

EFEKAT VIŠESTRUKIH ZEMLJOTRESA NA SEIZMIČKI ODGOVOR KONSTRUKCIJE

EFFECTS OF MULTIPLE EARTHQUAKES TO THE SEISMIC RESPONSE OF STRUCTURES

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1 UVOD

Sadašnji seizmički propisi, npr. EC8 [1], imaju važna ograničenja: ovim propisima usvaja se isključivo izolovan i redak „proračunski zemljotres“, dok se uticaj fenomena višestrukih zemljotresa potpuno ignoriše. Uprkos činjenici da je ovaj problem kvalitativno potvrđen, u literaturi se može naći izrazito malo studija koje se bave fenomenom višestrukih zemljotresa. Hatzigeorgiou i Beskos [2] i Hatzigeorgiou [3-5] proučavali su uticaj višestrukih zemljotresa u brojnim SDOF sistemima i pronašli su da niz seizmičkih potresa vodi povećanju pomeranja, u poređenju s „projektovanim“ zemljotresom. Nedavno, Hatzigeorgiou i Beskos [2] pokazali su opštu zabrinutost u vezi s datim problemom, uzimajući u obzir MDOF sisteme za armiranobetonske konstrukcije u seizmički podložnim zonama u svetu.

Ovaj rad prikazuje obimno parametarsko istraživanje neelastičnih odgovora četiri AB ravna rama pod uticajem pet stvarnih seizmičkih potresa. Ti višestruki zemljotresi zabeleženi su u istoj stanici, u istom smeru i u kratkom roku (tokom tri dana). Ispitvana su dva standardna i dva vertikalno nestandardna rama (stepenasto uvučeni spratovi). Vremenski odgovori betonskih ramova procenjeni su pomoću sredstava za analizu opterećenja softvera RUAUMOKO [7]. Kreirana je baza podataka sa

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1 INTRODUCTION

Current seismic design codes, e.g. EC8 [1], usually present an important limitation: they exclusively adopt the isolated and rare "design earthquake", while the influence of repeated earthquake phenomena is ignored. Despite the fact that the problem has been qualitatively acknowledged, very few studies have been reported in the literature regarding the multiple earthquake phenomena. Hatzigeorgiou and Beskos [2] and Hatzigeorgiou [3-5] examined the influence of multiple earthquakes in numerous SDOF systems and found that seismic sequences lead to increased displacement demands in comparison with the "design earthquake". Recently, Hatzigeorgiou and Beskos [2] presented a global consideration of the above problem considering MDOF systems for reinforced concrete (RC) structures in seismic-prone regions.

This paper presents an extensive parametric study on the inelastic response of four RC planar frames under five real seismic sequences. The multiple earthquakes have been recorded by the same station, in the same direction and in a short period of time, up to three days. Two regular and two vertically irregular (with setbacks) frames are examined. The time-history responses of these concrete frames are evaluated by means of the

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sveobuhvatnim analizama kako bi se izvukli važni zaključci.

2 OPIS RAMOVSKIH KONSTRUKCIJA I NJHOVO MODELIRANJE

U datoj komparativnoj studiji, posmatrane su četiri ramovske konstrukcije (Ramovi: A1, A2, A3 i A4) koje predstavljaju AB zgrade, niske visine (trospratne) i srednje visine (osmospratne). Ove četiri tipične AB zgrade sastoje se od greda i stubova bez smičućih zidova i locirane su u delovima Evrope koji su visoke seizmičnosti, a uzeta su u obzir i gravitaciona i seizmička opterećenja, gde su pretpostavljeni $PGA=0,2g$ i tlo klase B. Ove konstrukcije projektovane su za sledeću kombinaciju opterećenja:

- a) $1.35G+1.50Q$,
- b) $1.00G+yQ\pm 1.00E$,

gde G , Q i E redom odgovaraju stalnom, povremeno pokretnom i seizmičkom opterećenju, a y je koeficijent kombinacije i u ovoj studiji, za pokretno opterećenje, pretpostavljen je $y=1.00$. Slučaj smičućeg otkaza ovde nije ispitivan zbog odgovarajućeg poprečnog ojačanja. Stalna (izuzimajući sopstvenu težinu) i pokretna opterećenja redom su jednaka 20 kN/m i 10 kN/m , i nanešena su direktno na grede. Sve međuspratne tavanice su pretpostavljene kao krute u svojoj ravni i imaju efekat dijafragme betonskih ploča. Pretpostavljena je čvrstoća betona na pritisak 20 MPa (marka betona MB20), a za podužnu i poprečnu armaturu pretpostavljena je čvrstoća na razvlačenje (granica razvlačenja čelika). Na slici 1 prikazan je karakterističan unutrašnji ram konstrukcije koji predstavlja 2-D model ovih zgrada. Faktori ponašanja, q , kompatibilni su sa odredbama §5.2.2.2 EC8 – DCM kriterijuma. Zbog pojave pukotina, prilikom projektovanja uzete su redukovane vrednosti momenta inercije štapova ramovske konstrukcije, I_{ef} , za grede $I_{ef}=0.5I_g$ i stubove $I_{ef}=0.9I_g$, gde je I_g momenat inercije odgovarajućeg poprečnog preseka [8].

Kako bi se ispitao odgovor konstrukcije, korišteni su neelastični strukturni MDOF sistemi s viskoznom prigušenim odnosom sila-deformacija. Jednačina kretanja rešena je pomoću naprednog programa za seizmičku analizu ramovskih konstrukcija RUAUMOKO [7]. Zbog uklještene osnove, fenomen interakcije između tla i konstrukcije nije uzet u obzir. Efekti drugog reda (P - D efekti) uzeti su u obzir. Grede i stubovi modelirani su kao nelinearni elementi rama s plastičnim zglobovima na oba kraja greda i stubova. Pretpostavljeno je da su aksijalne sile u gredama jednake nuli, zbog pretpostavke o međuspratnim tavanicama kao krutim u sopstvenoj ravni, a koje imaju efekat dijafragme betonskih ploča. Za modeliranje poprečnih preseka svakog stuba i grede, u ovom radu korišten je program RESPONSE-2000 [9]. Treba primetiti da je za celu grupu analiza i sve članove usvojen histerezisni model Takeda [10]. Na parametre ovog modela utiče krajna otpornost greda i stubova. Objašnjenje ovih parametara i oblik histerezisne petlje analitički su prikazani u uputstvu za korišćenje programa RUAUMOKO [7].

structural analysis software RUAUMOKO [7]. Comprehensive analysis of the created response databank is employed in order to derive important conclusions.

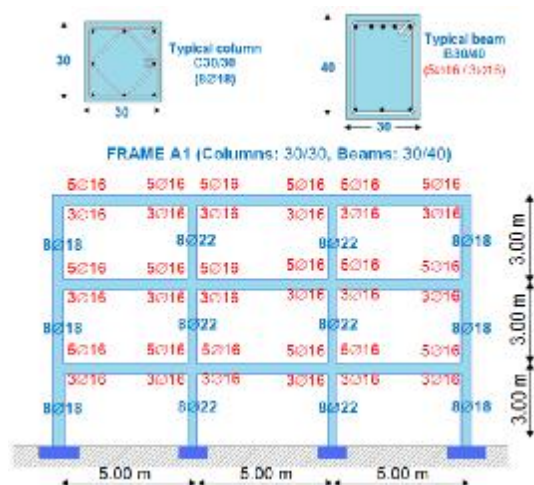
2 DESCRIPTION OF CONSIDERED STRUCTURES AND THEIR MODELLING

In the present comparative study, four structures (Frames: A1, A2, A3 and A4) are considered to represent low-rise (3-storey) and medium-rise (8-storey) RC buildings for study. They consist of 4 typical beam-column RC buildings without shear walls, located in a high-seismicity region of Europe considering both gravity and seismic loads where a PGA of $0.2g$ and soil class B are assumed. These structures have been designed for the following load combinations:

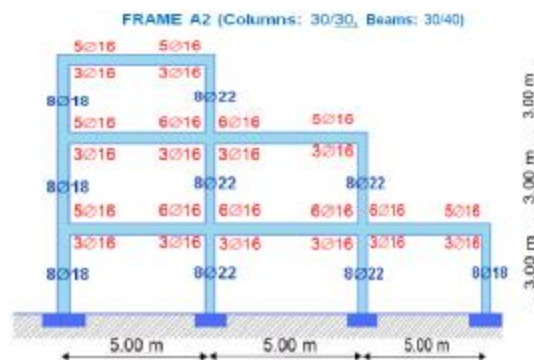
- a) $1.35G+1.50Q$,
- b) $1.00G+yQ\pm 1.00E$,

where G , Q and E correspond to dead, live and earthquake loads, respectively, and y is the combination coefficient for live load, assumed to be $y=1.00$ in this study. The case of shear failure is not examined here assuming adequate transverse reinforcement. The dead loads (excluding self-weight) and live loads are equal to 20 kN/m and 10 kN/m , respectively, and are directly applied on the beams. All floors are assumed to be rigid in plan to account for the diaphragm action of concrete slabs. Material properties are assumed to be 20 MPa for the concrete compressive strength (concrete grade C20) and 500 MPa for the yield strength of both longitudinal and transverse reinforcements (steel grade S500s). The characteristic interior frames of these structures, as shown in Fig. 1, represent 2-D models of these buildings. The behaviour factors, q , are compatible with the provisions of §5.2.2.2 of EC8 – DCM criteria. Reduced values of member moments of inertia, I_{ef} , were considered in the design to account for the cracking; for beams $I_{ef}=0.5I_g$ and for the columns $I_{ef}=0.9I_g$, where I_g is the moment of inertia of the corresponding gross section [8].

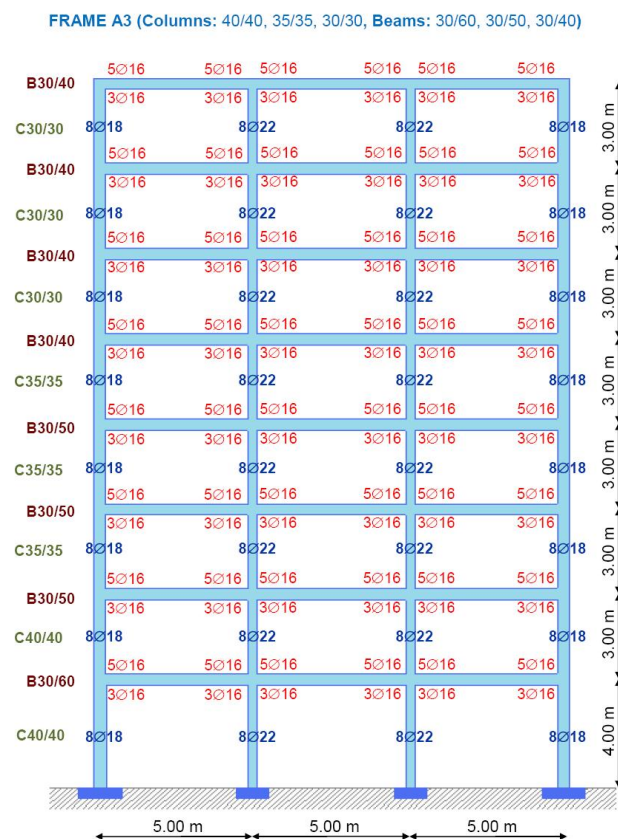
An inelastic structural MDOF system with viscously damped force-deformation relationship is used to investigate the structural response. The solution of the equation of motion has been performed using the RUAUMOKO program [7], which is an advanced program for seismic analysis of framed structures. The soil-structure interaction phenomenon is not taken into account, considering fixed base conditions. Second-order effects (P - D effects) are investigated. Beam and column elements are modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of the beams and columns. On the beams, axial forces were assumed to be zero since all floors are assumed to be rigid in plan to account for the diaphragm action of concrete slabs. In this work and for each column and beam, the program RESPONSE-2000 [9] is used for the section modelling. It should be noted that for the entire group of analyses and members, the modified Takeda [10] hysteretic model is adopted. The parameters of this model are affected by the end resistances of beams and columns. An explanation of these parameters and the shape of the hysteresis model are analytically presented in the RUAUMOKO user manual [7].



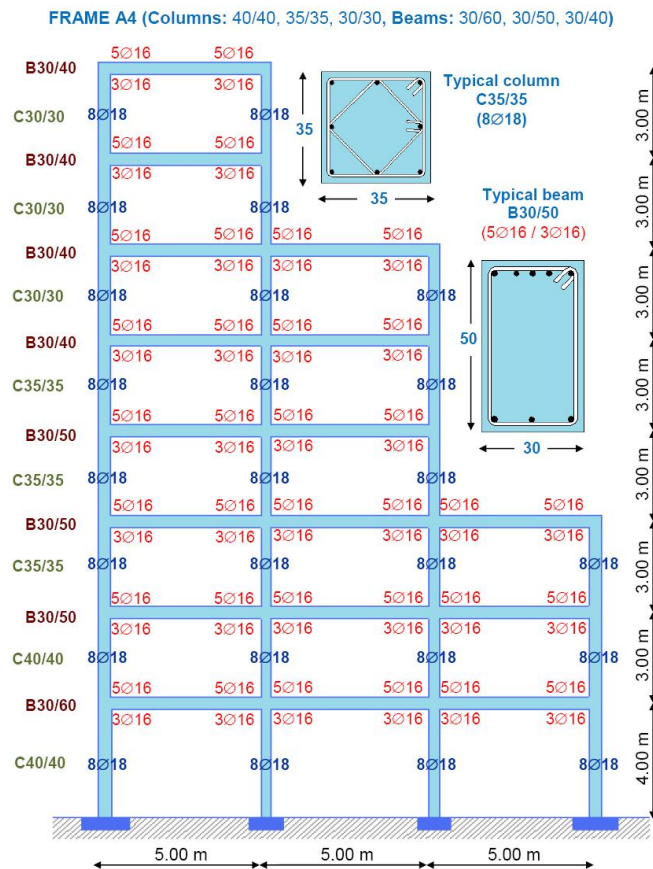
Slika 1. Ram A1
Figure 1. Frame A1



Slika 2. Ram A2
Figure 2. Frame A2



Slika 3. Ram A3
Figure 3. Frame A3



3 SEIZMIČKI ULAZNI PODACI

Baza podataka u vezi s pomeranjem tla sastoji se od niza pet realnih seizmičkih potresa koji su snimljeni za kratko vreme (do tri dana) u istoj stanici, u istom smeru, i na skoro istom odstojanju. Ovi nizovi seizmičkih potresa nazvani su zemljotresima: *Mamot Jezero* (maj 1980 – pet događaja), *Kalfant Dolina* (jul 1986 – dva događaja), *Koalinga* (jul 1983 – dva događaja), *Imperial Dolina* (oktobar 1979 – dva događaja) i *Vitier Klanci* (oktobar 1987 – dva događaja). Kompletan lista ovih zemljotresa preuzeta je iz baze podataka o pomeranju tla od Pacifičkog zemljotresnog inženjerskog istraživačkog centra (PEER) [11]. Videti tabelu 1.

Sve registracije uzastopnih pomeraja tla postaju jedan snimak pomeranja tla (serijski niz), gde je između dva uzastopna seizmička događaja apliciran vremenski razmak od 100 sekundi. Ovaj razmak je sasvim dovoljan da prekine pomeranje bilo koje konstrukcije zahvaljujući prigušenju. Na slikama 5a i 5b može se videti istorija korištenih nizova seizmičkih potresa. Zbog kompatibilnosti s procesom projektovanja, nizovi seizmičkih potresa su normalizovani i imaju $PGA=0.2g$.

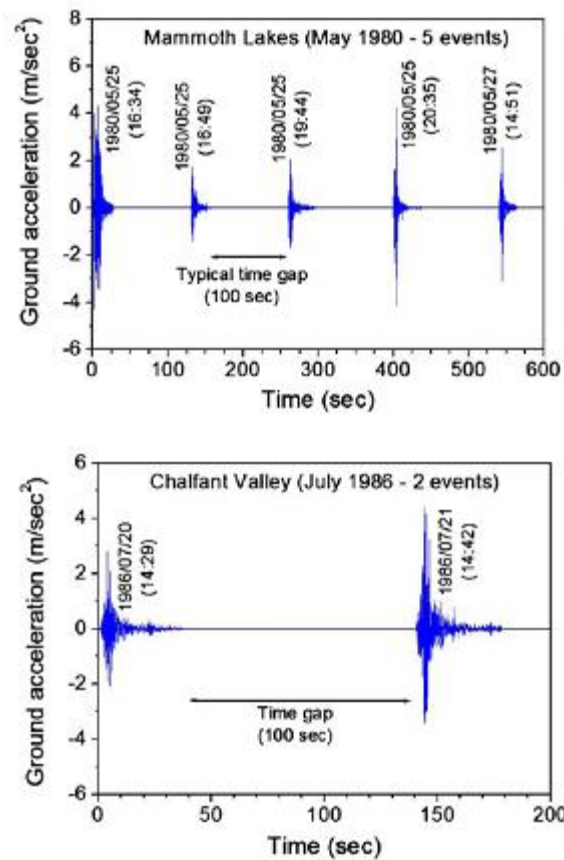
3 SEISMIC INPUT DATA

The strong ground motion database consists of five real seismic sequences, which have been recorded during a short period of time (up to three days), by the same station, in the same direction, and almost at the same fault distance. These seismic sequences are namely: Mammoth Lakes (May 1980 - 5 events), Chalfant Valley (July 1986 - 2 events), Coalinga (July 1983 - 2 events), Imperial Valley (October 1979 - 2 events) and Whittier Narrows (October 1987 - 2 events) earthquakes. The complete list of these earthquakes, which were downloaded from the strong motion database of the Pacific Earthquake Engineering Research (PEER) Center [11], appears in Table 1.

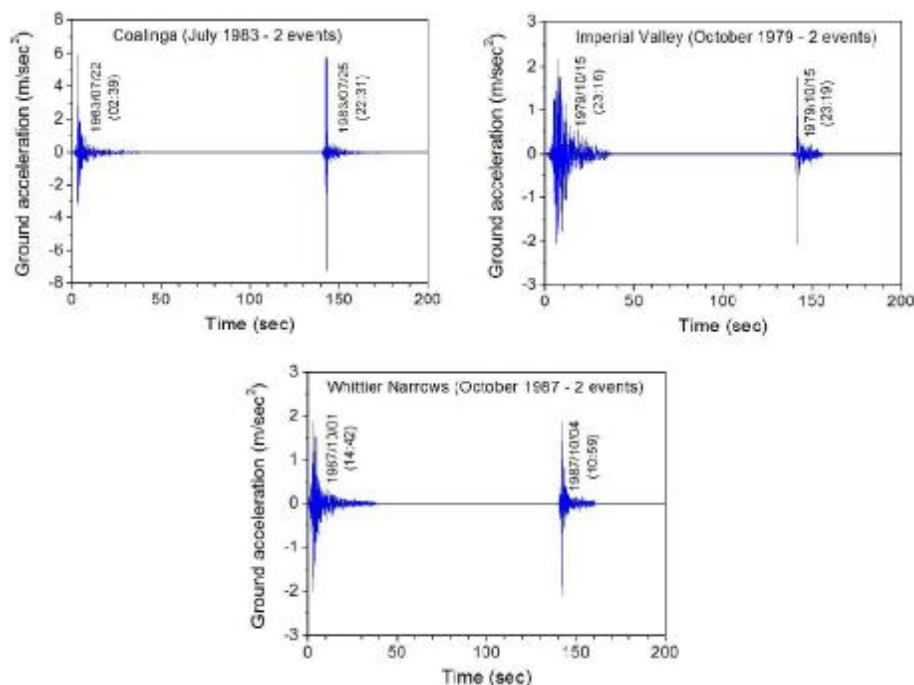
Every sequential ground motion records becomes a single ground motion record (serial array) where between two consecutive seismic events a time gap is applied, which is equal to 100 sec. This gap is enough to cease the moving of any structure due to damping. Figures 5a and 5b show the time histories of used seismic sequences. For compatibility reasons with the design process, the seismic sequences are normalized to have $PGA=0.2g$.

Tabela 1. Seizmički ulazni podaci
Table 2. Seismic input data

No.	Seismic sequence	Station	Comp.	Date (Time)	Recorded PGA(g)
1	Mammoth Lakes	54099 Convict Creek	N-S	1980/05/25 (16:34)	0.442
				1980/05/25 (16:49)	0.178
				1980/05/25 (19:44)	0.208
				1980/05/25 (20:35)	0.432
				1980/05/27 (14:51)	0.316
2	Chalfant Valley	54428 Zack Bros Ranch	E-W	1986/07/20 (14:29)	0.285
				1986/07/21 (14:42)	0.447
3	Coalinga	46104 CILP	N-S	1983/07/22 (02:39)	0.605
				1983/07/25 (22:31)	0.733
4	Imperial Valley	5055 Holtville P.O.	HPV315	1979/10/15 (23:16)	0.221
				1979/10/15 (23:19)	0.211
5	Whittier Narrows	24401 San Marino	N-S	1987/10/01 (14:42)	0.204
				1987/10/04 (10:59)	0.212



Slika 5a. Zemljotresi Mamot Jezero i Kalfant Dolina
Figure 5a. Mammoth Lakes and Chalfant Valley earthquakes



Slika 5b. Zemljotresi Koaling, Imperial Dolina i Vitier Klanci
Figure 5b. Coalina, Imperial Valley and Whittier Narrows earthquakes

4 IZABRANI REPREZENTATIVNI REZULTATI

U ovom delu rada proučavano je neelastično ponašanje ispitivanih AB ramovskih konstrukcija. Ovo istraživanje fokusira se na sledeće osnovne projektne parametre: lokalni ili globalni indeks oštećenja prema Park i Ang pristupu [12], maksimalno horizontalno pomeranje međuspratnih tavanica, odnosi međuspratnog pomeranja, razvoj plastičnih zglobova, odgovor konstrukcije prema tehnici inkrementalne dinamičke analize (IDA) [13] i trajna pomeranja. Park-Ang model [12] najpoznatiji je i najprimenjeniji indeks oštećenja (DI), koji se definiše kao kombinacija maksimalne deformacije i histerezisne energije:

$$DI = \frac{d_m}{d_u} + \frac{\beta}{d_u P_y} \int dE_h \quad (1)$$

gde je δ_m maksimalna deformacija elementa, δ_u krajnja deformacija, a β konstanta modela (obično se kreće $\beta=0.05\sim0.20$), koja kontroliše pogoršanje čvrstoće; $\int dE_h$ je histerezisna energija koju apsorbuje element za vreme zemljotresa, i P_y je čvrstoća razvlačenja elementa. U ovom radu, parametar β je 0.20. Ovaj oštećeni model se takođe može primeniti i na spratove i ukupni obim (globalni indeks oštećenja) sabiranjem indeksa oštećenja, koristeći odgovarajuće uvećane težine.

Slika 6 prikazuje lokalna i globalna oštećenja rama A2 pod uticajem zemljotresa Mamot Jezero (1980) i Vitier Klanci (1987). Očigledno je da, u svim slučajevima, nizovi seizmičkih potresa vode povećanju oštećenja – i na lokalnom i globalnom nivou.

Odnos međuspratnog pomeranja (IDR) za ram A3 i A4 može se videti na slici 7, za jedan pomeraj, ali i za

4 REPRESENTATIVE SELECTED RESULTS

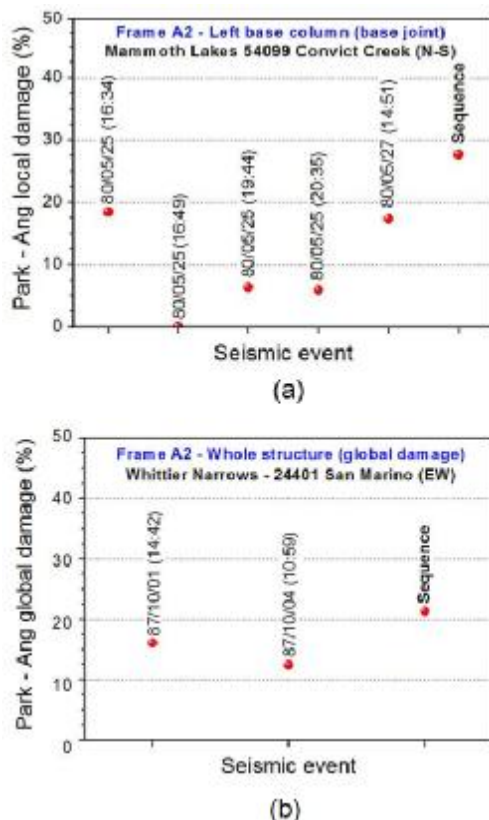
The inelastic behaviour of the examined RC framed structures is investigated in this section. This study focuses on the following basic design parameters: local or global damage index according to Park and Ang approach [12], maximum horizontal floor displacements, interstorey drift ratios, development of plastic hinges, structural response according to incremental dynamic analysis (IDA) [13] technique and permanent displacements. The Park-Ang model [12] is the best known and most widely used damage index (DI), which is defined as a combination of maximum deformation and hysteretic energy:

where δ_m is the maximum deformation of the element, δ_u is the ultimate deformation, β is a model constant parameter (usually, $\beta=0.05\sim0.20$) to control strength deterioration, $\int dE_h$ is the hysteretic energy absorbed by the element during the earthquake, and P_y is the yield strength of the element. In this work, parameter β is set equal to 0.20. This damage model can also be extended to the storey and overall scales (global damage index), by summation of damage indices using appropriate multiplication weights.

Figure 6 depicts the local and global damage, for the Frame A2 under the Mammoth Lakes(1980) and Whittier Narrows(1987) earthquakes. It is evident that, in any case, seismic sequences lead to increased damage, both in local and global level.

The interstorey drift ratio (IDR) for Frames A3 and A4 appear in Figure 7, both for single and sequential ground

niz pomeraja tla (zemljotresi *Koalinga* i *Imperial Dolina*). Očigledno je da niz seizmičkih potresa vodi do uvećanja *IDR*, u poređenju sa odgovarajućim jednim seizmičkim događajem.



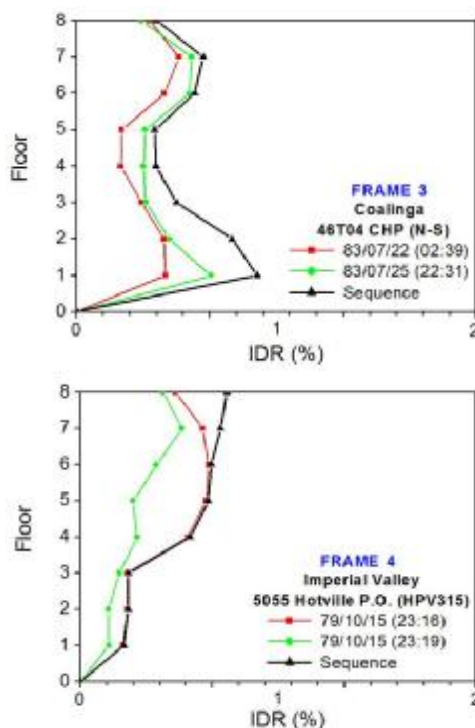
Slika 6. Lokalna i globalna oštećenja rama A2
Figure 6. Local and global damage for Frame A2

Konačni razvoj/konačna raspodela plastičnih zglobova na ramu A1 može se videti na slici 8. Očigledno je to da je zbog više zemljotresa raspodela plastičnih zglobova drugačija nego u slučaju odgovarajućeg jednog/izolovanog seizmičkog događaja.

Sve ispitivane konstrukcije analizirane su pomoću *IDA* tehnike [13]. Na slici 9 prikazani su rezultati za ramove A1 i A2 pod uticajem jednog i višestrukog pomeranja tla. Očigledno je da niz seizmičkih potresa vodi ka primetno različitim odgovorima u poređenju sa odgovarajućim jednim seizmičkim događajem, što uzrokuje potrebu za uvećanjem pomeranja. Kao što je očekivano, povećanje potrebe za pomeranjem vodi ka većim vrednostima pomeranja i oštećenja. Osnovni cilj *IDA* jeste da odredi količinu rezerve kapaciteta konstrukcije, kako ne bi došlo do kolapsa konstrukcije.

Otkako se u analizama uzima u obzir stanje kolapsa u vezi s degradacijom jačine nosivosti i čvrstoće, *IDA* tehnika pokazala se kao veoma korisna. Pretpostavlja se da se stanje loma postiže ekstremno velikim horizontalnim pomeranjima. Na slici 9 se vidi, za ispitivane konstrukcije i njihove *PGA*, da do kolapsa dolazi samo u slučajevima niza seizmičkih potresa, a ne u slučaju „izolovanog” jednog pomeraja tla.

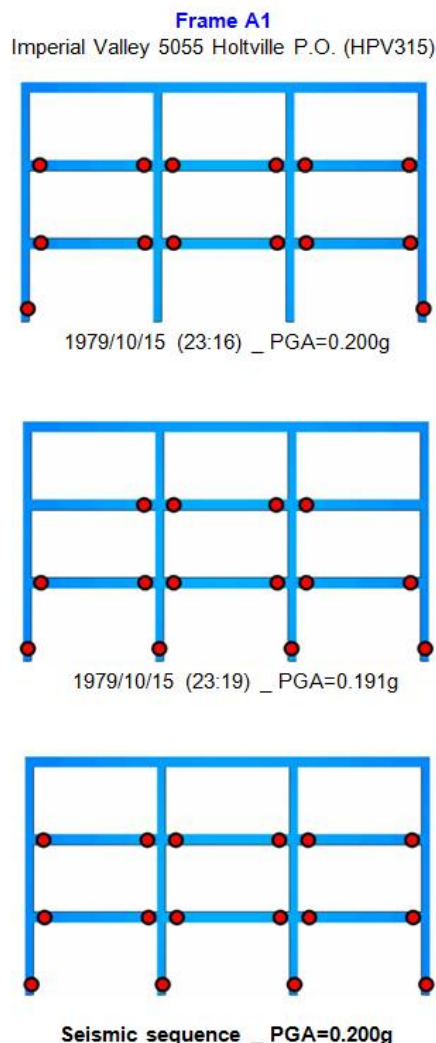
motions (Coalinga and Imperial Valley earthquakes). It is evident that seismic sequences lead to larger *IDR* in comparison with the corresponding single events.



Slika 7. IDR za ramove A3 i A4
Figure 7. IDR for Frames A3 and A4

The final development/distribution of plastic hinges of Frame A1 appears in Figure 8. It is evident that due to the multiplicity of earthquakes, the distribution of plastic hinges seems to be different than the corresponding one for single/isolated seismic events.

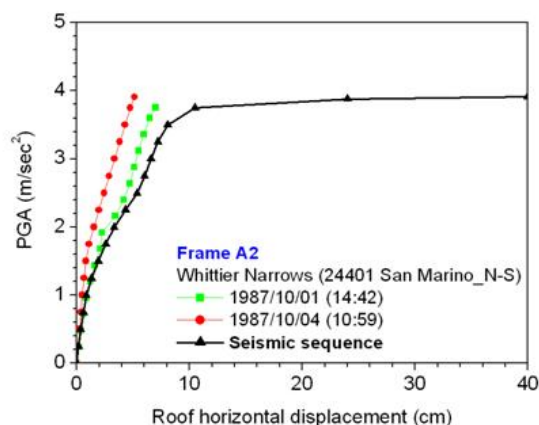
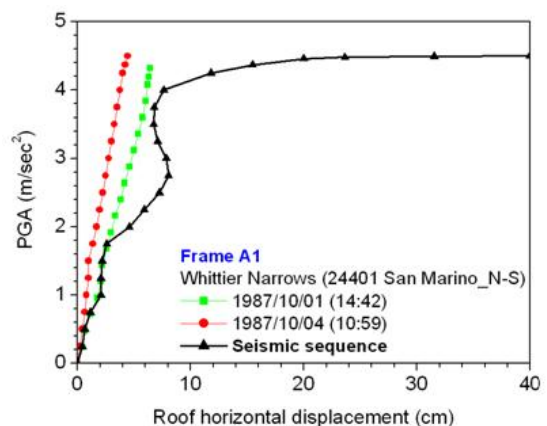
All the examined structures have been analyzed using the *IDA* technique [13]. Figure 9 shows selected results for the Frames A1 and A2 under single and multiple strong ground motions. It is evident that the seismic sequences lead to noticeably different response in comparison with the corresponding single seismic events and require increased displacement demands, in any case under consideration. As it is expected, the increased displacement demands lead to higher values of drift and damage. The primary goal of *IDA* is to quantify the reserve capacity of a structure against collapse. Since the analyses take into account the collapse state considering stiffness and strength degradation, the *IDA* seems to be very useful for this study. Assuming that the collapse state is represented by extremely large horizontal displacements, Figure 9 shows, for the examined structures and *PGA*'s that the collapse appears only for the cases of seismic sequences and not for the 'isolated' single ground motions.



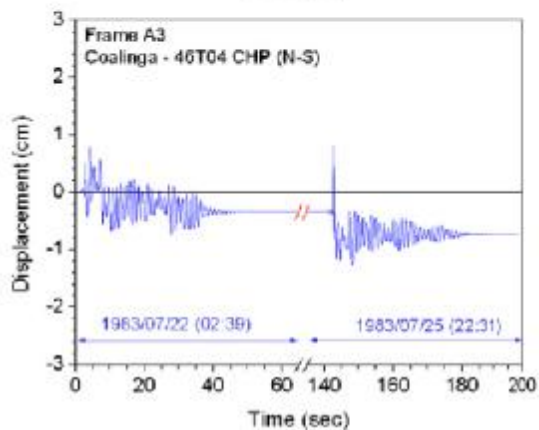
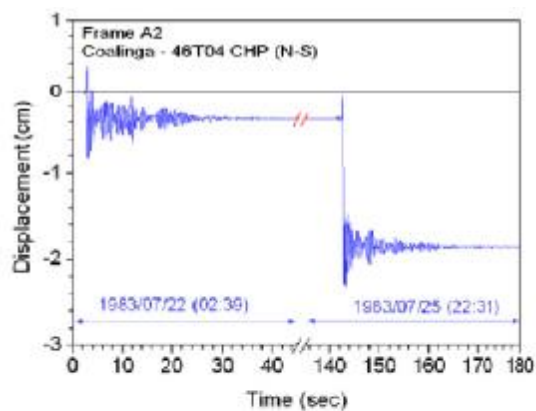
Slika 8. Raspodela plastičnih zglobova za pojedinačno i sekventno pomeranje tla – Ram A1
Figure 8. Plastic hinges distribution for single and sequential ground motions – Frame A1

Dobro je poznato da se trajna pomeranja moraju tačno proceniti, kako bi se zadovoljio željeni nivo ponašanja konstrukcije pod uticajem predefinisane seizmičke opasnosti. U ovom radu, pronađeno je da višestrukost zemljotresa snažno utiče na trajna pomeranja. Prema tome, fenomen višestrukog zemljotresa mora biti uzet u obzir, kako bi se postigao bezbedan nivo procene trajnog pomeranja. Na slici 10 prikazani su izabrani rezultati posmatranih konstrukcija, koje su podvrgnute nizu seizmičkih potresa, gde je prikazana i istorija horizontalnog pomeranja vrha ramova. Akumulacija trajnih pomeranja očigledna je u svakom posmatranom slučaju.

It is well-known that in order to satisfy the targeted performance levels under pre-defined seismic hazard levels, the permanent displacement should be accurately estimated. In this work, it is found that the multiplicity of earthquakes strongly influences the permanent displacements and therefore multiple earthquakes phenomena should be taken into account to achieve dependable estimation of permanent displacements. Figure 10 shows selected results for the considered structures subjected to seismic sequences, where the time history of horizontal displacement for the top of the frames is presented. The accumulation of permanent displacement is obvious, in any case under consideration.

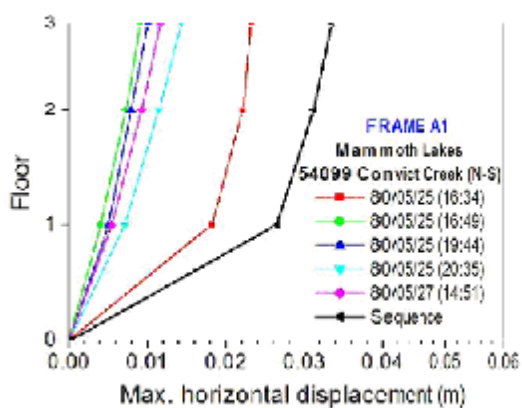


Slika 9. Aplikiranje IDA za sekventno pomeranje tla
Figure 9. Application of IDA for sequential ground motions



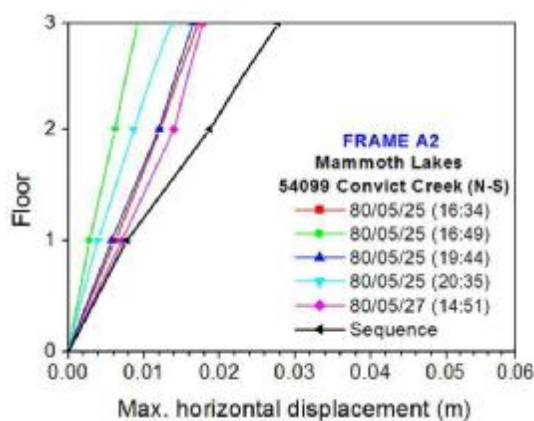
Slika 10. Akumulacija trajnog pomeranja za ramove A2 i A3.

Figure 10. The accumulation of permanent displacement for Frames A2 and A3.



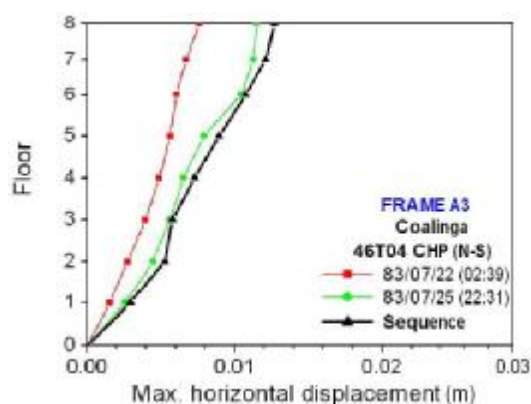
Slika 11a. Maksimalno horizontalno pomeranje – Ram A1

Figure 11a. Max. horizontal displacement – Frame A1



Slika 11b. Maksimalno horizontalno pomeranje – Ram A2

Figure 11b. Max. horizontal displacement – Frame A2



Slika 11c. Maksimalno horizontalno pomeranje – Ram A3
Figure 11c. Max. horizontal displacement – Frame A3

Konačno, kada su u pitanju maksimalna pomeranja i potreba duktilnosti, slike 11a, 11b, 11c prikazuju profile maksimalnih horizontalnih pomeranja, za jedan i niz uzastopnih pomeranja tla. Preciznije su ispitivani ramovi A1, A2 i A3, pod dejstvom zemljotresa *Mamot Jezera* i *Koalinga*. Pronađeno je da se pod uticajem višestrukih zemljotresa povećava potreba za pomeranjem, u svakom slučaju koji se razmatra. Dobro je poznato da neelastični fleksibilni sistemi pokazuju trajna pomeranja za pojedinačne jake zemljotrese. Za svaki drugi naredni pomeraj tla, trajna pomeranja se nagomilavaju i prema tome – maksimalna pomeranja se povećavaju. Osim toga, maksimalna pomeranja su u direktnoj vezi s potrebama duktilnosti.

5 ZAKLJUČCI

Pod uticajem više snažnih pokreta tla, istražili smo neelastična ponašanja ravnih AB ramova. Ispitali smo dve vrste ramova: prvi je regularan, a drugi vertikalno neregularan ram (stepenasto uvučeni spratovi). Ovi ramovi projektovani su za vertikalno odnosno za vertikalno i seizmičko opterećenje. Detaljno parametarsko istraživanje problema dovelo je do sledećih glavnih zaključaka:

- Višestruki zemljotresi dovode do povećanja pomeranja, u poređenju s jednim seizmičkim događajem. Osim toga, seizmička oštećenja su veća usled višestrukih zemljotresa nego u slučaju jedinog pomeraja tla. Ove karakteristike veoma su važne i trebalo bi ih uzeti u obzir prilikom seizmičkog projektovanja konstrukcija, ili pri konvencionalnom projektovanju zasnovanom na sili ili putem novije metode projektovanja, bazirane na pomeranju, a koja traži veoma visoku tačnost prilikom određivanja pomeranja.

- Istražili smo trajna pomeranja konstrukcija koje su bile izložene uzastopnom nizu pomeraja tla. Pronašli smo da sekventno pomeranje tla akumulira trajna pomeranja. Prema tome, za njihovo tačno određivanje trebalo bi uzeti u obzir fenomen višestrukih zemljotresa.

- Niz uzastopnih pomeraja tla snažno utiče na razvoj/raspodelu plastičnih zglobova, što se razlikuje u slučaju jednog/izolovanog seizmičkog događaja.

- Istražili smo tehniku inkrementalne dinamičke

Finally, concerning maximum displacements and ductility demands, the Figures 11a,b,c present maximum horizontal displacement profiles, both for single and sequential ground motions. More specifically, the Frames A1, A2 and A3, under the Mammoth Lakes and Coalinga seismic sequences are examined. It is found that due to the multiplicity of earthquakes, increased displacement demands are required, in any case under consideration. It is well-known that inelastic flexible systems present permanent displacements for single strong earthquakes. For any other oncoming ground motion, permanent displacements are obviously cumulated and therefore the maximum displacements appear to be increased. Furthermore, the maximum displacements are directly related to the ductility demands.

5 CONCLUDING REMARKS

The inelastic behaviour of planar RC frames under sequential strong ground motions has been investigated. Two families, the first of regular and the second one of vertically irregular (with setbacks) frames, are examined. These frames have been designed either for vertical or both for vertical and seismic loads. A detailed parametric study of the problem leads to the following main conclusions:

- Multiple earthquakes require increased displacement demands in comparison with single seismic events. Furthermore, the seismic damage for multiple earthquakes is higher than that for single ground motions. These characteristics are very important and should be taken into account for the seismic design of structures either by the conventional force-based or especially by the more recent displacement-based design method, which requires a high accuracy estimation of displacements.

- The permanent displacements of the structures, which are subjected to sequential ground motions, have been investigated. It is found that the sequential ground motions accumulate the permanent displacements. Therefore, an accurate estimation of them requires taking into account the multiple earthquakes phenomena.

- Sequential ground motions strongly affect the development/distribution of plastic hinges, which can be

analize (*IDA*) pod uticajem niza uzastopnih pomeranja tla. Pronašli smo da su odgovori konstrukcije pod nizom seizmičkih potresa znatno drugačiji nego u slučaju odgovarajućeg jednog seizmičkog događaja. Osim toga, za ispitivanje konstrukcije i njihove PGA, kolaps se javlja samo u slučaju niza seizmičkih potresa, dok se u slučaju „izolovanog” jednog pomeraja tla ne javlja.

Konačno, ovde prikazana procedura može se primeniti i u slučajevima seizmičke interakcije susednih AB konstrukcija pod uticajem višestrukih zemljotresa. Prvi rezultati ovog istraživanja pojavili su se nedavno [14].

different than that for the case of single/isolated seismic events.

- The incremental dynamic analysis (*IDA*) technique under sequential ground motions has been also investigated. It is found that the seismic sequences lead to quite different responses than the corresponding ones for single seismic events. Furthermore, for the examined structures and *PGA*'s, the collapse appears only for the cases of seismic sequences and not for the 'isolated' single ground motions.

Finally, the herein presented procedure can be extended to the case of seismically interacting adjacent RC structures under multiple earthquakes. First results of this research have appeared recently [14].

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REZIME

EFEKAT VIŠESTRUKIH ZEMLJOTRESA NA SEIZMIČKI ODGOVOR KONSTRUKCIJE

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Prethodna istraživanja pokazala su da su dobro projektovane, moderne, armiranobetonske (AB) zgrade, kao što su AB ramovske konstrukcije, sposobne da obezbede sigurnost stanara za vreme jakog zemljotresa. U seizmički aktivnim delovima sveta, armiranobetonski otporni ramovi su najčešći oblik trgovačkih, industrijskih i stambenih objekata. Međutim, postoje značajne mane u sadašnjim seizmičkim propisima. Slaba strana seizmičkih propisa jeste usvajanje isključivo izolovanog i retkog „projektog-proračunskog zemljotresa“, dok se uticaj fenomena višestrukih zemljotresa potpuno ignoriše. Uprkos činjenici da je ovaj problem kvalitativno potvrđen, u literaturi se može naći veoma malo studija koje se bave fenomenom višestrukih zemljotresa. Ovaj rad proučava ponašanje AB ramova koji su izloženi višestrukim zemljotresima. Ustanovljeno je da uzastopni niz pomeraja tla ima značajan efekat na odgovor, a samim tim i na projektovanje armiranobetonskih konstrukcija.

Ključne reči: Armiranobetonske konstrukcije; seizmičko projektovanje; višestruki zemljotresi.

SUMMARY

EFFECTS OF MULTIPLE EARTHQUAKES TO THE SEISMIC RESPONSE OF STRUCTURES

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Previous research has shown that well-designed modern reinforced concrete (RC) structures, e.g. RC frame buildings, are able to ensure the safety of building occupants during a strong earthquake. Reinforced concrete (RC) moment resisting frames are a prevalent form of commercial, industrial and multi-family residential construction in seismic-prone regions worldwide. However, there is a significant drawback for the current seismic codes. This concerns exclusive adoption of the isolated and rare “design earthquake”, while the influence of repeated earthquake phenomena is ignored. Despite the fact that the problem has been qualitatively acknowledged, very few studies have been reported in the literature regarding the multiple earthquake phenomena. This paper examines the behaviour of RC frames which are subjected to multiple earthquakes. It is found that the sequences of ground motions have a significant effect on the response and, hence, on the design of reinforced concrete structures.

Key words: Reinforced concrete structures; seismic design; multiple earthquakes