NUMERIČKA ANALIZA ARMIRANOBETONSKIH OKVIRNIH ZGRADA SA IZOLOVANOM ZIDANOM ISPUNOM

NUMERICAL ANALYSIS OF REINFORCED CONCRETE FRAME BUILDINGS WITH DECOUPLED INFILL WALLS

Marko MARINKOVIĆ
Santiago FLORES CALVINISTI
Christoph BUTENWEG

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1 UVOD

Značajan deo konstrukcija na svetu predstavljaju AB okvirne zgrade sa zidanom ispunom. Jednostavan razlog za to je potreba da se razdvoje prostorije unutar zgrade kao i da se razdvoji unutrašnjost zgrade od spoljašnje sredine. Pored toga, zidana ispuna je pokazala dobre performanse i trajnost u pogledu zvučne izolacije, vlage i požara kao i dobre termičke karakteristike. Zbog svega navedenog, upotreba zidane ispune u AB okvirnim zgradama česta je u mnogim zemljama, kao i u seizmički aktivnim oblastima. Međutim, kada su izložene dejstvu zemljotresa, AB okvirne zgrade sa zidanom ispunom pokazale su loše ponašanje, često praćeno značajnim oštećenjima zidane ispune. Ovo je potvrđeno u brojnim izveštajima koji prikazuju oštećenja AB okvirnih zgrada sa ispunom usled skorašnjih zemljotresa u: L'Aquila (Italija) 2009. godine [1], Lorca (Španija) 2011. godine [2], Van (Turska) 2011. godine [3] i Centralna Italija 2016. godine [4]. Velika i rasprostranjena oštećenja zidane ispune praćena kolapsima celih zidanih panela na nižim spratovima zgrada (slika 1a) prikazana su u izveštaju [5]

Marko Marinkovic, docent, dr, Katedra za tehničku mehaniku i teoriju konstrukcije, Univerzitet u Beogradu Građevinski fakultet, Bulevar kralja Aleksandra 73, 11000 Beograd, Srbija. (E-mail address: mmarinkovic@grf.bg.ac.rs)
Santiago Flores Calvinisti, Master student, Politecnico Di Milano, School of Civil, Environmental and Land Management Engineering, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy.
(E-mail address: santiago.flores@mail.polimi.it)
Christoph Butenweg, Full Professor, CWE – Center for Wind and Earthquake Engineering, RWTH Aachen University, Mies-van-der Rohe-Straße 1, 52074 Aachen, Germany. (E-mail address: butenweg@lbb.rwth-aachen.de)

1 INTRODUCTION

Significant portion of structures in the world goes to RC frame buildings with the masonry infill walls. The simple reason for that is need for separating space inside the building and between internal space of buildings and external environment. Furthermore, masonry infills demonstrated reasonable performance and durability with respect to noise, moisture and fire as well as good heat and sound insulation properties. Due to this, the use of masonry infill walls in RC frame buildings is common in many countries, as well as in the seismic active regions too. However, when subjected to an earthquake excitation, masonry infilled RC frame buildings behave rather poor experiencing very often severe damage of infill walls. This is confirmed with several reports presenting damage to RC frame buildings with masonry infill walls during the recent earthquake events in L'Aquila (Italy) in 2009 [1], in Lorca (Spain) in 2011 [2], in Van (Turkey) in 2011 [3] and Central Italy in 2016 [4]. Heavy and widespread damage of masonry infills with the collapse of infill panels at the lower stories of the buildings

Marko Marinkovic, Assistant Professor, Department of engineering mechanics and theory of structures, Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia. (E-mail address: mmarinkovic@grf.bg.ac.rs)
Santiago Flores Calvinisti, Master student, Politecnico Di Milano, School of Civil, Environmental and Land Management Engineering, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy.
(E-mail address: santiago.flores@mail.polimi.it)
Christoph Butenweg, Full Professor, CWE – Center for Wind and Earthquake Engineering, RWTH Aachen University, Mies-van-der Rohe-Straße 1, 52074 Aachen, Germany. (E-mail address: butenweg@lbb.rwth-aachen.de)

o poslednjem zemljotresu koji se dogodio u Albaniji u novembru 2019. godine. Brojne studije su pokazale da oštećenja zidane ispune predstavljaju značajan deo ukupnih troškova i gubitaka AB zgrada usled zemljotresa [6,7].

Slika 1. Novembarski zemljotres 2019. u Albaniji: a) kolaps zidova ispune; b) pojava „fleksibilnog prizemlja” AB okvirne konstrukcije sa zidanom ispunom [5]

Figure 1. November 2019 earthquake in Albania: a) failure of masonry infill walls and b) soft storey collapse of RC frame building with masonry infills [5]

Jedan od razloga za tako loše ponašanje jeste činjenica da zidana ispuna značajno povećava krutost AB okvirne zgrade i time menja njene dinamičke karakteristike. Međutim, ovo nije uzeto u obzir u svakodnevnoj inženjerskoj praksi. Umesto toga, zidana ispuna se smatra nekonstruktivnim elementom. Zapažanja nakon zemljotresa u Nepal, koji se dogodio 25.4.2015. godine, pokazuju da je zidana ispuna dovela do značajnog povećanja krutosti koja je uticala na sopstvene frekvencije konstrukcije [8]. Takođe, dinamički odgovor oštećene dvospratne AB okvirne zgrade, koji potvrđuje doprinos zidane ispune horizontalnoj nosivosti konstrukcije, ispitivan je u [9] uz to da je potencijalno oštećenje zidane ispune moglo da se odredi korišćenjem sofisticiranih numeričkih modela. Nekoliko autora [10–12] bavilo se istraživanjem promene perioda konstrukcije usled prisustva ispune. U zavisnosti od predominantnog perioda zemljotresa, smanjenje perioda konstrukcije usled ispune može dovesti do povećanja ili smanjenja očekivanog nivoa seizmičkog opterećenja.

Za vreme zemljotresa, zidovi ispune su izloženi dejstvu opterećenja u ravni, koje se javlja usled deformacije okvira. Visoko deformabilni AB okviri dovode do krkog odgovora krute ispune, što uzrokuje značajna oštećenja. Ponašanje zidane ispune pri takvom opterećenju istraživali su mnogi [13–17]. Pored opterećenja u ravni, ispuna je izložena i opterećenju upravno na ravan zida forces, koje se javlja usled ubrzanja i same mase zida. Opterećenje van ravni zida deluje upravno ne njegovu ravan i ponašanje ispune pri ovakvim uslovima, između ostalih, ispitivali su autori [18–20]. Sveobuhvatni pregled literature u vezi sa

(Figure 1a) during the recent earthquake in Albania, was reported in [5]. Studies showed that damage of infill walls considerably affects overall seismic losses of RC buildings [6,7].

One of the reasons for such a poor behaviour is that infill walls significantly increase the stiffness of RC frame buildings and thus change their dynamic characteristics. However, in everyday design this is not taken into account. Instead, infills are considered as non-structural elements. Field observation after the April 25th earthquake in Nepal showed that infills produced significant increase of stiffness that influenced the natural frequencies of the structure [8]. In addition, dynamic response of a damaged two-story infilled RC building confirming contribution of the infills to the lateral resistance of this structure was investigated in [9] adding that the potential damage in the infills should be accounted with the use of sophisticated numerical models. Several researchers [10–12] investigated change of period of structure due to the infill presence. Depending on the predominant periods of the earthquake, decrease in the natural period due to infill may produce increase or decrease of the expected seismic response.

During the earthquakes infill walls are subjected to in-plane (IP) loading that comes from the deformation of the frame. High deformable RC frames produce brittle response of stiff masonry infills causing severe damage. Behaviour of infill walls under such conditions was investigated by many researchers [13–17]. Besides in-plane loading, infills are subjected to out-of-plane (OOP) forces coming from the floor accelerations and mass of the wall itself. Out-of-plane load acts perpendicular to the wall panel and the behaviour of infills under these conditions was studied by [18–20], among others. Comprehensive literature review about out-of-plane experimental tests is given in [21], concluding that the

eksperimentalnim ispitivanjima ispune na dejstvo opterećenja van ravni dato je u [21], sa zaključkom da kvalitet izvođenja može značajno uticati na ponašanje zida upravno na svoju ravan time što bi se narušili granični uslovi zida. Uticaj interakcije opterećenja u ravni i van ravni zida je prikazan u [22] gde je rečeno da opterećenje u ravni može da dovede do odvajanja ispune od okolnog AB okvira i time spreči razvoj efekta luka bitnog za nosivost van ravni zida. U ovom radu su autori takođe pokazali da okvirna konstrukcija sa zidanom ispunom ima mnogo manja relativna međuspratna pomeranja u poređenju sa okvirnom konstrukcijom, ali kada se interakcija opterećenja u ravni i van ravni uzme u obzir, relativno međuspratno pomeranje konstrukcije sa ispunom bilo je čak veće od okvirne konstrukcije bez ispune. Drugi autori [23–26] takođe su naglasili neophodnost uzimanja u obzir interakcije opterećenja u ravni i van ravni. Samo nekoliko autora [26–28] istraživalo je uticaj istovremenog dejstva opterećenja u ravni i van ravni ispune, iako je očekivano da da u toku zemljotresa oba pravca opterećenja deluju na zid ispune. Eksperimentalna ispitivanja prikazana u [26] pokazala su značajno smanjenje kapaciteta deformacije u ravni i kapaciteta nosivosti van ravni, objašnjavajući da deformacija okvira dovodi do gubitka veze između okvira i ispune i time čini zidanu ispunu ranjivu na opterećenje van ravni.

Ukoliko ispuna nije uzeta u obzir u toku projektovanja kao noseći element, problemi kao što su dodatni uticaji na AB okviru mogu se zanemariti. Najčešći tipovi oštećenja uzrokovani neregularnim rasporedom ispune jesu efekti torzije, fleksibilno prizemlje/sprat i efekat kratkog stuba. Zgrade koje se nalaze na uglu ulice obično nemaju ispunu na strani do ulice a na druge dve ispuna je ozidana, što može dovesti do torzije konstrukcije u toku dejstva zemljotresa koja može biti pogubna za globalno ponašanje zgrade. Kao što je opisano u [29] nejednak raspored zidane ispune može da prouzrokuje globalnu torziju konstrukcije, koja može da dovede do velikih zahteva na stubovima što nije uzeto u obzir u originalnom proračunu. Uticaji nejednakog rasporeda ispune na oštećenja AB zgrada usled zemljotresa ispitani su u [30], uz zaključak da su ovi uticaji manje izraženi kod zgrada s jakim AB zidovima. Rušenje konstrukcije usled torzije i pojave fleksibilnog sprata (slika 1b) mogu da se pojave čak i u slučaju kada Evrokod 8 [31] ne zahteva amplifikaciju seizmičkih uticaja [32]. U [33] zaključeno je da će torzioni uticaji usled nejednakog rasporeda ispune verovatno dovesti do rušenja zidova ispune ispadanjem van ravni.

Uobičajeni problem dispozicije jeste fleksibilni sprat uzrokovan odsustvom zidova ispune ili postojanjem značajno manje zidova ispune na spratu iznad ili ispod. Ovakva konfiguracija javlja se usled funkcionalnih zahteva kao što su radnje i potreba za parking mestima. U [34] pokazano je da čak i kada se koriste zahtevi dati u propisima za ojačanje nosećih elemenata okvira, projektanti moraju modelirati zidanu ispunu i treba da verifikuju da se fleksibilni sprat neće javiti. Uticaji fleksibilnog sprata numerički su ispitivani u [35] primenom 3D modela, dok je u [36] pokazano da čak ni seizmička izolacija ponekad ne može da pomogne u slučaju nejednakog rasporeda ispune i formiranja fleksibilnog sprata, uz zaključak da se značajna oštećenja mogu

workmanship could significantly affect the panel OOP behaviour by disturbing their boundary conditions. The influence of in-plane/out-of-plane interaction was studied in [22] saying that in-plane loading can disable development of out-of-plane arching effect due to the detachment of infill walls from the surrounding RC frames. In this paper authors also show that the frame structure with infill has much lower IP drifts when compared to the bare frame structure, but when IP/OOP interaction is taken into account the drifts with infill walls are even higher than in the case of bare frame structure. Other researchers [23–26] also pointed out the necessity to take into account IP/OOP interaction. Just a few researchers [26–28] studied in-plane and out-of-plane loading acting simultaneously on the infill walls, although it is expected that during the earthquake infills are loaded in both directions. Experimental tests performed and presented in [26] showed high decrease of both in-plane and out-of-plane capacity, explaining that deformation of the frame causes loss of connection between frame and infill, thus making infill walls vulnerable to out-of-plane loads.

If infills are not considered during the design as load carrying elements, problems such as additional demands to the RC frame components can be missed. Most common damage configurations caused by irregular distribution of infill walls are torsion, weak and/or soft stories and short columns. Buildings located on the street corners usually have infill panels on the non-street sides, which can result in a torsional response during an earthquake that might be detrimental to the global performance of the building. As described in [29] the unbalanced distribution of infill walls can introduce global torsion in buildings, which can induce larger demands in columns that were not considered in the original design. Effects of the irregular placement of the infills on the seismic damage of RC buildings was investigated in [30], concluding that these effects are less pronounced for the buildings with strong RC shear walls. Structural failure due to torsion and soft-storey effects may occur even in cases where Eurocode 8 [31] does not require the amplification of the action effects [32]. In [33] it was concluded that torsional effects due to the irregular infill distribution would probably result in failure of the infill wall through out-of-plane collapse.

Very common configuration problem is a weak and/or soft story caused by the absence of infill walls or the presence of many fewer infill walls than the story above and/or below. This configuration appears due to the functional demands such as parking and shops. In [34] it was shown that even when using code provisions for strengthening open-story frame members, designers must model the infill walls and should verify that a weak story will not form. Soft story effect using numerical model on a 3D building was investigated in [35], whereas [36] showed that even base isolation sometimes cannot help with the irregular infill distribution and creation of soft storey effect, concluding that heavy damage is to be expected in the base isolated structures subjected to near-fault earthquakes.

Short column can appear in a case of non-structural partial-height masonry infills that are in a rigid contact with the columns causing high demand that even strong columns cannot take. In [37] it was reported that the presence of the partial height wall decreases the ultimate lateral load capacity of the system by 47%. As solution for

očekivati u slučaju seizmički izolovanih konstrukcija koje se nalaze blizu epicentra.

Efekat kratkog stuba može se javiti u slučaju zidane ispune koja nije u punoj visini u kontaktu sa okvirom kada je kontakt sa stubom krt, što ima za posledicu tako visoke zahteve da ih čak i jaki stubovi ne mogu prihvatiti. U [37] prikazano je da je prisustvo zidova koji se ne protežu celom visinom stuba dovelo do pada kapaciteta konstrukcije za 47%. Kao rešenje za efekat kratkog stuba, u [38] predloženo je da se ispuna razdvoji od okvira tako što će se ostaviti prostor između njih. U [39] savetuje se da se efekat kratkog stuba izbegne u toku rada na arhitektonskom konceptu konstrukcije, i dodaje da zidana ispuna u kontaktu sa stubom treba da se izoluje razdvajanjem od okvira.

Jedna opcija da se unapredi ponašanje AB okvirnih konstrukcija sa zidanom ispunom jeste da se ispuna modelira u toku projektovanja. Za ovu svrhu najpogodniji je pristup makro modeliranja. Na ovaj način se mogu opisati uticaji zidane ispune na globalno ponašanje AB zgrada u toku zemljotresa. U toku dugog perioda istraživanja ponašanja okvira sa zidanom ispunom, predloženo je više pristupa za makro modeliranje. Upotreba ekvivalentne pritisnute dijagonale, bez sumnje, najviše je prihvaćen i najviše izučavan pristup. Međutim, njena primena nije jednostavna i za sada ne postoji opšti konsenzus oko jedinstvenog pristupa.

Prva istraživanja [40–41] na okvirima sa ispunom bazirana su na konceptu ekvivalentne dijagonale. Navedeni autori pretpostavili su da se ispuna ponaša kao pritisnuta dijagonala, kao što je pokazano na slici 2.

Slika 2. Pritisnuta dijagonala i ekvivalentna dijagonala [42]
Figure 2. Diagonal compression strut and equivalent strut [42]

Pristupom ekvivalentne dijagonale može se modelirati globalno ponašanje okvira sa ispunom, ali model sa samo jednim elementom po dijagonali ne može da uzme u obzir promenu momenata savijanja i smičućih sila po dužini stuba koja se javlja usled panela ispune [43] i zbog toga je neefikasna u modeliranju kompleksnog ponašanja okvirnih konstrukcija [44]. Kako bi se prevazišlo ovo ograničenje, nekoliko autora [45–47] razvilo je modele s različitom orijentacijom i brojem dijagonalnih elemenata. Kako bi se koristila pritisnuta dijagonala za predstavljanje ispune, karakteristike kao što su širina dijagonale, krutost i veza sila–pomeranje moraju se definisati. Neki autori [29, 41, 48] definisali su širinu dijagonale kao procenat dužine dijagonale, dok su drugi [49–54] zaključili da

short column, [38] proposed an application of separation gap between infill and frame. In [39] it was suggested that the short column effect should be avoided during the architectural design stage itself adding that the infills in the short column region should be isolated from adjoining columns.

One option to improve the behaviour of masonry infilled RC frame buildings is to model the infills during the design phase. For this purpose the macro-modelling approach is the most convenient. This approach is used to describe the effect of the masonry infill walls to the global seismic behaviour of RC buildings. During the long period of studying the behaviour of infilled frames, there have been different proposals for macro-modelling approach. Using the strut to model the infill is undoubtedly the mostly accepted and the mostly studied approach. However, its application is also a difficult task and so far there is no overall consensus about the unique approach.

First studies [40–41] on infilled frames were based on the equivalent diagonal strut concept. They assumed that the infill wall acts as a diagonal compression strut, as shown in Figure 2.

The equivalent diagonal strut approach can model the global force-displacement behaviour of the infilled frame, but model of the infill wall with just one single strut element is incapable of properly taking into account the change in the bending moment and shear diagram along the column length due to the presence of the panel [43] and therefore it is ineffective in modelling the complex behaviour of infilled frames as reported in [44]. To overpass this limit, several researchers [45–47] developed models with different orientations and number of struts. In order to use the strut for representing an infill, characteristics such as strut width, stiffness and force-displacement relation have to be defined. Some authors [29, 41, 48] defined the width of the strut as percentage of the diagonal length, whereas

efektivna širina dijagonale zavisi od dužine kontakta okvira i ispune i parametra koji uzima u obzir relativni odnos krutosti okvira i ispune, λh , definisan u [55].

Kao što je slučaj sa širinom dijagonale, puno predloga je dato za definisanje nosivosti i određivanje kapaciteta različitih tipova loma ispune. Jednačine za neke od tipova loma ispune u ravni date su u [41, 49, 56], pri čemu su autori smatrali nerelevantnim one tipove loma koji nisu obuhvaćeni. Jedna od bitnih prednosti pristupa predloženog u [51, 52] jeste sposobnost da se pri određivanju nosivosti uzmu u obzir svi tipovi loma. Ovo je takođe predloženo u [57]. Definicija konstitutivnog zakona za pritisnute dijagonale neophodna je kako bi se model pritisnute dijagonale implementirao u program za proračun konstrukcija. Tipovi konstitutivnih modela neophodnih da se definiše pritisnuta dijagonala zavise od tipa analize (linearno-elastična ili nelinearna) i od tipa opterećenja (monotono, ciklično ili dinamičko). U [52] među prvima je predložena relacija sila–pomeranje za ekvivalentnu dijagonalu, definišući početnu krutost, granu ojačanja i omekšanja praćenu rezidualnom nosivošću. Slično, u [58] predložena je nelinearna zavisnost sila–pomeranje kako bi se opisao odgovor pritisnute dijagonale. Slična relacija s tri-linearnim odgovorom predložena je u [59, 60]. Kako bi se sproveda dinamička nelinearna analiza, potrebno je definisati histerezisno ponašanje materijala. U literaturi je dato samo par modela histerezisa za definiciju pritisnute dijagonale, zato što je većina istraživanja ispitivala ponašanje zidane ispune pri monotonom opterećenju, ali i zbog činjenice da uzimanje u obzir histerezisnog ponašanja u modelu povećava ne samo kompleksnost već i nepouzdanost modela. Jedan od prvih pokušaja prikazan je u [61], a jedan od najčešće korišćenih modela predložen je u [43, 62]. Nešto skorije, u [63] prikazan je unapređeni histerezisni model predložen prvo u [64] uviđanjem detaljne veze sila–pomeranje koja uzima u obzir ciklično i monotono ponašanje ekvivalentne dijagonale, kalibrisane uz pomoć eksperimentalnih rezultata. Iako eksperimentalna istraživanja pokazuju neophodnost uzimanja u obzir interakcije opterećenja u ravni i van ravni, njeno obuhvaćanje u numeričkom modelu izuzetno je kompleksan zadatak koji se trenutno nalazi u početnoj fazi razvijanja i verifikacije.

Druga opcija za unapređivanje ponašanja zidane ispune u AB ovirnim zgradama sa zidanom ispunom jeste da se primene konstruktivne mere na samoj ispuni. Ovo se može uraditi povećanjem nosivosti ispune dodavanjem armature u zidno platno [65, 66] ili primenom maltera armiranih tekstilnim mrežicama [67–69]. Unapređivanje ponašanja ispune podelom zida na horizontalne delove sa specijalnim klizajućim površinama između njih predložilo je nekoliko autora [70–73]. Na ovaj način povećava se deformabilnost zida ispune.

Treća opcija podrazumeva kompletnu izolaciju u ravni ispune u odnosu na okolni okvir, tako da se okviru dozvoli deformacija i time odloži aktivacija ispune. Najjednostavniji način da se razdvoji ispuna od okvira jeste ostavljanjem prostora između njih. A ovaj prostor se može popuniti mekim materijalom [29, 74, 75]. Dodatna korist razdvajanja ispune i okvira jeste smanjenje napona u stubovima usled mekog kontakta okvira i ispune. U ovom pristupu bitno je obezbediti adekvatnu vezu okvira i ispune koja može da prihvati opterećenje van ravni kako se zid ispune ne bi srušio. Za ovu svrhu, veza ispune i

others [49–54] found that effective width is dependent on the length of contact between the infill and the frame and relative panel to frame stiffness parameter, λh , defined by [55].

As it is the case for the width of the strut, many proposals for the strength are given in order to determine the capacities for the various failure modes that infill walls can experience. The equations for some of the in-plane failure modes are given by [41, 49, 56], considering the omitted ones as negligible. One of the important advantages of the approach proposed by [51, 52] for the calculation of strut strength is its ability to account for all failure mechanisms. This was also done by [57]. Definition of constitutive relations for the strut is necessary in order to implement a strut model in software for structural calculations. The types of constitutive models required to set the strut models depend on the type of analysis (linear elastic or nonlinear) and the type of loading (monotonic, cyclic or dynamic). One of the first to propose force-displacement relationship for the equivalent strut defining initial stiffness, hardening and softening branch followed with the residual strength was [52]. Similarly, [58] proposed a nonlinear force-displacement relationship to describe the response of equivalent strut. Similar relation with the tri-linear response for the strut was proposed in [59, 60]. In order to run dynamic nonlinear analysis the hysteretic behaviour of the material must be established. In literature just a few hysteretic models for diagonal strut can be found, because most researchers studied the behaviour of infill masonry under monotonic loading, but also due to the fact that the modelling of hysteretic behaviour increases not only the computational complexity but also the uncertainties of the problem. One of the early attempts was conducted by [61]. One of the most commonly used models was proposed by [43, 62]. More recently, [63] improved the hysteresis law proposed in [64] by introducing a detailed force-displacement law accounting for cyclic or monotonic behaviour of an equivalent strut, calibrated against experimental results. Although, experimental studies show necessity for taking into account in-plane/out-of-plane interaction, incorporating it in the numerical models is highly complex task being at the starting phase of development and verification.

Second option for improvement of the behaviour of masonry infilled RC frame buildings is to apply some construction measures to the infills itself. This can be done by increasing the infill strength with addition of reinforcement to the infill wall [65, 66] or by applying textile reinforced mortars for plastering [67–69]. Improving the behaviour of the infills by subdividing the wall in horizontal sections with special sliding surfaces between them was proposed by several authors [70–73]. In this way deformability of the infill panel is increased.

The third approach considers the complete in-plane isolation of non-structural elements from the surrounding frame, so to allow frame deformation and thus delayed infill activation. The simplest way to separate infill from the frame is by creating the gaps between them. This can be done by filling the gap with soft material [29, 74, 75]. Additional benefit of infill/frame decoupling is reduction of stresses induced to the frame because of the soft contact. Important aspect which should be covered in this approach is adequate out-of-plane restraint to prevent the infill wall to collapse due to the perpendicular loads.

okvira preko čeličnih ankera ispitivana je u [76, 77]. Izolacija ispune takođe je data kao jedno od rešenja u međunarodnim preporukama i propisima [78–80].

Problem je što ima puno pristupa i procedura, koji nisu standardizovani kako bi se primenili u inženjerskoj praksi. Štaviše, mnoga rešenja donose korist ispuni, ali za sada nije predloženo kompletno rešenje koje može da reši probleme ponašanja zidane ispune pri zemljotresnom dejstvu. Nedostaci su razni, od komplikovanih do praktično neprimenjivih rešenja i onih koja nisu efikasna u rešavanju istovremenog dejstva opterećenja u ravni i van ravni. Za neka od njih primena je problematična u smislu ostavljanja mogućnosti i fleksibilnosti za korišćenje prostorija, a neka nisu primenjiva za sve tipove cigli. Jedno od rešenja koje je pokazalo obećavajuće rezultate opisano je u [81]. To je sistem pod imenom INODIS (Innovative Decoupled Infill System) koji omogućava efikasnu izolaciju zida ispune u ravni i time odlaže aktivaciju ispune, čime smanjuje interakciju okvira i ispune i njene neželjene efekte. Zbog osobina i oblika koji pruža vezu koja može da prihvati opterećenje van ravni, ovaj sistem je izabran za detaljnu numeričku analizu prikazanu u ovom radu.

Kako bi se utvrdilo da li je sistem izolacije bolje rešenje u odnosu da tradicionalnu ispunu, niz numeričkih linearnih i nelinearnih analiza je sproveden. Novina ovog rada ogleda se u istraživanju ponašanja AB okvirnih konstrukcija sa izolovanom ispunom na nivou konstrukcije. Slična istraživanja su sprovedena s tradicionalnom ispunom ali nijedno sa izolovanom ispunom. S obzirom na to što INODIS sistem obezbeđuje izolaciju ispune u ravni, time uklanja interakciju opterećenja u ravni i van ravni, kao što je i eksperimentalno prikazano [81]. Stoga, u prikazanim numeričkim analizama uzeto je u obzir samo ponašanje ispune u ravni.

2 SISTEM IZOLACIJE ISPUNE

U ovom poglavlju je ukratko predstavljen sistem INODIS. Njegovi detalji i osobine su detaljno dati u [81, 82]. Osnovna ideja INODIS sistema (slika 3) jeste razdvajanje zidane ispune i AB okvira u ravni ispune u kombinaciji sa njihovom vezom duž ivica panela ispune koja može da prihvati opterećenje van ravni. Cilj ove veze je da poveća kapacitet i u ravni i van ravni putem konstruktivne veze koja omogućava klizanje na kontaktu rama i ispune. INODIS sistem razdvaja zidanu ispunu od AB okvira putem elastomera u obliku latiničkog slova „U” koji je postavljen duž vertikalnih ivica ispune i na vrhu zida ispune. Elastomeri u obliku latiničkog slova „U” projektovani su tako da dozvoljavaju relativno međuspratno pomeranje AB okvira tako da se ne ošteti zidana ispunu.

Osim toga, viskoelastično ponašanje elastomera povećava ukupno prigušenje zgrade. Plastični profili su ekserima ili zavrtanjima vezani za AB okvir dok su elastomeri u obliku latiničkog slova „U” zalepljeni za zid ispune s jedne strane i postavljeni oko plastičnih profila s druge strane (slika 3), sprečavajući time lom van ravni ispune. Flanše „U” elastomera na slici 3 napravljene su od mekog elastomera dok je krući elastomer iskorišćen za rebra „U” profila. Najkrući elastomer postavljen je na dno zida u vidu tri trake.

Therefore, the use of steel anchors connecting infills to the frame was studied by [76, 77]. Decoupling approach is also given as one of the options in some international guidelines [78-80].

The problem that can be found is that there are many approaches and the process has not been standardized in order to be used by the practical engineering community. Furthermore, many solutions bring the benefit to the infills, but so far no complete solution is proposed that solves the problems of the behaviour of the masonry infill walls under earthquake excitations. Shortcomings are different, from complicated to practically inapplicable solutions and solutions not effective for simultaneous in-plane and out-of-plane load. For some of them the application is problematic with respect to flexible room use and they are inapplicable to all types of bricks. One solution that has shown promising results is the decoupling system described in [81]. This system called INODIS (Innovative Decoupled Infill System) is able to effectively decouple and delay the activation of the infill walls, thus reducing the infill/frame interaction and the undesirable effects of it. Due to its features and the shape providing sufficient out-of-plane connection for infill walls, this system is chosen for detailed numerical study presented in this paper.

In order to determine whether the decoupling system is a better solution compared to traditional unreinforced masonry walls, a series of numerical linear and non-linear analyses were performed. The novelty of the paper is study of the behaviour of the RC frame buildings with decoupled infill walls at the structural level. Similar studies were done for traditional infills but none is performed on decoupled infills. Since the INODIS system provides in-plane decoupling it removes in-plane/out-of-plane interaction, as shown experimentally [81]. Therefore, in the numerical analyses just in-plane behaviour of the infill walls was considered.

2 DECOUPLING SYSTEM

In this section the decoupling system INODIS is briefly described. Its details and features are thoroughly given in [81, 82]. The basic idea of the INODIS system (Figure 3) is decoupling of infill masonry and RC frame in in-plane direction combined with the out-of-plane connection measures along the edges of the infill panel. It aims to raise the in- and out-of-plane resistance by means of dissipative and sliding connections along the contact areas of the infill to the RC frame. INODIS decouples the infill wall and RC frame with the U-shaped elastomers placed at the top and along the vertical edges of an infill, together with the elastomer divided in three strips at the bottom of the infill. The U-shaped elastomers are designed to allow the design drift of the reinforced concrete frame without inducing damages to the infill wall. Furthermore, the viscoelastic bearings enhance the overall damping capacity of the building. Plastic profiles are attached by metal nails or screws to the surrounding frame while U-shaped elastomers are glued to the masonry infill on one side and placed around plastic profiles on the other side (Figure 3), thus preventing the out-of plane failure. Flanges of the U-shaped elastomers shown on Figure 3 are made of soft elastomer while stiffer elastomers are used for the webs. The stiffest elastomer is applied at the bottom in a form of three strips.

Slika 3. Izgled i postavka INODIS sistema [81]
Figure 3. Layout of the INODIS system [81]

3 NUMERIČKI MODELI

U ovom poglavlju, predstavljeni su pristupi modeliranja svih komponenti AB okvira sa izolovanom ispunom. Budući da su tema istraživanja AB okviri sa zidanom ispunom, modeliranje se može podeliti na tri dela, jedan vezan za AB okvir, drugi se odnosi na zidanu ispunu i treći na elemente izolacije ispune. Tri različita modela su razvijena: prazan okvir, okvir sa ispunom i okvir sa izolovanom ispunom. Softverski paket SAP2000 [83] izabran je zbog široke upotrebe u projektantskoj praksi.

3.1 Modeliranje AB okvira

Grede i stubovi modelirani su linijskim konačnim elementima, pretpostavljajući uklještenje na dnu stubova (slika 4a). Kako bi se sprovedla nelinearna analiza, u modelima je uzeta u obzir nelinearnost materijala i preseka, uvođenjem plastifikacije preseka. Tačnije, na kraju elementa definisani su plastični zglobovi (slika 4a). Za betonske elemente, karakteristike zglobova uzete su prema Tabeli 6–7 za grede i prema Tabeli 6–8 za stubove iz FEMA-356 [84]. Kriva sila ili moment-deformacija zasniva se na krivoj prikazanoj na slici 5, gde je dato pet različitih tačaka (A do E) koje treba definisati. Tačke predstavljaju početak, tečenje, maksimalnu nosivost, zaostalu nosivost i lom [83].

3 NUMERICAL MODELS

In this section, modelling approaches for all parts of the RC frames with decoupled infills are presented. Since the topic of the investigation are masonry infilled RC frames, the modelling approaches can be divided into three sections, one related to the RC frame, second to the infill wall and third to the decoupling elements. Three different models have been developed: the bare frame model, the infilled model and model of the frame with the decoupled infills. The software SAP2000 [83] was chosen because it is a widely used commercial program in design practices.

3.1 Modelling of the concrete frame

Beams and columns are modelled as one-dimensional frame elements, assuming fixed end restraints at the base of the columns (Figure 4a). In order to perform nonlinear analysis, models include nonlinearity properties of materials and section, through a distributed plasticity approach. In particular, at the end section of the elements plastic hinges are placed (Figure 4a). For concrete elements, the hinge properties are taken from Tables 6-7 for beams and 6-8 for columns from FEMA-356 [84]. The force or moment-deformation curve is based, on the curve shown in Figure 5, where five different points (A to E) must be defined. The points

represent the place of origin, yielding, ultimate capacity, residual strength and failure, respectively [83].

Slika 4. a) Model praznog okvira s položajem „fiber” zglobova i b) makro model okvira s tradicionalnom ispunom
Figure 4. a) Bare frame model with location of fibre hinges and b) macro model of traditionally infilled frame

Slika 5. Ponašanje plastičnog zgloba prema FEMA 356 [84]
Figure 5. Plastic hinge behaviour according to FEMA 356 [84]

Za definisanje poprečnog preseka betonskih elemenata upotrebljena je posebna opcija dostupna u programu SAP2000 koja se zove „Section Designer”. Uz pomoć nje je moguće definisati proizvoljnu geometriju preseka i kreirati kombinaciju materijala. U opciji „Section Designer” moguće je definisati presek betona s različitim karakteristikama materijala kao i tačan raspored armature. Za zaštitni sloj betona definisan je neutegnuti beton dok je za ostali deo preseka zadat utegnuti beton. Glavna razlika je da pri niskom nivou napona, poprečna armatura je slabo opterećena i beton se ponaša kao neutegnuti. Dok pri naponima bliskim jednoosijalnoj nosivosti betona, pojava pukotina u betonu dovodi do značajne aktivacije uzengija koje onda pružaju utezanje betonskom elementu. Na ovaj način se obezbeđuje značajno povećanje nosivosti i duktilnosti betonskog elementa [85]. Kriva napon–dilatacija za utegnuti i neutegnuti beton (slika 6) zasniva se na modelu predloženom u [86]. Prema njoj, nosivost na pritisak i granična dilatacija određuje se u funkciji poprečne armature. Bitne karakteristike Manderove krive su da se može koristiti i za statička i dinamička opterećenja, kada su ona zadana monotono ili ciklično [86, 87]. Upotrebom

For creating specific frame section properties separate utility built into SAP2000 called “Section Designer” is used. It allows sections of arbitrary geometry and combinations of materials to be created. In Section Designer it is possible to create a section with different concrete material properties and precise disposition of reinforcement. For the concrete cover unconfined concrete was assigned and confined for the rest of the section. The main difference is that under the low levels of stress, transverse reinforcement is barely stressed and the concrete behaves like unconfined concrete. At stresses close to the uniaxial strength of concrete, fracturing causes the concrete to stress the stirrups which then provide confining action in concrete element. In this way, a significant increase of strength and ductility of concrete is present [85]. The stress-strain curve used for the confined and unconfined concrete (Figure 6) is based on the concrete model proposed [86]. It derives the compressive strength and ultimate strain values as a function of the transverse reinforcement. Important characteristic is that Mander’s curve can be used for both static and dynamic loadings, when they are applied monotonically or cyclically [86, 87]. With the use of

automatskog definisanja karakteristika plastičnih zglobova, program određuje krivu moment–rotacija i ostale karakteristike plastičnog zgloba prema FEMA 356 [84] kriterijumu koristeći preciznu geometriju i definiciju materijala datu u „Section Designer” [85].

automatic hinge properties, program calculates the moment-rotation curve and other hinge properties according to FEMA 356 [84] criteria using precise geometry and material defined in Section Designer [85].

Slika 6. Kriva napon–dilatacija za utegnuto i neutegnuto betono [86]
Figure 6. Stress-strain curves for unconfined and confined concrete [86]

Kako bi se modelirala plastifikacija duž elementa i po širini poprečnog preseka korišćen je takozvani „fiber” presek. Upotrebom „fiber” zglobova moguće je definisati uvezano ponašanje aksijalne sile i momenta savijanja. Poprečni presek diskretizuje se u niz aksijalnih vlakana koja se protežu podužno kroz celu dužinu plastičnog zgloba. Ovi plastični zglobovi su elastoplastični i sastoje se od seta materijalnih tačaka, gde svaka predstavlja deo poprečnog preseka i ima njegove materijalne karakteristike. Krive sila–deformacija i moment–rotacija nisu definisane, već se određuju u toku analize na osnovu krive napon–dilatacija za svaku materijalnu tačku [83].

To model distributed plasticity along the member length and across the section so-called fibre section models are used. With the employment of fibre hinges it is possible to define coupled axial force and bending behaviour. The cross section is discretized into a series of representative axial fibres which extend longitudinally along the hinge length. These hinges are elastic-plastic and consist of a set of material points, each representing a portion of the cross-section having the same material. Force-deflection and moment-rotation curves are unspecified, but computed during the analysis from the stress-strain curves of the material points [83].

3.2 Modeliranje zidane ispune

Kako bi se modeliralo ponašanje zida ispune u ravni, korišćen je makro model, primenom link-elementa za modeliranje ekvivalentne dijagonale. Link-element se može koristiti da spoji dva čvora konačnih elemenata i njima se može prikazati nelinearno ponašanje. Zbog toga su oni pogodan izbor za modeliranje ponašanja ispune u ravni. Link-element predstavlja šest opruga za svaki od šest stepeni slobode. Za svaku oprugu je moguće definisati različite tipove linearnog i nelinearnog ponašanja. Između više vrsta link-elemenata koji postoje u programu SAP 2000 *multi-linear plastic* link-element je izabran zbog sposobnosti da predstavi nelinearno ponašanje ispune. Unutar svakog rama su postavljena dva link-elementa, po jedan na svaku dijagonalu (Figure 4b).

Definisane su samo karakteristike u pravcu U1 nelinearnom krivom sila pomeranja. Za definisanje ove

3.2 Modelling of the infill wall

In order to model the in-plane behaviour of the infill walls, a macro modelling approach was employed, using link element to model equivalent strut. Link elements can be used to connect two joints together and they are able to capture a nonlinear behaviour. Therefore, they are a suitable choice for modelling in-plane behaviour of infill panel. A link element is assumed that is made of six springs for each of the six degrees of freedom. For each spring it is possible to assign different types of linear or nonlinear properties. Between several types of link elements available in SAP 2000 the multi-linear plastic link element was chosen due to its ability to present nonlinear behaviour of infill wall. Two link elements are placed inside the frame connecting diagonal opposite corners (Figure 4b).

Only the properties in the U1 direction were defined with the nonlinear force-deformation curve. For the

krive iskorišćen je pristup dat u [51, 52]. Tu je predložena kriva s četiri dela koja opisuje: (i) linearno-elastičnu fazu do H_{mf} ; (ii) fazu nakon prvih pukotina do dostizanja maksimalne nosivosti H_{mfc} ; (iii) silaznu granu do H_{mr} ; i (iv) rezidualnu nosivost definisanu horizontalnom linijom kao što se može videti na slici 7.

definition of this curve approach from [51, 52] was used. They proposed a four branched backbone curve that describe: (i) the linear elastic phase up to H_{mf} ; (ii) the post-cracking stage until reaching the maximum strength H_{mfc} ; (iii) the deterioration descending branch until H_{mr} ; and (iv) the residual stress characterized by a horizontal line as seen in Figure 7.

Slika 7. Veza sila–pomeranje zadata pritiskutoj dijagonali [88]
Figure 7. Force-displacement relationship for diagonal strut [88]

Za definiciju širine pritisnute dijagonale, navedeni autori su koristili parametar relativnog odnosa krutosti, λ_h , predložen u [55] i dve konstante K_1 i K_2 prema sledećim jednačinama:

For the definition of the equivalent strut width, the relative stiffness parameter was used, λ_h , proposed by [55] and two constants K_1 and K_2 according to the following equations:

$$\omega = \left(\frac{K_1}{\lambda_h} + K_2 \right) d \quad (1)$$

$$\lambda_h = h^4 \sqrt{\frac{E_m t_m \sin 2\theta}{4E_c I_c h_m}} \quad (2)$$

gde K_1 i K_2 uzimaju vrednosti iz Tabele 1 i gde E_m predstavlja modul elastičnosti zida; $E_c I_c$ je fleksiona krutost stuba, t_m je debljina zida ispune; h je visina stuba između osa greda; h_m je visina ispune; θ je ugao između horizontale i dijagonale zida kao što je prikazano na slici 2.

where K_1 and K_2 take the values from Table 1 and where E_m is the masonry panel's modulus of elasticity; $E_c I_c$ is the column's flexural rigidity, t_m is panel thickness of the infill panel; h is the column's height between beams' centre lines; h_m is the height of the infill; θ is the angle between the horizontal and the diagonal of the wall as seen in Figure 2.

Tabela 1. Vrednosti za koeficijente K_1 i K_2
Table 1. Values for coefficients K_1 and K_2

	$\lambda_h < 3.14$	$3.14 < \lambda_h < 7.85$	$\lambda_h > 7.85$
K_1	1.3	0.707	0.47
K_2	-0.178	0.01	0.04

Nosivost dijagonalnog elementa na pritisak definisana je uzimajući u obzir četiri tipa loma ispune: (i) zatezanje po dijagonali $\sigma_{br(1)}$; (ii) klizanje po horizontalnim malter-skim spojnicaama $\sigma_{br(2)}$; (iii) lom u uglu zida $\sigma_{br(3)}$; i (iv) lom po dijagonali usled pritiska $\sigma_{br(4)}$, definisanog prema sledećim jednačinama:

The compression failure stress of the strut is defined so that it takes into account four different failure modes: (i) diagonal tension $\sigma_{br(1)}$; (ii) bed joint sliding shear $\sigma_{br(2)}$; (iii) corner crushing $\sigma_{br(3)}$; and (iv) diagonal compression failure $\sigma_{br(4)}$, defined according to the following equations:

$$\sigma_{br(1)} = \frac{0.6\tau_{m0} + 0.3\sigma_0}{\omega/d} \quad (3)$$

$$\sigma_{br(2)} = \frac{(1.2 \sin \theta + 0.45 \cos \theta) f_{sr} + 0.3\sigma_0}{\omega/d} \quad (4)$$

$$\sigma_{br(3)} = \frac{(1.12 \sin \theta \cos \theta)}{K_1(\lambda_h)^{-0.12} + K_2(\lambda_h)^{0.88}} \sigma_{m0} \quad (5)$$

$$\sigma_{br(4)} = \frac{1.16\sigma_{m0} \tan \theta}{K_1 + K_2 \lambda_h} \quad (6)$$

gde je σ_{m0} nosivost zidarije na pritisak, τ_{m0} je smičuća nosivost određena iz testa pritiska po dijagonali, f_{sr} nosivost spojnice na klizanje i σ_0 je napon usled vertikalnog opterećenja.

Nosivost ekvivalentne pritisnute dijagonale računa se korišćenjem minimalnog napona od navedena četiri, kao i sledeće jednačine:

where σ_{m0} is the compression strength, τ_{m0} is the shear strength measured taken from the diagonal compression test, f_{sr} is the joint slide resistance, and σ_0 is the vertical stress of the applied loads.

Lateral strength of the equivalent diagonal strut is calculated using minimal stress and following equation:

$$H_{mfc} = \sigma_{br, \min} t \omega \cos \theta \quad (7)$$

Proračun elastične krutosti, K_0 , uzima u obzir elastičnu krutost okvira, K_{i0} , i krutosti zidane ispune kada je dostigla maksimalnu nosivost i ispucala, K_{mfc} , određene prema [89]:

The calculation of the elastic stiffness, K_0 , takes into account the elastic stiffness of the frame, K_{i0} , and the infill wall stiffness when it is completely cracked, K_{mfc} , calculated according to [89]:

$$K_0 = 3K_{i0} + 4K_{mfc} \quad (8)$$

gde je

where

$$K_{i0} = \frac{1 + 6\phi}{2 + 3\phi} \frac{12E_c I_p}{h^3} \quad (9)$$

$$\phi = \frac{I_{beam}}{I_{column}} \frac{h}{l} \quad (10)$$

$$K_{mfc} = \frac{E_m t \omega}{d} \cos^2 \theta \quad (11)$$

3.3 Modeliranje elastomera

S obzirom na to što se elastomeri koriste za razdvajanje okvira i ispune, treba izabrati element koji može da predstavi hiperelastično ponašanje elastomera. U tu svrhu takođe je izabran *multi linear plastic* link-element. Link-elementi koji predstavljaju elastomere postavljeni su u uglovima, povezujući link-element koji predstavlja ispunu sa okvirom (slika 8).

3.3 Modelling of the decoupling elastomer

Since elastomers are used for decoupling of frame and infill wall, an element that can present hyperelastic behaviour of elastomer should be chosen. For that purpose also multi linear plastic link element was employed. Link elements presenting elastomers are placed in the corners connecting infill's link element and frame (Figure 8).

Slika 8. a) Model okvira sa izolovanom ispunom; b) i c) detalj u uglu koji prikazuje link-element koji predstavlja elastomere

Figure 8. a) Decoupled infilled frame model; b) and c) corner details of link elements presenting elastomers

4 VALIDACIJA PREMA EKSPERIMENTALNIM REZULTATIMA

U ovom poglavlju prikazana je kalibracija i validacija numeričkih modela s ciljem da se razvije numerički model koji može da predstavi eksperimentalne testove na praznim AB okvirima, AB okvirima s tradicionalnom ispunom i AB okvirima sa izolovanom ispunom. Cilj je da se nakon toga validirani modeli iskoriste za parametarsku analizu na 2D ramovima konstrukcije i na 3D modelu zgrade.

Za validaciju numeričkih modela, iskorišćeni su rezultati testova za opterećenje u ravni iz [81]. Eksperimentalna ispitivanja sastojala su se od opterećenja u ravni zadatog na prazan okvir, okvir s tradicionalnom ispunom i okvir sa izolovanom ispunom. Eksperimentalna kampanja i svi detalji dati su u [81]. Prvo je urađena kalibracija numeričkih modela primenom statičke nelinearne analize (*pushover*) poređenjem rezultata sa anvelopom histerezisne krive dobijene u eksperimentu. Nakon toga je sprovedena dinamička nelinearna analiza (*time history*) za kalibraciju modela prema histerezisnoj krivoj dobijenoj usled cikličnog opterećenja.

4 VALIDATION WITH THE EXPERIMENTAL RESULTS

In this section the calibration and validation of the different models will be presented, the goal is to develop a numerical model to simulate tests on RC bare frame, traditionally infilled RC frame and RC frame with decoupled infills. The purpose is to later use this calibrated frame models to simulate the behaviour of the 2D structural frames and 3D building.

For the validation of the numerical model, test results for in-plane loading conditions from [81] will be used. Test campaign consisted of in-plane cyclic loading on full scale bare frame, traditionally infilled frame and frame with decoupled infills. Experimental campaign and all the details are given in [81]. Here, the calibration of the numerical models is first performed using pushover analysis and comparing the results with the envelope of the hysteretic curve and then the time history analysis is employed for calibrating the model to match the hysteretic curve from the cyclic loading.

4.1 Prazan okvir

Kako bi se validirao numerički pristup korišćen za modeliranje AB okvira, iskorišćeni su testovi na neskalinim uzorcima. Okvir je projektovan prema [90, 91] uzimajući u obzir nemački nacionalni aneks i klasu duktilnosti L. Stubovi su kvadratnog poprečnog preseka 25x25 cm sa 1.48% podužne armature, 0.63% poprečne armature na početku i kraju stuba, kao i 0.42% uzengija u sredini. S druge strane gređa je projektovana na dimenzije 25x45 cm (visina x širina) sa 1.05% podužne armature i 0.35% poprečne armature na početku/kraju grede i 0.23% u sredini.

Relativno rastojanje od 0.05 i 0.95 uzeto je u obzir za lokaciju „fiber” plastičnih zglobova (slika 4a). Tačne dimenzije i raspored armature definisani su za poprečne preseke. Koristeći *Section Designer*, armiranobetonski elementi se mogu modelirati prilično precizno (slika 9). Kao što se može videti, tačna lokacija armature zadata je, kao i dva različita materijala za beton (utegnut – žuta boja; neutegnuto – plava). Dva različita poprečna preseka generisana su za grede, takođe i za stubove, kako bi se uzela u obzir promena podužne armature i razmaka uzengija. Grede i stubovi preseka A zadati su na krajevima, a presek B je korišćen za središnje delove elemenata (slika 9). Slika 9 takođe pokazuje distribuciju mreže konačnih elemenata i poziciju vlakana (fiber). Svaki presek ima tri tipa vlakana korišćenih za različite materijale. Za beton je korišćen Manderov model [86] za definiciju krive napon–dilatacija, koja se automatski definiše u programu (slika 10). Za armaturu je korišćena kriva napon–dilatacija, ručno definisana prema materijalnim karakteristikama datim u [82].

4.1 Bare frame

To validate the numerical approach used for the concrete frame modelling, the test on full-scale RC frame is used. The frame was designed according to [90, 91] considering the German national annexes for ductility class L. Columns have a square cross section of 25x25cm with a 1.48% longitudinal reinforcement, 0.63% transverse reinforcement at the start and end of the column, as well as 0.42% middle section stirrups. On the other hand, the beam was designed with a size of 25x45cm (height x width) with a 1.05% of longitudinal reinforcement and 0.35% and 0.23% of transverse reinforcement at beam start/end and in middle section, respectively.

A relative distance of 0.05 and 0.95 was considered for the location of fibre hinges in the model (Figure 4a). Exact dimensions and reinforcement distribution was defined in the cross sections. With the use of *Section Designer* reinforced concrete elements can be modelled quite precise (Figure 9). As it can be seen, the exact location of the rebars is obtained as well as two different material properties of concrete (confined - yellow colour; unconfined - blue colour). Two different cross sections were generated for beams and also for columns, as there is a change in longitudinal reinforcement and spacing of stirrups. Beam and columns cross section A is the ones used near the edges while cross section B is used in the mid-section (Figure 9). Figure 9 also shows mesh distribution and fibre position. Each section was divided into three types of fibres for different kind of materials. For concrete material, the Mander model [86] was used for the definition of the stress-strain curves, which are auto defined by the program (Figure 10). For the rebars, a user defined stress-strain curve was defined, with the material characteristics described in [82].

Slika 9. a) Presek stuba A, 250 x 250 mm (mreža = 15x15); b) presek stuba B, 250 x 250 mm (mreža = 15x15); c) presek grede A, 250 x 450 mm (mreža = 15x15); d) presek grede B, 250 x 450 mm (mreža = 15x15)

Figure 9. a) column section A, 250 x 250mm (mesh = 15x15); b) column section B, 250 x 250mm (mesh = 15x15); c) beam section A, 250 x 450mm (mesh = 15x15); and d) beam section B, 250 x 450mm (mesh = 15x15)

Slika 10. Krive napon–dilatacija za a) utegnute beton b) neutegnute beton
Figure 10. Stress-strain curves for a) confined concrete and b) unconfined concrete

Numerički rezultati statičke nelinearne analize (*pushover*) upoređeni su sa anvelopom histerezisne krive iz eksperimentalnih rezultata (slika 11). Iz rezultata se može primetiti da je kriva dobijena iz numeričkog modela prilično blizu eksperimentalne krive. I degradacija krutosti i kapacitet nosivosti praznog okvira dobro se poklapaju. Numerički rezultati pokazuju skoro isti kapacitet do trenutka dostizanja maksimalne nosivosti i treba istaći da i numerički model i eksperimentalni rezultati pokazuju da je maksimalna nosivost dostignuta pri 2% relativnog međuspratnog pomeranja. Nakon toga postoji blago razilaženje ove dve krive, ali u granicama zadovoljavajućeg.

The results from the numerical pushover analysis were compared to the envelope curve of the hysteresis experimental results (Figure 11). From the results obtained it is possible to notice that, in general, the pushover curves from the numerical model are pretty close to one obtained in experimental test. Both stiffness degradation and strength capacity of the bare frame are matched very well. The numerical results follow almost the same capacity curve until it reaches a peak load capacity; it should be pointed out that both numerical and experimental results reach the peak at 2% of inter storey drift. After the peak there is a small and tolerable diversion between both curves.

Slika 11. Poređenje između numerički dobijene pushover krive i anvelope eksperimentalne histerezisne krive
Figure 11. Comparison between pushover curve from numerical model and the envelope of experimental hysteresis

Kako bi se uhvatilo histerezisno ponašanje materijala, histerezisni model je definisan za beton i za čelik definisan za armaturu. Za model betona, uzet je faktor degradacije energije $s = 0$. Za model armature, parametri korišćeni za kalibraciju dati su u Tabeli 2.

Rezultati dinamičke nelinearne analize prikazani su na slici 12, i može se videti jako dobro poklapanje u smislu krutosti i maksimalnog kapaciteta nosivosti. Takođe, histerezisne petlje su slične, što potvrđuje validnost modela praznog okvira.

In order to capture the hysteretic behaviour of the materials, the concrete hysteresis model was defined for concrete and for steel material of rebars degrading hysteresis model. For the concrete model, an energy degradation factor $s = 0$, was assigned. For the rebar model, the parameters used after calibration can be found in the Table 2.

From the results of the time history analysis shown in Figure 12, it can be seen a very good matching of the stiffness and maximum load capacity. In addition, hysteresis loops are very similar, confirming the validity of the bare frame model.

Tabela 2. Vrednosti korišćene za model armature
Table 2. Values used for rebar model

Faktor degradacije energije / Energy degradation factor, f_0	1.0
Faktor energije pri umerenim deformacijama / Energy factor at moderate deformation, f_1	1.5
Faktor energije pri maksimalnim deformacijama / Energy factor at maximum deformation, f_2	0.2
Umereni nivo deformacije u odnosu na nivo tečenja / Moderate deformation level as a ratio of yield, x_1	1.0
Maksimalni nivo deformacije u odnosu na nivo tečenja / Maximum deformation level as a ratio of yield, x_2	2.0
Akumulacioni deformacioni težinski faktor / Accumulation deformation weighting factor	0
Težinski faktor za krutost / Stiffness weighting factor	0.2
Veći-manji težinski faktor / Larger-smaller weighting factor	0.4

Slika 12. Poređenje rezultata numeričkog modela dinamičke nelinearne analize i eksperimentalnog histerezisa praznog okvira

Figure 12. Comparison between the numerical model time history results and the experimental hysteresis of the bare frame

4.2 AB okvir s tradicionalnom ispunom

Okvir s tradicionalnom ispunom iz eksperimenata prikazanih u [81] sastoji se od istog praznog AB okvira ispunjenog zidom od šupljih blokova od opeke povezanih tankoslojnim malterom. Detaljne materijalne karakteristike blokova i zidarije date su u [81, 82]. Za definisanje krive sila–pomeranje za link-element, iskorišćen je pristup zasnovan na četiri grane krive, definisan u [51, 52]. Kako bi se definisala kriva potrebno je da se odredi bezdimenzioni koeficijent λ_h korišćenjem Jednačine 2. U Tabeli 3 prikazane su korišćene vrednosti:

4.2 RC frame with traditional infills

The traditional infilled frame, used in the experimental tests performed by [81], was composed of the same frame that was infilled with masonry wall made of hollow clay bricks with thin-layer mortar connection. Detailed material characteristics of the bricks and masonry are given in [81, 82]. For the force-displacement curve defined for the link element, a four branch model based on [51, 52] was used. In order to define it, the calculation of the dimensionless parameter λ_h was performed using Equation 2. The following Table 3 shows the values used:

Tabela 3. Određivanje parametra λ_h
Table 3. Calculation of parameter λ_h

E_m	4870	N/mm ²
t_m	365	mm
Θ	0.738	rad
$\sin 2\Theta$	0.996	-
E_c	32559	N/mm ²
h_m	2520	mm
h	2750	mm
λ_h	5.54	-

Za određivanje širine dijagonale korišćena je Jednačina 1. Kao što se može videti u Tabeli 3 λ_h vrednost je između 3.14 i 7.85, K_1 i K_2 su onda 0.707 i 0.010, što daje širinu dijagonale od 514.93 mm.

S obzirom na to što test pritiska u pravcu dijagonale zida nije sproveden eksperimentalno, nosivost zida na smicanje je određena prema Jednačini 12, uzimajući nosivost na pritisak, f'_m , da iznosi 3.1 N/mm². Nosivost horizontalne malterske spojnice na smicanje takođe je određena prema Jednačini 13:

$$\tau_{m0} = 0.285 \sqrt{f'_m} \quad (12)$$

$$\tau_0 = 2/3 \tau_{m0} = 0.211 \sqrt{f'_m} \quad (13)$$

Obe jednačine predložene su u [92] i daju nosivost od 0.707 MPa za τ_{m0} i 0.01 MPa za τ_0 .

Za određivanje nosivosti dijagonale na pritisak upotrebene su Jednačine 3–6 i rezultati su prikazni u Tabeli 4.

For the calculation of the strut width, Equation 1 was used. As seen in Table 3, for λ_h values in between 3.14 and 7.85, K_1 and K_2 are equal to 0.707 and 0.010 respectively, which gives the strut width equal 514.93 mm.

Since the diagonal compression test was not performed in the experiments, the masonry shear strength was calculated using Equation 12 with a compressive strength, f'_m , equal to 3.1 N/mm². The bed joint shear strength was also calculated, using Equation 13 as shown below:

Both equations are proposed by [92] and they derive 0.707 MPa for τ_{m0} and 0.01 MPa for τ_0 .

For calculating the compression failure stress of the strut Equations 3-6 were used and results are shown in the Table 4.

Tabela 4. Naponi nosivosti na pritisak
Table 4. Compression failure stresses

$\sigma_{br(1)}$	2.19	N/mm ²
$\sigma_{br(2)}$	6.72	N/mm ²
$\sigma_{br(3)}$	2.78	N/mm ²
$\sigma_{br(4)}$	4.29	N/mm ²

Minimalna vrednost, $\sigma_{br(1)}$, i Jednačina 7 daju minimalnu nosivost pritisnute dijagonale H_{mfc} u iznosu od 303.77kN.

Kako bi se dobilo zadovoljavajuće poklapanje rezultata, neke vrednosti su morale da se kalibriraju. Minimalna nosivost je smanjena na 45% dajući $H_{mfc} = 136.68$ kN. Linearna elastična sila H_{mf} je uzeta kao 80% od H_{mfc} a H_{mr} kao 87.5% od H_{mfc} . Za određivanje elastične krutosti, K_0 (Jednačina 8), elastična krutost okvira, K_{i0} (Jednačina 9), i krutost ispune pri maksimalnoj nosivosti, K_{mfc} (Jednačina 11), iskorišćeni su za dobijanje $K_0 = 299.8$ kN/mm. Takođe, predložena je modifikacija za elastičnu krutost i krutost ispune uzimajući samo 15% vrednosti, čime je dobijeno $K_{mfc} = 13.04$ kN/mm. A za elastičnu krutost je uzeto 60% od vrednosti dajući $K_0 = 63.34$ kN/mm. Završna grana definisana sa K_{mr} uzeta je kao negativna krutost u iznosu od 35% krutosti ispune.

Slika 13 pokazuje rezultate dobijene numeričkim modelom i eksperimentalno. Može se uočiti dobro poklapanje krutosti i maksimalne nosivosti. Ovo pokazuje uspešnost kalibracije i validnost modela okvira sa ispunom.

The minimum value, $\sigma_{br(1)}$, and Equation 7 derive the minimum lateral strength H_{mfc} having the value of 303.77kN.

In order to match the experimental results better, some values had to be calibrated. The minimum lateral strength was considered to be only 45% of the lateral strength previously calculated, obtaining $H_{mfc} = 136.68$ kN. The linear elastic force H_{mf} was assumed as 80% of H_{mfc} and H_{mr} as 87.5% of H_{mfc} . For the calculation of the elastic stiffness, K_0 (Equation 8), the elastic stiffness of the frame, K_{i0} (Equation 9), and the infill wall stiffness when it is completely cracked, K_{mfc} (Equation 11), were used obtaining $K_0 = 299.8$ kN/mm. Also a modification is proposed for the elastic stiffness and the infill stiffness taking only 15% of the infill stiffness, giving a value of $K_{mfc} = 13.04$ kN/mm, and 60% of the elastic stiffness, giving a value of $K_0 = 63.34$ kN/mm. The final branch defined with K_{mr} is considered to have negative slope equal to 35% of the infill stiffness.

Figure 13 shows the results obtained with the numerical model and experimental test. A good matching of stiffness and maximal load capacity can be seen. This demonstrates a good calibration and validates the infill frame model.

Slika 13. Poređenje pushover krive dobijene numerički i anvelope eksperimentalne histerezisne krive za okvir s tradicionalnom ispunom

Figure 13. Comparison between pushover curve from numerical model and the envelope of experimental hysteresis for traditionally infilled frame

Za definisanje histerezisnog modela ispune izabran je pivot model. Ovaj model podešava uzlaznu i silaznu granu parametrima α_1 , α_2 , β_1 i β_2 . Uzlazna grana podešava se parametrom α dok β parametar podešava silaznu granu. S obzirom na to što nosivost ispune na zatezanje nije uzeta u obzir, parametri α_1 i β_1 su 0, dok α_2 ima vrednost 5 [83]. Rezultati dinamičke nelinearne analize prikazani na slici 14 pokazuju dobro poklapanje numeričkih rezultata (crveno) i eksperimentalnih rezultata (plava), potvrđujući time validnost korišćenja numeričkog modela za dinamičku nelinearnu analizu.

For the definition of the hysteresis model for the infill wall a pivot model was chosen. This model is defined by adjusting the loading and unloading branches, with the parameters α_1 , α_2 , β_1 and β_2 . The α parameters adjust the unloading zone while the β parameters adjust the loading zone. Since the tension strength of the infill panel is unconsidered, parameters α_1 and β_1 are set to 0, while α_2 is set to 5 [83]. Results of the time history analysis in Figure 14 show a good resemblance between the numerical results (red) and the experimental results (blue), confirming the validity of using the model for nonlinear time history analysis.

Slika 14. Poređenje rezultata dinamičke nelinearne analize dobijene numeričkim modelom i eksperimentalno dobijene histerezisne krive za okvir s tradicionalnom ispunom

Figure 14. Comparison between the numerical model time history results and the experimental hysteresis of the traditionally infilled frame

4.3 AB okvir sa izolovanom ispunom

Kako bi se uzelo u obzir razdvajanje ispune od okvira primenom elastomera u sistemu INODIS, nelinearni link element je dodat u uglove zidnog panela povezujući dijagonale sa okvirom (slika 8). Koristeći širinu dijagonale ispune (ω) i njen ugao Θ , kontaktna dužina između pritisnute dijagonale i stuba, L_c , i grede, L_b , jeste određena:

$$L_c = \omega \cos \theta = 380.89 \text{ mm} \quad (14)$$

$$L_b = \omega \sin \theta = 346.51 \text{ mm} \quad (15)$$

4.3 RC frame with decoupled infills

In order to take into account decoupling with the elastomers that are applied in the INODIS system, nonlinear link elements are added to the corners of the infill panel connecting the diagonal links with the frame (Figure 8). Using the strut width of the infill (ω) and its angle Θ , contact length between the diagonal strut and the column, L_c , and beam, L_b , are determined:

Uzimajući širinu elastomera od 250 mm, kontaktna površina je određena kao $A_c = 95222.52 \text{ mm}^2$ i $A_b = 86628.43 \text{ mm}^2$.

Debljina elastomera do stuba je 37.5 mm a za grede 25 mm. Koristeći ove podatke, krive sila–pomeranje su definisane (slika 15) i zadate link-elementima koji predstavljaju elastomer. Takeda model je korišćen za definiciju histerezisnog modela za elastomere. Ovo je najjednostavniji histerezisni model jer ne zahteva definiciju nijednog parametra.

Using the width of the elastomers of 250 mm, the contact area is calculated giving a value of $A_c = 95222.52 \text{ mm}^2$ and $A_b = 86628.43 \text{ mm}^2$.

Thickness of the column elastomers is of 37.5mm and for the beams 25 mm. Using this data, the force-displacement curves were defined (Figure 15) and assigned to the links presenting the elastomers. The Takeda model was used for the definition of the hysteretic model for the elastomers. This is the simplest model as it does not require definition of any parameter.

Slika 15. Krive sila–pomeranje primenjene za definiciju ponašanja link-elemenata koji predstavljaju elastomere
Figure 15. Force-displacement curves applied to the links presenting elastomers

Test na okviru sa izolovanom ispunom, izloženom opterećenju u ravni upotrebljen je za validaciju numeričkog modela i rezultati (slika 16) pokazuju dobro poklapanje. Rezultati dinamičke nelinearne analize (*time history*) za test opterećenja u ravni (slika 17) i za kombinovano opterećenje u ravni i van ravni zida (slika 18) pokazuju takođe dobro poklapanje, sa blago užim histerezisnim petljama u poređenju sa eksperimentalnim. Ovo takođe potvrđuje da ponašanje u ravni ispunje nije u zavisnosti sa opterećenjem van ravni u slučaju kada je primenjena izolacija ispunje od okvira.

Nakon validacije sva tri modela uz pomoć eksperimentalnih rezultata, moguće je analizirati uticaj izolacije ispunje na ponašanje višespratnih zgrada uz pomoć dvodimenzionalnih i trodimenzionalnih modela s različitim konfiguracijama ispunje.

In-plane test on the decoupled infilled frame was used for validation of the numerical model and results (Figure 16) show a good resemblance between the numerical model (red) and the experimental results (blue). The time history results for the pure in-plane test (Figure 17) and for the combined in-plane and out-of-plane loading phase (Figure 18) show a good matching as well, with slightly narrower loops compared with the experimental ones. This also confirms that in-plane behaviour is independent on the out-of-plane load when decoupling is applied.

After validating all three models with the experimental results, it is possible to study and analyse the influence of decoupling on the behaviour of multi storey buildings in two and three dimensions with different configurations of infill walls

Slika 16. Kriva dobijena statičkom nelinearnom analizom (pushover) i kriva koja predstavlja anvelopu eksperimentalno dobijene histerezisne krive za okvir sa izolovanom ispunom

Figure 16. Pushover curve of the numerical model and experimental hysteresis envelope for the infilled frame with elastomers

Slika 17. Poređenje rezultata numeričkog modela i eksperimentalno dobijene histerezisne krive za okvir sa izolovanom ispunom pri opterećenju u ravni

Figure 17. Comparison between the numerical model time history results and the experimental hysteresis of the infilled frame with elastomers for pure in-plane loading

Slika 18. Poređenje rezultata numeričkog modela i eksperimentalno dobijene histerezisne krive za okvir sa izolovanom ispunom pri kombinaciji opterećenja u ravni i van ravni

Figure 18. Comparison between the numerical model time history results and the experimental hysteresis of the infilled frame with elastomers for combined in-plane and out-of-plane loading

5 ANALIZA 2D OKVIRA KONSTRUKCIJE

Nakon validacije numeričkih modela, korišćenjem eksperimentalnih rezultata, mogu se sprovesti naredne analize ponašanja AB okvirnih konstrukcija sa izolovanom ispunom. Dvodimenzionalni okvir konstrukcije analiziran je primenom statičke nelinearne analize i dinamičke nelinearne analize. Kako bi se modelirao okvir konstrukcije s više spratova i brodova, prethodno validirani numerički modeli jednospratnih i jednobrodnih okvira multiplicirani su u visinu i širinu. Svi poprečni presezi i karakteristike greda, stubova, ispune i elastomera zadržani su isti.

U tu svrhu, analizirana je višespratnica srednje visine (M) koja ima šest spratova. Primenjujući pristup iz [93], analizirane su različite konfiguracije ispune uključujući: prazan okvir, okvir sasvim popunjen ispunom, okvir sa otvorenim prizemljem i okvir s delimično otvorenim prizemljem. U svim ovim konfiguracijama, i tradicionalna i izolovana ispuna je ispitana. To znači da je sedam različitih konfiguracija analizirano (slika 19) – prazan okvir (1); okvir sasvim popunjen tradicionalnom ispunom i sa INODIS sistemom (2 i 5); okvir s delimično otvorenim prizemljem, popunjen tradicionalnom ispunom i sa INODIS sistemom (3 i 6) i okvir sa otvorenim prizemljem, popunjen tradicionalnom ispunom i sa INODIS sistemom (4 i 7).

5 ANALYSIS OF 2D STRUCTURAL FRAMES

After validating numerical models using experimental results further analysis of the behaviour of RC frame structures with decoupled infills can be done. Two dimensional structural frames were analysed using pushover and dynamic time-history analysis. In order to model structural frames with several floors and bays, the previously validated models of one-bay and one-storey frame were multiplied in height and width. All cross-section and properties of beams, columns, infills and elastomers were kept the same.

For this purpose a medium (M) rise six story building was analysed. Following the approach by [93], different infill configurations were studied including: bare frame, fully infilled frame, open ground storey frame and partially open ground storey frame. For all these configurations, both traditional and decoupling approaches were studied. That means seven different configurations were analysed (Figure 19) - bare frame (1); fully infilled frame with traditional infill and INODIS system (2 and 5, respectively); partially open ground storey frame with traditional infill and INODIS system (3 with traditional infill and 6 with the INODIS system); and open ground storey frame with traditional infill and INODIS system (4 and 7, respectively).

Dodatno opterećenje je uzeto u obzir u iznosu od 2.0 kN/m² za slojeve podova i pregradne zidove i 2.0 kN/m² za korisno opterećenje. Sopstvena težina konstrukcije uzeta je u obzir u samom numeričkom modelu. Za težinu ispune uzeto je linijsko opterećenje u iznosu od 6.0 kN/m.

Additional loads were considered taken as 2.0 kN/m² for floor finishes and partitions and 2.0 kN/m² for the live load. The self-weight of the structure is taken into account in the numerical model. For the weight of the infills, a line load of 6.0 kN/m was used.

Slika 19. Dispozicija zidova ispune u zgradi srednje visine [93]
Figure 19. Disposition of infill walls for medium rise building [93]

5.1 Tipovi analize

Prvo je sprovedena modalna analiza kako bi se uporedile dinamičke karakteristike različitih konfiguracija i proverio uticaj zidova ispune na okvir konstrukcije. Nakon toga, statička nelinearna analiza (*pushover*) upotrebljena je da se dobije kapacitet sila-pomeranje i ukupne smičuće sile. Na kraju je sprovedena nelinearna dinamička analiza (*time history*) kako bi se poredila apsolutna pomeranja i relativno međuspratno pomeranje. Akcelerogrami korišćeni u nelinearnoj dinamičkoj analizi veštački su generisani na osnovu linearnog spektra Tipa 1 datog u Evrokodu [31], sa uslovima tla B, i za dva nivoa ubrzanja PGA=0.1g i PGA=0.3g, korišćenjem relativnog prigušenja u iznosu od 5%. Generisanje akcelerograma sprovedeno je uz pomoć softverskog paketa SeismoArtif [94] uz korak od 256 Hz i ukupno trajanje od 25s s korekcijom osnovne funkcije. Slika 20 prikazuje spektar odgovora za ubrzanje PGA=0.3g i odgovarajući akcelerogram.

5.1 Types of analysis

First, a modal analysis was performed to compare the dynamic characteristics of different configurations and check the influence of the infill walls on the structural frame. Then static nonlinear (*pushover*) analysis is used to check force-displacement capacity and base shear forces. At last, nonlinear time history analysis is employed to compare the displacements and inter storey drifts. Accelerogram used in time history analysis is generated artificially based on a Eurocode 8 [31] linear elastic response spectrum Type 1, with soil condition B, for two different PGA values, PGA=0.1g and PGA=0.3g, and damping ratio of 5%. Generation of accelerogram is done using software SeismoArtif [94] with the sampling rate of 256 Hz and total duration of 25s with the base line correction. Figure 20 shows response spectrum for PGA=0.3g and corresponding accelerogram.

Slika 20. a) Spektar odgovora i b) akcelerogram za PGA=0.3g
Figure 20. a) Response spectrum and b) time history signal for PGA=0.

5.2 Rezultati za 2D okvire konstrukcije

Slika 21 pokazuje sopstvene periode za prva tri tona za sve konfiguracije. Iz poređenja praznog okvira i okvira s tradicionalnom ispunom može se uočiti značajan pad, oko četiri puta, u sopstvenim periodima konstrukcije od 1.2 s za prazan okvir na 0.33 s za okvir s tradicionalnom ispunom. Malo manji efekat smanjenja je kod konfiguracije sa otvorenim prizemljem, ali je i tu smanjenje perioda dva puta. S druge strane, smanjenje perioda u slučaju okvira sa izolovanom ispunom u odnosu na prazan okvir je mnogo manje. Sasvim popunjen ram sa izolovanom ispunom ima osnovni period 0.95 s, što predstavlja umanjeње od 21%. Ta razlika je još manja u slučaju okvira s delimično ili potpuno otvorenim prizemljem i iznosi 17%.

Slika 21. Sopstveni periodi za prvi, drugi i treći ton za različite konfiguracije
Figure 21. Natural periods of the first, second and third mode for different configurations

Kada se postave periodi na krivu spektra odgovora (Slika 22), može se videti jasna razlika između praznog okvira (plava boja) i okvira s tradicionalnom ispunom (crvena boja), pokazujući značajno potcenjivanje nivoa seizmičkog opterećenja ukoliko ispuna nije uzeta u obzir u toku proračuna. Period okvira s tradicionalnom ispunom nalazi se na platou spektralnog ubrzanja imajući skoro tri puta veće opterećenje od praznog okvira. Kod okvira sa izolovanom ispunom (zeleni), ne samo da su im periodi blizu za sve tri konfiguracije već su i blizu perioda praznog okvira. Razlika u nivou seizmičkog opterećenja manja je od 12%, što pokazuje da se model praznog okvira može koristiti za projektovanje AB okvira sa izolovanom zidanom ispunom.

Okvir s tradicionalnom ispunom (crvena) aktivira ukupnu horizontalnu silu (Slika 23) skoro dva puta veću od praznog okvira. Ova horizontalna sila dostiže se mnogo ranije u odnosu na sistem sa izolovanom ispunom. Bitno je napomenuti da postoji značajno smanjenje sile u slučaju okvira s tradicionalnom ispunom i otvorenim prizemljem, dok to nije slučaj za okvir sa izolovanom ispunom. Ali je ta sila malo veća od sile za prazan okvir.

5.2 Results for 2D structural frames

Figure 21 shows fundamental periods for the first three modes for all configurations studied. Comparing the bare frame and the traditionally infilled, it can be seen a significant drop in natural period from the bare frame to the other configurations. Looking at the first natural period natural period being 1.20s for the bare frame and 0.33s for the frame with traditional infills, a four times reduction can be seen. Slightly lower effect is for open ground configuration, but again being almost twice smaller. On the other hand, the reduction on the natural period of the frames with decoupled infills with respect to the bare frame is much lower. The fully infilled frame with decoupling system gave a natural period of 0.95s. This represents a reduction of 21%. This is even lower for partially open ground and open ground where difference is 17%.

When locating the periods on the response spectrum curve (Figure 22), it can be seen a clear difference between the bare frame (blue) and the traditionally infilled frames (red), showing significant underestimation of the seismic load if infill walls are not taken into account during the design. Traditional infills fall into the plateau with the spectral acceleration almost three times higher than for bare frame. For the frames with decoupled infills instead (green), not only the periods remain close in between each other, but also are much closer to the ones of the bare frame. The difference in the seismic load level is less than 12%, showing that bare frame model can be used for the design of RC frames with decoupled infill walls.

The traditionally infilled structural frame (red) activates base shear (Figure 23) almost double than the bare frame (blue). This base shear, however is achieved at a much earlier stage compared to the decoupled system. It is important to notice significant reduction in base shear force in the case of open ground story of traditionally infilled frame whereas for the case of decoupled frame there is no significant change in the base shear force level. However it is slightly higher than for the bare frame.

a)

b)

Slika 22. Prvi period oscilovanja na spektru odgovora za a) $PGA=0.1g$ and b) $PGA=0.3g$
Figure 22. First natural periods on the response spectrum curves for a) $PGA=0.1g$ and b) $PGA=0.3g$

Slika 23. Krive dobijene pushover analizom
Figure 23. Pushover analysis curves

Relativno međuspratno pomeranje okvira s tradicionalnom ispunom i otvorenim prizemljem pokazuje pojavu fleksibilnog sprata (slika 24). Gledajući u rezultate nelinearne dinamičke analize za $PGA=0.1g$ maksimalno relativno međuspratno pomeranje na prvom nivou je 0.93%. Uočava se da postoji značajan skok na prelazu prvog i drugog nivoa, na kome dolazi do pada relativnog međuspratnog pomeranja na 0.07% i 0.04%. Za $PGA=0.3g$ okvir sasvim popunjen tradicionalnom ispunom i sa otvorenim prizemljem ima relativno međuspratno pomeranje 0.15% i 0.11% na prvom i drugom spratu, ostajući u granicama malih vrednosti i na višim spratovima; dok se 3.85% relativnog međuspratnog pomeranja javilo u prizemlju. Ovo relativno međuspratno pomeranje tri puta je veće u odnosu na ono za slučaj delimično ispunjenog prizemlja i četiri puta veće od sasvim popunjenog okvira.

Kao što je i očekivano, usled povećanja krutosti, uzrokovanog zidanom ispunom, pomeranje poslednjeg sprata okvira s tradicionalnom ispunom je značajno manje od ostalih okvira. Takođe, u slučaju oba sistema uočava se povećanje apsolutnog pomeranja kako se broj zidova ispune smanjuje u prizemlju. Za slučaj tradicionalne ispune, za delimično ili potpuno otvoreno prizemlje, apsolutna pomeranja su 0.307 m i 0.351m, dok su ona za izolovanu ispunu 0.616 m i 0.635 m. Isto ponašanje je za oba nivoa ubrzanja. Uočava se da su za okvire s tradicionalnom ispunom, apsolutna pomeranja nekoliko puta manja od praznih okvira i okvira sa izolovanom ispunom. Ovo jeste slučaj za konfiguraciju s delimično otvorenim prizemljem ili sa sasvim popunjenom ispunom.

The inter storey drifts of the fully open ground storey for frame with traditional infills, show that a soft storey behaviour occurred (Figure 24). Looking at the results of the nonlinear time history analysis for $PGA=0.1g$ the maximum inter story drift at the first level is 0.93%. It can be observed that for the first floor and second floor, there was a significant and abrupt reduction in the drift, 0.07% and 0.04%. For $PGA=0.3g$ fully open ground storey frame with traditional infills had inter storey drift of 0.15% and 0.11% at first and second floor, remaining small and almost constant for the rest of the floors; whereas 3.85% of drift occurred at the ground floor. This drift is three times higher than for the case of partially open ground floor and four times higher than fully infilled frame.

As it was expected due to the increase in stiffness caused by the infill walls, the top floor displacement of the frames with traditional infills are significantly lower than for the other frames. Also for both systems, it can be noticed an increase in absolute displacements as the amount of infilled frames in the ground floor is reduced. For the traditional infill, for the partial and fully open ground floor the absolute displacements were 0.307m and 0.351m, respectively; while with the decoupling system, they were 0.616m and 0.635m respectively. The same behaviour can be seen for both PGA levels. It can be observed that for the traditional infilled systems, the absolute displacements are several times smaller than the bare frame and the decoupled system. This is true for the structural frame fully infilled with traditional infills and also for the partially open ground floor configuration. However, fully open ground floor configuration with

Ali za potpuno otvoreno prizemlje s tradicionalnom ispunom, apsolutna pomeranja u prizemlju su najveća. Apsolutna pomeranja okvira sa izolovanom ispunom nalaze se između pomeranja za prazan okvir i okvir s tradicionalnom ispunom, ali su bliža pomeranjima praznog okvira.

S druge strane, u slučaju sa izolovanim ispunama, postoji ujednačen prelaz u relativnim međuspratnim pomeranjima između spratova, gde je najveća vrednost u prizemlju a najmanja na poslednjem spratu. Ono što je još bitnije jeste da je za sve konfiguracije sa izolovanom zidanom ispunom nelinearna dinamička analiza kao rezultat dala relativna međuspratna pomeranja bliska onima kod praznog okvira. Pored toga, efekat fleksibilnog sprata se nije javio u slučaju okvira sa izolovanom ispunom niti postoji nagli prelaz u vrednostima relativnog međuspratnog pomeranja između spratova.

traditional infills experienced highest displacement in the ground floor. The displacements of the decoupled frame fall in between the displacements of the bare frame and the traditional one, but they resemble more and are closer to the values of the bare frames.

On the contrary, for the decoupling system, there is a smooth reduction of inter storey drift from its maximum along the first floors up to its minimum at the top floor. What is more important is that all infill configurations for nonlinear time history analysis, frames with decoupled infills had drifts in a range of bare frame model distributed in the same manner along the frame height. Furthermore, soft storey effect is absent in the case of decoupled infills and there is no sudden increase of drift between the floors.

Slika 24. Rezultati nelinearne dinamičke analize za svaki sprat: a) maksimalna apsolutna pomeranja (za $PGA=0.1g$); b) maksimalna relativna međuspratna pomeranja (za $PGA=0.1g$); c) maksimalna apsolutna pomeranja (za $PGA=0.3g$) i d) maksimalna relativna međuspratna pomeranja (za $PGA=0.3g$)

Figure 24. Nonlinear time history results at each storey: a) max absolute displacement (for a $PGA=0.1g$); b) max inter storey drift (for a $PGA=0.1g$); c) max absolute displacement (for a $PGA=0.3g$) and d) max inter storey drift (for a $PGA=0.3g$)

6 ANALIZA 3D ZGRADE

Za trodimenzionalnu zgradu, analizirane su tri konfiguracije zidane ispune, pored praznog okvira (slika 25a). Analizirana je petospratnica s tri polja u poprečnom pravcu i pet polja u podužnom pravcu. U prvoj konfiguraciji zidana ispunjena se nalazi samo u spoljašnjim okvirima praveći tako jezgro od ispune (slika 25b). Druga konfiguracija predstavlja zgradu lociranu na uglu ulice koja sa te dve strane nema ispunu a sasvim su popunjeni okviri s druge dve strane (slika 25c). Ova konfiguracija je uobičajena u praksi i bitno je da se analizira jer nesimetričan raspored zidane ispune dovodi do nepoklapanja centra mase i centra krutosti što dovodi do pojave torzije cele zgrade. Kao što je navedeno u uvodu, analiza efekata fleksibilnog prizemlja takođe je jako bitna zbog prakse da se zidana ispunjena ukloni iz nivoa prizemlja zbog funkcionalnih zahteva za garaže i radnje. Prema tome, ova konfiguracija je takođe analizirana (slika 25d). Sve konfiguracije su analizirane za slučaj s tradicionalnom ispunom i sa izolovanom ispunom. Analizirani modeli su: Model br. 1: Zgrada s praznim AB okvirima; Model br. 2: zgrada sa okvirima sa sasvim punom tradicionalnom ispunom; Model br. 3: zgrada na uglu s tradicionalnom ispunom; Model br. 4: zgrada sa otvorenim prizemljem s tradicionalnom ispunom; Model br. 5: zgrada sa ovirima sa sasvim punom izolovanom ispunom; Model br. 6: zgrada na uglu sa izolovanom ispunom; Model br. 7: zgrada sa otvorenim prizemljem sa izolovanom ispunom; i Modeli 8, 9 i 10 koji su kao Modeli 5, 6 i 7, samo bez elemenata na dijagonali, koji predstavljaju zidanu ispunu. Umesto toga, oni imaju samo masu predstavljenu kao linijsko opterećenje na poziciji zidova ispune. Poslednje tri konfiguracije su bitne kako bi se istražio potencijal upotrebe modela praznog okvira za proračun AB zgrada sa izolovanom zidanom ispunom. Ploča je modelirana s debljinom 0.2 m i opterećenja prethodno definisana za 2D okvire konstrukcije takođe su uzeta u obzir. Dispozicija u osnovi kao i raspored zidane ispune prikazan je na slici 26.

a)

b)

6 ANALYSIS OF A 3D BUILDING

For the three-dimensional building, three infill configurations were studied, besides a bare frame (Figure 25a). A five-storey high building consisting of 3 bays in the transversal direction and 5 bays in the longitudinal direction was analysed. In the first configuration infills are located in the most outer frames creating an infill core (Figure 25b). Second configuration represents the buildings located in a corner where two adjacent sides are without infill walls, whereas the other two are infilled (Figure 25c). This configuration is common in practice and important to be studied because if the walls are not symmetrically placed along the whole plan of the building, the position of the centre of stiffness and mass could be mismatch creating a torsional effect on the building. As discussed in introduction, the study of the soft storey mechanism is important due to the common practice to remove infill walls in the ground storey because of the functional requirement for shops or garages. Therefore, this configuration is also investigated (Figure 25d). All configurations were studied for the case of traditional infills and decoupled infills. The models analysed were: Model No. 1: bare frame building; Model No. 2: fully traditionally infilled frames; Model No. 3: corner building with traditionally infilled frames; Model No. 4: open ground floor with traditionally infilled frames; Model No. 5: fully infilled frame building with decoupled system; Model No. 6: corner building with decoupled infill system; Model No. 7: open ground floor building with decoupled infills; and Models 8, 9 and 10 made as Models 5, 6 and 7 just without struts presenting decoupled infill walls. Instead they have just mass at the position of infill walls assigned as line loads. Last three configurations are important to investigate the potential of the use of bare frame model for the design of RC buildings with decoupled infill walls. The slab was modelled with a 0.20m thickness and the loads previously defined for 2D structural frames were also taken into account. Ground plan configuration and distribution of infills is given on Figure 26.

c)

d)

Slika 25. a) zgrada s praznim okvirima; b) zgrada sa okvirima sa sasvim punom ispunom; c) zgrada na uglu; i d) zgrada sa otvorenim prizemljem

Figure 25. a) bare frame building; b) fully infilled frames; c) corner building; and d) open ground floor building

a)

b)

c)

Slika 26. Prikaz osnove: a) prazni okviri i zgrada sa otvorenim prizemljem; b) okviri sasvim popunjeni ispunom; i c) zgrada na uglu

Figure 26. Ground plan of: a) bare frame and open ground floor building; b) fully infilled frames; and c) corner

6.1 Tipovi analize

Za 3D model zgrade, korišćene su iste analize (modalna, *pushover* i nelinearna dinamička) kao za 2D okvire konstrukcije. Za nelinearnu dinamičku analizu (*time history*) veštački generisani akceleroگرامи korišćeni za analizu 2D okvira konstrukcije i ovde su upotrebljeni.

6.2 Rezultati za 3D zgradu

Krenuvši od modalne analize, može se uočiti da zgrade s tradicionalnom zidanom ispunom imaju značajno veću krutost u poređenju sa zgradama sa izolovanom ispunom. Rezultati (slika 27) pokazuju da zgrada sa sasvim popunjenom tradicionalnom ispunom ima dva puta manji prvi period oscilovanja u odnosu na zgradu s praznim okvirima. Za razliku od njih, zgrade sa izolovanom ispunom imaju periode koji su samo 6% manji. Za njih su takođe i druga dva perioda beznačajno manja za 10 i 14%. Suprotno od njih, zgrade s tradicionalnom ispunom imaju periode manje za 62 i 69% za drugi i treći ton. Ova razlika je manja za zgradu na uglu i zgradu sa otvorenim prizemljem, dok je za zgrade sa izolovanom ispunom period skoro isti za sve tri konfiguracije. Ono što je još važnije jeste da zgrade s masom koja predstavlja izolovanu ispunu imaju iste periode kao one s dijagonalnim elementima koji predstavljaju izolovanu ispunu.

6.1 Types of analysis

For the 3D building model, the same analyses (modal, pushover and nonlinear time history) as for 2D structural frames were used. Artificial accelerograms created for 2D structural frames are also used for the nonlinear time history calculations.

6.2 Results for 3D building

Starting from the modal analysis, it can be observed that the building which uses a traditional infills, presents a much stiffer behaviour in comparison with the one with decoupled infills. From the results (Figure 27), the completely infilled building with traditional infills has a two times smaller first period with respect to the bare frame building. Instead, for the building fully infilled with the decoupled walls, the reduction was of only 6% for the first period. For this building with decoupling system, the other two periods also presented a lower decrease in the period, with 10% and 14% representing the second and third mode period, respectively. In contrast, the traditional infilled system had a reduction of 62% and 69% of the second and third mode period. This difference is slightly smaller in the case of corner and open ground building for traditional infill, whereas it is almost the same for the decoupled infills in all three configurations. What is even more important that the buildings with the mass presenting decoupled infills have almost the same periods as the one with struts used for decoupled infills.

Slika 27. Sopstveni periodi za prvi, drugi i treći ton za različite konfiguracije
Figure 27. Natural periods of the first, second and third mode for different configurations

a)

b)

Slika 28. Prvi ton oscilovanja 3D zgrade na spektru odgovora za a) $PGA=0.1g$ i b) $PGA=0.3g$
Figure 28. First natural periods of a 3D buildings on the response spectrum curves for a) $PGA=0.1g$ and b) $PGA=0.3g$

Kada se periodi postave na spektar odgovora (slika 28), može se videti da zgrada sa izolovanom ispunom ima nivo opterećenja koji je blizak za sve konfiguracije, i on je blizak i s vrednošću za zgradu s praznim okvirima. S druge strane, zgrade s tradicionalnom ispunom nalaze se na platou spektra odgovora, daleko od vrednosti koja odgovara zgradi s praznim okvirima. Ukoliko se zgrade s tradicionalnom ispunom projektuju prema modelima praznih okvira, slično kao i za 2D okvire, potcenjuje se nivo spektralnog ubrzanja za više od 50%, dok je za zgrade sa izolovanom ispunom ta razlika zanemarljiva (manja od 10%). Rezultati pokazuju da se AB okvirne zgrade sa izolovanom ispunom, kada je ona predstavljena samo preko mase prikazane linijskim opterećenjem, poklapaju s nivoom seizmičkog opterećenja sa zgradama u kojima je ispun modelirana pritisnutim dijagonalama. Stoga, jednostavan model s praznim okvirima s masom umesto pritisnutih dijagonala može biti iskorišćen za projektovanje AB ramovskih konstrukcija sa izolovanom ispunom.

Faktori participacije (slika 29) na najbolji način prikazuju efekat neujednačenog rasporeda tradicionalne ispune na slučaju zgrade na uglu. Od svih konfiguracija, jedino zgrada s tradicionalnom ispunom ima u odgovoru kombinaciju tonova. Zgrada na uglu s tradicionalnom ispunom ima 40% participacije torzionog tona u odgovoru konstrukcije. Suprotno od toga, zgrada sa izolovanom ispunom ima samo 0.5% participacije mase u rotaciji oko Z ose.

Slika 29. Faktori participacije za prvi ton za različite konfiguracije
Figure 29. Modal participation mass ratios for the first mode for different configurations

Slično rezultatima na 2D okvirima, zgrade s tradicionalnom ispunom aktiviraju najveće horizontalne sile i u X i u Y pravcu (slika 30). Tradicionalni sistem takođe pokazuje nagli pad sile kada se dostigne maksimalna nosivost nakon čega kriva prati krivu kapaciteta praznog okvira. Takođe, uklanjanje tradicionalne ispune iz prizemlja smanjuje maksimalnu silu koju konstrukcija može da prihvati za 50%. Zgrada sa otvorenim prizemljem i tradicionalnom ispunom dolazi do kapaciteta pri mnogo manjim deformacijama u odnosu na ostale konfiguracije. Suprotno od toga, zgrada sa izolovanom ispunom ponaša se skoro identično u svim konfiguracijama, bez pokazivanja naglog pada sile i dostižući mnogo veći kapacitet deformacije.

When the periods are located on the response spectrum curve (Figure 28), it can be seen that the buildings with the decoupling system are close together for all configurations, and also very close to the position of the bare frame period. On the other hand, it can be seen that the periods of the traditional infilled building are all located at the plateau of the response spectrum, far away from the bare frame. If buildings with traditional infills are designed with the bare frame model, similar to 2D structural frames, underestimation of the spectral acceleration would be more than 50%, whereas for the decoupled infills it is negligible (less than 10%). The results show that RC frame buildings where decoupled infills are taken into account as a line load presenting their mass match the seismic load level of the building with the struts presenting decoupled infills and bare frame building. Therefore, simple bare frame model with the mass instead of struts can be used for the design of RC frame buildings with decoupled infills.

The modal participation mass ratios (Figure 29) in the best way presents the effect of traditional infill irregular arrangement in the case of corner building. Only, the corner building with traditional infills had mixed modes. The traditional corner building presented a 40% of mass participation in the rotational Z direction in the first mode. In contrast, the corner building with the decoupled infills presented only a 0.5% mass participation in the rotational Z direction.

Similar to the results from the 2D frames, the traditionally infilled frame buildings activate higher maximum base shear force in both X and Y direction than the building with decoupled infills and bare frame building (Figure 30). The traditional system also experiences a fast or sudden drop in load when the maximum was reached followed by a curve that follows the capacity curve of the bare frame. It can also be noticed that removing traditional infill walls in the ground floor reduces by 50% the maximum base shear attained by the structure. Building with open ground floor with traditional infills has reached its deformation capacity much sooner than all other configurations. In contrast, buildings with decoupled infills behave almost the same for all configurations, not experiencing sudden drop in the base shear force and providing higher deformation capacity.

a)

b)

Slika 30. Pushover krive za zgradu za a) X pravac i b) Y pravac
Figure 30. Three-dimensional building pushover curves for a) X direction and b) Y direction

Rezultati nelinearne dinamičke analize (slike 31 i 32) pokazuju da zgrada s tradicionalnom ispunom ima generalno manja apsolutna pomeranja ali mnogo veće relativno međuspratno pomeranje, osim u slučaju otvorenog prizemlja. U ovoj konfiguraciji postoji ogromna razlika u relativnom međuspratnom pomeranju između prizemlja i prvog sprata. Ovo je više izraženo u Y pravcu a još više za slučaj ubrzanja $PGA = 0.3g$, dok je u X pravcu promena relativnog međuspratnog pomeranja postepena ali ponovo sa značajno većom promenom nego u ostalim konfiguracijama. Za zgradu na uglu s tradicionalnom ispunom, slično ponašanje se može uočiti ali s manjim relativnim međuspratnim pomeranjem u prizemlju.

Što se tiče konfiguracija sa izolovanom ispunom, apsolutna pomeranja za sasvim pune okvire, zgradu na uglu i zgradu sa otvorenim prizemljem u granicama su vrednosti zgrade s praznim okvirima. Pojava fleksibilnog sprata nije prisutna ni u jednoj od konfiguracija sa izolovanom ispunom. Ovo je značajno unapređivanje koje dolazi kao rezultat toga da izolacija ispunne uklanja efekat povećanja krutosti usled zidova ispunne i usled toga nema skokova u nivou krutosti između različitih spratova.

Results of nonlinear time history analyses (Figure 31 and 32) show that buildings with traditional infills have in overall a lower absolute displacements and a much smaller inter storey drift, except for the case of the open ground configuration. For this situation huge difference in the inter storey drift between ground floor and first floor can be seen. This is more pronounced in Y direction and even higher for the case of $PGA = 0.3g$, whereas in X direction the change in inter storey drift is much smoother but with a noticeable higher change in the values compared with the rest of the models. For the corner building with traditional infills, a similar behaviour can be seen but with a smaller inter storey drifts in the ground floor.

For the decoupled infills, the absolute displacements for the fully infilled building, the corner building and the open ground floor building are in the range of the values of the bare frame model. The soft story effect cannot be observed in any of the configurations having decoupled infills. This is significant improvement coming from the decoupling measure that diminishes increase of stiffness coming from the infill walls and thus there are no jumps in stiffness between the floors.

a)

b)

Slika 31. Rezultati nelinearne dinamičke analize za $PGA=0.1g$: a) maksimalna apsolutna pomeranja i b) maksimalno relativno međuspratno pomeranje u X pravcu i c) maksimalna apsolutna pomeranja i d) maksimalno relativno međuspratno pomeranje u Y pravcu

Figure 31. Nonlinear time history results for $PGA=0.1g$: a) max absolute displacements and b) max inter storey drift along X direction and c) max absolute displacements and d) max inter storey drift along Y direction

Usled nejednakog rasporeda ispune u slučaju zgrade na uglu, interesantno je analizirati rezultate u pravcu upravno na pravac nanetog opterećenja. Za tradicionalnu ispunu, nejednačen raspored apsolutnih pomeranja i relativnog međuspratnog pomeranja može se uočiti u ovom slučaju. Ovi uticaji koji dolaze od aktiviranja torzionog ponašanja zgrade nisu prisutni u zgradi sa izolovanom ispunom, čime pokazuju da se izolovanje ispune može koristiti kao mera za rešavanje problema torzije u slučaju nejednakog rasporeda zidane ispune, posebno kod zgrada na uglu.

Due to the irregular distribution of the infill walls in the corner building configuration, it is interesting to analyse the results in the perpendicular direction of the applied load. For the traditional infill, a prominent and uneven distribution of absolute displacements and inter storey drift can be observed in this case. These effects coming from the activation of the torsional displacements are absent in the case of buildings with decoupled infill walls, showing that decoupling can be used as measure to solve torsional problems in the case of irregular distribution of infill walls, specifically corner building.

Slika 32. Rezultati nelinearne dinamičke analize za $PGA=0.3g$: a) maksimalna apsolutna pomeranja i b) maksimalno relativno međuspratno pomeranje u X pravcu i c) maksimalna apsolutna pomeranja i d) maksimalno relativno međuspratno pomeranje u Y pravcu

Figure 32. Nonlinear time history results for $PGA=0.3g$: a) max absolute displacements and b) max inter storey drift along X direction and c) max absolute displacements and d) max inter storey drift along Y direction

7 ZAKLJUČAK

Ovaj rad predstavlja istraživanje ponašanja AB okvirnih zgrada sa izolovanom ispunom. Istraživanje je sprovedeno kako bi se ispitao uticaj izolacije ispune na nivou zgrade. Kao rešenje za izolaciju ispune korišćen je sistem INODIS. On pruža izolaciju u ravni i stabilnu vezu za opterećenje van ravni. S obzirom na to što pristup izolacije omogućava da se opterećenje u ravni i van ravni mogu razmatrati razdvojeno, za razliku od tradicionalne ispune, fokus istraživanja je ponašanje zidane ispune u ravni.

Prvo je sprovedena kalibracija i validacija numeričkih modela na jednospratnim okvirima s jednim brodom, koji su prethodno ispitani eksperimentalno. Zatim su analizirani 2D okviri s različitim rasporedom ispune. Tri različite konfiguracije koje su istraživane su: sasvim ispunjen okvir, okvir s delimično praznim prizemljem i okvir sa otvorenim prizemljem i njihovo ponašanje je poređeno s praznim okvirom. Za sve ove konfiguracije su istražene i tradicionalna i izolovana ispuna. Rezultati pokazuju da tradicionalna ispuna značajno smanjuje sopstvene periode okvira, i time značajno menja nivo seizmičkog opterećenja koje deluje na konstrukciju. To nije slučaj sa izolovanom ispunom, gde je promena perioda beznačajna. Krive sila-pomeranje dobijene pushover analizom potvrđuju nizak kapacitet deformacije okvira s tradicionalnom ispunom u poređenju s praznim okvirima i okvirima sa izolovanom ispunom. Nelinearna dinamička analiza je na najbolji način pokazala negativne efekte tradicionalne ispune na ponašanje okvira. U slučaju otvorenog prizemlja veliki skok u relativnom međuspratnom pomeranju javlja se u prizemlju u odnosu na ostale spratove. Suprotno od toga, AB okviri sa izolovanom ispunom ponašaju se slično kao prazni okviri imajući malo niže relativno međuspratno pomeranje i postepen porast apsolutnih pomeranja duž visine okvira.

7 SUMMARY

The paper presents investigation on the behaviour of RC frame buildings with decoupled infill walls. Research was performed in order to study the effects of infill decoupling on the building level. As a solution for decoupling the INODIS system was used. It provides in-plane decoupling and stable out-of-plane connection. Since the decoupling approach enables in-plane and out-of-plane loads to be studied separately, in contrast to the traditional infills, here the focus was on the numerical modelling of in-plane behaviour of infill walls. For that purpose equivalent strut model was employed.

First, calibration and validation of the numerical model was done on one-bay frames with one storey, previously tested experimentally. Then, 2D structural frames with different infill distribution were analysed. Three different infill configurations were studied including: fully infilled frame, open ground storey frame and partially open ground storey frame and its behaviour was compared with the bare frame. For all these configurations, both traditional and decoupling approaches were studied. Results show that traditional infill walls significantly reduce natural period of the frame, thus considerably change the level of seismic loading acting on the structure. This is not the case with decoupled infills, where the change of period is insignificant. Force-displacement curves obtained in pushover analysis confirm low deformation capability of traditionally infilled frames in comparison with the bare frames and frames with decoupled infills. Nonlinear time history analysis showed in the best way negative effects of traditional infills on the behaviour of structural frames. In the case of open ground floor configuration huge jump in the inter storey drift can be noticed on the ground floor in comparison with the other storeys. In contrast, RC frames with decoupled infill walls behaved similarly as the bare frame configuration

Za 3D zgradu analizirana je petospratnica s pet spratova i tri polja u poprečnom pravcu i pet polja u podužnom pravcu. Konfiguracija sa ispunom u spoljašnjim okvirima ispitivana je zajedno sa zgradom na uglu i zgradom sa otvorenim prizemljem. Pored zgrade sa praznim okvirima, ove tri konfiguracije su istražene za slučaj tradicionalne i izolovane ispune. Pored toga, dodatna tri modela su napravljena koji su imali masu zadatu kao linijsko opterećenje na mestima izolovane ispune. Rezultati jasno pokazuju veliku razliku u periodima oscilovanja između zgrade s praznim okvirima i zgrade s tradicionalnom ispunom. Ovo nije slučaj sa zgradama sa izolovanom ispunom kod kojih se periodi oscilovanja razlikuju za 10% u odnosu na zgradu s praznim okvirima. To značajno utiče na nivo seizmičkog opterećenja koje deluje na zgradu, koji je u slučaju s tradicionalnom ispunom 50% veći u odnosu na zgradu s praznim okvirima koja se uobičajeno koristi danas u praksi u toku proračuna. Međutim, razlika u slučaju izolovane ispune je zanemarljiva. Ovo jasno pokazuje prednosti pristupa izolacije, koji pruža jasan i jednostavan postupak proračuna, s obzirom na to što eventualna primena izolacije ispune beznačajno menja trenutnu građevinsku praksu. Pored toga, rezultati oblika odgovora zgrade na uglu pokazuju značajne torzione efekte u slučaju tradicionalne ispune, što nije slučaj kada se primeni izolovana ispuna. Razlog za to je činjenica da izolovanje ispune uklanja efekat povećanja krutosti koja dolazi od zidane ispune.

Slično rezultatima na 2D okvirima, okviri s tradicionalnom ispunom aktiviraju najveću horizontalnu silu i u X i u Y pravcu. Takođe, zgrada sa otvorenim prizemljem i tradicionalnom ispunom dostigla je kapacitet deformacije mnogo ranije od svih ostalih konfiguracija.

Nelinearna dinamička analiza pokazala je katastrofalne efekte tradicionalne ispune na celokupno ponašanje zgrade. Krta veza okvira i ispune dovodi do značajne promene krutosti cele zgrade što za rezultat ima smanjenje pomeranja i pojavu torzije u slučaju zgrade na uglu kao i pojave fleksibilnog sprata u slučaju zgrade sa otvorenim prizemljem. Rezultati pokazuju da je zgrada s tradicionalnom ispunom imala značajno manja apsolutna pomeranja i relativno međuspratno pomeranje u odnosu na druge konfiguracije, osim u slučaju zgrade sa otvorenim prizemljem gde se javlja veliko relativno međuspratno pomeranje. Apsolutno pomeranje koje se javlja duž visine zgrade potvrđuje pojavu fleksibilnog sprata u slučaju tradicionalne ispune kao rezultat velikih pomeranja u odnosu na sve ostale konfiguracije iako su relativna međuspratna pomeranja mala. Ovo se javlja usled velikih pomeranja na nivou prizemlja, koja dovode do toga da se cela zgrada značajno pomera. Ovi negativni efekti mogu biti uklonjeni primenom izolacije ispune koja za rezultat ima blagu promenu pomeranja i relativnog međuspratnog pomeranja. Pojava fleksibilnog sprata u ovom slučaju nije prisutna zato što izolacija ispune uklanja promenu krutosti između spratova, koja dolazi od zidane ispune. I apsolutna pomeranja i relativno međuspratno pomeranje zgrade sa izolovanom ispunom su u granicama zgrade s praznim okvirima. Ovo potvrđuje da model s praznim okvirima može da predstavi realno situaciju zgrade sa izolovanom ispunom, umesto da bude daleko od pravog ponašanja što je slučaj s tradicionalnom ispunom. To pokazuje potencijal primene modela s

with slightly lower inter storey drifts and having smooth rise in absolute displacements along the height.

For the three-dimensional building a five-storey building was analysed, consisting of 3 bays in the transversal direction and 5 bays in the longitudinal direction. Configuration with outer frames completely filled with masonry walls was studied, together with the case of corner and open ground floor building. Besides bare frame building, these three configurations were studied in the case of traditional infills as well as decoupled infills. Furthermore, additional three models were investigated with only mass as line load presenting decoupled infill walls. The results clearly show huge difference in natural period between bare frame configuration and building with traditional infill walls. This is not the case with buildings having decoupled infills, where natural periods defer from the bare frame ones less than 10%. This affects a lot the level of seismic load actually acting on the building, which in the case of traditional infill can be even 50% higher than in the case of bare frame configuration that is usually used in the design today. However, the difference in the case of decoupled infills is negligible. This shows the advantage of decoupling approach having clear and simple design process, since the eventual implementation of decoupling system alter only marginally the current design practice. Furthermore, results for the mode shapes of corner building configuration show significant torsional effects in the case of traditional infills, which is not the case for the decoupled infill walls. This is due to the fact that decoupling diminishes increase of stiffness coming from the infill walls.

Similar to the results from the 2D frames, the traditionally infilled frames presented a higher maximum base shear in both X and Y direction than the decoupled and bare frame structures. In addition, building with open ground floor and traditional infills has reached its deformation capacity much sooner than all other configurations.

Nonlinear time history analysis show disastrous effects of traditional infill walls on the overall building behaviour. Rigid connection between infills and frame produce significant change in the stiffness of the overall building, resulting in reduction of displacements but producing torsional behaviour in the case of corner building and soft storey effect in the case of open ground floor. Results show that buildings with traditional infills have lower absolute displacements and inter storey drifts than other configurations, except in the case of open ground floor configuration where a huge inter storey drifts are present at the ground floor. The absolute displacements along the building height confirm appearance of soft storey in the case of traditional infills, resulting in the highest displacements of all configuration even the inter storey drifts at higher floors are low. This is due to the very high displacement in the ground floor producing whole building to move significantly. These negative effects are removed with the application of decoupling resulting in smooth change of displacement and inter storey drift. The soft storey effect is absent in the case of decoupled infill because the decoupling diminishes change of stiffness between the floors that comes from the infill walls. Both absolute displacements and inter storey drifts of the buildings with decoupled infills are in the range of the bare frame configuration. This

praznim okvirima u proračunu AB okvirnih konstrukcija sa izolovanom ispunom.

Treba napomenuti da interakcija uticaja u ravni i van ravni ispunne nije uzeta u obzir u modelima, što je opravdano za slučaj izolovane ispunne. Međutim, za slučaj tradicionalne ispunne ova interakcija ne može biti zanemarena i tada bi numerički modeli predstavili još lošije ponašanje. Pored toga, model ispunne predstavljene elementom po dijagonali ne može da predstavi efekte ispunne na stubove i povećanje momenata i smičuće sile, što ponovo nije problem za slučaj izolovane ispunne zbog eliminisane interakcije okvira i ispunne, ali u slučaju tradicionalne ispunne to bi dovelo do još gorih rezultata.

Na osnovu prikazanih rezultata može se zaključiti da tradicionalna ispunna vezana za ram preko maltera značajno menja ponašanje AB zgrada i to je neophodno uzeti u obzir u toku projektovanja. Jedini način da se to uradi jeste da se zidana ispunna modelira, što je prilično kompleksan, praktično neprimenjiv zadatak za svakodnevnu praksu. Pogotovo kada taj numerički model treba da uzme u obzir interakciju uticaja van ravni i u ravni, što je neophodno. Tada je proračun AB okvirnih konstrukcija s tradicionalnom ispunom praktično nemoguć. Prema tome, koncept proračuna AB zgrada sa zidanom ispunom mora se unaprediti tako da ponudi inženjerima pouzdano i stabilno rešenje zasnovano na konstruktivnim merama a ne na detaljnim numeričkim modelima. Jedno od obećavajućih rešenja jeste izolacija ispunne od okolnog okvira. Ova konstruktivna mera pruža značajna poboljšanja u poređenju s tradicionalnom ispunom. Korist postupka izolacije ogleda se u odloženoj aktivaciji zidane ispunne i time se značajno povećava kapacitet deformacije, kao i uklanjanje interakcije uticaja u ravni i van ravni, čime se značajno poboljšava ponašanje AB zgrade sa zidanom ispunom. Dodatni doprinos izolacije ispunne vidi se u slučaju bilo kakve promene u konstrukciji ili tradicionalnoj ispunni za vreme izvođenja ili u toku upotrebe objekta, svaka ta promena mora se adekvatno opravdati i verifikovati, što nije slučaj sa izolovanom ispunom. Pored toga, jednostavan numerički model koji uzima u obzir izolovanu zidanu ispunu samo kao masu atraktivan je za aplikaciju u inženjerskoj praksi, što pristupu izolacije ispunne pruža veliki potencijal za primenu.

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confirms that bare frame model will present a real situation in the case of decoupled infills, instead of being far from the real behaviour for the case of traditional infills. This shows the potential of use of bare frame model in the design of RC frame buildings with decoupled infills.

It should be pointed out that in-plane/out-of-plane interaction is not taken into account in these models, which is justified when decoupling approach is applied. However, for the case of traditional infill this interaction cannot be neglected and even worse behaviour than the one presented in these models can be expected. Furthermore, infill model with one diagonal strut cannot present the effects of infill wall to the columns and increase of moment and shear force, which again is not the problem for decoupled due to the eliminated infill/frame interaction, but in the case of traditional infill it would lead to much worse results.

Based on the results it can be concluded that traditionally connected infill walls using mortar to fill the gaps between frame and infill wall are significantly changing the behaviour of the RC buildings and they should be appropriately designed. The only way to correctly design traditional infills is to model infill walls, which is rather complex and inapplicable for everyday engineering works. Especially, when numerical model should take into account IP/OOP interaction, which is necessary. Then the design of RC frame buildings with traditional infills is practically impossible. Therefore, the design concept of infilled frame buildings should be improved in the sense that offers engineers to apply reliable and stable solution based on constructional improvements and not detailed numerical models. One of the promising options is decoupling infill walls from the frame. This construction measure shows significant improvements when compared to the traditional infills. Benefits of decoupling approach such as delayed infill activation and thus significant deformation capacity, as well as removal of in-plane/out-of-plane interaction, significantly improve overall behaviour of the RC buildings with infill walls. Additional benefit of decoupling can be seen in the case of any change in the structure or in the traditional infills during the construction phase or during the subsequent life of the structure, this change should be properly justified and verified, which is not the case for decoupled infills. Furthermore, simple numerical model that considers decoupled infill walls with their mass is attractive for application in the engineering practice, thus the approach of infill decoupling shows huge potential for application.

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REZIME

NUMERIČKA ANALIZA ARMIRANOBETONSKIH OKVIRNIH ZGRADSA IZOLOVANOM ZIDANOM ISPUNOM

Marko MARINKOVIĆ
Santiago FLORES CALVINISTI
Christoph BUTENWEG

Armiranobetonske (AB) zgrade sa zidanom ispunom se izvode u mnogim zemljama širom sveta. Iako se zidana ispuna posmatra kao nekonstruktivni element, ona značajno utiče na promenu dinamičkih karakteristika AB ramovskih konstrukcija u toku zemljotresnog dejstva. Oskora, značajan napor je utrošen na istraživanje izolovanih ispuna, koje su odvojene od okolnog rama obično ostavljanjem prostora između rama i ispune. U ovom slučaju deformacija rama ne aktivira ispunu i na taj način ispuna ne utiče na ponašanje rama. Ovaj rad predstavlja rezultate istraživanja ponašanja AB ramovskih zgrada sa INODIS sistemom koji izoluje ispunu u odnosu na okolni ram. Uticaj izolovane ispune je prvo ispitan na jednospratnim i jednobrodnim ramovima. Ovo je iskorišćeno kao osnova za parametarsku analizu na višespratnim i višebrodnim ramovima, kao i na primeru zgrade. Promena krutosti i dinamičkih karakteristika je analizirano kao i odgovor pri zemljotresnom dejstvu. Izvršeno je poređenje sa praznom ramovskom konstrukcijom kao i ramovima ispunjenim ispunom na tradicionalni način. Rezultati pokazuju da je ponašanje ramova sa izolovanom ispunom slično ponašanju praznih ramova, dok je ponašanje ramova sa tradicionalnom ispunom daleko drugačije i zahteva kompleksne numeričke modele. Ovo znači da ukoliko se primeni adekvatna konstruktivna mera izolacije ispune, proračun ramovskih zgrada sa zidanom ispunom se može značajno pojednostaviti.

Ključne reči: zidana ispuna, seizmika, INODIS, ponašanje u ravni; ponašanje van ravni, izolovana ispuna, zemljotres.

ABSTRACT

NUMERICAL ANALYSIS OF REINFORCED CONCRETE FRAME BUILDINGS WITH DECOUPLED INFILL WALLS

Marko MARINKOVIĆ
Santiago FLORES CALVINISTI
Christoph BUTENWEG

Reinforced concrete (RC) buildings with masonry infill walls are widely used in many countries all over the world. Although infills are considered as non-structural elements, they significantly change dynamic characteristics of RC frame structures during earthquake excitation. Recently, significant effort was spent on studying decoupled infills, which are isolated from the surrounding frame usually by adding a gap between frame and infill. In this case, the frame deformation does not activate infill wall, thus infills are not influencing the behaviour of the frame. This paper presents the results of the investigation of the behaviour of RC frame buildings with the INODIS system that decouples masonry infills from the surrounding frame. Effect of masonry infill decoupling was investigated first on the one-bay one-storey frame. This was used as a base for parametric study on the frames with more bays and storeys, as well as on the building level. Change of stiffness and dynamic characteristics was analysed as well as response under earthquake loading. Comparison with the bare frame and traditionally infilled frame was performed. The results show that behaviour of the decoupled infilled frames is similar to the bare frame, whereas behaviour of frames with traditional infills is significantly different and demands complex numerical models. This means that if adequate decoupling is applied, design of infilled frame buildings can be significantly simplified.

Keywords: masonry infill, seismic, INODIS, in-plane behaviour, out-of-plane behaviour, decoupled infill, earthquake.