

Organizatori



SVEUČILIŠTE U ZAGREBU
GRAĐEVINSKI FAKULTET
UNIVERSITY OF ZAGREB
FACULTY OF CIVIL ENGINEERING



SVEUČILIŠTE U SPLITU
FAKULTET GRAĐEVINARSTVA,
ARHITEKTURE I GEODEZIJE



Hrvatska komora
inženjera građevinarstva

WEBINAR

"SAVJETOVANJE 4: OBNOVA ZAGREBA NAKON POTRESA – ZAGREBU OD SPLITA"



Glavni pokrovitelj



ISKUSTVA I EKSPERIMENTALNA ISTRAŽIVANJA U
VEZI SEIZMIČKE SANACIJE ZIDANIH ZGRADA

Doc. dr. sc. Hrvoje Smoljanović
Fakultet građevinarstva, arhitekture i geodezije,
Katedra za teoriju konstrukcija
Split, Hrvatska



SVEUČILIŠTE U SPLITU
FAKULTET GRAĐEVINARSTVA,
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UNIVERSITY OF SPLIT
FACULTY OF CIVIL ENGINEERING,
ARCHITECTURE AND GEODESY

KATEDRA ZA TEORIJU KONSTRUKCIJA

PRIMJENA FDEM METODE U POTRESNOM INŽENJERSTVU



istraživanja ponašanja
 konstrukcija izloženih seizmičkom opterećenju

**RAZVOJ NUMERIČKIH MODELA ZA
 SIMULACIJU DINAMIČKOG
 ODGOVORA**

- SUHO ZIDANIH KAMENIH KONSTRUKCIJA
- NEARMIRANIH ZIDANIH KONSTRUKCIJA OD BLOKOVA POVEZANIH MORTOM
- SUVREMENIH ZIDANIH KONSTRUKCIJA OMEĐENIH AB SERKLAŽIMA
- AB KONSTRUKCIJE

RAZVOJ NUMERIČKOG MODELA ZA SIMULACIJU DINAMIČKOG ODGOVORA GORE NAVEDENIH KONSTRUKCIJA KOJI MOŽE OBUHVATITI POJAVE VEZANE ZA:

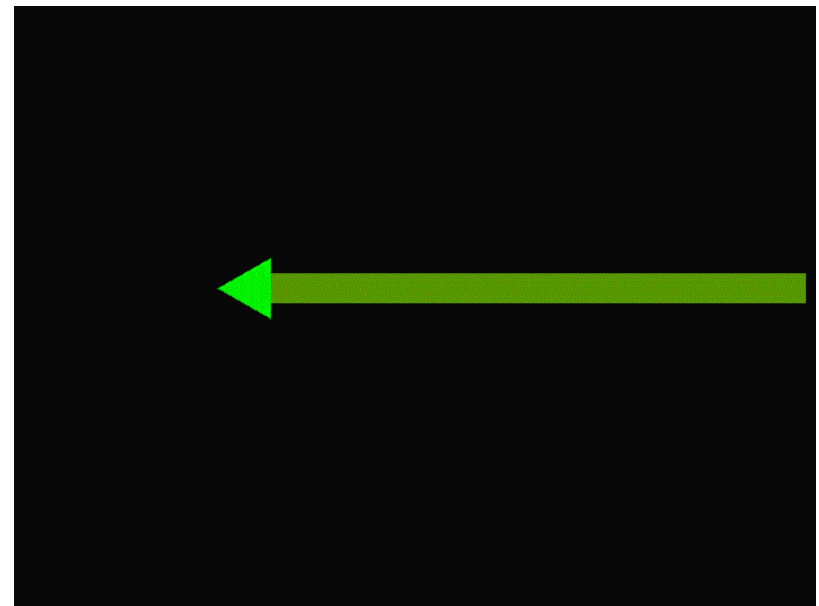
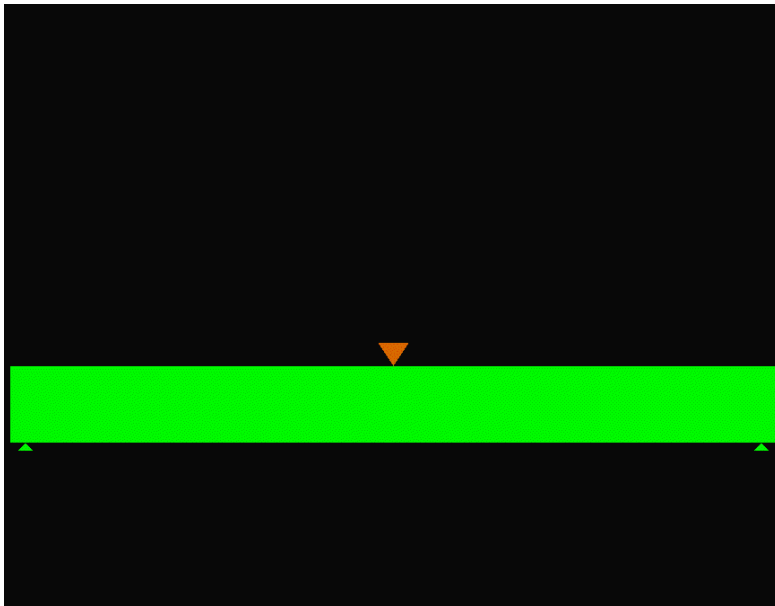
- NASTANAK I RAZVOJ PUKOTINA
- GUBITAK ENERGIJE USLIJED POJAVE NELINEARNIH EFEKATA
- INERCIJALNE EFEKTE USLIJED GIBANJA
- MEĐUDJELOVANJA KOJA SU POSLJEDICA DINAMIČKOG KONTAKTA
- PREDVIĐANJE NAČINA SLOMA KONSTRUKCIJA IZLOŽENIH SEIZMIČKOM OPTEREĆENJU

**KOMBINIRANA METODA
 KONAČNO-DISKRETNIH
 ELEMENATA (FEM/DEM)**

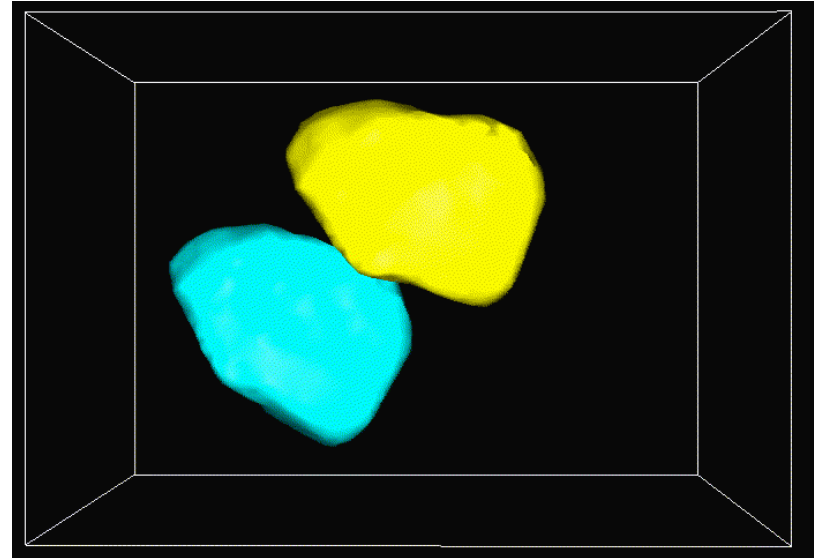


1. OSNOVE KOMBINIRANE METODE KONAČNO-DISKRETNIH ELEMENATA

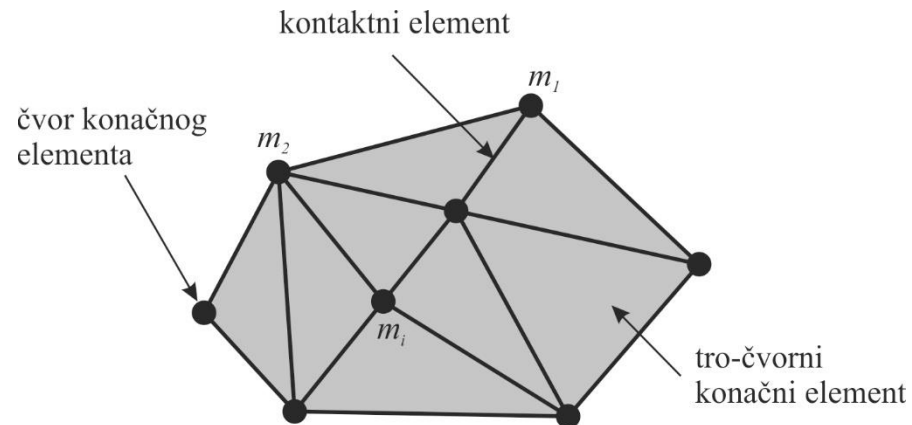
- FDEM (hybrid finite-discrete element method) kombinirana metoda konačno-diskretnih elemenata, čiji je začetnik, prof. Ante Munjiza je namijenjena prvenstveno za simulaciju kontaktne interakcije među deformabilnim diskretnim elementima pri čemu od jednog diskretnog elementa kroz proces nastanka i širenja pukotina može nastati njih više



... OSNOVE KOMBINIRANE METODE KONAČNO-DISKRETNIH ELEMENATA

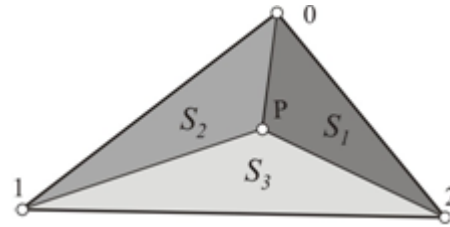
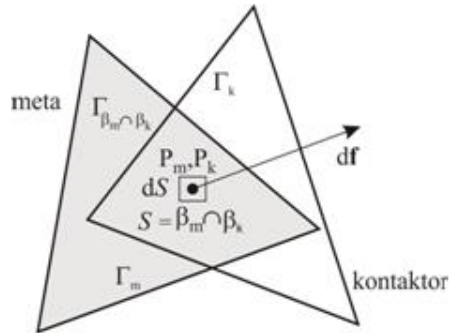


DISKRETIZACIJA KONSTRUKCIJE



... OSNOVE KOMBINIRANE METODE KONAČNO-DISKRETNIH ELEMENATA 2D

DETEKCIJA I INTERAKCIJA KONTAKTA

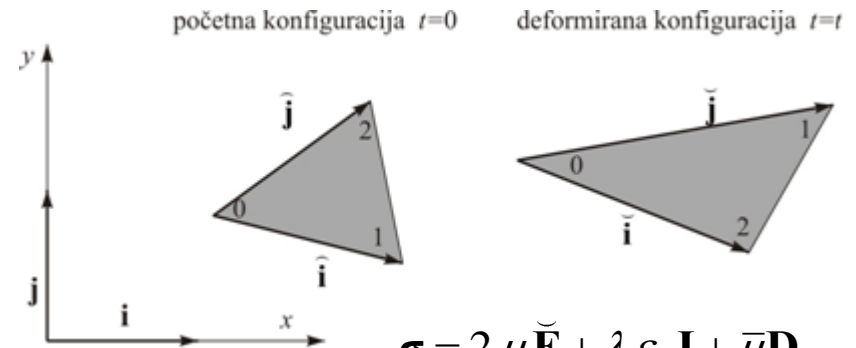


$\varphi(P)$ – polje potencijala

$$\varphi(P) = p_0 \min \{3S_1 / S, 3S_2 / S, 3S_3 / S\}$$

p_0 – penalty koeficijent

DEFORMABILNOST KONAČNIH ELEMENATA



$$\boldsymbol{\sigma} = 2\mu \check{\mathbf{E}} + \lambda \varepsilon_v \mathbf{I} + \bar{\mu} \mathbf{D}$$

μ, χ -Lameove konstante

$\check{\mathbf{E}}$ - Green – St – Venantov tenzor deformacija

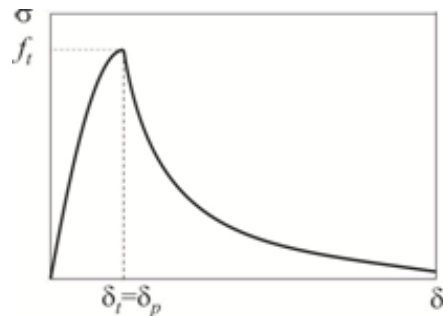
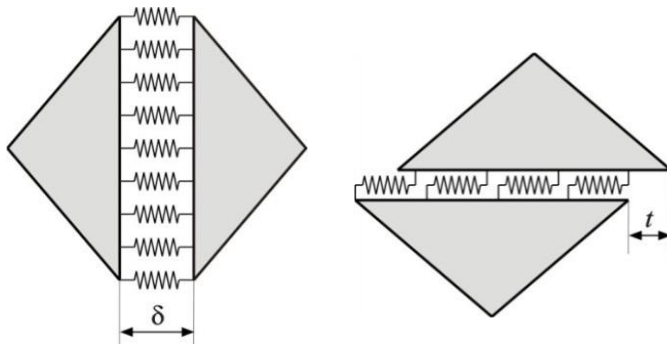
ε_v -volumenska deformacija

$\bar{\mu}$ -koeficijent prigušenja

\mathbf{D} -tenzor brzine deformiranja

PRIJELAZ IZ KONTINUUMA U DISKONTINUUM

- Kontaktni element – materijalna nelinearnost
- Simulaciju pojave i razvoja pukotina u vlaknu i posmiku



VREMENSKA DISKRETIZACIJA

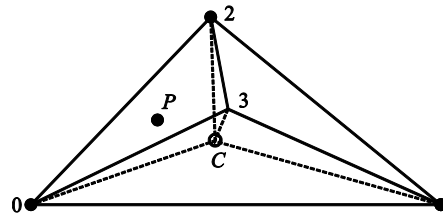
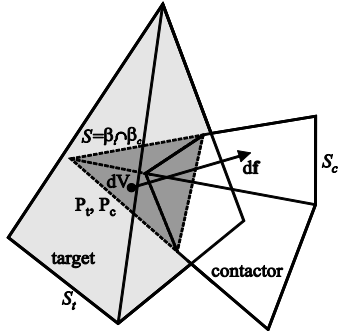
- Metoda konačnih razlika

$$\mathbf{v}_{t+\Delta t/2} = \mathbf{v}_{t-\Delta t/2} + \Delta t \mathbf{m}^{-1} \mathbf{f}_t$$

$$\mathbf{x}_{t+\Delta t} = \mathbf{x}_t + \Delta t \mathbf{v}_{t+\Delta t/2}$$

... OSNOVE KOMBINIRANE METODE KONAČNO-DISKRETNIH ELEMENATA 3D

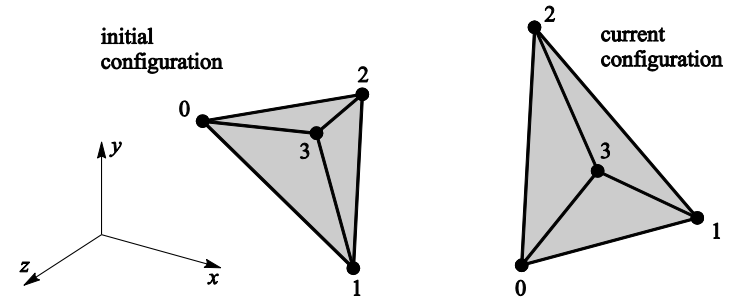
DETEKCIJA I INTERAKCIJA KONTAKTA



$\varphi(P)$ – polje potencijala

$$\varphi(P) = p_0 \min \{ 3S_1 / S, 3S_2 / S, 3S_3 / S \}$$

p_0 – penalty koeficijent



$$\boldsymbol{\sigma} = 2\mu \check{\mathbf{E}} + \lambda \varepsilon_v \mathbf{I} + \bar{\mu} \mathbf{D}$$

μ, χ -Lameove konstante

$\check{\mathbf{E}}$ - Green – St – Venantov tenzor deformacija

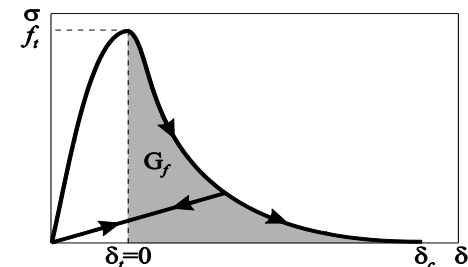
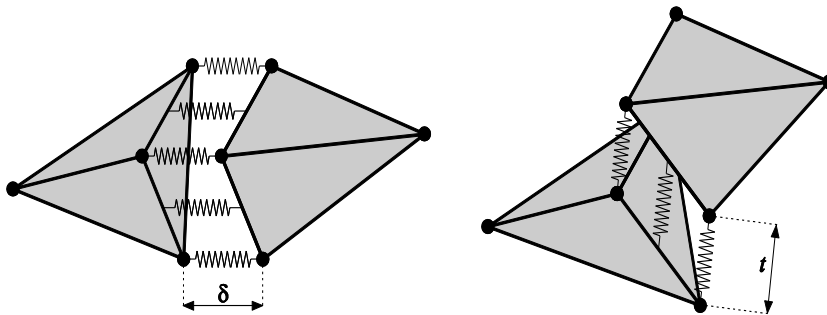
ε_v -volumenska deformacija

$\bar{\mu}$ -koeficijent prigušenja

\mathbf{D} -tenzor brzine deformiranja

PRIJELAZ IZ KONTINUUMA U DISKONTINUUM

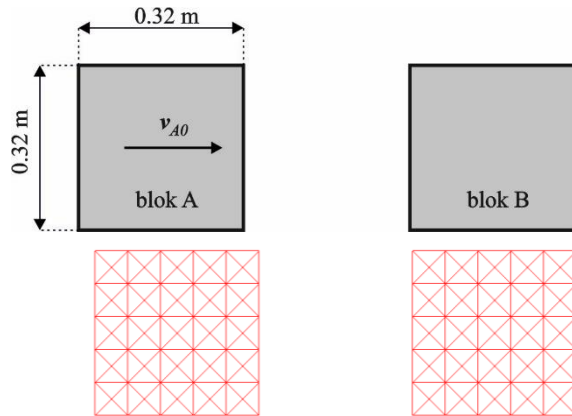
- Kontaktni element – materijalna nelinearnost
- Simulaciju pojave i razvoja pukotina u vlaknu i posmiku



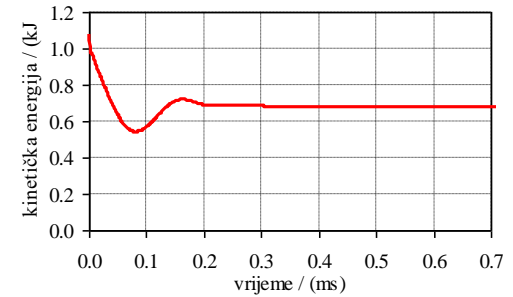
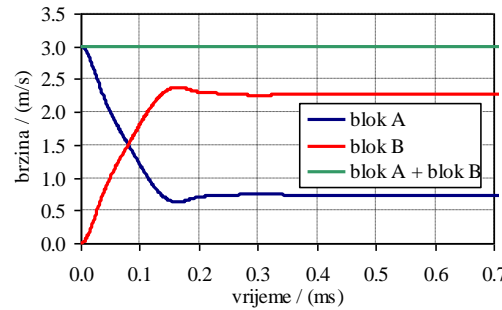


... OSNOVE KOMBINIRANE METODE KONAČNO-DISKRETNIH ELEMENATA

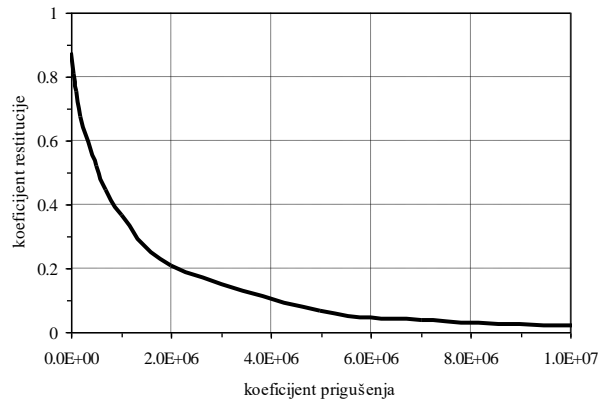
Sudar dvaju blokova



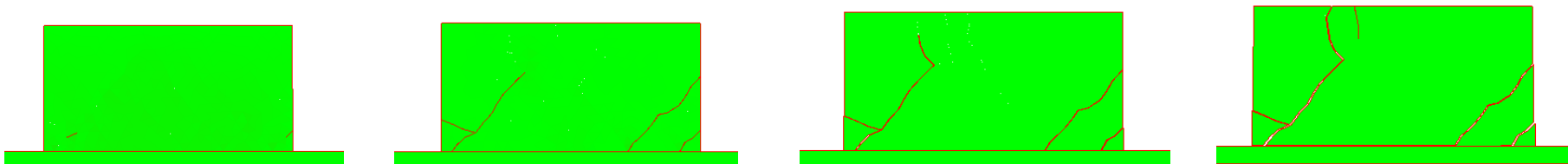
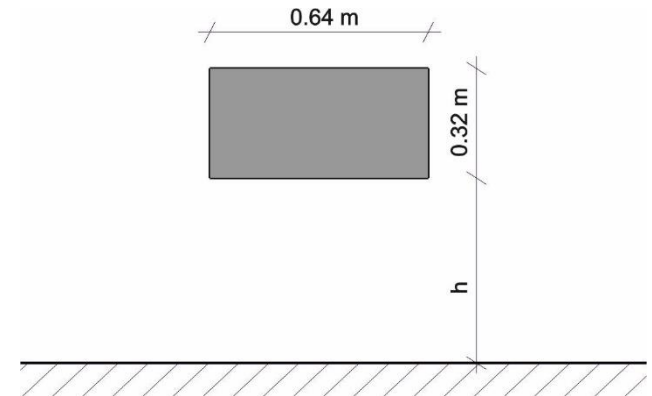
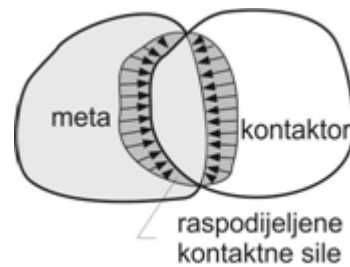
Brzina i kinetička energija za: $\bar{\mu} = 5.0e+05$, $p_0 = 100 E$, mreža B, bez kontaktnih elemenata



Mreža konačnih elemenata

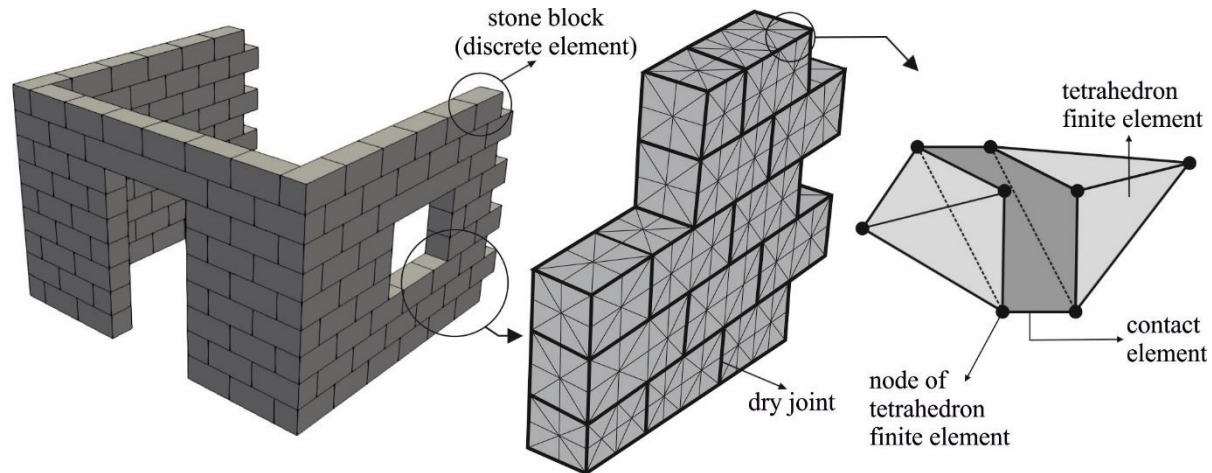
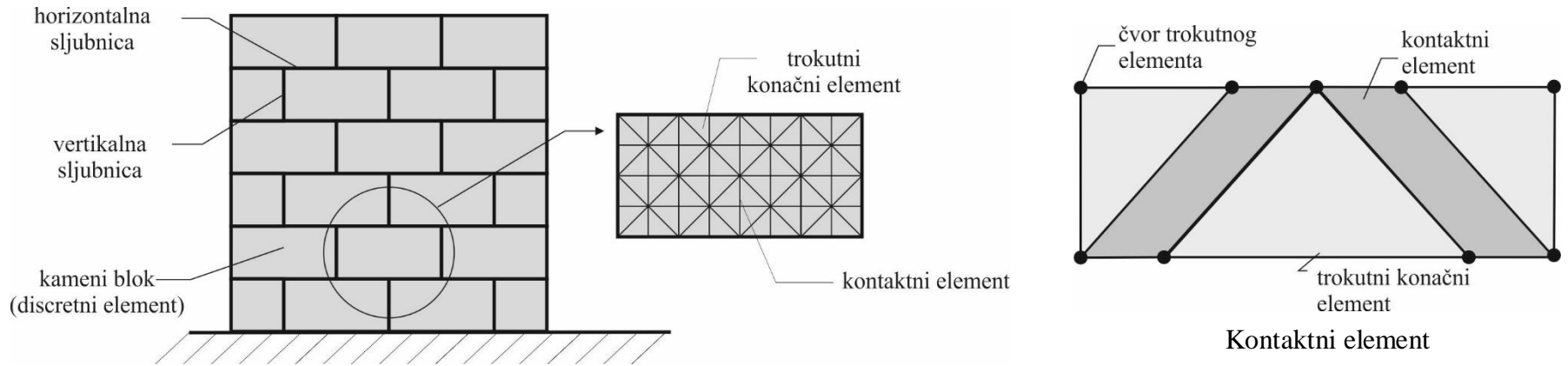


Slobodni pad kamenog bloka na krutu podlogu



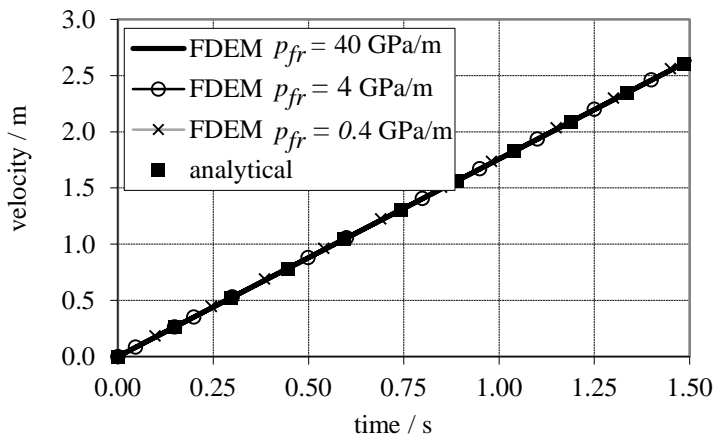
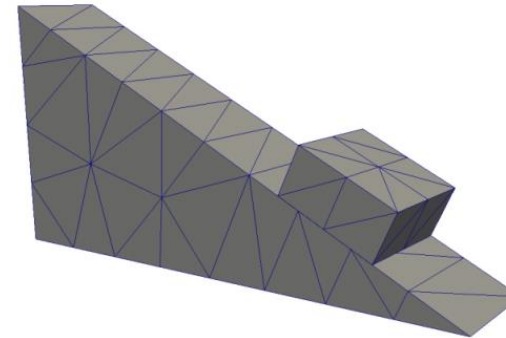
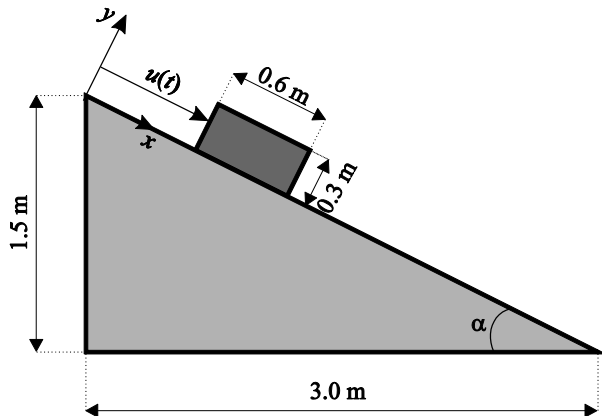
2. FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Diskretizacija kamene konstrukcije

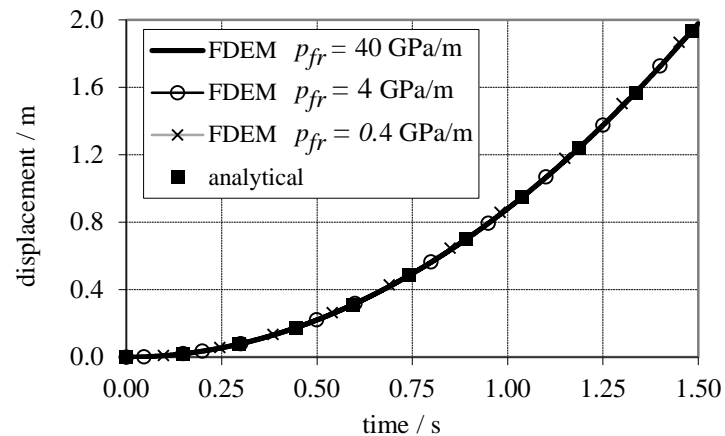


.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Verifikacija trenja uslijed klizanja bloka niz kosinu



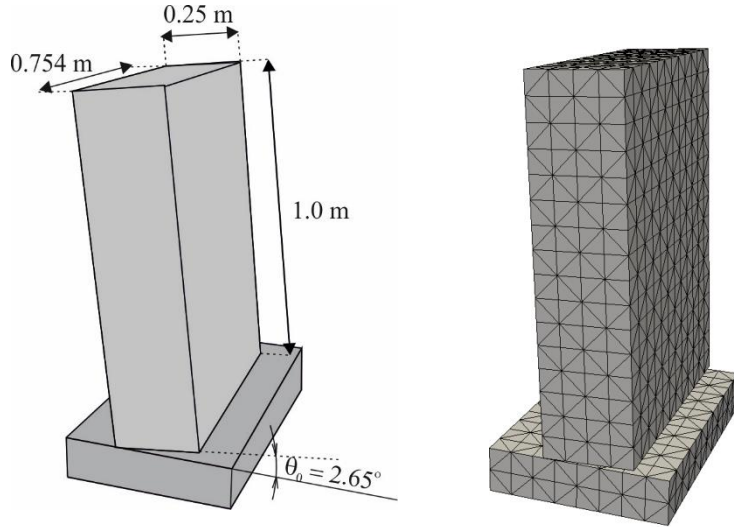
Usporedba analitičkih i numeričkih rezultata
 za brzinu bloka u vremenu



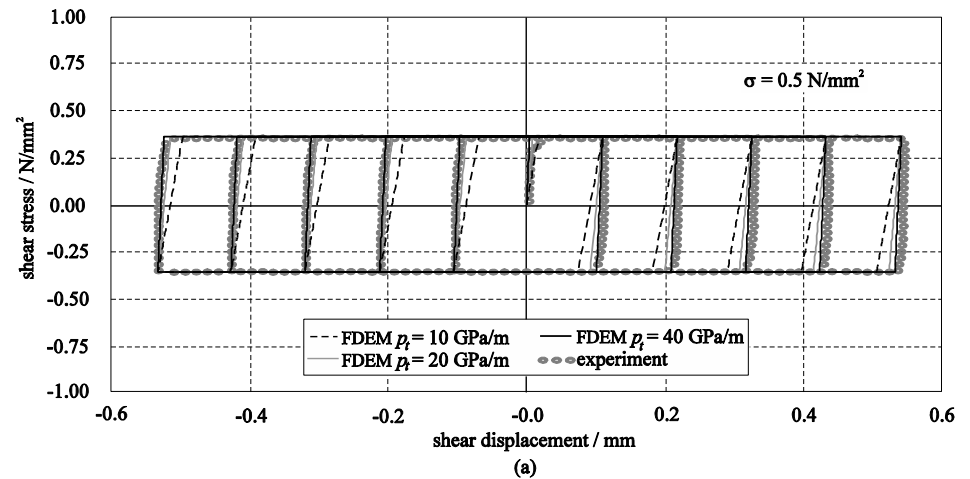
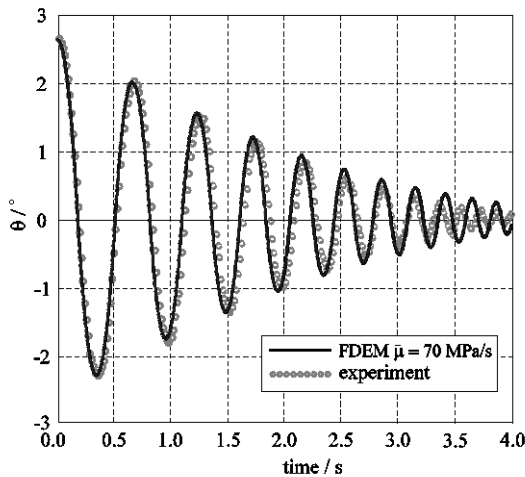
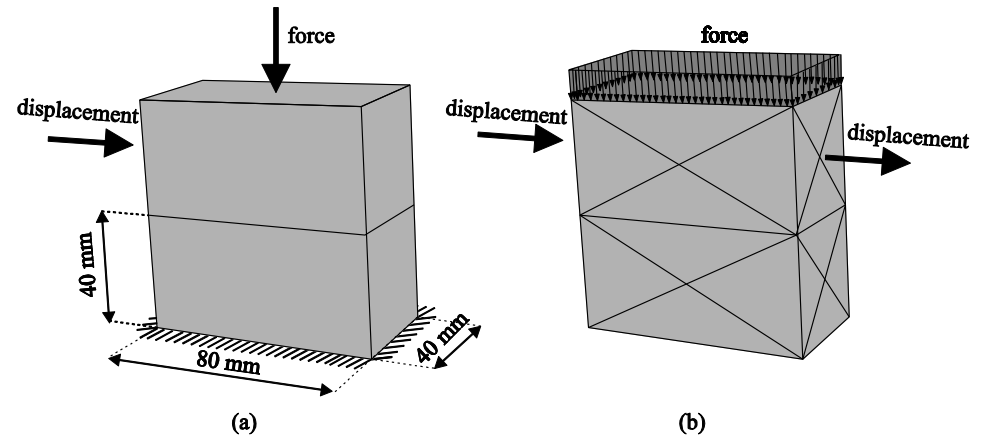
Usporedba analitičkih i numeričkih rezultata
 za pomak bloka u vremenu

.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Njihanje bloka na krutoj podlozi

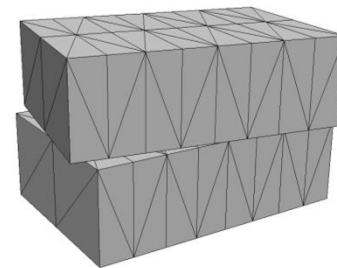
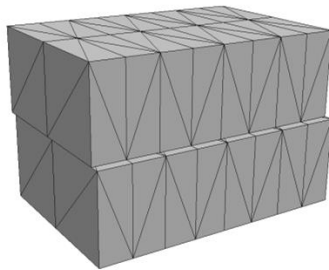
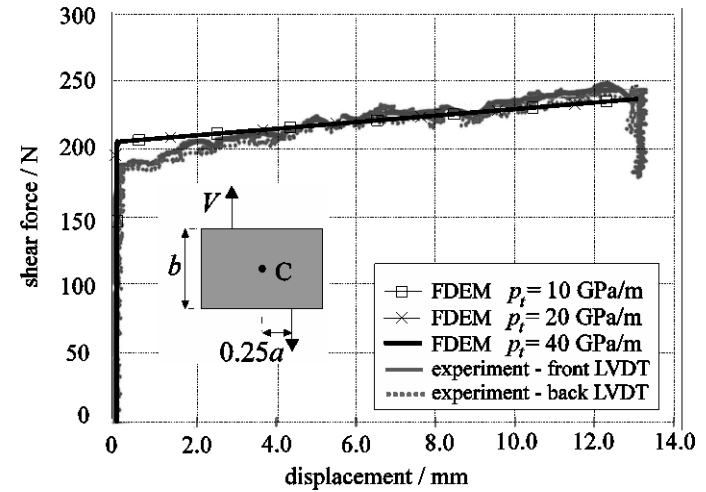
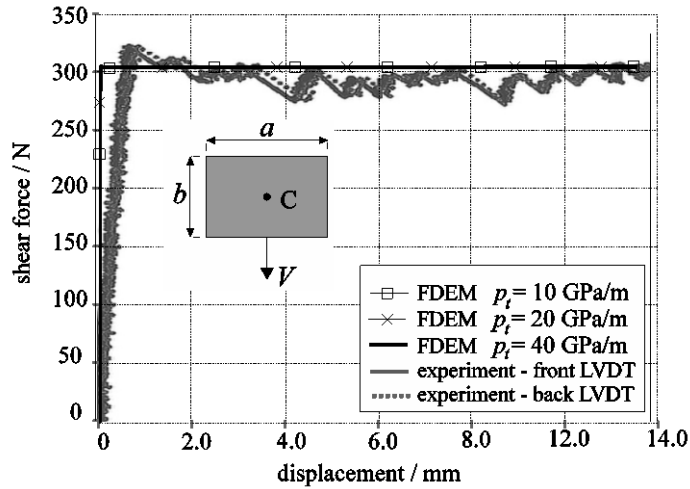


Suho trenje između dva bloka



.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

.... Suho trenje između dva bloka



.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

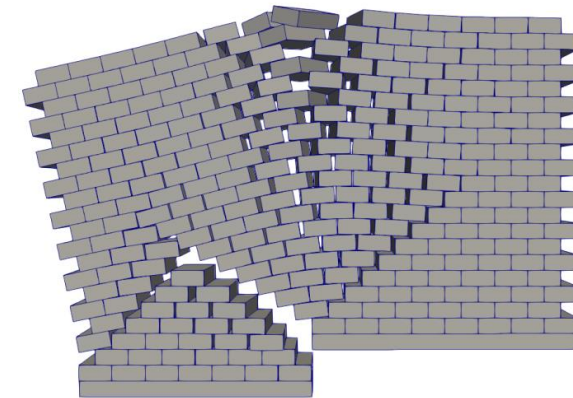
Zidani zid izložen slijeganju temelja



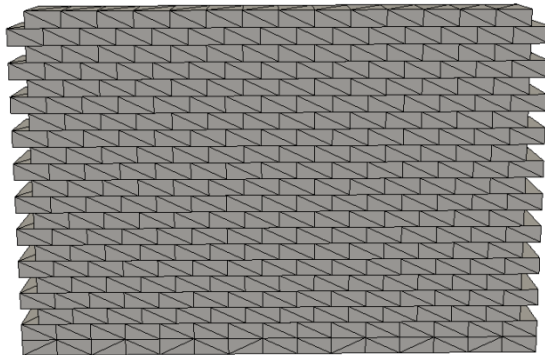
Konfiguracija eksperimenta



Eksperiment CL1 (T. T. Bui et al.)



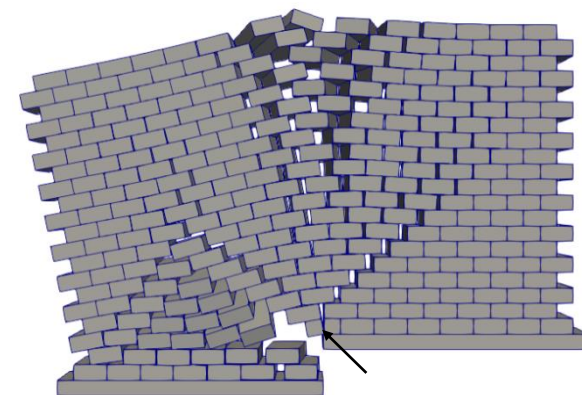
FDEM CL1



Diskretizacija konstrukcije



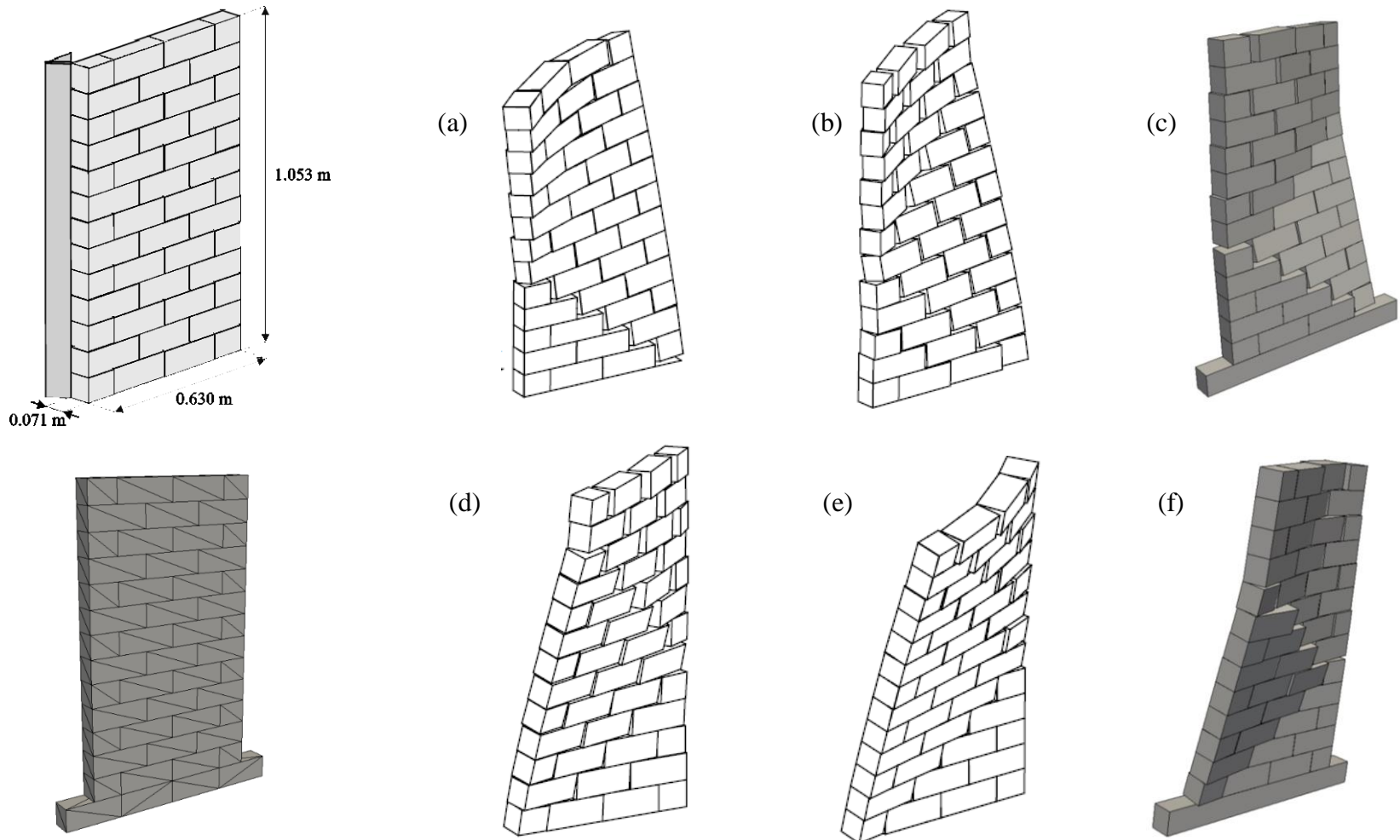
Eksperiment CL3 (T. T. Bui et al.)



FDEM CL3

.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Zidani zid izložen horizontalnom opterećenju izvan ravnine

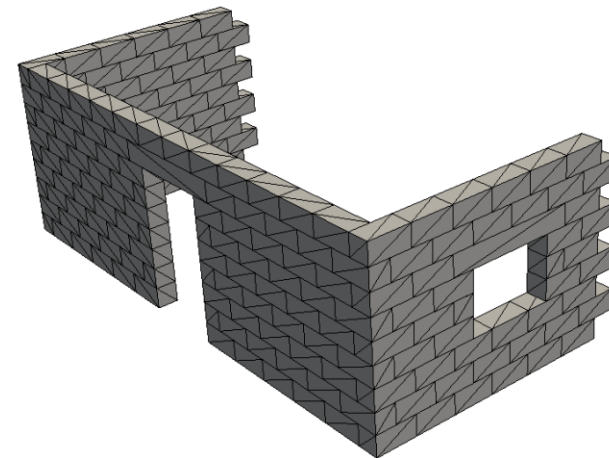
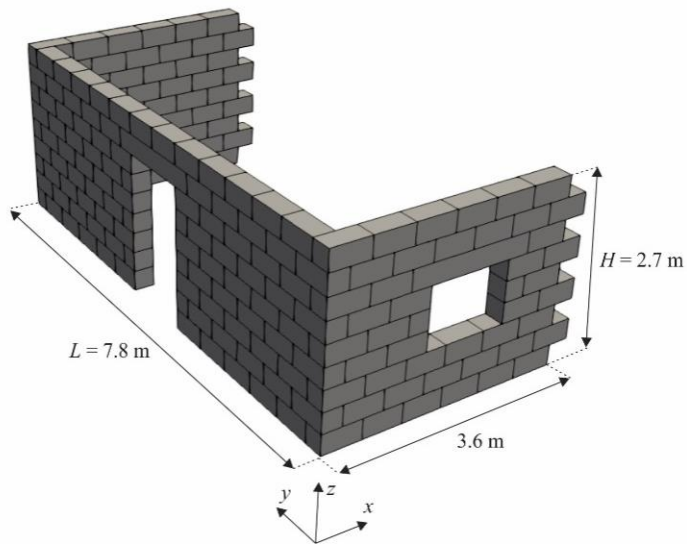
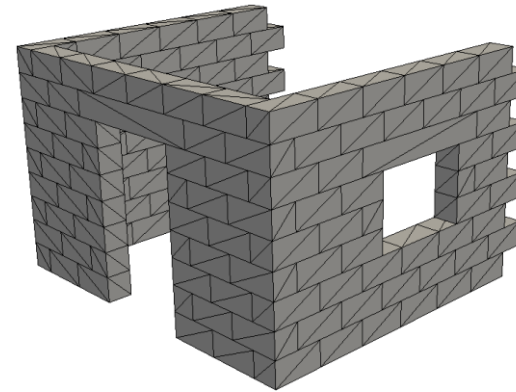
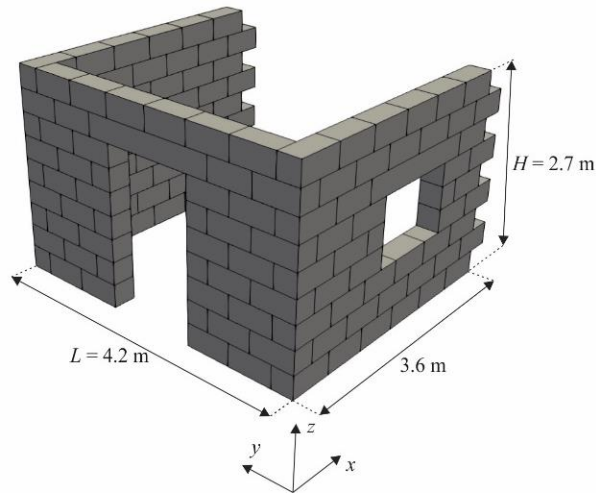


Mehanizam sloma za različite analize: (a, d) FEM, (b, e) limit-analysis [36] i (c, f) FDEM



... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

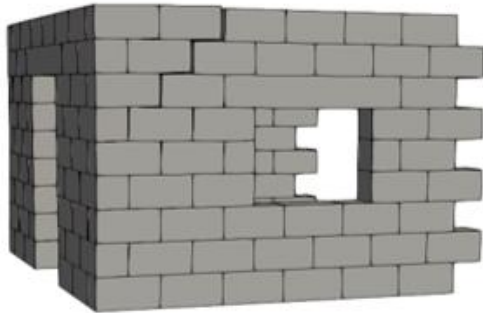
Konstrukcija izložena monotono rastućem horizontalnom ubrzanju



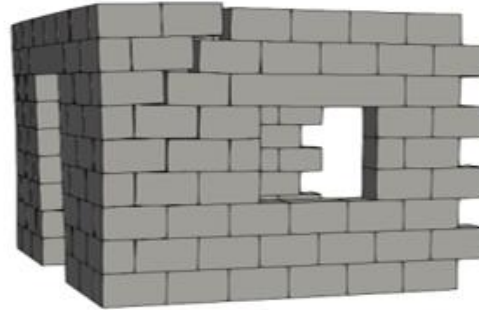


... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

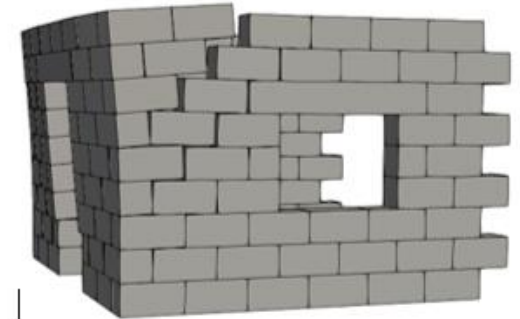
Konstrukcija izložena monotono rastućem horizontalnom ubrzanju



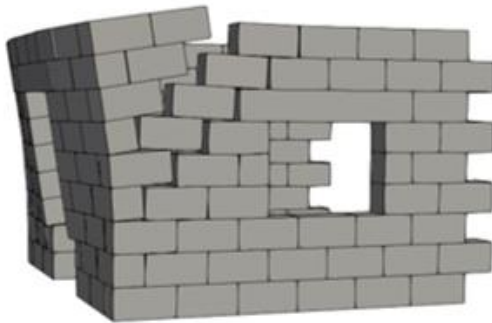
(a) $t=14.396$ sek ($a_{0x}/g=0.288$)



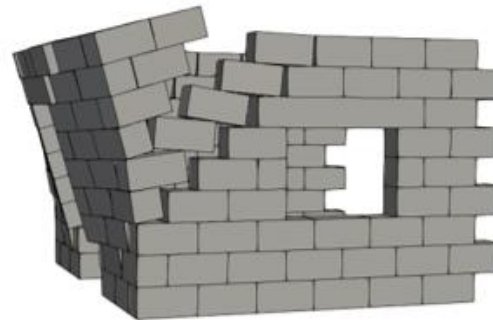
(b) $t=14.596$ sek ($a_{0x}/g=0.292$)



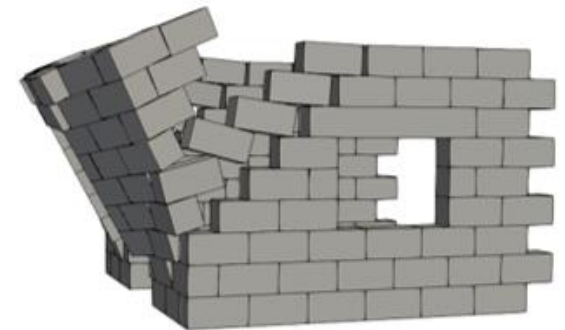
(c) $t=14.796$ sek ($a_{0x}/g=0.296$)



(d) $t=14.996$ sek ($a_{0x}/g=0.300$)



(e) $t=15.196$ sek ($a_{0x}/g=0.304$)

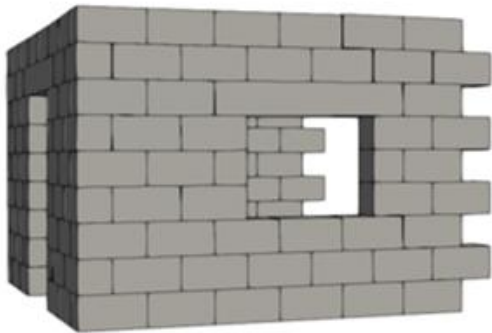


(f) $t=15.396$ sek ($a_{0x}/g=0.308$)

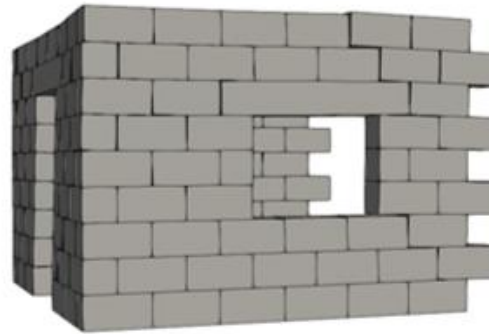
Mehanizam slomaza horizontalno monotono povećanje ubrzanja baze u pozitivnom x smjeru, $L/H = 1.56$

.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

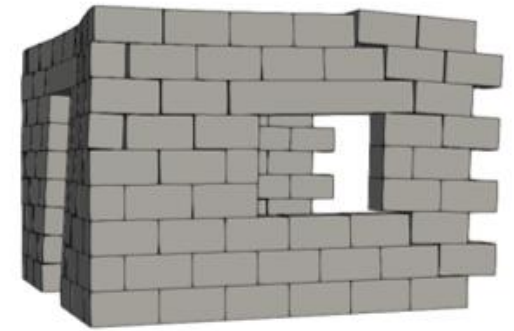
Konstrukcija izložena monotono rastućem horizontalnom ubrzanju



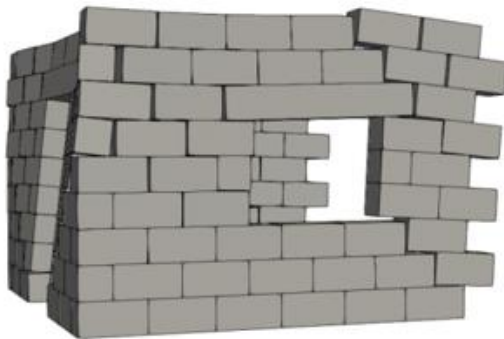
(a) $t=21.194$ sek ($a_{0x}/g=0.424$)



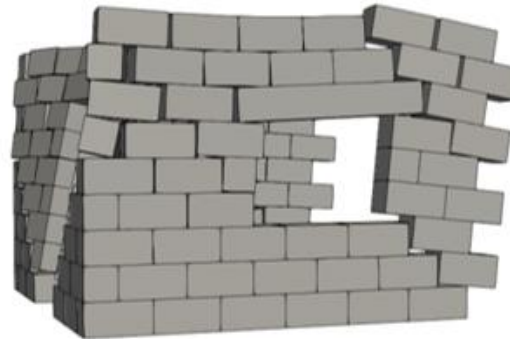
(b) $t=21.394$ sek ($a_{0x}/g=0.428$)



(c) $t=21.594$ sek ($a_{0x}/g=0.432$)



(d) $t=21.796$ sek ($a_{0x}/g=0.436$)

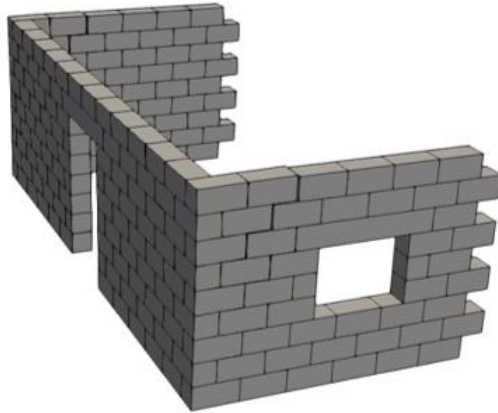


(e) $t=21.994$ sek ($a_{0x}/g=0.440$)

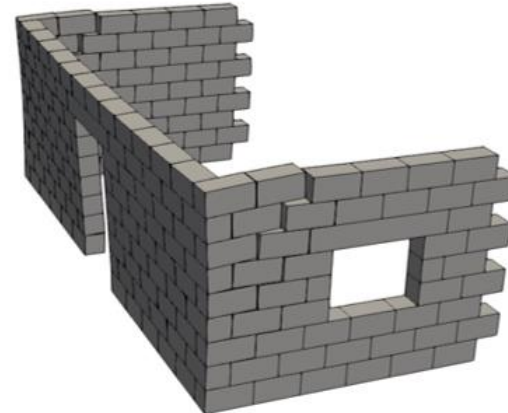


(f) $t=22.194$ sek ($a_{0x}/g=0.444$)

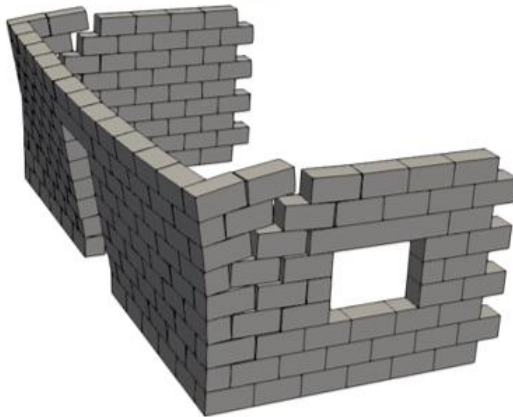
Konstrukcija izložena monotono rastućem horizontalnom ubrzanju



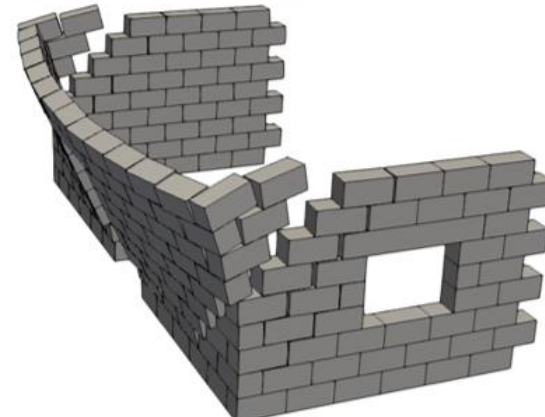
(a) $t=11.004$ sek ($a_{0x}/g=0.220$)



(b) $t=11.404$ sek ($a_{0x}/g=0.228$)



(d) $t=11.705$ sek ($a_{0x}/g=0.234$)

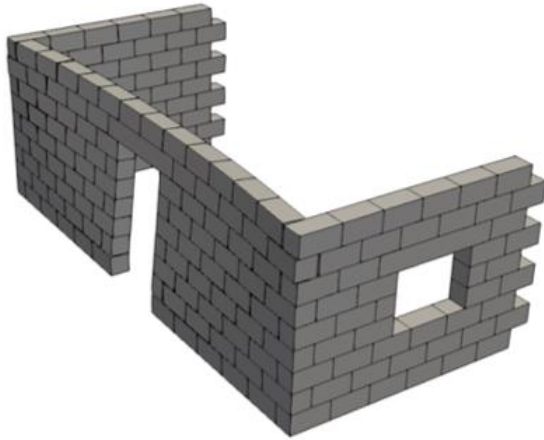


(d) $t=12.005$ sek ($a_{0x}/g=0.240$)

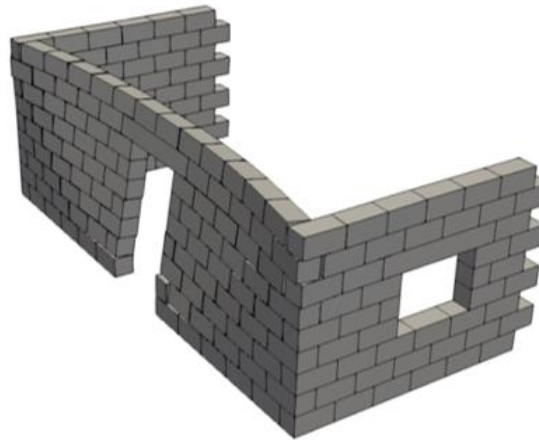


... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Konstrukcija izložena monotono rastućem horizontalnom ubrzanju



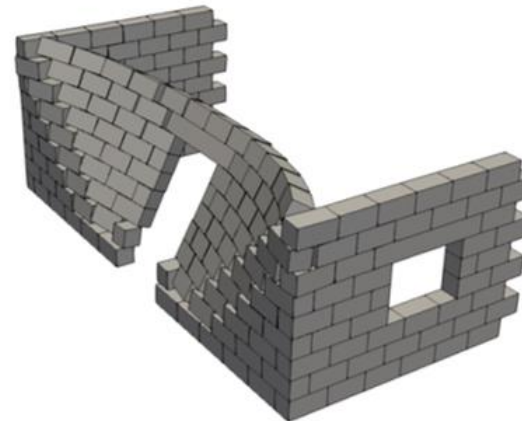
(a) $t=12.805$ sek ($a_{0x}/g=0.256$)



(b) $t=13.00$ sek ($a_{0x}/g=0.260$)



(d) $t=13.205$ sek ($a_{0x}/g=0.264$)

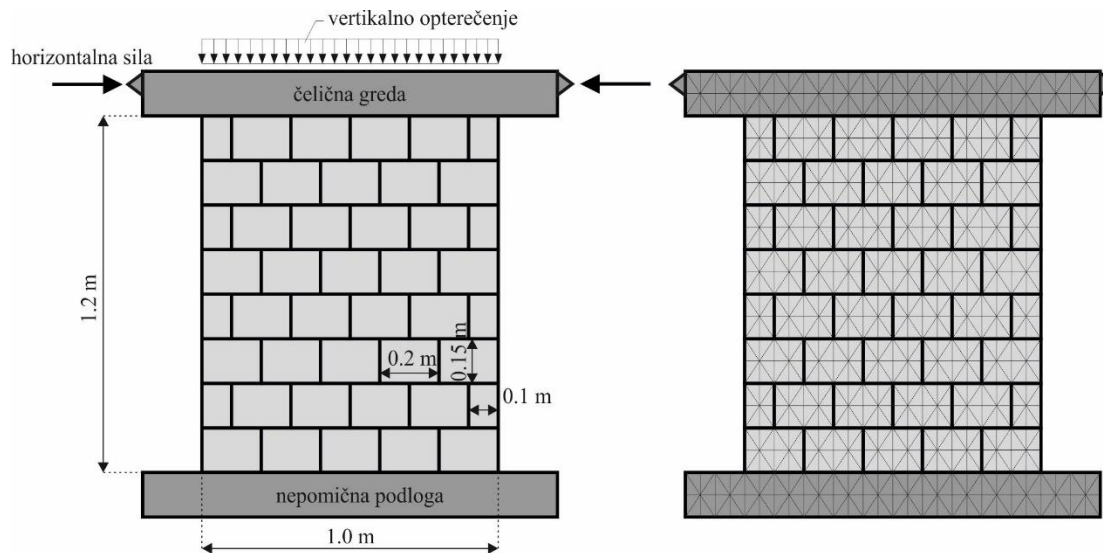


(d) $t=13.405$ sek ($a_{0x}/g=0.268$)

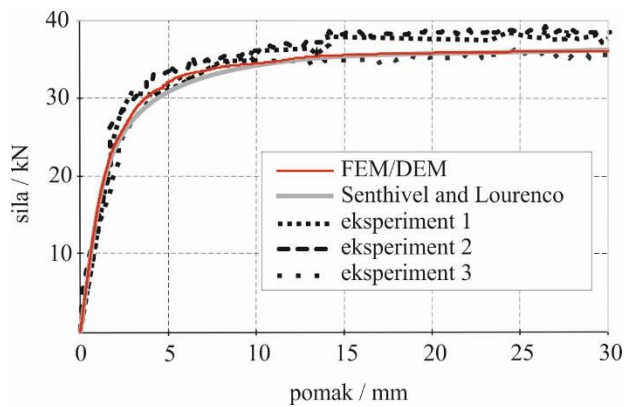
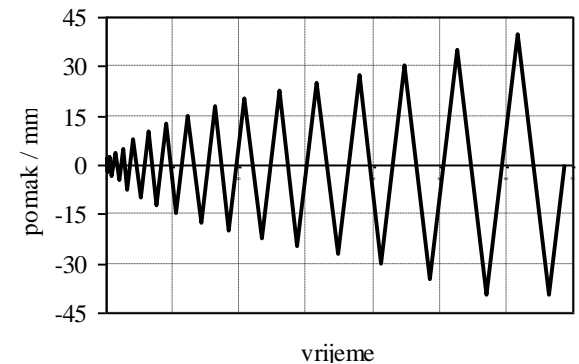
Mehanizam slomaza horizontalno monotono povećanje ubrzanja baze u negativnom x smjeru, $L/H = 2.89$

.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

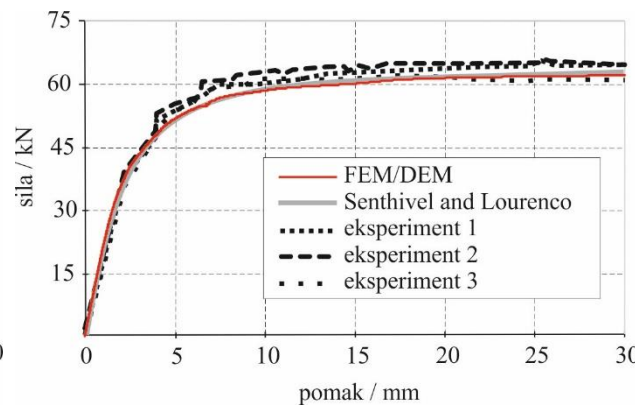
Monotono i cikličko ponašanje suho zidanog kamenog zida



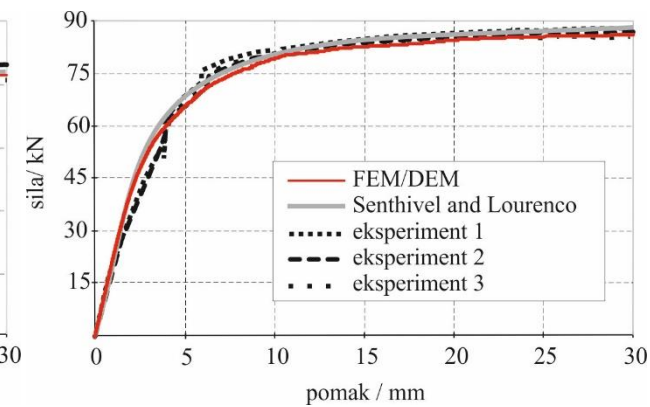
- eksperiment je proveo Vasconcelos
- predlačno naprezanje u iznosu od:
- 0.5 MPa, 0.875 MPa i 1.25 MPa



(a)



(b)

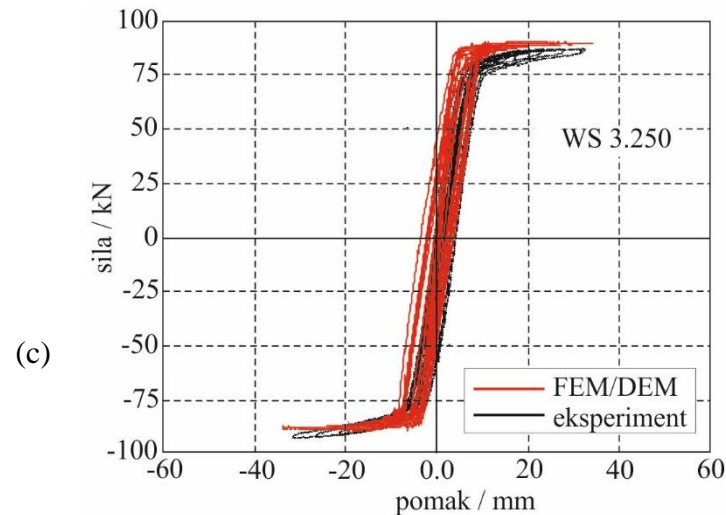
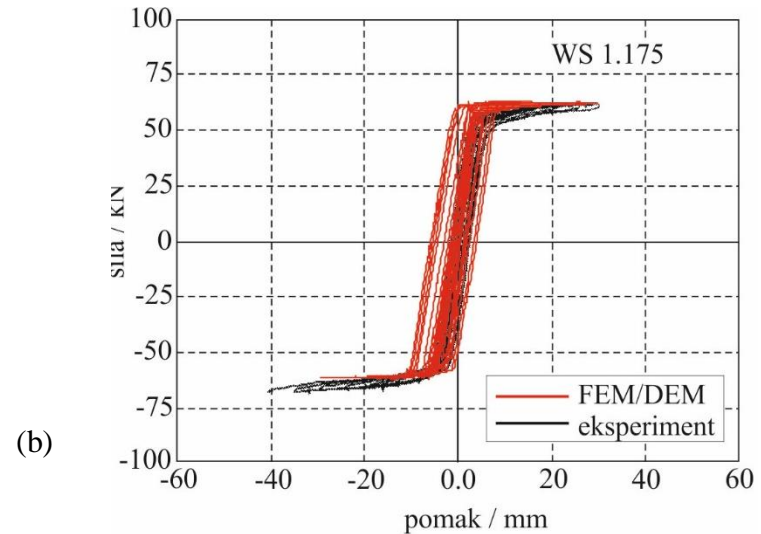
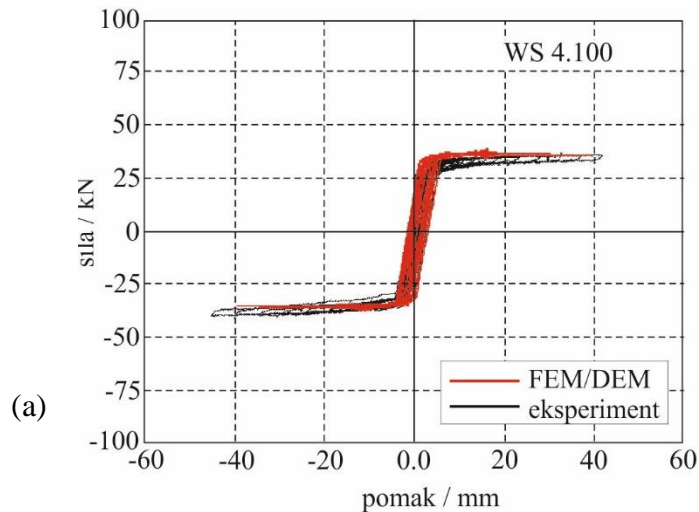


(c)

Dijagrami sila pomak za predlačna naprezanja od: (a) 0.5 MPa; (b) 0.875 MPa; (c) 1.25 MPa

.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

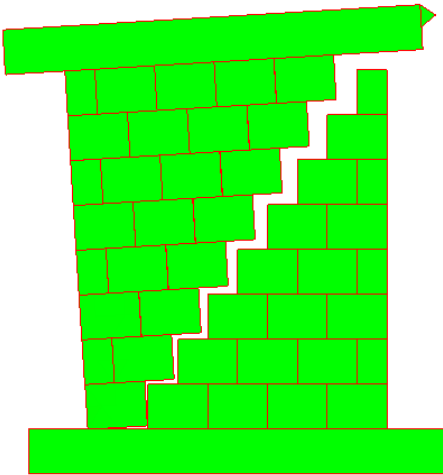
... Monotono i cikličko ponašanje suho zidanog kamenog zida



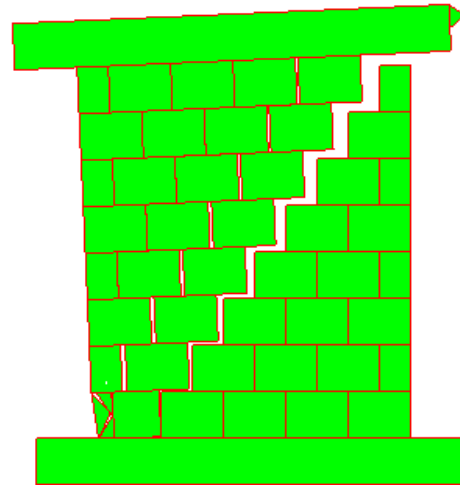
Usporedba numeričkih i eksperimentalnih rezultata za predtlačno naprezanje od: (a) 0.5 MPa; (b) 0.875 MPa; (c) 1.25 MPa

.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

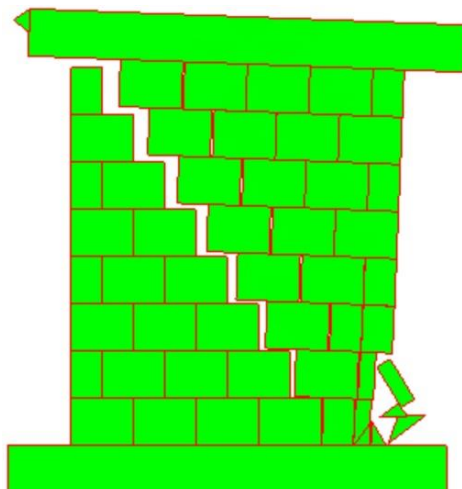
... Monotono i cikličko ponašanje suho zidanog kamenog zida



(a)



(b)



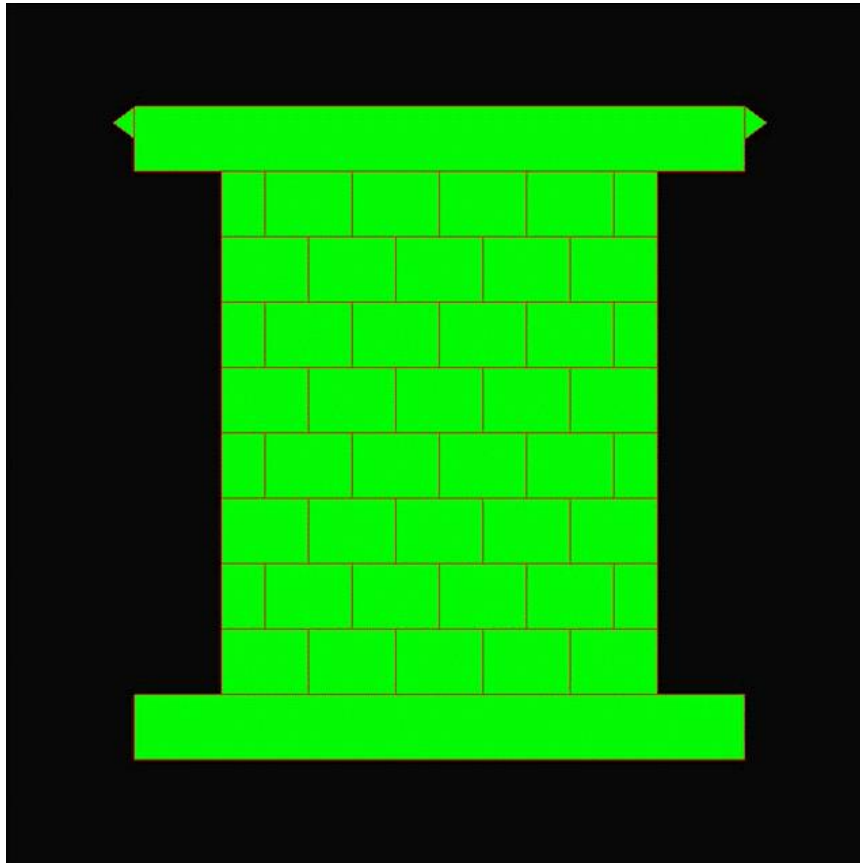
(c)





.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

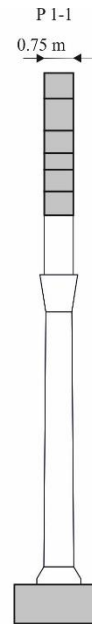
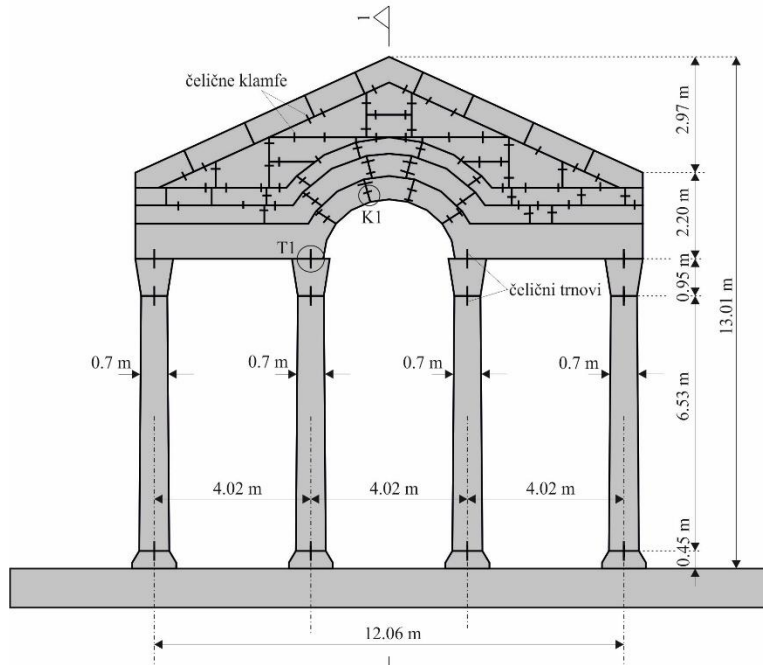
... Monotono i cikličko ponašanje suho zidanog kamenog zida



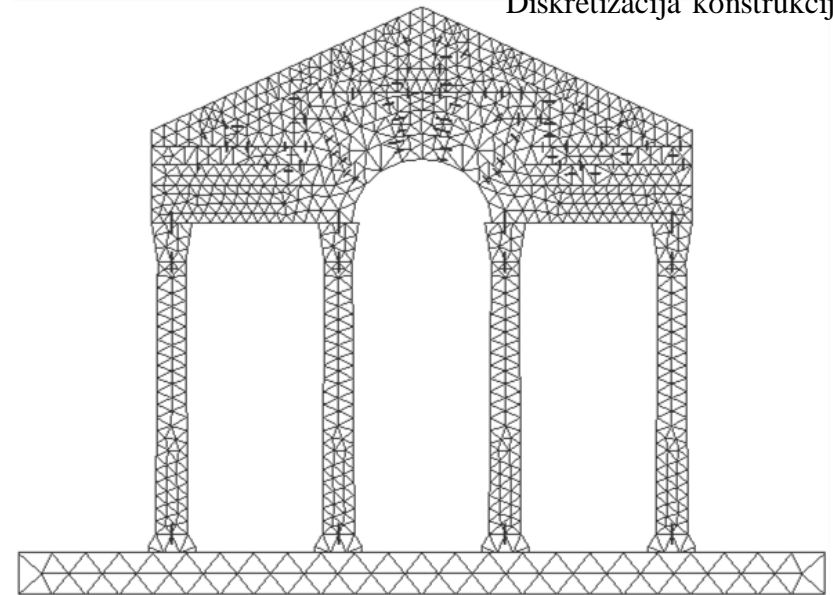
Numerički mehanizma sloma za predtlačno naprezanje od 0.5 Mpa

.... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

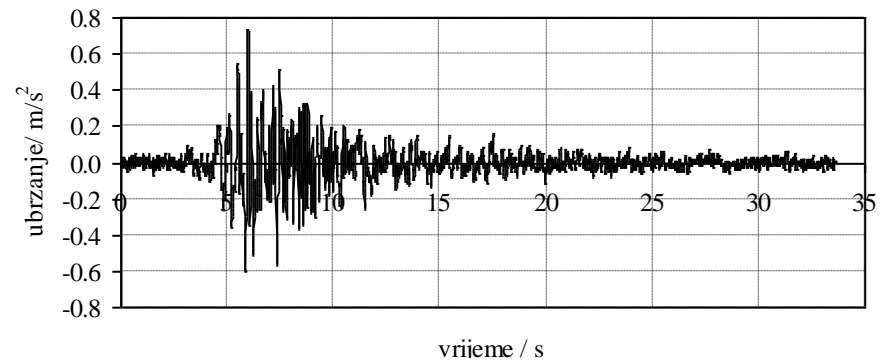
Seizmička analiza konstrukcije Protirona s ugrađenim klamfama i trnovima



Diskretizacija konstrukcije



inkrementalna dinamička analiza

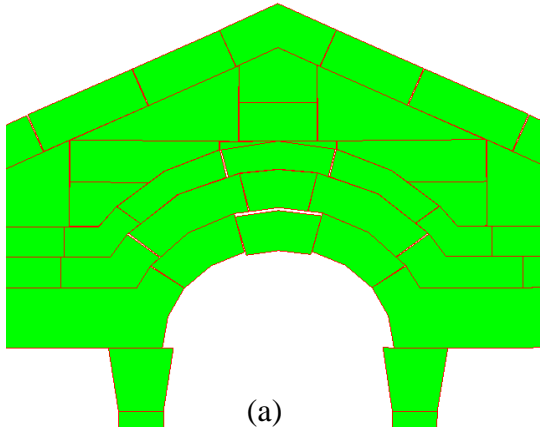


Vremenski zapis ubrzanja za vrijeme potresa u Petrovcu 1979.

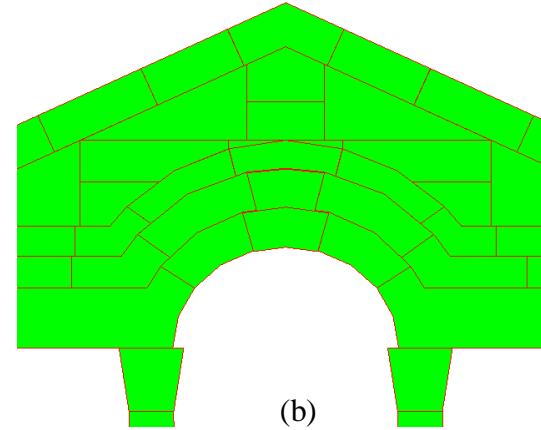


... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Seizmička analiza konstrukcije Protirona s ugrađenim klamfama i trnovima

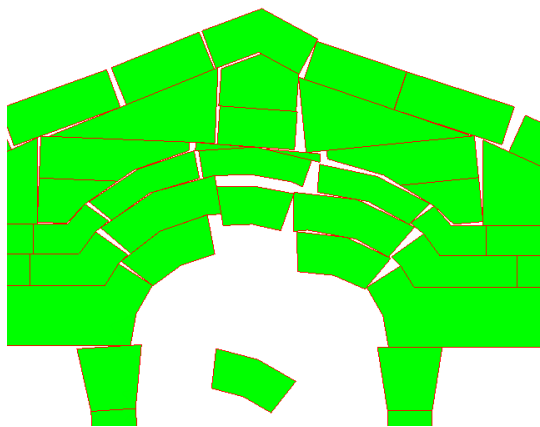


(a)

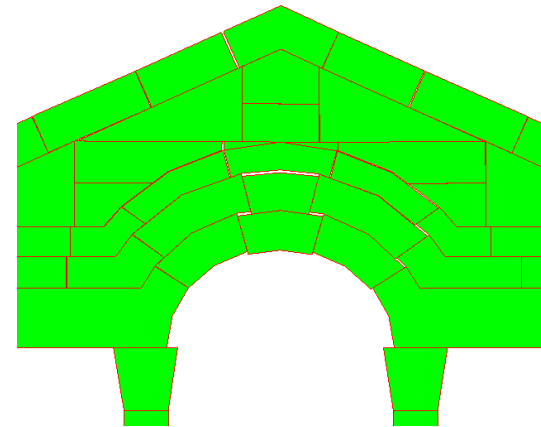


(b)

Središnji dio konstrukcije Protirona nakon potresa vršnog ubrzanja $a_g=0.22$ g: (a) konstrukcija s ugrađenim trnovima; (b) konstrukcija s ugrađenim trnovima i klamfama



(a)



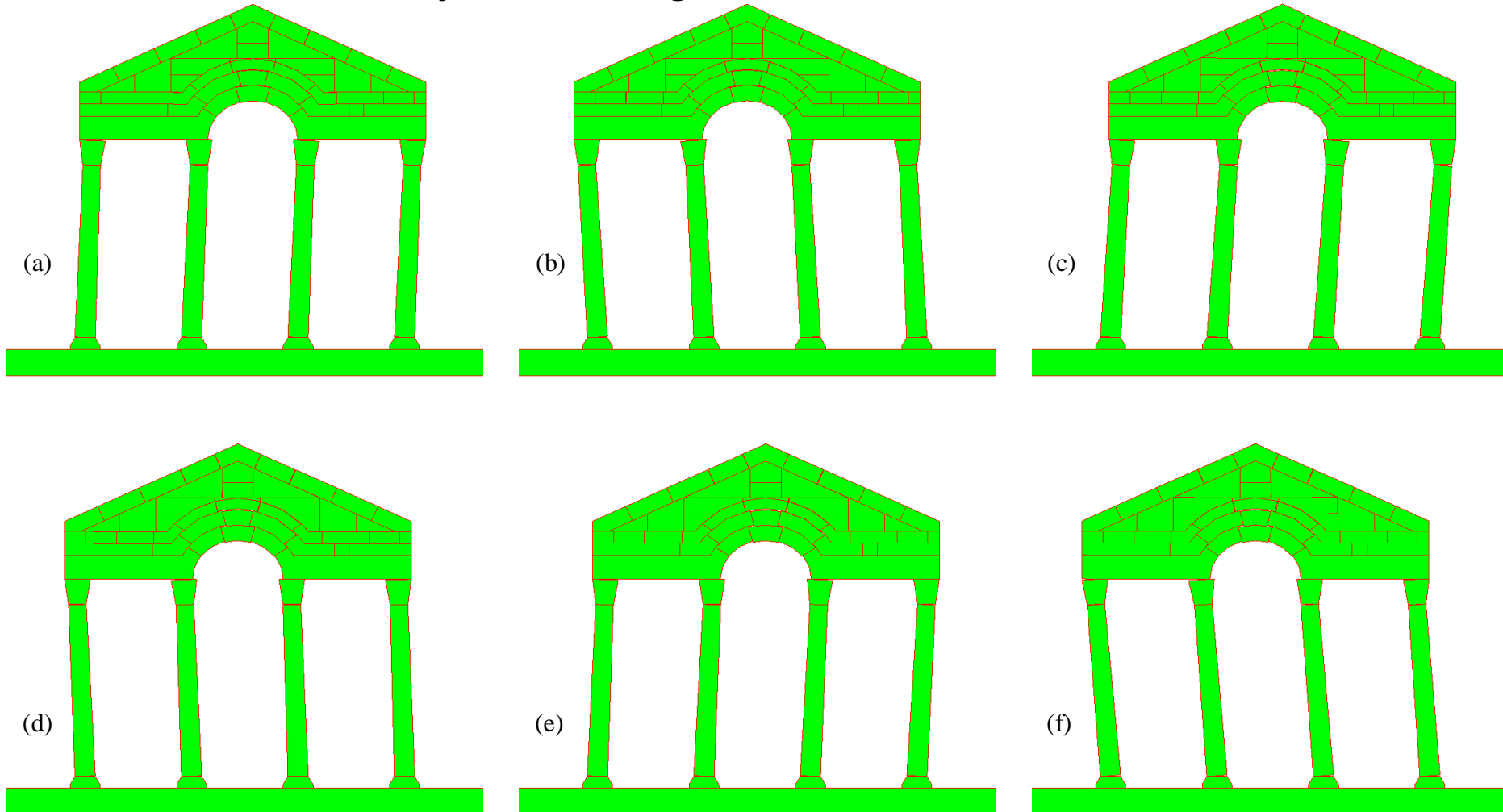
(b)

Središnji dio konstrukcije Protirona nakon potresa vršnog ubrzanja $a_g=0.60$ g: (a) konstrukcija s ugrađenim trnovima; (b) konstrukcija s ugrađenim trnovima i klamfama



... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Seizmička analiza konstrukcije Protirona s ugrađenim klamfama i trnovima

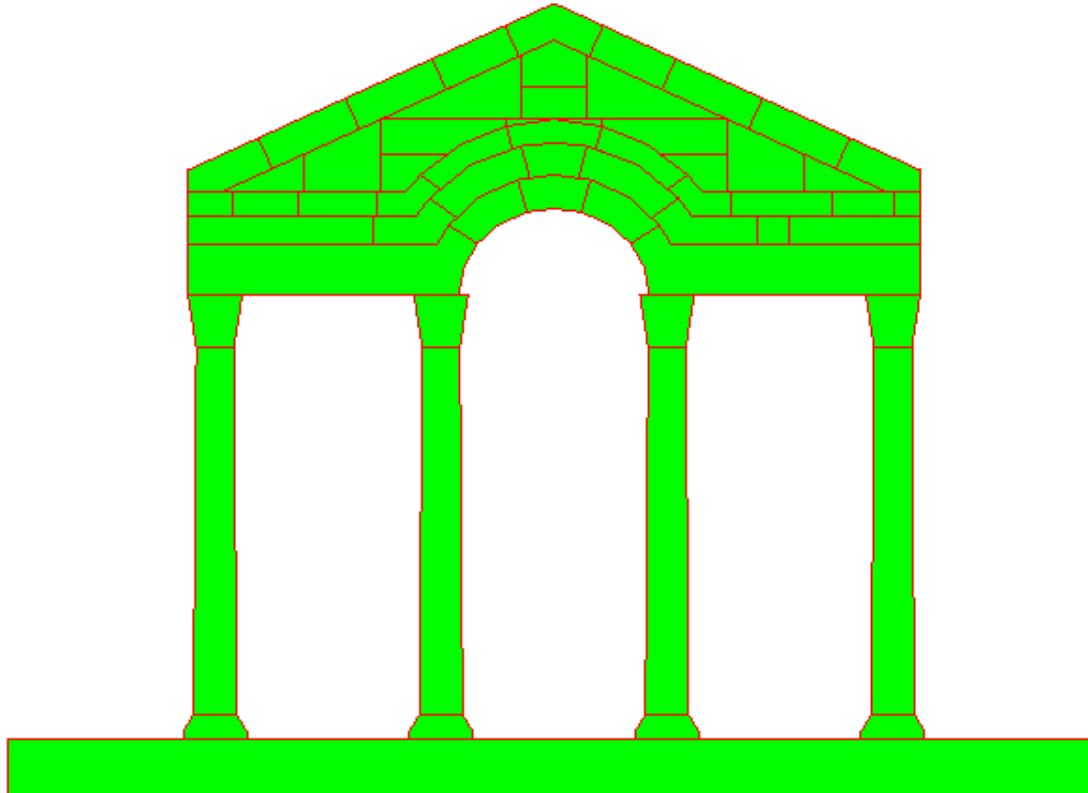


Konstrukcija Protirona s ugrađenim metalnim klamfama i trnovima pri djelovanju potresa vršnog ubrzanja $a_g=2.00$ g u vremenskim trenucima: (a) $t=7.9$ s; (b) $t=9.3$ s; (c) $t=22.0$ s; (d) $t=24.5$ s; (e) $t=30.5$ s; (f) $t=32.9$ s.



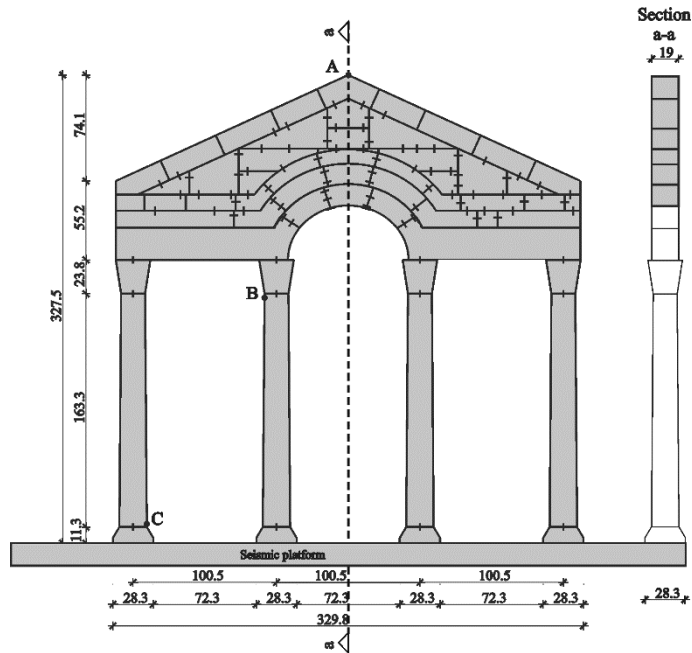
... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Seizmička analiza konstrukcije Protirona s ugrađenim klamfama i trnovima

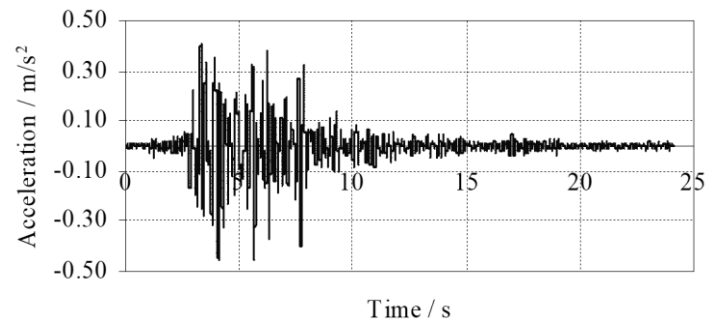


... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Seizmička analiza konstrukcije Protirona s ugrađenim klamfama i trnovima



Model konstrukcije Protiron: (a) geometrijske karakteristike; (b) fizikalni model

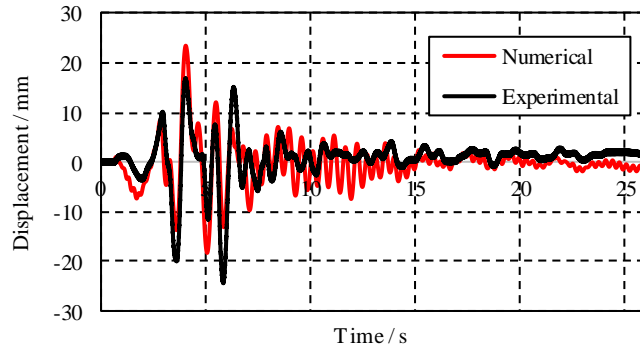


Skalirano vremensko ubrzanja u vremenu, N-S komponenta potresa u Petrovcu (Crna Gora) 1979. godine

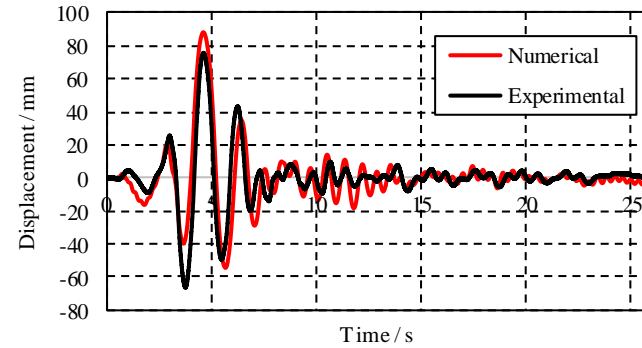


... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

Seizmička analiza konstrukcije Protirona s ugrađenim klamfama i trnovima

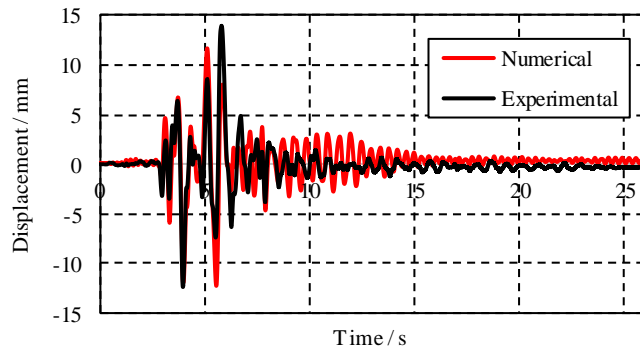


(a)

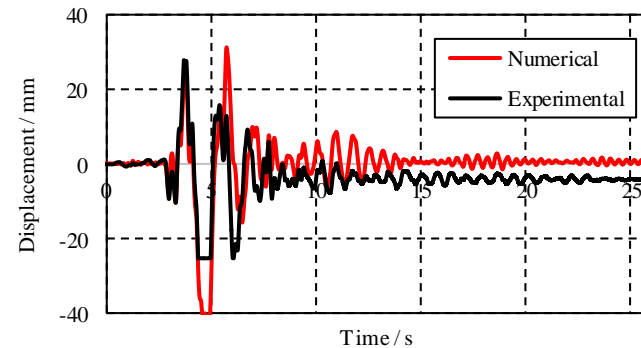


(b)

Horizontalni pomak točke A za vršno ubrzanje tla od: (a) $a_g=0.47$ g; (b) $a_g=1.1$ g



(a)



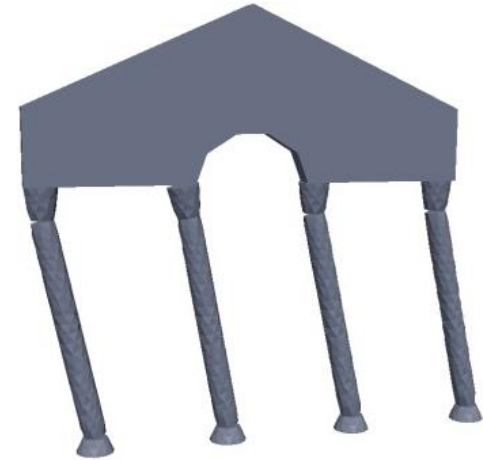
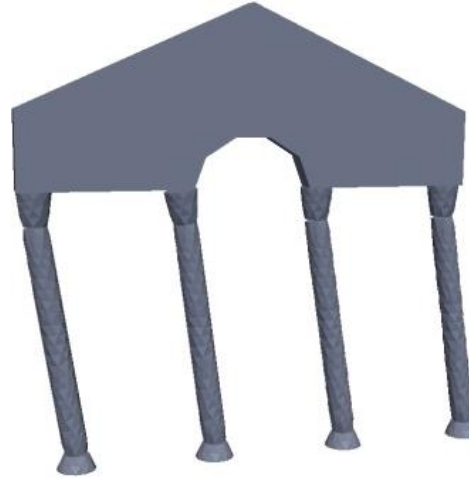
(b)

Dijagonalni pomak između točaka A i B za vršno ubrzanje tla od: (a) $a_g=0.47$ g; (b) $a_g=1.1$ g



... FDEM METODA U ANALIZI SUHO ZIDANIH KAMENIH KONSTRUKCIJA

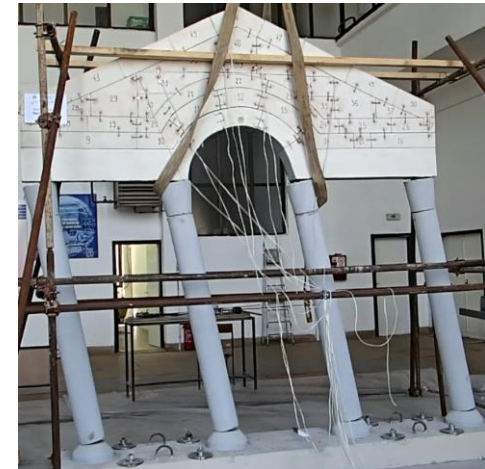
Seizmička analiza konstrukcije Protirona s ugrađenim klamfama i trnovima



(a)



(b)

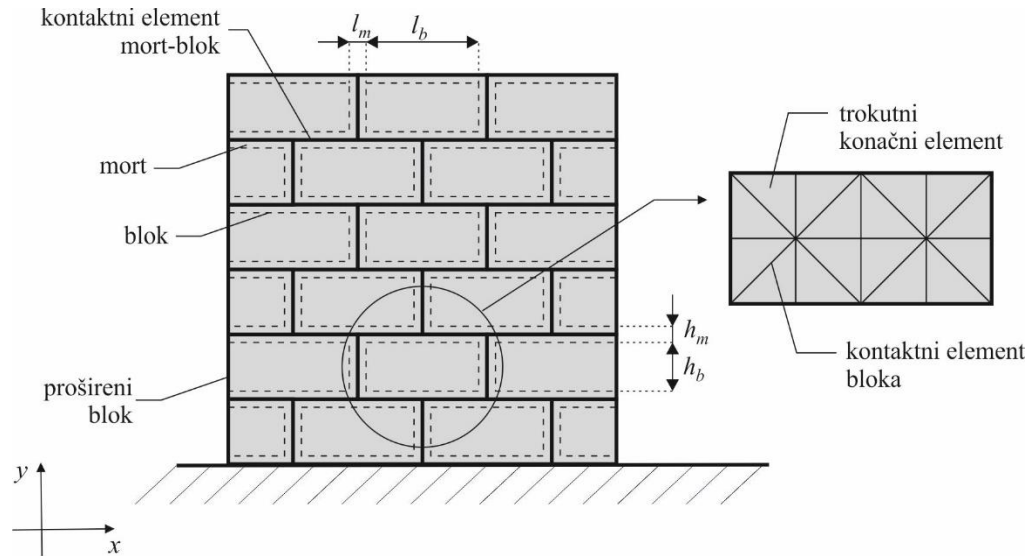


(c)

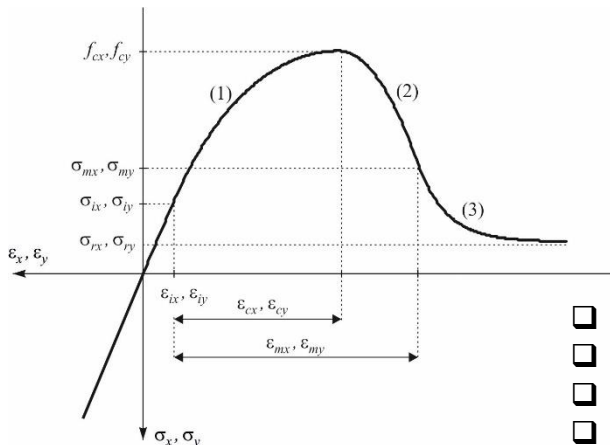
Usporedba numeričkog i eksperimentalnog mehanizma sloma za $a_g = 1.1$ g u vremenu: (a) $t = 3.2$ s; (b) $t = 3.8$ s i (c) $t = 4.3$ s

3. FDEM METODA U ANALIZI ZIDANIH KONSTRUKCIJA

Diskretizacija zidane konstrukcije od elemenata povezanih mortom



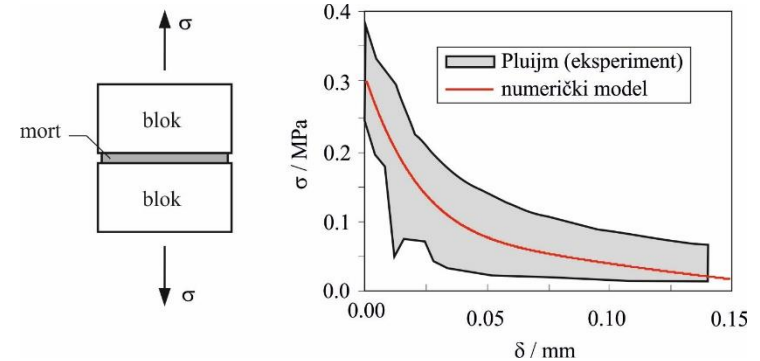
Model materijala u konačnom elementu



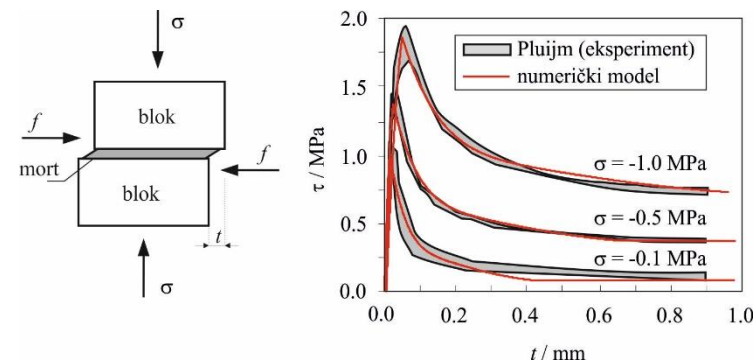
- Ortotropno ponašanje materijala
- Linearno-elastično ponašanje materijala u vlaku
- Pojava omekšanja u tlaku
- Različite čvrstoće materijala u horizontalnom i vertikalnom smjeru

Model materijala u kontaktnom elementu mort-blok

- Omekšanje u vlaku po eksponencijalnom zakonu



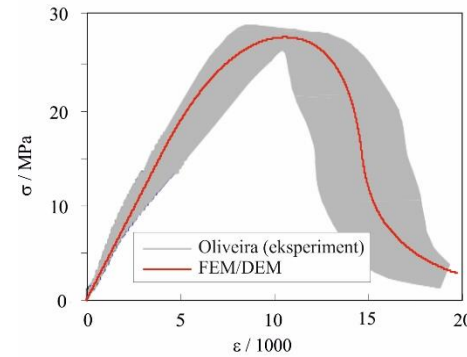
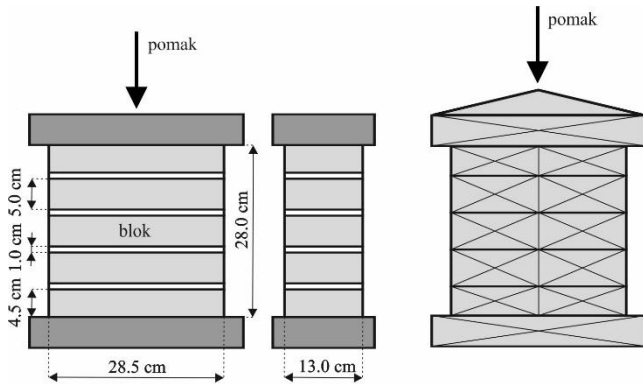
- Smanjenje koeficijenta trenja uslijed posmične deformacije



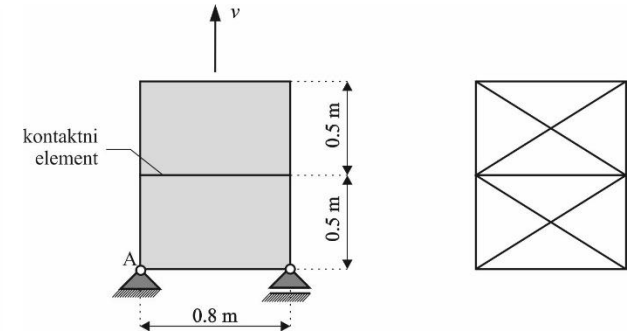


... FDEM METODA U ANALIZI ZIDANIH KONSTRUKCIJA

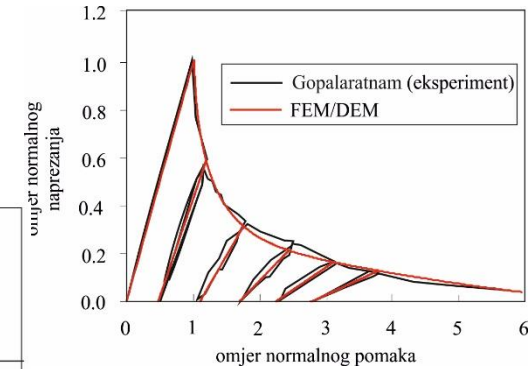
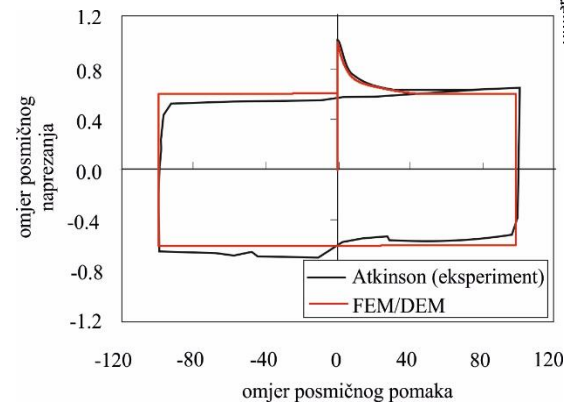
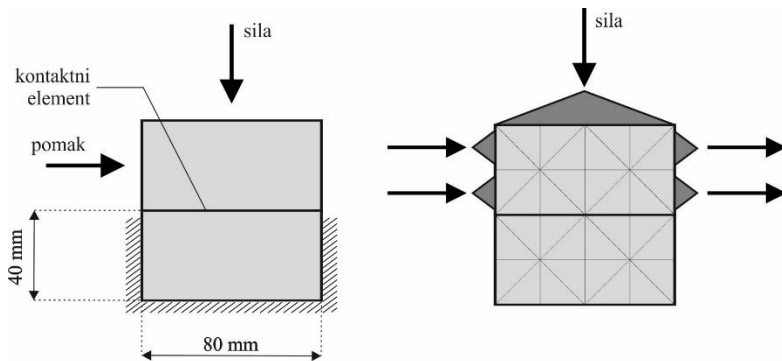
Validacija numeričkog modela za monotono rastuće tlačno opterećenje



Validacija vlačnog ponašanja u kontaktnom elementu mort-blok

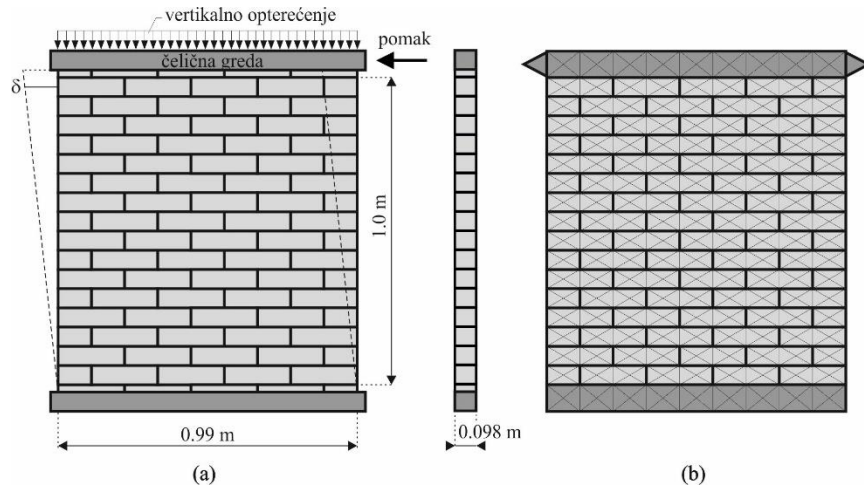


Validacija posmičnog ponašanja u kontaktnom elementu mort-blok

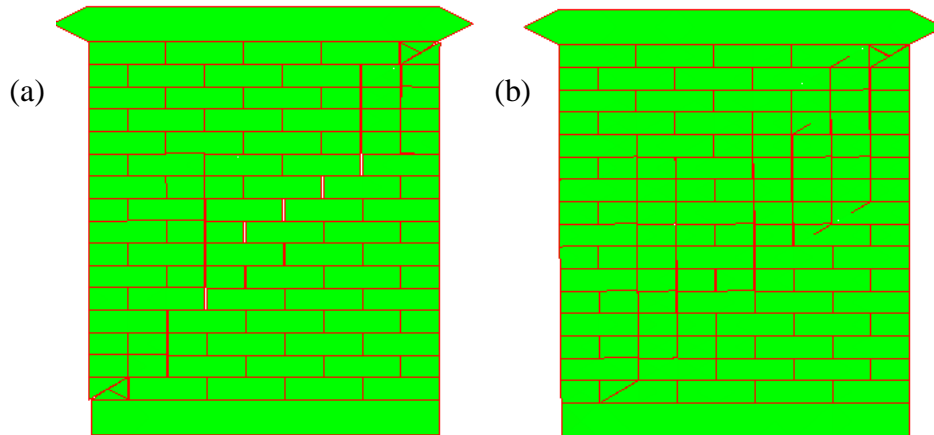
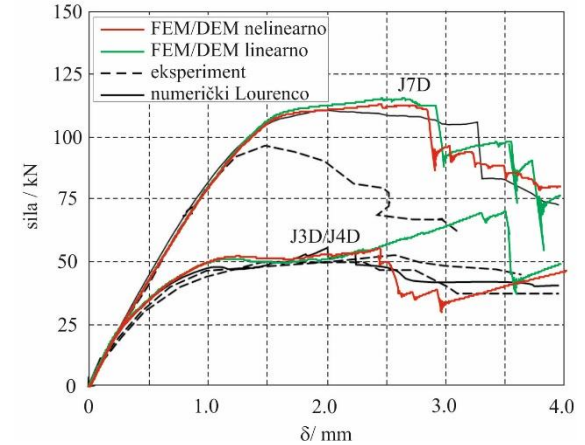


... FDEM METODA U ANALIZI ZIDANIH KONSTRUKCIJA

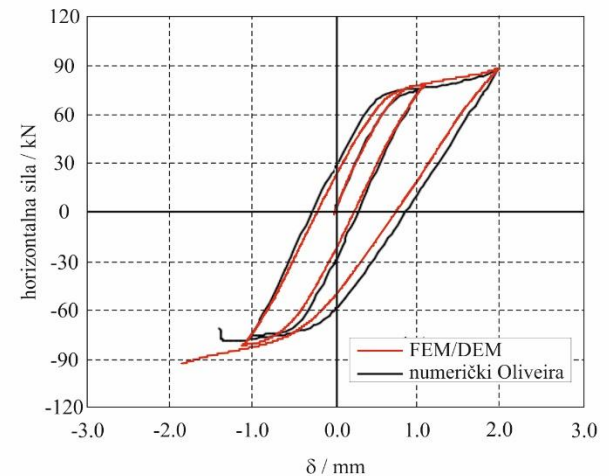
Zidani posmični zidovi izloženi monotono rastućem i cikličkom opterećenju



Posmični zid: (a) geometrija; (b) mreža konačnih elemenata

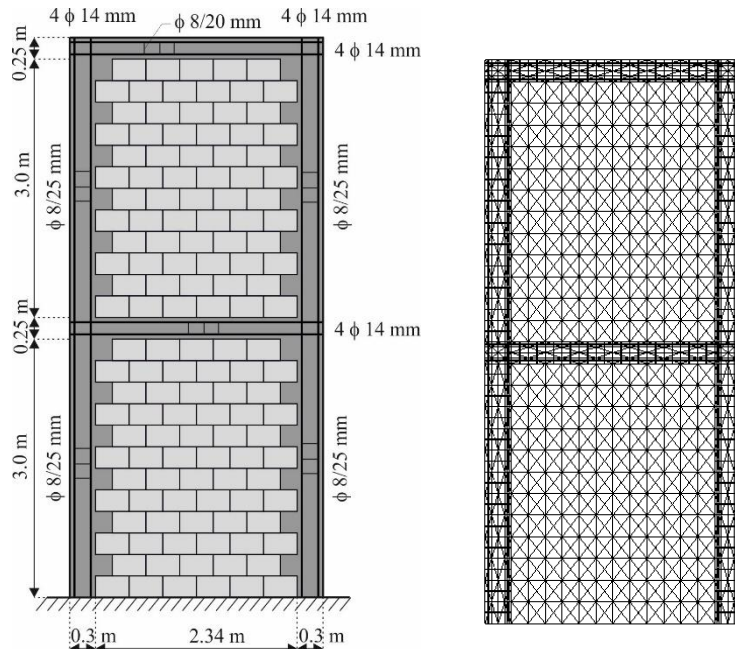


Stanje pukotina u zidovima: (a) J3D i J4D; (b) J7D

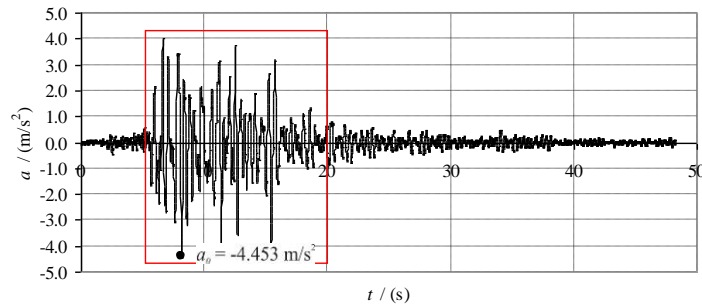


... FDEM METODA U ANALIZI ZIDANIH KONSTRUKCIJA

Omeđeni zidovi izloženi potresnom opterećenju

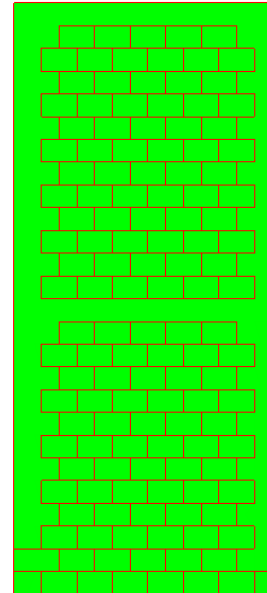


Zidani zid omeđen armiranobetonskim serklažima: (a) geometrijske karakteristike i način armiranja; (b) mreža konačnih elemenata

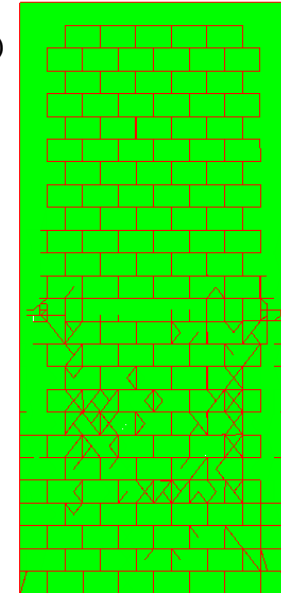


Potres iz baze podataka European Strong-motion Database, Petrovac (1979.)

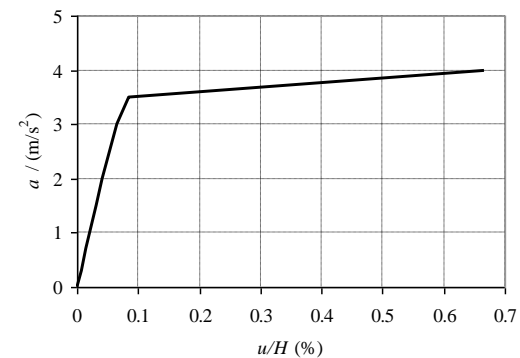
(a)



(b)



Pukotine u zidu nakon potresa vršnog ubrzanja od: (a) 3.0 m/s^2 ; (b) 4.0 m/s^2



Maksimalni pomaci u vrhu samostalnog zida ovisno o ubrzanju

Hvala na pažnji