ANALIZA PRIMENE SEKUNDARNIH SEIZMIČKIH ELEMENATA U PRORAČUNU PREMA EVROKODU 8

THE ANALYSIS OF APPLICATION OF SECONDARY SEISMIC ELEMENTS IN DESIGN ACCORDING TO EUROCODE 8

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1 UVOD

Projektovanje seizmički otpornih konstrukcija s ciljem zaštite ljudskih života, iako jeste najvažniji, nije i jedini cilj analize ponašanja i projektovanja objekata u seizmičkim područjima. Osim obezbeđivanja prostorne stabilnosti, predmet istraživanja su i performanse objekta tokom i nakon zemljotresa, naročito nekonstruktivnih delova - fasade, pregrada, opreme, i uopšte povredljivost objekata [1]. Ipak, imajući u vidu potrebu za predstavljanjem zahteva i mogućnosti tehničkog propisa koji reguliše ovu oblast, Evrokoda 8 [2], u svetlu predstojećeg usvajanja ovog dokumenta kao nacionalnog standarda, fokus rada biće na rasvetljavanju jednog od aspekata primene Evrokoda 8 [2] u projektovanju objekata visokogradnje.

Savremeni seizmički propisi, među kojima je i Evrokod 8 [2], nude mogućnost da se doprinos pojedinih konstruktivnih elemenata u obezbeđivanju prostorne stabilnosti objekta za dejstvo zemljotresa zanemari. Takvi delovi konstrukcije nazivaju se „sekundarnim” seizmičkim elementima [2] za koje nije neophodno ispuniti sve zahteve Evrokoda 8 [2], već je moguće primeniti samo odredbe Evrokoda 2 [3]. Nekoliko je razloga za uvođenje mogućnosti podele konstruktivnih elemenata na „primarne” i „sekundarne” u aseizmičkom projektovanju. Pre svega, na ovaj način proširene su mogućnosti utvrđivanja osnovnog nosećeg sistema konstrukcije, jasnom definicijom elemenata koji su ključni

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1 INTRODUCTION

Design of structures for earthquake resistance with the purpose to protect human lives, although the most important, is not the only aim of behaviour analysis and design of structures in seismic regions. Apart from ensuring overall stability, the subjects of research are also building performances during and after earthquakes, particularly of non-structural elements – facades, partition walls, mechanical and electrical equipment and resiliency in general [1]. From the perspective of structural engineering society, there is a necessity to present requirements and possibilities of technical code that covers this field – Eurocode 8 [2], in light of the upcoming adoption of this document as a national standard. Therefore, the focus of this paper is on the presentation of one of the aspects of Eurocode 8 [2] implementation in seismic design of building structures.

Contemporary seismic codes, including Eurocode 8 [2], allow neglecting the contribution of some of the structural elements in assuring building's lateral stability during the earthquake action. Those structural elements are called “secondary seismic elements” [2] and they do not need to conform to all requirements of Eurocode 8 [2] but only to those of Eurocode 2 [3]. There are several reasons for introducing the distinction of structural elements between “primary” and “secondary” in aseismic design. First of all, it expands the possibilities for deter-

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za prijem uticaja zemljotresa i onih „sekundarnih”, kojima se prihvata isključivo gravitaciono opterećenje. Pored toga, čest je slučaj da neke odredbe Evrokoda 8 kao što su geometrijski uslovi, uslovi duktilnosti i zahtevi za oblikovanje detalja ili uslovi kapaciteta nosivosti, nije moguće ispuniti poštujući zahteve koji se odnose na položaj i dimenzije konstruktivnih elemenata. Ukoliko nije moguće promeniti dispoziciju ili bar dimenzije preseka, vodeći računa o dobro koncipiranom nosećem sistemu, označavanje tih elemenata kao sekundarnih može rešiti problem. Ovo je takođe i opcija za prevazilaženje problema da neki od konstruktivnih sistema, kao što su prethodno napregnuti sistemi ili sistemi ramova sastavljenih od stubova i delova ploča oslonjenih na njih (eng. *Flat slab frames*), nisu obuhvaćeni Evrokodom 8 [2]. Naime, postojeći eksperimentalni podaci i teorijska razmatranja nisu dovoljni da bi se sa adekvatnim stepenom sigurnosti objasnilo njihovo ponašanje pri dejstvu zemljotresa i da bi se na osnovu njih formirala pouzdana pravila za primenu u praksi. Dakle, jedna od opcija je svrstavanje ovakvih sistema u sekundarne seizmičke elemente, po principu - ako problem nije moguće rešiti na zadovoljavajući način, možda ga je moguće eliminisati [4]. Konačno, čest slučaj je da se konstrukcija visokogradnje dominantno sastoji od armiranobetonskih zidova, ali da iz konstruktivnih razloga (npr. prihvatanja teškog fasadnog zida) dođe do formiranja relativno malog broja ramova. Strogo i formalno gledano, prema aktuelnim domaćim propisima [5] ovakav sistem bi se klasifikovao kao mešovit i značajni deo seizmičkog opterećenja od čak 25% bi morao biti „dodeljen” ramovima. Potpuno suprotno osnovnoj ideji projektanta - zidovima se prihvata seizmičko opterećenje a stubovima samo gravitaciono, značajno se povećavaju dimenzije stubova i greda. Takođe, poštovanjem pravila za obezbeđivanje duktilnosti preseka povećavaju se količine armature u ovim elementima. Zato, svrstavanje pojedinih elemenata, u ovom slučaju fasadnih ramova, u grupu sekundarnih seizmičkih elemenata deluje kao primamljiva mogućnost u okviru savremenih seizmičkih propisa [2]. Ipak, iako opcija ovakve klasifikacije elemenata na prvi pogled izgleda kao jedno od najjednostavnijih rešenja, primena u proračunu konstrukcije nije trivijalna zbog niza uslova i zahteva koje treba ispuniti.

Objašnjenje koncepta, uslova i zahteva koje treba ispuniti, kao i posledica klasifikacije elemenata u grupu sekundarnih seizmičkih elemenata prema EC8 [2] osnovni je cilj ovog rada. Kako bi se detaljno objasnili svi koraci prilikom projektovanja seizmički otporne konstrukcije sa sekundarnim seizmičkim elementima, osmišljen je adekvatan numerički primer. Na bazi razmatranja rezultata analize konkretnog objekta, sprovedeno je tumačenje odredaba propisa [2] i donošenje odgovarajućih zaključaka.

2 KONCEPT PRIMARNIH I SEKUNDARNIH ELEMENATA

Osnovni koncept rada sa sekundarnim seizmičkim elementima zasniva se na zanemarenju krutosti sekundarnih elemenata pri analizi odgovora sistema u seizmičkoj proračunskoj situaciji. Da bi ovakav pristup

mining the basic lateral-force-resisting system of the building, by clearly defining the elements which are essential for resisting seismic action – primary seismic elements and those used only for supporting gravity loads – secondary seismic elements. Furthermore, there are some provisions of Eurocode 8 such as geometrical constrains, ductility requirements and detailing rules or capacity design conditions, which commonly cannot be satisfied as a result of architectural constrains regarding structural layout and dimensions of structural elements. If it is impossible to change the layout or at least cross-sectional dimensions, designation of those elements as secondary can solve the problem, while ensuring good and clear structural concept. It is also an option to overcome the problem concerning the structural systems that are not covered by Eurocode 8 [2], such as prestressed concrete structures or systems of flat slab frames. The reason is that the existing experimental data and theoretical analyses are insufficient to explain their behaviour during earthquakes with adequate certainty and to establish reliable recommendations and requirements for design practice. Therefore, one option is to classify these systems as secondary seismic elements, guided by the principle - when the problem is impossible to solve in a satisfactory manner, maybe it can be eliminated [4]. Finally, concrete building structures often consist of structural walls with only a few RC frames used for the purpose of bearing gravity loads (e.g. for supporting heavy facades). Strictly speaking, this structural system would be classified as a dual system according to current Serbian seismic design code [5] and a large portion of seismic load would be assigned to RC frames (at least 25%). As a result, column's and beam's dimensions are heavily increased which is contrary to the original designer's intention – only structural walls resist seismic force and frames are used as gravity load-carrying elements. Furthermore, satisfying ductility demands would lead to an increase of required reinforcement area in those members. For this reason, classification of some elements as secondary seismic elements is certainly an appealing possibility in the framework of modern seismic design codes [2]. Although this option seems to be the simplest solution, its application in structural design is unlikely trivial since a number of conditions and requirements should be met.

The aim of this paper is to describe the concept of secondary seismic elements considering EC8 [2] demands and requirements and to present the consequences of classification of some structural elements as secondary. In order to explain all steps in the seismic design of building structures with secondary seismic elements in detail, an appropriate application example of the reinforced concrete building is designed. Eurocode 8 [2] provisions are commented based on the analysis of design results which led to the important conclusions.

2 THE CONCEPT OF PRIMARY AND SECONDARY ELEMENTS

The concept of secondary seismic elements is based on neglecting their lateral stiffness in the analysis of building structure's seismic response. This approach is permitted only if the total contribution to building's lateral bio moguć, doprinos krutosti sekundarnih elemenata u ukupnoj krutosti sistema je ograničen na 15% s ciljem da se globalni odgovor konstrukcije ne promeni značajno. Iz istog razloga, označavanje nekih elemenata kao sekundarnih nije dozvoljeno s namerom da se promeni klasifikacija konstrukcije iz neregularne u regularnu [2]. Ova odredba ima pre svega preventivni karakter i treba da suzbije mogućnost da se neregularnosti značajnog dela konstruktivnog sistema „prikriju" plaštom sekundarnih elemenata - npr. zidovi postoje na svim spratovima po visini „samo" ih nema u prizemlju.

Uz uvažavanje činjenice da svi konstruktivni elementi moraju da prihvate i prenesu sva gravitaciona opterećenja u seizmičkoj proračunskoj situaciji, suštinska razlika u proračunu primarnih i sekundarnih seizmičkih elemenata leži u pretpostavci ponašanja tih elemenata pri dostizanju istih maksimalnih pomeranja konstrukcije. Poznato je da duktilnost pomeranja konstruktivnog sistema zavisi od duktilnosti krivine preseka njegovih primarnih elemenata, koja odgovara faktoru redukcije seizmičkog opterećenja odnosno faktoru ponašanja *q*. Kako bi se postigla adekvatna duktilnost krivine, za takve elemente u Evrokodu 8 [2] propisani su zahtevi u pogledu armiranja preseka koji se odnose na geometrijske uslove, minimalne i maksimalne procente armiranja podužnom armaturom, kao i osiguranja od smicanja i načina utezanja preseka u kritičnim oblastima. S druge strane, svi elementi koji su klasifikovani kao sekundarni moraju da izdrže pomeranja uslovljena krutošću primarnih elemenata, ali bez jasno definisanog kapaciteta duktilnosti prema Evrokodu 8 [2]. Prva opcija zasniva se na obezbeđivanju adekvatne nosivosti koja bi odgovarala njihovom elastičnom ponašanju pri dejstvu zemljotresa, s ciljem sprečavanja krtog loma pri očekivanim, realnim pomeranjima konstrukcije. Ovakvi zahtevi rezultuju znatno većim statičkim uticajima u njima od onih koji se dobijaju uobičajenim proračunom konstrukcije - kada su svi elementi označeni kao primarni, ali ih istovremeno oslobađaju svih ograničenja i zahteva Evrokoda 8 [2] koji važe za primarne elemente. Vodeći računa o tome da svi konstruktivni elementi poseduju izvesnu duktilnost, druga mogućnost je da se sekundarni elementi dimenzionišu prema statičkim uticajima određenim na osnovu usvojenog faktora ponašanja, koji je niži od onog koji je usvojen za primarne seizmičke elemente. Time bi uticaji u sekundarnim elementima bili manji od onih koji su određeni primenom prve opcije tj. na osnovu pretpostavke elastičnog ponašanja pri zemljotresu. Međutim, sam standard [2] ne daje uputstvo za ovakav način proračuna. Treća opcija za određivanje uticaja u sekundarnim seizmičkim elementima je svakako i neka od nelinearnih metoda analize, npr. *pushover* analiza, kojom bi se realnije uzeo u obzir kapacitet duktiliteta ovih elemenata. Kako se nelinearne metode analize zasnivaju na prethodno usvojenim karakteristikama poprečnih preseka (u pogledu poprečne i podužne armature), proračun je iterativan, a za prvu iteraciju bi mogla da se primeni prva metoda proračuna. U ovom radu detaljno je objašnjena primena prve metode proračuna analizom konstrukcije u numeričkom primeru, koja daje najkonzervativnije rešenje.

Sigmund i ost. [6] pokazali su, primenom *pushover* analize na primeru kombinovanog sistema ramova i zidova (gde su ramovi klasifikovani kao sekundarni) da čak i pri zadovoljenju propisanih uslova, globalni

stiffness of all secondary seismic members is unlikely to exceed 15%, which precludes the global response of the structure to change significantly. For the same reason, designation of some structural elements as secondary members is not allowed if it changes the classification of the structure from non-regular to regular [2]. This provision serves as a preventive measure and it should suppress the possibility to conceal irregularities of building structures by designating them as secondary (e.g. structural walls that are continuous along the full height of the building except at the ground level).

On the basis of the fact that all structural elements should support and transfer gravity loads during earthquakes, the substantial difference in the design of primary and secondary seismic elements lies in the assumption of their behaviour when the structure is subjected to the same maximal displacements. It is well known that global ductility of a structural system depends on curvature ductility of its primary elements, which corresponds to the reduction factor of seismic action called the behavior factor *q*. Eurocode 8 [2] specifies the requirements for these elements in terms of design and detailing which refer to geometrical constrains, minimum and maximum values of longitudinal reinforcement ratios, as well as shear reinforcement ratio and confinement measures of boundary elements, in order to provide the sufficient curvature ductility. On the other hand, all elements classified as secondary members should withstand displacements governed by a primary system without clearly defined curvature capacity according to Eurocode 8 [2]. The first option is to provide adequate design resistance of secondary elements corresponding to the assumption of their elastic behaviour during an earthquake, in order to prevent brittle failure modes when subjected to the expected displacements induces by the seismic action. As a result of applying these demands, internal forces in secondary elements are much higher than those obtained from the usual seismic design – in which all elements are designated as primary, but they do not need to conform to the requirements of Eurocode 8 [2] specified for primary elements. Based on the fact that all structural elements with certain ductility, the other option is to design secondary elements for internal forces calculated from the analysis with adopted behaviour factor, which is lower than the one adopted for primary seismic elements. This would lead to lower internal forces in secondary elements than those obtained from the former option, i.e., based on the assumption of their elastic behaviour in the seismic design situation. However, the code [2] fails to provide the guidance for this type of analysis. Ultimately, the option for the analysis of secondary seismic elements is certainly some of the non-linear methods, e.g. *pushover* analysis, which takes into account ductility capacity of those members more realistically. Since the non-linear methods use predefined cross-sectional characteristics (in terms of longitudinal and transverse reinforcement), the analysis is iterative and the first option for the analysis of secondary elements can be used for the first iteration. Because of its simplicity and conservatism, this paper presents the application of the first method in the analysis of RC building structure considered in the numerical example.

odgovor konstrukcije može značajno da se razlikuje u zavisnosti od toga da li su ramovi označeni kao primarni ili kao sekundarni elementi. Takođe, uočeno je otvaranje plastičnih zglobova i na stubovima, kada su označeni kao sekundarni. Kako su ti elementi dimenzionisani samo prema EC2 [3], jako je važno sekundarne elemente dimenzionisati za uticaje koji se javljaju pri maksimalnim očekivanim pomeranjima konstrukcije u kojoj je krutost sekundarnih elemenata zanemarena. Fardis [7] je predložio postupak kojim je moguće proceniti ove uticaje, na osnovu odnosa relativnih međuspratnih pomeranja sistema u kome je krutost sekundarnih elemenata zanemarena i sistema u kome je krutost ovih elemenata uzeta u obzir.

There are only a few analyses of secondary seismic elements in relevant literature. Sigmund et al [6] conducted *pushover* analysis of the dual system of RC frames and shear walls, with frames taken as secondary elements. The results showed that global building response may significantly differ, depending on whether the frames are classified as primary or secondary even if the code requirements are met. Furthermore, plastic hinges development at ends of secondary columns was noticed. Since those elements are designed only in accordance with Eurocode 2 [3], it is crucial that the design of secondary elements is carried out by internal forces determined from maximal deformations of a primary seismic structure. Fardis [7] proposed a procedure for estimating these forces based on the ratio of inter-storey drifts: one in which the stiffness of secondary elements is not considered and another in which it is.

3 NUMERIČKI PRIMER

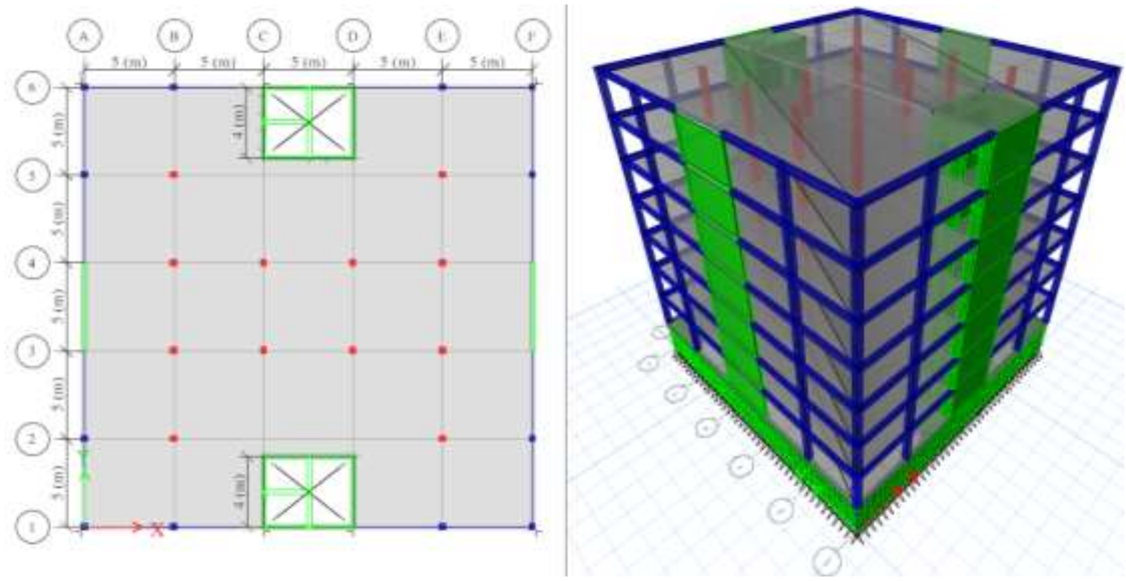
3.1 Ulazni podaci

Postupak klasifikacije primarnih i sekundarnih seizmičkih elemenata, njihova analiza i dimenzionisanje opisani su na primeru simetrične, osmoetažne armirano-betonske konstrukcije spratne visine h_s = 3,5 m, prikazane na slici 1.

3 NUMERICAL EXAMPLE

3.1 Geometry and design parameters

The classification procedure as well as the analysis, and design of primary and secondary seismic elements are described for symmetric reinforced concrete building, presented in Figure 1. The building has eight storeys and the story height of h_s = 3,5 m.



Slika 1. Numerički model razmatrane AB konstrukcije, Etabs 2015 (CSI)
Figure 1. Numerical model of RC building, Etabs 2015 (CSI)

Elementi konstrukcije koji učestvuju u prijemu horizontalnog opterećenja su armiranobetonski zidovi, fasadni ramovi koje čine stubovi sa gredama po obimu konstrukcije i ramovi koje čine unutrašnji stubovi sa delovima ploče koja je direktno oslonjena na njih (eng. *Flat slab* frames). Dimenzije elemenata konstrukcije su: debljina ploče h_p = 20 cm, debljine zidova d_z = 25 cm, dimenzije greda b_g/h_g = 25/40 cm a dimenzije stubova b_s/h_s = 40/40 cm.

Pored sopstvene težine, u nivou tavanice deluje

The lateral-force resisting system comprises reinforced concrete walls, columns and beams of the perimeter frames and flat slab directly supported on the columns – flat slab frames. Cross-sectional dimensions of structural elements are: slab thickness h_p = 20 cm, wall thickness d_z = 25 cm, beam dimensions b_g/h_g = 25/40 cm, and column dimensions b_s/h_s = 40/40 cm.

Design loads include apart from self-weight, additional dead load and live load of 2.5 kN/m^2 and 3.0 kN/m^2, respectively, as a uniform area load. The gravitaciono, jednakoraspodeljeno dodatno stalno i povremeno opterećenje intenziteta 2,5 kN/m^2 i 3,0 kN/m^2, respektivno. Usvojena je klasa čvrstoće betona C 30/37, i armatura kvaliteta B 500 (klase duktilnosti B) [3].

Projektno ubrzanje tla na osnovnoj steni a_g = 0,2g. Usvojen je projektni spektar tipa 1 za tlo kategorije B, prema EN 1998-1 [2]. Proračunom smičućih sila u zidovima utvrđeno je da sistem duktilnih zidova prihvata preko 65% ukupne seizmičke sile u oba ortogonalna pravca (približno 92%) što konstrukciju definiše kao sistem nepovezanih zidova [2]. Zahvaljujući regularnosti konstrukcije u osnovi i po visini, proračun seizmičkih uticaja izvršen je metodom Ekvivalentnih bočnih sila, sa usvojenim faktorom ponašanja q = 3,0 za klasu DCM [2].

Proračun stubova B1 i B2, grede u preseku ose 1 sa osama B i C, kao i njihovih veza, izvršen je primenom linearno-elastične analize prema EN 1992-1-1 [3] i EN 1998-1[2].

3.2 Analiza sekundarnih seizmičkih elemenata

Projektovanje i oblikovanje detalja sekundarnih elemenata i njihovih veza potrebno je izvršiti za uticaje koji nastaju pri maksimalnim deformacijama koje se javljaju usled dejstva zemljotresa, kako bi imali dovoljni kapacitet nosivosti da prihvate i prenesu gravitaciono opterećenje uključeno u seizmičku proračunsku situaciju [2]. Maksimalne deformacije sistema moguće je odrediti iz analize modela u kome je doprinos bočne krutosti svih sekundarnih elemenata zanemaren, dok se fleksiona i smičuća krutost primarnih elemenata modelira sa isprskalim presecima, pri čemu se moraju uključiti i P-Δ efekti.

Prethodni zahtevi Evrokoda 8 [2] podrazumevaju da je potrebno izvršiti dve analize razmatrane konstrukcije za svaki pravac seizmičkog dejstva: jednu, u kojoj se uzima u obzir horizontalna krutost svih elemenata i, drugu, u kojoj je krutost svih sekundarnih elemenata zanemarena. Da bi ovakva analiza bila moguća potrebno je formirati dva numerička modela konstrukcije [7]:

- model koji obuhvata krutost primarnih i sekundarnih elemenata - SP model, i
- model koji obuhvata krutost samo primarnih elemenata - P model.

Formiranje P modela zasniva se na zanemarenju bočne krutosti elemenata konstrukcije koje projektant želi proglasiti sekundarnim. To se postiže njihovim modeliranjem bez fleksione krutosti (redukcijom momenta inercije ili modula elastičnosti) ili postavljanjem momentnih zglobova na njihovim krajevima. Na osnovu maksimalnih deformacija dobijenih iz P modela, određuju se uticaji u sekundarnim elementima u SP modelu, postupkom koji je opisan u 3.2.2.

Osim za potrebe određivanja maksimalnih deformacija sistema, P model koristi se još i za klasifikaciju sekundarnih elemenata kao i za proračun primarnih elemenata pri dejstvu seizmičkog opterećenja (slika 3a). S druge strane, SP model koristi se za proračun sekundarnih elemenata u seizmičkoj proračunskoj situaciji, ali i za proračun cele konstrukcije u svim ostalim proračunskim situacijama.

S ciljem da se u što većoj meri pokažu specifičnosti analize nakon izbora pojedinih elemenata kao sekun-

concrete class C 30/37 and reinforcement B500 Class B are used as per Eurocode 2 [3].

The design ground acceleration of a_g= 0,2g is adopted as a design parameter. The Type 1 design spectrum applied for Ground type B is used, according to EN 1998-1 [2]. A preliminary static analysis is conducted in order to determine the fraction of seismic base shear taken by the walls. It was concluded that vertical structural walls resistance exceeds 65% of the total shear resistance of the whole structural system in both directions (approximately 92%). Therefore, the system is classified as a “wall system” [2]. The structure is regular both in plan and in elevation, which enables Lateral force method of analysis. The behaviour factor is adopted as q = 3.0 for ductility class DCM [2].

The columns B1 and B2, perimeter beams at an intersection of axis 1 and axes B and C, as well as their connections, are designed by linear-elastic analysis in accordance with EN 1992-1-1 [3] and EN 1998-1[2].

3.2 The analysis of secondary seismic elements

Secondary seismic elements and their connections should be designed and detailed for internal forces which occur at the maximum displacements during earthquakes, in order to have sufficient bearing capacity to support and transfer gravity loads included in seismic design condition [2]. Maximum deformations should be calculated in the analysis which neglects the contribution of secondary elements to the lateral stiffness of the structure while primary elements are modelled with their cracked flexural and shear stiffness. The analysis should also include P-Δ effects.

The Eurocode 8 [2] requirements mentioned above imply that it is necessary to conduct two separate analyses of the building structure, for each of two horizontal directions: one, in which the stiffness of all structural elements is considered and, another in which the lateral stiffness of all secondary elements is neglected. For this reason, it is necessary to build two separate numerical models of structure [7]:

- a model which includes the stiffness of primary and secondary elements - SP model, and
- a model which includes only the stiffness of primary elements - P model.

The P model is built based on neglecting lateral stiffness of those structural elements which are intended to be classified as secondary by the designer. This could be accomplished by modelling secondary elements without flexural stiffness (by reducing the moment of inertia or modulus of elasticity) or by modelling them with moment releases on their ends. Maximum displacements calculated from the P model are used for estimation of internal forces in the secondary elements in the SP model, by the procedure described in 3.2.2.

Besides being used for determination of maximum displacements of the structure, P model is also used for the purpose of classification of secondary elements as well as for the design of primary elements in seismic design situation (Figure 3a). On the other hand, SP model is used for the design of secondary elements in the seismic design situation, and for analysis and design of whole structure in all other design situations.

The aim of the paper is to highlight, as much as darnih, u ovom numeričkom primeru kao sekundarni elementi razmatrani su fasadni ramovi i ramovi koje čine unutrašnji stubovi s pločom.

3.2.1 Klasifikacija sekundarnih seizmičkih elemenata

Prema odredbi 4.2.2 (4) Evrokoda 8 [2], ukupan doprinos bočne krutosti svih sekundarnih seizmičkih elemenata ne sme da pređe 15% od doprinosa primarnih elemenata. Međutim, način određivanja doprinosa krutosti sekundarnih elemenata nije definisan, što omogućava dva pristupa analizi. Prva, i jednostavnija metoda bazira se na određivanju udela seizmičkih sila u posmatranom pravcu koje ovi elementi prihvataju u nivou osnove [7]. Druga metoda podrazumeva određivanje odnosa relativnih međuspratnih pomeranja konstrukcije $\delta_{r,P}/\delta_{r,SP}$ u P i SP modelu u nivou posmatrane etaže, sračunatih prema EN 1998-1: 4.3.4 [2], za isti sistem horizontalnih sila u razmatranom pravcu [7], gde su:

- $\delta_{r,P}$ relativna spratna pomeranja u P modelu, a
- $\delta_{r,SP}$ relativna spratna pomeranja u SP modelu.

Ovakav način klasifikacije razmatra odnos krutosti sistema preko fleksibilnosti, što je jednostavniji pristup u praktičnoj primeni, pri korišćenju softvera za analizu konstrukcija. Metoda se zasniva na analizi dva sistema sa jednim stepenom slobode, koji odgovaraju P i SP modelima definisanim u delu 3.2. Zahtev ograničenja doprinosa krutosti sekundarnih elemenata prema Evrokodu 8 [2] može se prikazati izrazom (1):

possible, all the specifics of analysis which arise when certain structural elements are classified as secondary. For this purpose, in the current numerical analysis perimeter frames and flat slab frames (i.e. interior columns) are designated as secondary members.

3.2.1 The classification of secondary seismic elements

The total contribution to the lateral stiffness of all secondary seismic elements should not exceed 15% of that of all primary elements, according to the requirement 4.2.2 (4) of Eurocode 8 [2]. However, the procedure for estimating the contribution of the stiffness of secondary elements is not defined, which allows two approaches to be used. The first method, and a simpler one, is based on the estimation of the fraction of base shear taken by secondary elements [7]. The second method uses inter-storey drift ratios of building structure $\delta_{r,P}/\delta_{r,SP}$ obtained from the analysis of P model and SP model at each building level. Interstorey drifts are calculated in accordance with EN 1998-1: 4.3.4 [2], for the same system of horizontal forces in each of the two horizontal directions [7], where:

- $\delta_{r,P}$ is the design inter-storey drift obtained from P model, and
- $\delta_{r,SP}$ is the design inter-storey drift obtained from SP model.

This method analyzes the contribution to the lateral stiffness through flexibility, which is a simpler approach in practical application when using software for structural analysis. The method is based on the analysis of two systems with a single degree of freedom (SDOF), corresponding to P model and SP model defined in Section 3.2. The requirement that limits the contribution of the stiffness of secondary elements, according to Eurocode 8 [2], can be presented by the Expression (1):

$$\frac{K_S}{K_P} \le 0{,}15, \tag{1}$$

gde su:

- K_S krutost sekundarnih seizmičkih elemenata,
- K_P krutost primarnih seizmičkih elemenata koja odgovara P modelu.

Kako se klasifikacija sekundarnih seizmičkih elemenata sprovodi na osnovu pomeranja P i SP modela, uslov za klasifikaciju se može prikazati preko odgovarajućih fleksibilnosti:

where:

- K_S is the lateral stiffness of all secondary seismic elements,
- K_P is the lateral stiffness of all primary seismic elements which corresponds to P model.

Since the classification of secondary seismic elements is conducted for the displacements of P and SP models, the condition for the classification can be presented by using the corresponding flexibility:

$$\frac{\delta_P}{\delta_{SP}} = \frac{K_{SP}}{K_P} = \frac{K_S + K_P}{K_P} = \frac{K_S}{K_P} + 1 \le 0{,}15 + 1 = 1{,}15 \tag{2}$$

gde je:

- K_{SP} ukupna krutost sistema, koja obuhvata krutost primarnih i sekundarnih seizmičkih elemenata, $K_{SP} = K_P + K_S$.

Konačno, doprinos krutosti sekundarnih elemenata u ukupnoj krutosti sistema, izražen preko odnosa fleksibilnosti δ_P/δ_{SP}, glasi:

where:

- K_{SP} is the total lateral stiffness of the system, which comprises the stiffness of both primary and secondary seismic elements, $K_{SP} = K_P + K_S$.

Finally, the contribution to the global lateral stiffness of secondary elements can be expressed in terms of the ratio of corresponding flexibilities δ_P/δ_{SP}:

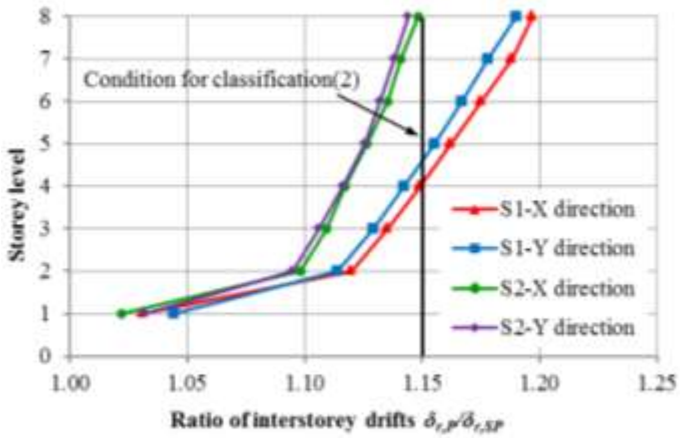
$$\frac{K_S}{K_{SP}} = \frac{K_{SP} - K_P}{K_{SP}} = 1 - \frac{K_P}{K_{SP}} = 1 - \frac{\delta_{SP}}{\delta_P} \tag{3}$$

Imajući u vidu definiciju krutosti konstrukcije, akcenat je na istom sistemu horizontalnih sila - iste raspodele po visini, ali i istog intenziteta. Prema preporuci nekih autora, raspodela opterećenja po visini treba da odgovara seizmičkom opterećenju [7]. Međutim, vrlo često se pri aproksimaciji krutosti sistema koristi i jednako raspodeljeno opterećenje po visini, što može biti jednostavnije za unos u proračunski model. Ghali i Gayed [8] pokazali su, na primeru konstrukcije od 12, 25 i 50 spratova, da je uticaj primene ove dve raspodele na odnos međuspratnih pomeranja manji od 1,0%. U ovom numeričkom primeru, razlike su manje od 1,7%, pri čemu raspodela koja odgovara seizmičkom opterećenju daje konzervativnije rezutate.

Odstupanja rezultata analize primenom ove dve metode mogu biti značajna, a posledica su različitih oblika deformisanja pojedinih konstruktivnih elemenata za prijem horizontalnog opterećenja po visini konstrukcije, koje druga metoda uzima u obzir. Razlika u obliku deformisanja elemenata posebno je naglašena u ovom numeričkom primeru (i to na višim etažama), imajući u vidu izbor elemenata koji se razmatraju kao sekundarni (fasadni ramovi i unutrašnji stubovi). Analizom relativnih spratnih pomeranja u oba modela (dijagrami S1 na slici 2), koja su sračunata za isti sistem seizmičkog opterećenja, pokazano je da zbir doprinosa krutosti svih ramova ne zadovoljava propisani uslov u oba ortogonalna pravca - $\delta_{r,P}/\delta_{r,SP}$ > 1,15. Poređenja radi, u nivou osnove ovi elementi prihvataju (svega) 8,9% ukupne seizmičke sile u X pravcu odnosno 8,6% u Y pravcu, čime bi propisani zahtev bio ispunjen. Pored rešenja u kome bi se samo jedan sistem ramova klasifikovao kao sekundarni sistem (sistem fasadnih ramova ili ploče sa unutrašnjim stubovima), za zadovoljenje uslovljenog odnosa međuspratnih pomeranja pri klasifikaciji oba sistema ramova treba ili povećati doprinos krutosti primarnih elemenata ili smanjiti doprinos krutosti sekundarnih, ukoliko je to moguće. U ovom slučaju, smanjen je doprinos krutosti sekundarnih elemenata, smanjenjem dimenzija poprečnog preseka stubova u fasadi koje iznose b_s/h_s = 25/40 cm, a određene su iz uslova duktilnosti. Rezultati analize korigovanog konstruktivnog sistema, na koji deluje sistem seizmičkih sila primenjen u prvoj iteraciji, prikazani su dijagramima S2 na slici 2.

In order to compare the lateral stiffness of two structures (P and SP models), the same system of horizontal forces – with the same distribution along the height, but of the same intensity also should be applied. The distribution of horizontal forces should correspond to the seismic load i.e. to the height-wise linear one [7]. However, it is common practice to use uniformly distributed load along the height to estimate lateral stiffness of the system, which arises from its simple application in the numerical analysis. Ghali and Gayed [8] showed that the influence of application of these two load distributions on the inter-storey drifts is less than 1.0%, based on the analysis of building structures with 12, 25 and 50 storeys. In the current numerical analysis, the differences are less than 1.7%, and the load distribution which corresponds to seismic load gives slightly conservative results.

The discrepancies of the analysis results arising from the application of these two methods can be significant. They are the result of the different deformed shape of the certain structural elements that are a part of a lateral-force-resisting system, which the other method takes into account. The difference between the deformed shapes of the elements is especially noticeable (at higher levels), considering the selection of the elements which are analyzed as secondary (perimeter frames and interior columns). The analysis of inter-storey drifts of both models (curves S1 in Figure 2), calculated for the same system of seismic load, have shown that the stiffness contribution of all frames (perimeter frames and flat slab frames) fail to fulfill the code requirement in both horizontal directions - $\delta_{r,P}/\delta_{r,SP}$> 1,15. For the purpose of comparison, these elements resist only 8.9% of total seismic base shear in X direction and 8.6% in Y direction, which would satisfy the code requirements. There are few possible solutions that satisfy code requirements in terms of the ratio of inter-storey drifts: (1) to increase the contribution to the lateral stiffness of primary elements, (2) to decrease the contribution of secondary elements, or (3) to classify only one system of frames as secondary (system of perimeter frames or system of flat slab frames). In this particular case, the contribution to the lateral stiffness of secondary members is decreased, by decreasing the cross-sectional dimensions of perimeter column to b_s/h_s = 25/40 cm,



Slika 2. Doprinos krutosti sekundarnih seizmičkih elemenata
Figure 2. Contribution of secondary seismic elements

determined from the ductility condition. The curves S2 depicted in Figure 2 present the analysis results of modified structure, loaded with the same seismic force system as in the first iteration.

3.2.2 Uticaji u sekundarnim seizmičkim elementima

Zahtev koji Evrokod 8 primenjuje za dimenzionisanje sekundarnih elemenata zasniva se na principu „jednakih pomeranja” koji vodi računa o različitom (smanjenom) kapacitetu duktilnosti sekundarnih elemenata (i njihovih veza) u odnosu na duktilnost primarnih elemenata. Ukoliko nije preciznije utvrđen kapacitet duktilnosti svih sekundarnih elemenata, potrebno je obezbediti onu nosivost koja bi odgovarala njihovom elastičnom ponašanju pri dejstvu zemljotresa. Štaviše, uticaje u ovim elementima treba odrediti na osnovu maksimalnih pomeranja u fleksibilnijem sistemu (P model), sa ciljem da se obuhvati najnepovoljniji mogući slučaj njihovog naprezanja (slika 3.a). To praktično znači da će uticaji u sekundarnim elementima biti veći od onih koji bi se javili kada bi ponašanje cele konstrukcije bilo elastično pri seizmičkom dejstvu, i to srazmerno odnosu pomeranja P i SP modela. Sličan princip proračuna uticaja u sekundarnim elementima prikazao je Milev [9]. Dobra procena ovih uticaja po visini konstrukcije može se dobiti pomoću odnosa relativnih spratnih pomeranja $d_{r,P,m}/d_{r,SP,m}$ (slika 3.b), određenih za seizmičko opterećenje koje je sračunato prema dinamičkim karakteristikama odgovarajućeg modela [7], za razliku od slučaja analize njihovog doprinosa krutosti pri klasifikaciji. Koristeći definisane odnose, uticaji na *m*-tom spratu u svim sekundarnim elementima u SP modelu (slika 3a), dobijaju se modifikacijom kombinacije opterećenja u seizmičkoj proračunskoj situaciji [10], koeficijentom α, tako da je:

3.2.2 Internal forces in secondary seismic elements

The Eurocode 8 requirement for the design of secondary elements is determined on the basis of “equal displacement” rule which considers different (reduced) ductility capacity of secondary elements (and their connections) in comparison with ductility capacity of primary elements. If the ductility capacity of all secondary members is not determined precisely, it is crucial to provide adequate resistance corresponding to the assumption of their elastic behaviour during the earthquake action. Moreover, the internal forces in these elements are determined from seismic displacements of the system which is more flexible (P model), in order to take into account the most unfavourable design condition (Figure 3.a). In other words, the internal forces in secondary elements are higher than those obtained from the analysis of the whole structure under seismic actions with the assumed elastic behaviour, proportionally to the inter-storey drift ratio of P and SP models. Milev [9] presented similar approach for calculation of internal forces in secondary members. A relatively accurate estimation of internal forces in secondary elements throughout the structure can be obtained by using the inter-storey drift ratios $d_{r,P,m}/d_{r,SP,m}$ (Figure 3.b). Unlike the case of the interstorey drift analysis for the classification of secondary elements, the interstorey drifts $d_{r,P,m}$ and $d_{r,SP,m}$ are calculated under the actual design seismic load acting on corresponding structural model [7]. Finally, the internal forces in secondary members at the floor level *m*, are computed in the SP model for the seismic combination [10], with introducing the coefficient α as a multiplier of the seismic action:

$$\sum_i G_{ki} + \alpha \cdot A_{Ed} + \sum_i \psi_{2,i} Q_{ki} \tag{4}$$

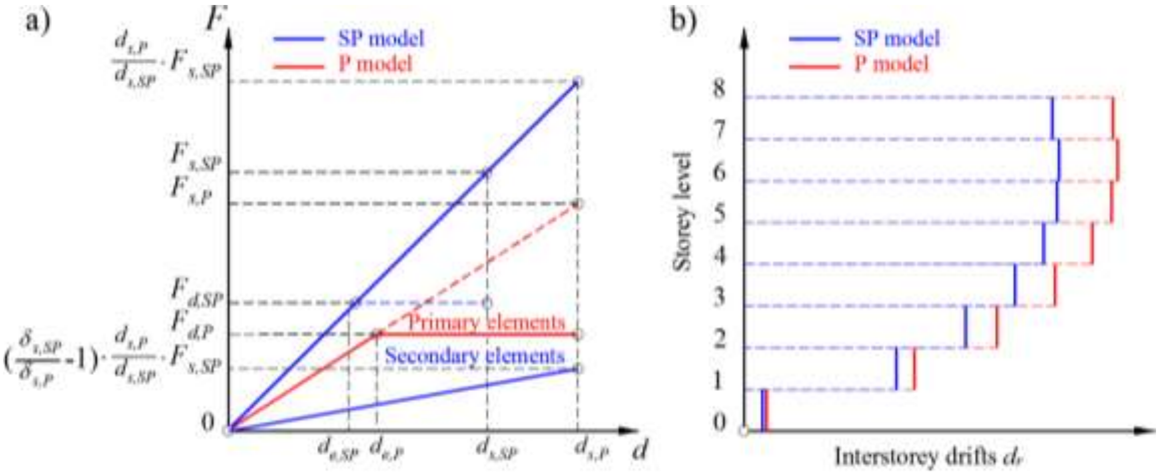
$$\alpha = q \cdot \frac{d_{r,P,m}}{d_{r,SP,m}} \cdot \frac{1}{(1-\theta_m)} \tag{5}$$

gde je:

- A_{Ed} seizmičko opterećenje;
- q faktor ponašanja konstrukcije u posmatranom pravcu i za usvojenu klasu duktilnosti;
- $d_{r,P,m}$ relativno spratno pomeranje u P modelu na *m*-tom spratu;
- $d_{r,SP,m}$ relativno spratno pomeranje u SP modelu na *m*-tom spratu, a
- θ_m koeficijent kojim se definišu *P-Δ* efekti, sračunat prema 4.4.2.2 (2) i (3) [2].

where:

- A_{Ed} is the design value of seismic action;
- q is the behaviour factor of the building, determined for each horizontal direction and for adopted Ductility Class;
- $d_{r,P,m}$ is the interstorey drift of the P model at level *m*;
- $d_{r,SP,m}$ is the interstorey drift of the SP model at level *m*, and
- θ_m is the interstorey drift sensitivity coefficient, which takes into account *P-Δ* effects, calculated in accordance with 4.4.2.2 (2) and (3) [2].



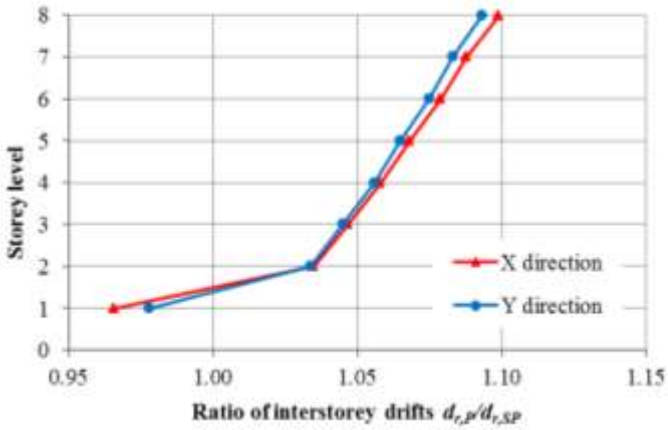
Slika 3. Primena principa „jednakih pomeranja" na proračun sekundarnih elemenata
Figure 3. Application of "equal displacement" rule in the design of secondary seismic elements

Opisani postupak može da se zakomplikuje pri analizi relativno krutih konstrukcija, sa osnovnim periodom oscilovanja manjim od T_c [2], gde princip „jednakih pomeranja" ne važi već princip „jednakih energija deformacija". Smatra se da je dovoljno tačno sračunati relativna međuspratna pomeranja koristeći izraz za duktilnost pomeranja μ_δ koji je dat u 5.2.3.4 (3) [2] i pomoću njih odrediti koeficijent α.

Uticaji u sekundarnim elementima razmatrane konstrukcije određeni su principom „jednakih pomeranja", imajući u vidu da su osnovni periodi oscilovanja u oba pravca približno jednaki 0,80 s i 0,85 s za SP model i P model, respektivno, što je veće od propisane vrednosti perioda T_c za kategoriju tla B (T_c = 0,5 s). Odgovarajuće vrednosti seizmičkih sila, određene metodom Ekvivalentnih bočnih sila, približno su jednake 4860 kN odnosno 4575 kN.

The procedure described above is inadequate for the analysis of rigid, short-period structures (with fundamental period of vibration smaller than T_c [2]), and instead of the "equal displacement" rule, the so-called "equal energy approximation" is used. In this case, the calculation of interstorey drifts on the basis of the displacement ductility factor μ_δ (given in 5.2.3.4 (3) [2]), for the purpose of determining the coefficient α, is considered as a reasonably accurate.

In the current numerical analysis, the fundamental periods of SP model and P model are approximately equal to 0.80 s and 0.85 s, respectively, which are larger than T_c = 0.5 s (Ground type B). The corresponding seismic forces, determined by Lateral force method of analysis, are about 4860 kN and 4575 kN. Therefore, the internal forces in secondary members are computed by using "equal displacement" rule.



Slika 4. Odnos relativnih spratnih pomeranja
Figure 4. Interstorey drift ratios

S obzirom na to što se *P-Δ* efekti mogu zanemariti (vrednost koeficijenta θ_{max} ≈ 0,03), uticaji u sekundarnim elementima dobijaju se množenjem odnosa relativnih pomeranja prikazanim na slici 4, faktorom ponašanja q = 3,0, što povećava uticaje od seizmičkog opterećenja od

Since the value of sensitivity coefficient is low (θ_{max} ≈ 0.03), the *P-Δ* effects can be neglected. As a result, the internal forces in secondary elements are obtained by multiplying the interstorey drift ratios, presented in Figure 4, with a behaviour factor q equal to 3.0. This increases

3,0 do 3,3 puta u odnosu na uticaje dobijene za primarne elemente, izraz (5). U nastavku su analizirani rezultati proračuna pojedinih konstruktivnih elemenata, koji su razmatrani kao: (1) primarni i (2) sekundarni elementi.

3.3 Analiza rezultata proračuna

Kako je to ranije istaknuto, pri proračunu primarnih elemenata od ključnog značaja je obezbediti njihovo duktilno ponašanje pri dejstvu zemljostresa oblikovanjem detalja kako bi izdržali nelinearne deformacije koje se tom prilikom javljaju. Ne vodeći računa o kapacitetu duktilnosti, sekundarni elementi svojom nosivošću treba da izdrže ista pomeranja konstrukcije.

Na primeru fasadnog stuba B1 i grede BC-1, unutrašnjeg stuba B2 i ploče koja se direktno oslanja na taj stub izvršena je uporedna analiza rezultata proračuna i istaknute su razlike u zahtevima koje ovi elementi moraju da ispune u slučaju kada su deo primarnog, odnosno sekundarnog sistema sa prihvatanje seizmičkog opterećenja.

3.3.1 Rezultati proračuna stuba B2 i njegove veze sa direktno oslonjenom pločom

Prikaz rezultata proračuna stuba B2 na slici 5, na osnovu merodavnih uticaja na pojedinim etažama, jasno pokazuje posledice njegove klasifikacije kao primarnog (PSE) odnosno sekundarnog (SSE) elementa. Kada je on razmatran kao primarni, zahvaljujući malom doprinosu unutrašnjeg stuba ukupnoj krutosti razmatrane konstrukcije, potrebne površine podužne armature su značajno manje od minimalno propisane za klasu DCM (slika 5a). Ista (minimalna) armatura dovoljna je da obezbedi zahtevanu nosivost stuba kada je razmatran i kao sekundarni, osim na poslednjoj etaži koja je merodavna za dimenzionisanje preseka. Pored toga, moguće je i smanjiti dimenzije preseka, imajući u vidu da uslov propisani duktilnosti ne važi za sekundarne elemente tj. da se dimenzije preseka mogu odrediti iz uslova maksimalnog dozvoljenog napona u betonu [3], što u konkretnom primeru znači smanjenje dimenzije sa 40 cm na 35 cm (tabela 1). Poređenja radi, za konstrukciju od 11 etaža sa istom dispozicijom, ovo smanjenje bi iznosilo oko 45% površine stuba.

the seismic action effects from 3.0 to 3.3 times in relation to the effects obtained for the primary elements, as per Equation (5). The following sections are focused on the differences between the analysis results of certain structural elements when considered as (1) primary and (2) secondary seismic elements.

3.3 The analysis of the design results

As pointed out before, the foundation for the design of primary elements is their capability of developing ductile behaviour which enables them to sustain large deformations in inelastic range under the seismic action. This is achieved by proper detailing of those members, especially in certain (“dissipative”) zones i.e. “critical regions” [2]. Unlike, the secondary members rely upon their strength, instead of ductility, to support gravity loads when subjected to the same displacements as primary members.

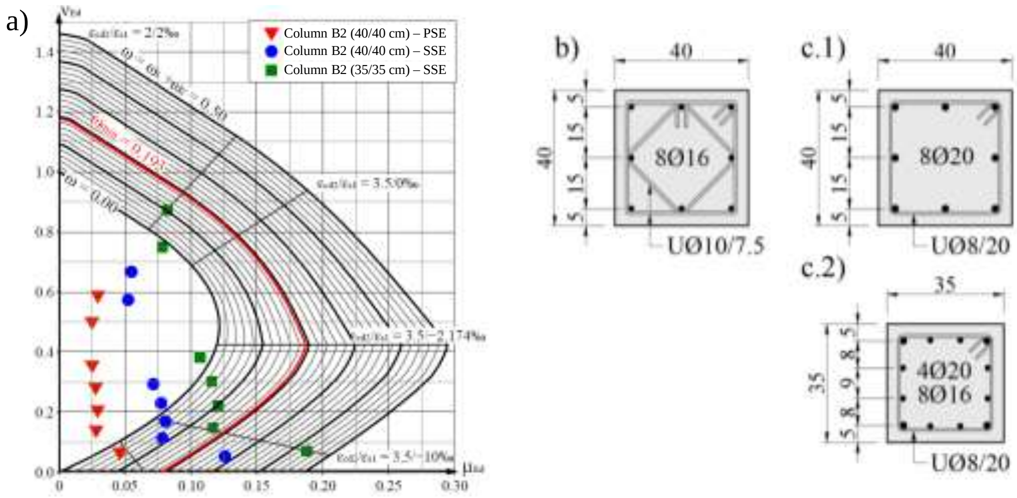
For the purpose of comparative study, the perimeter column B1 and beam BC-1, interior column B2 and its connection to flat slab are analyzed and discussed in cases of their classification as part of (1) primary and (2) secondary system for resisting seismic action.

3.3.1 The design results of column B2 and corresponding slab-to-column connection

The design results for column B2 under the extreme design combination of actions at each floor level are presented in Figure 5. It clearly shows the influence of the classification of column as primary (PSE) and secondary (SSE) element, in terms of required longitudinal reinforcement ratio. In case of its designation as primary element, the required reinforcement ratio is clearly lower than a minimum value required for Ductility class DCM (Figure 5.a), which arises from its small contribution to the global lateral stiffness. The same (minimum) amount of reinforcement is sufficient to ensure the required resistance of the column when it is designated as secondary, except at the top storey which is critical for section design. Furthermore, it is possible to decrease its cross-sectional dimensions, considering the fact that they are not governed by ductility requirements in terms of the maximum value of normalized axial force. Instead, the cross-sectional dimensions can be determined by limiting the compressive stresses in serviceability limit states [3]. In this case, the cross-sectional side length is decreased from 40 cm to 35 cm. For comparison, the cross-sectional area of the same column of 11-storey building with the same structural layout can be decreased by 45 %.

Tabela 1. Rezultati proračuna stuba B2
Table 1. Design results of column B2

Klasifikacija *Classification*	*b/h [cm]*	$\rho_{sl,max}$ *[%]*	$\omega_{wd,1}$	$\omega_{wd,2\text{-}7}$
PSE	40/40	1,00	0,187	0,113
SSE	40/40	1,57	0,106	0,106
SSE	35/35	2,34	0,125	0,125



Slika 5. Rezultati proračuna stuba B2: a) dijagram interakcije, b) poprečni presek stuba B2 kao PSE, c) poprečni preseci stuba B2 kao SSE

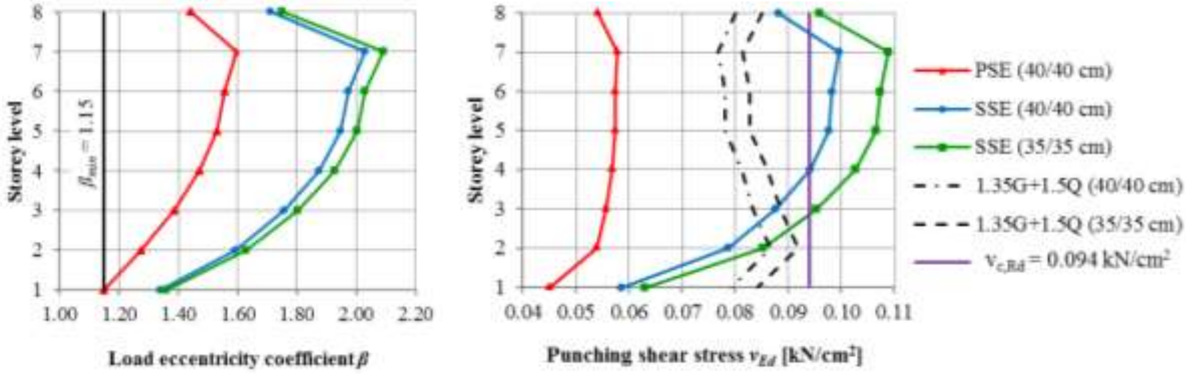
Figure 5. Design results of column B2: a) interaction diagram, b) cross section of the column B2 (PSE), c) cross section of column B2 (SSE)

Razlike u potrebnoj količini uzengija prikazane su na slikama 5b i 5c, kao i u tabeli 1 pomoću mehaničkog zapreminskog procenta armiranja $\omega_{wd,m}$ određenog za ceo *m*-ti sprat. Na osnovu prikazanih rezultata može se zaključiti da zahtevi za armiranje uzengijama primarnog seizmičkog stuba u kritičnim oblastima imaju rezultat u značajnom povećanju količine uzengija, i do 75% u nivou osnove gde je potrebno obezbediti adekvatno utezanje preseka. Jasno je, takođe, da klasifikacija u sekundarne rezultuje većom podužnom armaturom, ali kada se povede bitka za svaki kvadratni centimetar (skupog) slobodnog prostora, verovatno će opcija jače armiranih stubova manjih dimenzija dobiti prednost nad stubovima većih dimenzija s minimalnom armaturom.

Pored dokaza nosivosti stuba, neophodno je dokazati i nosivost veze stuba s pločom pri maksimalnim pomeranjima usled dejstva zemljotresa, kao što je navedeno u 3.2, što pre svega podrazumeva kontrolu smičućih napona od probijanja. Poznato je da ovi naponi zavise od gravitacionog opterećenja, ali se njihova vrednost značajno povećava pri dejstvu zemljotresa, što je posledica povećanja ekscentriciteta opterećenja obuhvaćenog koeficijentom β [3]. Na slici 6 prikazane su vrednosti koeficijenta β kao i smičućih napona u kritičnom preseku po visini konstrukcije, za stalnu proračunsku situaciju i seizmičku, pri različitoj klasifikaciji stuba B2. Može se zaključiti da ploča ima dovoljnu nosivost na probijanje bez armature za smicanje ($v_{c,Rd}$ = 0,094 kN/cm^2) pri dejstvu gravitacionog opterećenja u stalnoj proračunskoj situaciji. Kao rezultat povećanja momenata savijanja u sekundarnim elementima, rastu vrednosti koeficijenta β (gotovo dva puta više od minimalne propisane vrednosti od 1,15 [3]) i smičućih napona, koje prevazilaze vrednosti sračunate u stalnoj proračunskoj situaciji kao i nosivost ploče bez smičuće armature, što rezultuje potrebom za osiguranjem ploče armaturom za smicanje od probijanja.

The differences in required shear reinforcement area are shown in Figure 5b and 5c as well as in Table 1, in terms of mechanical volumetric ratio $\omega_{wd,m}$ calculated for the whole storey *m*. Based on presented results, it can be concluded that the detailing requirements of primary seismic column in critical areas give an increase of the shear reinforcement, up to 75 % at the column base where adequate degree of the confinement is needed. It is also clear that an increase of longitudinal reinforcement is a consequence of classification of the column as secondary. However, in the discussion for each square centimetre of (expensive) available space, the option of more heavily reinforced columns with smaller cross-sectional dimensions will probably prevail over the option of column with larger cross-sectional dimensions and minimum reinforcement ratios.

Apart from the column, the slab-to-column connections should also be designed and detailed when subjected to the maximum displacements due to earthquakes, as mentioned in Section 3.2. This implies, above all, that punching shear stresses need to be checked. It is well known that these stresses are a function of the intensity of gravity loads, but they also increase during earthquakes, as a consequence of an increase of the load eccentricity presented with the coefficient β [3]. Figure 6 presents the values of coefficient β as well as the shear stresses at the basic control perimeter along the height of the building as a function of different classification of column B2, for persistent and seismic design situation. It can be concluded that the slab has sufficient punching shear resistance ($v_{c,Rd}$ = 0,094 kN/cm^2) under gravity loads in the persistent design situation. The increase of bending moments in secondary columns leads to increase of coefficient β (almost two times than minimum prescribed value of 1.15 [3]) and punching shear stresses, which are higher than corresponding values calculated in persistent design situation. Moreover, the punching shear resistance is exceeded and, therefore, punching shear reinforcement is required.



Slika 6. Vrednosti koeficijenta β i napona smicanja od probijanja u funkciji klasifikacije stuba B2
Figure 6. Values of coefficient β and punching shear stress as a function of classification of column B2

Kako bi veza stuba i ploče u sekundarnom sistemu imala dovoljni kapacitet nosivosti da u elastičnoj oblasti prenese gravitaciono opterećenje pri dejstvu zemljotresa, od suštinske je važnosti obezbediti i odgovarajuću armaturu za savijanje na mestima oslonaca ploče, tj. na vezi ploča-stub. Imajući u vidu da se momenti velikog intenziteta na krajevima stubova uravnotežuju s momentima u ploči, javlja se potreba za armiranjem obe zone ploče nad osloncem usled momenata alternativnog znaka. U konkretnom slučaju, ovi momenti dostižu i do 80% negativnih oslonačkih momenata od gravitacionog opterećenja. Rešavanje detalja armiranja ploče direktno oslonjene na stubove s ciljem obezbeđivanja adekvatnog kapaciteta duktilnosti umesto nosivosti, kao što je ranije naglašeno, nije obuhvaćeno Evrokodom 8 [2].

3.3.2 Rezultati proračuna rama u osi 1 - stub B1 i greda BC-1

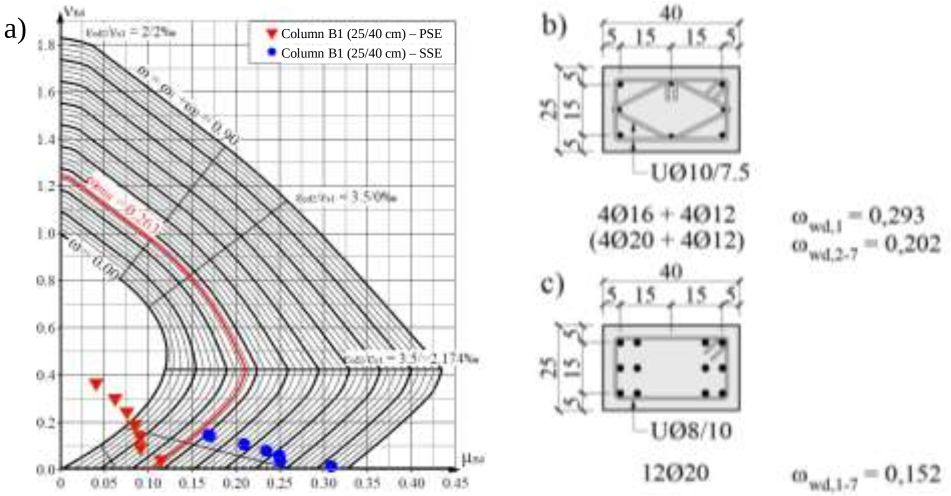
Činjenica da je uticaj krutosti ramova na veličinu i oblik deformacije čitave konstrukcije po visini dominantan, obrazložena je u delu 3.2.1. Do istog zaključka dolazi se analizom rezultata proračuna elemenata rama u osi 1, prikazanih na slici 7 i u tabeli 2. Kao posledica ramovskog dejstva u kome je izražen uticaj aksijalnih sila u stubovima, primena izraza (1) na proračun fasadnih stubova kao sekundarnih elemenata dovodi do smanjenja aksijalnih sila uz povećanje momenata što dodatno utiče na povećanje potrebne površine armature, posebno na donjim etažama (slika 7a). Zbog smanjene širine preseka stuba (određene iz uslova duktilnosti), normalizovane aksijalne sile u kritičnoj oblasti u osnovi su visoke ($\nu_{d,max}$ = 0,53), što rezultuje izraženom potrebom za utezanjem stubova kao primarnih elemenata. Vrednosti mehaničkog zapreminskog procenta armiranja $\omega_{wd,m}$ su za 33% do 93% veće od vrednosti koje odgovaraju stubovima kada su razmatrani kao sekundarni. Međutim, to nije dovoljno dobar razlog da bi se opravdala klasifikacija ovog stuba kao sekundarnog, pre svega iz ekonomskog aspekta, imajući u vidu znatno veće količine potrebne podužne armature. Smanjenje dimenzija poprečnog preseka, u ovom slučaju, nije opcija jer dovodi do prekoračenja maksimalnog koeficijenta armiranja od 4% [3]. Očigledno je da klasifikacijom ovih stubova kao sekundarnih nije

In order to provide sufficient bearing capacity of slab-to-column connection to support gravity loads during earthquakes in the elastic range, it is crucial to provide adequate amount of slab reinforcement at the supports i.e. at the slab-to-column connection. Considering the fact that the large bending moments at column ends are in equilibrium with slab bending moments, it is necessary to provide sufficient reinforcement area both at the top and the bottom since bending moments change sings under seismic action. In this particular case, the values of these moments are close to 80% of negative (hogging) bending moments due to gravity loads. As mentioned above, design and detailing of flat slabs with aim to provide sufficient ductility capacity instead of strength is not covered by Eurocode 8 [2].

3.3.2 The design results of perimeter frame in axis 1-column B1 and beam BC-1

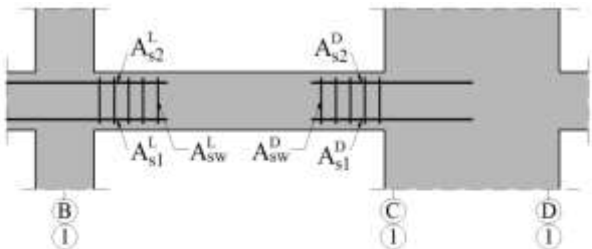
The influence of the perimeter frame stiffness on the magnitude of deformations and the shape of deformed structure is explained in Section 3.2.1. The same conclusion can be drawn from the analysis of design results of perimeter frame in axis 1, presented in Figure 7 and Table 2. As a result of the frame action and high axial forces in perimeter columns under lateral loads, the implementation of Equation (1) in design of perimeter columns, classified as secondary, leads to reduction of axial forces followed by an increase of bending moments. The design for such internal forces gives a large amount of reinforcement area, especially in lower storeys (Figure 7a). On the other hand, the normalized axial forces in primary columns are high ($\nu_{d,max}$ = 0,53) due to narrowed cross-sectional width (determined from ductility demands) which subjects them to strict rules for detailing and confinement of the concrete core. The values of mechanical volumetric ratio $\omega_{wd,m}$ are from 33% to 93% higher than those determined for secondary perimeter columns. However, this is insufficient reason for their classification as secondary, mainly for economic reasons, because of a large amount of longitudinal reinforcement. In this case, the reduction of cross-sectional dimensions is unlikely an option since it would further increase the reinforcement ratio, above the maximum value of 4% [3]. It is evident that the desired moguće postići željene rezultate i da ih je najbolje razmatrati kao deo primarnog sistema.

results could not be achieved by classification of the column B1 as secondary, and that it is reasonable to treat them as a part of primary system for supporting seismic loads.



Slika 7. Rezultati proračuna stuba B1: a) dijagram interakcije, b) poprečni presek stuba B1 kao PSE, c) poprečni presek stuba B1 kao SSE

Figure 7. Design results of the column B1: a) interaction diagram, b) cross-section of the column B1 (PSE), c) cross section of the column B1 (SSE)



Slika 8. Armatura grede BC–1

Figure 8. Reinforcement layout for the beam BC-1

Tabela 2. Rezultati proračuna grede BC-1 na etaži 5
Table 2. Design results of the beam BC-1 at floor level 5

Klasifikacija *Classification*	A_{s1}^{L}	A_{s2}^{L}	A_{s1}^{D}	A_{s2}^{D}	A_{sw}^{L}	A_{sw}^{D}	$\omega_{wd,5}$
PSE	3Ø16	2Ø20	3Ø16	3Ø20	UØ8/10	UØ8/10	0,227
SSE	6Ø20	3Ø25	5Ø20	5Ø25	UØ8/7,5	UØ8/10	0,265

Slični zaključci mogu se primeniti i na grede koje su deo fasadnih ramova. Rezultati proračuna grede BC-1 pokazuju očigledan uticaj povećanja momenata savijanja u sekundarnim seizmičkim gredama, dobijenih primenom izraza (1), koji rezultuje povećanjem armature i do tri puta. U ovom primeru, uzengije u primarnim gredama određene iz uslova kapaciteta nosivosti praktično su iste kao uzengije sekundarnih greda određene iz elastičnih uticaja (tabela 2).

Similar conclusions apply for the perimeter beams. The design results of the beam BC-1 indicate that the bending moments are significantly increased by application of Equation (1) for secondary seismic beams, which increases the required reinforcement area up to three times. Table 2 shows that, in this case, the amount of transverse reinforcement is similar to the different classification of the beam i.e. the capacity design shear forces in primary beams are almost equal to the elastic shear forces in secondary ones, calculated by an implementation of Equation (1).

4 ZAKLJUČCI

Analiza proračuna armiranobetonske konstrukcije sa sekundarnim seizmičkim elementima predstavljena u ovom radu ukazala je na prednosti i nedostatke primene ovog zanimljivog koncepta u aseizmičkom projektovanju objekata visokogradnje. Iako projektantski primamljiv, jer je dimenzionisanje i oblikovanje detalja definisano „samo” Evrokodom 2 [3], sprovođenje koncepta sekundarnih seizmičkih elemenata je zametan posao s prilično neizvesnim ishodom. Očekivana korist u vidu lakšeg proračuna kompromitovana je postupkom klasifikacije i proračuna statičkih uticaja na bazi uporedne analize dva modela. U radu je pokazano da se, u nekim slučajevima, zahtevi za armiranje sekundarnih elemenata ne razlikuju značajno od zahteva Evrokoda 8 [2] koji važe za primarne (duktilne) elemente. Takođe, pokazano je da postoje značajne posledice na ponašanje čvora stub-ploča i osiguranje ploče od proboja. Potencijalno se može očekivati smanjenje dimenzija poprečnih preseka vertikalnih elemenata ukoliko je njihov doprinos krutosti sistema relativno mali, uz „naplatu” kroz veću količinu podužne armature. Uvođenjem ovog koncepta Evrokod 8 [2] otvara mogućnosti za kompleksno tretiranje pojedinih delova konstruktivnog sistema, a tumačenje zahteva propisa svakako predstavlja istraživački i projektantski izazov.

4 CONCLUSIONS

The analysis of reinforced concrete structure with secondary seismic elements presented in this paper highlighted the advantages and disadvantages of application of this interesting concept in aseismic design of building structures. Although this concept may seem appealing to the designer because secondary members can be designed and detailed according to Eurocode 2 [3] “only”, its application in design practice is rather demanding with uncertain outcome. The expected benefit in terms of the simple design procedure is compromised by classification procedure and methods for calculation of internal forces which are based on comparative analysis of two numerical models of the same structure. The results of the analysis showed that, in some cases, design requirements for secondary elements are almost the same as Eurocode 8 requirements [2], which apply for primary (ductile) elements. Further, it is shown that the choice of this classification has significant influence on the behaviour of slab-to-column connection and on the values of punching shear stresses. The decrease in cross-sectional dimensions of secondary members can be expected if their contribution to the lateral stiffness is low. However, this will increase the amount of longitudinal reinforcement. The implementation of this concept in Eurocode 8 [2] provides the possibility for complex analysis of certain structural elements, and the interpretation of the code rules is certainly a challenge for both designers and researchers.

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REZIME

KONCEPT PRORAČUNA SEKUNDARNIH SEIZMIČKIH ELEMENATA PREMA EVROKODU 8

Ivan MILIĆEVIĆ
Ivan IGNJATOVIĆ

U radu je analiziran koncept proračuna armiranobetonske konstrukcije sa sekundarnim seizmičkim elementima prema zahtevima Evrokoda 8. Iako se doprinos krutosti ovih elemenata zanemaruje prilikom seizmičkog odgovora konstrukcije, primena ovog koncepta je kompleksna zbog niza zahteva u pogledu klasifikacije i načina proračuna statičkih uticaja. S ciljem da se istaknu i objasne specifičnosti primene, pokažu prednosti, ali i kritički razmotri upotreba opcije sekundarnih elemenata, izvršen je proračun osmoetažne armiranobetonske konstrukcije. Prikazane su dve metode za klasifikaciju sekundarnih elemenata, način proračuna uticaja u njima, kao i rezultati uporedne analize u kojoj su određeni elementi konstrukcije razmatrani kao primarni i kao sekundarni.

Ključne reči: aseizmičko projektovanje, sekundarni seizmički elementi, beton, duktilnost, Evrokod 8

SUMMARY

DESIGN CONCEPT OF SECONDARY SEISMIC ELEMENTS ACCORDING TO EUROCODE 8

Ivan MILICEVIC
Ivan IGNJATOVIC

Analysis of conceptual design of reinforced concrete (RC) structure with secondary seismic elements in compliance with Eurocode 8 is presented in this paper. The application of this concept is complex due to the requirements regarding the classification and calculation of design internal forces, although the contribution of these elements in the total structural stiffness is neglected. The basic calculations of 8-story RC structure are performed with the main goal to emphasize and explain the problems of utilization of this concept. Its advantages are clearly presented and critical analysis of application in aseismic structural design is performed. The results of comparative analysis of structural design in which some structural elements are treated as a primary or as a secondary are presented.

Key words: seismic design, secondary seismic elements, concrete, ductility, Eurocode 8