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

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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 ravn i ravn dat je u [21], sa zaključkom da kvalitet izvođenja može značajno uticati na ponašanje zida upravno na svoju ravan time što bi se narušili grančani uslovi zida. Uticaj interakcije opterećenja u ravn i van ravn zida je prikazan u [22] gde je rečeno da opterećenja u ravn i van ravn može da dovode do odvajanja ispune od okolnog AB okvira i time spriči razvoj efekta luka bitnog za nosivost van ravn zida. U ovom radu su autori takođe pokazali da okvira konstrukcija sa zidanim ispunom ima mnogo manja relativna međuspratna pomeranja u poredenju sa okvirnom konstrukcijom, ali kada se interakcija opterećenja u ravn i van ravn uzmune u obzir, relativno međuspratna pomeranja 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 ravn i van ravn. Samo nekoliko autor [26–28] istraživalo je uticaj istovremenog dejstva opterećenja u ravn i van ravn ispune, iako je očekivano da to u toku zemljotresa oba pravca opterećenja deluju na zid ispune. Eksperimentalna ispitivanja prikazana u [26] pokazala su značajno smanjenje kapaciteta deformacije u ravn i kapaciteti nosivosti van ravn objašnjavaći da deformacija okvira dovodi do gubitka veze između okvira i time čini zidanu ispunu ranjivu na opterećenje van ravn.

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 ispune je ozidana, što može dovesti do torzije konstrukcije u toku dejstva zemljotresa koja može biti pogubna za globalno ponašanje zgrade. Kao je to opisano u [29] nejednak raspored zidane ispune može da prouzrokuje globalnu torziju konstrukcije, koja može da dovede do veličih 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 manji u zgradama s jakim AB zidovima. Rušenje konstrukcije usled torzije i pokove fleksibilnog sprata (slika 1b) mogu da se pojave čak i u slučaju kada Eirokod 8 [31] ne zahteva amplifikaciju seizmičkih uticaja. U [33] zaključeno je da će torzioni uticaji usled nejednakog rasporeda ispune verovatno dovesti do rušenja zidova ispunom ispadanjem van ravn.

Uobičajeni problem dispozicije jeste fleksibilni sprat uzrokovano odsustvom zidova ispune ili postojanjem značajno manje zidova ispunе na spratu iznad ili ispod. Ovakva konfiguracija javlja se usled funkcionalnih zahteva kao što su radnja i potreba za parking mestima. U [34] poznano 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 modele, dok je u [36] pokazano da čak i seizmička izolacija ponekad ne može da pomogne u slučaju nejednakog rasporeda ispune i formiranja fleksibilnog sprata, uz zaključak da se snažna 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-storey 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 ispunе koja nije u punoj visini u kontaktu sa okvirom kada je kontakt sa stubom krat, što ima za posledicу tako visoke zahtеve da ih čak i jaki stubovi ne mogu prihvatiti. U [37] prikazano je da je prisustvo zidova koji se ne protežu celom visinom stuba dovelо do pada kapaciteta konstrukcije za 47%. Kao rešenje za efekat kratkog stuba, u [38] predloženo je da se ispuna razdvoji od okvira kako što će se ostaviti prostor između nijh. U [39] savjetuje se da se efekat kratkog stuba izbegavaj od okvira.

Jedna opcija da se unapredi ponašanje AB okvирnih konstrukcija sa zidanom ispunom jeste da se ispuna modelira u toku projektovanja. Za ovu svrhu najpogodниj je pristup makro modeliranja. Na ovaj način se mogu opisati uticaji zidane ispunе na globalno ponašanje AB zgrada u toku zemljotresa. U toku dugog perioda istraživanja ponašanja okvira sa ispunом, 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 ispunом bazirana su na konceptu ekvivalentne dijagonale. Navedeni autori pretpostavili su da se ispunе ponašа 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 ispunом, ali model sa samo jednim elementom po dijagonali ne može da uzme u obzir promenu momenata savijanja i smičućih silа po dužini stuba koja se javlja usled panela ispunе [43] i zbog toga je neefikasna u modeliranju kompleksnог ponašanja okvирних konstrukcija [44]. Kako bi se prevazišlo ovo ograničеnje, nekoliko autora [45–47] razvilo je modele s različитom orijentacijom i brojem dijagonalnih elemenata. Kako bi se koristila pritisnuta dijagonala za predstavljanje ispunе, karakteristike kao što su širina dijagonale, krutost i veza silа–pomeranje morаju se definisati. Neki autori [29, 41, 48] definisali su širinu dijagonale kao procenat dužine dijagonale, dok su други [49–54] zaključili da

short column, [38] proposed an application of separation gap between infil 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.
efaaktivna širina dijagonalne 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 predloha je dato za definisanje nosivosti i određivanje kapaciteta različitih tipova loma ispune. Jednačine za neke od tipova loma ispunjene su u ravnim rastojanjima [41, 42, 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 pritisnutu dijagonalnu neophodna je kako bi se model pritisnute dijagonale implementirao u program za proračun konstrukcija. Tipovi konstitutivnih modela neophodnih da se definira pritisnuta dijagonala zavise od tipa analize (linearno-elastična ili nelinearna) i od tipa opterećenja (monotono, cikličko ili dinamičko). U [52] među prvima je predložena relacija sila–pomeranje za ekvivalentnu dijagonalu, definišući početnu krutost, granu ojačanja i omekšanja, pružajući rezidualnu nosivost. 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]. Bilo kako se provela dinamička nelinearna analiza, potrebno je definirati histerезe rno ponašanje materijala. U literaturi je dato samo par modela histerезe za definiciju pritisnute dijagonale, zato što je većina istraživanja ispitivala ponašanje zidane ispune pri monotonom opterećenju, ali i izbog činjenice da uzimanje u obzir histerезe rno 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]. Nešteto skorije, u [63] prikazan je unapređeni histerезe rni model predložen prvo u [64] uvijđanjem detaljne veze sila–pomeranje koja uzima u obzir cikličko i monotono ponašanje ekvivalentne dijagonale, kalibrirane uz pomoć eksperimentalnih rezultata. Iako eksperimentalna istraživanja pokazuju nepohodnost uzimanja u obzir interakcije opterećenja u ravnim i van ravnim, 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 ovinim zgradama sa zidanom izazonom jeste da se primene konstruktivne mere na samoj ispunoi. 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 kompletan izolaciju u ravni ispune u odnosu na okolin okvir, tako da se okviru dozvoli deformacija i time odozi 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 bilo 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 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, incorporation 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 restrain to prevent the infill wall to collapse due to the perpendicular loads.
The problem 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 a 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.

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].
3 NUMERICAL MODELS

In this section, modelling approaches for all parts of the RC frames with decoupled in fills are presented. Since the topic of the investigation are masonry in filled 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 in filled model and model of the frame with the decoupled in fills. 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
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 sa 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 neutegnut. Dok pri naponima bliskim jednoaksijalnoj nosivosti betona, pojava pukotina u betonu dovodi do značajne aktivacije uzengija koje onda pružaju uteganja betonskom elementu. Na ovaj način se obezbeđuje značajno povećanje nosivosti i duktilnosti betonskog elemenata [85].

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].

3.2 Modeliranje zidine 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-elementa 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 svaki dijagonalu (Figure 4b).

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

3.2 Modelling of the infill wall

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].

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Figure 6. Stress-strain curves for unconfined and confined concrete [86]
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:

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

$\lambda_h = h^4 \sqrt{\frac{E_m I_m \sin 2\theta}{4 E_c I_c h_m}}$  

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; $I_m$ 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; $\theta$ is the angle between the horizontal and the diagonal of the wall as seen in Figure 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             |

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$\lambda_h = h^4 \sqrt{\frac{E_m I_m \sin 2\theta}{4 E_c I_c h_m}}$
\[ \sigma_{br(1)} = \frac{0.6 \tau_{m0} + 0.3 \sigma_0}{\omega / d} \]  
(3)

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

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

\[ \sigma_{br(4)} = \frac{1.16 \sigma_{m0} \cos \theta}{K_1 + K_2 \lambda_h} \]  
(6)

gde je \( \sigma_{m0} \) nosivost zidarije na pritisak, \( \tau_{m0} \) je smičuća nosivost određena iz testa pritiska po dijagonali, \( f_{sr} \) nosivost spojnice na klizanje i \( \sigma_0 \) je napon usled vertikalnog opterećenja.

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

\[ H_{mfc} = \sigma_{br, max} \cos \theta \cos \phi \]  
(7)

Proračun elastične krutosti, \( K_0 \), uzima u obzir elastičnu krutost okvira, \( K_{t0} \), i krustost zidane ispune kada je dostigla maksimalnu nosivost i ispučala, \( K_{mfc} \), određene prema [89]:

\[ K_0 = 3K_{t0} + 4K_{mfc} \]  
(8)

gde je

\[ K_{t0} = \frac{1 + 6\phi}{2 + 3\phi} \frac{12EcI_p}{h^3} \]  
(9)

\[ \phi = \frac{I_{\text{beam}}}{I_{\text{column}}} \frac{h}{l} \]  
(10)

\[ K_{mfc} = \frac{E_{\text{eff}} \omega}{d^2 \cos \theta} \]  
(11)

3.3 Modeliranje elastomera

3.3 Modelling of the decoupling elastomer

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).
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 2D ramovima konstrukcije i na 3D modelu zgrade.

Za validaciju numeričkih modela, iskorišćeni su rezultati testova za opterećenje u ravni iz [81]. Eksperimentalna ispitivanja sastoje 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) poredenjem 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 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). 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 (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 automatically defined by the program (Figure 10). For the rebars, a user-defined stress-strain curve was defined, with the material characteristics described in [82].

Figures 4a, 9a, and 9c-d: Column sections A and B, Beam sections A and B, with fibre positions.
Numerički rezultati statičke nelinearne analize (pushover) upoređeni su sa anvelopom histerezisne krive iz eksperimentalnih rezultata (slika 11). Iz rezultata se može primjetiti 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 različenje ove dve krive, ali u granicama zadovoljavajučeg.

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.

Kako bi se uhvatio 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.

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.

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

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.
Табела 2. Вредности коришићене за модел арматура
Table 2. Values used for rebar model

| Фактор дејстве енергији / Energy degradation factor, $f_0$ | 1.0 |
| Фактор енергије при умереним деформацијама / Energy factor at moderate deformation, $f_1$ | 1.5 |
| Фактор енергије при максималним деформацијама / Energy factor at maximum deformation, $f_2$ | 0.2 |
| Умерени ниво деформације у односу на ниво тећенja / Moderate deformation level as a ratio of yield, $x_1$ | 1.0 |
| Максимални ниво деформације у односу на ниво тећенja / Maximum deformation level as a ratio of yield, $x_2$ | 2.0 |
| Акумулациони деформацији технички фактор / Accumulation deformation weighting factor | 0.2 |
| Тежински фактор за кратост / Stiffness weighting factor | 0.2 |
| Већи-манji тежински фактор / Larger-smaller weighting factor | 0.4 |

Фигура 12. Поредење резултата нумериčког модела динамичке нелинеарне анализе и експерименталног хистерезиса празног оквира
Figure 12. Comparison between the numerical model time history results and the experimental hysteresis of the bare frame

4.2 AB оквир с традиционалном испуном

Оквир с традиционалном испуном из експеримената приказаних у [81] састоји се од истог празног AB оквира испуњеног зидом од щуплих блока од опеке повезаних танкослойним мајтером. Деталне матерijалне карактеристике блока и зидарије date су у [81, 82]. За дефинisanje крива сила–померања за интер-елемент, искоришћен је приступ заснован на четири грани криве, дефинисан у [51, 52]. Како би се дефинисала крива требало је да се одреди бездимензиони коefицијент $\lambda_h$ коришћенjem Једначине 2. У Табели 3 приказане су коришићене вредности:

Табела 3. Одређивање параметра $\lambda_h$
Table 3. Calculation of parameter $\lambda_h$

| $E_m$ | 4870 | N/mm² |
| $t_m$ | 365 | mm |
| $\Theta$ | 0.738 | rad |
| $\sin 2\Theta$ | 0.996 | - |
| $E_c$ | 32559 | N/mm² |
| $h_m$ | 2520 | mm |
| $h$ | 2750 | mm |
| $\lambda_h$ | 5.54 | - |
Za određivanje širine dijagonale korišćena je Jednačina 1. Kao što se može videti u Tabeli 3, $A_H$ vrednost je između 3.14 i 7.85, $K_f$ i $K_s$ 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 spojnica na smicanje takođe je određena prema Jednačini 13:

$$\tau_{m0} = 0.285 \sqrt{f_m}$$  \hspace{1cm} (12)

$$\tau_0 = 2/3 \tau_{m0} = 0.211 \sqrt{f_m}$$  \hspace{1cm} (13)

Obe jednačine predložene su u [92] i daju nosivost od 0.707 MPa za $\tau_{m0}$ i 0.01 MPa za $\tau_0$.

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

| $\sigma_{br(1)}$ | 2.19 | N/mm² |
| $\sigma_{br(2)}$ | 6.72 | N/mm² |
| $\sigma_{br(3)}$ | 2.78 | N/mm² |
| $\sigma_{br(4)}$ | 4.29 | N/mm² |

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 $H_mfc = 136.68kN$. Linearna elastična sila $H_{meq}$ je uzeta kao 80% od $H_mfc$, a $H_{meq}$ kao 87.5% od $H_mfc$. Za određivanje elastične krutosti, $K_f$ (Jednačina 8), elastična krutost okvira, $K_{mf}$ (Jednačina 9), i krutost ispune pri maksimalnoj nosivosti, $K_{mfc}$ (Jednačina 11), iskorišćeni su za dobijanje $K_f = 299.8$ 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 $K_{mf}$ 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.

For the calculation of the strut width, Equation 1 was used. As seen in Table 3, for $A_H$ values in between 3.14 and 7.85, $K_f$ and $K_s$ 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:

$$\tau_{m0} = 0.285 \sqrt{f_m}$$  \hspace{1cm} (12)

$$\tau_0 = 2/3 \tau_{m0} = 0.211 \sqrt{f_m}$$  \hspace{1cm} (13)

Both equations are proposed by [92] and they derive 0.707 MPa for $\tau_{m0}$ and 0.01 MPa for $\tau_0$.

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

Tabel 4. Naponi nosivosti na pritisak

Table 4. Compression failure stresses

| $\sigma_{br(1)}$ | 2.19 | N/mm² |
| $\sigma_{br(2)}$ | 6.72 | N/mm² |
| $\sigma_{br(3)}$ | 2.78 | N/mm² |
| $\sigma_{br(4)}$ | 4.29 | N/mm² |

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 $H_mfc=136.68kN$. The linear elastic force $H_{meq}$ was assumed as 80% of $H_mfc$ and $H_{meq}$ as 87.5% of $H_mfc$. For the calculation of the elastic stiffness, $K_f$ (Equation 8), the elastic stiffness of the frame, $K_{mf}$ (Equation 9), and the infill wall stiffness when it is completely cracked, $K_{mf}$ (Equation 11), were used obtaining $K_f = 299.8$ 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 $K_{mfc}$ as 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 $K_{mf}$ 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.
Figure 13. Comparison between pushover curve from numerical model and the envelope of experimental hysteresis for traditionally infilled frame

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 $\alpha_1$, $\alpha_2$, $\beta_1$ and $\beta_2$. The $\alpha$ parameters adjust the unloading zone while the $\beta$ parameters adjust the loading zone. Since the tension strength of the infill panel is unconsidered, parameters $\alpha_1$ and $\beta_1$ are set to 0, while $\alpha_2$ 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.

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 ispunе 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 ($\omega$) i njen ugao $\Theta$, kontaktna dužina između pritisnute dijagonale i stuba, $L_c$, i grede, $L_b$, jeste određena:

$$L_c = \omega \cos \theta = 380.89 \text{ mm}$$

$$L_b = \omega \sin \theta = 346.51 \text{ mm}$$

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 ($\omega$) and its angle $\Theta$, contact length between the diagonal strut and the column, $L_c$, and beam, $L_b$, are determined:

$$L_c = \omega \cos \theta = 380.89 \text{ mm}$$

$$L_b = \omega \sin \theta = 346.51 \text{ mm}$$
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 37.5 mm 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.

Test in the 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.

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 histerezinske krive za okvir sa izolovanim 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 sprovedi naredne analize ponašanja AB okvira konstrukcija sa izolovanim ispunom. Dvodimenzionalni okvir konstrukcije analiziran je primenom statičko nelinearne analize i dinamičke nelinearne analize. Kako bi se modelirao okvir konstrukcije sa više spratova i brodova, prethodno validirani numerički modeli jednospratnih i jednobrodnih okvira multiplicirani su u visinu i širinu. Svi poprečni preseci 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], analiziran je različite konfiguracije ispune uključujući: prazan okvir, okvir sa sasvim popunjen ispunom, okvir sa otvorenim prizemljem i okvir sa delimično otvorenim prizemljem. U svim ovim konfiguracijama, i tradicionalna i izolovana ispun na ispitana. To znači da je jedan različitih konfiguracija analizirano (slika 19) – prazan okvir (1); okvir sa sasvim popunjen tradicionalnom ispunom i sa INODIS sistemom (2 i 5); okvir sa 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.

**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 sile. Na kraju je sprovedena nelinearna dinamička analiza (time history) kako bi se poredila apsolutna sile i relativno međuspratno pomeranje. Akcelerogrami korišćeni u nelinearnoj dinamičkoj analizi 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=0.3 g, 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 ubrzanja 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.
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%.

5.2 Rezultati za 2D okvire konstrukcije

Slika 21 pokazuje sopstvene periode za prva tri tona za sve konfiguracije. Iz poredenja 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 umanjenje od 21%. Ta razlika je još ishrane u slučaju okvira sa delimično ili potpuno otvorenim prizemljem i iznosi 17%.

Kada se postave periođi 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 (zelena), ne samo da su im periodi blizu za sve tri konfiguracije već i su 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.
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 relativno međuspratno pomeranje 0.15% i 0.11% na prvom i drugom spratu, ostajući u granicama malih vrednosti i na višim nivoima; 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 ispunene smanjuje u prizemlju. Za slučaj tradicionalne ispunene, za delimično ili potpuno otvoreno prizemlje, apsolutna pomeranja su 0.307 m i 0.351 m, dok su ona za izolovanu ispunu 0.616 m i 0.635 m. Isto ponašanje je za oba nivoa ubrzanja. Uočava se da su okvire s tradicionalnom ispunom, apsolutna pomeranja nekoliko puta manja od praznih okvira i okvira sa izolovanom ispunom. Ovo je 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 storey 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 0.307 m 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 pomeranijima praznog okvira.

S druge strane, u slučaju sa izolovanim ispunama, postoji ujednačen prelaz u relativnim međuspratnim pomeranijima 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.

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.

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 ANALYZING 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.

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 ispuna se nalazi samo u spoljašnjim okvirima praveći tako jezgro od ispune (slika 25b). Druga konfiguracija predstavlja zgradu lociranu na uglu 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 pojavljivanja torzije cele zgrade. Kao što je navedeno u uvodu, analiza efekata fleksibilnog prizemlja takođe je jako bitna zbog 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 oprimirima sa sasvim punom izolovanom ispunom; Model br. 6: zgrada na uglu sa izolovanom ispunom; Model br. 7: zgrada sa otvorenim prizemljem s 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 definišana za 2D okvire konstrukcije takođe su uzeta u obzir. Dispozicija u osnovi kao i raspored zidane ispune prikazan je na slici 26.
Slika 25. a) zgrada sa 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

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 building
6.1 Tipovi analize

Za 3D model zgrade, korišćene su iste analize (modalna, pushover i nelinearna dinamička) kao za 2D okvire konstrukcije. Za nelineamu dinamičku analizu (time history) veštački generisani akcelerogrami 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 sa praznim okvirima. Za razliku od njih, zgrade sa izolovanom ispunom imaju period koji je samo 6% manji. Za njih su takođe i druga dva periodo beznačajno manja za 10 i 14%. Suprotno od njih, zgrade s tradicionalnom ispunom imaju period manje za 62 i 69% za drugi i treći ton. Ova razlika je manja od gubitka 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 period 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

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 vidjeti da zgrada sa izolovanim 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, potencijuje 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 ispuna modelirana pritisnutim dijagonalam. 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 raspoređenja tradicionalne ispune na slučaju zgrade na uglu. Od svih konfiguracija, jedina zgrada s tradicionalnom ispunom ima u odgovoru kombinaciju tonova. Zgrada na uglu s tradicionalnom ispunom ima 40% participacije torzii tona u odgovoru konstrukcije. Suprotno od toga, zgrada sa izolovanom ispunom ima samo 0.5% participacije mase u rotaciji oko Z ose.

Kada se periodi postave na spektar odgovora (slika 28), može se vidjeti 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, potencijuje 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 ispuna modelirana pritisnutim dijagonalam. Stoga, jednostavan model s praznim okvirima s masom umesto pritisnutih dijagonala može biti iskorišćen za projektovanje AB ramovskih konstrukcija sa izolovanom ispunom.

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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.

![Modal participation mass ratios for the first mode for different configurations](image)

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 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.

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.

![Modal participation mass ratios for the first mode for different configurations](image)

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 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.

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.
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 izolovanim ispunom, apsolutna pomeranja za sasvim pune okvire, zgradu na uglu i zgradu sa otvorenim prizemljem u granicama su vrednosti zgrade s praznim okvire. Pojava fleksibilnog sprata nije prisutna ni u jednoj od konfiguracija sa izolovanim ispunom. Ovo je značajno unapređivanje koje dolazi kao rezultat toga da izolacija ispune uklanja efekat povećanja krutosti usled zidova ispune 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.
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, neujednačen 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 zgradama 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 a measure to solve torsional problems in the case of irregular distribution of infill walls, specifically corner building.
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.
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 differ 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 drifts. 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 okvirišne konstrukcije sa izolovanom ispunom.

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

Na osnovu prikazanih rezultata može se zaključiti da tradicionalna ispuna vezana za ram preko maltera značajno menja ponašanje AB zgrada i to je neophodno uzeti u obzir u toku projekovanja. Jedini način da se to uradi jeste da se zidana ispuna modelira, što je prilično komplesan, praktično neprijemljiv zadatak za svakodnevnu praksu. Pogotovo kada kada numerički model treba da uzme u obzir interakciju uticaja van ravi i u ravi, što je neophodno. Tada je proračun AB okvirišne konstrukcija sa tradicionalnom ispunom praktično nemoguć. Prema tome, koncept proračuna AB zgrada sa zidanom ispunom mora se unapreti tako da ponudi inženjerima pouzdano i stabilno rešenje zasnovano na konstruktivnim merama a ne na detaljnim numeričkim modelima. Jedno od obećavajućih rešenja jeste izolacija ispune od okolnog okvira. Ova konstruktivna mera pruža značajnu poboljšanja u poređenju s tradicionalnom ispunom. Korist postupka izolacije ogleda se u području stvarajućim izolacije u ravni i van ravi, čime se značajno poboljšava kapacitet deformacije, kao i uklanjanje interakcije uticaja u ravi i van ravi, čime se značajno poboljšava ponašanje AB zgrada sa zidanom ispunom. Dodatni doprinos izolacije ispune vidi se u slučaju bilo kakve promene u konstrukciji ili tradicionalnoj ispuni za vreme izvođenja ili u toku upotrebe objekta, svaka ta promena mora se adekvatno opravdati i verifikovati, što nije slučaj sa izolovanim 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 ispune pruža veliki potencijal za primenu.

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ABSTRACT

NUMERICAL ANALYSIS OF REINFORCED CONCRETE FRAME BUILDINGS WITH DECOUPLED INFILL WALLS

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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.

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