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IN-PLANE BEHAVIOUR OF RC FRAMES WITH TRADITIONAL AND DECOUPLED INFILLS: PARAMETRIC STUDY

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Abstract

Masonry infills are used as outer and inner partitions in reinforced concrete (RC) frame buildings. Although regarded as non-structural elements, masonry infills are activated under seismic actions. Because of this activation, masonry infills experience life-threatening damage. Moreover, they affect the seismic response of the whole RC frame structure, as they modify the dynamic characteristics of the structure. An innovative decoupling solution is developed to improve the seismic response of the infilled RC frames. In this paper, the in-plane behaviour of the RC frames with traditional and innovative decoupled infills is investigated by means of the simplified micro-model developed in Abaqus. Firstly, the numerical model is validated against the in-plane experimental tests on the RC frames, fully infilled with traditional and decoupled infill. Afterwards, a parametric study is carried out, focusing on the effect of the brick thickness and infill height-to-length ratio on the in-plane behaviour of the infilled RC frames. The level of the frame-infill interaction is evaluated through a comparison of the numerical results on the referent bare RC frame and RC frames with traditional and decoupled infills. The damage on masonry infills and surrounding RC frames, infill contribution forces and initial in-plane stiffness of the RC frames are observed. Additionally, a distribution of internal forces on the RC frames is evaluated in the post-processing of the results, which represents an important novelty of the study. Numerical results show that the decoupling system significantly reduces the activation of the decoupled infills, for all investigated infill geometries. Furthermore, the overall in-plane response of the RC frames with decoupled infills is very similar to the in-plane response of the bare RC frame up to 2.0 % of in-plane drift, which is certainly not the case for the traditionally infilled RC frames.

Keywords: Traditional infill, Decoupled infill, INODIS, brick thickness, height-to-length ratio

1. Introduction

Buildings composed of load-bearing reinforced concrete (RC) frames are widespread all over the world. In these buildings, after the erection of the RC frame elements, masonry walls are usually built as inner and outer partitions, with a stiff mortar connection to the surrounding RC frame. These walls are called masonry infills, and in seismic design, they are commonly regarded as non-structural elements. Therefore, while carrying out the design of the RC frame structures, the effect of masonry infills is taken only as an additional vertical line load on the RC load-bearing element. However, masonry infills interact with the surrounding RC frames under seismic loads. This plays an important role, as masonry infills can significantly affect the in-plane response of the RC frame structure considered in the design. This raises questions about the accuracy of the whole design of the RC frame structure and its safety. The severe damage to masonry infills and RC frames in recent earthquakes in Albania (2019) [1], Croatia (2020) [2], and Turkey (2023) [3], for instance, confirms that neglecting masonry infills in the design is far from conservative and can therefore have serious consequences for the economy of the affected regions and the safety of the inhabitants.

RC frames with masonry infills have been intensively investigated for decades. Most of the research work is focused on the in-plane behaviour of infilled RC frames. Some relevant experimental studies have been carried out by Dawe and Seah (1989) [4], Mehrabi et al. (1994) [5], Flanagan and Bennett

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(1999a) [6], Stylianidis (2012) [7], Morandi et al. (2017a) [8], and Di Trapani et al. [9]. In these studies, it has been recognised that numerous parameters (frame-infill interface conditions, brick thickness, height-to-length ratio, openings) influence the in-plane response of the infilled RC frames. With the development of computers, the number of research studies that use numerical models to investigate the behaviour of infilled RC frames has largely increased. For instance, some authors [10,11] have developed complex micro-models that can genuinely replicate the behaviour of experimental specimens, while others [12,13] have developed less complicated but faster macro-models that can be applied for the studies of the infilled frames on the building level. Despite the significant amount of both experimental and numerical research, simple and efficient approaches to considering masonry infills in engineering codes are still absent.

Recently, a lot of the work by research teams has been dedicated to developing solutions that can improve the seismic performance of infilled RC frames. For instance, groups of authors propose strengthening masonry infills and thus increasing their load-bearing capacity, e.g., [14,15]. However, a major disadvantage of strengthening measures is that masonry infills become part of the load-bearing system, and they need to be carefully designed, along with the frames around them, which is already a problem. The second direction is to increase the ductility of masonry infills, for instance, by installing horizontal [16] or vertical sliding joints [17]. These solutions can efficiently improve the in-plane response of infilled RC frames. However, the shear demand on the columns can increase due to the sliding along the horizontal joints [18]. In addition to this, a significant disadvantage is the absence of vertical arching to carry the out-of-plane loads, which results in more complicated and rather expensive solutions for addressing out-of-plane loads. The third direction is to decouple masonry infills from the RC frame. This can be achieved by inserting soft material between the infill and the frame, as done in [19,20], for example. The idea of decoupling appears to be the most promising one, and it is already recommended in some codes [21,22]. However, providing out-of-plane stability to the infill can be challenging for decoupled infills.

In the present work, RC frames with traditional infills and decoupled infills are investigated. RC frames with decoupled infills are made with the innovative decoupling system INODIS. The efficiency of the system has already been proved in an extensive experimental campaign [23]. In this study, the in-plane behaviour of RC frames with decoupled infills and traditional infills is investigated numerically. A three-dimensional model developed by Marinković and Butenweg (2022) [24] is employed, calibrated, and validated against the results of the experimental tests [23,25]. Afterwards, the numerical model is used for the parametric study. The investigated parameters are brick thickness and height-to-length infill (frame) ratio. The in-plane behaviour of different RC frames with traditional and decoupled infills is compared with the in-plane behaviour of the referent bare RC frame. Based on the numerical results, conclusions regarding the level of frame-infill interaction of RC frames with traditional and decoupled infills are derived.

2. Experimental specimens

The basis for the numerical simulations carried out in this work is a large experimental campaign. The first part of the experimental campaign addresses the behaviour of RC frames with traditional infills [25] and the second part of the experimental campaign addresses the behaviour of RC frames with decoupled infills [23]. Detailed information on the construction of the experimental specimens, materials used and experimental results can be found in [23,25]. In this study, in-plane parts of the experimental tests on the RC frames fully infilled with traditional (test T2) and decoupled infill (test D2) are used for the calibration and validation of numerical model.

For the construction of both traditional and decoupled infills modern hollow clay bricks are used, with a thickness 30 cm. Bed joints are filled with the thin layer mortar, while head joints are made as dry joint connections, following the usual practice. Traditional infill is connected to the surrounding RC frame with the mortar. On the other side, between RC frame and decoupled infill, the decoupling system called INODIS is installed. It consists of three strips made of recyclable elastomeric material. The middle strip is glued to the RC frame elements, and the outer strips to the masonry infill. This

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distribution of elastomeric strips is important for providing stable boundary conditions at the infill parameter against out-of-plane loads. The strips between columns and infill are softer and thicker, in order to absorb the frame deformation under in-plane drifts, while strips at the infill top and bottom are stiffer because of the out-of-plane load safety requirements. In addition to this, bottom surface of the middle elastomer at the top beam is covered with a sliding surface, as well as the top surfaces of the outer elastomers at the infill top. This significantly reduces the friction between frame and infill. More details about the decoupling system can be found in [23].

3. Numerical modelling

The three-dimensional numerical model developed in [24] is used for conducting numerical simulations. The numerical model consists of concrete elements (columns and beam), brick units, and elastomer strips (in case of the decoupled infill), which are modelled with three dimensional 8-node hexahedral continuum finite elements, with reduced integration (C3D8R), and reinforcement, which is modelled with truss elements (T3D2) elements that are embedded in the solid concrete elements. The stiff and strong bottom beam of the experimental frame is replaced by three discrete rigid plates in order to reduce the number of elements and calculation time. Two rigid plates are tied with the columns of the RC frame, and the middle one is tied with the masonry infill. In this way reaction forces of RC columns and masonry infill are separately measured, which presents a small difference to the original model described in [24].

Brick units are modelled as parts, while mortar in bed joints is not modelled with separate elements, but its effect is accounted for by defining a specific interaction that can simulate its response. This technique is called "simplified micro-modelling". More information on the definition of interactions can be found in [24].

The concrete damage plasticity (CDP) model available in Abaqus [26] is used as a constitutive model for concrete and masonry. In this model, different stress-strain and stress-displacement relationships can be used to define the response of the material under compression and tension, respectively. In addition, the CDP model can define different damage characteristics in compression and tension. Material curves of the concrete and masonry with detailed explanations can be found in [24]. To define the stress-strain curve of reinforcement bars experimental data are used.

In decoupled infills, the hyperfoam material model available in Abaqus [26] is used to simulate the hyperelastic material of elastomers. This model allows using the stress-strain curves obtained from experimental tests on the softer and stiffer elastomer mixtures. The experimental curves used in the model can be found in [23]. Furthermore, to model the sliding surface a new interaction is defined, with a friction coefficient of 0.1.

It should be pointed out that brick units and mortar used in this study have different material characteristics than in [24]. Therefore, a number of parameters that are necessary to calibrate the material models and interaction properties had to be calibrated again. The validation of the numerical model against the experimental tests on RC frame with traditional (T2) and decoupled infill (D2) are presented in Section 4.

In addition to this, a novelty of this numerical study is a detailed post-processing of the results, which enables the extraction of internal forces (bending moments and shear forces) along columns of the RC frame. This is an important step in the analysis of the results, as there are fewer studies in the literature that investigate the internal forces on the RC frame with a simplified micro-model.

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4. Numerical simulations of experimental tests

4.1. Validation of numerical model

Numerical simulations of experimental tests consist of three loading steps that simulate the loading conditions in the in-plane loading phases of experimental tests: gravity load, vertical loads on columns (200 kN per column) and in-plane displacements. In-plane displacements in the experimental tests have a form of the quasi-static cyclic loads, while in numerical simulations they are applied only in one direction (from left to the right) and increase monotonically up to the target value. Due to this, numerical force-drift curves are compared with the envelopes of the experimental force-drift curves. More detailed information on the loading conditions in the experimental tests can be found in [23,25], and in the numerical model in [24].

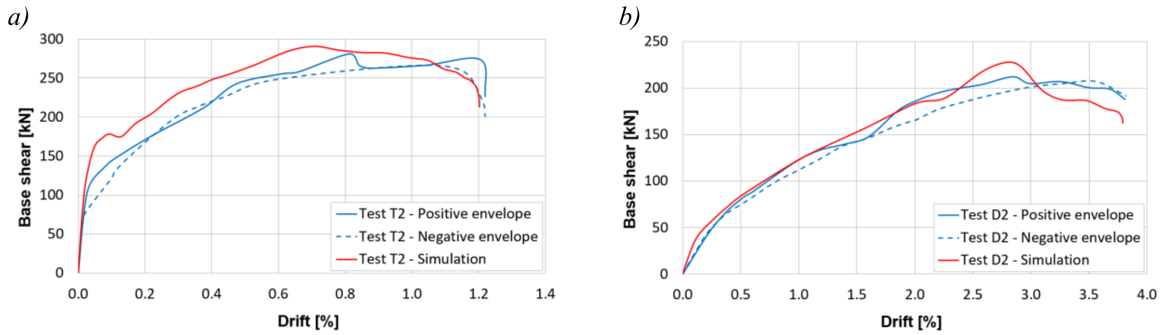

Figure 1. Comparison of numerical and experimental in-plane force-drift curves: a) Test T2 and b) Test D2

Firstly, the in-plane loading phase of a test on the traditionally fully infilled RC frame is simulated (Test T2). Figure 1a shows that the calibrated numerical model can quite accurately reproduce the in-plane response of an experimental specimen. Additionally, Figure 2a shows the major strain propagation on the experimentally tested traditional infill, whereas Figure 2b shows the tensile damage propagation in numerical simulation, at 1.2 % of in-plane drift. It can be seen that the cracking pattern in the numerical simulation corresponds to the one observed in the experimental test.

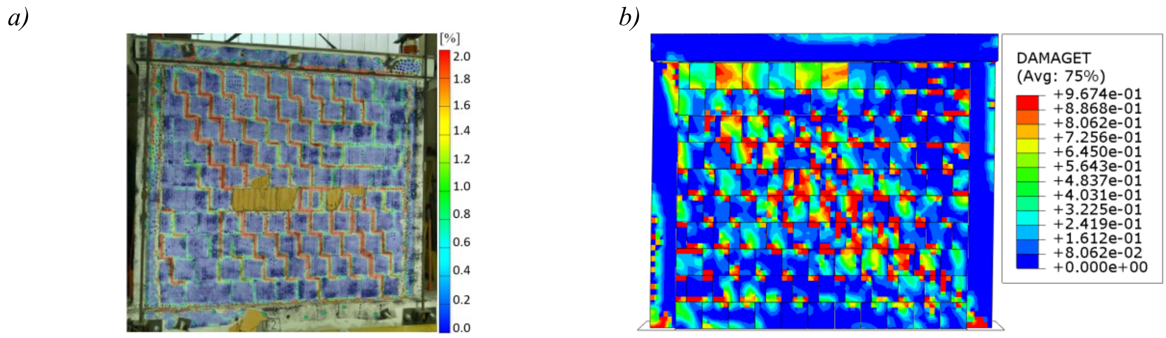

Figure 2. a) Major strain propagation on masonry infill in test T2 at 1.2 % of in-plane drift [25]; b) Tensile damage propagation in numerical simulation of test T2 at 1.2 % of in-plane drift

In-plane loading phases of the experimental test on the RC frame with a decoupled infill (Test D2) are simulated too. A good match between experimental and numerical force-drift curves can be seen in Figure 1b. Furthermore, Figures 3a and 3b show that the numerical model can quite well predict the crack propagation on decoupled masonry infill too. It can be observed that at 2.0 % of in-plane drift only stepwise cracks are visible on decoupled masonry infill, both in test D2 and its numerical simulation.

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a) *b)*

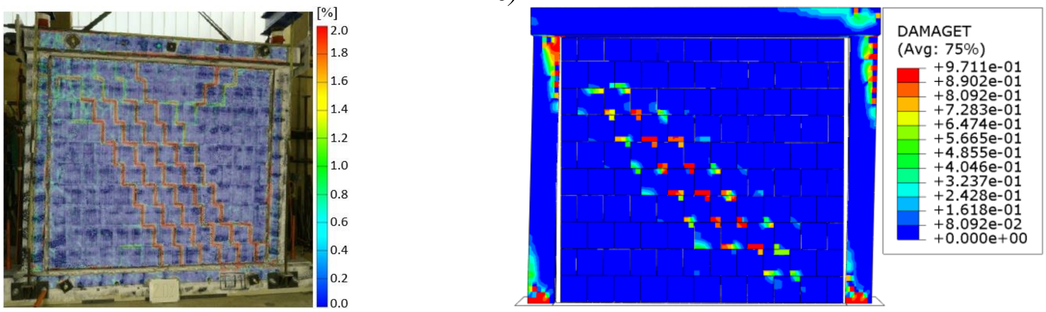

Figure 3. a) Major strain propagation on masonry infill in test T2 at 2.0 % of in-plane drift [23]; b) Tensile damage propagation in numerical simulation of test T2 at 2.0 % of in-plane drift

4.2. Comparison of in-plane behaviour of RC frame with solid traditional and decoupled infill

In this section, frame-infill interaction effects are further investigated by comparing numerical force-drift curves of infilled RC frames and a bare frame and numerical force-drift curves of masonry infill contribution of traditional and decoupled infill (Fig. 4). Because of the decoupling system, the initial stiffness of the RC frame infilled with the decoupled infill (D-TOTAL) remains unchanged in comparison to the initial stiffness of the bare RC frame (BF-TOTAL). On the other side, the initial stiffness of the traditionally infilled RC frame (T-TOTAL) is significantly higher because of the infill activation at in-plane drifts lower than 0.1 %. The activated traditional infill contributes significantly to the stiffness and total horizontal force up to around 0.8 % of in-plane drift. At this point, the maximum in-plane force is reached by traditional infill, and its contribution starts to decline. Because of the delayed activation of the decoupled infill, a more significant discrepancy between the force-drift curve of the RC frame infilled with decoupled infill and bare RC frame can be noticed only after 2.0 % of in-plane drift when the first cracks appear on masonry infill. The contribution of decoupled masonry infill to the total stiffness and force up to this point is rather small. Furthermore, Figure 5a shows that the traditional infill suffers significant damage already at around 0.7 % of in-plane drift. The decoupled infill gets activated at around 2.0 % of in-plane drift and experiences significant damage at around 3.0 % of in-plane drift (Fig. 5b).

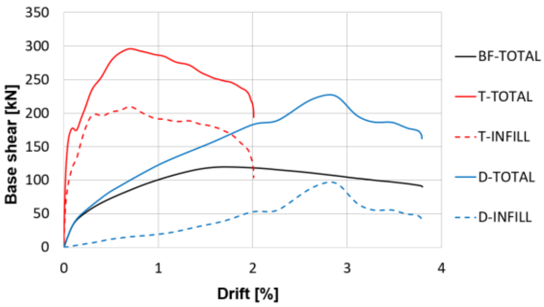

Figure 4. Force-drift curves of bare RC frame, infilled RC frames and masonry infills

a) *b)*

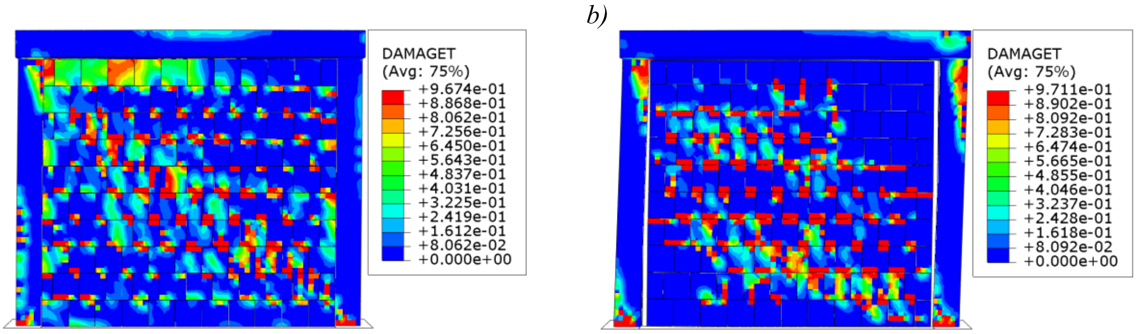

Figure 5. Significant damage on a) traditional infill (Δ = 0.7 %) and b) decoupled infill (Δ = 3.0 %)

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In the post-processing of numerical results internal forces on the bare RC frame (BF), RC frame with traditional infill (T) and RC frame with decoupled infill (D) are determined. For instance, distribution of bending moments on the left column is compared between bare RC frame and traditionally infilled RC frame in Figure 6a and between bare RC frame and RC frame with decoupled infill in Figure 6b. Interaction between RC frame and traditional infill significantly affects the bending moment propagation on the left column, starting already at 0.1 % of in-plane drift. Opposite to this, there is almost no difference in bending moments of the bare RC frame and RC frame with decoupled infill. The effect of infill activation can only be seen at 2.0 % of in-plane drift. The result of the strong frame-infill activation in the case of traditional infill can be observed in Figure 5a too. Because of the increased bending moments, left column experiences cracking up to half of its height. On the other side, damage propagation on the RC frame with decoupled infill corresponds to the common damage propagation of bare RC frames, concentrated in the column corners (Fig. 5b).

The numerical results are compared in the similar way for the distribution of shear forces in Figure 7a. An early activation of traditional masonry infill imposes high shear forces on the top left corner of the RC frame. For instance, at 0.1 % of in-plane drift, shear force in the top left corner of the traditionally infilled RC frame is around 2.76 times larger than the shear force in the bare RC frame. At 0.5 % and 1.0 % of in-plane drift, this ratio is equal to 2.39. At 1.5 % and 2.0 % of in-plane drift it drops to 2.17 and 1.84, respectively, due to the damage to the infill. On the other side, the decoupling system reduces the local effects in the top left corner of the RC frame, in comparison to the traditionally infilled RC frame. More significant increase of the shear forces in the top left corner can be noticed at around 1.5 % and 2.0 % of in-plane drift. For instance, at 1.5 % and 2.0 % of in-plane drift shear force on the RC frame with decoupled infill is around 1.45 and 1.76 larger than the shear force on the bare RC frame, respectively (Fig. 7b).

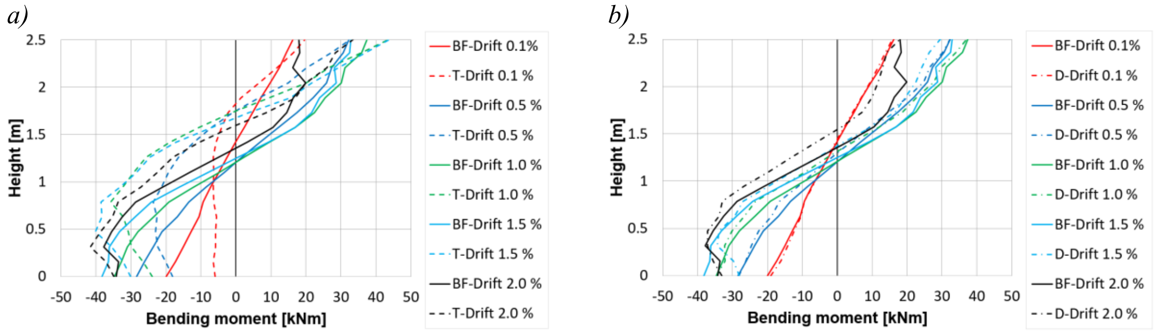

Figure 6. a) Bending moments on the left column of the bare frame and RC frame with traditional infill and (b) bare frame and RC frame with decoupled infill

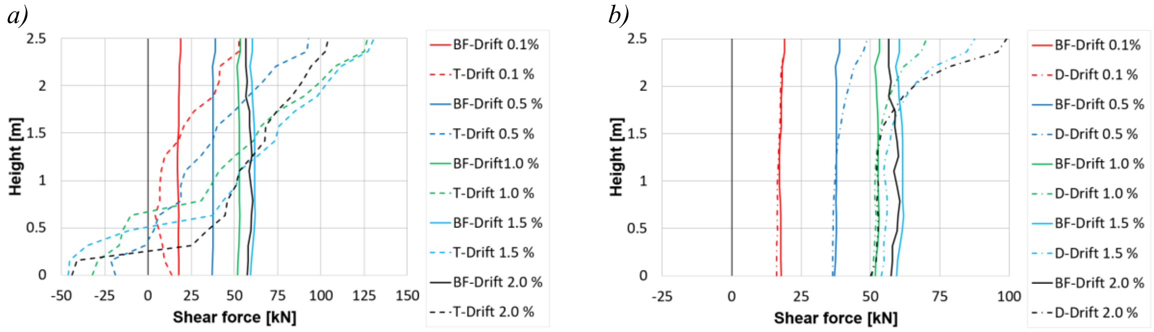

Figure 7. a) Bending moments on the left column of the bare frame and RC frame with traditional infill and (b) bare frame and RC frame with decoupled infill

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5. Parametric study

In the parametric study, parameters that represent infill geometry are varied, such as brick thickness and infill (frame) height-to-length ratio. The level of frame-infill interaction is evaluated through the comparison of force-drift curves of infilled frames and masonry infills, initial in-plane stiffness, ratio of the horizontal force of the infilled frame to the horizontal force of the bare RC frame (H_{IF}/H_{BF}), ratio of the horizontal force of decoupled masonry infill to the horizontal force of the bare RC frame (H_{INF}/H_{BF}), and ratio of the shear force in the top left corner of the infilled frame to the bare RC frame ($V_{TL,IF}/V_{TL,BF}$).

5.1. Brick thickness

The effect of brick thickness of 10 cm, 20 cm, 30 cm and 36.5 cm is investigated. The results of the RC frame with 30 cm thick masonry infill are presented in Section 4 in detail. In Figure 8 and Table 1 it can be seen that all traditional infills (T) significantly affect the in-plane response of the RC frame. The force-drift curves of traditionally infilled RC frames have high initial stiffness, and the maximum horizontal forces are reached at around 0.6 – 0.9 % of in-plane drift, depending on the brick thickness (Fig. 8a). Due to the damage to traditional infills, the horizontal forces of infilled RC frames start to drop. Force-drift curves of traditional infills also point that traditional infills strongly contribute to the total horizontal force up to around 0.8 % of in-plane drift. Expectedly, larger brick thickness leads to a higher infill contribution (Fig. 8b). The force-drift curves of RC frames with decoupled infills (D) are very similar to the force-drift curves of the bare RC frame. For instance, up to 1.0 % of in-plane drift, almost no difference can be seen between the curves of the RC frames with decoupled infills and bare RC frame. For in-plane drifts between 1.0 % and 2.0 % horizontal forces of the RC frames with decoupled infills slowly start to increase (Fig. 8a). However, the first stepwise cracks in all investigated decoupled infills appear at around 2.0 % of in-plane drift. This is followed by a more noticeable increase of the horizontal force, which is more pronounced for the infills with a brick thickness of 30 cm (T30-D) and 36.5 cm (T36.5-D) and less for infills with a thickness of 20 cm (T20-D) and 10 cm (T10-D) (Fig. 8b).

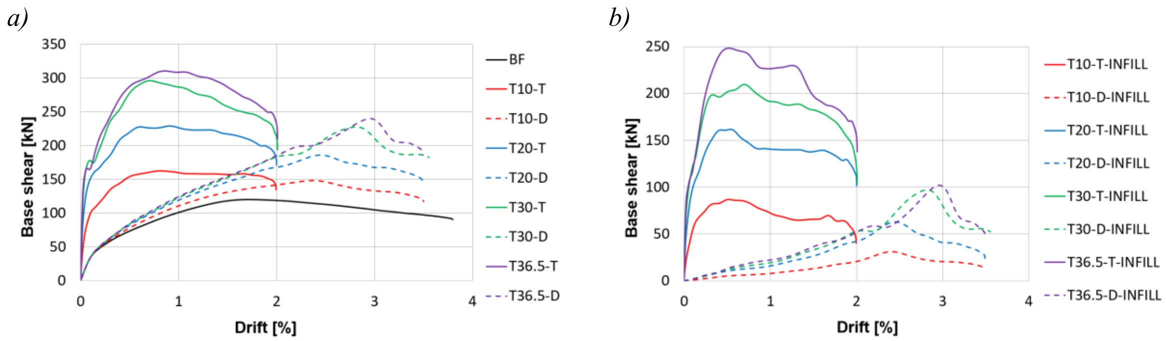

Figure 8. a) Force-drift curves of infilled RC frames; b) Force-drift curves of masonry infills with different brick thicknesses

For a direct comparison, the results of numerical simulations are summarised in Table 1. It can be seen that there is no difference between the initial stiffness of the bare RC frame and RC frame with decoupled infills, for all investigated thicknesses. On the other side, the initial stiffnesses of the traditionally infilled RC frames are around 5, 10, 15 and 17 times higher than the initial stiffness of the bare RC frame for the infill thicknesses of 10 cm, 20 cm, 30 cm and 36.5 cm, respectively. Furthermore, it can be seen that the H_{IF}/H_{BF} ratio for traditional infills takes the highest values at already 0.1 % of in-plane drift. For instance, at 0.1 % of in-plane drift horizontal force of the traditionally infilled RC frame (H_{IF}) is around 2.9, 4.4, 5.1 and 4.8 times larger than the horizontal force of the bare RC frame (H_{BF}), for infill thickness of 10 cm, 20 cm, 30 cm and 36.5 cm respectively. With an increase of in-plane drift, this ratio decreases because of the propagating damage to the masonry infill and surrounding RC frame. On the other side, at 0.1 % of in-plane drift, the H_{IF}/H_{BF} ratio is equal to 1.0 for decoupled infills with

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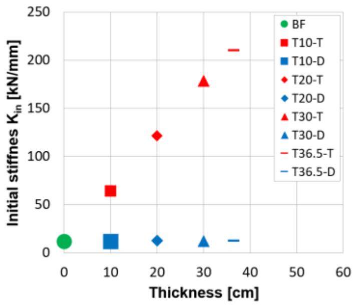
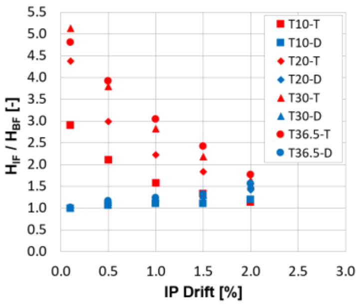
all thicknesses. Because of the decoupling system, the H_{IF}/H_{BF} slowly increases with an increase of the in-plane drift. For instance, for the infills with thicknesses of 30 cm and 36.5 cm, it is around 1.6 and 1.7 at 2.0 % of in-plane drift, whereas for thinner infills, it is even smaller (1.1 and 1.4 for 10 cm and 20 cm thick decoupled infill, respectively). In Table 1 the H_{INF}/H_{BF} is presented only for decoupled infills. At 0.1 % of in-plane drift, the horizontal forces of decoupled infill are less than 2 % of the horizontal force taken by the horizontal force of the bare RC frame. The diagram shows that the H_{INF}/H_{BF} ratio increases for higher in-plane drifts, but at 1.5 % of in-plane drift it is still less than 0.3 for all configurations. At 2.0 % of in-plane drift, the H_{INF}/H_{BF} ratio is equal to 0.44 for decoupled infills with thicknesses of 30 cm and 36.5 cm. For decoupled infills with thicknesses of 20 cm and 10 cm it is around 0.35 and 0.17, respectively. The negative effects of the traditional infills on the frame behaviour can also be seen in Table 1. The $V_{TL,IF}/V_{TL,BF}$ ratio is around 3 for the 36.5 cm thick traditional infill, up to 1.0 % of in-plane drift, and at 1.5 % and 2.0 % of in-plane drift, it takes the values of around 2. The 30 cm and 20 cm thick traditional infills also impose shear forces on the top left corner of the left column of the RC frame that are around 2-3 times larger than the shear forces of the bare RC frame, up to 2.0 % of in-plane drift. Even the $V_{TL,IF}/V_{TL,BF}$ ratio for infill with a 10 cm thickness is larger than 2.0 for in-plane drifts of 0.5 % and 1.0 %, and between 1.5 and 2.0, for in-plane drifts between 1.0 % and 2.0 %. These results indicate that traditional infills impose shear forces that are much higher than the shear forces that act on the RC frame without traditional infills, which can lead to additional damage to the RC frame column. If the decoupling system is installed, the $V_{TL,IF}/V_{TL,BF}$ ratio is equal to 1.0 for all infill thicknesses at 0.1 % of in-plane drift, and it remains smaller than 1.5 for all infill thicknesses up to 1.5 % of in-plane drift, with a rather small differences in the $V_{TL,IF}/V_{TL,BF}$ ratios for different thicknesses. Only at 2.0 % of in-plane drift, the $V_{TL,IF}/V_{TL,BF}$ ratio is around 1.75 for 30 cm and 36.5 cm thick decoupled infills, 1.6 for the 20 cm thick decoupled infill, and 1.3 for 10 cm thick decoupled infill.

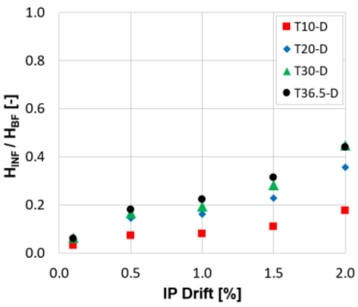
Table 1. Summary of results on RC frames with traditional and decoupled infills with different brick thicknesses



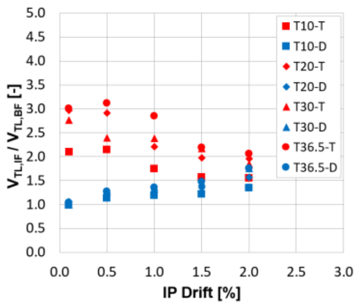
Initial stiffnesses



H_{IF}/H_{BF} ratio in function of in-plane drift



H_{INF}/H_{BF} ratio in function of in-plane drift



$V_{TL,IF}/V_{TL,BF}$ ratio in function of in-plane drift

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5.2. Height-to-length ratio

In addition, the influence of the height-to-length ratio is investigated by varying the infill length. Other parameters are kept the same, and the considered brick thickness is 30cm. Three infill lengths are considered: 1.5 m (short infill-S), 2.77 m (infill that is also investigated experimentally) and 4.5 m (long infill-L). The results of the RC frame with 2.77 m long masonry infill are presented in Section 4 in detail. Bare RC frames with different opening lengths are also investigated: BF-S ("short" bare frame), BF (experimentally tested bare frame with 2.77 m long opening) and BF-L ("long" bare frame). Force-drift curves in Figure 9a show that all investigated bare RC frames (BF) have an almost identical in-plane response. The in-plane response of all traditionally infilled RC frames (T) is recognisable by the high initial stiffness. However, it can be seen that the RC frame with the short traditional infill (T_Short) reaches a significantly smaller maximum horizontal force than the other two traditionally infilled RC frames. Furthermore, RC frames with a 2.77 m long traditional masonry infill and a 4.5 m long traditional masonry infill reach the maximum horizontal forces at around 0.7 % and 1.1 % of in-plane drift, respectively, and the RC frame with a 1.5 m long traditional masonry infill at around 1.5 % of in-plane drift. However, the horizontal force of the RC frame with a 1.5 m long traditional masonry infill is almost constant at in-plane drifts larger than 1.0 %. Force-drift curves of traditional infills show that the longer the infill, the higher its contribution to the total horizontal force (Fig. 9b). Additionally, the traditional infill force-drift curves also indicate that the short infill can experience a more drastic loss of the force capacity because of the high compressive stresses developed in the infill that lead to the severe damage. Force-drift curves of RC frames with decoupled infills indicate that the in-plane response of the RC frames with decoupled infills with different lengths (D) is similar to the in-plane response of corresponding bare RC frames (Fig. 9a). Up to 1.0 % of in-plane drift, there is no significant discrepancy between the curves of the RC frames with decoupled infills and corresponding bare RC frames. Between 1.0 % and 2.0 % of in-plane drift, a rather slow increase in the horizontal force can be seen for RC frames with two longer infills, while the horizontal force of the RC frame with a short decoupled infill is dominantly constant after around 1.3 % of in-plane drift. This is because the short decoupled infill is activated sooner, at around 1.3 % of in-plane drift, which can be observed by the jump of the horizontal force of decoupled infill in Fig. 9b. The first stepwise cracks appear later on other two decoupled infills, at around 2.0 % of in-plane drift, when the more pronounced increase in the horizontal force on both decoupled infill and infilled RC frame can be observed (Fig. 9a,b).

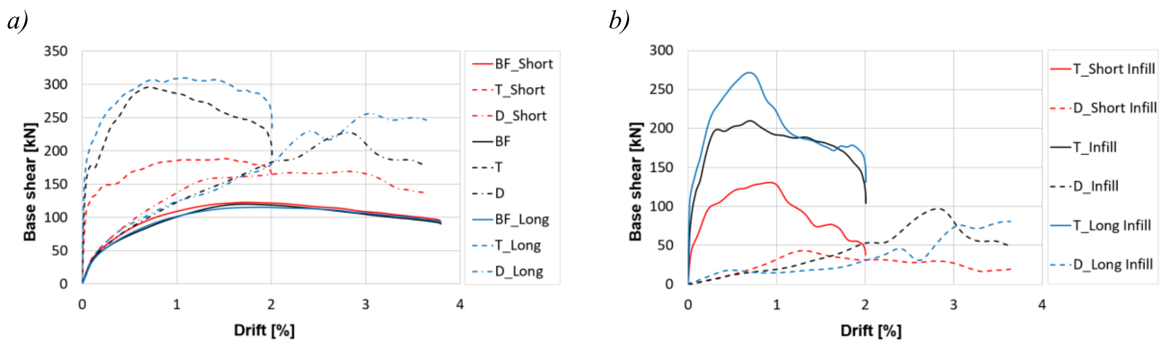

Figure 9. a) Force-drift curves of infilled RC frames; b) Force-drift curves of masonry infills with different height-to-length ratios

Table 1 summarises the results of the numerical simulations on bare RC frames infilled RC frames with different height-to-length ratios (H/L). Firstly, it can be seen that the change of the infill (and frame) length has no influence on the initial stiffness of bare RC frames, as well as on the initial stiffness of the RC frames with decoupled infills. In the case of traditional infills, the initial stiffness of the short-infilled RC frame is around 12, and of the long-infilled RC frame, 26 times larger than the initial stiffness of corresponding bare RC frames. Furthermore, the H_{IF}/H_{BF} ratio for RC frames with traditional and decoupled infills with different infill lengths is presented. At 0.1 % of in-plane H_{IF}/H_{BF} is around 6.5, 5.1 and 3.6 for long infill, almost square infill, and short infill, respectively. At 0.5 % of in-plane drift, this ratio drops to around 2 for the short infill and to around 3.8 for the other two cases. With

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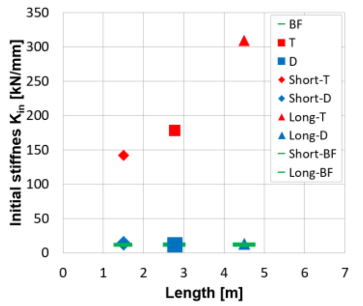
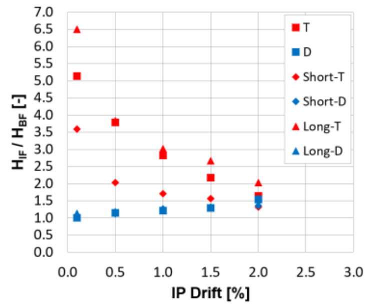
further damage to traditional infills, the H_{IF}/H_{BF} ratio further reduces. The opposite can be seen in the case of the RC frames infilled with decoupled infills. At 0.1 % of in-plane drift, there is no difference in the horizontal forces of the infilled and bare RC frames. At larger in-plane drifts, the H_{IF}/H_{BF} ratio increases slowly, taking similar values for different infill lengths. At 2.0 % of in-plane drift, the H_{IF}/H_{BF} values are 1.4 for the short and around 1.6 for the almost square and long infill. Table 1 also presents the H_{INF}/H_{BF} ratio for decoupled infills. It can be seen that the horizontal forces of decoupled infills are rather low in comparison with the horizontal force of the corresponding bare RC frame. For instance, horizontal forces of all decoupled infills are less than 30 % of the horizontal force of the bare RC frame. Only at 2.0 % of in-plane drift, the H_{INF}/H_{BF} ratio is 0.44 for the almost square decoupled infill. A high $V_{TL,IF}/V_{BF}$ ratio can be seen for all traditional infills. For instance, up to 1.0 % of in-plane drift, long traditional infill imposes shear forces in the top of the left column that are more than 3 times larger than the shear forces of the corresponding bare RC frame, and for in-plane drifts of 1.5 % and 2.0 % the $V_{TL,IF}/V_{BF}$ ratio is around 2.5. For the RC frame with the almost square traditional infill, the $V_{TL,IF}/V_{BF}$ ratio is around 2-3 times larger than for the corresponding bare RC frame, with the largest shear forces imposed at the lower in-plane drifts. At 0.1 % of in-plane drift, the short traditional infill imposes shear forces 2.5 times larger than the shear forces on the corresponding bare RC frame. For higher in-plane drifts, this ratio is between 1.5 and 2.0 because of the propagating damage to the short traditional infill. On the other side, the decoupling system reduces the local effects. For instance, at 0.1 % of in-plane drift, the $V_{TL,IF}/V_{TL,BF}$ ratio is around 1.3 for the long infill, and around 1.0 for other two configurations. Up to 1.5 % of in-plane drift, the ratio slowly increases, but it is lower than 1.5 for all configurations. Only at 2.0 % of in.plane drift, $V_{TL,IF}/V_{BF}$ is around 1.75 for the long and almost square infill, but still around 1.4 for the short decoupled infill.

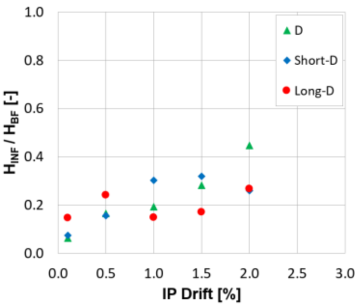
Table 2. Summary of results on RC frames with traditional and decoupled infills with different H/L ratios



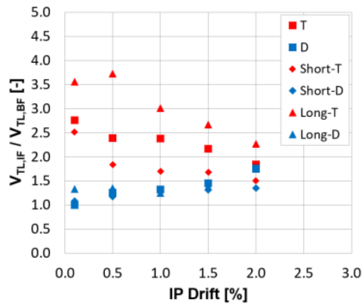
Initial stiffnesses



H_{IF}/H_{BF} ratio in function of in-plane drift



H_{INF}/H_{BF} ratio in function of in-plane drift



$V_{TL,IF}/V_{TL,BF}$ ratio in function of in-plane drift

6. Conclusions

In this paper, the in-plane behaviour of RC frames with traditional and decoupled infills is investigated by means of numerical simulations. Traditional infills represent common masonry infills connected to the RC frame by the mortar, while decoupled infills refer to masonry infills decoupled from the RC frame by the innovative decoupling system INODIS. After validation of the numerical model against the available experimental results, a parametric study is carried out. The parameters varied are brick thickness and infill height-to-length ratio. The results of numerical simulations clearly show the benefits

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of the decoupling system for all investigated infill configurations. All traditional infills activate at low in-plane drifts. Due to this, the initial in-plane stiffnesses of the traditionally infilled RC frames are between 5 and 26 times larger than the initial stiffness of the corresponding bare RC frame. Furthermore, for all investigated configurations, the horizontal forces of the traditionally infilled RC frames are at least 2-3 times larger than the horizontal forces of the corresponding bare RC frames, already at in-plane drifts up to 0.5 %. Because of the significant damage to traditional infills, the H_{INF}/H_{BF} ratio has a descending trend. Moreover, the strong infill action imposes shear forces at the top of the left column that are at least around 2 times larger than the shear forces of the bare RC frame, already at in-plane drifts of 0.1 % and 0.5 %. It can be concluded that neglecting traditional masonry infills in the seismic design is incorrect and dangerous, as they change the response of the bare RC frame, and suffer significant damage at low in-plane drifts. However, the level of their activation strongly depends on the brick thickness and height-to-length ratio, which complicates the development of a design concept for their verification. On the contrary, the frame-infill interaction is significantly reduced between decoupled infills and RC frames. Firstly, the initial in-plane stiffnesses of the RC frames with decoupled infills obtain the same values as the initial in-plane stiffnesses of the corresponding bare RC frames. In addition to this, the H_{IF}/H_{BF} ratio has an increasing trend because of the slow infill activation, and it takes the values between 1.0 and 1.5 up to the in-plane drift of 1.5 %. At 2.0 % of in-plane drift, the H_{IF}/H_{BF} ratio is slightly over 1.5 just for three investigated configurations. The horizontal forces of decoupled infills also remain low, and up to 1.5 % of in-plane drift, they are less than 30 % of the bare frame horizontal force, whereas at 2.0 % of in-plane drift only three configurations obtain infill horizontal forces that are between 35 % and 45 % of the bare frame horizontal force. Additionally, the decoupling system reduces the local effects. The shear forces at the top of the left column slowly increase with the increase of the in-plane drift, but even at 2.0 % of in-plane drift, the $V_{TL,IF}/V_{TL,BF}$ ratio is lower than 1.5 for most of the infill configurations, and it is around 1.75 for only three considered configurations. Finally, the in-plane behaviour of all considered RC frames with decoupled infills is similar, as no big differences in the in-plane response can be observed, up to 2.0 % of in-plane drift. After 2.0 % of in-plane drift, most of the decoupled infills get more activated and some differences in their behaviour can be noticed. However, the in-plane response for in-plane drifts larger than 2.0 % is not important for the practice, as 2.0 % of in-plane drift usually represents the design limit value. Therefore, based on the observed in-plane response of RC frames with decoupled infills, the development of a simple design concept seems promising. In future work, authors plan to study the effect of other important parameters, such as openings in the infills, and derive recommendations regarding the seismic design of RC frames with decoupled infills, applicable in the engineering practice.

References

[1] Marinković, M., Baballëku, M., Isufi, B., Blagojević, N., Milićević, I., Brzev, S. (2022): Performance of RC cast-in-place buildings during the November 26, 2019 Albania earthquake. *Bulletin of Earthquake Engineering,* 20:5427-5480. https://doi.org/10.1007/s10518-022-01414-y

[2] Marinković, M., Brzev, S., Baballëku, M., Isufi, B., Blagojević, N., Milićević, I., Žugić, Ž., Bursać, P. (2021): Out-of-plane behaviour of loadbearing and non-structural masonry walls during recent earthquakes. In Conference proceedings from 1st Croatian Conference on Earthquake Engineering-1CroCEE, 22nd to 24th March 2021, Zagreb, 2021 (Vol. 64, pp. 213-207). University of Zagreb, Faculty of Civil Engineering.

[3] Dilsiz A. et al. (2023): "StEER: 2023 Mw 7.8 Kahramanmaras, Türkiye Earthquake Sequence Preliminary Virtual Reconnaissance Report (PVRR)", in StEER- February 6, 2023, Kahramanmaras, Türkiye, Mw 7.8 Earthquake. DesignSafe-CI. https://doi.org/10.17603/ds2-7ry2-gv66

[4] Dawe, J.L., Seah, C.K. (1989): Behaviour of masonry infilled steel frames. *Canadian Journal of Civil Engineering*, *16*(6), 865-876.

[5] Mehrabi, A.B., Shing, P.B., Schuller, M.P., Noland, J.L. (1994): Performance of Masonry-Infilled R/C Frames under in-Plane Lateral Loads; Report No. CU/SR-94-6; Department of Civil, Environmental, and Architectural Engineering, University of Colorado: Denver, CO, USA

Copyright © 2025 CroCEE
DOI: https://doi.org/10.5592/CO/3CroCEE.2025.96

[6] Flanagan, R.D., Bennett, R.M. (1999a): In-plane behavior of structural clay tile infilled frames. *Journal of Structural Engineering,* 125(6): 590-599. https://doi.org/10.1061/(ASCE)0733-9445(1999)125:6(590)

[7] Stylianidis, K.C. (2012): Experimental investigation of masonry infilled RC frames. The Open Construction *& Building Technology Journal,* 6 (1):194-212. https://doi.org/10. 2174/1874836801206010194

[8] Morandi, P., Hak, S., Magenes, G. (2017a): Experimental and numerical seismic performance of strong clay masonry infills. In Appendix: guideline proposal for seismic design of masonry infills. Research Report 2017a/02. EUCENTRE Foundation

[9] Di Trapani, F., Khan, N. A., Zhou, L., Demartino, C., Monti, G. (2024): Cyclic response of infilled RC frames with window and door openings: Experimental results and damage interpretation. *Earthquake Engineering & Structural Dynamics*, *53*(1), 43-67. https://doi.org/10.1002/eqe.4005

[10] Stavrdis, A., Shing, P.B. (2010): Finite-element modelling of nonlinear behaviour of masonry-infilled RC frames. *Journal of Structural Engineering*, 136(3), 285-296.

[11] Nasiri, E., Liu, Y. (2017): Development of a detailed 3D FE model for analysis of the in-plane behaviour of masonry infilled concrete frames. *Engineering Structures*, 143, 603-616.

[12] Di Trapani, F., Shing, P.B., Cavaleri, L. (2018): Macroelement Model for in-plane and out-of-plane responses of masonry infills in frame structures. *Journal of Structural Engineering,* 144(2):04017198. https:// doi. org/ 10. 1061/(ASCE) ST. 1943- 541X. 00019 26

[13] Kubalski, T. (2023): Modellierung von seismisch beanspruchten Mauerwerksausfachungen in Stahlbetonrahmentragwerken (Doctoral dissertation, RWTH Aachen Univresity, 2022)

[14] Koutas, L., Bousias, S.N., Triantafillou, T.C. (2015): Seismic strengthening of masonry-infilled RC frames with TRM: Experimental study. *Journal of Composites for Construction,* 19(2):04014048. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000507

[15] da Porto, F., Donà, M., Verlato, N., Guidi, G. (2020): Experimental testing and numerical modeling of robust unreinforced and reinforced clay masonry infill walls, with and without openings. *Frontiers in Built Environment,* 6:591985. https://doi.org/10.3389/fbuil.2020.591985

[16] Morandi, P., Milanesi, R.R., Magenes, G. (2018a): Innovative solution for seismic-resistant masonry infills with sliding joints: in-plane experimental performance. *Engineering Structures,* 176:719-733. https://doi.org/10.1016/j.engstruct.2018.09.018

[17] Preti, M., Bolis, V. (2017): Masonry infill construction and retrofit technique for the infill-frame interaction mitigation: test results. *Engineering Structures,* 132:597-608. https://doi.org/10.1016/j.engstruct.2016.11.053

[18] Bolis, V., Stavridis, A., Preti, M. (2017): Numerical investigation of the in-plane performance of masonry-infilled RC frames with sliding subpanels. *Journal of Structural Engineering*, 143(2), 04016168. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001651

[19] Tsantilis, A.V., Triantafillou, T.C. (2018a): Innovative seismic isolation of masonry infills using cellular materials at the interface with the surrounding RC frames. *Engineering Structure,s* 155:279-297. https://doi.org/10.1016/j.engstruct.2017.11.025

[20] Jin, W., Zhai, C., Zhang, M., Liu, W., Wei, Y., Xie, L. (2023): Experimental investigation on the in-plane and out-of-plane interaction of isolated infills in RC frames. *Engineering Structures*, *293*, 116569. https://doi.org/10.1016/j.engstruct.2023.116569

[21] GB 50011-2010 (2010) Code for Seismic Design of Buildings, Architecture & Building Press, Beijing, China (In Chinese)

[22] Standards New Zealand (2004) NZS 4230:2004, Design of Reinforced Concrete Masonry Structures, Standards New Zealand, Wellington, New Zealand.

[23] Milijaš, A., Marinković, M., Butenweg, C., Klinkel, S. (2024): Experimental investigation on the seismic performance of reinforced concrete frames with decoupled masonry infills: Considering in-plane and out-of-plane load interaction effects. *Bulletin of Earthquake Engineering*, 22, 7489-7546, https://doi.org/10.1007/s10518-024-02012-w

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DOI: https://doi.org/10.5592/CO/3CroCEE.2025.96

[24] Marinković, M., Butenweg, C. (2022): Numerical analysis of the in-plane behaviour of decoupled masonry infilled RC frames. *Engineering Structures*, *272*, 114959. https://doi.org/10.1016/j.engstruct.2022.114959

[25] Milijaš, A., Marinković, M., Butenweg, C., Klinkel, S. (2023): Experimental results of reinforced concrete frames with masonry infills with and without openings under combined quasi-static in-plane and out-of-plane seismic loading, *Bulletin of Earthquake Engineering*, 21:3537-3579. https://doi.org/10.1007/s10518-023-01664-4

[26] Simulia, Abaqus, User Manual. Version 6.13. Providence, RI, USA: DS SIMULIA Corp., 2013. URL https://www.3ds.com/products-services/simulia/products/abaqus/