INNOVATIVE SOLUTION FOR DECOUPLING RC FRAMES FROM MASONRY INFILLS WITH OPENINGS: EXPERIMENTAL RESULTS

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Abstract: *Masonry infills are a common solution for inner and outer partitions in RC frame structures. However, uncontrolled and heavy damage to masonry infills in recent earthquake events often caused by the interaction of masonry infills with RC frames showed the high seismic vulnerability. Severe damage to masonry infills results in high economic losses and presents a threat to human safety. The bad seismic performance of masonry infills is a strong motivation for finding solutions that can prevent or reduce the damage to masonry infills. This paper presents the principles of an innovative system for decoupling of masonry infills from the surrounding frame. The decoupling is achieved by inserting recycled rubber strips between masonry infills and RC frame. The installed decoupling system postpones the activation of masonry infills under in-plane seismic loads and provides support under out-of-plane seismic loads. Experimental results on RC frames with rigidly connected infills and RC frames with decoupled infills are presented and compared for infills with and without openings. Results of the study show the highly improved seismic performance of masonry infills with the innovative decoupling system.*

1. Introduction

Reinforced concrete (RC) frame structures with masonry infills represent a prevalent architectural style worldwide. Typically, the design of such structures does not account for masonry infills as they are considered non-structural elements. However, seismic loads usually activate masonry infills, inducing considerable in-plane (IP) stresses and deformations. In addition to the in-plane loads, masonry infills are simultaneously loaded also by out-of-plane (OOP) seismic forces. Despite their influence on dynamic response of structure and behavior modification, the complex nature of the problem and the absence of a realistic yet simple analytical model have led infill walls in frame buildings to be neglected.

Contrary to this, post-earthquake observations by various researchers show the impact of interaction between infill walls and the structural system during seismic events and its effect on the structure's dynamic response (e.g. Braga et al., 2011; De Luca et al., 2014; Marinković et al., 2022; Sezen et al., 2023; Dilsiz et al., 2023). Researchers such as Ricci et al. (2011) and Asteris et al. (2015) have recognized an increase in stiffness and a change in the period of a structure due to the presence of infills. The consensus is that the effects of infills must be considered to ensure adequate design; otherwise, the design may be inadequate.

However, if infills are isolated from the surrounding frame with low interaction, the design can focus solely on the bare frame.

Given the frequent occurrence of IP or OOP failures of infill walls during earthquakes (Figure 1), limiting damage in these elements becomes a critical public safety concern. Neglecting this consideration could result in injuries or casualties, even for earthquakes with less than design intensity. Additionally, the economic implications of infill damage are substantial, encompassing repair or reconstruction costs for infills, structural system damages, non-structural components, equipment, rental and relocation expenses, and general income losses

Figure 1. Damage and OOP collapse of infills in RC buildings: left (Turkey 2023), right (Albania 2019)

The complex interaction between frames and infills in the context of seismic performance of infilled frame buildings has been a subject of study for several decades. Numerous experimental investigations have primarily focused on the response of infilled frames under IP loads, as evidenced by studies such as Mehrabi et al. (1996), Shing and Mehrabi (2002), Stylianidis (2012), Morandi et al. (2014), and Hak et al. (2017), among others. In contrast, studies by Dawe and Seah (1989), Griffith and Vaculik (2007), Furtado et al. (2021), and Milijaš et al. (2023) have presented varying findings regarding OOP loads and deformation capacity. Notably, insufficient connections between frames and infills have been linked to tilting and OOP failure, as observed in the aftermath of recent earthquakes in Wenchuan 2008 (Mohyeddin-Kermani et al., 2008), L'Aquila 2009 (Braga et al., 2011; Vicente et al., 2012), Central Italy 2016 (Perrone et al., 2019), and Albania (Marinković et al., 2022).

Moreover, extensive numerical simulations conducted by Kadysiewski and Mosalam (2009) and Marinković and Butenweg (2022a) have delved into the effects of IP, OOP, and combined IP/OOP actions on infills. Butenweg et al. (2019) emphasize the significance of considering IP/OOP interaction, as their testing campaign revealed a reduction in OOP load capacity by 3-5 times and IP drift capacity by 2 times.

Recent research by Blasi et al. (2017), Bolis et al. (2018), and Milanesi et al. (2018) has extensively explored the local effects on reinforced concrete frames induced by masonry infills, underscoring the importance of incorporating these effects into considerations for a comprehensive understanding of the structural behavior.

The increase of research projects and recurring instances of seismic damage underscore the challenges in designing traditional masonry infill walls in direct contact with RC frames to withstand earthquakes. Consequently, various strategic approaches have been developed to enhance the seismic resilience of masonry-infilled RC frames, broadly categorized into three methods: strengthening, ductile infills, and isolated/decoupled infills.

In the first approach, the emphasis is on significantly increasing the load-bearing capacity of the masonry infill through a rigid connection to the frame. Various techniques for reinforcement can be found in the literature (Calvi and Bolognini, 2001; Porto et al., 2013; Vintzileou et al., 2016), substantially improving the load-bearing and deformation capacities of the masonry infills. However, it's crucial to note that reinforced masonry infills become integral to the horizontal load bearing system, losing their non-load-bearing status. This compromises flexibility in use, as these infills become structural elements that cannot be simply and arbitrarily removed. Moreover, such masonry walls are economically unattractive in comparison to reinforced concrete, primarily due to the extensive manual construction work involved.

The second approach focuses on enhancing the seismic behavior by augmenting the deformation capacity of the masonry infill wall through specific construction measures. Preti et al. (2015, 2016) proposed a solution involving multiple horizontal sliding surfaces in the wall. Verlato et al. (2016) and Morandi et al. (2018) developed comparable approaches with unique sliding surfaces and connection elements. However, additional edge profiles are needed for reliable boundary conditions, especially around window and door openings (Morandi et al., 2018).

The third approach seeks to improve the seismic behavior by decoupling the frame and masonry infill, preventing frame deformations from imposing high stress on the infills, thus making them non-interacting infill walls. Aliaari and Memari (2005) demonstrated that such decoupling significantly reduces infill damage. Kuang and Wang (2014) explored a solution involving gaps between the infill and columns, using additional steel anchors to prevent OOP failure. Nevertheless, Marinković and Butenweg (2022b) highlighted that steel anchors lead to stress concentrations, diminishing both OOP load capacity and IP drift capacity. Various researchers (Paulay and Priestley, 1992; Bennett et al., 1996; Tsantilis and Triantafillou, 2018) suggested isolation/decoupling for improving the behavior of infill walls under earthquake excitation.

This paper presents an extensive experimental campaign on a infill protection solution that is based on isolating/decoupling infill walls from the surrounding frame. Through thorough experimental campaigns and numerical simulations, the system was tested and refined to offer a practical solution. The results show substantial improvements in the behavior of infill walls.

2. Non-interacting infills as a possible solution for masonry infill walls

The article introduces a novel decoupling system designed for earthquake-resistant connections of masonry infills in RC frames. Developed through several research projects, this system has received Europe-wide patent approval. This paper presents a progression of the decoupling system initially proposed by Marinković and Butenweg (2019). The investigation focuses on a full-scale RC frame infilled with hollow clay bricks, subjected to both separate and combined IP and OOP loads to assess the performance of the decoupling system. Its effectiveness is demonstrated through a comparative analysis with test results from traditionally infilled RC frames.

The primary objective of the decoupling system is to enhance IP drift and OOP load capacity, particularly under seismic excitation-induced loads. Constructed from recycled rubber material, the system offers a cost-efficient solution that can be applied to various brick types and easily installed on-site. The conceptual design of the system is illustrated in Figure 2 for a fully infilled RC frame. Figure 3 shows details of the REGUPOL INODIS decoupling system for non-interacting infills. Comprising three rubber stripes, the system employs a strategic arrangement: the middle stripes are affixed to the surrounding RC frame, while the outer stripes are attached to the bricks, using a thin layer of mortar for adhesion. Thicker, lower stiffness stripes are placed between the masonry infill and columns at the sides to absorb IP deformation and delay infill activation. Thinner rubber stripes with higher compression and shear stiffness are positioned at the top and bottom interfaces, crucial for ensuring OOP stability. These stripes limit OOP displacements until arching action in the infill is activated. Additionally, rubber support at the sides enhances the masonry infill against OOP loads. Moreover, there are thin plastic profiles with sliding surfaces between rubber stripes at the top. This configuration minimizes the transfer of shear forces to the masonry infill due to friction, an essential element for successful decoupling of masonry infills and RC frames in the IP direction.

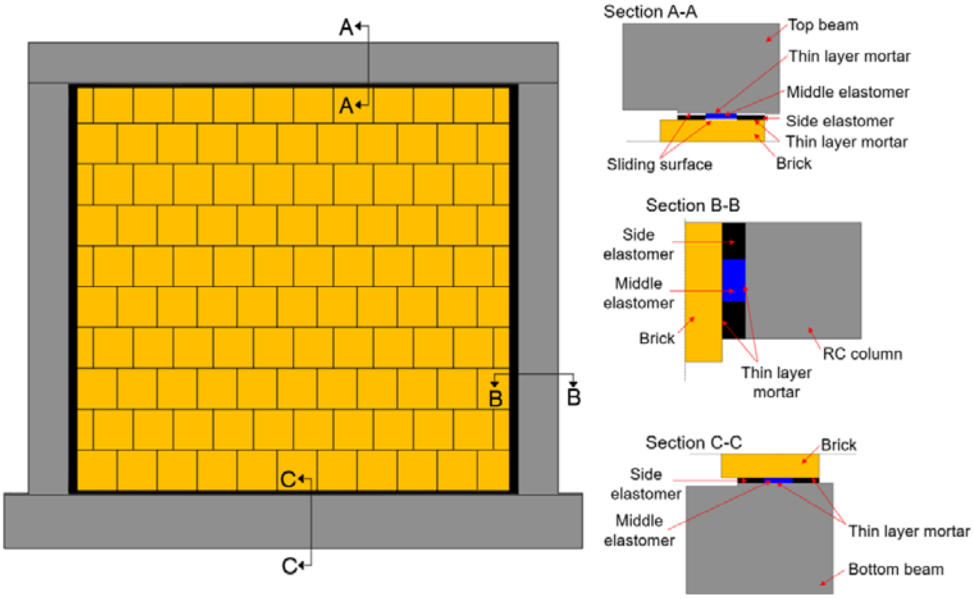


Figure 2. Conceptual setup of the decoupling system

The arrangement and selection of decoupling profiles in this system enable the simultaneous achievement of high IP drifts and substantial OOP forces. Depending on the design value of the interstorey drift, modifying the thickness and stiffness of rubber stripes between columns and RC frames becomes a straightforward way to safeguard masonry infills from IP damage. Notably, there is no need for variation in rubbers at the top and bottom, as their primary function is to provide boundary conditions for OOP loads and minimize shear force transfer, already addressed by adding sliding surfaces to the top rubber stripes. Importantly, this concept is applicable also to masonry infills with openings, requiring no additional measures for such configurations.

Figure 4 illustrates the construction of masonry infills with the decoupling system. In the initial step, middle rubber stripes are affixed to the columns and beams of the surrounding frame. The subsequent step involves placing outer side rubber stripes on the bottom beam, with initial pieces of outer rubber stripes on the columns. After applying thin layer mortar to the outer bottom stripes, bricks of the bottom layer are laid and bonded with mortar to the outer rubber stripes on the bottom beam and columns. In the third step, outer rubber stripes are further placed on columns, and thin layer mortar is applied to them. Bricklaying then continues in the standard manner. After constructing the last row of bricks, thin layer mortar is applied to the outer rubber stripes in the fourth step. Finally, outer rubber stripes are inserted and glued to the bricks of the uppermost row.

These steps highlight that the construction of infills with the decoupling system closely resembles that of traditional infills. The mortaring of rubber stripes to the surrounding frame and bricks using thin layer mortar is an additional advantage. Apart from rubber and sliding surfaces, already attached during the construction process, and only for the rubber stripes at the top frame-infill connection, no new materials are required. Furthermore, the installation of the system is robust enough for construction sites, adding to its practicality.

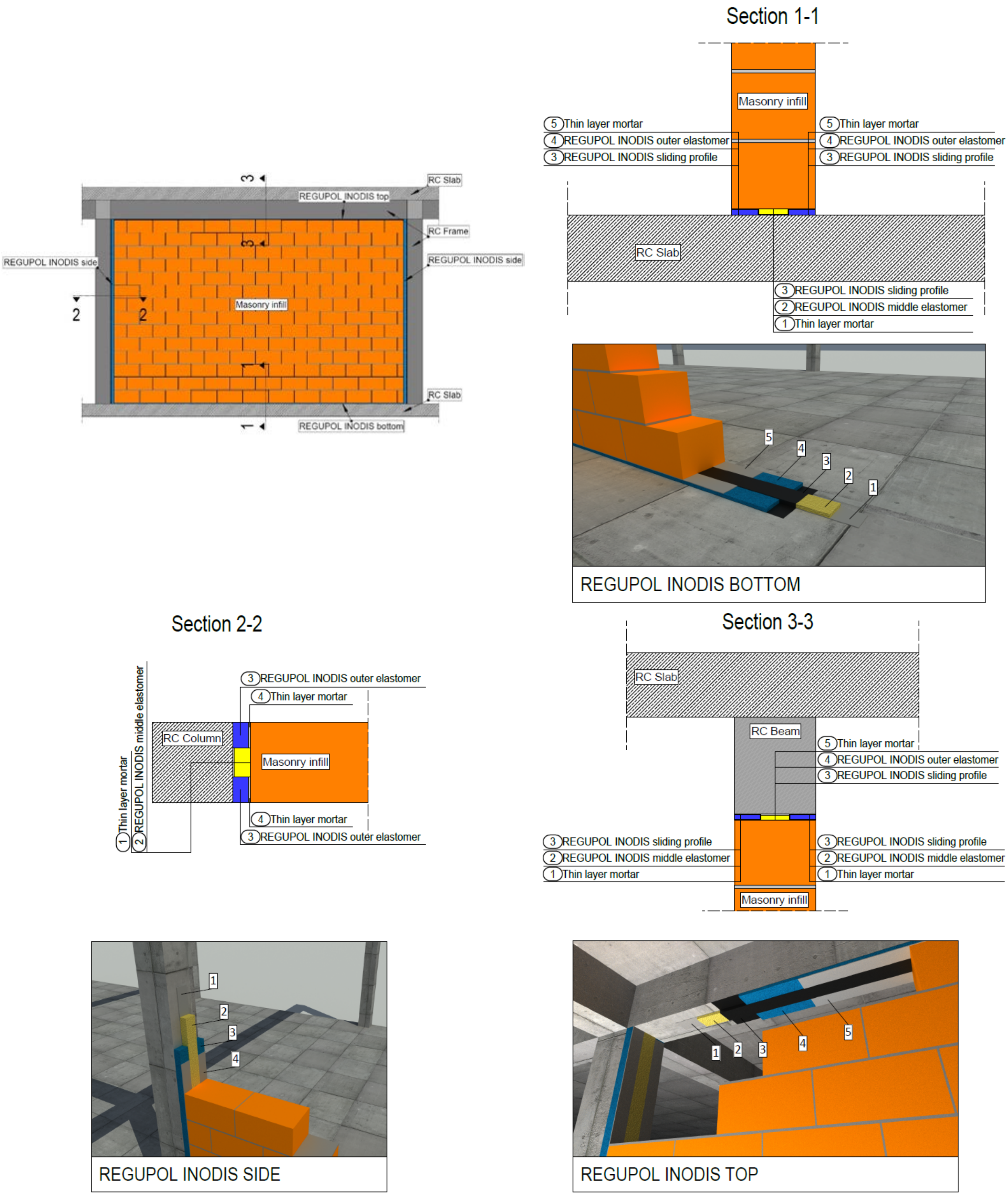
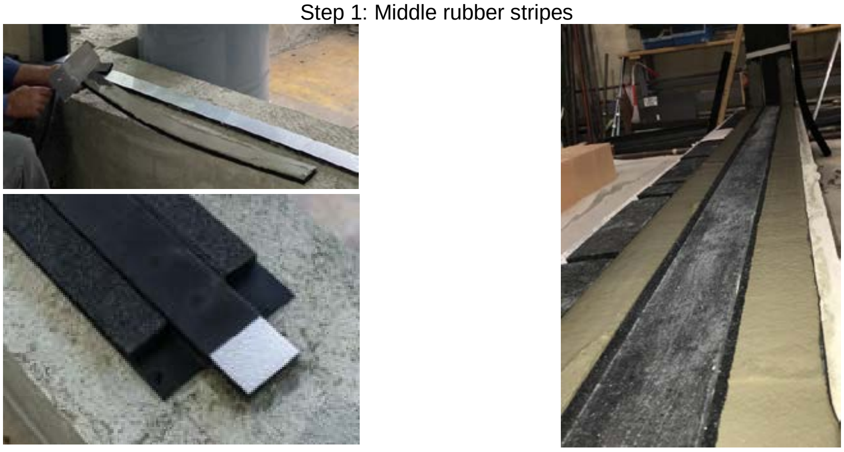


Figure 3. Details of the REGUPOL INODIS system

Step 1: Middle rubber stripes



Step 2: Bottom rubber stripes

Step 3: Brick laying

Step 4 – Insertion of outer rubber stripes at the top

Figure 4. Installation steps of the REGUPOL INODIS system

3. Experimental campaign

The RC frame utilized in the experimental campaign is composed of concrete with a strength class of C30/37, and reinforcing steel B500B. The columns are designed with a quadratic cross-section of 25/25 cm, while the beams have a rectangular cross-section of 25/45 cm. Additional details regarding the frame design, geometry, and distribution of reinforcement can be found in the work of Milijaš et al. (2023). For the construction of masonry infills, Thermoplan SX10 clay bricks with narrow vertical voids, representative of modern high thermal-insulating bricks with significant thickness, are used. The bricks are connected using Maxit 900D thin-layer mortar, applied only in bed joints. Head joints are implemented as dry tongue and groove connections, a common practice. In the case of traditional infills, general-purpose mortar is used as a height compensation layer at the bottom of the wall and around lintels for infills with window openings. Mortar fills the connections of infills to the columns, and the remaining gap at the top is meticulously filled with thin-layer mortar, a process that might be challenging on all construction sites.

The experimental tests, summarized in Figure 5, are conducted on full scale RC frames with traditional and decoupled infills to investigate their behavior under separate and combined IP and OOP loads. Tests T1/D1, T4/D4, and T7D7 are pure OOP tests conducted on solid infill, infill with a window, and infill with a door opening, respectively. In tests T2/D2, T5/D5, and T8/D8, solid infill, infill with a window, and infill with a door opening are subjected to sequential IP and OOP loads. Tests T3/D3, T6/D6, and T9/D9 investigate all considered infill configurations under simultaneous IP and OOP loads. Subsequently, the experimental results of these nine tests on RC frames with decoupled infills (D1-D9) are compared with the results of nine tests on RC frames with traditional infills (T1-T9), as thoroughly presented in Milijaš et al. (2023). Within this paper IP behaviour of the specimens is compared. It's noteworthy that the primary distinction between tests T1-T9 and tests D1-D9 lies in the application of the decoupling system in the latter, while same infill configurations and loading protocols are considered. This allows for a direct comparison of experimental results between RC frames with traditional and decoupled infills. Figure 6 shows RC frame with full masonry infill wall and decoupled REGUPOL INODIS system that surrounds the infill wall.

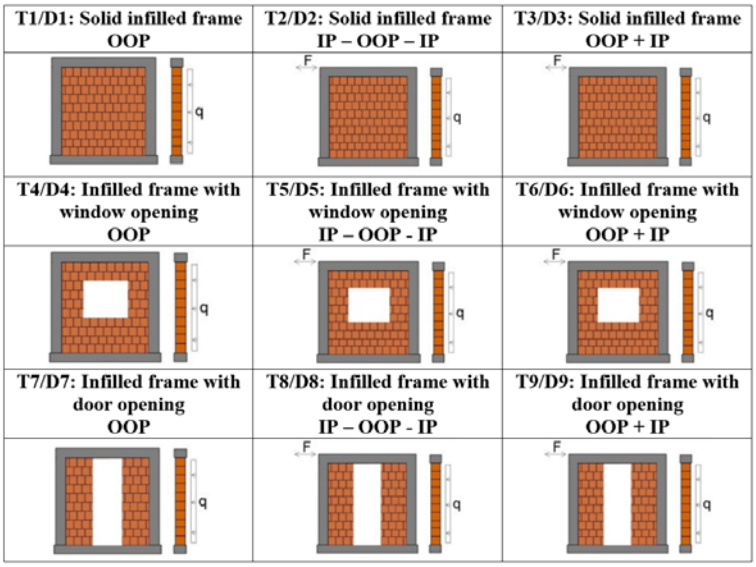


Figure 5. Test specimens and loading conditions

The test set-up designed to apply IP or OOP loads separately or simultaneously is depicted in Figure 7. One-way hydraulic actuators with a capacity of 600 kN are employed to apply vertical forces to the columns of the RC frame. These actuators are connected to a pressure accumulator to ensure nearly constant pressure during the test. Positioned on top of the columns, the actuators are covered by a traverse steel beam connected to two steel rods per column. The steel rods are linked to the foundation beam by specially designed steel angles, facilitating the application of vertical loads by activating tension forces in the rods using the actuators.

For the cyclic IP load, two servo hydraulic-controlled actuators, each with a maximum force of 250 kN and a stroke of ±20 cm, are utilized, providing a total capacity of 500 kN. These actuators are connected on one side to a robust reaction wall and on the other side to the top beam of the RC frame. Tension forces transfer is achieved by four horizontally aligned steel tie rods along the top beam, anchored to a sturdy steel plate at the end. OOP loading is applied through four airbags, each with a capacity of approximately 60 tons at 8 bar. To push the wall in the unfavorable direction from the inside to the outside, the airbags are installed between the infill and a timber reaction wall at the back. The reaction wall consists of eight vertical and four horizontal H20 timber scaffolding beams, with timber scaffolding plates installed between the airbags and the beams. The OOP reaction wall is connected to the RC frame beams using four threaded M36 8.8 rods. Load cells with a capacity of 500 kN are installed at each rod, measuring the applied OOP force.

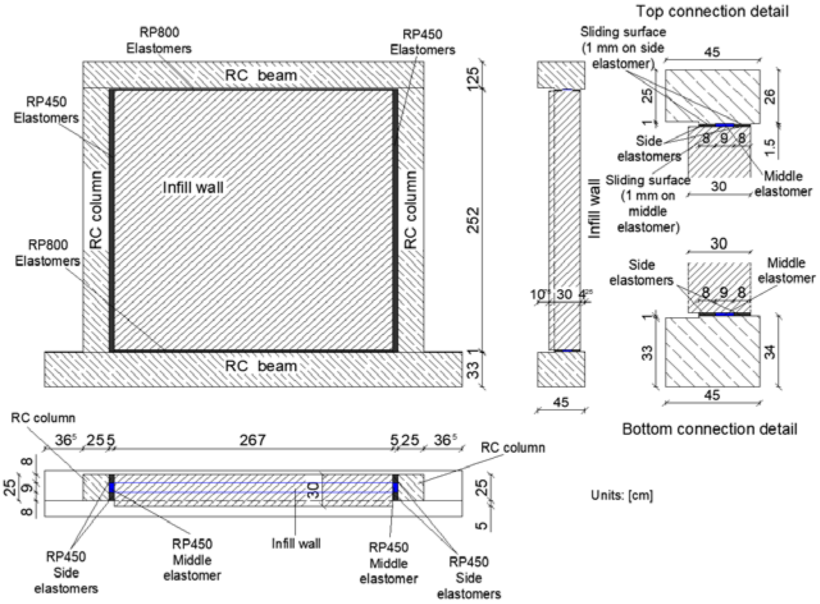


Figure 6. Decoupled infill specimen (D1, D2, D3)

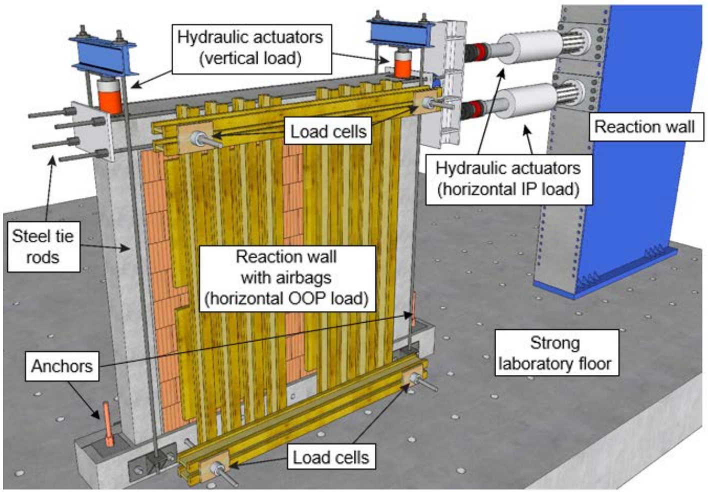
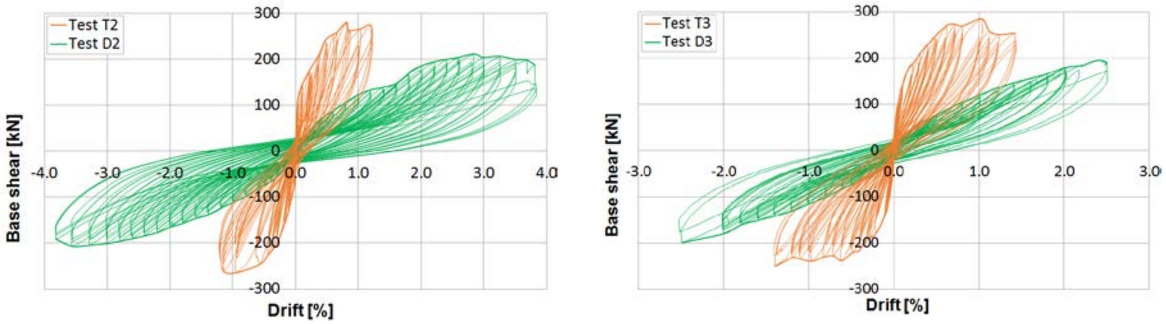


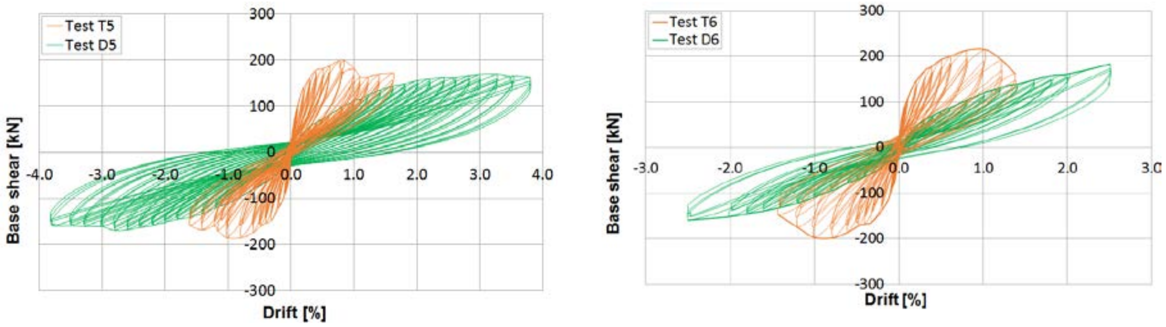
Figure 7. Test set-up

The assessment of IP behavior, accounting for the effects of the decoupling system, is conducted through a comparison of results from sequential and simultaneous load tests. Figures 8-11 present a comparison of hysteretic curves for RC frames with traditional and decoupled infills, considering each infill configuration. The hysteretic curves of RC frames with traditional infills exhibit high initial stiffness and a pinching effect, with maximum IP forces attained at low IP drifts (between 0.8% and 1.0%). Conversely, the curves of RC frames with decoupled infills are stable and broad, featuring lower initial stiffness. Maximum IP load capacities are reached at IP drifts exceeding 2.0%. Importantly, the decoupling system enables much higher IP drifts with little to no damage to masonry infills. Figure 11a (traditional infill-solid lines, decoupled infills-dashed lines) compares the envelopes of all IP loading tests. RC frames with decoupled infills exhibit an IP response similar to the bare frame, particularly at lower IP drifts (up to around 0.5%), indicating that the initial stiffness and dynamic characteristics of RC frames remain unaltered when the decoupling measures are applied. This is in contrast to traditionally infilled RC frames, where traditional infills significantly increase the initial stiffness, with different stiffness observed for frames with varying opening percentages. This highlights the complexity of estimating the dynamic characteristics of traditionally infilled RC frames, a challenge not present in frames with decoupled infills. Figure 11b (traditional infill-solid lines, decoupled infills-dashed lines) illustrates infill contribution curves derived by subtracting bare frame curves from infilled frame curves. Decoupled infills are activated to a much lesser extent, with activation starting at higher IP drifts compared to traditional infills. For example, in test T2, full traditional infill achieves a maximum force of 192 kN at 0.8% of IP drift with significant damage at 1.0%, while in test D2, at 1.2% of IP drift, the contribution force of the decoupled infill is only 28.6 kN with no damage. Similar trends are observed for tests T3 and D3. Traditional infill in test T3 reaches a maximum force of 195 kN at 0.64% of IP drift, leading to wall collapse at 1.4%, while in test D3, at 1.4% of IP drift, the force in the decoupled infill is only 35.8 kN. The trend continues for infills with window openings, where in test T5, the maximum contribution force of around 115 kN is reached at 0.4% of IP drift, while the decoupled infill with a window opening is barely activated at this IP drift. In test T6, the maximum contribution force of 125.8 kN is reached at 0.8%, whereas in test D6, the contribution force is only 16.7 kN. Decoupled infills with door openings in tests D8 and D9 remain isolated from the RC frame, with negligible contribution forces measured only after 2.0% of IP drift. Conversely, traditional infill with a door opening experiences complete collapse at 1.6% of IP drift in sequential loading test T8, while under simultaneous load, traditional infill with a door opening collapses at 1.0% of IP drift due to the adverse effect of combined IP and OOP loads.



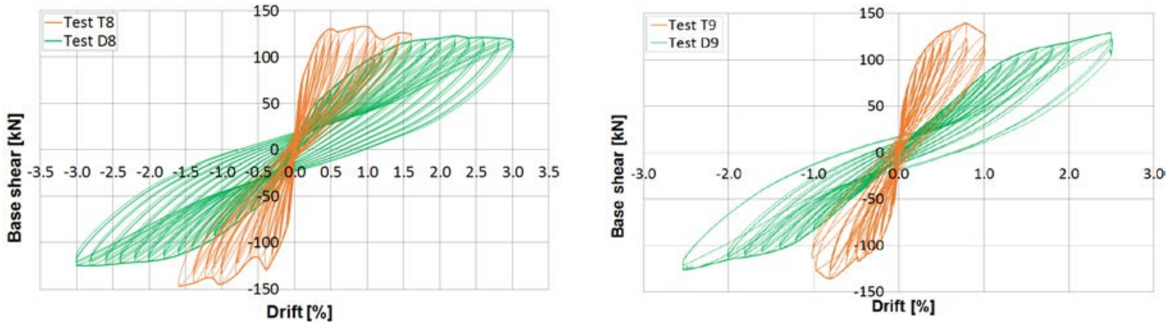
(a) (b)

Figure 8. Hysteresis curves for fully infilled frames: a) sequential and b) simultaneous loading tests



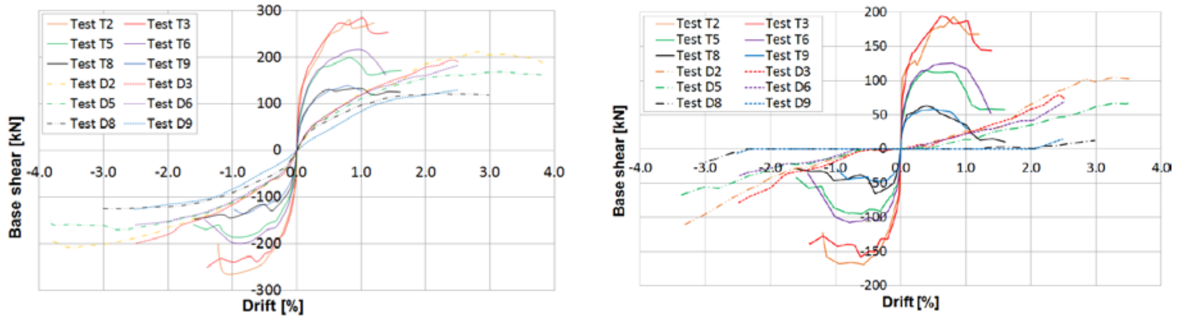
(a) (b)

Figure 9. Hysteresis curves for frames with infills with window: a) sequential and b) simultaneous loading tests



(a) (b)

Figure 10. Hysteresis curves for frames with infills with door: a) sequential and b) simultaneous loading tests



(a) (b)

Figure 11. a) Envelope curves and b) contribution curves for IP loading phases

4. Conclusions

This article presents experimental findings on RC frames with decoupled infills and a direct comparison with RC frames with traditional infills under identical conditions. The developed decoupling system effectively minimizes the impact of prior IP drifts on OOP behaviour. Simultaneous IP and OOP loading tests demonstrate a negligible reduction in OOP capacity for decoupled infills, even under high IP drifts. In contrast, traditional infills exhibit high susceptibility to IP and OOP interaction. In IP tests, the effectiveness of the decoupling system is evident, with masonry infills in fully infilled RC frames becoming active at high IP drifts after utilizing the rubber stripe capacity. Initial cracks in decoupled infills appear at elevated drifts, enhancing infill activation without compromising load capacity. Sequential and simultaneous loading on traditional infills increase vulnerability to combined IP and OOP loads. Importantly, decoupled masonry infills maintain nearly the same initial IP stiffness as the bare frame, unlike traditional infills that significantly increase stiffness. This represents an additional advantage of the decoupling system, as its application does not change the lateral stiffness of the bare frame and, consequently, the dynamic properties of the infilled RC structures, simplifying the design process. Traditional infills exhibit cracking at small IP drifts, while decoupled infills reach peak IP loads at higher drifts (between 2.4% and 3.25%) due to delayed activation. Significant damage in decoupled infills is visible only at around 3.0% of IP drift.

This innovative solution, utilizing recycled rubber material, presents a cost-effective approach applicable to various brick types that can be seamlessly integrated into on-site construction processes. Beyond protecting infill walls, it prevents stress concentration in the frame, causing negligible decreases in the natural period of the bare frame. The simplicity and reliability in design hold promise for engineers in practice. The innovation has the potential to revolutionize the seismic performance of masonry infills, ensuring their resilience and stability while streamlining the construction process. Furthermore, the presented system can be used for construction of decoupled (non-interacting) infill according to the updated guidelines for masonry infill walls.

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