NUMERIČKA SIMULACIJA PONAŠANJA UZORAKA OD LAKOAGREGATNOG BETONA U SLUČAJEVIMA LABORATORIJSKOG ISPITIVANJA

NUMERICAL SIMULATION OF THE BEHAVIOUR OF THE LIGHTWEIGHT CONCRETE SPECIMEN IN THE LABORATORY TESTING

Vladimir ŽIVALJEVIĆ
Dušan KOVAČEVIĆ
Ivan LUKIĆ
Vlastimir RADONJANIN

ORIGINALNI NAUČNI RAD
ORIGINAL SCIENTIFIC PAPER
UDK:691.32:620.178.1
doi:10.5937/GRMK1904037Z

1 UVOD

Beton je veštački kompozitni građevinski materijal dobijen očvršćavanjem mešavine veziva, vode, agregata (i u mnogim slučajevima različitih dodataka) i već duže od jednog veka predstavlja najčešće korišćen građevinski materijal. Budući da godišnja proizvodnja betona premašuje količinu od deset milijardi tona, sve je značajnija upotreba alternativnih materijala. Jedna od mogućnosti upotrebe alternativnih komponenata jeste upotreba lakog agregata, umesto dela ili celokupne količine običnog agregata, kao punioca u betonskoj smeši. Iako je hetegoren, za svakodnevne potrebe projektovanja građevinskih konstrukcija, beton se smatra homogenim materijalom. Tretiranje betona kao homogenog kontinuuma opravdano je kada se beton nalazi u elastičnoj fazi rada, što u najvećem broju situacija i jeste slučaj budući da su konstrukcije u izuzetno retkim slučajevima opterećene graničnim opterećenjima [8]. Napregnute graničnim opterećenjem, armiranobetonske konstrukcije

1 INTRODUCTION

Concrete is an artificial composite building material obtained by curing the mixture of the binders, water, aggregates (and in many cases various additives) and has been the most commonly used building material for over a century. Since the annual production of the concrete exceeds ten billion tonnes, the use of the alternative materials is of increasing importance. One possibility of using alternative components would be to use a lightweight aggregate instead of a part or the whole amount of a conventional aggregate as a filler in a concrete mixture. Although considered as heterogeneous, for everyday design purposes, concrete is considered to be a homogeneous material. The treatment of concrete as a homogeneous continuum is justified when the concrete is in an elastic phase of operation, which in the most situations is the case, since structures are loaded by the ultimate loads in extremely rare cases [8]. Loaded by the ultimate load reinforce

Vladimir Živaljević, mast. inž. građ. – asistent, Fakultet tehničkih nauka Univerziteta u Novom Sadu, Trg Dositeja Obradovića 6, 21000 Novi Sad, e-mail: zivaljevic.vladimir@uns.ac.rs
Profesor dr Vlastimir Radonjanin, dipl. inž. građ. Fakultet tehničkih nauka Univerziteta u Novom Sadu, Trg Dositeja Obradovića 6, 21000 Novi Sad, e-mail: radonv@uns.ac.rs
Docent dr Ivan Lukić, dipl. inž. građ. Fakultet tehničkih nauka Univerziteta u Novom Sadu, Trg Dositeja Obradovića 6, 21000 Novi Sad, e-mail: lookic@uns.ac.rs
Profesor dr Dušan Kovačević, dipl. inž. građ. Fakultet tehničkih nauka Univerziteta u Novom Sadu, Trg Dositeja Obradovića 6, 21000 Novi Sad, e-mail: dušan@uns.ac.rs

Vladimir Zivaljevic, MSc in Civil Engineering, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovica 6, 21000 Novi Sad, e-mail: zivaljevic.vladimir@uns.ac.rs
Vlastimir Radonjanin, Prof. PhD in Civil Engineering, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovica 6, 21000 Novi Sad, e-mail: radonv@uns.ac.rs
Ivan Lukic, Asistant prof. PhD in Civil Engineering, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovica 6, 21000 Novi Sad, e-mail: lookic@uns.ac.rs
Dusan Kovacevic, Prof. PhD in Civil Engineering, University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovica 6, 21000 Novi Sad, e-mail: dušan@uns.ac.rs

moгу da dođive lom na nekoliko razliĉitih naĉina: pucanje (prskanje), drobljenje i otpadanje betona, teĉenje i izvlaĉenje zategnutih šipki armature, te teĉenje i izvijanje pritisnutih šipki armature. Radi što bolje opisivanja i sagledavanja ponašanja armiranobetonskih konstrukcija pri lomu, neophodne su napredne numeričke simulacije zasnovane na mehanici kontinuuma. Ovom zahtevu u suprotnosti stoje računarske mogućnosti i vreme koje na raspolaganju imaju inženjeri, te je upotreba pojednostavljenih modela, kako konstrukcije, tako i ponašanja materijala, uobiĉajena u praksi.

Veliki broj istrađivanja urađen je u prethodnih nekoliko godina, kako u pogledu razvika novih, sveobuhvatnijih numeričkih modela materijala betona, tako i u pogledu eksperimentalnog ispitivanja lakoagregatnog betona. Numeričko modeliranje pojave plastiĉnosti betona, te razvika oštećenja moguće je sprovesti upotrebom CDP (concrete damage plasticity) modela materijala. Ovaj model materijala uvodi pretpostavku da su dva glavna mehanizma loma betona pojava prslina usled zatezanja i drobljenje usled pritiska. Ovaj model materijala predstavljen je u [4], a tokom prethodne decenije dođivao je brojna unapređivanja u pogledu određivanja varijabli neophodnih za njegovo definisanje [2, 5, 9]. Neka od znaĉajnijih eksperimentalnih ispitivanja lakoagregatnog betona data su u [7, 8, 10].

U ovom radu predstavljen je koncept CDP modela materijala i urađena je numerička simulacija ponašanja uzoraka od lakoagregatnog betona u sluĉajevima laboratorijskog ispitivanja. Razmatrane su dve konfiguracije ispitivanja: određivanje ĉvrstoće betona pri pritisku na beotnskoj kocki stranice 150 mm i određivanje statičkog modula elastiĉnosti betona na betonskom cilindru preĉnika 150 mm i visine 300 mm. S ciljem obuhvata realnog stanja i ponašanja materijala, u ovom radu je korišćen CDP model materijala betona.

2 MODEL PONAŠANJA BETONA

Ponašanje materijala pri lomu usled napona pritiska i napona zatezanja mođe se opisati na razliĉite naĉine. U sluĉaju zatezanja, dolazi do pojave prslina, što se na dijagramu napon-deformacija ogleda u naglom padu krutosti u materijalu, a potom i padu krutosti rasterećujuće grane dijagrama. U sluĉaju napona pritiska, dolazi do povećanja zapremine materijala, drobljenja i klizanja unutar materijala. U kombinovanim stanjima napona, lom obiĉno zavisi od odnosa između glavnih napona [2].

Nelinearno ponašanje betona je u ovom radu opisano korišćenjem CDP modela, implementiranog u softver Abaqus®. Ovaj model nelinearnog ponašanja materijala prvenstveno je namenjen modeliranju problema u kojima je moguća pojava plastiĉnosti betona, međutim, njime je moguće modelirati i druge kvazi-krte materijale. Glavna pretpostavka jeste da su dva glavna mehanizma loma betona pojava prslina usled zatezanja i drobljenje usled pritiska [1]. Pretpostavka ponašanja materijala usled jednoosnog napona pritiska i zatezanja data je na slici 1.

concrete structures can suffer failure in several different ways: cracking, crushing and scraping the concrete, yielding and pulling the tensioned reinforcement bars, and yielding and buckling the compressed reinforcement bars. Advanced numerical simulations based on continuum mechanics are required to better describe and understand the behaviour of the reinforced concrete structures during the failure. This requirement fails to agree with the computational capabilities and the time available to the engineers. Therefore, the use of the simplified models, both of the structure and of the material behaviour, is common in practice.

A great number of research activities has been done in the past few years, both with regard to the development of new, more comprehensive numerical concrete material models and the experimental testing of lightweight concrete. The numerical modelling of the concrete plasticity and the damage development can be performed using the CDP (concrete damage plasticity) material model. This material model introduces the assumption that the two main mechanisms of the concrete failure are cracking due to the tension and crushing due to the compression. This material model has been presented in [4]. It has undergone numerous improvements over the past decade while considering determination of the variables necessary to define it [2, 5, 9]. Some of the more significant experimental tests on lightweight concrete are given in [7, 8, 10].

In this paper, the concept of CDP material model is presented and numerical simulation of the behaviour of the lightweight concrete samples in the laboratory testing cases is done. Two test configurations were considered: the determination of the concrete compressive strength on a 150mm concrete cube and the determination of the concrete static modulus of elasticity on a concrete cylinder 150 mm in diameter and 300 mm in height. In order to capture the realistic behaviour of the material, the CDP model of the concrete was used in this paper.

2 CONCRETE BEHAVIOUR MODEL

The behaviour of the material at failure due to compressive and tensile stress can be described in various ways. In the case of tension, cracks occur, which is reflected in the stress-strain diagram in a sharp drop in the stiffness of the material, followed by a decrease in the stiffness of the load-bearing branch of the diagram. In the case of compression stress, an increase in material volume, crushing and slipping within the material occurs. In combined stress states, failure usually depends on the relation between the principal stresses [2].

The nonlinear behaviour of concrete is described in this paper using a CDP model, implemented in Abaqus® software. This model of non-linear behaviour of materials is primarily intended to model problems where the plasticity of concrete is possible, however, it is also possible to model other quasi-rigid materials. The main assumption is that the two main mechanisms of the concrete failure are cracking due to the tension and crushing due to the compression [1]. The assumption of the material behaviour due to the uniaxial tension and the tensile stress is given in Figure 1.

Slika 1. Odgovor betona na jednoosno zatezanje (levo) i pritisak (desno) [1]
Figure 1. Concrete response to the uniaxial tension (left) and compression (right)[1]

Usled jednoosnog zatezanja, veza između napona i dilatacije je linearno-elastična sve dok se ne postigne vrednost čvrstoće betona pri zatezanju σ_{t0} . Dostizanje ove vrednosti napona tretira se kao početak formiranja mikroprrsline u betonu, koje se prikazuje padom napona, odnosno povećanjem dilatacije.

Usled jednoosnog pritiska, veza između napona i dilatacije je linearno-elastična sve dok se ne postigne vrednost napona tečenja σ_{c0} . Tokom plastifikacije, odgovor se karakteriše ojačanjem napona, koje je potom praćeno omekšanjem dilatacije nakon dostizanja čvrstoće betona pri pritisku σ_{cu} [1].

3 EKSPERIMENTALNO ISPITIVANJE

U ovom radu su korišćeni eksperimentalni podaci laboratorijskih ispitivanja predstavljenih u [7], [8] i [10]. Predmet ovog istraživanja su konstrukcijski lakoagregatni betoni, pri čemu je akcenat stavljen na analizu najznačajnijih fizičko-mehaničkih svojstava svežeg i očvrslog betona. U tom istraživanju je predstavljeno pet različitih betonskih mešavina, pri čemu su u ovom radu korišćeni rezultati dobijeni od jedne mešavine, označene sa LLK-1.

Uzorci za koje je u ovom radu izvršeno poređenje eksperimentalnih i numeričkih rezultata spravljani su od lakog agregata na bazi ekspandirane gline „Leca-Laterlite“ (Italija). Upoređeni su rezultati ispitivanja čvrstoće betona na pritisak, kao i određivanja modula elastičnosti betona [7].

U Tabeli 1 date su količine komponentnih materijala korišćenih za spravljanje uzoraka za eksperimentalno ispitivanje i zapreminska masa betona za betonsku mešavinu LLK-1.

Due to the uniaxial tension, the stress-strain relation is linear-elastic until the tensile strength of σ_{t0} is reached. Reaching this stress value is treated as the beginning of the formation of micro cracks in concrete, which is represented by a decrease in stress, or by an increase in strains.

Due to uniaxial compression, the stress-strain relation is linear-elastic until the value of the yield stress σ_{c0} is reached. During the plastification, the response is characterized by the stress strengthening, which is then followed by softening the strain after reaching the concrete compressive strength σ_{cu} [1].

3 EXPERIMENTAL TESTING

In this paper, the experimental data of the laboratory tests presented in [7], [8] and [10] were used. The subject of this research was structural lightweight concrete, with the emphasis on the analysis of the most important physical and mechanical properties of fresh and hardened concrete. Five different concrete mixtures were presented in that study, while the results obtained from a single mixture, labelled as the LLK-1, were used in this paper.

Specimens for which the experimental and numerical results were compared in this paper were made from lightweight aggregate, which is based on the expanded clay "Leca-Laterlite" (Italy). The results of the concrete compressive strength tests as well as the determination of the modulus of elasticity of concrete were compared [7].

Table 1 lists the amounts of component materials used for the specimen mixtures for the experimental testing, as well as the density of the concrete for the LLK-1 concrete mixture.

Tabela 1. Karakteristike mešavine lakoagregatnog betona [7]
Table 1. Properties of the lightweight concrete mixture [7]

Oznaka Label	Cement Cement [kg/m ³]	Voda / Water [kg/m ³]		Agregat / Aggregate [kg/m ³]		Zapreminska masa betona Concrete density [kg/m ³]
		m _v	m _{v,dod}	Rečni 0/4 River 0/4	Leca-laterlite 4/15 Leca-laterlite 4/15	
LLK-1	450	180	15.3	940	333	1902

3.1 Konfiguracija 1: Određivanje čvrstoće betona pri pritisku

Čvrstoća betona pri pritisku određena je prema standardu SRPS ISO 4012 na uzorcima oblika kocke ivice 150 mm, starosti 28 dana, kao srednja vrednost čvrstoća dobijenih na tri uzorka. Brzina nanošenja opterećenja iznosila je 0.6 ± 0.2 MPa/s. Ispitivanje čvrstoće pri pritisku prikazano je na slici 2. Vrednost čvrstoće pri pritisku lakoagregatnog betona starosti 28 dana određena eksperimentalnim putem iznosi $f_{cu,28} = 50.6$ MPa [8].

Slika 2. Određivanje čvrstoće pri pritisku [8]
Figure 2. Determination of the compressive strength [8]

3.1 Configuration 1: Determination of the concrete compressive strength

The compressive strength of the concrete was determined according to the standard SRPS ISO 4012 on cube shaped specimens with the dimension of 150mm, 28 days old, as the mean value of the strengths obtained on three different specimens. The loading rate was 0.6 ± 0.2 MPa/s. The compressive strength test is shown in Fig. 2. The compressive strength of the 28-days-old lightweight concrete, determined experimentally, is $f_{cu,28} = 50.6$ MPa [8].

3.2 Konfiguracija 2: Određivanje modula elastičnosti betona

Određivanje statičkog modula elastičnosti urađeno je prema standardu SRPS ISO 6784 na uzorcima oblika cilindra prečnika 150 mm i visine 300 mm, starosti između 28 i 35 dana. Ispitivanje je sprovedeno na tri cilindra, a reprezentativna vrednost modula elastičnosti dobijenih merenjem napona i deformacija na svakom uzorku. Brzina nanošenja opterećenja iznosila je 0.6 ± 0.2 MPa/s. Deformacije su registrovane pomoću ekstenzometra tačnosti 0.001 mm s mernom bazom 200 mm. Gornja granica opterećenja ($\sigma_a \approx 1/3 \cdot f_{c,28}$) definisana je na osnovu prethodno određene čvrstoće betona pri pritisku, dok je donja granica opterećenja definisana na način da mora biti ostvarena deformacija od 0.01 mm. Ispitivanje uzoraka je izvršeno u dva ciklusa (serije opterećenja) [7].

Nakon izvršenih ciklusa opterećenja i rasterećenja, modul elastičnosti je određen na osnovu izraza:

3.2 Configuration 2: Determination of the concrete modulus of elasticity

The determination of the static modulus of elasticity was done according to the standard SRPS ISO 6784, on specimens of cylinder shape with the dimensions of 150mm in diameter and 300mm in height, between 28 and 35 days old. The test was conducted on three different cylinders, and the representative value of the modulus of elasticity was determined as the mean value of the modulus of elasticity obtained by measuring the stresses and strains on each specimen. The loading rate was 0.6 ± 0.2 MPa/s. Deformations were recorded using an extensometer of the accuracy of 0.001mm with a measuring base of 200mm. The upper load limit ($\sigma_a \approx 1/3 \cdot f_{c,28}$) was defined based on the pre-determined concrete compressive strength, while the lower load limit is defined in the way that the deformation of 0.01mm must be achieved. Specimen testing was performed in two cycles (load series) [7].

After the load-unload cycles have been completed, the modulus of elasticity is determined using the expression:

$$E = \frac{2 \cdot \Delta \sigma}{\Delta \varepsilon_{long}} \quad (1)$$

gde su $\Delta\sigma = \sigma_a - \sigma_b$ razlika čitanja napona usled maksimalne sile na presi (σ_a – napon usled maksimalne sile P_a na presi, σ_b – napon usled sile P_b koja izaziva nultu dilataciju), $\Delta\varepsilon_{long}$ registrovana dilatacija koja odgovara naponu $\Delta\sigma$, određena prema sledećem izrazu:

$$\Delta\varepsilon_{long} = \frac{(\Delta l_{long,a} - \Delta l_{long,b})}{200} \quad (2)$$

gde je $\Delta l_{long,a} - \Delta l_{long,b}$ izraženo u mm razlika izduženja usled napona σ_a i σ_b , a 200 mm je merna baza deformetra.

Ispitivanje modula elastičnosti prikazano je na slici 3. Vrednost modula elastičnosti lakoagregatnog betona određena eksperimentalnim putem iznosi $E = 23.21$ GPa [7].

where $\Delta\sigma = \sigma_a - \sigma_b$ is the difference in the stress readings due to the maximal force on the press (σ_a - stress due to maximal force P_a on the press, σ_b - stress due to force P_b that causes zero strain), $\Delta\varepsilon_{long}$ is registered strain corresponding to the stress $\Delta\sigma$, determined by the following expression:

where $\Delta l_{long,a} - \Delta l_{long,b}$ is expressed in mm as the difference in elongation due to the stresses σ_a and σ_b , and 200 mm is the measuring base of the deformer.

Experimental testing of the modulus of the elasticity is shown in Figure 3. The value of the modulus of elasticity of lightweight concrete determined experimentally is $E = 23.21$ GPa [7].

Slika 3. Određivanje statičkog modula elastičnosti [10]
Figure 3. Determination of the static modulus of elasticity [10]

4 NUMERIČKI MODELI

Numeričke analize sprovedene su u softveru Abaqus® [1], baziranom na metodi konačnih elemenata. Sprovedene su numeričke analize na dve različite konfiguracije modela: na modelu cilindra dimenzija $d/L = 150/300$ mm i na modelu kocke stranice 150 mm. Prilikom modeliranja, korišćeni su 3D konačni elementi oblika heksoedra, prosečne veličine 10 mm.

MKE model kocke korišćen je s ciljem upoređenja sa eksperimentalnim rezultatima ispitivanja čvrstoće betona pri pritisku. Model se sastoji od betonske kocke dimenzija stranica 150 mm i dve čelične ploče dimenzija $170 \times 170 \times 40$ mm. MKE model cilindra je korišćen radi upoređenja sa eksperimentalnim rezultatima određivanja modula elastičnosti betona. Model se sastoji od

4 NUMERICAL MODEL

Numerical analyses were performed in Abaqus® [1] software, based on the finite element method. Numerical analyses were performed on two different model configurations: on the cylinder model with dimensions $d/L = 150/300$ mm and on the 150 mm cube model. 3D finite element hexahedrons, average size of 10 mm, were used for the modelling.

The FEM model of the cube was used in order to compare with the experimental results of the concrete compressive strength tests. The model consists of the 150 mm cube and two $170 \times 170 \times 40$ mm steel plates. The FEM cylinder model was used for comparison with the experimental results of the determination of the concrete modulus of elasticity. The model consists of the concrete

betonskog cilindra dimenzija $d/L = 150/300$ mm i, kao u prethodnom slučaju, dve čelične ploče dimenzija $d/L = 160/40$ mm.

Čelične ploče, koje se nalaze sa gornje i donje strane betonskih uzoraka korišćene su u modelima radi što vernijeg prikaza realnog stanja, gde se kocka u hidrauličkoj presi oslanja s donje strane na čeličnu ploču, dok se opterećenje aplicira sa gornje strane, takođe preko čelične ploče. Ovim je omogućeno realnije modeliranje kontaktnih uslova između uzoraka i podloge. Debljina čeličnih ploča od 40 mm obezbeđuje dovoljnu krutost da njihove deformacije budu višestruko manje od deformacije betonskog uzorka.

U oba slučaja je model oslonjen površinski preko donje površine donje čelične ploče, na način da su sprečena pomeranja u sva tri pravca. Trodimenzionalni MKE modeli betonske kocke i cilindra prikazani su na slici 4.

cylinder with dimensions $d/L = 150/300$ mm and, as in the previous case, two steel plates with dimensions $d/L=160/40$ mm. Steel plates, located on the top and bottom of the concrete specimens, were used to achieve the real situation, where the cube in the hydraulic press is supported on the bottom on the steel plate, while the load is applied on the upper side, also via steel plate. This allows more realistic modelling of the contact conditions between the specimens and the pedestal. The steel plates thickness of 40mm provides sufficient rigidity for their deformation that should be several times lesser than the deformation of the concrete specimen. In both cases, the model rests over the lower surface of the lower steel plate, in the way that displacements in all three directions are prevented. Three-dimensional FEM models of concrete cube and cylinder are shown in Figure 4.

Slika 4. 3D prikaz modela: a) betonska kocka i b) betonski cilindar
Figure 4. 3D view of the model: a) concrete cube and b) concrete cylinder

4.1 Model ponašanja materijala

U modelu su korišćena dva tipa modela materijala: linearno-elastični model i elasto-plastični model (CDP model). Linearno-elastični model materijala korišćen je za potrebe modeliranja čeličnih ploča u obe konfiuracije. Ovakva pretpostavka ponašanja materijala je opravdana iz više razloga. Prvo, vrednost modula elastičnosti čelika (210 GPa) više je od devet puta veća od vrednosti modula elastičnosti razmatranog lakoagregatnog betona (23.21 GPa). Drugo, vrednosti napona dostignute u modelu višestruko su manje od granice proporcionalnosti čelika, stoga, čelik ni u jednom trenutku neće ući u plastičnu fazu rada.

CDP model materijala je korišćen za potrebe modeliranja betonskog cilindra i kocke. Ovaj model uvodi pretpostavku o nelinearnom ponašanju materijala. Veza napon-dilatacija lakoagregatnog betona pri pritisku je definisana prema [6] izrazom:

4.1 Material model

Two types of material models were used in the model: the linear-elastic model and the elasto-plastic model (CDP model). A linear-elastic material model was used for modelling steel plates in both configurations. This assumption of material behaviour is justified for several reasons. Firstly, the value of the modulus of elasticity of steel (210 GPa) is more than nine times higher than the value of modulus of elasticity of lightweight aggregate concrete (23.21 GPa). Secondly, the stress values reached in the model are several times lesser than the steel proportionality limit. Therefore, the steel will not enter the plastic phase of the operation at any time.

The CDP material model was used for the purpose of modelling the concrete cylinder and cube. This model introduces the assumption of nonlinear material behaviour. The stress-strain relationship of lightweight

concrete due to the compression is defined according to [6]:

$$\sigma = \frac{E_0 \varepsilon}{1 + \left(\frac{E_0}{E_s} - 2\right) \cdot \frac{\varepsilon}{\varepsilon_{cu}} + \left(\frac{\varepsilon}{\varepsilon_{cu}}\right)^\alpha} \quad (3)$$

gde su E_0 inicijalni modul elastičnosti, E_s sekantni modul elastičnosti koji odgovara maksimalnom naponu i odgovarajućoj dilataciji, ε_{cu} dilatacija koja odgovara maksimalnom naponu, a α parametar koji kontroliše oblik krive, čija je vrednost usvojena prema [6] i iznosi 1.5.

Ovde je pretpostavljeno da veza napon-dilatacija postaje nelinearna nakon dostizanja dilatacije od $5.5 \cdot 10^{-4}$, što odgovara naponu od 12.65 MPa.

Veza napon-dilatacija betona pri zatezanju usvojena je kao linearna do dostizanja vrednosti čvrstoće betona na zatezanje, nakon čega nastupa lom. Čvrstoća lakoagregatnog betona na zatezanje definisana je prema [3] izrazom:

$$f_t = 0.81 \cdot \left[\left(\frac{\rho_c}{\rho_0} \right)^{1.5} \cdot f'_c \right]^{0.35} \quad (4)$$

gde su ρ_c zapreminska masa lakoagregatnog betona, ρ_0 referentna vrednost zapreminske mase koja iznosi 2200 kg/m^3 , f'_c čvrstoća betona pri pritisku određena na cilindru $d/L = 150/300 \text{ mm}$.

Nakon što se u izraz (4) uvrste vrednosti zapreminske mase analiziranog betona (1902 kg/m^3), referentna vrednost zapreminske mase (2200 kg/m^3) i čvrstoća betona pri pritisku (39.7 MPa; vrednost dobijena množenjem čvrstoće betona pri pritisku određena na kocki dimenzija 150 mm i koeficijenta 0.79 koji predstavlja odnos čvrstoće pri pritisku cilindra ($d/L = 150/300 \text{ mm}$) i kocke ($a = 150 \text{ mm}$)), dobija se vrednost čvrstoće betona pri zatezanju od 2.72 MPa.

4.2 Konačni elementi

Za modeliranje problema u Abaqus® dostupni su 1D, 2D, 3D i drugi, specijalni, konačni elementi. U ovom radu korišćeni su trodimenzionalni (zapreminski; solid) KE. U zavisnosti od tipa i reda 3D elementa, softver nudi mogućnosti izbora od tetraedarnog elementa prvog reda sa 4 čvorova do heksaedarnog elementa drugog reda sa 27 čvorova. Čvorovi trodimenzionalnih elemenata imaju 3 stepena slobode, koja se odnose na tri moguće translacije u prostoru.

U ovom radu su korišćeni C3D8R konačni elementi (3D heksaedarni KE prvog reda sa 8 čvorova). Ovaj tip elementa koristi redukovanu integraciju za formiranje matrice krutosti, pri čemu je broj integracionih tačaka 1 [1].

4.3 Modeliranje kontakta

Stav da usled jednoosnog pritiska uzorak ne trpi nikakva ograničenja u smislu poprečnog deformisanja ne važi u zoni oslanjanja uzorka, već samo u zoni koja se može aproksimirati srednjom trećinom visine uzorka. U zonama oslanjanja, usled trenja koje se javlja na kon-

crete due to the compression is defined according to [6]:

where E_0 is the initial modulus of elasticity, E_s is the secant modulus of elasticity corresponding to the maximum stress and the corresponding strain, ε_{cu} is the strain corresponding to the maximum stress, and α is the parameter controlling the shape of the curve, whose value is adopted according to [6] and equals to 1.5.

Here, it is assumed that the stress-strain relationship becomes non-linear after reaching a strain of $5.5 \cdot 10^{-4}$, which corresponds to the stress of 12.65 MPa. The tension stress-strain relationship of the concrete is adopted as linear until the tensile strength of the concrete is reached, followed by failure. Tensile strength of lightweight concrete is defined according to [3]:

where ρ_c is the volume mass of lightweight concrete, ρ_0 is the reference mass density of 2200 kg/m^3 , f'_c is the tensile strength of the concrete determined on the cylinder $d/L = 150/300 \text{ mm}$.

The value of the concrete tensile strength of 2.72 MPa is obtained when the values of the bulk mass of the analyzed concrete (1902 kg/m^3), the reference value of the density (2200 kg/m^3) and the concrete compressive strength (39.7 MPa; the value obtained by multiplying the concrete strength at compression determined by the 150mm cube and coefficient 0.79 representing the ratio of the compressive strength of the cylinder ($d/L = 150/300 \text{ mm}$) and the cube ($a = 150 \text{ mm}$)) are incorporated in the expression (4).

4.2 Finite elements

1D, 2D, 3D and other special, finite elements are available for modelling in Abaqus®. Three-dimensional (solid) FEs were used in this paper. Depending on the type and order of the 3D element, the software offers choices from a 4-node tetrahedral element to a 27-node hexahedral element. Nodes of the three-dimensional elements have 3 degrees of freedom, which refer to three possible translations in space.

In this paper, C3D8R finite elements (3D first order hexahedral KE with 8 nodes) were used. This type of element uses reduced integration to form a stiffness matrix, with the number of integration points being 1 [1].

4.3 Contact modelling

The premise that due to the uniaxial compression the specimen fails to suffer any restrictions since transverse deformation does not apply in the area of support of the specimen, but only in the zone that can be approximated by the middle third of the height of the specimen. In the support zones, due to the friction occurring at the

taktima uzorak-ploča, dolazi do određenog ograničavanja bočnih deformacija uzoraka. Stoga, naponsko stanje će u tim zonama biti znatno složenije u odnosu na uslove aksijalnog pritiska.

Radi zadovoljenja ovog stava, kontakt između uzoraka (kocke; cilindra) i čeličnih ploča modeliran je koristeći tangencijalne i normalne komponente. Tangencijalnoj komponenti (trenje na spoju uzorak-ploča) dodeljena je vrednost koeficijenta trenja od 0.57, što predstavlja uobičajenu vrednost koeficijenta trenja između betona i čelika. Normalna komponenta je modelirana na način da se, kada su površine u kontaktu, može preneti bilo koji kontaktni pritisak između njih, pri čemu dolazi do razdvajanja kontaktnih površina ako kontaktni pritisak dostigne nultu vrednost. Drugim rečima, zatezanje na kontaktnoj površini nije dozvoljeno.

4.4 Definisane opterećenja

Opterećenje je u oba slučaja (ispitivanje na kocki i ispitivanje na cilindru) definisano kao jednakopodeljeno površinsko i deluje na gornjoj površini gornje čelične ploče.

Vremenske funkcije opterećenja za obe konfiguracije ispitivanja date su na slici 5. Nanošenjem opterećenja u intervalima od 100 s i 27 s aproksimirano je realno stanje u kojem se opterećenje koje izaziva napone u preseccima kocke i cilindra u iznosu od 50.3 MPa i 13.5 MPa nanosi brzinom od 0.6 ± 0.2 MPa/s.

specimen-plate contacts, there is some limitation of the lateral deformations of the specimens. Therefore, the stress state in these zones will be much more complex than the axial compression conditions.

The contact between specimens (cubes; cylinders) and steel plates was modelled using tangential and normal components to meet this argument. Coefficient of friction of 0.57 was assigned to the tangential component (friction at the specimen-steel plate surface), which is the common value of the friction coefficient between the concrete and steel. The normal component is modelled in the way that, when the surfaces are in contact, any contact compression between them can be transferred, whereby the contact surfaces are separated if the contact compression reaches zero. In other words, tension on the contact surface in normal direction is not allowed.

4.4 Load definition

The load is defined in both cases (cube test and cylinder test) as uniformly distributed surface load and acts on the upper surface of the upper steel plate.

The time load functions for both test configurations are given in Figure 5. Applying a load at 100 and 27 s intervals approximates the real state in which the load that causes stresses in the cube and cylinder sections of 50.3 MPa and 13.5 MPa, respectively, is applied at the rate of 0.6 ± 0.2 MPa/s.

Slika 5. Vremenska funkcija opterećenja betonske kocke (levo) i betonskog cilindra (desno)
Figure 5. Time function of the load of concrete cube (left) and concrete cylinder (right)

5 ANALIZA REZULTATA NUMERIČKOG MODELA

Sprovedene su nelinearne statičke analize za dve konfiguracije numeričkih modela. Za iterativno rešavanje sistema jednačina korišćena je Njutnova metoda, pri čemu je maksimalan broj inkremenata bio 100.

Rezultati nelinearne statičke analize dati su samo za deo numeričkog modela koji obuhvata betonske uzorke, budući da su čelične ploče u numeričkom modelu prisutne radi što vernijeg prikaza kontaktnih uslova u zoni kontakta sa uzorkom. Zbog svoje debljine i činjenice da imaju višestruko veći modul elastičnosti, kao i grancu tečenja, čelične ploče u svakom trenutku ostaju u elastičnoj fazi rada, te u ovom radu neće biti predmet razmatranja.

5 ANALYSIS OF THE RESULTS OF THE NUMERICAL MODEL

Nonlinear static analyses were performed for the two configurations of numerical models. Newton's method was used to iteratively solve the system of equations, with the maximum number of increments being 100.

The results of the nonlinear static analysis are given only for the part of the numerical model that includes concrete specimens, since the steel plates in the numerical model are present for the most accurate representation of the contact conditions in the contact zone with the specimen. Due to their thickness and the fact that their modulus of elasticity is several times larger, as well as the yield strength, steel plates remain in the elastic phase during the analysis, and will not be considered in this paper.

5.1 Konfiguracija 1

Rezultati modela kocke prikazuju pomeranja, napone i odgovarajuće dilatacije uzorka, kao i napone smicanja na kontaktu između uzorka i čelične ploče.

Na slici 6 prikazan je deformisan oblik uzorka u pogledu sa strane s vrednostima vertikalnog pomeranja, dok je na slici 7 prikazano bočno pomeranje uzorka u X pravcu.

Slika 6. Vertikalno pomeranje – deformisana i nedeformisana kontura [mm]

Figure 6. Vertical displacement - deformed and undeformed contour [mm]

Uočljivo je da se uzorak deformiše na način koji odgovara realnom stanju: budući da usled jednoosnog pritiska uzorak ne trpi nikakva ograničenja u smislu poprečnog deformisanja, on se slobodno deformiše u poprečnom pravcu u zoni srednje trećine uzorka. Približavanjem osloncima poprečna deformacija se smanjuje usled trenja koje se javlja na kontaktima uzorak-ploča. Maksimalno vertikalno pomeranje uzorka iznosi: $U_2 = 0.8124 \text{ mm} - 0.0137 \text{ mm} = 0.7987 \text{ mm}$.

Na slici 8 prikazani su naponi i odgovarajuće dilatacije u podužnom pravcu kocke (po visini).

a)

Slika 7. Bočno pomeranje u X pravcu [mm]

Figure 7. Lateral displacement in the X direction [mm]

It is noticeable that the specimen deforms in the way that corresponds to the real state: since, due to uniaxial compression, the specimen does not suffer any restrictions in terms of transverse deformation. It freely deforms in the transverse direction in the zone of the middle third of the specimen. When approaching the supports, the transverse deformation is reduced due to the friction that occurs on the specimen-plate contacts. The maximum vertical displacement of the specimen is: $U_2 = 0.8124 \text{ mm} - 0.0137 \text{ mm} = 0.7987 \text{ mm}$.

Figure 8 shows the stresses and corresponding strains in the longitudinal direction of the cube (in height).

b)

Slika 8. Polovina uzorka (horizontalni presek): a) napon S22 [MPa] i b) dilatacija E22
Figure 8. Half of the specimen (horizontal section): a) stress S22 [MPa] and b) strain E22

Slike 9 i 10 daju prikaz napona i odgovarajućih dilatacija u preostala dva ortogonalna pravca u

Figures 9 and 10 show the stresses and corresponding strains in the remaining two orthogonal

poprečnom preseku (po visini) kocke. Ovde se uočava jasno izražena granica između zategnutog i pritisnutog i dela betonske kocke, koji zauzima prostorni X-oblik. Ovakav oblik loma posledica je sila trenja na kontaktu sa čeličnim pločama, koje deluju tako da „utežu” beton. Utegnuti deo betona je oblika klina u donjem i gornjem delu kocke, koji deluje na način da istiskuje okolni zategnuti beton nakon dostizanja čvrstoće betona na zatezanje i formiranja prvih prslina.

Veće vrednosti napona u unutrašnjosti kocke posledica su „utegnutosti” betona, odnosno činjenice da beton bliži spoljašnjosti sprečava bočne deformacije betona u unutrašnjosti kocke.

Slika dilatacija prati sliku napona. Maksimalne dilatacije na spoljašnjoj strani imaju vrednosti $3.150 \cdot 10^{-3}$ i $-5.547 \cdot 10^{-3}$ a u unutrašnjosti $3.494 \cdot 10^{-3}$ i $-7.160 \cdot 10^{-3}$.

directions in the cross-section (vertical section) of the cube. Here, a clear distinction is made between the tensiled and the compressed sections of the concrete cube, which occupies a spatial X-shape. This type of failure occurs due to the friction forces on contact with the steel plates, which confine the concrete. The confined part of the concrete is a wedge-shaped part in the lower and upper parts of the cube, which acts in such a way to squeeze out the surrounding tensiled concrete after reaching the tensile strength of the concrete and formation of the first cracks.

Higher values of stress inside the cube are due to the confinement of the concrete, i.e. the fact that the concrete closer to the outside prevents lateral deformation of the concrete inside the cube.

The strain pattern follows the stress pattern. The maximal strains on the outside are $3.150 \cdot 10^{-3}$ and $-5.547 \cdot 10^{-3}$ and on the inside are $3.494 \cdot 10^{-3}$ and $-7.160 \cdot 10^{-3}$.

Slika 9. Polovina uzorka (vertikalni presek): a) napon S11 [MPa] i b) dilatacija E11
Figure 9. Half of the specimen (vertical section): a) stress S11 [MPa] and b) strain E11

Slika 10. Polovina uzorka (vertikalni presek): a) napon S33 [MPa] i b) dilatacija E33
Figure 10. Half of the specimen (vertical section): a) stress S33 [MPa] and b) strain E33

Na slici 11 prikazani su naponi u ravni kontakta kocke i čelične ploče s gornje strane

Figure 11 shows the stresses in the contact surface between the cube and the steel plate on the upper side.

Slika 11. Napon smicanja [MPa] na kontaktu između betonske kocke i čelične ploče:
a) u X pravcu i b) u Y pravcu
Figure 11. Shear stress [MPa] on contact between concrete cube and steel plate:
a) in the X direction and b) in the Y direction

5.2 Konfiguracija 2

Rezultati modela cilindra prikazuju pomeranja uzorka u vertikalnom i bočnom pravcu, napone u pravcu poduže ose cilindra i odgovarajuće dilatacije, dilatacije u poprečnim pravcima kao i napone smicanja na kontaktu između uzorka i čelične ploče.

Na slici 12 prikazan je deformisan oblik uzorka u pogledu sa strane s vrednostima vertikalnog pomeranja, dok je na slici 13 prikazano bočno pomeranje uzorka u X pravcu.

Slika 12. Vertikalno pomeranje – deformisana i nedeformisana kontura [mm]
Figure 12. Vertical displacement - deformed and undeformed contour [mm]

5.2 Configuration 2

The results of the cylinder model show the displacements of the specimen in the vertical and lateral directions, the stresses in the longitudinal direction of the cylinder axis and the corresponding strains, the strains in the transverse directions, and the shear stresses at the contact between the specimen and the steel plate.

Figure 12 shows the deformed shape of the specimen in the side view with the values of the vertical displacement, while Figure 13 shows the lateral displacement of the specimen in the X direction

Slika 13. Bočno pomeranje U1 [mm]

Figure 13. Lateral displacement U1 [mm]

Može se zapaziti sličnost u pogledu oblika deformacije uzoraka cilindra i kocke: slobodna poprečna defor-

The similarity may be observed with respect to the deformation patterns of the cylinder and cube speci-

macija cilindra usled jednoosnog pritiska u zoni srednje trećine uzorka. Približavanjem osloncima poprečna deformacija smanjuje se usled trenja koje se javlja na kontaktima uzorak-ploča. Maksimalno vertikalno pomeranje uzorka iznosi: $U_2 = 0.2482 \text{ mm} - 0.0027 \text{ mm} = 0.2455 \text{ mm}$.

Na slici 14 dati su slika i vrednosti napona u podužnom pravcu cilindra, na jednoj polovini uzorka i na celom uzorku. Slike 15 i 16 daju prikaz slike i vrednosti podužnih i poprečnih dilatacija uzorka.

mens: free transverse deformation of the cylinder due to uniaxial compression in the mid-third zone of the specimen. When approaching the supports, the transverse deformation is reduced due to the friction that occurs on the specimen-plate contacts. The maximum vertical displacement of the specimen is: $U_2 = 0.2482 \text{ mm} - 0.0027 \text{ mm} = 0.2455 \text{ mm}$.

Figure 14 shows the pattern and the values of the stress in the longitudinal direction of the cylinder, on the one half of the specimen and on the entire specimen. Figures 15 and 16 show the pattern and values of the longitudinal and transverse strains of the specimen.

a)

b)

Slika 14. Napon S22: a) polovina uzorka i b) ceo uzorak
Figure 14. Stress S22: a) half of the specimen and b) whole specimen

Slika 15. Dilatacija E22
Figure 15. Strain E22

Slika 16. Dilatacija E11
Figure 16. Strain E11

Maksimalan napon na spoljašnjoj strani cilindra iznosi 15.09 MPa, a u unutrašnjosti cilindra 15.91 MPa. Vrednosti napona pritiska u unutrašnjosti cilindra veće su u odnosu na spoljašnje delove zbog istog razloga opisanog u prethodnoj konfiguraciji.

I ovde, kao i u prethodnoj konfiguraciji, slika dilatacija prati sliku napona. Maksimalna dilatacija na spoljašnjoj strani cilindra iznosi $8.336 \cdot 10^{-4}$, a u unutrašnjosti $8.733 \cdot 10^{-4}$.

Na slici 17 prikazani su naponi u ravni kontakta cilindra i čelične ploče s gornje strane.

The maximal stress on the outside of the cylinder is 15.09 MPa and 15.91 MPa on the inside of the cylinder. The compression values inside the cylinder are higher than the outer parts for the same reason described in the previous configuration.

Here, as in the previous configuration, the strain pattern follows one of the stress. The maximum strain on the outside of the cylinder is $8.336 \cdot 10^{-4}$ and $8.733 \cdot 10^{-4}$ on the inside.

Figure 17 shows the stresses in the contact surface between the cylinder and the steel plate on the upper side.

Slika 17. Napon smicanja [MPa] na kontaktu između betonskog cilindra i čelične ploče (polovina uzorka):

a) u X pravcu i b) u Y pravcu

Figure 17. Shear stress [MPa] at the contact between the concrete cylinder and the steel plate (half of the specimen): a) in the X direction and b) in the Y direction

5.3 Rekapitulacija rezultata

U Tabeli 2 prikazani su najznačajniji rezultati laboratorijskih ispitivanja i numeričkih analiza.

5.3 Result summary

Table 2 shows the most significant results of the experimental testing and the numerical analyses.

Tabela 2. Rekapitulacija rezultata numeričkih analiza

Table 2. Recapitulation of numerical analysis results

	Konfiguracija 1 / Configuration 1		Konfiguracija 2 / Configuration 2	
	Laboratorijski uzorak <i>Experimental specimen</i>	Numerički model <i>Numerical model</i>	Laboratorijski uzorak <i>Experimental specimen</i>	Numerički model <i>Numerical model</i>
Maksimalno vertikalno pomeranje U_2 [mm] <i>Maximum vertical displacement U_2 [mm]</i>	/	0.7987	0.218	0.245
Dilatacija na spoljašnjosti uzorka / <i>Strain on the outside of the specimen</i>	/	$3.150 \cdot 10^{-3}$ $-5.547 \cdot 10^{-3}$	$1.10 \cdot 10^{-3}$	$8.336 \cdot 10^{-4}$
Maksimalan napon [MPa] <i>Maximum stress [MPa]</i>	-50.6	-51.29 (spoljašnja strana uzorka) <i>-51.29 (on the outer side of the specimen)</i>	/	-15.14 (spoljašnja strana uzorka) <i>-15.14 (on the outer side of the specimen)</i>

Maksimalan napon [MPa] Maximum stress [MPa]	-50.6	-96.97 (unutrašnja strana uzorka) -96.97 (in the inside of the specimen)	/	-16.12 (unutrašnja strana uzorka) -16.12 (in the inside of the specimen)
--	-------	---	---	---

6 ZAKLJUČAK

Eksperimentalni podaci laboratorijskih ispitivanja predstavljenih u [7], [8] i [10] poslužili su kao osnova za formiranje MKE modela ponašanja lakoagregatnog betona. Eksperimentom su određeni čvrstoća betona pri pritisku i modul elastičnosti betona starosti 28 dana za nekoliko različitih mešavina, dok je numeričkom analizom obuhvaćena jedna mešavina (LLK-1). Ponašanje betona kao materijala obuhvaćeno je tzv. concrete damage plasticity (CDP) modelom. Sprovedena je statička nelinearna (inkrementalno-iterativna) analiza za dve konfiguracije modela, po jedna za ispitivanje čvrstoće betona pri pritisku i određivanje modula elastičnosti betona. Prva konfiguracija modela sadrži kocku dimenzija 150 x 150 x 150 mm, a druga cilindar dimenzija d/L = 150/300 mm. Potom su analizirani rezultati proračuna i izvučeni su sledeći zaključci:

- Ponašanje betonske kocke u MKE analizi blisko je ponašanju kocke tokom laboratorijskog ispitivanja. Naime, kao i u eksperimentu, i u numeričkom modelu je jasno izražen oblik, tj. mehanizam loma uzorka. Ovaj oblik zauzima prostorni X-oblik, budući da se usled sila trenja na kontaktu sa čeličnim pločama obrazuje utegnuti deo betona oblika klina koji deluje na način da istiskuje okolni zategnuti beton nakon dostizanja čvrstoće betona na zatezanje i formiranja prvih prslina. Pritisnuti beton ovde je već pomenutog X-oblika, dok se u betonu bližem spoljašnjim stranama javlja zatezanje, pa je jasno uočljiva i granica između zona ova dva naponska stanja. Upravo se na ovoj granici javljaju prsline koje će narušiti integritet uzorka i diktirati oblik loma.

- Rezultati numeričkog modela u celokupnom pogledu ukazuju na poklapanje sa eksperimentalnim rezultatima. Međutim, neophodna su dalja, finija podešavanja MKE modela, pre svega modela ponašanja betona, radi potpune kompatibilnosti sa eksperimentalnim podacima.

- Ponašanje betonskog cilindra u MKE analizi, kao i u slučaju betonske kocke, blisko je ponašanju cilindra tokom laboratorijskog ispitivanja. Skraćenje cilindra u MKE modelu u iznosu od 0.245 mm veoma je blisko prosečnom skraćenju cilindra u eksperimentu, koje iznosi 0.218 mm, pri istom nivou opterećenja.

- Deformacija cilindra u MKE modelu približno odgovara realnom stanju, gde usled jednoosnog pritiska u zoni srednje trećine uzorka, uzorak ne trpi nikakva ograničenja u smislu poprečnog deformisanja, te se on slobodno deformiše u poprečnom pravcu. U zoni kontakta sa čeličnim pločama, poprečna deformacija smanjuje se usled trenja koje se javlja na kontaktima uzorak-ploča.

- Takođe, dilatacija na spoljašnjoj strani cilindra, u srednjoj trećini visine, u MKE modelu ima vrednost od $0.85 \cdot 10^{-3}$, dok je u toj istoj zoni u eksperimentu registrovana dilatacija od $1.10 \cdot 10^{-3}$.

- Veće vrednosti napona u unutrašnjosti cilindra (15.91 MPa) u odnosu na vrednosti napona na

6 CONCLUSIONS

The experimental data from the laboratory tests presented in [7], [8] and [10] served as the basis for the formation of the FEM model of the behaviour of the lightweight concrete. The experiment determined the compressive strength of the concrete and the modulus of elasticity of concrete at 28 days of age for several different mixtures, while numerical analysis included one mixture (LLK-1). The behaviour of concrete as a material was accounted by the concrete damage plasticity (CDP) model. The static nonlinear (incremental-iterative) analysis was conducted for two model configurations, one for the determination of the compressive strength of concrete and the other for the determination of the modulus of elasticity of concrete. The first configuration of the model consists of the cube measuring 150x150x150 mm and the second one of the cylinder d/L = 150/300mm. The results of the numerical analyses were analyzed and the following conclusions were drawn:

- Concrete cube behaviour in FEM analysis is close to cube behaviour during laboratory testing. Namely, as in the experiment, the failure mechanism pattern is clearly expressed in the numerical model as well. This shape takes the spatial X-shape, since due to the friction forces on the contact with the steel plates, a wedge-shaped portion of concrete is formed, which acts to squeeze out the surrounding tensiled concrete after reaching the tensile strength and forming the first cracks. The compressed concrete has aforementioned X-shape, while in the concrete closer to the outside the tension occurs, so that the boundary between the zones of these two stress states is clearly visible. It is at this border that cracks appear that will impair the integrity of the specimen and dictate the shape of the failure.

- The results of the numerical model in the overall view indicate a congruence with the experimental results. However, further fine-tuning of the FEM model, especially the concrete behaviour model, is required in order to be fully compatible with the experimental data.

- The behaviour of the concrete cylinder in the FEM analysis is, as in the case of the concrete cube, close to the behaviour of the cylinder during laboratory testing. The 0.245 mm cylinder shortening in the FEM model is very close to the average cylinder shortening in the experiment, which is amounted to 0.218 mm, at the same load level.

- The deformation of the cylinder in the FEM model approximates the real state, where due to uniaxial compression in the middle third zone of the specimen, the specimen fails to suffer any restrictions in terms of transverse deformation, and it deforms freely in the transverse direction. In the contact zone with the steel plates, the transverse deformation is reduced due to the friction that occurs on the specimen-plate contact surface.

- In addition, the strain on the outside of the cylinder,

spoljašnjoj strani cilindra (15.09 MPa) u MKE modelu su posledica „utegnutosti“ betona, odnosno činjenice da beton bliži spoljašnjosti sprečava bočne deformacije betona u unutrašnjosti cilindra. Takođe, razlozi za veće vrednosti napona u MKE modelu u odnosu na eksperiment mogu se tražiti u činjenici da je prilikom eksperimenta napon određen kao količnik ukupne sile i površine poprečnog preseka cilindra, dok je u MKE analizi cilindar posmatran kao trodimenzionalno telo, s mogućnošću obuhvatanja u obzir triaksnog stanja pritiska.

ZAHVALNOST

U radu je prikazan deo istraživanja koje je pomoglo Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije u okviru tehnološkog projekta TR 36017 pod nazivom: „Istraživanje mogućnosti primene otpadnih i recikliranih materijala u betonskim kompozitima, sa ocenom uticaja na životnu sredinu, u cilju promocije održivog građevinarstva u Srbiji“.

7 LITERATURA

- [1] Abaqus Analysis User's Guide, 2016
- [2] Alfarah B., López-Almansa F., Oller S.: New methodology for calculating damage variables evolution in Plastic Damage Model for RC structures, *Engineering Structures* 132, 2017, 70-86.
- [3] Choi S., Yang K., Sim J., Choi B.: Direct tensile strength of lightweight concrete with different specimen depths and aggregate sizes, *Construction and Building Materials* 63, 2014, 132-141.
- [4] Cicekli U., Vojadjijs G., Al-Rub R.: A plasticity and anisotropic damage model for plain concrete, *International Journal of Plasticity* 23, 2007, 1874-1900.
- [5] Grassi P., Xenos D., Nystrom U., Rempling R., Gylltoft K.: CDPM2: A damage-plasticity approach to modelling the failure of concrete, *International Journal of Solids and Structures* 50, 2013, 3805-3816.
- [6] Han B., Xiang T.: Axial compressive stress-strain relation and Poisson effect of structural lightweight aggregate concrete, *Construction and Building Materials* 146, 2017, 338-343.
- [7] Malešev M., Radonjanin V., Lukić I., Bulatović V.: The effect of aggregate, type and quantity of cement on modulus of elasticity of lightweight aggregate concrete, *Arabian Journal for Science and Engineering* 39, 2014, 705-711.
- [8] Malešev M., Radonjanin V., Lukić I., Bulatović V.: Basic properties and possibilities of use of structural lightweight aggregate concrete with aggregate from industrial waste materials - Part 1, 12th International Scientific Conference iNDiS 2012, 28-30 November 2012, Novi Sad, Serbia, 634-645.
- [9] Poliotti M., Bairan J.M.: A new concrete plastic-damage model with an evolutive dilatancy parameter, *Engineering structures* 189, 2019, 541-549.
- [10] Radonjanin V., Malešev M., Lukić I., Bulatović V.: Basic properties and possibilities of use of structural lightweight aggregate concrete with aggregate from industrial waste materials - Part 2, 12th International Scientific Conference iNDiS 2012, 28-30 November 2012, Novi Sad, Serbia, 646-657.
- [11] Wang X., Zhanga M., Jivkov P.A.: Computational technology for analysis of 3D meso-structure effects on damage and failure of concrete, *International Journal of Solids and Structures* 80, 2016, 310-333.

in the middle third of the height, has a value of $0.85 \cdot 10^{-3}$ in the FEM model, while a strain of $1.10 \cdot 10^{-3}$ was registered in the same zone in the experiment. Higher values of stress inside the cylinder (15.91 MPa) compared to the stress values on the outside of the cylinder (15.09 MPa) in the FEM model are due to the confinement of the concrete, i.e. the fact that the concrete closer to the outside prevents lateral deformation of the concrete inside the cylinder. In addition, the reasons for higher stress values in the FEM model compared to the experiment can be found in the fact that in the experiment the stress was determined as a quotient of the total force and the cross-sectional area of the cylinder, while in the FEM analysis the cylinder was considered as a three-dimensional body, with the possibility of consideration of the triaxial compression state.

ACKNOWLEDGEMENTS

The paper has been prepared within the scientific research project TR 36017 "Utilization of by-products and recycled waste materials in concrete composites in the scope of sustainable construction development in Serbia: investigation and environmental assessment of possible applications ", which is funded by the Ministry of Science of Serbia.

REZIME

NUMERIČKA SIMULACIJA PONAŠANJA UZORAKA OD LAKOAGREGATNOG BETONA U SLUČAJEVIMA LABORATORIJSKOG ISPITIVANJA

Vladimir ŽIVALJEVIĆ
Vlastimir RADONJANIN
Ivan LUKIĆ
Dušan KOVAČEVIĆ

U ovom radu prikazano je numeričko modeliranje eksperimentalnog određivanja čvrstoće lakoagregatnog betona pri pritisku i statičkog modula elastičnosti primenom metode konačnih elemenata (MKE). U okviru teorijskog pregleda predstavljen je i opisan CDP (concrete damage plasticity) model ponašanja betona. Numeričko modeliranje i nelinearni statički (inkrementalno-iterativni) proračuni rađeni su za dve različite konfiguracije primenom softvera Abaqus®. Prva konfiguracija modela obuhvata eksperimentalno određivanje čvrstoće betona pri pritisku betonske kocke, a druga određivanje statičkog modula elastičnosti na betonskom cilindru. Trodimenzionalnim MKE modelima uzete su u obzir i čelične ploče, koje se nalaze s gornje i donje strane uzorka i služe za oslanjanje, odnosno apliciranje opterećenja, čime su na realan način obuhvaćeni kontakti uslovi betonskih uzoraka sa opremom za ispitivanje.

Ključne reči: concrete damage plasticity model, lakoagregatni beton, numerička simulacija, čvrstoća pri pritisku, modul elastičnosti

ABSTRACT

NUMERICAL SIMULATION OF THE BEHAVIOUR OF THE LIGHTWEIGHT CONCRETE SPECIMEN IN THE LABORATORY TESTING

Vladimir ŽIVALJEVIĆ
Vlastimir RADONJANIN
Ivan LUKIĆ
Dusan KOVACEVIC

This paper presents the numerical modelling of the experimental determination of the compressive strength and the static modulus of elasticity of the lightweight concrete using the finite element method (FEM). In the theoretical review, a concrete damage plasticity (CDP) model of the concrete behaviour is described. Numerical modelling and nonlinear static (incremental-iterative) analyses were performed for two different configurations using the Abaqus® software. The first configuration of the model considers the experimental determination of the concrete compressive strength of the concrete cube, and the second one the determination of the static modulus of elasticity on the concrete cylinder. Steel plates in the three-dimensional FEM models located on the upper and lower sides of the specimens, which serve as the support or for the load application, thus capturing the contact conditions of concrete specimens with testing equipment more realistically, have also been taken into account.

Key words: concrete damage plasticity model, lightweight concrete, numerical simulation, compressive strength, modulus of elasticity