ANALIZA ŠIRINE PUKOTINA GREDA OD MIKROARMIRANOG BETONA SA ČELIČNIM VLAKNIMA

CRACK WIDTH ANALYSIS OF STEEL FIBERS REINFORCED CONCRETE BEAMS

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1 UVOD

Radi poboljšanja svojstava betonskih elemenata i konstrukcija, sprovedena su brojna istraživanja s dodacima organskih i neorganskih vlakana betonskim mješavinama. Sa ovim dodacima, poboljšana su svojstva kao što su čvrstoća pri zatezanju, čvrstoća pri savijanju, žilavost, dinamička čvrstoća i tako dalje. U posljednje vrijeme, beton ojačan vlaknima (Fiber Reinforced Concrete – FRC) ima široku primjenu kod različitih konstrukcija i konstruktivnih elemenata kao što su: tunelske cijevi, prefabrikovani segmenti, prskani beton, industrijski podovi, željeznički pragovi i tako dalje. Jedna od najpopularnijih vlakana u upotrebi jesu čelična vlakna, te se takav beton zove beton ojačan čeličnim vlaknima (Steel Fiber Reinforced Concrete – SFRC). Dodavajući čelična vlakna mješavini betona, svojstva betonskih elemenata prije stvaranja pukotina neće se bitno mijenjati, ali se vrlo mijenja postpukotinsko ponašanje takvih elemenata [7].

U slučaju krutih materijala kao što je beton, pukotine se javljaju za relativno niske vrijednosti opterećenja (savijanje). Ovo se može objasniti činjenicom da kruti materijali imaju veoma nisku mogućnost apsorbovanja energije, što je rezultat malih deformacija koje mogu podnijeti [2]. Prisustvo čeličnih vlakana poboljšava apsorpciju totalne energije, gdje vlakna apsorbiraju energiju deformisanjem i čupanjem.

1 INTRODUCTION

In order to improve the properties of concrete elements and constructions, numerous studies have been carried out with the addition of organic and inorganic fibers to concrete mixtures. With these additions properties such as tensile strength, flexural strength, toughness, dynamic strength etc. have been improved. Recently, Fiber Reinforced Concrete (FRC) is widely used in various constructions and constructive elements such as: tunnel linings, prefabricated segments, shotcrete, industrial floors, railway sleepers and so on. One of the most popular fibers are steel fibers, and such concrete is called Steel Fiber Reinforced Concrete (SFRC). By adding steel fibers to a concrete mixture, the properties of concrete elements before cracking will change insignificantly, but the post-cracking behaviour of such elements considerably changes [7].

For brittle materials such as concrete, cracks occur for relatively low loading values (bending). This can be explained by the fact that brittle materials have very low ability to absorb energy, which is the result of small deformations that they can bear [2]. The presence of steel fibers improves the absorption of total energy, where the fibers absorb energy by deforming and pulling out.

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Očigledno, pojava pukotina je neminovna. Čelična vlakna ne mogu spriječiti formiranje pukotina, ali mogu ih smanjiti [15]. Studije pokazuju da postoji veliki uticaj dodatka čeličnih vlakana mješavini na širinu pukotina kod betonskih elemenata. Smanjenje širine pukotina ovisi o tipu i vrsti čeličnog vlakna, te o količini (procentu) vlakana u mješavini. Ali čak i u slučaju malog procenta čeličnih vlakana, primijećeno je smanjenje širine pukotina betonskog elementa [17,7].

Klepša i dr. [10] ispitivali su širinu i razmak pukotina kod greda od običnog betona i betona s dodatkom 30 kg/m³ čeličnih vlakana. Nakon pojave velikih pukotina, registrirano je povećanje širine pukotina kod greda bez vlakana u poređenju s gredama s vlaknima za oko deset puta. Šalna i Marčiukaitis [16] sproveli su istraživanje uticaja čeličnih vlakana kod betonskih greda s različitim rasponima. Grede su sadržavale 1.0, 1.5 i 2.0% čeličnih vlakana i pokazano je da grede sa 2.0% čeličnih vlakana imaju skoro tri puta manju širinu pukotina nego grede sa 1.0% vlakana za prosječno opterećenje. Nadalje, pokazano je da se grede sa 2.0% čeličnih vlakana imaju 32% veću silu pri lomu nego grede sa 1.0% čeličnih vlakana. Vasanelli i dr. [17] istraživali su uticaj vrste i količine vlakana na širinu pukotina armirano-betonskih greda. Grede koje su sadržavale 0.6% čeličnih vlakana za karakterističnu silu pokazale su 42% manju vrijednost širine pukotina od greda bez vlakana. Dupont i Vandewalle [7] ispitivali su uticaj dodatka čeličnih vlakana različitih količina i profila glavne armature na širinu pukotina armirano-betonskih greda. Pokazano je da se povećanjem količine čeličnih vlakana – širina pukotina smanjuje, a rezultati su izražajniiji za manje profile glavne armature, što je i očekivano. Prosječno smanjenje širine pukotina za grede s maksimalnom količinom vlakana od 60 kg/m³ za srednje vrijednosti momenata savijanja jeste oko 70% u odnosu na grede bez vlakana. Ispitivanja širine pukotina još uvijek predstavljaju predmet interesa istraživača, pošto njihovo ponašanje u betonskim elementima još uvijek nije u potpunosti istraženo [5, 9].

U ovom radu predstavljeni su rezultati i analiza eksperimentalnog istraživanja širine i formiranja pukotina kod betonskih greda sa čeličnim vlaknima. Proračun graničnog stanja pukotina (raspucavanja) ima zadaću da ograniči širinu pukotina betonskih elemenata, radi sprječavanja propadanja betonskih konstrukcija, koje je veoma često rezultat korozije uslijed curenja tečnosti i gasova kroz široke pukotine betonskih elemenata. Analiziran je uticaj dodatka čeličnih vlakana na širinu pukotina armiranih betonskih greda opterećenih do loma kratkotrajnim ultimnim statičkim opterećenjem s jednim ciklusom rasterećenja. Grede su izrađene od dvije vrste betona: betona obične čvrstoće (OSC) – C30/37 i betona visoke čvrstoće (HSC) – C60/70, sa 0,45% čeličnih vlakana i bez njih.

2 EKSPERIMENTALNO ISTRAŽIVANJE

2.1 Materijali

U eksperimentalnom istraživanju korištene su dvije vrste betona – beton obične čvrstoće (OSC) – C30/37 i beton visoke čvrstoće (HSC) – C60/70 (tabela 1). Obe vrste betona spravljane su sa 0,45% čeličnih vlakana i bez njih. Korištena čelična vlakna su tipa IRI 50/30

Obviously, the crack appearance is inevitable. Steel fibers cannot prevent the crack formation, but they can reduce it. Studies show that there is a high influence of steel fiber addition to a concrete mixture to the crack width in concrete elements. Crack width reduction depends on the type of steel fibers and quantity (percentage) in mixture. But even with a small percentage of steel fibers, the crack width reduction was noticed [17, 7].

Klepša et al. [10] investigated the crack width and spacing for beams of ordinary concrete and concrete with the addition of 30 kg/m³ of steel fibers. After the appearance of large cracks, the crack width for beams of ordinary concrete were increased about ten times. Šalna and Marčiukaitis [16] conducted the study of influence of steel fibers for concrete beams with different spans. The beams consisted of 1.0, 1.5 and 2.0% of steel fibers and it has been shown that beams with 2.0% steel fibers have almost 3 times lower crack width compared to beams with 1.0% fibers for average load. Furthermore, it has been shown that beams with 2.0% steel fibers have 32% greater load capacity compared to beams with 1.0% steel fibers. Vasanelli et al. [17] investigated the influence of the fiber type and quantity on the crack width of reinforced concrete beams. Beams containing 0.6% of steel fibers showed 42% less cracks width compared to beams without fibers for characteristic force. Dupont and Vandewalle [7] investigated the effect of the steel fibers addition of different quantities and main reinforcement profiles to the crack width of reinforced concrete beams. It has been shown that by increasing the amount of steel fibers the crack width is reduced, and the results are more pronounced for smaller profiles of the main reinforcement, as expected. The average reduction of the crack width for beams with a maximum of 60 kg/m³ of fibers for the mean values of bending moments is about 70% compared to the beams without fibers. Crack width analysis is still in focus of research, as the behaviour of concrete elements is insufficiently explored [5, 9].

In this paper the experimental results and analysis of crack width and crack formation in concrete beams with steel fibers are presented. Calculation of crack ultimate limit state (cracking) has the purpose to limit the crack width of concrete elements, with the aim to prevent deterioration of concrete structures, which is often a result of corrosion due to the flow of liquids and gases through large cracks in concrete elements. The effect of the steel fibers addition to the crack width of reinforced concrete beams loaded with a short-term ultimate static load with a single unload cycle was analysed. The beams were made of two types of concrete: ordinary strength concrete (OSC) – C30/37 and high strength concrete (HSC) – C60/70, with and without 0.45% of steel fibers.

2 EXPERIMENTAL RESEARCH

2.1 Materials

In the experimental research two types of concrete were used: ordinary strength concrete (OSC) – C30/37 and high strength concrete (HSC) – C60/70 (table 1). Both types were made with and without 0.45% of steel fibers. Used steel fibers were type IRI 50/30 (VJ2),

(VJ2), dužine 30 mm i prečnika 0,50 mm, čvrstoće pri zatezanju 900 MPa. Tako da se u konačnici razmatraju četiri vrste betona: kontrolna mješavina običnog betona bez vlakana OSC, mješavina običnog betona sa čeličnim vlaknima FROSC, kontrolna mješavina betona visoke čvrstoće HSC, mješavina betona visoke čvrstoće sa čeličnim vlaknima FRHSC.

length 30 mm and diameter 0.50 mm, with tensile strength of 900 MPa. Therefore, four types of concrete were considered: control mixture of ordinary concrete without fibers OSC, mixture of ordinary concrete with steel fibers FROSC, control mixture of high strength concrete without fibers HSC, mixture of high strength concrete with steel fibers FRHSC.

*Tabela 1. Sastav betona obične i betona visoke čvrstoće
Table 1. Mixtures of ordinary and high strength concrete*

	C30/37	C60/75
Cement / <i>Cement</i>	360 kg/m ³ ; CEM I 42,5 R	414 kg/m ³ ; CEM I 42,5 R
Voda / <i>Water</i>	210 kg/m ³	158 kg/m ³
v/c odnos / <i>w/c ratio</i>	0,58	0,36
Agregat / <i>Aggregate</i>	1850 kg/m ³	1870 kg/m ³
I frakcija <i>I fraction (0/4)</i>	740 kg/m ³ (40%); riječni pijesak <i>river sand</i>	691,9 kg/m ³ (37%); riječni pijesak <i>river sand</i>
II frakcija <i>II fraction (4/8)</i>	407 kg/m ³ (22%); drobljenac <i>crushed stone</i>	467,5 kg/m ³ (25%); drobljenac <i>crushed stone</i>
III frakcija <i>III fraction (8/16)</i>	703 kg/m ³ (38%); drobljenac <i>crushed stone</i>	710,6 kg/m ³ (38%); drobljenac <i>crushed stone</i>
Mineralni dodaci <i>Mineral additives</i>	-	36 kg/m ³ ; Silicijska prašina sa 91% SiO ₂ , 8% u odnosu na masu cementa od 450kg/m ³ <i>36 kg/m³; Silica fume with 91% SiO₂, 8% compared to 450kg/m³ of cement</i>
Hemijski dodaci <i>Chemical additives</i>	-	5 kg/m ³ ; Superplastifikator, superfluid-21, 1,1% u odnosu na masu cementa od 450kg/m ³ <i>5 kg/m³; Superplasticizer, superfluid-21, 1,1% compared to 450kg/m³ of cement</i>

Prethodno su ispitane sledeće fizičko-mehaničke osobine svih mješavina na kontrolnim tijelima: čvrstoća pri pritisku, čvrstoća pri zatezanju cijepanjem, čvrstoća pri zatezanju savijanjem, te modul elastičnosti [13, 14]. Osobine su ispitane pri starosti kontrolnih tijela od t=35-40 dana i t=420-430 dana. Čvrstoća pri pritisku i čvrstoća pri zatezanju cijepanjem ispitane su na uzorcima oblika kocke 15x15 cm. Čvrstoća pri zatezanju savijanjem ispitana je na uzorcima oblika prizme 10x10x40 cm, a modul elastičnosti na uzorcima oblika valjka 15/30 cm. Ispitivanja su sprovedena prema JUS standardima. Srednje vrijednosti rezultata ispitivanja fizičko-mehaničkih osobina prikazane su u tabeli 2.

The physical – mechanical properties of all concrete mixtures were previously tested: compressive strength, splitting tensile strength, bending tensile strength and modulus of elasticity [13, 14]. Properties were tested for the concrete age of t=35-40 days and t=420-430 days. Compressive strength and splitting tensile strength were tested on cube samples 15x15 cm. Bending tensile strength was tested on prismatic samples 10x10x40 cm, and modulus of elasticity on cylinder samples 15/30 cm. Tests were conducted according to JUS standards. Average values of test results are presented in table 2.

*Tabela 2. Srednja vrijednost rezultata ispitivanja fizičko-mehaničkih osobina
Table 2. Average value of test results of physical - mechanical properties*

Vrsta i starost betona <i>Type and the age of concrete</i>		Osobina / <i>Property</i>			
		Čvrstoća pri pritisku <i>Compressive strength</i> [MPa]	Čvrstoća pri zatezanju cijepanjem <i>Splitting tensile strength</i> [MPa]	Čvrstoća pri zatezanju savijanjem <i>Bending tensile strength</i> [MPa]	Modul elastičnosti <i>Modulus of elasticity</i> [GPa]
OSC	35-40 dana/days	39,70	2,90	5,70	30,5
	420-430 dana/days	43,10	3,50	6,10	33,3
FROSC	35-40 dana/days	32,60	3,40	6,90	29,8
	420-430 dana/days	41,70	3,90	8,30	30,9
HSC	35-40 dana/days	84,40	5,30	9,30	39,5
	420-430 dana/days	95,80	5,40	9,30	41,2
FRHSC	35-40 dana/days	75,60	5,20	9,90	38,9
	420-430 dana/days	88,20	5,40	10,20	39,7

2.2 Grede

Ukupno je ispitano šesnaest greda. Sve grede su dimenzija u poprečnom presjeku 15x28 cm i dužine 300 cm (slika 1). Grede su podijeljene u četiri serije: A, F, G, H. Serije A i G jesu grede u slučaju kojih je ispitivano naponsko-deformacijsko stanje betona pri starosti od $t=35-40$ dana, dok su u slučaju serija F i H ispitivane grede pri starosti $t=420-430$ dana. Nadalje, sve serije su podijeljene na četiri podgrupe (1, 2, 3, 4), gdje podgrupe 1 i 2 predstavljaju običan beton, a podgrupe 3 i 4 beton visoke čvrstoće. Pregled greda po serijama dat je u tabeli 3. Grede su armirane podužnom armaturom S500 i vilicama klase 240, kako je pokazano na slici 1. Izabrane dimenzije greda i armature (podužna, poprečna i vlakna) odgovaraju primjenama u praksi. Izgled grede prije ispitivanja s mjernim uređajima, kao i način opterećenja prikazani su na slici 2.

Slika 1. Prikaz grede sa armaturom (mjere u cm)
Figure 1. Display of beam with reinforcement (measures in cm)

Pri ispitivanju greda na kratkotrajno opterećenje do loma s jednim ciklusom rasterećenja, grede su opterećene s dvije koncentrirane sile, na međusobnom rastojanju od 80 cm i na rastojanju od 100 cm od ležišta (slika 1.). Grede su opterećene sa stalnim opterećenjem jedne sile $F_G=4,00$ kN, koje je konstantno u periodu ispitivanja. Na to opterećenje, dodavano je eksploataciono opterećenje $F_Q=7,60$ kN. Ukupna sila opterećenja u tom trenutku jeste $F_{G+Q}=11,6$ kN. Nakon toga, sila je smanjena na vrijednost stalnog opterećenja. Posljednji nivo opterećenja za koje je vršeno očitavanje na svim gredama (ultimno) jeste vrijednost od $F_U=20,60$ kN, nakon čega se dodavalo opterećenje (sila) u jednakim inkrementima do loma.

2.2 Beams

In total 16 beams were tested. All beams are in cross section 15x28 cm and length 300 cm (figure 1). The beams are divided into four series: A, F, G, H. Series A and G are $t=35-40$ days of age, while F and G series were $t=420-430$ days. Furthermore, all series are divided into 4 subgroups (1, 2, 3, 4), where subgroups 1 and 2 represent ordinary strength concrete, and subgroups 3 and 4 high strength concrete. The beams' overview is presented in table 3. The beams are reinforced with longitudinal reinforcement S500 and stirrups class 240, as presented in figure 1. The chosen beams dimensions and reinforcement (longitudinal, stirrups and fibers) correspond to the application in practice. The beams layout with measuring devices prior to testing, as well as loading is shown in figure 2.

In the beams test with ultimate short-term load with one unloading cycle, beams were loaded with two concentrated forces at a distance of 80 cm, and 100 cm from bearings (figure 1). The beams are loaded with a constant load with the value of one force $F_G=4.00$ kN, which is the constant in the test period. On that force, exploitation load was added $F_Q=7.60$ kN. Total force in that moment is $F_{G+Q}=11.6$ kN. Last loading level for which measurements were carried out (ultimate) was $F_U=20.60$ kN, after which the force was added to failure.

Tabela 3. Pregled greda po serijama
Table 3. Beams' overview per series

Seriya Series	Podgrupa Subgroup	Vrsta betona Concrete type	Seriya Series	Podgrupa Subgroup	Vrsta betona Concrete type	Vrijeme ispitivanja [dani] Testing period [days]
A	A1	OSC	G	G1	FROSC	$t=35-40$
	A2	OSC		G2	FROSC	$t=35-40$
	A3	HSC		G3	FRHSC	$t=35-40$
	A4	HSC		G4	FRHSC	$t=35-40$
F	F1	OSC	H	H1	FROSC	$t=420-430$
	F2	OSC		H2	FROSC	$t=420-430$
	F3	HSC		H3	FRHSC	$t=420-430$
	F4	HSC		H4	FRHSC	$t=420-430$

Slika 2. Prikaz grede prije ispitivanja s mjernim uređajima i nanošenje opterećenja
Figure 2. Beam prior to the test with measuring devices and loading application

Širine pukotina mjerene su u sredini grede na tri ili više mjesta – ovisno o pojavi pukotina, sa obe strane grede. Mjerilo se s mikroskopskom lupom tačnosti 0,05 mm. Postupak mjerenja prikazan je na slici 3. Zbog preciznosti, finalno mjerenje rađeno je u programu AutoCAD.

The crack width was measured in the centre of the beams on three or more places on both sides, depending on crack formation. The measurement was performed with a microscope of accuracy of 0.05 mm. The measurement procedure is shown in figure 3. Due to precision, the final measurement was performed in AutoCAD software.

Slika 3. Postupak mjerenja širine pukotina
Figure 3. Measurement of the crack width

3 REZULTATI I ANALIZA ISTRAŽIVANJA

Širina pukotina i propagacija pukotina mjerene i analizirane su na ukupno šesnaest armirano-betonskih greda, sa 0,45% čeličnih vlakana i bez njih. Ispitan je uticaj čeličnih vlakna i starosti betona na širinu pukotina. U tabeli 4 prikazani su rezultati srednjih vrijednosti izmjerenih širina pukotina s mjernih mjesta za sve podgrupe greda za tri nivoa opterećenja.

3 RESEARCH RESULTS AND ANALYSIS

The crack width and crack propagation were measured and analyzed on a total of 16 reinforced concrete beams, with and without 0.45% of steel fibers. The effect of steel fibers and the concrete age on the crack width was investigated. In table 4 average crack width results from measuring points for all subgroups and three loading levels are presented.

Tabela 4. Rezultati srednjih vrijednosti širina pukotina armirano-betonskih greda
Table 4. The average values of crack width of reinforced concrete beams

Sila / Force [kN]	Širina pukotina / Crack width [mm]				Povećanje / Smanjenje Increase / Decrease [%]
Seriya Series	A				
Podgrupa Subgroup	A1	A2	A3	A4	$(A3,4^{av}-A1,2^{av})/A3,4^{av}$
$F_{G+Q}=11,60$	0,19	0,15	0,13	0,08	-64
$F_G=4,00$	0,08	0,08	0,07	0,05	-33
$F_U=20,60$	0,45	0,31	0,23	0,23	-66
Seriya Series	F				
Podgrupa Subgroup	F1	F2	F3	F4	$(F3,4^{av}-F1,2^{av})/F3,4^{av}$
$F_{G+Q}=11,60$	0,16	0,12	0,20	0,08	0,00
$F_G=4,00$	0,12	0,07	0,09	0,04	-38
$F_U=20,60$	0,32	0,18	0,21	0,20	-21
Seriya Series	G				
Podgrupa Subgroup	G1	G2	G3	G4	$(G3,4^{av}-G1,2^{av})/G3,4^{av}$
$F_{G+Q}=11,60$	0,20	0,07	0,07	0,03	-155
$F_G=4,00$	0,17	0,05	0,04	-	-181
$F_U=20,60$	0,26	0,14	0,14	0,09	-71
Seriya Series	H				
Podgrupa Subgroup	H1	H2	H3	H4	$(H3,4^{av}-H1,2^{av})/H3,4^{av}$
$F_{G+Q}=11,60$	0,11	0,10	0,08	0,06	-45
$F_G=4,00$	0,07	0,06	0,05	0,04	-53
$F_U=20,60$	0,19	0,23	0,16	0,13	-49

Na gredi G4, prva pukotina pojavila se nakon ciklusa rasterećenja, te je stoga ta greda izuzeta iz daljnje analize. Prikaz razvoja pukotina za jednu karakterističnu armirano-betonsku gredu sa čeličnim vlaknima može se videti na slici 4.

Pri definisanju efekata čeličnih vlakana na širinu pukotina za grede starosti $t=35-40$ dana, uspoređene su grede serija A i G, a za grede starosti $t=420-430$ dana, to su grede serija F i H. Prosječna širina pukotina i analiza efekata dodatka vlakana data je u tabelama 5 i 6. Dijagramski prikaz odnosa sila – širina pukotine dat je na slikama 5 i 6.

For beam G4, first crack appeared after the unloading cycle, therefore this beam was excluded from further analysis. Crack development for one characteristic beam is shown in figure 4.

When defining the effects of steel fibers to the crack width for the beams' age $t=35-40$ days, series A and G were compared, and for the age $t=420-430$ days that are F and H series. The average crack width and the analysis of the fiber addition effect are given in tables 5 and 6. Diagram of the relation force (F) – crack width (w) is shown on figures 5 and 6.

Slika 4. Razvoj pukotina karakteristične armirano-betonske grede sa čeličnim vlaknima
Figure 4. Crack development for characteristic reinforced beam with steel fibers

Tabela 5. Efekat čeličnih vlakana za grede starosti $t=35-40$ dana
Table 5. Steel fibers effect for beams' age $t=35-40$ days

Sila / Force [kN]	A1,2 ^{av} [mm]	A3,4 ^{av} [mm]	G1,2 ^{av} [mm]	G3 [mm]	(G1,2 ^{av} -A1,2 ^{av})/ G1,2 ^{av} [%]	(G3-A3,4 ^{av})/ G3 [%]
F _{G+Q} =11,60	0,17	0,10	0,13	0,07	-31	-43
F _{G,R} =4,00	0,08	0,06	0,11	0,04	27	-55
F _U =20,60	0,38	0,23	0,20	0,14	-90	-64

Tabela 6. Efekat čeličnih vlakana za grede starosti $t=420-430$ dana
Table 6. Steel fibers effect for beams' age $t=420-430$ days

Sila / Force [kN]	F1,2 ^{av} [mm]	F3,4 ^{av} [mm]	H1,2 ^{av} [mm]	H3,4 ^{av} [mm]	(H1,2 ^{av} -F1,2 ^{av})/ H1,2 ^{av} [%]	(H3,4 ^{av} -F3,4 ^{av})/ H3,4 ^{av} [%]
F _{G+Q} =11,60	0,14	0,14	0,10	0,07	-36	-99
F _{G,R} =4,00	0,09	0,07	0,06	0,04	-43	-59
F _U =20,60	0,25	0,20	0,21	0,14	-16	-43

Slika 5. Dijagrami sila (F) – širina pukotine (w) za grede serija A i G
Figure 5. Diagram force (F) – crack width (w) for series A and G

Slika 6. Dijagrami sila (F) – širina pukotine (w) za grede serija F i H
Figure 6. Diagram force (F) – crack width (w) for series F and H

Prema prikazanim rezultatima u tabelama i na slikama, može se zaključiti da dodatak čeličnih vlakana smanjuje širinu pukotina kako kod običnog betona, tako i kod betona visoke čvrstoće. Za nivo eksploatacionog opterećenja prosječne vrijednosti širine pukotina za betonske grede starosti $t=35-40$ dana, manje su za 31% kod FROSC nego kod OSC, a za ultimno opterećenje ta razlika je 90%. FRHSC grede starosti $t=35-40$ dana za nivo eksploatacionog opterećenja imaju 43% manje vrijednosti širine pukotina nego HSC grede iste starosti, dok za ultimno opterećenje ta razlika iznosi 64%. Za betonske grede starosti $t=420-430$ dana primijećeno je nešto drugačije ponašanje. Za nivo eksploatacionog opterećenja širine pukotina FROSC greda su 36% manje u odnosu na OSC, ali za nivo ultimnog opterećenja ta razlika je svega 16%. FRHSC grede imaju znatno smanjenje širine pukotina za nivo eksploatacionog opterećenja u poređenju s HSC gredama od 99%, dok za nivo ultimnog opterećenja razlika je nešto niža – iznosi 43%.

Sa slika 5 i 6 može se vidjeti da je razvoj pukotina OSC i FROSC greda u početku ispitivanja izjednačen; međutim, dostizanjem nivoa ultimnog opterećenja (nešto ispod i iznad F_u vrijednosti), razlika u razvoju pukotina je očigledna (za obe ispitane starosti betona). Od tog trenutka, FROSC grede imaju mnogo manje širine pukotina od OSC greda. Kod greda starosti $t=35-40$ dana, približavajući se sili F_u , razlika širine pukotina

According to the results shown in the tables and in the figures, it can be concluded that the addition of steel fibers reduces the crack width both for ordinary concrete and for high strength concrete. For the exploitation load level average crack width for concrete beams of $t=35-40$ days age are lower for FROSC compared to OSC for 31%, and for ultimate load level the difference is 90%. FRHSC beams age $t=35-40$ days for exploitation load level have 43% lower crack width values compared to HSC beams of the same age, while for ultimate load level the difference is 64%. For concrete beams of age $t=420-430$ days a slightly different behavior was noticed. For exploitation load level average crack width of FROSC beams are 36% lower compared to OSC beams, but for ultimate load level the difference is only 16%. FRHSC beams have significant crack width values reduction for exploitation load level compared to HSC beams of 99%, while for ultimate load level the difference is 43%.

From the figures 5 and 6 it can be seen that crack development for OSC and FROSC beams at the beginning of the test is equal, however by reaching the ultimate load level (slightly below and above F_u) the difference in the crack development is obvious (for both concrete age). From that point FROSC beams have significantly lower crack width values compared to OSC beams. For the beams of age $t=35-40$ days, by approaching the F_u force, difference in the crack width is

razvija se postepeno, dok se kod greda starosti $t=420-430$ dana razlika pojavljuje relativno naglo. Za grede betona visoke čvrstoće primjećeno je nešto drugačije ponašanje. Od početka eksperimenta, širine pukotina greda sa čeličnim vlaknima znatno su niže (~50%), a dostizanjem ultimnog nivoa opterećenja, razlika se samo povećava.

Pri definisanju efekata starosti betona na širinu pukotina za grede sa 0,45% čeličnih vlakana i bez njih, uspoređene su grede serija A i F, te grede serija G i H. Prosječna širina pukotina i analiza efekata starosti betona data je u tabelama 7 i 8. Dijagramski prikaz odnosa sila – širina pukotine dat je na slikama 7 i 8.

developing gradually, but for beams of age $t=420-430$ days the difference occurs relatively rapidly. From the beginning of the experiment crack width are lower for steel reinforced concrete beams (~50%), and by reaching the ultimate load level the difference is only increasing.

For defining the effect of concrete age to the crack width of concrete beams with and without 0.45% of steel fibers, series A and F, as well as G and H are compared. The average crack width and the analysis of the concrete age effect is given in tables 7 and 8. Diagram of the relation force (F) – crack width (w) is shown on figures 7 and 8.

Tabela 7. Efekat starosti betona za grede bez čeličnih vlakana
Table 7. Concrete age effect for the beams without steel fibers

Sila / Force [kN]	A1,2 ^{av} [mm]	A3,4 ^{av} [mm]	F1,2 ^{av} [mm]	F3,4 ^{av} [mm]	(F1,2 ^{av} -A1,2 ^{av})/ F1,2 ^{av} [%]	(F3,4 ^{av} -A3,4 ^{av}) / F3,4 ^{av} [%]
$F_{G+Q}=11,60$	0,17	0,10	0,14	0,14	-21	26
$F_{G,R}=4,00$	0,08	0,06	0,09	0,07	13	10
$F_U=20,60$	0,38	0,23	0,25	0,20	-53	-12

Tabela 8. Efekat starosti betona za grede sa čeličnim vlaknima
Table 8. Concrete age effect for the beams with steel fibers

Sila / Force [kN]	G1,2 ^{av} [mm]	G3 [mm]	H1,2 ^{av} [mm]	H3,4 ^{av} [mm]	(H1,2 ^{av} -G1,2 ^{av})/ H1,2 ^{av} [%]	(H3,4 ^{av} -G3)/ H3,4 ^{av} [%]
$F_{G+Q}=11,60$	0,13	0,07	0,10	0,07	-27	-3
$F_{G,R}=4,00$	0,11	0,04	0,06	0,04	-70	8
$F_U=20,60$	0,20	0,14	0,21	0,14	7	3

Slika 7. Dijagrami sila (F) – širina pukotine (w) za grede serija A i F
Figure 7. Diagram force (F) – crack width (w) for series A and F

Slika 8. Dijagrami sila (F) – širina pukotine (w) za grede serija G i H
Figure 8. Diagram force (F) – crack width (w) for series G and H

Prosječne vrijednosti širine pukotina OSC greda za nivo eksploatacionog opterećenja manje su za 21% kod greda starosti $t=420-430$ dana nego kod greda starosti $t=35-40$ dana, a za nivo ultimnog opterećenja – ta razlika iznosi 53%. U slučaju HSC greda, za nivo eksploatacionog opterećenja grede starosti $t=420-430$ dana imaju veće prosječne vrijednosti širine pukotina od greda starosti $t=35-40$ dana i to za 26%, dok porastom sile do nivoa ultimnog opterećenja grede starosti $t=420-430$ dana imaju manje prosječne vrijednosti širine pukotina u odnosu na grede starosti $t=35-40$ dana za 12%.

Dodatak čeličnih vlakana u konačnici ne utiče značajno na širinu pukotina betonskih greda s obzirom na njihovu starost. Prosječne vrijednosti širine pukotina FROSC greda za nivo eksploatacionog opterećenja manje su kod greda starosti $t=420-430$ dana od greda starosti $t=35-40$ dana za 27%, dok kod FRHSC greda ta razlika iznosi svega 3%. Za nivo ultimnog opterećenja prosječne širine pukotina FROSC greda su 7% veće za grede starosti $t=420-430$ dana, a kod FRHSC greda ta razlika je 3%.

Sa slika 7 i 8 može se vidjeti da starost betona utiče na širinu pukotina OSC i HSC greda samo nakon dosezanja nivoa ultimnog opterećenja. Primjetne su nešto niže vrijednosti širine pukotina greda starosti $t=420-430$ dana. Za grede sa čeličnim vlaknima nije primjetna značajnija razlika u toku formiranja pukotina u početku ispitivanja. Prekoračenjem nivoa ultimnog opterećenja, grede starosti $t=420-430$ dana pokazuju znatno niže vrijednosti širine pukotina.

4 PRORAČUN ŠIRINE PUKOTINA

4.1 Proračun širine pukotina prema EC2 – EN 1992:2004

U EC2-EN 1992:2004 [8] prikazan je indirektni dokaz proračuna širine pukotina, koji je za svakodnevnu inženjersku praksu zadovoljavajuće tačnosti. Karakteristična širina pukotina računa se kao proizvod razlike između srednje dilatacije u zatežućoj armaturi ϵ_{sm} , srednje dilatacije u zategnutom betonu između pukotina ϵ_{cm} i maksimalnog razmaka naprslina $s_{r,max}$:

Average crack width values for OSC beams at exploitation load level are lower for the beams of age $t=420-430$ days compared to the beams of age $t=35-40$ days for 21%, for ultimate load level the difference is 53%. For HSC beams at exploitation load level beams of age $t=420-430$ days have greater average crack width values compared to the beams of age $t=35-40$ days for 26%, while by increasing load level to ultimate beams of age $t=420-430$ days have lower average crack width values compared to the beams of age $t=35-40$ days for 12%.

The addition of steel fibers ultimately fails to significantly affect the crack width of reinforced concrete beams due to their age. Average crack width of FROSC beams for exploitation load level are lower for beams of age $t=420-430$ days compared to beams of age $t=35-40$ days for 27%, while for FRHSC beams the difference is only 3%. For ultimate load level average crack width of FROSC beams is 7% greater for beams of age $t=420-430$ days, and for FRHSC beams the difference is 3%.

From the figures 7 and 8 it can be seen that the concrete age affects the crack width of OSC and HSC beams only after reaching the ultimate load level. Slightly lower values of the crack width for concrete age of $t = 420-430$ days are noticeable. For beams with steel fibers no significant difference was observed in crack formation at the beginning of the test. By exceeding the ultimate load level, beams of age $t=420-430$ days shows significantly lower values of the cracks width.

4 CRACK WIDTH CALCULATION

4.1 Crack width calculation according to EC2 – EN 1992:2004

In EC2 – EN 1992:2004 [8] indirect method of crack width calculation is presented, which has satisfactory accuracy for everyday engineering practice. Characteristic crack width is calculated as the product of mean dilatation in reinforcement ϵ_{sm} , mean dilatation in tensioned concrete ϵ_{cm} and maximum crack distance $s_{r,max}$:

$$w_k = b \cdot s_{rm} \cdot e_{sm}$$

ili / or

$$w_k = s_{r,max} \cdot (e_{sm} - e_{cm}) \quad (1)$$

gdje je:

β – odnos računске i srednje širine pukotina ($\beta=1,70$ za naprezanje izazvano opterećenjem ili prinudnim deformacijama; $\beta=1,30$ za naprezanje izazvano prinudnim deformacijama);

s_{rm} – srednji razmak pukotina koji se računa iz izraza (2):

where:

β – relation between calculated and average crack width ($\beta=1,70$ for stress caused by load or forced deformations; $\beta=1,30$ for stress caused by forced deformations),

s_{rm} – mean crack distance calculated from the expression (2):

$$s_{rm} = 50 + 0,25 \cdot k_1 \cdot k_2 \cdot \frac{\Phi_s}{r_{p,eff}} \quad (2)$$

gdje je:

Φ_s – prečnik armaturene šipke;

k_1 – koeficijent kojim se uzima u obzir kvaliteta spoja armature i betona;

k_2 – koeficijent koji zavisi od oblika dijagrama dilatacija po visini poprečnog presjeka;

$\rho_{p,eff}$ – efektivni geometrijski stepen podužne armature u odnosu na efektivnu površinu poprečnog presjeka zategnutog betona $A_{c,eff}$ koji se računa iz izraza (3):

where:

Φ_s – bar diameter,

k_1 – coefficient that takes into account the quality of the bond between reinforcement and concrete,

k_2 – coefficient that depends on dilatation diagram by the height of the cross section shape,

$\rho_{p,eff}$ – effective reinforcement ratio of longitudinal reinforcement compared to effective cross section area of tensed concrete $A_{c,eff}$ calculated from the expression (3):

$$r_{p,eff} = \frac{A_s}{A_{c,eff}} \quad (3)$$

Srednja dilatacija u zategnutoj armaturi ϵ_{sm} računa se:

Mean dilatation of tensed reinforcement ϵ_{sm} is calculated as:

$$e_{sm} = \frac{s_s}{E_s} \cdot \left[1 - b_1 \cdot b_2 \left(\frac{s_{sr}}{s_s} \right)^2 \right] \quad (4)$$

gdje je

σ_s – napon u armaturi na pukotini;

β_1 – koeficijent koji ima u vidu uticaj spoja armature;

β_2 – koeficijent koji ima u vidu uticaj trajanja opterećenja ili ponavljanja opterećenja;

σ_{sr} – napon u zategnutoj armaturi izračunat na početku sekcije s pukotinom pod uslovima opterećenja, koja uzrokuju prvu pukotinu;

E_s – Youngov modul elastičnosti za armaturu.

where:

σ_s – stress in reinforcement on crack,

β_1 – coefficient that takes into account the reinforcement bond,

β_2 – coefficient that takes into account the effect of load duration or load repetition,

σ_{sr} – stress in tensed reinforcement calculated at the beginning of crack section under load conditions that cause the first crack,

E_s – Youngs' modulus of elasticity for reinforcement.

4.2 ACI building code metod

ACI building code 318 [1] za proračun širine pukotina predlaže empirijsku formulu:

$$w = 0.011 \cdot b_b \cdot s_s \cdot \sqrt[3]{d_c \cdot A_c} \quad (5)$$

gdje je:

β_b – odnos udaljenosti do neutralne osi od zategnutog ruba i od težišta glavne armature

σ_s – napon u armaturi

d_c – udaljenost od težišta armature do donjeg ruba elementa

A_e – efektivna površina betona.

4.2 ACI building code method

ACI building code 318 [1] for crack width calculation suggest empirical formula:

where:

β_b – ratio of distance between neutral axis and tension face to distance between neutral axis and reinforcing steel,

σ_s – stress in the reinforcement,

d_c – distance between reinforcements' center and lower edge of the element,

A_e – effective concrete area.

4.3 Proračun širine pukotina za beton sa čeličnim vlaknima

4.3.1 RILEM TC162-TDF metod

Za proračun širine pukotina za betone sa čeličnim vlaknima, Međunarodni savez laboratorija i eksperata u građevinskim materijalima, sistemima i strukturama (RILEM – fr. Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages) predložio je primjenu metoda prikazanog u EN 1992:2004. Način proračuna, predstavljen u EN 1992:2004, dopunjen je korekcijom formule za proračun srednjeg razmaka pukotina [12]. Nadalje, napon u zategnutoj armaturi treba izračunati imajući u vidu to što će čelična vlakna koja „premošćavaju“ pukotinu preuzeti zaostale zatežuće naponne (σ_{fb}) uniformno po visini pukotine. Modifikovani izraz za proračun srednjeg razmaka pukotina dat je izrazom:

$$s_m = \left(50 + 0,25 \cdot k_1 \cdot k_2 \cdot \frac{\Phi_s}{r_r} \right) \cdot \left(\frac{50}{L/\Phi} \right) \quad (6)$$

gdje je:

k_1 – koeficijent koji uzima u obzir svojstva spoja armature;

k_2 – koeficijent koji uzima u obzir formu raspodjele deformacije;

ρ_r – efektivni odnos armature ($A_{s1}/A_{c,eff}$);

Φ – poluprečnik čeličnog vlakna;

L – dužina čeličnog vlakna.

Veliki nedostatak ovog metoda jeste to što se ne uzima u obzir procenat, odnosno količina vlakana koja se ugrađuju u betonski element. Također, određivanje zaostalih napona uslijed dodatka čeličnih vlakana jeste diskutabilno [4].

Sličnu preporuku korekcije metoda EN 1992:2004 dao je Moffatt [6, 11]. Njegov model koriguje formulu za proračun srednjeg razmaka pukotina, ali sa odnosom postpukotinskog zaostalog napona i napona pri nastanku pukotine:

$$s_m = \left(50 + 0,25 \cdot k_1 \cdot k_2 \cdot \frac{\Phi_b}{r_r} \right) \cdot \left(1 - \frac{f_{res}}{f_{cr}} \right) \quad (7)$$

gdje je:

f_{res} – postpukotinski zaostali napon;

f_{cr} – napona pri nastanku pukotine.

U ovom prijedlogu, određivanje f_{res} nije u potpunosti jasno definisano bez prethodnih ispitivanja na betonskom elementu bez konvencionalne armature.

4.3.2 ACI building code metod

Za proračun širine pukotina betonskog elementa sa čeličnim vlaknima, ACI Committee 544 [3] predlaže dodavanje zatezne sile koju podnosi mikroarmirani beton. Doprinos vlakana je u konstantnom zateznom naponu σ_f u raspuknutom dijelu elementa:

$$s_f = 0.00772 \cdot \frac{l_f}{d_f} \cdot V_f \cdot F_{be} \quad (8)$$

gdje je:

l_f i d_f – geometrijske karakteristike vlakna;

V_f – procenat vlakana;

F_{be} – efektivnost veze čeličnih vlakana i betona

4.3 Crack width calculation for concrete with steel fibers

4.3.1 RILEM TC162-TDF method

For calculation the crack width of steel fiber reinforced concrete RILEM (fr. Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages – en. International Union of Laboratories and Experts in Construction Materials, Systems and Structures) proposed the application of the EN 1992:2004 method. Method of calculation presented in EN 1992:2004 is corrected by supplementing the formula for mean crack distance calculation [12]. Furthermore, stress in the tensile reinforcement should be calculated considering that steel fibers that are "bridging" the crack will take residual tensile stresses (σ_{fb}) uniformly by the crack height. The modified expression for the mean crack distance is given by:

where:

k_1 – coefficient that takes into account bond properties of reinforcement,

k_2 – coefficient that takes into account form of deformation distribution,

ρ_r – effective reinforcement ratio ($A_{s1}/A_{c,eff}$),

Φ – radius of steel fiber,

L – steel fiber length.

The great disadvantage of this method is not taking into consideration the percentage, i.e. the amount of steel fibers embedded in the concrete elements. Also, the determination of residual stress due to the addition of steel fibers is questionable.

Similar correction of EN 1992:2004 method was given by Moffatt [6, 11]. His model is based on correction of mean crack distance formula, but with relation of post-cracking residual stress and stress at crack formation:

where:

f_{res} – post-cracking residual stress,

f_{cr} – stress at crack formation.

In this proposal determination of f_{res} is partially defined without previous tests on the concrete element without conventional reinforcement.

4.3.2 ACI building code method

Committee 544 [3] suggests adding tensile force which is taken by fiber reinforced concrete for crack width calculation of concrete element with steel fibers. The fiber contribution is in constant tensile stress σ_f in cracked part of the element:

where:

l_f i d_f – geometrical characteristics of fibers,

V_f – fiber percentage,

F_{be} – effectiveness of bond between steel fibers and

(varira između 1.0 i 1.2, zavisno od osobina vlakna).

5 ZAKLJUČAK

Na osnovu prikazanih rezultata istraživanja, te sprovedene analize za posljednji (ultimni) nivo opterećenja nakon jednog ciklusa rasterećenja za koji je vršeno očitavanje na svim gredama, uticaj dodatka čeličnih vlakana na razvoj i širinu pukotina betonskih greda jeste sledeći:

- za grede običnog betona (starost $t=35-40$ dana), prosječno smanjenje širine pukotina FROSC greda u poređenju sa OSC gredama jeste 90%;
- za grede betona visoke čvrstoće (starost $t=35-40$ dana), prosječno smanjenje širine pukotina FRHSC greda u poređenju sa HSC gredama jeste 64%;
- za grede običnog betona (starost $t=420-430$ dana), prosječno smanjenje širine pukotina FROSC greda u poređenju sa OSC gredama jeste 16%;
- za grede betona visoke čvrstoće (starost $t=420-430$ dana), prosječno smanjenje širine pukotina FRHSC greda u poređenju sa HSC gredama jeste 43%;

Starost betona za grede s dodatkom vlakana ne utiče značajno na smanjenje širine pukotina (od 3% do 7%).

Cilj rada jeste prvenstveno predstaviti eksperimentalne rezultate mjerenih širina pukotina na armirano-betonskim gredama realnih dimenzija (15/28/300 cm), za dvije starosti betona ($t=35-40$ i $t=420-430$ dana), o čemu postoji malo registrovanih podataka. Rad upotpunjuje bazu podataka iz predmetne problematike. U radu je data i teorijska osnova za proračun širine pukotina armirano-betonskih greda prema EN 1992:2004 i ACI building code, kao i armirano-betonskih greda s dodatkom čeličnih vlakana za proračun širine pukotina po prijedlogu RILEM TC162-TDF i ACI building code modela.

Data teorijska osnova predstavlja podlogu za buduća istraživanja, radi poređenja izmjerenih širina pukotina dobivenih eksperimentom sa empirijskim obrascima u važećim standardima i preporukama.

Ovim radom otvorena su mnoga pitanja u polju definisanja ponašanja elemenata i konstrukcija od mikroarmiranog betona sa dodatkom čeličnih vlakana tokom vremena, zbog njegove sve češće primjene kao konstruktivnog materijala u inženjerskoj praksi.

6 LITERATURA REFERENCES

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concrete (ranging from 1.0 and 1.2 depending on the fiber characteristics).

5 CONCLUSION

Based on the results and analysis for final (ultimate) load level after one unloading cycle for which measurement was taken for all the beams, effect of steel fiber addition to crack formation and crack width of concrete beams is as follows:

- For ordinary concrete beams (age $t=35-40$ days) average crack width reduction of FROSC beams compared to OSC beams is 90%;
- For high strength concrete beams (age $t=35-40$ days) average crack width reduction of FRHSC beams compared to HSC beams is 64%;
- For ordinary concrete beams (age $t=420-430$ days) average crack width reduction of FROSC beams compared to OSC beams is 16%;
- For high strength concrete beams (age $t=420-430$ days) average crack width reduction of FRHSC beams compared to HSC beams is 43%;

The concrete age fails to significantly affect crack width reduction for beams with steel fibers (from 3% to 7%).

The aim of this paper is primarily to present the experimental results of the measured crack width in reinforced concrete beams with real dimensions (15/28/300 cm), for two concrete ages ($t=35-40$ and $t=420-430$ days), for which there is a little recorded data. The paper complements the database of the subject matter. Also, theoretic basis for calculating crack width of reinforced concrete beams by EN 1992:2004 and ACI building code method is given, as well as method for calculating crack width of reinforced concrete beams with steel fibers by RILEM TC162-TDF and ACI building code method.

The theoretical basis presented is the foundation for future research with the purpose of comparing the measured crack widths obtained by experiment with empirical formula given in standards and recommendations.

This paper has opened many issues in the field of defining the behavior of elements and constructions of fiber reinforced concrete with steel fibers over time, for the purpose of its increasingly frequent application as a constructive material in engineering practice.

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REZIME

ANALIZA ŠIRINE PUKOTINA GREDA OD MIKRO-ARMIRANOG BETONA SA ČELIČNIM VLAKNIMA

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Beton armiran vlaknima posljednjih godina je od eksperimentalnog materijala napredovao u dosta upotrebljiv materijal u praksi, zbog svojih pozitivnih osobina kao što su, na primer, povećane čvrstoće pri zatezanju, čvrstoće pri savijanju, žilavosti. Međutim, postoji još dosta nerazjašnjenih pitanja koja su predmeti istraživanja. U radu su prikazani rezultati i analiza ispitivanja širine pukotina greda od armiranog betona sa čeličnim vlaknima. U okviru analize, razmatra se uticaj dodatka čeličnih vlakana na širinu pukotina betonskih greda (dimenzija 15/28/300 cm), koje su opterećene do loma kratkotrajnim ultimnim statičkim opterećenjem s jednim ciklusom rasterećenja. Grede su izrađene od dvije vrste betona: betona obične čvrstoće (OSC) – C30/37 i betona visoke čvrstoće (HSC) – C60/70, sa 0,45% čeličnih vlakana i bez njih. Rezultati upućuju na zaključak da postoji značajan uticaj dodatka vlakana na širinu pukotina, naročito kod betona obične čvrstoće. Na kraju rada, prikazani su empirijski proračuni širine pukotina betonskih elemenata sa čeličnim vlaknima, prema preporukama RILEM – a i ACI building code.

Cljučne riječi: beton, čelična vlakna, statičko opterećenje, širina pukotina

SUMMARY

CRACK WIDTH ANALYSIS OF STEEL FIBERS REINFORCED CONCRETE BEAMS

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Fibre reinforced concrete in recent years has grown from experimental material to a practical usable material, due to its positive properties such as increased tensile strength, bending strength, toughness etc. However, still there are many unanswered questions that are the subject of many research. In this paper results and analysis of crack width of concrete beams with steel fibres are presented. This analysis considers influence of steel fibre addition on the crack width of reinforced concrete beams (dimensions 15/28/300 cm) loaded up to fracture during short-term ultimate static load with one unloading cycle. Concrete beams were made of two types of concrete: ordinary strength concrete (OSC) – C30/37 and high strength concrete (HSC) – C60/70, with and without 0.45% of steel fibres. The results indicate that there is a significant influence of fibre addition on crack width, especially for ordinary concrete. At the end, empirical calculations of the concrete elements' crack width with steel fibres according to the recommendations of RILEM and ACI building code are given.

Key words: concrete, steel fibres, static load, crack width