



# Utjecaj različitih parametara na ponašanje i nosivost betonskih i čeličnih okvira sa zidanom ispunom pri potresu

Goran Baloević

Jure Radnić

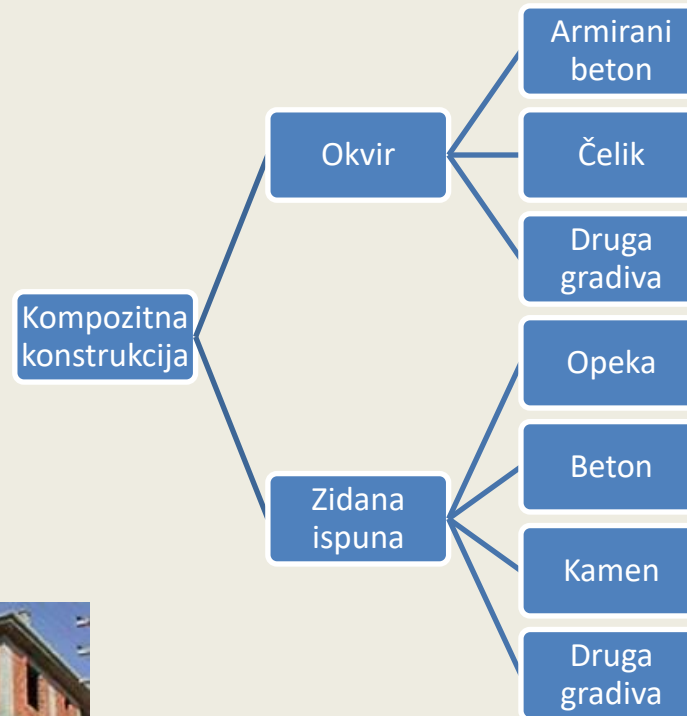
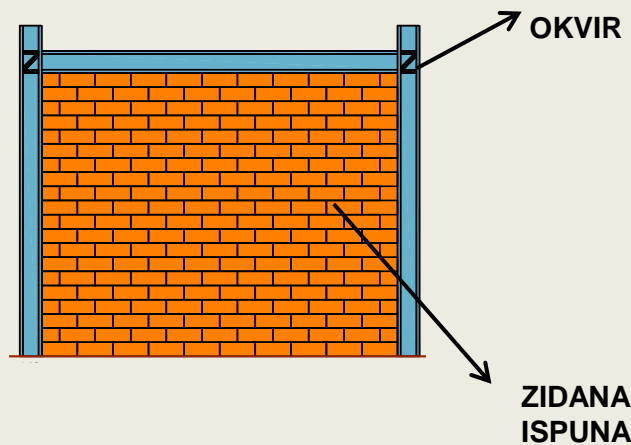
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Prof. dr. sc. Jure Radnić, dipl.ing.građ., FGAG, Split

- Učestale konstrukcije u građevinskoj praksi



- Kompozitna konstrukcija



- Složeno ponašanje:

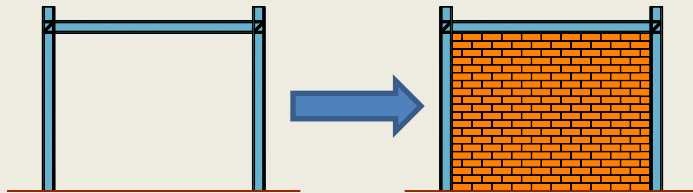
- Ponašanje individualnog sustava
- Međudjelovanje okvir-ispuna
- Ostali faktori (otvori, masa, tlo, itd.)



## Dosadašnji inženjerski proračuni

NOSIVI SUSTAV

- OKVIR ✓
- ZIDANA ISPUNA ✗



### REZULTAT

- Povećana globalna nosivost sustava
- Povećana globalna krutost sustava
- **Povećane potresne sile**

- Na strani veće sigurnosti za nosivost konstrukcije
- Na strani manje sigurnosti za veličinu potresnih sila

## Suvremeni propisi (npr. Eurocode 8, FEMA 356)

- predviđaju uključivanje ispune pri seizmičkom proračunu okvira s ispunom
- prilično složen pristup
- nedovoljna preciznost za široku projektantsku primjenu





# Uvod



Olive View Hospital, 1971  
San Fernando, California



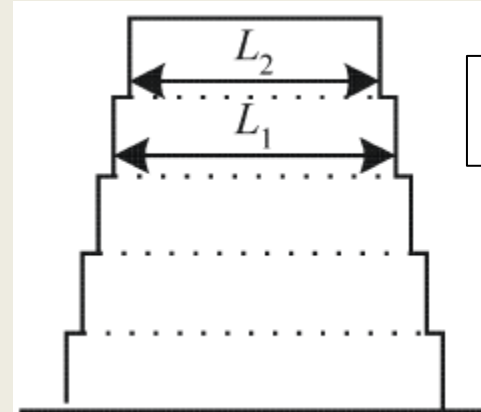
Chi Chi 1999  
Taiwan earthquake

**Fleksibilnost etaža!**



Bhuj 2001  
India earthquake

Goran Baloević, Jure Radnić



Prema EC8 – tlocrtna pravilnost po visini



Osnovna svrha ovog rada je trojaka:

1. Provedba eksperimentalnih istraživanja betonskih i čeličnih okvira s ispunom
  - statičko opterećenje do sloma
  - dinamičko opterećenje - potresna platforma
  - ispitivanje utjecaja više faktora (žbuka, armatura, krutost okvira, krutost ispune, otvori, fleksibilne etaže, pobuda, itd.)
2. Poboljšanje postojećeg numeričkog modela za statičku i dinamičku analizu ravninskih konstrukcija od betona, čelika i ziđa
  - modeliranje efekta faznog nastajanja okvira s ispunom
  - modeliranje utjecaja žbuke (nearmirane i armirane)
  - provjera modela
  - primjena modela – parametarske analize
3. Preporuke za proračun u praksi

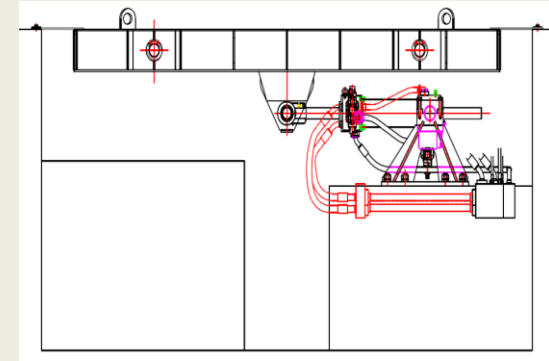


## Eksperimentalna ispitivanja:

1. Čelični okviri sa zidanom ispunom
  - Statička ispitivanja
  - Dinamička ispitivanja
2. Betonski okviri sa zidanom ispunom
  - Dinamička ispitivanja

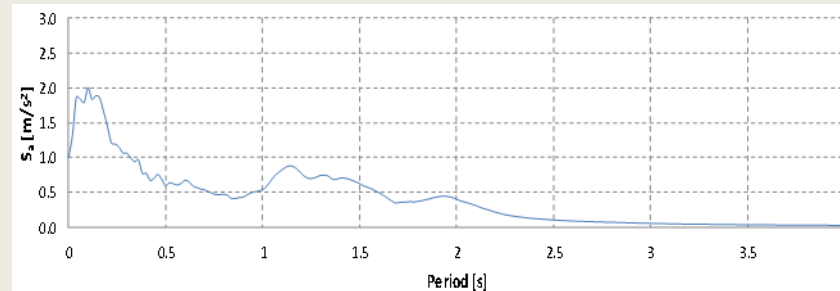
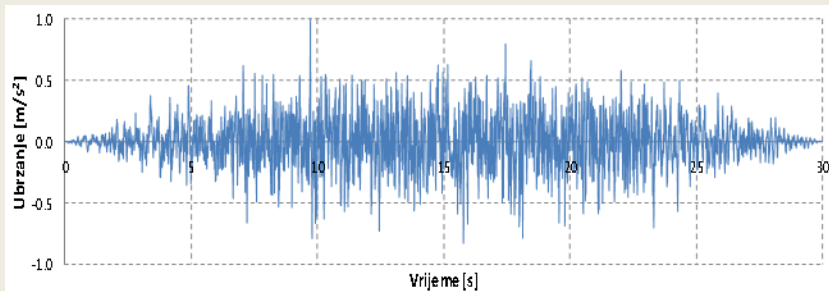


Laboratorij za potresna ispitivanja  
Fakultet građevinarstva, arhitekture i geodezije  
Sveučilište u Splitu

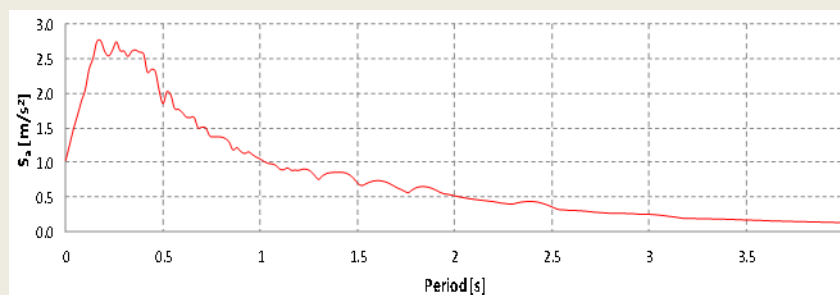
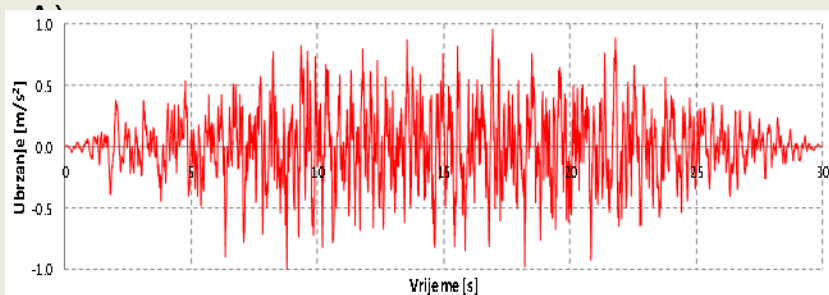


# Opterećenje

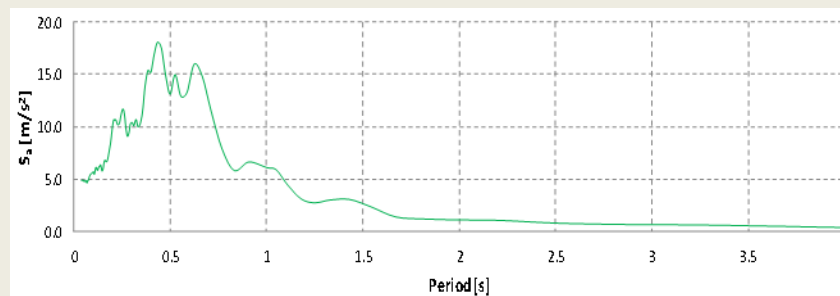
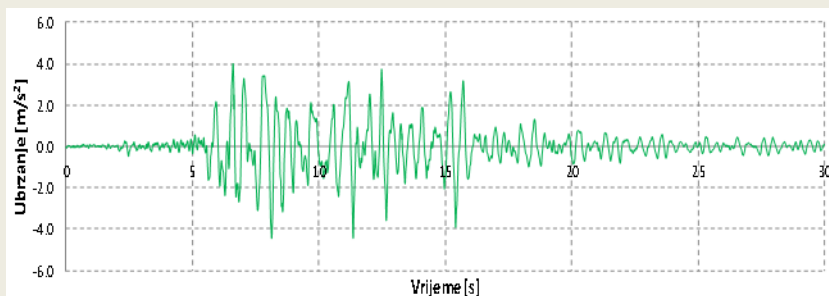
## Umjetni akceleroگرام AA1



## Umjetni akceleroگرام AA2 (EN 1998; tip 1, tip tla)



## Potres Petrovac (Crna Gora, 1979)



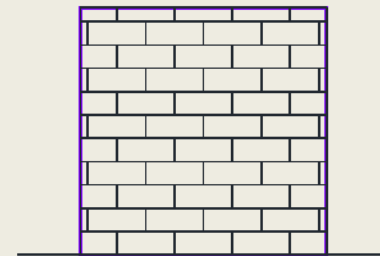
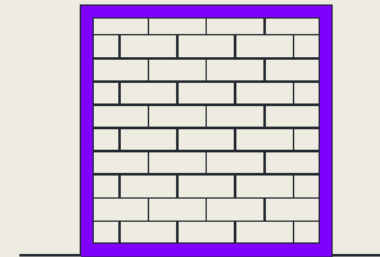
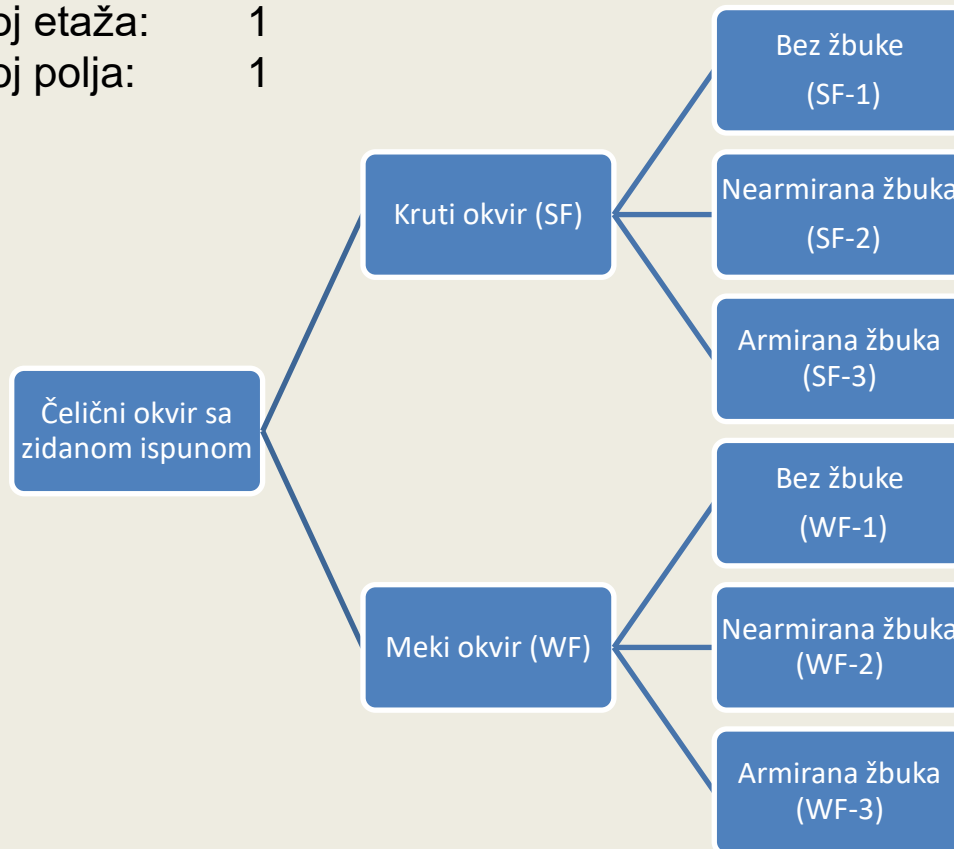


## 1. Statička ispitivanja čeličnih okvira sa zidanom ispunom

Mjerilo: 1/3

Broj etaža: 1

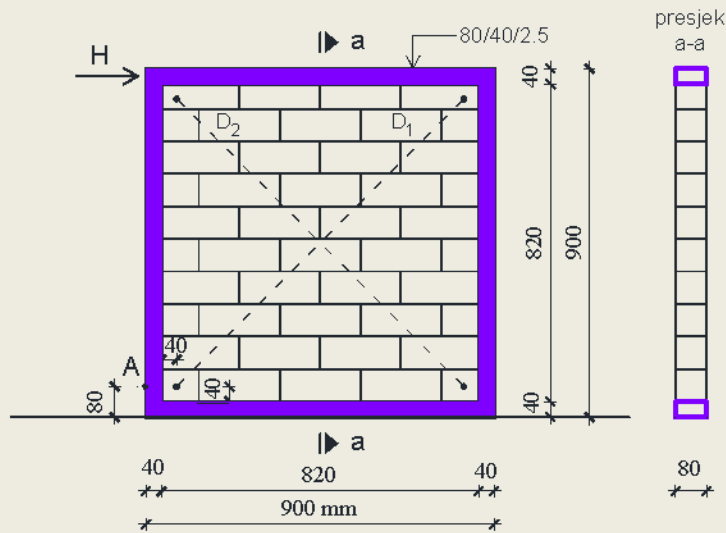
Broj polja: 1



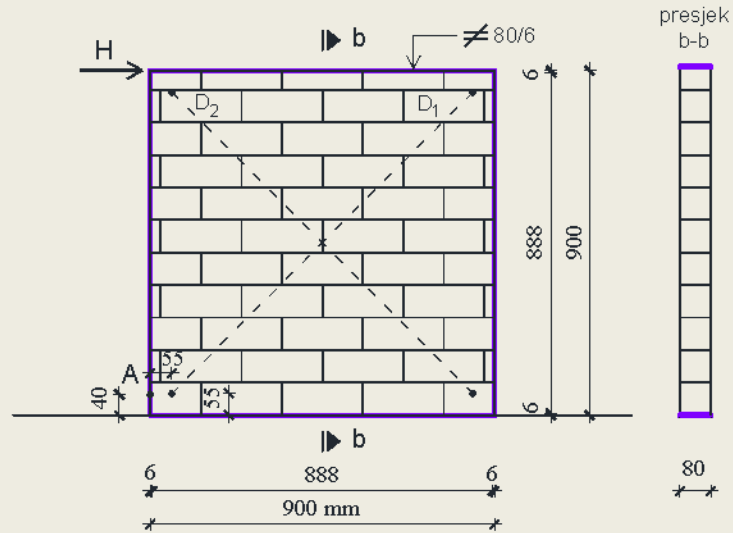
Broj uzoraka: 6

# Geometrija uzoraka

Kruti okvir (SF)



Meki okvir (WF)



## Mjerene veličine:

H – horizontalna sila

u – pomak vrha okvira

$\epsilon_A$  – deformacija čelika pri dnu stupa

$\epsilon_{D1}$  – prosječna deformacija u smjeru vlačne dijagonale D1

$\epsilon_{D2}$  – prosječna deformacija u smjeru tlačne dijagonale D2

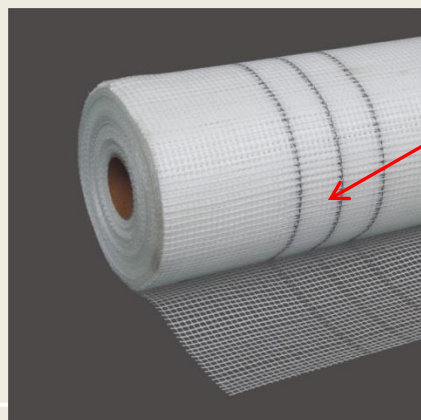


# Materijali

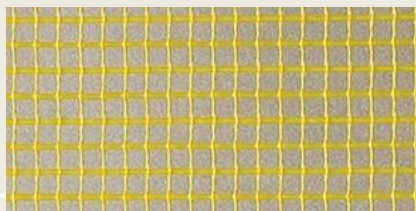
- čelik (klasa S240/360)
- porobetonski blok ( $\rho \approx 450 \text{ kg/m}^3$ ,  $f_b \approx 3 \text{ MPa}$ )
- bijeli tankoslojni mort (M10)
- mineralna predgotovljena žbuka s vlaknima
- staklena mrežica ( $4 \times 4 \text{ mm}$ )



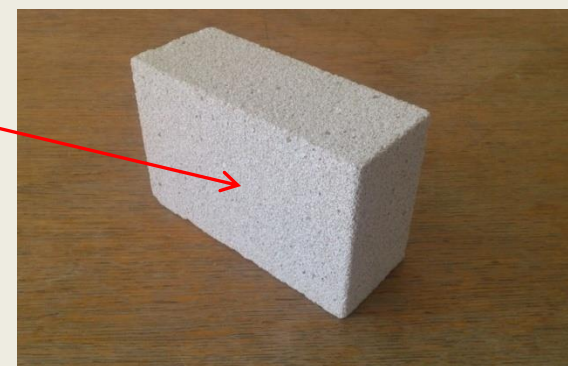
Debljina žbuke 10 mm



Staklena mrežica



Porobeton



## Uzorak prije ispitivanja

- konstantno vertikalno  $p = 5 \text{ kN/m}^2$
- monotono rastuća horizontalna sila  $H$





Uzorak: SF-1



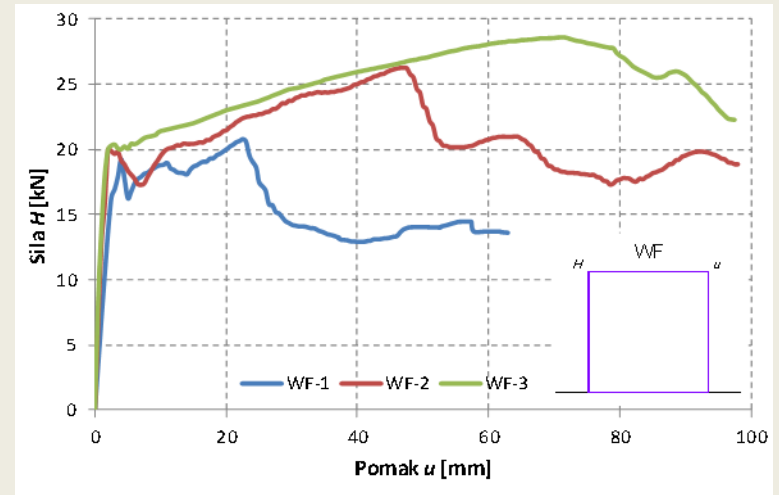
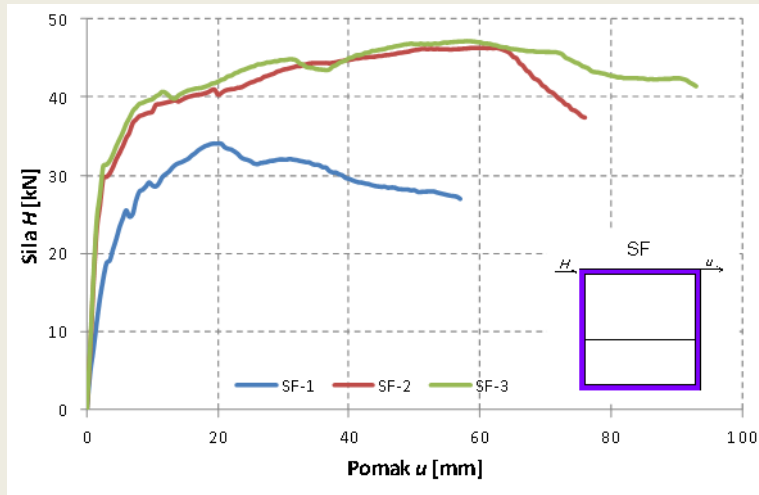
Uzorak: WF-1



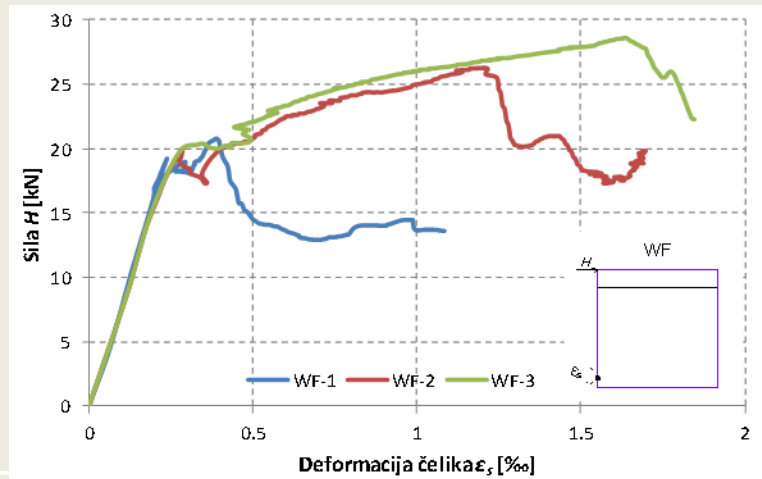
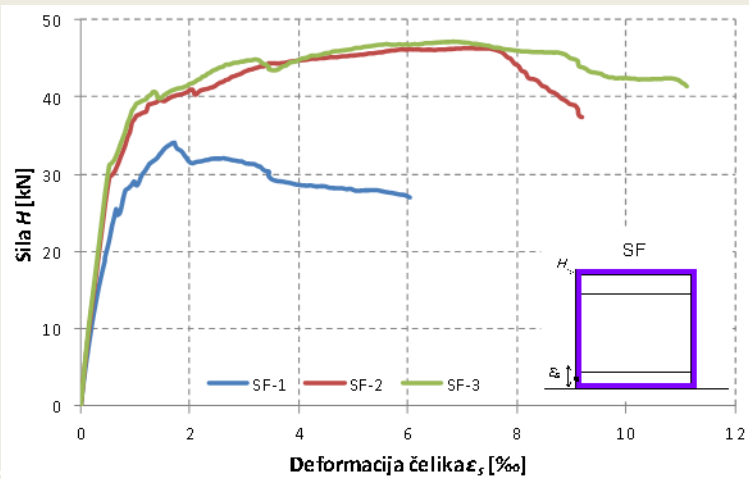


# Rezultati

## Veza sila ( $H$ ) - pomak ( $u$ )



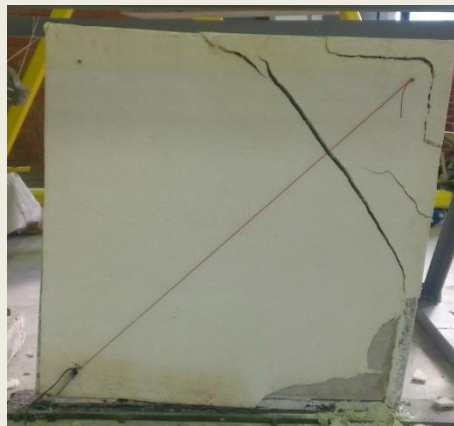
## Veza sila ( $H$ ) - deformacija ( $\epsilon_s$ )



## Konačno stanje pukotina i deformacija



SF-1



SF-2



SF-3



WF-1



WF-2



WF-3

## Konačno stanje pukotina i deformacija



- Drobljenje ispune u uglovima tlačne dijagonale
- Lokalno savijanje stupa



- Lokalno savijanje stupa na mjestu djelovanja sile



- Odizanje ispune
- Odvajanje ispune od okvira

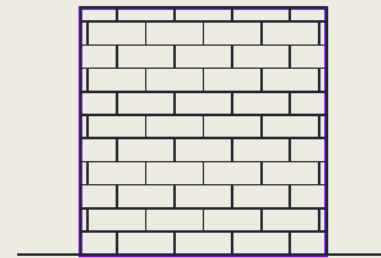
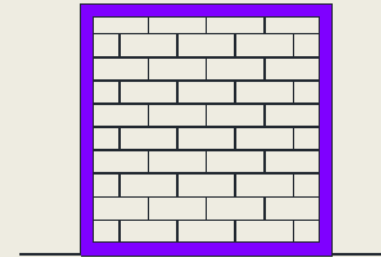
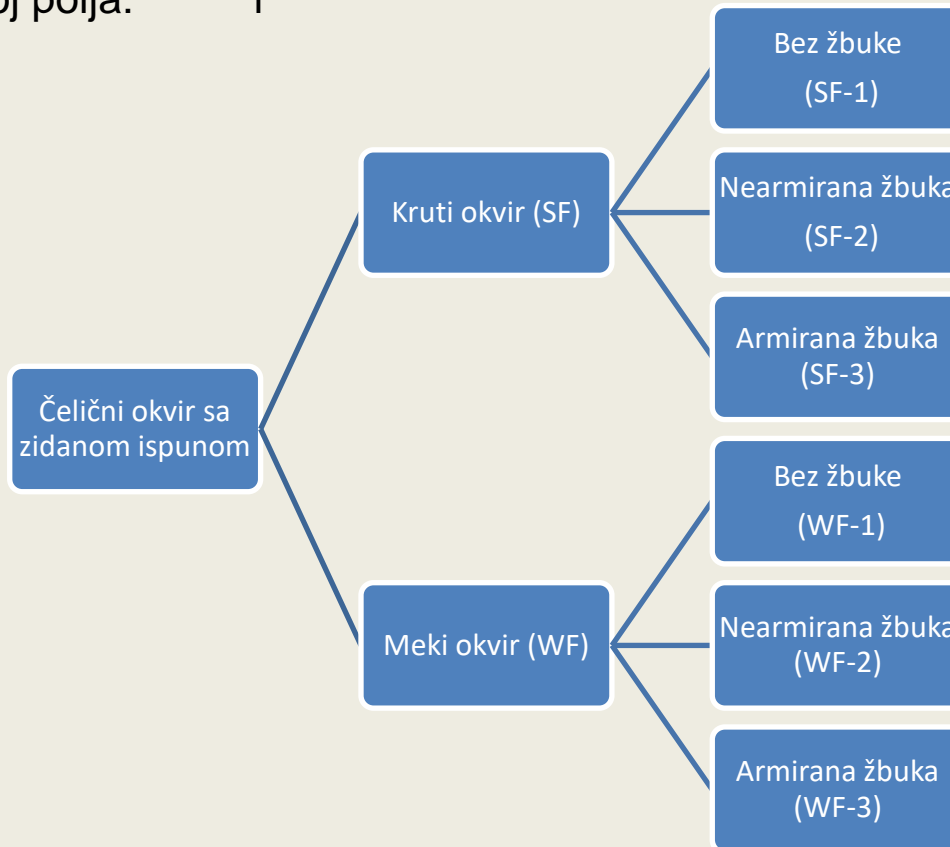


## 2. Dinamička ispitivanja čeličnih okvira sa zidanom ispunom

Mjerilo: 1/3

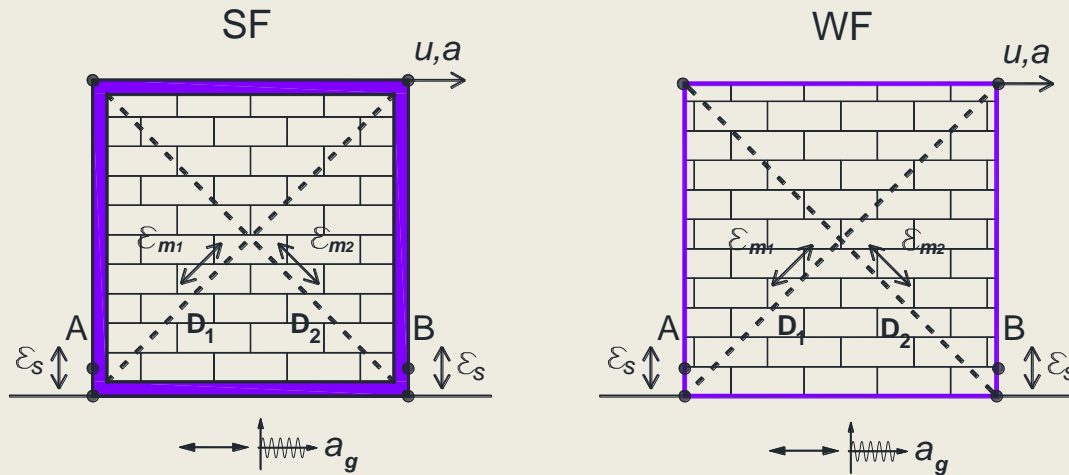
Broj etaža: 1

Broj polja: 1



Broj uzoraka: 6

# Mjerene veličine



$u$  – pomak vrha okvira

$a$  – ubrzanje vrha okvira

$\epsilon_s$  – deformacija čelika pri dnu stupa

$\epsilon_{D1}$  – prosječna deformacija u smjeru dijagonale D1

$\epsilon_{D2}$  – prosječna deformacija u smjeru dijagonale D2

$a_g$  – ubrzanje podloge (platforme)

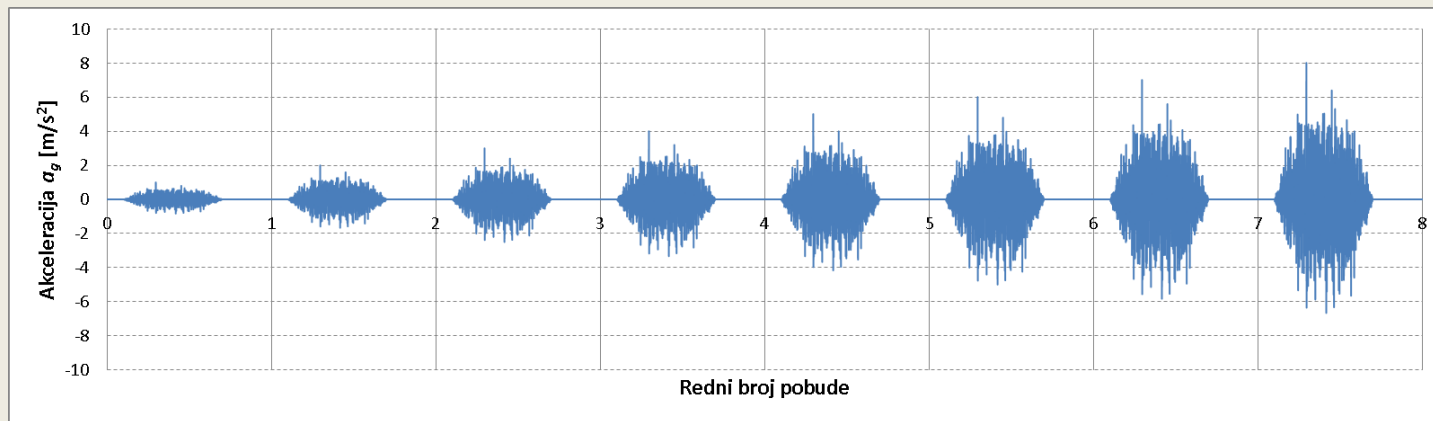




# Opterećenje

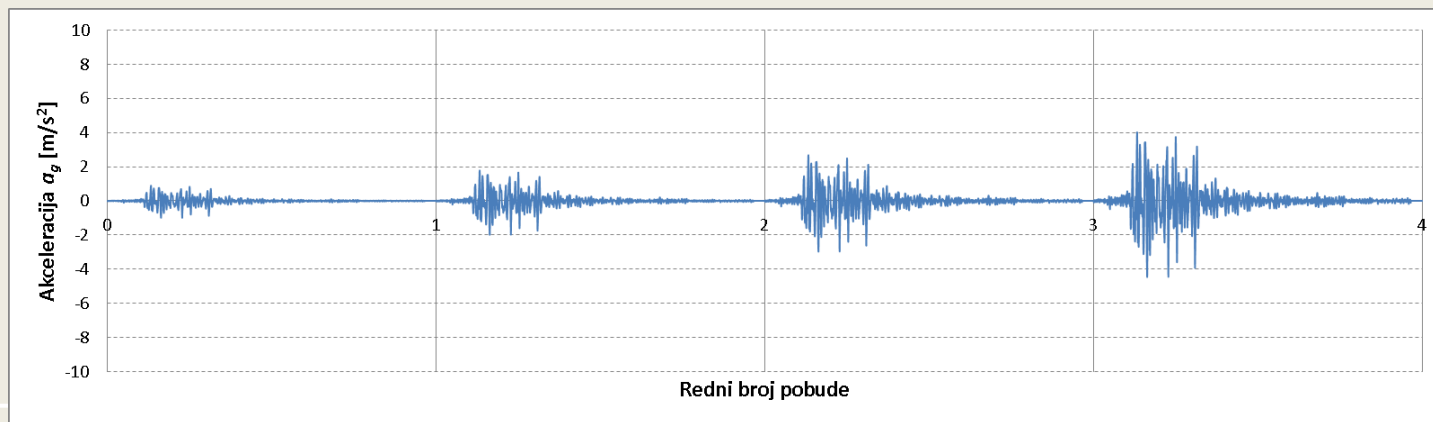
## Umjetni akceleroگرام AA1

PGA	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g	0.6 g	0.7 g	0.8 g
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## Potres Petrovac

PGA	0.1 g	0.2 g	0.3 g	0.45 g
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# Uzorak prije ispitivanja



- Vertikalno opterećenje  $G = 30 \text{ kN}$



**Uzorak: SF-1**  
**Pobuda: AA1**  
**PGA: 0.8 g**



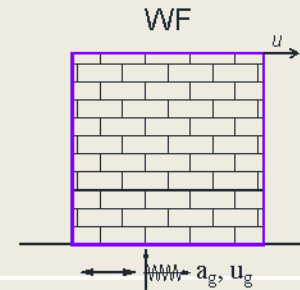
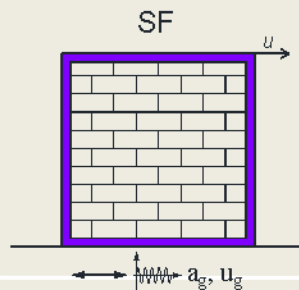
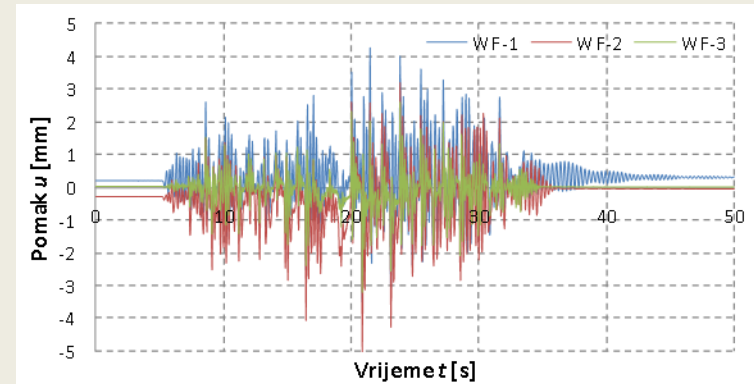
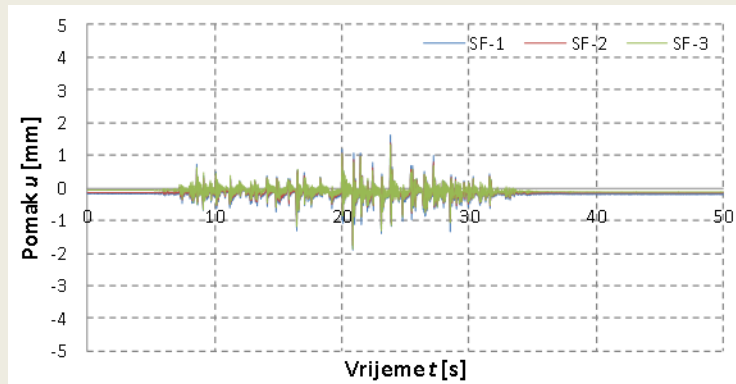
# Rezultati

Horizontalni pomak vrha okvira ( $u$ )

Umjetni akceleroگرام AA1

PGA = 0.8 g

- Veća krutost okvira → manji pomaci sustava
- Veća krutost ispune → manji pomaci sustava



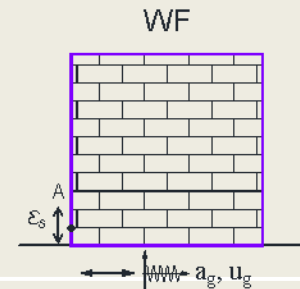
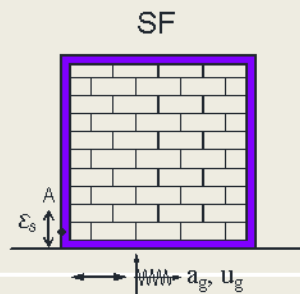
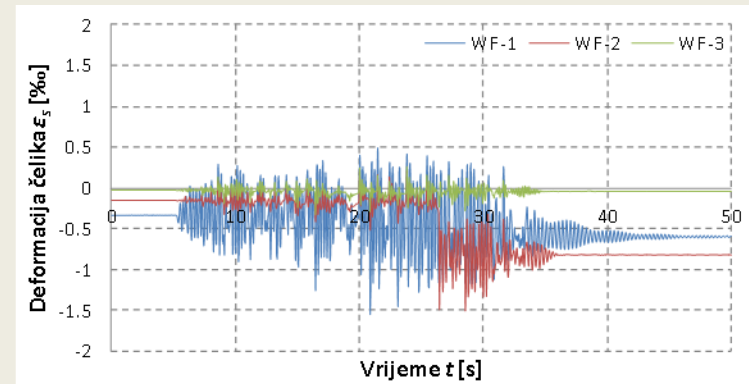
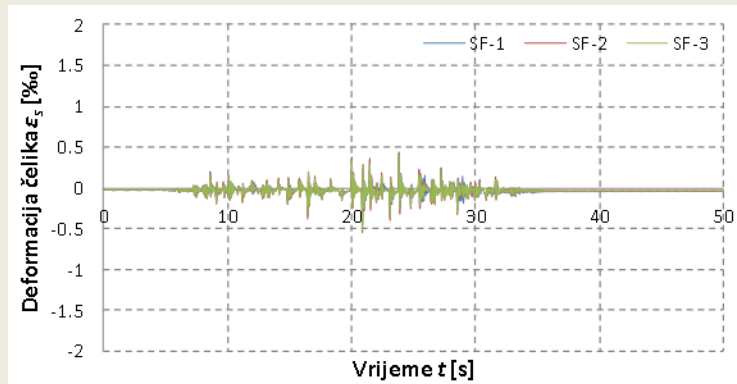
# Rezultati

Deformacija čelika pri dnu stupa u točki A ( $\epsilon_s$ )

Umjetni akcelorogram AA1

PGA = 0.8 g

- Veća krutost okvira → manje deformacije u okviru
- Veća krutost ispune → manje deformacije u okviru

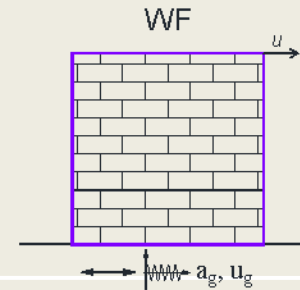
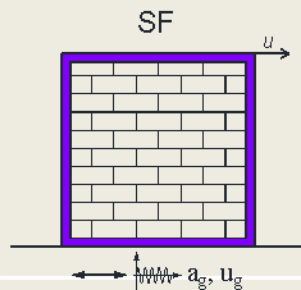
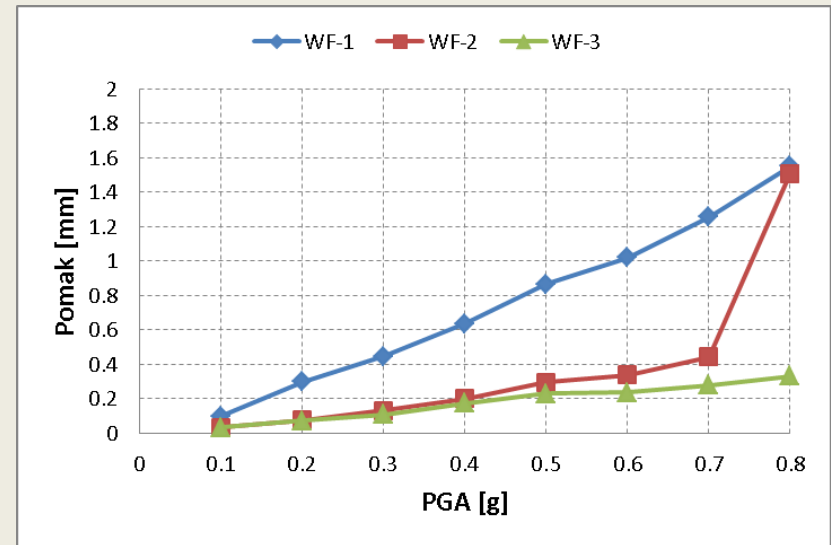
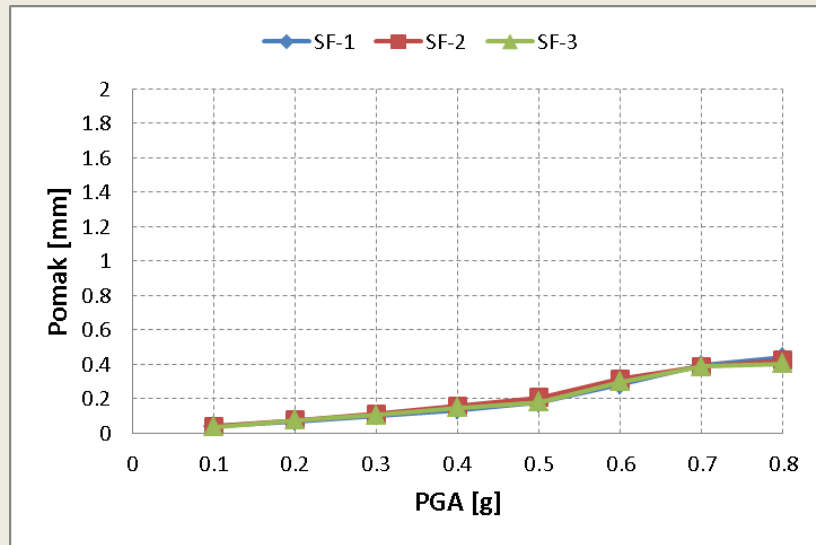




# Maksimalne vrijednosti

Horizontalni pomak vrha okvira (u)

Umjetni akcelorogram AA1



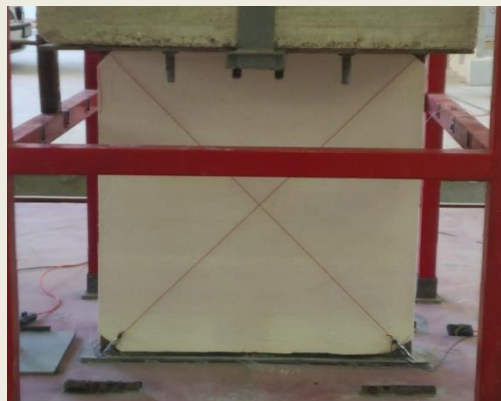
**Uzorak: SF-1**  
**Pobuda: Petrovac**  
**PGA: 0.3 g**



## Konačno stanje deformacija i pukotina



SF-1



SF-2



SF-3



WF-1



WF-2



WF-3

Napomena:

- Odvajanje ispune od okvira
- Pukotine u zidu i drobljenje ispune – okviri bez žbuke (SF-1 i WF-1)





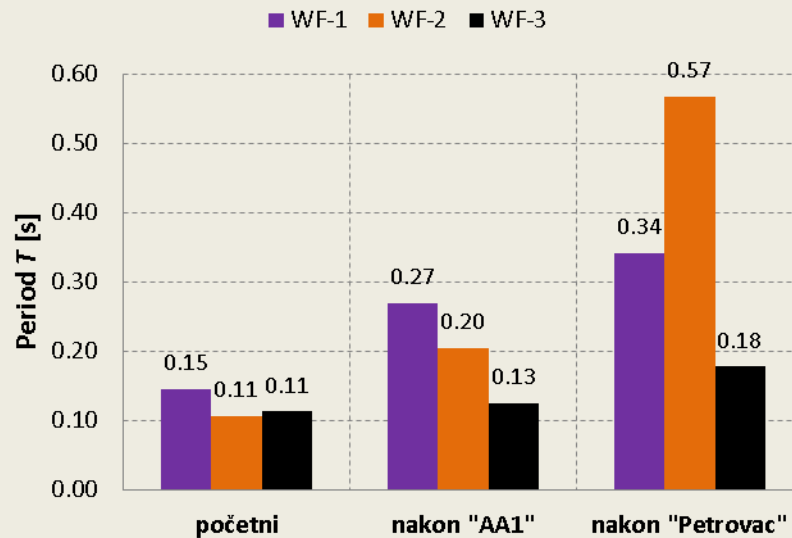
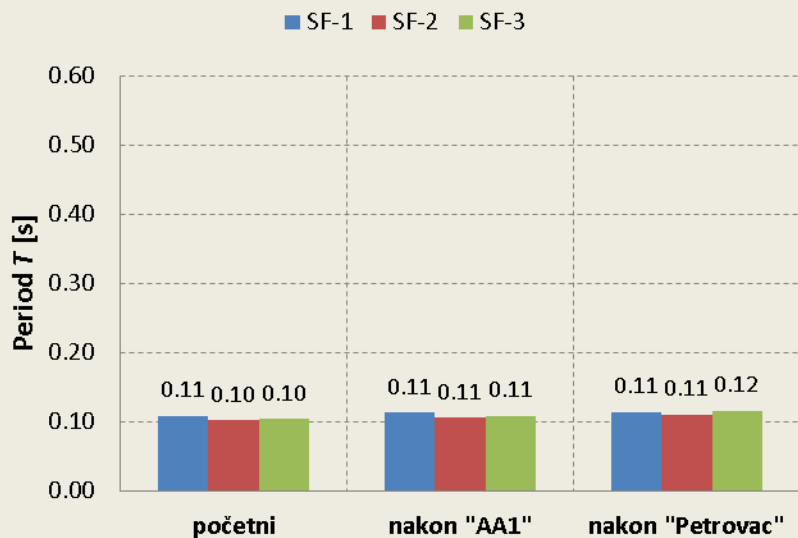
# Konačno stanje deformacija i pukotina



# Svojstvene vrijednosti

## VLASTITA FREKVENCIJA SUSTAVA

Frekvencija (Hz)	Uzorak					
	SF-1	SF-2	SF-3	WF-1	WF-2	WF-3
početni	9.20	9.76	9.57	6.84	9.37	8.80
nakon "AA1"	8.79	9.40	9.18	3.70	4.88	8.00
nakon "Petrovac"	8.78	8.98	8.59	2.93	1.76	5.60



## PRVI PERIODI SUSTAVA



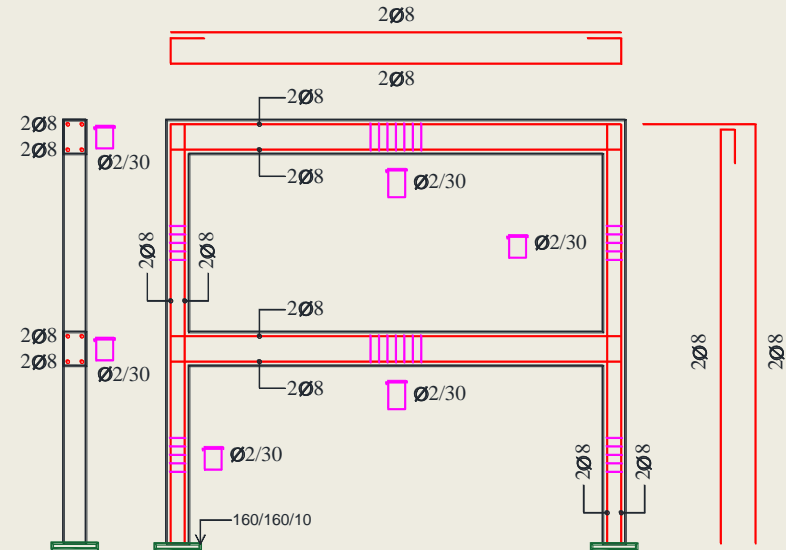
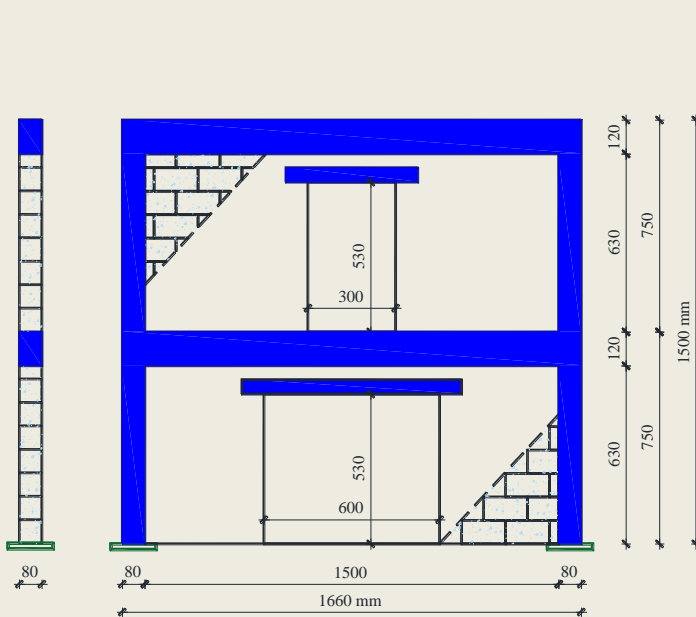


## 3. Dinamička ispitivanja armiranobetonskih okvira sa zidanom ispunom

- okvir bez ispune (BF)
- okvir s fleksibilnim prizemljem (FF1)
- okvir s fleksibilnim katom (FF2)
- okvir s manjim otvorom u ispuni na obje etaže (PF1)
- okvir s većim otvorom u ispuni na obje etaže (PF2)
- potpuno ispunjeni okvir (IF)



## GEOMETRIJA I ARMATURA ISPITNIH UZORAKA



Mjerilo: 1/4

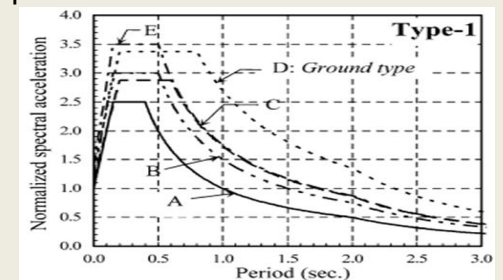
Broj etaža: 2

Broj polja: 1

Broj uzoraka: 6

Prototip okvira → proračun prema EN 1998:

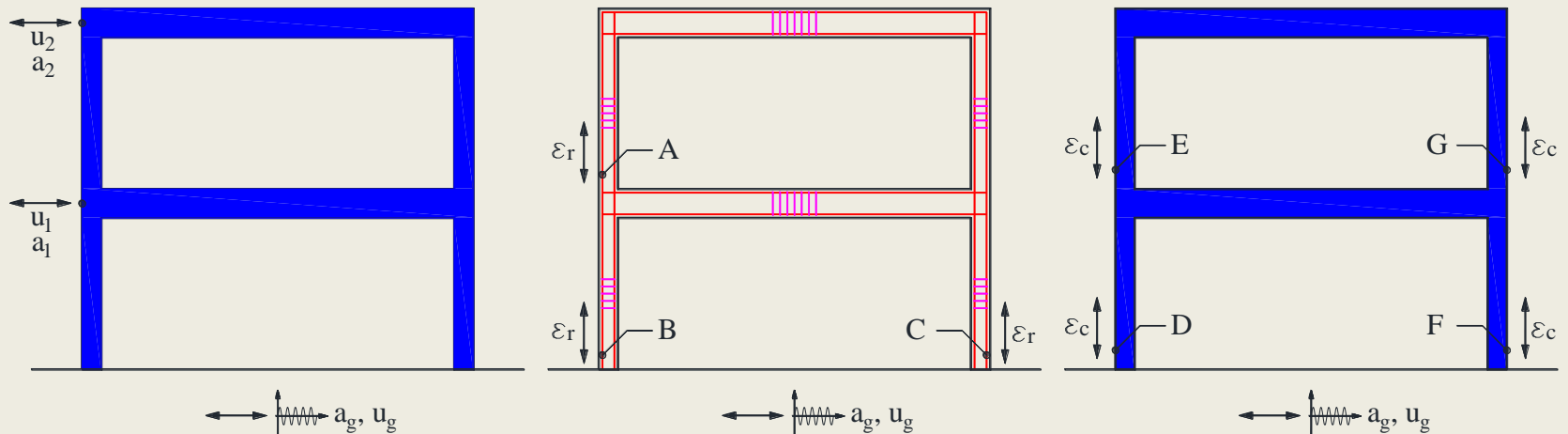
Tip 1  
Tip tla A



# Izrada uzoraka



# Mjerene veličine



$u_1$  pomak 1. etaže okvira  
 $u_2$  pomak 2. etaže okvira

$a_1$  ubrzanje 1. etaže okvira  
 $a_2$  ubrzanje 2. etaže okvira

$\epsilon_r$  deformacija u armaturi pri dnu stupa 1. i 2. etaže (točke A, B i C)  
 $\epsilon_c$  deformacija u betonu pri dnu stupa 1. i 2. etaže (točke D, E, F i G)

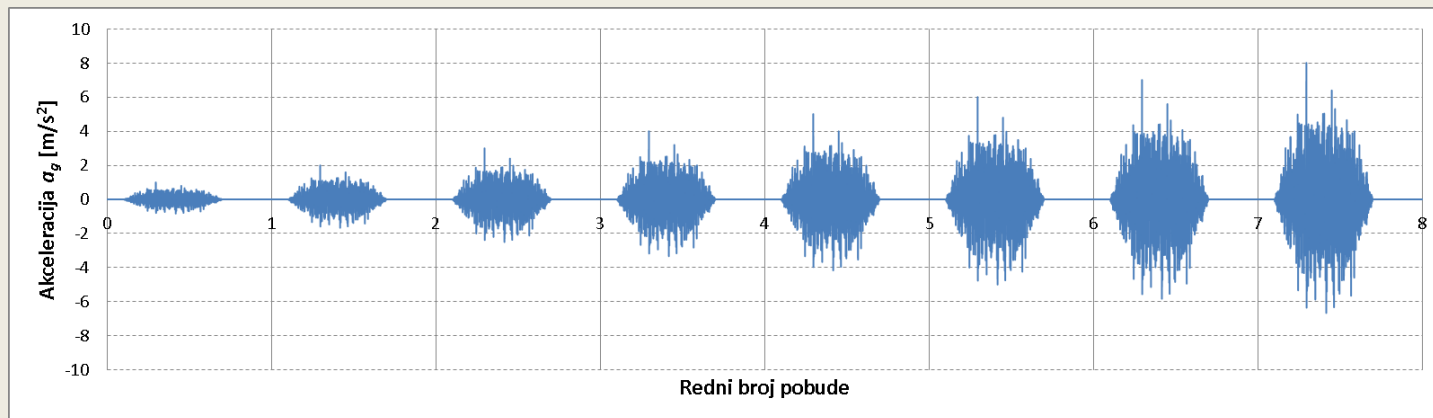
$a_g$  ubrzanje podloge (platforme)  
 $u_g$  pomak podloge (platforme)



# Potresno opterećenje

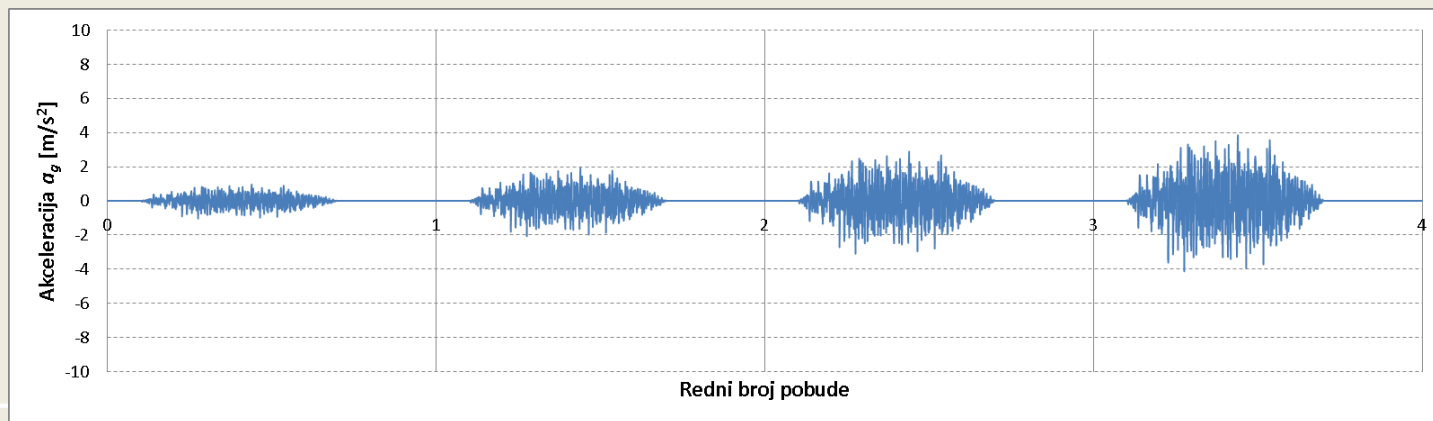
## Umjetni akceleroگرام AA1

PGA	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g	0.6 g	0.7 g	0.8 g
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## Umjetni akceleroگرام AA2

PGA	0.1 g	0.2 g	0.3 g	0.4 g
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# Priprema uzorka

- Vertikalno opterećenje (konstantno  $p = 3 \text{ kN/m}^1$ )



# Uzorci prije ispitivanja



BF



FF1



FF2



PF2



PF1



IF

# Vizualizacija

Uzorak: BF  
Pobuda: AA1  
PGA: 0.8 g



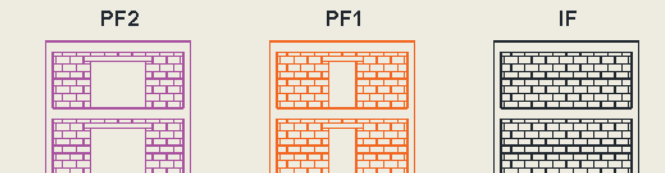
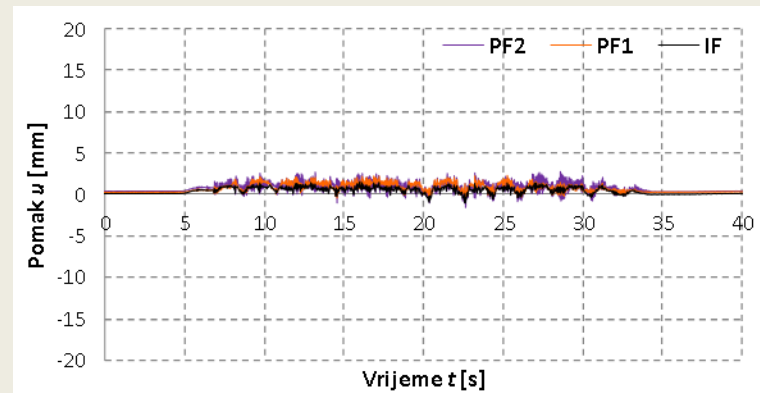
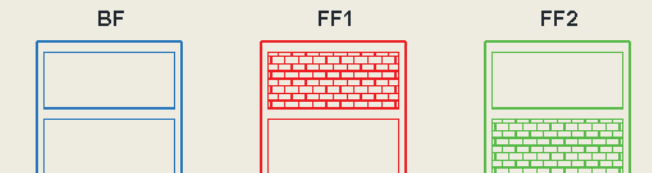
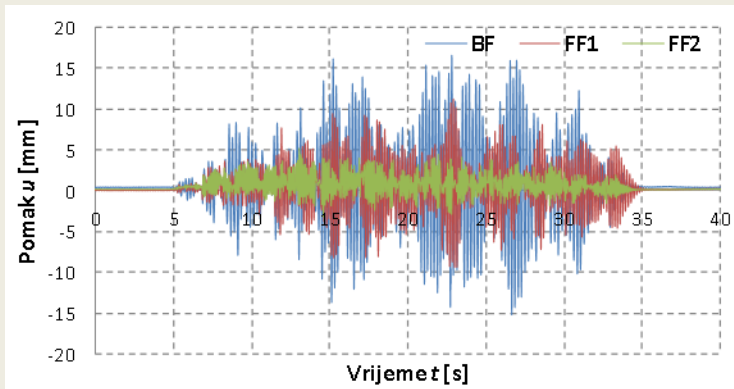
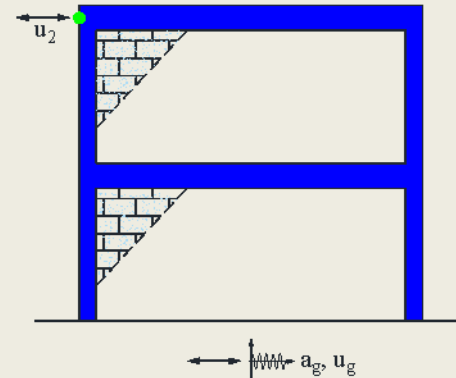


# Rezultati

Horizontalni pomak vrha gornje etaže okvira ( $u_2$ )

Umjetni akcelorogram AA1

PGA = 0.8 g

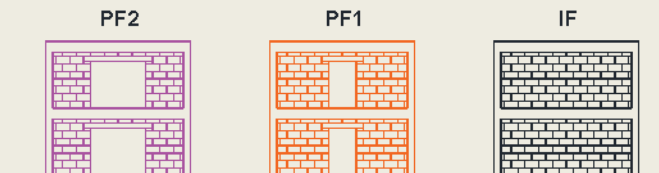
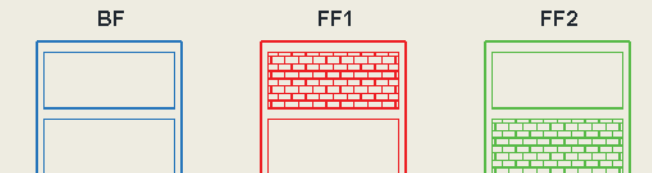
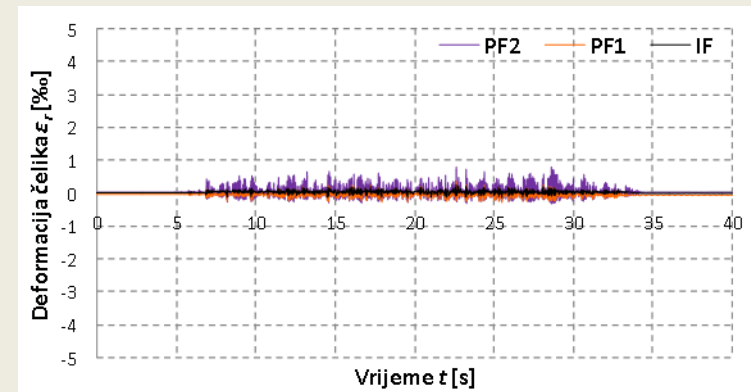
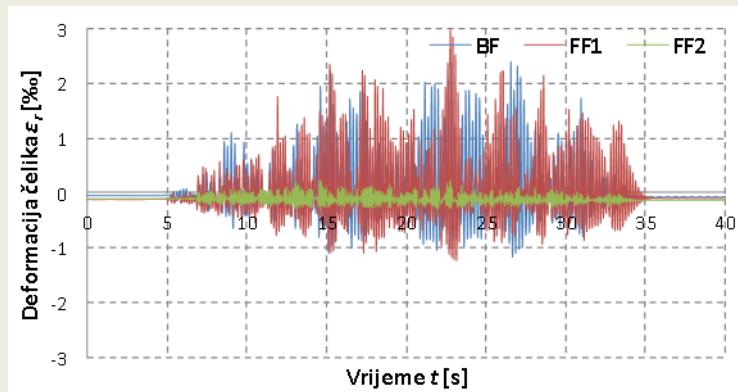
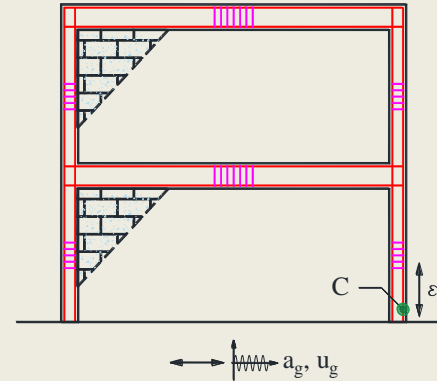


# Rezultati

Deformacija armature pri dnu stupa donje etaže okvira (točka C)

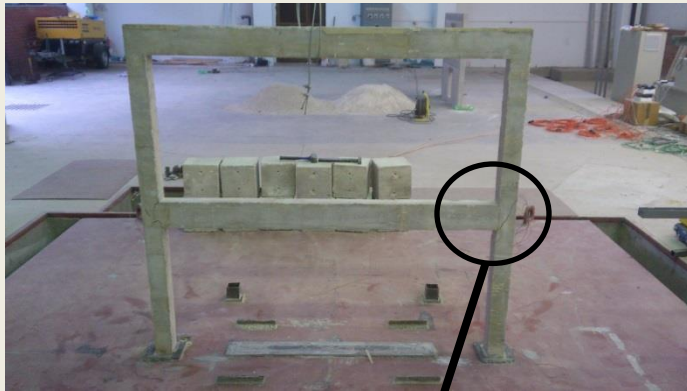
Umjetni akceleroگرام AA1

PGA = 0.8 g





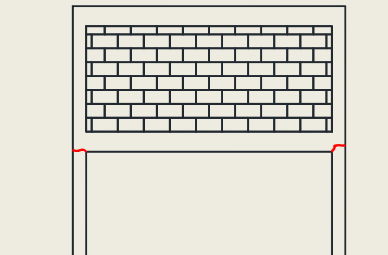
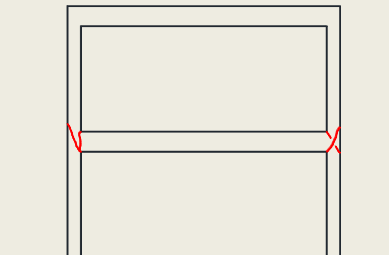
# Konačno stanje pukotina i deformacija



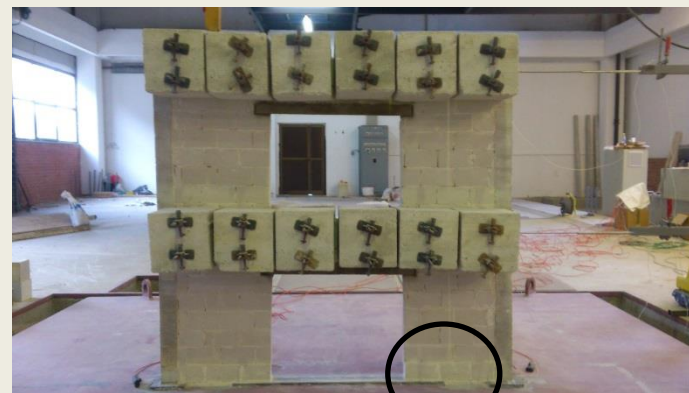
**BF**



**FF1**

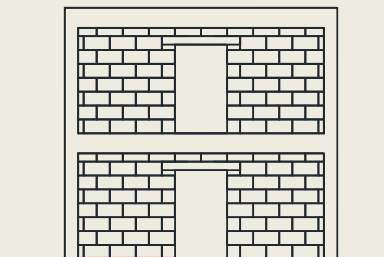
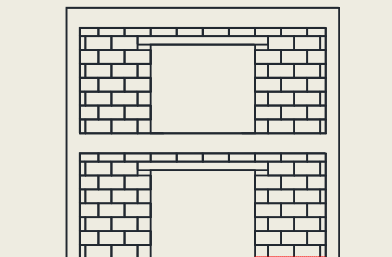


# Konačno stanje pukotina i deformacija



PF2

PF1

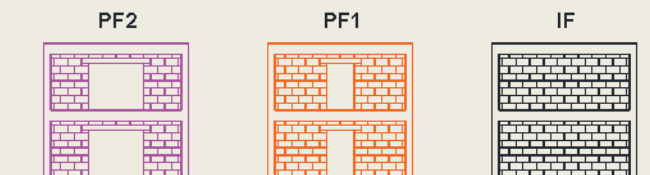
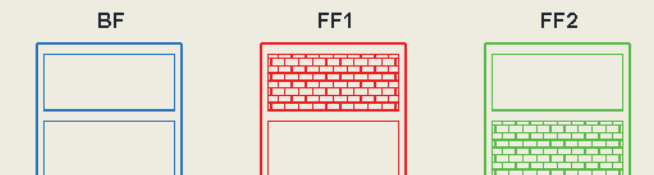
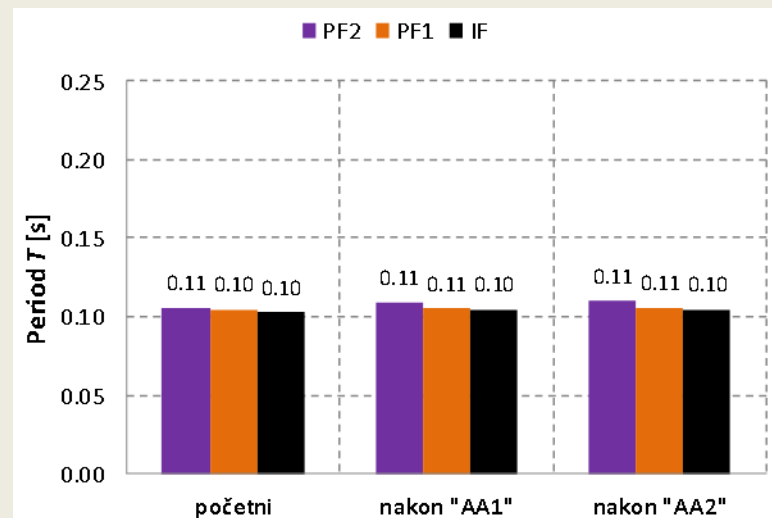
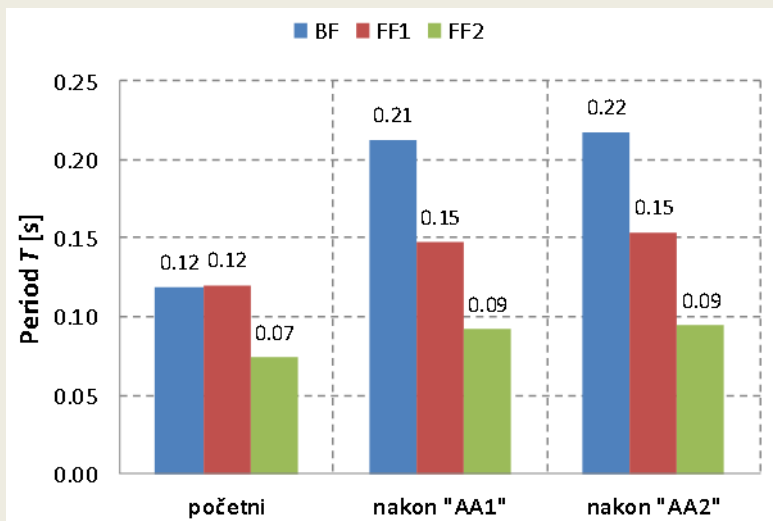


# Svojsvene vrijednosti

## VLASTITA FREKVENCIJA SUSTAVA

Frekvencija (Hz)	Uzorak					
	BF	FF1	FF2	PF2	PF1	IF
početni	8.40	8.30	13.50	9.45	9.55	9.75
nakon "AA1"	4.70	6.80	10.90	9.17	9.50	9.56
nakon "AA2"	4.60	6.50	10.60	9.10	9.45	9.56

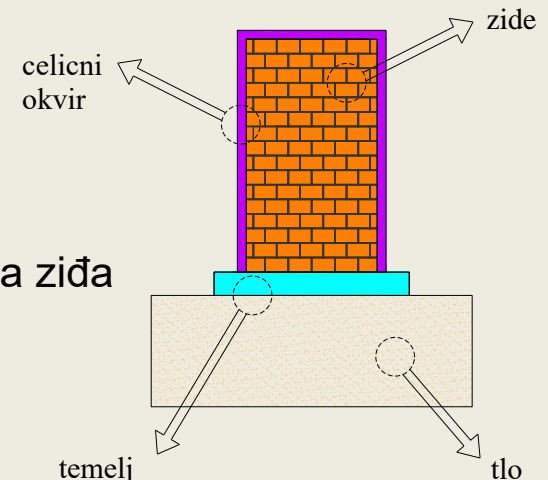
## PRVI PERIODI SUSTAVA



Numerički model za statičku i dinamičku analizu ravninskih konstrukcija od betona (okviri, zidovi), čelika (okviri) i žiđa

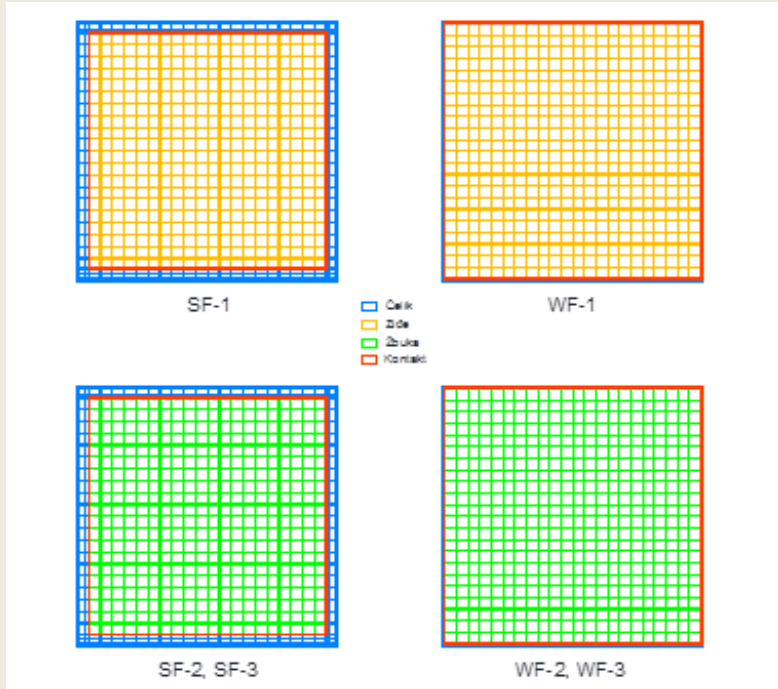
Model simulira sve najvažnije nelinearne efekte sustava okvir-ispuna-temelj-tlo

- Materijalna nelinearnost
- Geometrijska nelinearnost (veliki pomaci)
- Nelinearno ponašanje na spoju dva različita materijala (utiskivanje, klizanje, odvajanje)
- Popuštanje tla ispod temelja
- Interakcija zid-tlo pri dinamičkom opterećenju
- Efekt faznog nastajanja konstrukcije (okvira s ispunom)
- Simulacija nearmirane i armirane žbuke na vanjskim ploham zida



## 1. Statička ispitivanja čeličnih okvira sa zidanom ispunom

### PROSTORNA DISKRETIZACIJA



### NEKI PRORAČUNSKI ASPEKTI

2×2 Gauss-ova integracija

kriterij konvergencije = 0.1 %

### USVOJENI PARAMETRI MATERIJALA

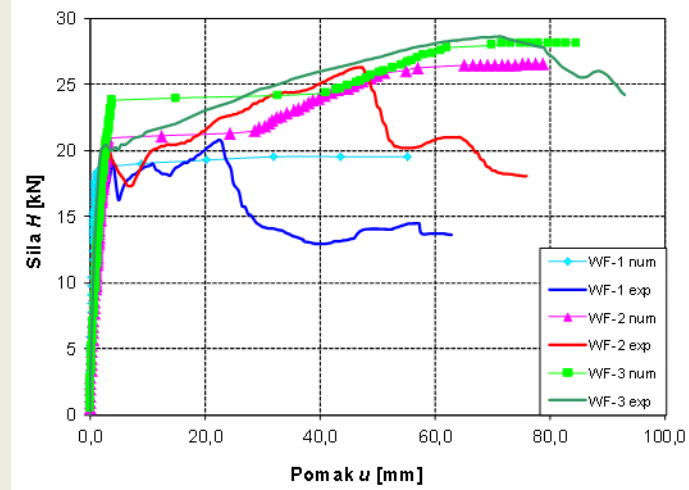
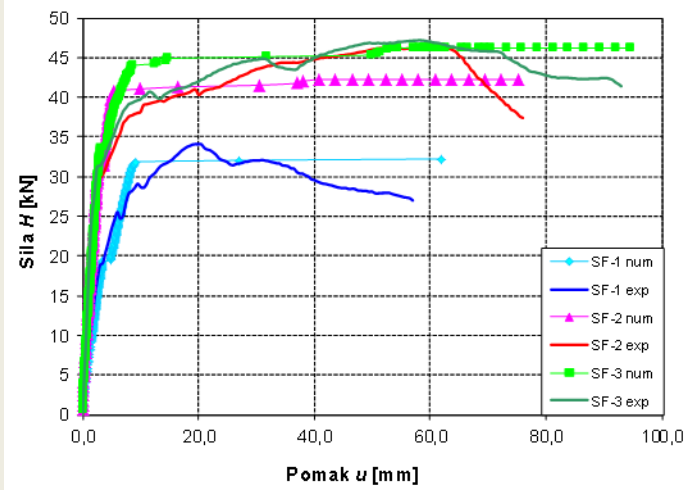
Varijabla	Jedinica	Materijal				
		Čelik	Zide	Žbuka	Stak mreža	Kontakt
Modul elastičnosti	MPa	200 000	1 020	3 500	1 231	1 020
Poissonov koeficijent	-	0.30	0.1	0.15	-	-
Modul posmika	MPa	76 923	464	1 522	-	464
Tlačna čvrstoća	MPa	360.0	2.2	3.0	-	2.2
Vlačna čvrstoća	MPa	360.0	0.2	1.0	42.8	0.0
Granična tlačna deformacija	-	0.0500	0.0035	0.0035	-	0.0035
Granična vlačna deformacija	-	0.0500	0.0029	0.0029	0.0348	0.0000



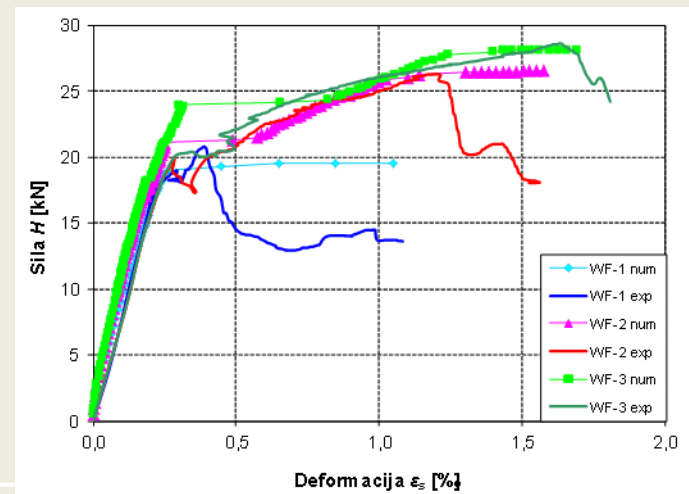
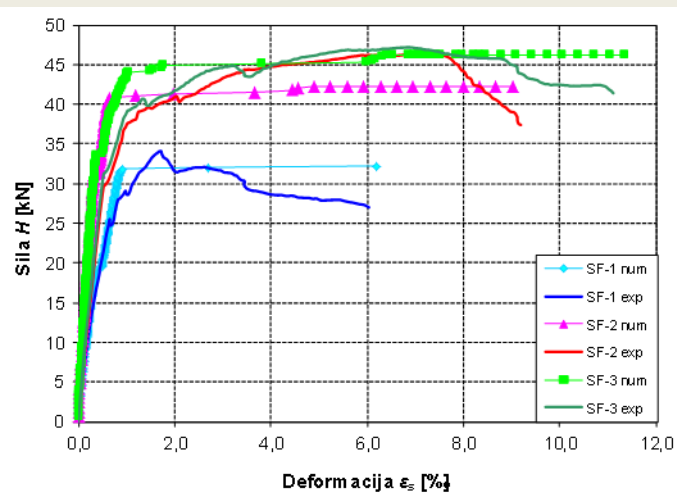


# Verifikacija numeričkog modela

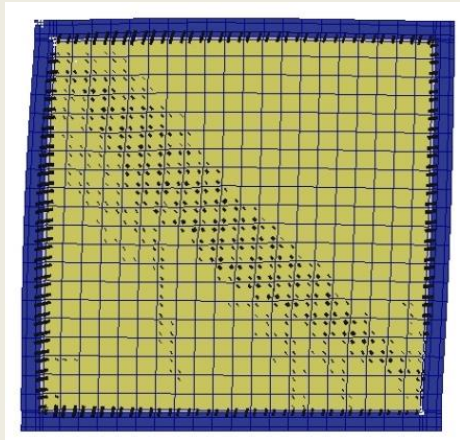
## Veza sila ( $H$ ) - pomak ( $u$ )



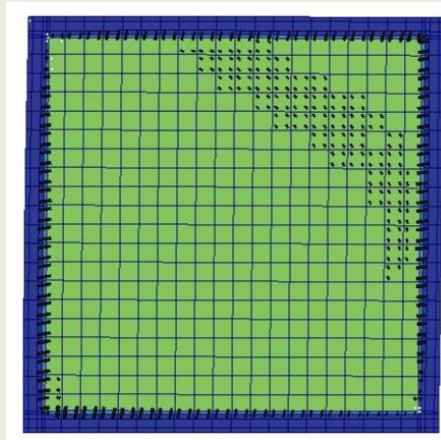
## Veza sila ( $H$ ) - deformacija ( $\epsilon_s$ )



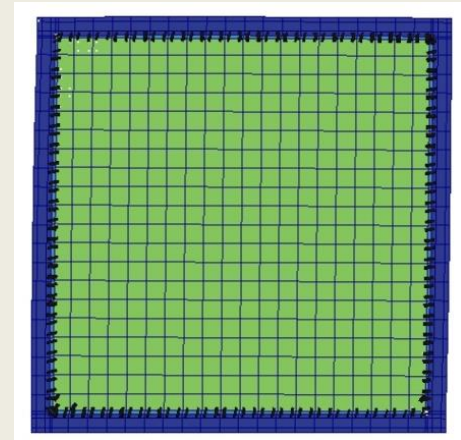
# Verifikacija numeričkog modela



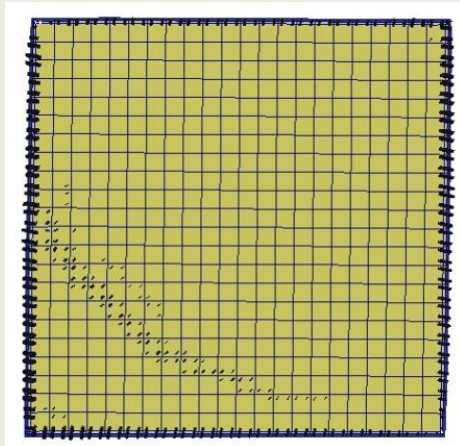
SF-1



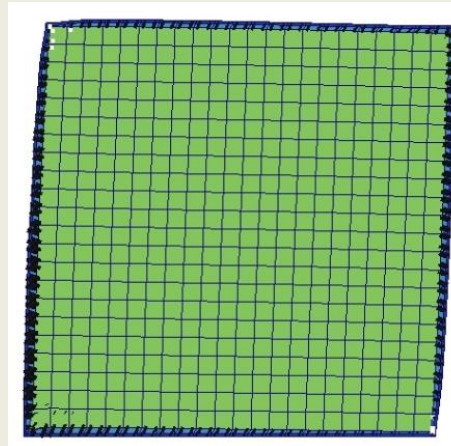
SF-2



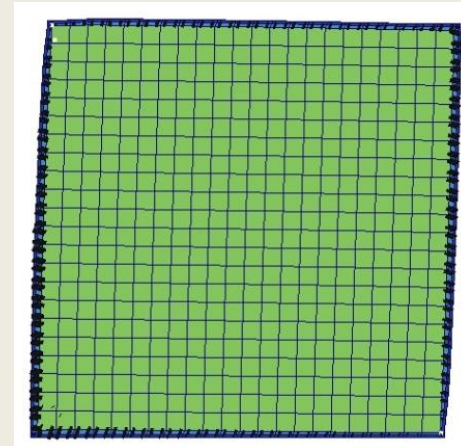
SF-3



WF-1



WF-2

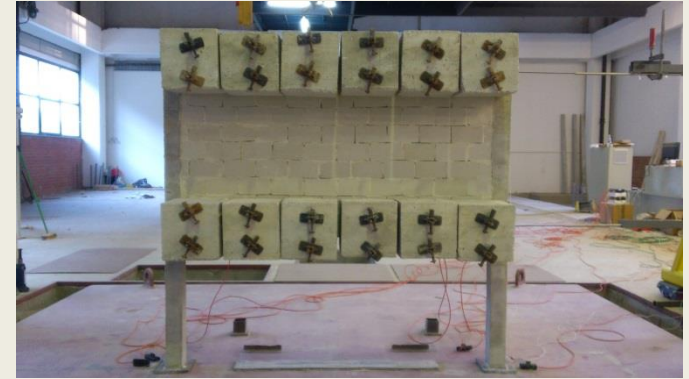
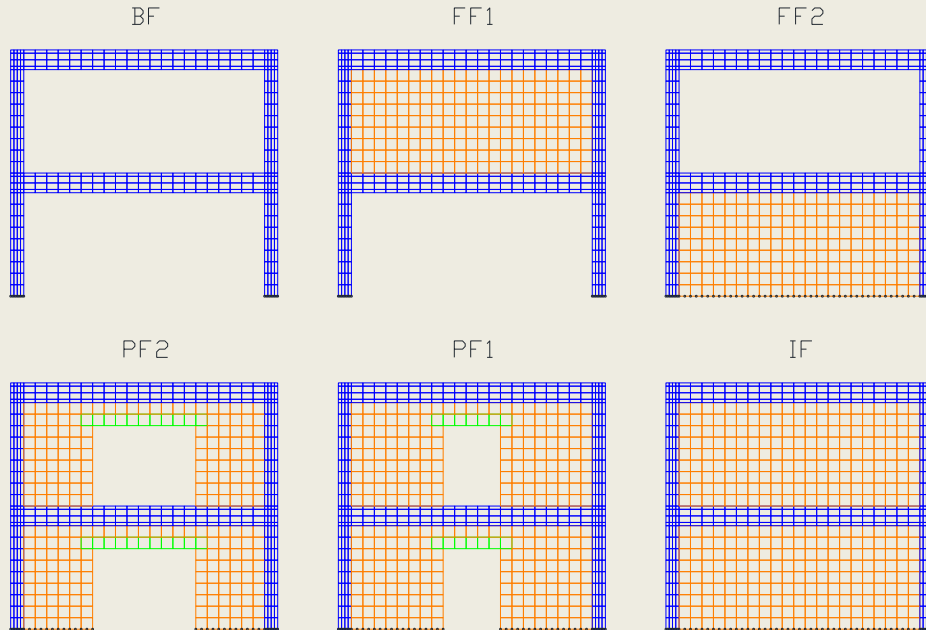


WF-3



## 4. Dinamička ispitivanja betonskih okvira sa zidanom ispunom

### PROSTORNA DISKRETIZACIJA



### NEKI PRORAČUNSKI ASPEKTI

2×2 Gauss-ova integracija

implicitna vremenska integracija

$$\Delta t = 1/100 T_1$$

kriterij konvergencije = 0.1 ‰

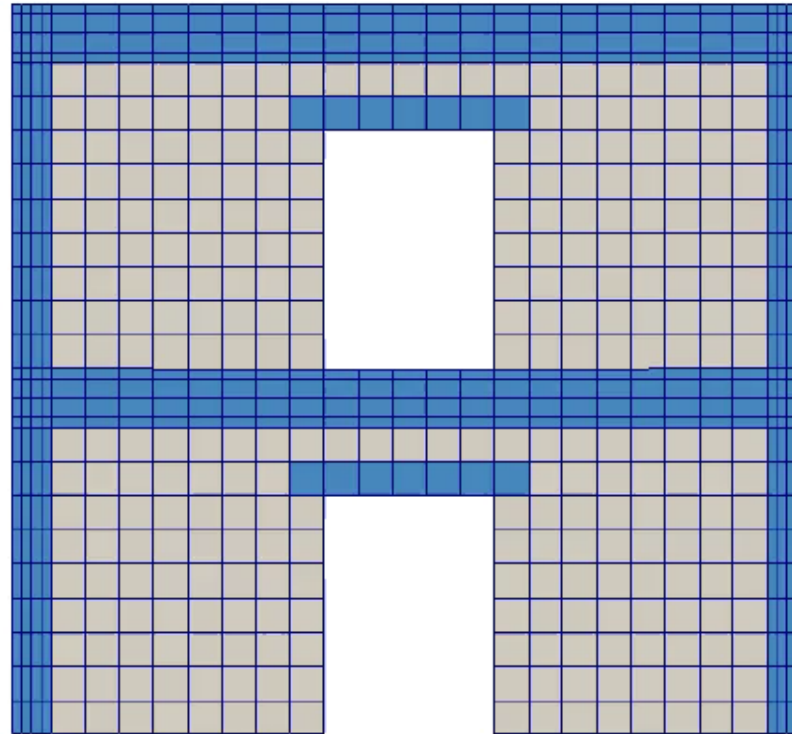
viskozno prigušenje = 2 ‰

### USVOJENI PARAMETRI MATERIJALA

Varijable	Jedinica	Materijal			
		Beton	Ziđe	Armatura	Kontakt
Modul elastičnosti	MPa	36 000	1 020	200 000	1 020
Poissonov koeficijent	-	0.15	0.1	-	-
Modul posmika	MPa	13 000	464	-	464
Tlačna čvrstoća	MPa	50.0	2.2	500.0	2.2
Vlačna čvrstoća	MPa	3.0	0.2	500.0	0.0
Grafična tlačna deformacija	-	0.0035	0.0035	0.0100	0.0035
Grafična vlačna deformacija	-	0.0010	0.0029	0.0100	0.0000



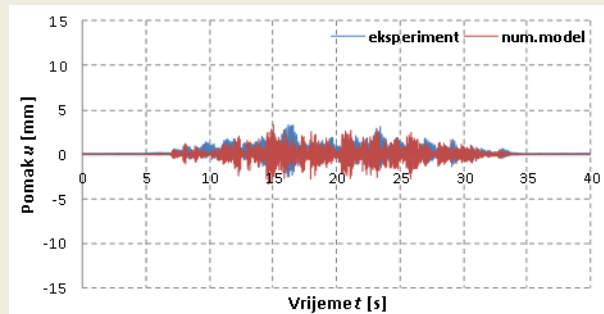
**Specimen: PF-1**  
**Excitation: AA1**  
**PGA: 0.4 g**



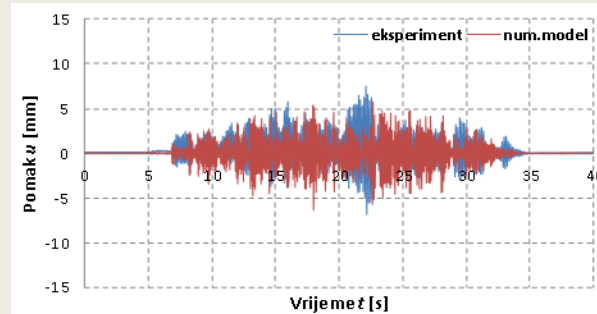
# Verifikacija numeričkog modela

Uzorak: FF1 (okvir s fleksibilnim prizemljem) - pomak vrha gornje etaže  $u_2$

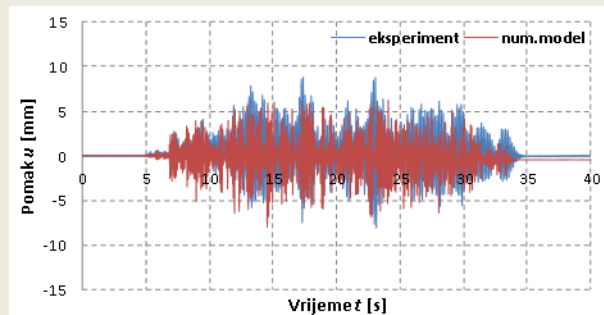
Umjetni akcelorogram AA1



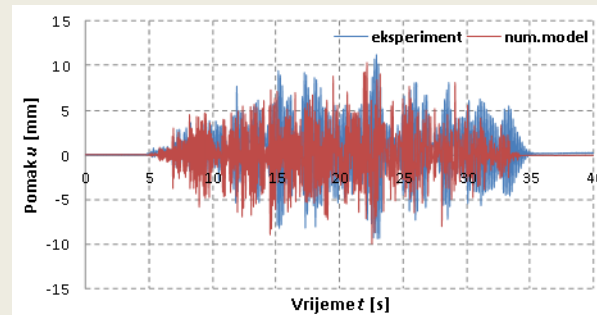
PGA = 0.2 g



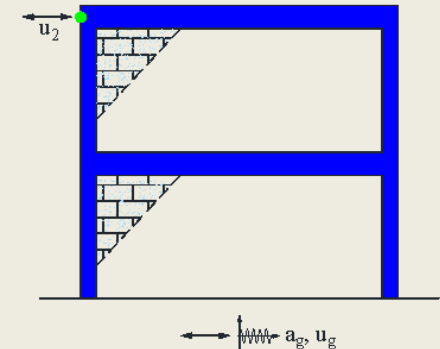
PGA = 0.4 g



PGA = 0.6 g



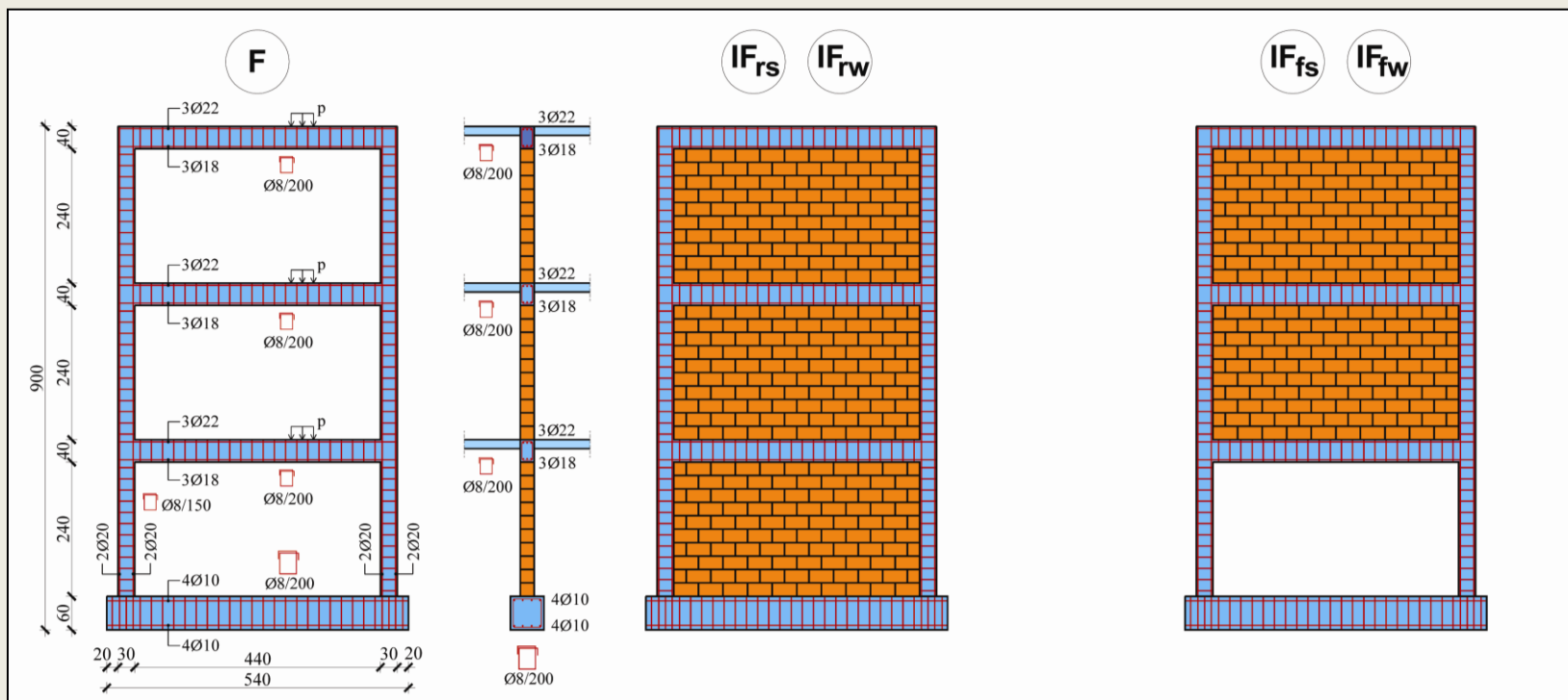
PGA = 0.8 g





# Analiza troetažnog okvira

- F čisti armiranobetonski okvir  
IF<sub>rs</sub> armiranobetonski okvir s krutim zidom na svim etažama  
IF<sub>rw</sub> armiranobetonski okvir s mekim zidom na svim etažama  
IF<sub>fs</sub> armiranobetonski okvir s fleksibilnim prizemljem i krutim zidom na gornjim etažama  
IF<sub>fw</sub> armiranobetonski okvir s fleksibilnim prizemljem i mekim zidom na gornjim etažama

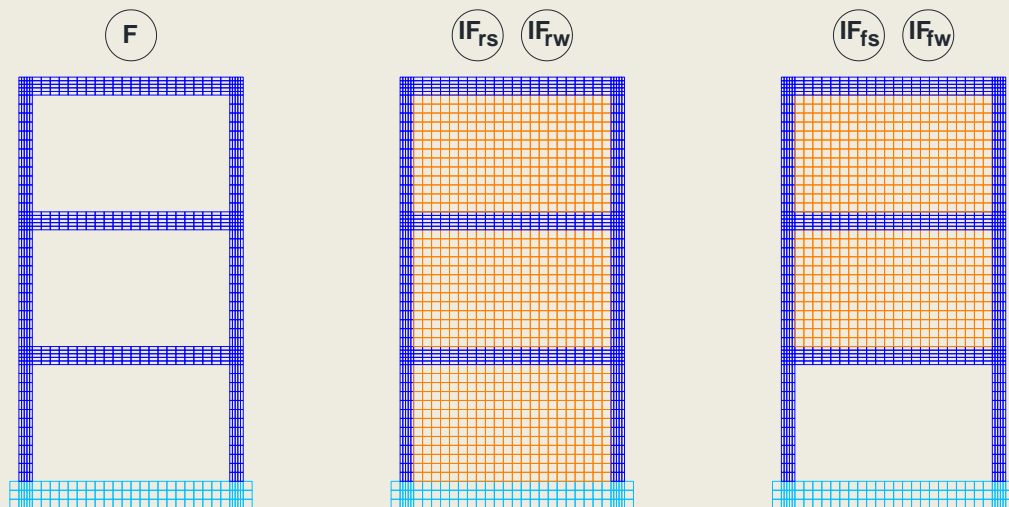


Proračun prema EN 1998:

- proračunsko ubrzanje tla 0.3 g
- faktor ponašanja  $q = 3.6$



## DISKRETIZACIJA KONSTRUKCIJE



## NEKI PRORAČUNSKI ASPEKTI

2×2 Gauss-ova integracija  
 implicitna vremenska integracija  
 $\Delta t = 1/100 T_1$   
 kriterij konvergencije = 0.1 ‰  
 viskozno prigušenje = 2 %

## USVOJENI PARAMETRI GRADIVA

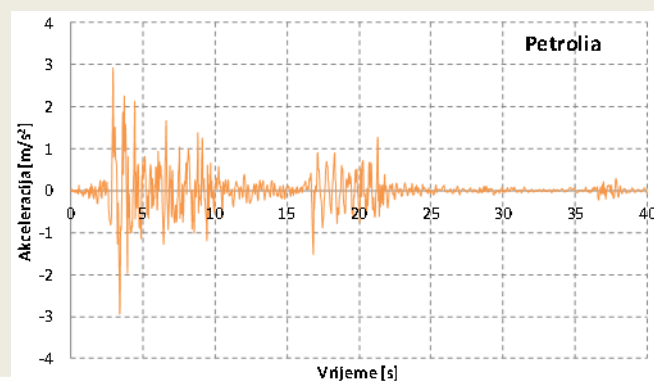
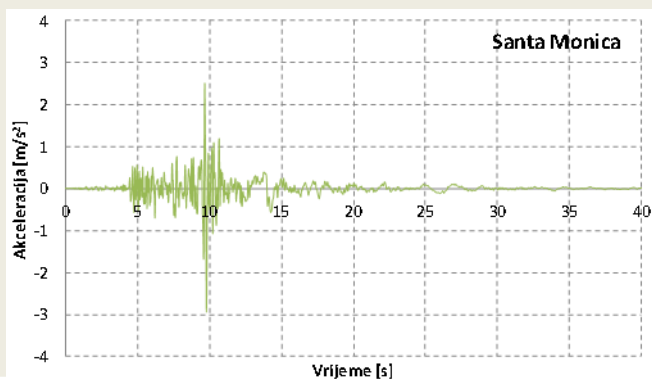
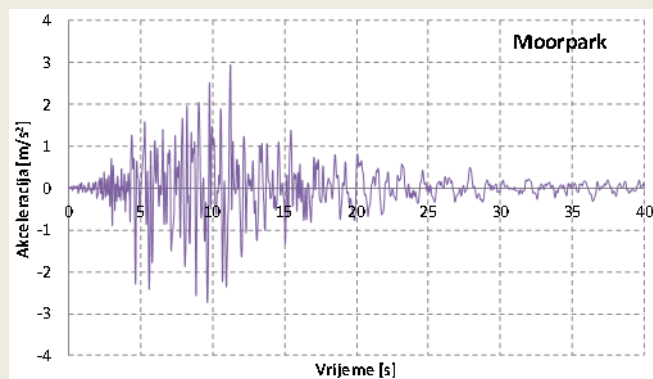
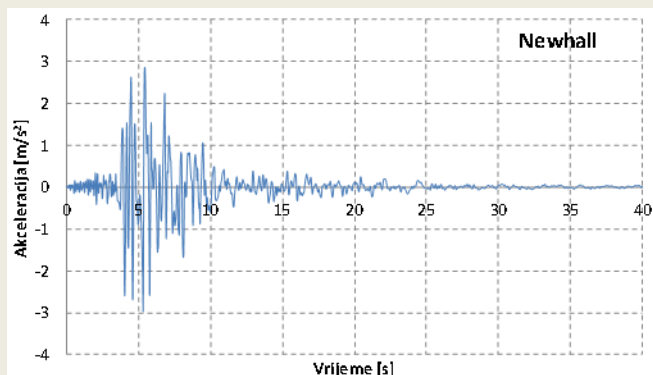
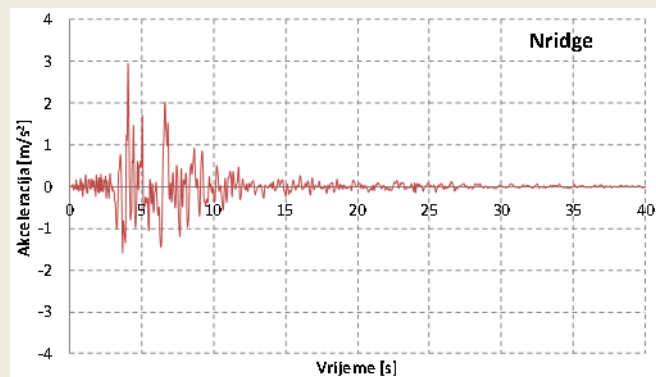
Varijabla	Jedinica	Materijal				
		Beton	Čelik	Kruto ziđe	Meko ziđe	Kontakt
Modul elastičnosti	MPa	30 000	200 000	5 000	1 000	30 000
Poissonov koeficijent	-	0.2	-	0.1	0.1	-
Modul posmika	MPa	12 500	-	1000	200	12 500
Tlačna čvrstoća	MPa	30	600	5	1	30
Vlačna čvrstoća	MPa	3	600	0.15	0.03	0
Grafična tlačna deformacija	-	-0.0035	-0.02	-0.01	-0.01	-0.0035
Grafična vlačna deformacija	-	0.001	0.02	0.0003	0.0003	0



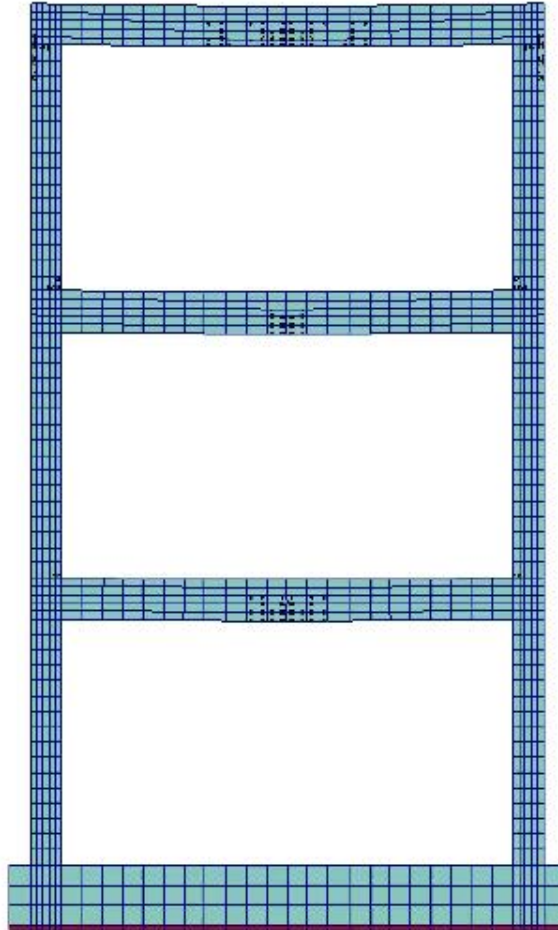
# Analiza troetažnog okvira

## OPTEREĆENJE

- vlastita težina
- dodatno stalno opterećenje iznosa  $p = 35 \text{ kN/m}^1$
- potres (PGA = 0.3 g)

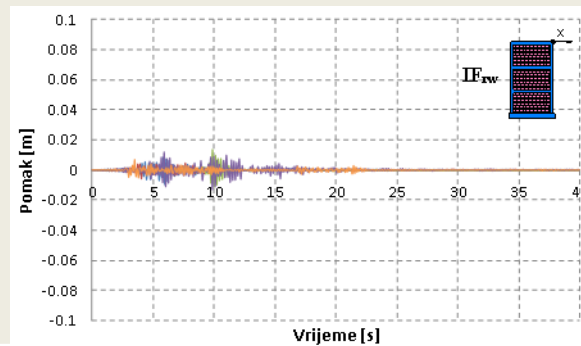
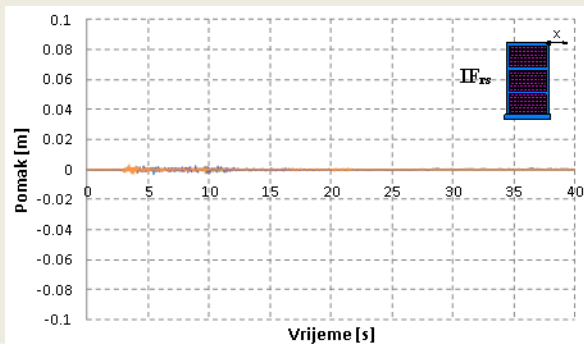
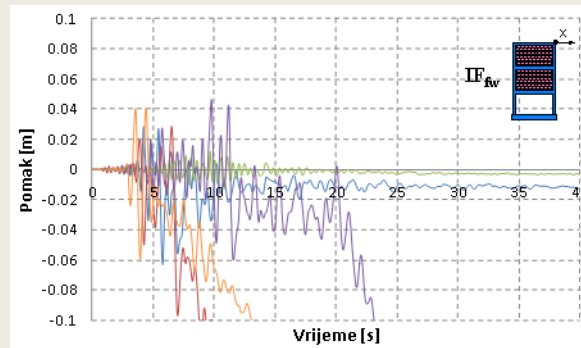
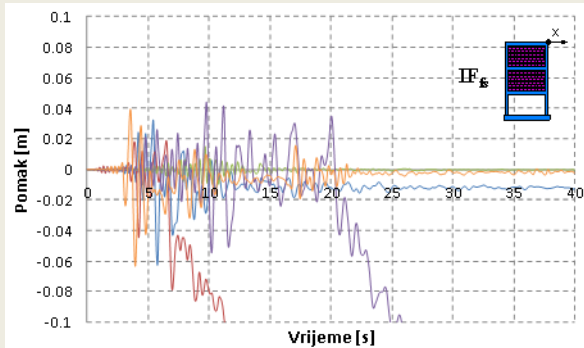
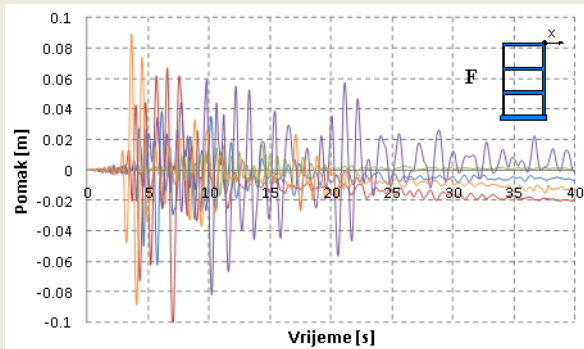


Oznaka: F  
Potres: Newhall



# Rezultati

## Pomak vrha okvira ( $u$ )





- Utjecaj krutosti okvira: veća krutost → manji pomaci i oštećenja konstrukcije
- Utjecaj ispune: veća krutost sustava → veće seizmičke sile
- Utjecaj žbuke: veća krutost i duktilnost sustava
- Fleksibilnost prizemlja: veći pomaci konstrukcije
- Otvori u ispuni: veći pomaci konstrukcije

HVALA NA  
PAŽNJI!

