Građevinski materijali i konstrukcije. 2013;56(1), pp.3–15.
[19] Malaeb Z, AlSakka F, Hamzeh F. Chapter 6. 3D Concrete Printing: Machine Design, Mix Proportioning, and Mix Comparison Between Different Machine Setups. In: 3D Concrete Printing Technology - Construction and Building Applications. Oxford: Elsevier; 2019.,pp. 115–136.
[20] Nerella VN. Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion-based 3D-printing. Construction and Building Materials. 2019;16.
[21] Nevil AM, Brooks JJ. Concrete Technology. 1987, 2nd ed., 978-0-273-73219-8.
[22] Panda B, Lim JH, Tan MJ. Mechanical properties and deformation behaviour of early age concrete in the context of digital construction. Composites Part B: Engineering. 2019 May;165, pp. 563–571.
[23] Panda B, Ruan S, Unluer C, Tan MJ. Improving the 3D printability of high volume fly ash mixtures via the use of nano attapulgite clay. Composites Part B: Engineering. 2019 May;165, pp. 75–83.
[24] Panda B, Singh GB, Unluer C, Tan MJ. Synthesis and characterization of one-part geopolymers for extrusion-based 3D concrete printing. Journal of Cleaner Production. 2019 May;220, pp. 610–619.
[25] Panda B, Tan MJ. Experimental study on mix proportion and fresh properties of fly ash based geopolymer for 3D concrete printing. Ceramics International. 2018 Jun 15;44(9), pp. 10258–10265.
[26] Panda B, Unluer C, Tan MJ. Extrusion and rheology characterization of geopolymer nanocomposites used in 3D printing. Composites Part B: Engineering. 2019 Nov;176:107290.
[27] Perrot A, Amziane S. 3D Printing in Concrete: General Considerations and Technologies [Internet]. In: Perrot A, editor. 3D Printing of Concrete. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2019 [cited 2020 Jul 10]. p. 1–40.Available from: http://doi.wiley.com/10.1002/9781119610755.ch1
[28] Perrot A, Rangeard D. 3D Printing with Concrete: Impact and Designs of Structures. In: 3D Printing of Concrete. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2019., pp. 125–144.
[29] Perrot A, Rangeard D, Pierre A. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. Mater Struct. 2016 Apr;49(4), pp. 1213–1220.
[30] Radeka M, Milović T, Malešev M, Radonjanin V, Laban M. Hydration process and compressive strength of cement pastes containing natural zeolite. Građevinski materijali i konstrukcije. 2016;59(2), pp. 29–45.
[31] Radulović R, Jevtić D, Radonjanin V. The properties of the cement screeds with the addition of polypropylene fibres and the shrinkage-reducing admixture. Građevinski materijali i konstrukcije. 2016;59(1), pp. 17–35.
[32] Rahul AV, Santhanam M. Evaluating the printability of concretes containing lightweight coarse aggregates. Cement and Concrete Composites. 2020 May;109:103570.
[33] Rahul AV, Santhanam M, Meena H, Ghani Z. 3D printable concrete: Mixture design and test methods. Cement and Concrete Composites. 2019 Mar;97, pp. 13–23.
[34] Roussel N. Rheological requirements for printable concretes | Elsevier Enhanced Reader. Cement and Concrete Research. 2018; pp. 76–85.
[35] Sanjayan JG, Nematollahi B. Chapter 1. 3D Concrete Printing for Construction Applications. In: 3D Concrete Printing Technology - Construction and Building Applications. Oxford: Elsevier; 2019., pp. 1–11.
[36] Tay YWD, Li MY, Tan MJ. Effect of printing parameters in 3D concrete printing: Printing region and support structures. Journal of Materials Processing Technology. 2019 Sep;271, pp. 261–270.
[37] Tay YWD, Qian Y, Tan MJ. Printability region for 3D concrete printing using slump and slump flow test. Composites Part B: Engineering. 2019 Oct;174:106968.
[38] Wangler T, Flatt RJ, editors. First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018 [Internet]. Cham: Springer International Publishing; 2019 [cited 2020 Jul 6]. Available from: http://link.springer.com/10.1007/978-3-319-99519-9
[39] Wangler T, Roussel N, Bos FP, Salet TAM, Flatt RJ. Digital Concrete: A Review. Cement and Concrete Research. 2019 Sep;123:105780.
[40] Weng Y, Li M, Tan MJ, Qian S. Design 3D printing cementitious materials via Fuller Thompson theory and Marson-Percy model. Construction and Building Materials. 2018 Feb;163, pp. 600–610.
[41] Wolfs RJM. Early age mechanical behaviour of 3D printed concrete_ Numerical modelling and experimental testing. Cement and Concrete Research. 2018;14.
[42] Xia M, Nematollahi B, Sanjayan JG. Chapter 11. Development of Powder-Based 3D Concrete Printing Using Geopolymers. In: 3D Concrete Printing Technology - Construction and Building Applications. Oxford: Elsevier; 2019., pp. 223–240.
[43] Zhang C. Design of 3D printable concrete based on the relationship between flowability of cement paste and optimum aggregate content. Cement and Concrete Composites. 2019;10.
[44] Zhang J. A review of the current progress and application of 3D printed concrete. Composites Part A. 2019;13.

[45] Zhang J, Khoshnevis B. Optimal machine operation planning for construction by Contour Crafting. Automation in Construction. 2013 Jan;29, pp. 50–67.

[46] Zhang Y, Zhang Y, Liu G, Yang Y, Wu M, Pang B. Fresh properties of a novel 3D printing concrete ink. Construction and Building Materials. 2018 Jun;174, pp. 263–271.

[47] How Thomas Edison Tried and Failed to Make Single-Pour Concrete Homes, ArchDaily [Internet]. 2016 [cited 2020 Aug 26];Available from: https://www.archdaily.com/781961/how-thomas-edison-tried-and-failed-to-make-single-pour-concrete-homes

APSTRAKT

OSNOVNA SVOJSTVA EKSTRUDIRANOG 3D ŠTAMPANOG BETONA U SVEŽEM STANJU

Olivera BUKVIĆ
Vlastimir RADONJANIN
Mirjana MALEŠEV
Mirjana LABAN

Cilj ovog rada je pregled osnovnih svojstava trodimenzionalnog (3D) štampanog betona u svežem stanju, štampanog procesom ekstrudiranja, kako bi se objasnila specifična svojstva ove tehnologije građenja. Pregled je sproveden pristupom „odozdo na gore”. Kao polazna tačka, korišćena je aktuelna literatura u oblasti štampanja betona procesom ekstrudiranja, dok je, pregledom referenci relevantnih naučnih radova, odabrana dodatna literatura za pregled. Na osnovu kriterijuma za inkluziju, analizirani su pregledni i eksperimentalni radovi koji sadrže podatke o svojstvima 3D štampanog betona u svežem stanju, kao i oni koji sadrže podatke o materijalima korišćenim za 3D štampanje, s obzirom na to što njihova svojstva direktno utiču na svojstva betonske mešavine u svežem stanju. Radovi koji sadrže podatke samo o svojstvima betona u očvrslom stanju nisu uzeti u obzir. Svojstva koja su predmet pregleda jesu: tehnološka svojstva (pumpabilnost i sposobnost tečenja) i svojstva koja određuju sposobnost štampanja (engl. printability – sposobnost ekstrudiranja, kvalitet štampanja i svojstvo buildability).

Ključne reči: 3D štampanje, aditivna proizvodnja, svojstva betona u svežem stanju, proces ekstrudiranja, tehnološka svojstva, svojstva koja određuju sposobnost štampanja

ABSTRACT

BASIC FRESH-STATE PROPERTIES OF EXTRUSION-BASED 3D PRINTED CONCRETE

Olivera BUKVIC
Vlastimir RADONJANIN
Mirjana MALESEV
Mirjana LABAN

This paper aims at reviewing the basic properties of fresh-state extrusion-based three-dimensional (3D) printed concrete in order to explain the specific properties of this construction technology. The review was conducted using the bottom-up approach. The most recent literature in the field of extrusion-based concrete printing was used as a starting point, while additional papers were included through screening the references of relevant papers. Based on the inclusion criteria, review and experimental papers containing data on fresh-state 3D printed concrete properties were included, as well as materials used for 3D printing, since their properties directly affect the fresh-state properties of concrete mixture. Papers concerning data only on hardened properties were excluded. Reviewed properties are: technological properties (pump ability and flow ability) and printability properties(extrudability, print quality and buildability).

Key words: 3D printing, additive manufacturing, fresh-state properties, extrusion-based process, technological properties, printability properties

IN MEMORIAM

Prof. Eng. **Vladimír Křístek**, DrSc., Dr. h. c., FEng.
(1938-2020)

On September 9, 2020 in Prague Prof. Eng. Vladimír Křístek, DrSc., Dr. h. c., FEng, suddenly left us at age of 82. Born on Oktober 15, 1938 in Prague, he is professor since 1977 in the Department of Reinforced Concrete and Masonry Structures at the Faculty of Technical Sciences in Prague, Czech Republic. Two-time winner of the State Prize of Czechoslovakia and two-time winner of the Czech Academy of Sciences for extremely high contributions in the field of research. Member of the Presidium of the Academy of Engineering of the Czech Republic. Chairman of the attestation commission for selection of doctoral students. He has won over 100 international and national research grants from 1970 to the present. Prof. DrSc. Eng. Vladimir Krsistek is a world-renowned expert in the field of stress and strain of reinforced concrete bridges and multi-storey buildings, taking into account the influence of the rheological properties of concrete. He gives lectures on reinforced concrete structures and bridges, stability of building structures, taking into account the influence of creep and drying of concrete and the method of the finite strips. Invited as a guest lecturer in the USA, Germany, England, Belgium, Finland, Italy, Greece. He is the author of 14 monographs and over 750 scientific publications in peer-reviewed international journals. Under his leadership, a total of twenty-four researchers defended their doctoral dissertations. Expert and designer of a number of complex with large openings bridges with box-shaped cross sections. Licensed civil engineer and consultant for a large number of reinforced concrete structures and facilities in the Czech Republic and abroad. He is the author and co-author of several edited manuals books:

1)Theory of Box Girders, Wiley and Sons, New York Chichester, Brisbane, Toronto, 1979;

2) Creep and Shrinkage of Concrete Elements and Structures, (co-author Z. Šmerda), Elsevier, Amsterdam, Oxford, New York, Tokyo, 1988; 3) Advanced Analysis and Design of Plated Structures, (co-author M. Škaloud), Elsevier, Amsterdam, Oxford, New York, Tokyo, 1991; 4) Stability Problems of Steel Box Girder Bridges, (co-author M. Škaloud), ČSAV, Prague 1981; 5) Thin-walled beams of deformable box sections (in Czech), ČSAV,

Prague, 1968; 6) Theory of Analysis of Box Girders (in Czech), SNTL Prague, 1974; Creep and Shrinkage of Concrete (in Czech, co-author Z. Šmerda), SNTL Prague, 1978; 7) Slender Compressed Concrete Members (in Czech, co-authors L.Janda, M. Kvasnička, J. Procházka), SNTL Prague, 1983; 8) Green Bridges, Eng.. Academy IAČR and SMP Construction, Prague 2004; 9) Mathematical Modeling of Creep and Shrinkage of Concrete (Chap. Effects of Shear Lag and Randomness of Material Creep Properties on deflections and Stresses in Prestressed Concrete Box Girder), (Ed. Z.P. Bažant), John Wiley and Sons, Chichester - New York - Brisbane - Toronto - Singapore, 1988; 10) Analysis of transport of humidity in porous materials, (in Czech), (co-authors) Pardubice, 2008; 11) Plated Structures - Stability and Strength (Chap. Shear Lag in Box Girders), Applied Science Publishers, Elsevier, London ,1983; 12) Composite Steel - Concrete Structures (Chap. Composite Girders with Deformable Connection), (co-author J. Studnička), Applied Science Publishers, Elsevier, London, 1988.

As major Awards and Honours: we can mention: Prize of Czech Society of Civil Engineers (1977); Czechoslovak State Prize (1977); Prize of Czechoslovak Academy of Sciences (1982); Prize of Czech Publishers of Technical Literature (1980); Czechoslovak State Prize (1988); Czech Technical University Golden Felber Medal (1998); Two Prizes of Czechoslovak Academy of Sciences (1982 and 1989); Two Medals of the Ministry of Education of the Czech Republic (1998 and 2002); Prize of Ministry of Transportation of the Czech Republic (2008).

During the period beween 1979 and 1994 he was visiting researcher and lecturer at: University of California, Berkeley, USA (1979); University College, Cardiff, UK (1981); University of Dortmund, Germany (1982); University of Dortmund, Germany (1984); Northwestern University, Evanston, USA (1985, 1999, 2000); University of Dortmund, Germany (1985); University College, Cardiff, UK (1986); University College, Cardiff, UK (1988); University College, Cardiff, UK (1989); University of Stuttgart, Germany (1989); University of Liege, Belgium (1990); Helsinki University of Technology, Finland (1991); University of Milano, Italy (1992); University College, Cardiff, UK (1992); Helsinki University of Technology, Finland (1992); National Technical University of Athens, Greece (1993); Helsinki University of Technology, Finland (1994); University of Oulu, Finland (1994); International Centre for Mechanical Sciences, Udine, Italy (1994).

His scientific interests and professional activity covered a wide range of fields in Civil and Structural Engineering, as follows: Structural Mechanics, Advanced Structural Analysis, Mathematical Elasticity, Thin-walled Structures, Stability Problems, Bridges, Tall Buildings, Composite Structures, Creep and Shrinkage of Concrete, Advanced Analysis of Concrete Structures, Fibre Reinforced Concrete, Historical bridges, Sustainable Development. Consultancy to bridge design and construction.

For his serious merits in raising the authority of VSU. L. Karavelov, he was awarded with the honorary title "Doctor Honoris Causa" of VSU "Lyuben Karavelov" with a decision of the Academic Council - Protocol №17/03.04.2014.

Drafted on behalf of your colleagues and friends:
Doncho Partov, Radomir Folic and Asterios Liolios

IN MEMORIAM

Vladimir Vlada Denić
Vladimir Vlada Denic

(1929-2020)

Jula meseca 2020. godine, u 91. godini života, preminuo je Vladimir Vlada Denić, dipl. inž. tehnologije, čovek koji će u stručnim krugovima biti zapamćen kao dugogodišnji direktor Udruženja ciglarske industrije Srbije SIG (Savremena industrija glinenih proizvoda). Pri ovome se slobodno može reći da će on u našem sećanju zauvek biti i sinonim vezan za pojam „ciglar", pa i za celokupnu ciglarsku industriju Srbije.

Mada je do početka rada u SIG-u, a po završetku Tehnološko-metalurškog fakulteta u Beogradu, bio zaposlen i na drugim mestima (u Kombinatu šećera i vrenja u Beogradu, u fabrici ležajeva IKL, u Udruženju industrije građevinskog materijala Vojvodine, u Savetu industrije građevinskog materijala u Beogradu, u udruženju IZMA), on je sebe, u stručnom pogledu, u punom smislu reči našao tek u SIG-u, gde je od 1968. pa do penzije (punih 30 godina), bio na mestu direktora. Tada je u potpunosti ispoljena velika ljubav Vlade Denića prema ciglarstvu i ciglarima, pa je on na tom polju dobio i priliku da u punoj meri iskaže svoje znanje, umeće i snalažljivost, ali i svoju inovativnost i kreativnost. S tim u

In July 2020, at the age of 91, Vladimir Vlada Denić, graduate engineer of technology, passed away, a man who will be remembered in professional circles as a long-term director of the Association of Brick Industry of Serbia - SIG (Contemporary Industry of Clay products). At the same time, it can be freely said that in our memory, he will forever be a synonym related to the term "brick-maker", and even to the entire brick industry of Serbia.

After graduating from the Faculty of Technology and Metallurgy in Belgrade, he worked in other places before beginning to work in SIG (in the Sugar and Fermentation Plant in Belgrade, in the IKL bearing factory, in the Association of Construction Material Industry of Vojvodina, in the Council of Industry of Construction Materials in Belgrade, in the IZMA association), but he only found himself accomplished in professional sense in SIG, where he became the director in 1968, and remained in that position until his retirement (full 30 years). Then, Vlada Denić's great love for brick making and brick makers fully expressed, so in that field he was given the opportunity to fully express his knowledge, skills and vezi, treba posebno istaći njegove aktivnosti u smislu poboljšanja i unapređivanja proizvodnje i zakonske regulative u vezi sa industrijom glinenih proizvoda, a sve to s ciljem što boljeg pozicioniranja ove industrijske grane u okviru privrede zemlje.

U vezi s navedenim, treba posebno istaći doprinose Vlade Denića na polju kreiranja tehničke regulative na osnovama evropskih trendova, njegove doprinose na razradi te regulative s obzirom na domaće uslove, kao i na prilagođavanje nekih od tih uslova primeni u svakodnevnoj domaćoj praksi. Na toj liniji on je bio i inicijator prijema SIG-a u Evropsko udruženje ciglara, tako da je udruženje SIG bilo prvo udruženje s naših prostora primljeno u ovu prestižnu stručnu organizaciju.

U svom radu Vlada Denić je dao nemerljiv doprinos saradnji ciglara i građevinske struke, a u vezi s praktičnom primenom materijala na bazi gline u domaćem graditeljstvu. To se potpuno iskazivalo u vezama koje je SIG imao ne samo s tehnološkim fakultetima i tehnološkim institutima s naših prostora, već i s fakultetima i institutima s područja građevinarstva. Ta saradnja se posebno ispoljavala u visokom nivou saradnje SIG-a i društva DIMK – Društva za ispitivanje i istraživanje materijala i konstrukcija – u ranijim vremenima Jugoslavije, a danas Srbije.

U periodu dok je bio na čelu SIG-a, Vlada Denić je bio organizator mnogih stručnih skupova na kojima se radila permanentna edukacija ljudi iz oblasti ciglarstva. Isto se može konstatovati i analizom tadašnjih aktivnosti DIMK-a (kongresi, simpozijumi, seminari), kada su skupovi tog društva u najvećem broju slučajeva bili organizovani zajedno sa SIG-om ili uz podršku i pomoć ciglara, a što je svakako bilo od koristi i jednima i drugima.

Kao rezultat dugogodišnjeg rada, iza Vlade Denića ostao je niz stručnih publikacija iz oblasti proizvodnje, standardizacije i primene opeke i crepa u graditeljstvu. Ovde se posebno ističe njegov *Priručnik o upotrebi opekarskih proizvoda*, publikovan 2005. godine (106 stranica), napisan s ciljem da se u njemu ukaže na principe pravilnog korišćenja opeke i crepa kao osnovnih elemenata za zidanje i pokrivanje zgrada, pri čemu su u poglavlju o crepu izvršene i određene dopune – posebno u delu o asortimanu tih elemenata.

Čini se da na ovom mestu treba pomenuti i zapaženo izlaganje *Nova kretanja u industriji cigle i crepa u svetu i kod nas,* koje je Vlada Denić imao na skupu održanom povodom Dana inženjera na Sajmu građevinarstva u Beogradu 2011. godine.

Kao neumoran pregalac i vredan čovek, Vlada Denić je iza sebe ostavio i dva priloga koji pripadaju kategoriji preglednih radova. To su sledeći bibliografski prilozi:

– IZGRADNJA – *Bibliografija časopisa publikovanih u periodu 1947–2016* (rad štampan 2018. godine);

– MATERIJALI I KONSTRUKCIJE – *Pregled radova publikovanih u časopisu u periodu 1958–2010* (štampano u broju časopisa 4/2010).

Nakon odlaska u penziju, Vlada Denić je i dalje ostao aktivan na stručnom polju; on je nastavio da sarađuje sa svojim ciglarima, sa udruženjem DIMK Srbije, kao i sa redakcijama stručnih časopisa *Izgradnja* i *Građevinski materijali i konstrukcije.*

A danas, kada ga više nema, slobodno se može reći da je Vladimir Vlada Denić ostvario zavidne domete kako na profesionalnom tako i na privatnom planu, pri čemu će

resourcefulness, but also his innovation and creativity. In this regard, special emphasis should be placed on his activities in terms of improving and advancing production and legislation related to the industry of clay products, all with the improving the positioning of this industry within the country's economy.

Thus, we should especially highlight the contribution of Vlada Denić in the field of creating technical regulations based on the European trends, his contribution to the elaboration of those regulations with regard to domestic conditions, as well as to adapt some of those conditions to everyday practice. Accordingly, he was the initiator of the admission of SIG to the European Brick Association, so that the SIG was the first association from our region to be admitted to this prestigious professional organization.

In his work, Vlada Denić made an immeasurable contribution to the cooperation between brick makers and the engineering profession, in relation to practical application of clay-based materials in domestic civil engineering. This was fully reflected in connections that SIG had with both technological faculties and technological institutes from our area, but also with faculties and institutes in the field of civil engineering. This cooperation was especially evident in the high level of cooperation between SIG and DIMK - the Society for Materials and Structures Testing of first Yugoslavia and then Serbia - DIMK of Serbia.

During the period when he was the head of SIG, Vlada Denić was the organizer of many professional gatherings at which permanent education of people in the field of brick making was conducted. The same can be stated in the analysis of the activities of DIMK at that time (congresses, symposia, seminars), when gatherings of the society were in most cases organized together with SIG or with the support and help of brick makers, which was certainly useful to both organizations.

As a result of many years of work, Vlada Denić made a number of professional publications in the field of production, standardization and application of bricks and tiles in the field of construction. We can specifically highlight his *Handbook on the Use of Brick Products*, published in 2005 (106 pages), written with the aim of pointing out the principles of proper use of bricks and tiles as basic elements for masonry and roofing of buildings; note that certain additions were made in the chapter on tiles - especially in the section on the assortment of these elements.

It seems that at this place we should also mention the notable presentation *New Trends in the Brick and Tile Industry in the World and in Our Country*, which Vlada Denić delivered at the gathering held on the occasion of the Engineers' Day at the Building Trade Fair in Belgrade in 2011.

As a tireless and hard-working man, Vlada Denić left two articles behind that belong to the category of review papers. These are the following bibliographic contributions:

– CONSTRUCTION - *Bibliography of journals published in the period 1947–2016* (paper printed in 2018);

– MATERIALS AND STRUCTURES - Review of papers published in the journal in the period 1958–2010 (printed in the issue 4/2010).

njegov lik svima koji su ga poznavali ostati u sećanju kao lik „čoveka od reči”, vrednog, upornog, požrtvovanog i iznad svega – vedrog.

Prof. dr Mihailo Muravljov, dipl. inž. građevine
Dr Zoran Bačkalić, dipl. inž. tehnologije

After retiring, Vlada Denić remained active in the professional field; he continued to cooperate with his brick makers, with the DIMK association, as well as with the editorial boards of the professional magazines *Izgradnja* and *Građevinski materijali i konstrukcije*.

Today, when he left us, it can be freely said that Vladimir Vlada Denić achieved great results both professionally and privately, while his character will be remembered by all who knew him as a "man of his word", diligent, persistent, self-sacrificing and above all - cheerful.

Prof. dr. Mihailo Muravljov, graduate engineer of civil engineering
Dr Zoran Bačkalić, graduate engineer of technology

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.

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.

---

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

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

Website of the Society and the journal: www.dimk.rs

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

INSTITUT IMS AD, BEOGRAD

doka

Oplatna tehnika.

Vaš pouzdan partner

za brzu, bezbednu i ekonomičnu gradnju!

Doka Serb je srpski ogranak austrijske kompanije **Doka GmbH**, jednog od svetskih lidera na polju inovacija, proizvodnje i distribucije oplatnih sistema za sve oblasti građevinarstva. Delatnost kompanije Doka Serb jeste isporuka oplatnih sistema i komponetni za primenu u visokogradnji i niskogradnji, pružanje usluga konsaltinga, izrade tehničkih planova i asistenicije na gradilištu.

Panelna oplata za ploče Dokadek 30 – Evolucija u sistemima oplate za ploče
Dokadek 30 je ručna oplata lake čelične konstrukcije, bez nosača sa plastificiranim ramovima, koji su prekriveni kompozitnim drveno-plastičnim panelom površine do 3 m^2.

Izuzetno brzo, bezbedno i lako postavljanje oplata
- Mali broj delova sistema i pregledna logistika uz samo dve veličine panela (2,44 x 1,22 m i 2,44 x 0,81 m)
- Dovoljan 2-člani tim za jednostavnu i brzu montažu elemenata sa tla bez merdevina i bez krana
- Sistemski određen položaj i broj podupirača i panela, unapred definisan redosled postupaka
- Prilagođavanje svim osnovama zahvaljujući optimalnom uklapanju sa Dokaflex-om
- Specijalni dizajn sprečava odizanje panela pod uticajem vetra
- Horizontalno premeštanje do 12 m^2 Dokadek 30 pomoću DekDrive

Više informacija o sistemu naći ćete na našem sajtu **www.doka.rs**

Doka Serb d.o.o. | Svetogorska 4, 22310 Šimanovci | Srbija | **T** +381 22 400 100
F +381 22 400 124 | serb@doka.com | **www.doka.rs**


MAPEI
PoroMap DEUMIDIFICANTE
Mapelastic
Dursilite
Keraquick Maxi S1
Ultralite S1
Adesilex P9 Express
Planitop Rasa&Ripara

MATEST

YOUR PARTNER IN TESTING

iT TECH

INELAS ERECO d.o.o

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

iT TECH pokriva
- INOVATIVNOST
- INTERNET KONEKCIJA
- 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

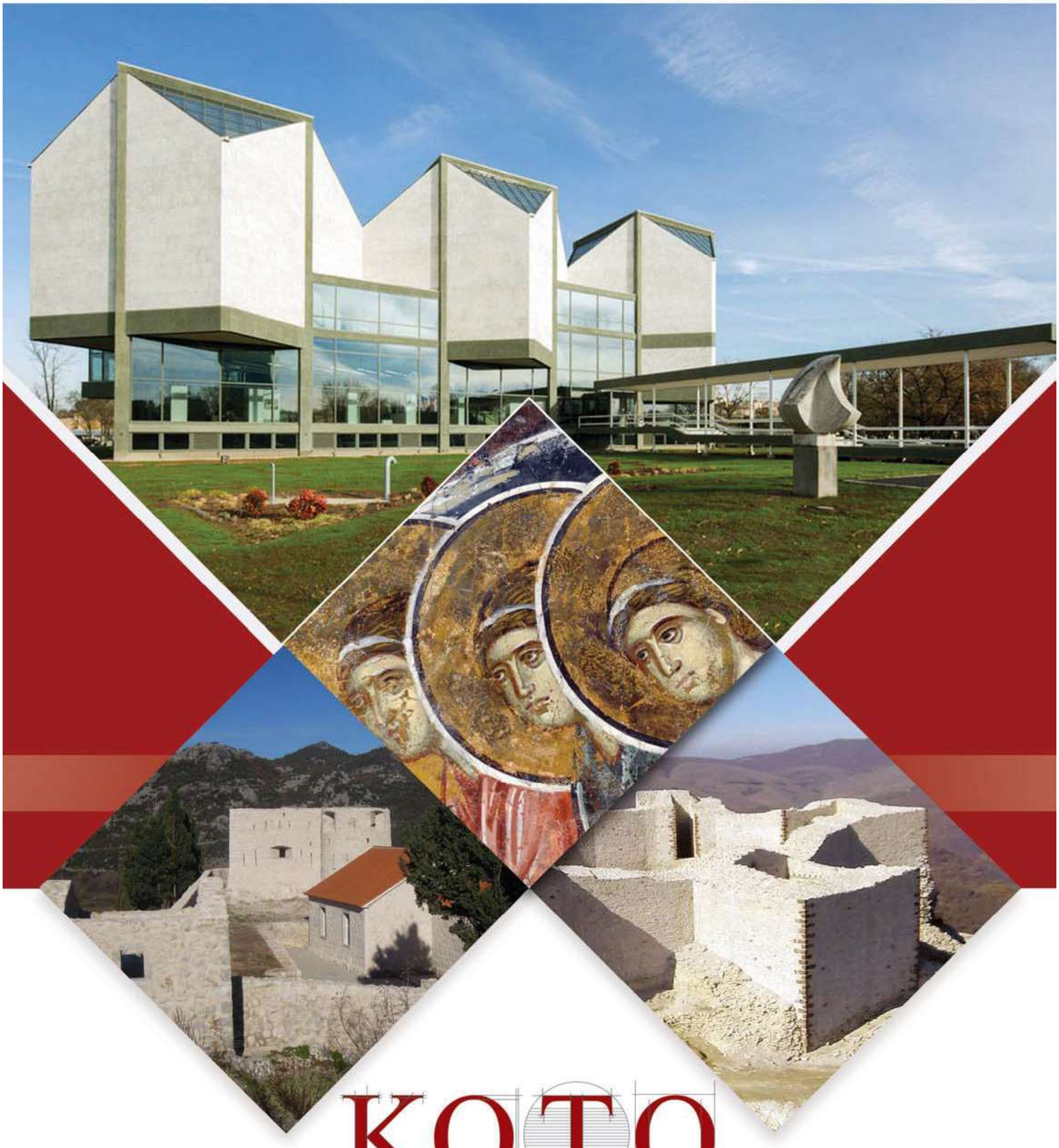
- CBR/Marshall digital machines
- Universal multispeed load frames
- UNITRONIC 50kN or 200kN Universal multipurpose compression/flexural and tensile frames

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

INELAS ERECO D.O.O
Tošin bunar 274a, 11070 , Novi Beograd tel. +381 11 2284 574 email. info@inelasereco.rs




TKK
CEMENTOL®
TKK
SINCE1947
TKK
CEMENTOL DELTA EXTRA
TKK
TEKAMAL
HIDROIZOL
N
25kg

INSTITUT IMS a.d.

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.

Poslovni centri Instituta IMS :

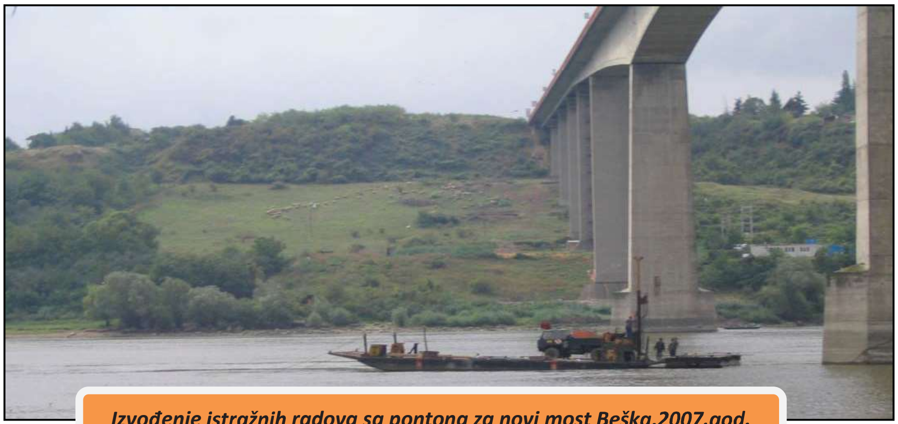
- Centar za puteve i geotehniku
- Centar za materijale
- Centar za metale i energetiku
- Centar za konstrukcije i prednaprezanje

INSTITUT IMS a. d.
Bulevar vojvode Mišića 43
11 000 Beograd
Tel: 011-2651-949
Faks: 011-3692-772
office@institutims.rs
www.institutims.rs

Institut IMS sertifikovao je sistem kvaliteta prema zahtevima standarda SRPS ISO 9001:2001. Svoju kompetentnost je potvrdio najvećim obimom akreditacije kod Akreditacionog tela Srbije (ATS) i Sertifikacionog tela.

Kadrovsku strukturu Instituta IMS čine doktori nauka, diplomirani inženjeri sa licencama Inženjerske komore Srbije i stručni tehnički kadar. Inženjeri Instituta IMS aktivno učestvuju na naučno-stručnim skupovima u zemlji i inostranstvu.

Institut IMS kontinuirano unapređuje kvalitet poslovanja na svim nivoima, kako u okviru terenskih i laboratorijskih ispitivanja, tako i na izradi projektno-tehničke dokumentacije s ciljem uspešne realizacije postavljenih zadataka.



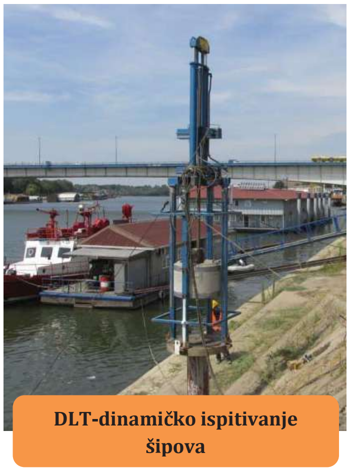
Izvođenje istražnih radova sa pontona za novi most Beška,2007.god.

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.

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).



DLT-dinamičko ispitivanje šipova

CPT/CPTU opiti

Aktivno klizište

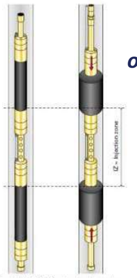


Fig. 9. IPAC GD Regular double packer

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.


ZAŠTITNI
PREMAZI
ZA BETON

BUILDING TRUST

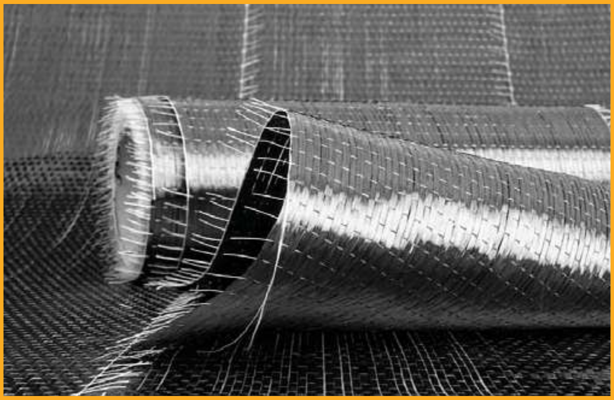
NAPREDNA SIKA REŠENJA U OBLASTI STRUKTURALNIH OJAČANJA

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 m³ do 10 m³ betonske mase. Za ugradnju betona posedujemo auto-pumpu za beton, radnog učinka 150 m³/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
beograd@putinzenjering.com

MOBECO

www.putinzenjering.com


Tunel Čortanovci
PERI