LINEAR AND NONLINEAR STRUCTURE ANALYSIS ACCORDING TO EN 1998-1: 2004

LINEARNA I NELINEARNA ANALIZA KONSTRUKCIJE PREMA EN 1998-1:2004

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Summary: The subject of this paper is the basis of structural design according to the proposal EN 1998-1: 2004, in seismically active areas. The static linear-elastic method, the method of equivalent lateral forces and the nonlinear ("pushover") method for estimating the nonlinear behavior of reinforced concrete load-bearing structures during seismic actions are presented. The paper presents the requirements for the adoption of dimensions and reinforcement of sections in accordance with the regulations of Eurocode 8, which should, in addition to the required load-bearing capacity, meet the requirements of local ductility, which prevents the formation of a plastic mechanism in the form of a flexible floor. By the method of equivalent lateral forces, the seismic action is represented over the acceleration spectrum. Linear elastic analysis of the structure was done using the program "Tower", where the cross sections were adopted and sizing was done strictly taking into account the recommendations from EC 8. In the Tower, two-dimensional elements were used in the analysis of the structure. A nonlinear analysis of the frame with the same adopted dimensions, reinforcement and authoritative load combination was done in the “Abaqus” program, the result of which is the push curve. For modeling columns and

Rezime: Predmet rada je osnova proračuna konstrukcije prema predlogu EN 1998-1:2004, u seizmički aktivnim područjima. Predstavljena je statička linearno-elastična metoda, metoda ekvivalentnih bočnih sila i nelinearna (,,pushover”) metoda za procenu nelinearnog ponašanja armiranobetonskih nosećih konstrukcija pri seizmičkim dejstvima. U radu su predočeni zahtevi za usvajanje dimenzija i armiranje preseka u skladu sa propisima Evrokoda 8 koji treba da, pored uslova potrebne nosivosti, zadovolje i uslove lokalne duktilnosti čime se sprečava formiranje plastičnog mehanizma u vidu fleksibilnog sprata. Metodom ekvivalentnih bočnih sila seizmičko dejstvo se predstavlja preko spektara ubrzanja. Linearno elastična analiza konstrukcije urađena je primenom programa ,,Tower” pri čemu su usvojeni poprečni preseci i urađeno je dimenzionisanje strogo vodeći računa o preporukama iz EC 8. U Tower-u su korišćeni dvodimenzionalni elementi pri analizi konstrukcije. Nelinearna analiza rama sa istim usvojenim dimenzijama, armaturom i merodavnom kombinacijom opterećenja je urađena u programu ,,Abaqus” čiji je rezultat pushover kriva. Za modeliranje stubova i greda u Abaqus-u korišćeni su trodimenzionalni heksaedarski elementi C3D8R koji imaju šest stepeni slobode na svakom čvoru, tri translaciona stepena slobode

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beams in Abaqus, three-dimensional hexahedral elements C3D8R were used, which have six degrees of freedom at each node, three translational degrees of freedom (1,2,3) and three rotational degrees of freedom (4,5,6). During the reinforcement modeling, the elements of the B21 linear beam were used, which have two translational degrees of freedom (1,2) and one rotational degree of freedom (6).

Keywords: Pushover analysis, nonlinear static analysis, Pushover curve.

(1,2,3) i tri rotaciona stepena slobode (4,5,6). Prilikom modeliranja armature korišćeni su elementi B21 linearne grede, koje imaju dva translaciona stepena slobode (1,2) i jedan rotacioni stepen slobode (6).

Ključne reči: Pushover analiza, nelinearna statička analiza, pushover kriva.

1. INTRODUCTION

The basic requirements for the calculation of structures according to EC 8 regulations are the requirement that the building does not collapse and the requirement for limited damage [1]. For conventional structures the first requirement should be met for a reference earthquake with a 10% probability of exceeding 50 years or with a return period of 475 years, while the second, for conventional structures should be met for a reference earthquake with 10% probability of exceeding 10 years or with a return period of 95 years.
An earthquake is an accidental and short-term load. Devastating earthquakes may or may not occur during the normal life of a structure. For that reason, the fact is accepted that during the action of stronger earthquakes, the stress of the structural elements approaches their limit bearing capacity, and in some parts of the structure it can be reached. It also means crossing the load constructions into a nonlinear response range. To design a structure so that even for the strongest anticipated earthquakes in a locality remains in the linear-elastic area of material work is irrational from a constructive, but also economic,

1. UVOD

Osnovni zahtevi za proračun konstrukcija prema pravilniku EC 8 su zahtev da se objekat ne sruši i zahtev za ograničenim oštećenjem [1]. Za uobičajene konstrukcije prvi zahtev treba ispuniti za referentni zemljotres sa 10% verovatnoće prekoračenja u 50 godina ili sa povratnim periodom od 475 godina, dok drugi, za uobičajene konstrukcije treba ispuniti za referentni zemljotres sa 10% verovatnoće prekoračenja u 10 godina ili sa povratnim periodom od 95 godina.
Zemljotres je slučajno i kratkotrajno opterećenje. Razorni zemljotresi se mogu, ali i ne moraju dogoditi za vreme uobičajenog veka trajanja konstrukcije. Iz tog razloga se prihvata činjenica da se tokom delovanja jačih potresa naprezanje konstruktivnih elemenata približava njihovoj graničnoj nosivosti, a kod pojedinih delova konstrukcije ona može biti i dostignuta. To znači i prelazak nosive konstrukcije u nelinearno područje odgovora. Projektovati neku konstrukciju tako da i za najjače predviđene potrese na nekom lokalitetu ostane u linearno-elastičnom području rada materijala je neracionalno i sa konstruktivnog, ali i ekonomskog, estetskog i funkcionalnog stanovišta. Za povoljan odgovor na

aesthetic and functional point of view. Reliable behavior of the structure in a nonlinear region is important for a favorable response to an earthquake. The goal is to use the ductility of the load-bearing structure and achieve the dissipation of energy introduced by the earthquake. The seismic response of a structure can best be followed by computational analyzes that assume a nonlinear response of structural elements, but such calculations are impractical for everyday engineering practice in which reliable results should be obtained in a relatively short time. The nonlinear behavior of the structural elements is included in the reduction of the bearing capacity, which the structure should have, in order to remain in the elastic response area for the predicted earthquake intensity. Since the load-bearing capacity of the structure is not known in advance, it is practically possible to reduce the earthquake requirements that the structure should satisfy.

Along with stiffness and load-bearing capacity, ductility is one of the basic parameters on which the behavior of the structure due to earthquakes depends. Designing according to the concept proposed in EC 8, the so-called programmed behavior (capacity desing) enables the fulfillment of ductility requirements. The ductility of the structural system is achieved by enabling the appearance of plastic joints at the ends of the beams while avoiding the appearance of plastic joints on the columns, which could bring the system into a kinematically labile state. Therefore, nonlinear deformations in the columns should be avoided [2].

2. BASICS OF BUDGET ACCORDING TO EN 1998-1: 2004

The aim of EC 8 is to ensure the

zemljotres važno je pouzdano ponašanje konstrukcije u nelinearnom području. Cilj je iskoristiti duktilnost nosive konstrukcije i ostvariti disipaciju energije unesene zemljotresom. Seizmički odgovor konstrukcije se najbolje može pratiti proračunskim analizama koje pretpostavljaju nelinearan odgovor konstruktivnih elemenata, ali su takvi proračuni nepraktični za svakodnevnu inženjersku praksu u kojoj treba za relativno kratko vreme doći do pouzdanih rezultata. Nelinearno ponašanje konstruktivnih elemenata se obuhvata umanjenjem nosivosti, koju konstrukcija treba da ima, kako bi za predviđeni intenzitet zemljotresa ostala u elastičnom području odgovora. S obzirom da nosivost konstrukcije nije unapred poznata, praktično se vrši umanjenje zahteva potresa koji konstrukcija treba da zadovolji.

Uz krutost i nosivot, duktilnost je jedan od osnovnih parametara od kojih zavisi ponašanje konstrukcije usled zemljotresa. Projektovanje po konceptu predloženog u EC 8 tzv. programiranog ponašanja (capacity desing) omogućava ispunjenje zahteva duktilnosti. Duktilnost konstruktivnog sistema se postiže omogućavanjem pojave plastičnih zglobova na krajevima greda izbegavajući pri tome pojavu plastičnih zglobova na stubovima, što bi moglo da dovede sistem u kinematički labilno stanje. Dakle, nelinearne deformacije u stubovima treba izbegavati [2].

2. OSNOVE PRORAČUNA PREMA EN 1998-1:2004

Cilj EC 8 je da obezbedi zaštitu ljudskih života tokom većih zemljotresa protection of human lives during major earthquakes while limiting the damage to structures during frequent earthquakes. The standard allows the reception of seismic forces either with damping energy (ductile behavior) or without damping energy (elastic behavior). Ductility is defined as the ability of a structure or structural components to undergo inelastic deformations, while maintaining sufficient strength and rigidity to carry the load, so that the structure remains standing despite being cracked or damaged and on the verge of collapse.[3]

For elastic analysis of the structure by choosing a high ductility class DCH, for the frame structure the behavior factor - q is

istovremeno sa ograničenjem štete konstrukcija tokom čestih zemljotresa. Standard omogućava prijem seizmičkih sila bilo sa prigušnom energijom (duktilno ponašanje) ili bez prigušne energije (elastično ponašanje). Duktilnost se definiše kao sposobnost konstrukcije ili strukturnih komponenata da prolaze kroz neelastične deformacije, zadržavajući pritom dovoljnu čvrstoću i krutost za nošenje opterećenja, tako da konstrukcija ostaje da stoji uprkos tome što je pukla ili je oštećena i na ivici kolapsa.[3]

Za elastičnu analizu konstrukcije birajući visoku klasu duktilnosti DCH, za okvirnu konstrukciju faktor ponašanja - q iznosi

$$q = 5.85 \tag{1}$$

The significance factor of the building for the object in question is II, so it follows that the importance factor is equal to $\gamma_1 = 1.0$, which further implies

Faktor značaja zgrade za predmetni objakat je II pa sledi da je faktor važnosti jednak $\gamma_1 = 1.0$, što dalje implicira

$$a_g = 0.25g \tag{2}$$

For the assumed soil category C on which the construction is envisaged, it follows from Table EC 8: S = 1.15; T_B=0.20 s; T_C=0.6 s; T_D=2.0 s.

Za prepostavljenu kategoriju tla *C* na kojoj se predviđa konstrukcija, sledi iz tabele EC 8: S=1.15; T_B=0.20 s; T_C=0.6 s; T_D=2.0 s.

3. LINEAR ANALYSIS

3.1 Calculation methods according to EC 8

Representation of seismic action over the acceleration spectrum, is used in the methods of equivalent lateral forces and multimodal spectral analysis and they represent linear-elastic methods. The nonlinear methods recommended in EC 8 are the nonlinear static method (push-over analysis) and the dynamic time response analysis (time history analysis).

The method of equivalent lateral forces is applied to buildings in which the

3. LINEARNA ANALIZA

3.1 Metode proračuna prema EC 8

Predstavljanje seizmičkog dejstva preko spektara ubrzanja, koristi se u metodama ekvivalentnih bočnih sila i multimodalna spektralne analize i one predstavljaju linearno-elastične metode. Nelinearne metode preporučene u EC 8 su nelinearna statička metoda (push-over analiza) i dinamička analiza vremenskog odgovora (time history analysis).

Metoda ekvivalentnih bočnih sila se primenjuje za zgrade kod kojih je dominantan odgovor u prvoj formi dominant response is in the first form of its own oscillation and whose structural response does not depend on higher inherent forms of oscillation. Additional two conditions for the application of the method are:

- the base period of rape in the two main directions must be less than the following values

sopstvene oscilacije i čiji odgovor konstrukcije ne zavisi od viših svojsvenih oblika oscilovanja. Dodatna dva uslova za primenu metode su:

- osnovni period osilovanja u dva glavna pravca mora biti manji od sledećih vrednosti

$$T_1 \leq \begin{cases} 4 \cdot T_c = 4 \cdot 0.6 = 2.4\ s \\ 2.0\ s \end{cases} \tag{3}$$

where is:
T_1 - basic period of oscillation for the analyzed direction in the base of the building;
T_C - period of oscillation in the project spectra which marks the end of the region of constant acceleration.

- the criterion of regularity in height must be met.

The basic period of oscillation can be calculated according to an approximate pattern for buildings up to 40 m in height

gde je:
T_1 - osnovni period oscilovanja za analizirani pravac u osnovi zgrade;
T_C - period oscilovanja u projektnim spektrima koji označava kraj područja konstantnog ubrzanja.

- kriterijum regularnosti po visini mora biti zadovoljen.

Osnovni period oscilovanja može da se sračuna prema približnom obrascu za zgrade do 40 m visine

$$T_1 = c_1 \cdot H^{3/4} = 0.050 \cdot 18^{3/4} = 0.437\ s \tag{4}$$

where is:
$C_1 = 0.050$ for other constructions - parameter determined depending on the type of construction;
H - height of the building from the foundation (*m*);
The basic period of oscillation according to EC 8 for *Type 1* spectra is between the periods T_B and T_C, ie

gde je:
$C_1 = 0.050$ za ostale konstrukcije - parametar određen u zavisnosti od tipa konstrukcije;
H - visina zgrade od temelja (*m*);
Osnovni period oscilovanja prema EC 8 za spektre *Tipa 1*, nalazi se između perioda T_B i T_C, odnosno

$$T_B \leq T_1 \leq T_C \tag{5}$$

It follows that the corresponding calculated or design value of the spectral acceleration is obtained as follows

Sledi da se odgovarajuća računska ili projektna vrednost spektralnog ubrzanja dobija na sledeći način

$$S_d(T_1) = a_g \cdot S \cdot \frac{2.5}{q} = 0.25g \cdot 1.15 \cdot \frac{2.5}{5.85} = 0.1229g \tag{6}$$

The total seismic shear force is basically determined by applying the expression

Ukupna seizmička smičuća sila u osnovi se određuje primenom izraza

$$F_b = S_d(T_1) \cdot m \cdot \lambda \quad (7)$$

where is:
S_d (T_1) - ordinate of the project spectrum for the period T_1;
T_1 - basic period of oscillation for the analyzed direction in the base of the building;
m - total mass of the building above the foundation;
λ - correction factor.
The value of the correction factor is $\lambda = 0.85$ if $T_1<2T_C$ and the building has more than two floors, otherwise $\lambda = 1.0$. The factor *λ* takes into account that in buildings with at least three floors and translational degrees of freedom in both horizontal directions, the effective modal mass of the first form of natural frequency is on average 15% less than the total mass of the building. In the case of multi-storey buildings, the total seismic force is, as a rule, distributed in height in proportion to the first own form of oscillation, for each direction separately. The F_i forces are applied at the floor levels, and are calculated according to the challenge

gde je:
S_d (T_1) - ordinata projektnog spektra za period T_1;
T_1 - osnovni period oscilovanja za analizirani pravac u osnovi zgrade;
m - ukupna masa zgrade iznad temelja;
λ - korekcioni faktor.
Vrednost korekcionog faktora iznosi $\lambda=0.85$ ako je $T_1<2T_C$ i zgrada ima više od dva sprata, inače je $\lambda=1.0$. Faktorom *λ* se uzima u obzir da u zgradama koje imaju najmanje tri sprata i translacione stepene slobode u oba horizontalna pravca, efektivna modalna masa prve forme sopstvene frekvencije je u proseku za *15 %* manja od ukupne mase zgrade. Kod višespratnih zgrada ukupna seizmička sila se u pravilu raspoređuje po visini proporcionalno prvoj sopstvenoj formi oscilovanja, i to za svaki pravac posebno. Sile F_i se apliciraju u nivoima spratova, a računaju se prema izazu

$$F_i = F_b \frac{z_i \cdot m_i}{\sum_{j=1}^{n} z_j \cdot m_j} \quad (8)$$

where is:
F_i - horizontal force acting at floor height and;
F_b - total horizontal seismic force;
s_i , s_j - mass displacements mi, mj in the basic form of oscillation;
m_i, m_j - masses of individual floors;
z_i ,, z_j - heights of masses mi, mj above the level of application of seismic action (above the foundation structure).

gde je:
F_i - horizontalna sila koja deluje u visini sprata *i*;
F_b - ukupna horizontalna seizmička sila;
m_i, m_j - mase pojedinih spratova;
z_i,, z_j - visine masa m_i, m_j iznad nivoa aplikacije seizmičkog dejstva (iznad temeljne konstrukcije).

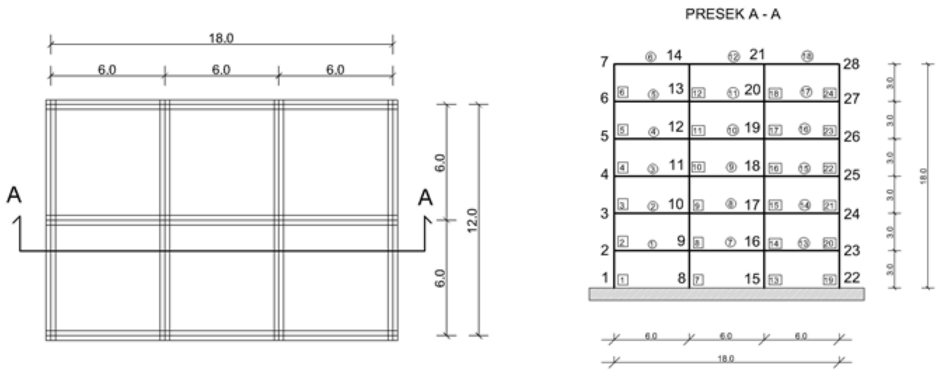
3.2 Results of the analysis using the program "Tower"

Static linear-elastic analysis of the structure was done using the *"Tower"* program. The cross sections were dimensioned according to the relevant load combination and plastic joints were defined. Figure 5 shows a building with

3.2 Rezultati analize primenom programa ,,Tower“

Statička linearno-elastična analiza konstrukcije urađena je primenom programa *,,Tower”*. Dimenzionisani su poprečni preseci prema merodavnoj kombinaciji opterećenja i definisani su plastični zglobovi. Na *slici 1* prikazana a constant floor height *h=3.0 m*, and a total height *H=18.0 m*, with three span fields *l=6.0 m*. The dimensions of the cross sections of the beams are *b/h = 30/40 cm*, and the pillars *b/h = 60/60 cm*. It is a building of importance of category II, soil category C. The calculation model is formed so that the beams are considered absolutely rigid in their plane, ie their axial deformations are neglected. Only one of the two orthogonal directions of the earthquake is analyzed, and the central frame is observed.

je zgrada konstantne spratne visine *h=3.0 m*, a ukupne visine *H=18.0 m*, sa tri polja raspona *l=6.0 m*. Dimenzije poprečnih preseka greda su *b/h=30/40 cm*, a stubova *b/h=60/60 cm*. Radi se o zgradi značaja *II* kategorije, kategorije tla *C*. Proračunski model je formiran tako da se grede smatraju apsolutno krutim u svojoj ravnini, odnosno zanemaruju se njihove aksijalne deformacije. Analizira se samo jedan od dva ortogonalna pravca dejstva zemljotresa, i posmatra se središnji ram.



Slika 1 - a) Osnova; b) Presek sa oznakama čvorova i štapova
Figure 1 - a) Base; b) Section with marks of knots and rods

The total weight of the object is ***W_{uk} = 4131.00 kN***, the total mass of the object *m_{uk} = 4131 / 9.81 = 421.10 kN s2 / m*. The seismic load can now be calculated and distributed across the ceilings.
If we know that *S_d (T_1) = 0.1229g*, *m = 396.79 (kNs²) / m* and *λ = 0.85* follows

Ukupna težina objekta je ***W_{uk}* = 4131.00 kN**, ukupna masa objekta *m_{uk}* = 4131/9.81 = 421.10 *kN s^2/m*. Sada može da se sračuna seizmičko opterećenje i rasporedi po tavanicama.
Ako znamo da je $S_d(T_1) = 0.1229g$, $m = 396.79$ *(kNs²) / m* i $\lambda = 0.85$ sledi

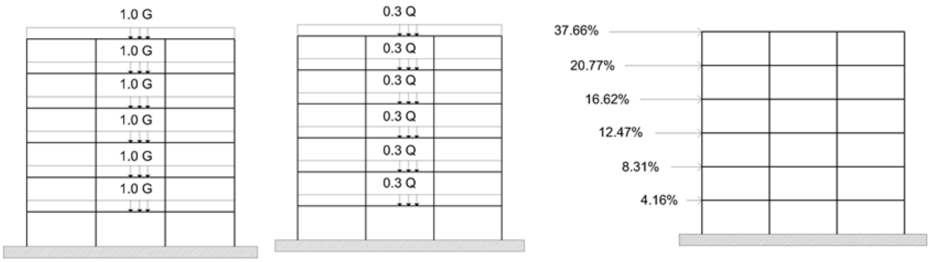
$$F_b = S_d(T_1) \cdot m \cdot \lambda = 0.1229g \cdot 421.10 \cdot 0.85 = 431.54 \text{ kN} \qquad (9)$$

The distribution of the total seismic force by floors was performed using expression (8) and is shown in Table 1 and Figure 2 c).

Raspored ukupne seizmičke sile po spratovima izvršen je upotrebom izraza (8) i prikazan je Tabelom 1 i Slikom 2 c).

Tabela 1 - Raspored seizmičke sile po spratovima Fi
Table 1 - Distribution of seismic force on floors Fi

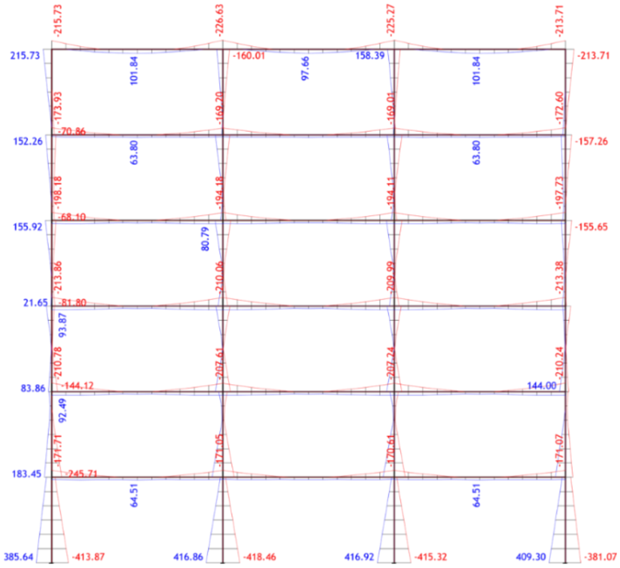
sprat	F_b[kN]	$z_i \cdot m_i$	$\frac{z_i \cdot m_i}{\sum_{j=1}^{n} z_i \cdot m_i}$	F_i[kN]	Q_i[kN]	raspored sila [%]
6	431.54	17253.00	0.38	162.54	162.54	37.666
5		9517.50	0.21	89.67	252.21	20.778
4		7614.00	0.17	71.73	323.94	16.622
3		5710.50	0.12	53.80	377.74	12.467
2		3807.00	0.08	35.87	413.61	8.3112
1		1903.50	0.04	17.93	431.54	4.1556
		45805.50		431.54 kN		100%



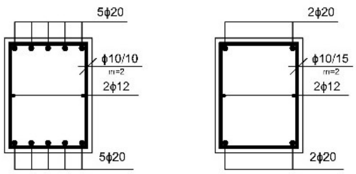
Slika 2 - a) Stalno opterećenje; b) Korisno opterećenje; c) Seizmičko opterećenje
Figure 2 - a) Constant load; b) Payload; c) Seismic load

The dimensioning of the cross sections of the structural elements was performed on the basis of the authoritative combinations of actions, the envelope of bending moments shown in Figure 3. Concrete C25 / 30 and reinforcement B-500B were used for dimensioning the elements. The adopted arrangement of reinforcement in the beams is shown in Figure 4 and the columns in Figure 5. The columns are reinforced with 12ϕ20 and stirrups *Uϕ10/15 cm*. The beams are reinforced with *2ϕ20 + 2ϕ12* and stirrups *Uϕ10/15 cm*, in the support zones *5ϕ20 + 2ϕ12* and stirrups *Uϕ10/10 cm*. A modal analysis was also performed. The first tone obtained by calculation using the program *"Tower"* is $T_1 = 0.441s$, which agrees well with the calculated values of the first tone $T_1^{rac} = 0.437s$ obtained by the recommendations from EC 8.

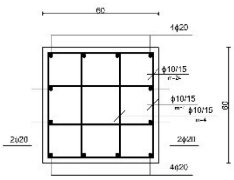
Dimenzionisanje poprečnih preseka elemenata konstrukcije izvršeno je na osnovu merodavnih kombinacija dejstva, anvelopa momenata savijanja prikazana na Slici 3. Za dimenzionisanje elemenata korišten je beton *C25/30* i armatura *B-500B*. Usvojen raspored armature u gredama prikazan je na Slici 4 i stubovima na Slici 5. Stubovi su armirani sa *12ϕ20* i uzengijama *Uϕ10/15 cm*. Grede *su* armirane sa *2ϕ20 + 2ϕ12* i uzengijama *Uϕ10/15 cm*, u zonama oslonaca *5ϕ20 + 2ϕ12* i uzengijama *Uϕ10/10 cm*. Urađena je i modalna analiza. Prvi ton dobijen proračunom pomoću programa *„Tower”* iznosi $T_1=0.441s$ što se dobro slaže sa računskom vrednosti prvog tona $T_1^{rač}=0.437s$ dobijen preporukama iz EC 8.



Slika 3 - Anvelopa momenata
Figure 3 - Envelope of moments



Slika 4 - Raspored usvojene armature u gredama u polju i zoni oslonca
Figure 4 - Arrangement of the adopted reinforcement in the beams in the field and the support zone



Slika 5 - Raspored usvojene armature u stubovima
Figure 5 - Arrangement of the adopted reinforcement in the column

4. NONLINEAR ANALYSIS OF CONSTRUCTION RESULTS OF ANALYSIS USING "ABAQUS" PROGRAMS

In modern regulations (EC8, FEMA 273) the reference method for

4. NELINEARNA ANALIZA KONSTRUKCIJE REZULTATI ANALIZE PRIMENOM PROGARAMA „ABAQUS“

U savremenim propisima (EC8, FEMA 273) referentni metod za određivanje determining seismic influences is the response spectrum method and modal analysis, using a linearly elastic model of the structure and reduced spectra. Depending on the characteristics of the building's load-bearing system, a simplified method is applied, for buildings that meet certain conditions, and multimodal response spectrum analysis for all types of buildings. Nonlinear analyzes in the time or frequency domain can be used as alternative methods under certain conditions. The amplitudes of the accelerogram, for the reference return period, should be multiplied by the building significance factor. Through the example of the calculation of the construction presented here, the advantages and disadvantages of certain methods in terms of the practicality of their application can be seen.

4.1 Results of the analysis using the "ABAQUS" program

In the "Abaqus" program, a frame with the dimensions of pillars and beams was modeled and reinforced in the way it was adopted in the "Tower" program. Three-dimensional C3D8R hexahedral elements were used to model the columns and beams. They represent linear general-purpose elements with a single integration point. Three-dimensional beams have six degrees of freedom at each node, three translational degrees of freedom (1,2,3) and three rotational degrees of freedom (4,5,6). During the modeling of reinforcement, elements of B21 - linear beam were used. The elements of the node in the plane have two translational degrees of freedom (1,2) and one rotational degree of freedom (6). **B21** elements belong to the so-called. Tymoshenko beams using linear interpolation. The finite element network is shown in Figure 8. The load is applied according to the relevant load combination as calculated and shown in

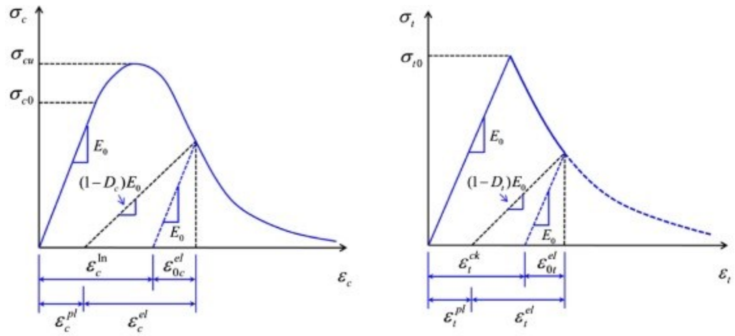
seizmičkih uticaja je metoda spektra odgovora i modalna analiza, pri čemu se koristi linearno elastični model konstrukcije i redukovani spektri. Zavisno od karakteristika nosećeg sistema zgrade, primenjuje se uprošćena metoda, za zgrade koje ispunjavaju određene uslove, i multimodalna spektralna analiza (multimodal response spectrum analysis) za sve tipove zgrada. Nelinearne analize u vremenskom ili frekventnom domenu mogu se koristiti kao alternativne metode uz određene uslove. Pri tome amplitude akcelerograma, za referentni povratni period, treba množiti faktorom značaja zgrade. Kroz primer proračuna konstrukcije koja je ovde prikazana, mogu se sagledati prednosti i nedostaci pojedinih metoda u smislu praktičnosti njihove primene.

4.1 Rezultati analize primenom progarama ,,ABAQUS“

U programu *,,Abaqus“* modeliran je ram sa dimenzijama stubova i greda i armiran na način kako je usvojeno u programu *,,Tower“.* Za modeliranje stubova i grede korišteni su su trodimenzionalni heksaedarski elementi C3D8R. Oni predstavljaju linearne elemente opšte namene sa jednom integracijskom tačkom. Trodimenzionalne grede imaju šest stepeni slobode na svakom čvoru tri translaciona stepena slobode (1,2,3) i tri rotaciona stepena slobode (4,5,6). Prilikom modeliranja armature korišćeni su elementi B21 - linearne grede. Elementi čvora u ravni imaju dva translaciona stepena slobode (1,2) i jedan rotacioni stepen slobode (6). **B21** elementi spadaju u tzv. Timošenkove grede koji koriste linearnu interpolaciju. Mreža konačnih elemenata prikazana je na slici 8. Opterećenje je naneto prema merodavnoj kombinaciji opterećenja tako kako je sračunato i prikazano na slici 2 a), b) i c). Horizontalno

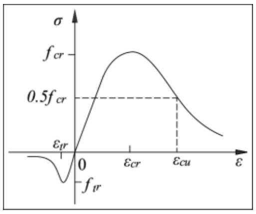
Figure 2 a), b) and c). The horizontal displacement is shown in Figure 9, while Figure 10 shows the dependence of the horizontal displacement and the total shear force - **the pushover curve**. Nonlinearity for concrete was entered as recommended for Abaqus “concrete damaged plasticity” according to Figure 6. A bilinear stress-dilation diagram was used to propagate the crack by Hillerborg 1985, which was recommended by the CEB and given an example in [4] and [5].

pomeranje prikazano je na Slici 9., dok je na Slici 10 prikazana zavisnost horizontalnog pomeranja i ukupne smičuće sile - **pushover kriva**. Nelinearnost za beton je unešena kako se preporučuje za Abaqus ,,concrete damaged plasticity” prema Slici 6. Korišćen je bilinearni dijagram napon - dilatacija pri širenju pukotine čiji je autor Hillerborg 1985, a koji je preporučen u CEB-u i dat primer u [4] i [5].



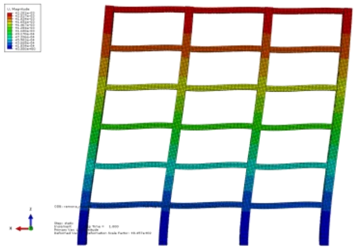
(a) Definition of the compressive material property (b) Definition of the tensile material property

Slika 6 - Proračun parametara za plastičnost betona
Figure 6 - Calculation of parameters for concrete plasticity

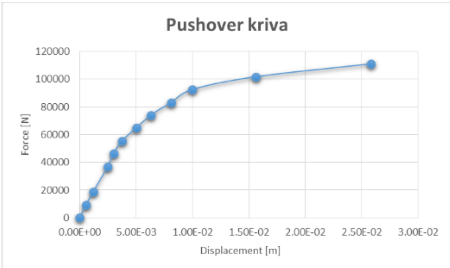


Slika 7 - Dijagram napon-dilatacija pri otvaranju prsline
Figure 7 - Diagram of stress-dilation at crack opening

Slika 8 - Mreža konačnih elemenata
Figure 8 – The mesh of the finite elements



Slika 9 - Horizontalno pomeranje
Figure 9 - Horizontal displacement



Slika 10 - Pushover kriva
Figure 10 - Pushover curve

5. CONCLUSION

The previous calculation was performed with the assumption of a high ductility class. For that reason, the influence of cross-sections is due to the gravitational load, which is significantly more pronounced than the seismic load. A more accurate calculation of the own oscillation periods, using the program *"Tower"*, obtained a basic oscillation period of $T_1 = 0.441$ *s*, which is within satisfactory limits in relation to the estimated value of $T_1^{rac} = 0.437$ *s*. The non-linear calculation with the *"Abaqus"* program provides a solution that helps to understand the actual behavior of the structure during an earthquake.
Pushover analysis can be used to assess whether the structure has the required load-bearing capacity and sufficient deformation capacity under the projected seismic action. The purpose of the nonlinear calculation would be justified from several aspects,

5. ZAKLJUČAK

Prethodni proračun je sproveden uz pretpostavku visoke klase duktilnosti. Iz tog razloga za dimenzionisanje poprečnih preseka merodavni uticaji su od gravitacionog opterećenja koje je znatno izraženije od seizmičkog opterećenja. Tačniji proračun sopstvenih perioda oscilovanja, korišćenjem programa ‚Tower", dobijen je osnovni period oscilovanja koji iznosi T_1=0.441 s što je u zadovoljavajućim granicama u odnosu na procenjenu vrednost koja iznosi $T_1^{rač}$=0.437 s. Nelinearni proračun programom ,,Abaqus" daje rešenje koja pomažu razumevanje stvarnog ponašanja konstrukcije pri zemljotresu.
Pushover analizom može se proceniti da li konstrukcija poseduje zahtevanu nosivost i dovoljan kapacitet deformisanja pri projektovanom seizmičkom dejstvu. Svrha nelinearnog proračuna bi bila opravdana iz više aspekata, jedan od njih je obezbeđenje

one of them is to ensure the load-bearing capacity of the structure, which is the most important from the aspect of engineers, and financial, which is the most important for investors. If the designers would carry out more extensive calculations, there would be a greater use of cross-sections. An hour of computer work is cheaper than one kilogram of reinforcement or a cubic meter of concrete. However, it must be emphasized that the concept is incomplete if the structure, in an earthquake that can occur every fifty years, for example, several times during the operation of the facility, behaves in such a way that all glass, partition walls and expensive equipment would be destroyed. In that case, nonlinear analysis is not justified because the building could pass without damage to the supporting structure whose price is otherwise of the order of 25% of the total price of the building, while all other, non-bearing parts of the structure would be unusable.

nosivosti konstrukcije koji je sa aspekta inženjera najvažniji, i finansijskih koji je najvažniji investitorima. Ukoliko bi projektanti sprovodili obimnije proračune došlo bi do većeg iskorišćenja preseka. Sat rada na računaru je jeftiniji od jednog kilograma armature ili kubika betona. Međutim, mora se naglasiti da je koncept nepotpun ukoliko bi se konstrukcija, pri zemljotresu koji može da se pojavi svakih pedeset godina na primer, nekoliko puta u toku eksploatacije objekta, ponašala tako što bi tom prilikom sva stakla, pregradni zidovi i skupocena oprema biti upropašćeni. U tom slučaju nije opravdana nelinearna analiza jer bi objekat pri takvom zemljotresu mogao proći bez oštećenja noseće konstrukcije čija je cena inače reda veličine 25% ukupne cene objekta, dok bi sve ostali, nenoseći delovi konstrukcije bili neupotrebljivi.

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