HEAVY DAMAGE TO INFILLS IN THE FEBRUARY 2023 KAHRAMANMARAS EARTHQUAKES: REASONS AND POTENTIAL SOLUTION

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Abstract: *The most dominant type of damage in the February 2023 Kahramanmaras earthquakes was the failure of masonry infill walls. The paper presents documentation of widespread damage observed during field visits. One of the reasons for such a heavy infill damage was the flexible configuration of RC frame structures. However, substantial infill damage was also noticed in cases of RC wall and dual systems. Usually, infills at the lower stories experienced out-of-plane collapse, demonstrating that in-plane/out-of-plane interaction is decisive for the level of infill damage. Therefore, this needs to be taken into account during the design. Field observations show that the infill/frame contact plays a major role in the behaviour of infills during earthquakes. It can be seen that mortar connection and other variations such as polyurethane foam are inadequate to provide out-of-plane restraint for the infill panels, and therefore so many infill walls have collapsed in out-of-plane. Due to the lack of infill isolation, despite being prescribed by the Turkish code, substantial in-plane damage occurred due to the deflection of the RC structure. This is also confirmed in a comprehensive experimental campaign documented in the paper. The main results of the 18 full-scale tests on infilled RC frames are summarized, highlighting the issues with traditional infill and its poor behaviour. An infill isolation system that provides in-plane decoupling and out-of-plane infill/frame connection is presented, along with the results of the experimental campaign. All potential benefits of the solution are summarized based on the comparison of the experimental results on traditional infills and isolated specimens.*

1. Introduction

Throughout the course of history, humanity has faced an enduring threat from earthquakes, classifying them as one of the most devastating natural disasters. In just the past century, countries have required significant financial aid in the aftermath of these events (European Commission, 2021). A significant portion of the global building inventory consists of reinforced concrete (RC) structures, making them particularly susceptible to earthquakes, especially in densely populated urban areas. This vulnerability has, in some instances, resulted in the damage or complete collapse of these structures (Alih et al. 2019, Braga et al. 2011, Brzev et al. 2017). While there is extensive documentation on the structural damage in RC constructions caused by earthquakes, it is essential to emphasize that substantial economic losses are often associated with the impairment or failure of non-structural components (Taghavi et al. 2003, Marinković et al. 2022).

Reinforced concrete (RC) frame structures featuring masonry infills represent a common structural system found globally. In the design process for these structures, masonry infills are typically regarded as non-structural elements since they are not subjected to vertical (compressive) loads. However, when exposed to seismic forces, these masonry infills, often constructed in direct contact with the surrounding RC frame, become involved in in-plane (IP) actions due to frame deformation. In addition to IP loads, masonry infills also experience out-of-plane (OOP) seismic forces caused by acceleration acting perpendicular to the wall plane. These seismic influences, originating from two perpendicular directions, can affect masonry infills either individually or simultaneously, depending on the seismic conditions. Consequently, this phenomenon contributes significantly to the substantial damage suffered by infill walls (Fig. 1), a pattern observed in all seismic events of medium to high intensity.

Figure 1. Damage and OOP collapse of infills in RC buildings without structural damage (Turkey 2023)

Decades of extensive research have been dedicated to unravelling the intricate interaction between frames and infills within the realm of seismic performance assessment for infilled frame buildings. This inquiry has encompassed both experimental investigations (Crisafulli 1997, Mehrabi et al. 1994, Kakaletsis and Karayannis 2008) and numerical simulations (Kadysiewski et al. 2009, Yuen et al. 2016, Marinković and Butenweg 2022). Unfortunately, masonry infills often receive insufficient attention in seismic design, a non-conservative assumption considering their significant impact on the behaviour of such structures. Disregarding their effect can lead to a substantial misestimation of the dynamic properties of RC frame structures. Additionally, the out-of-plane (OOP) behaviour of masonry infills is strongly influenced by parameters such as boundary conditions and slenderness ratio. Various studies (Dawe and Seah 1989, Furtado et al. 2021, Milijaš et al. 2023) have generated different findings regarding OOP load and deformation capacity. Notably, inadequate frame-infill connections 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).

This paper presents the outcomes of reconnaissance studies conducted by the authors in collaboration with members of the Serbian Association for Earthquake Engineering (SUZI-SAEE) and ETH Zurich. This joint effort also constituted the authors' second visit as part of the ACI-133 reconnaissance mission. The visits focused on areas affected by severe earthquakes in Turkey, covering 16 cities, several villages around major cities, as well as industrial facilities, hospitals, educational institutions, bridges, and water towers. The primary objective of these reconnaissance visits was to document the earthquake's impact on construction facilities and infrastructure, along with plans for the recovery of the southern part of Turkey.

The paper delves into the main observations related to the seismic performance of reinforced concrete (RC) buildings during the earthquakes in February 2023, with a specific emphasis on the most prevalent damage type – masonry infill walls. Recognizing the frequent and widespread failure of infills during medium to strong earthquakes, the authors conducted an extensive experimental campaign, the results of which are summarized in this paper. Additionally, the authors developed a system designed to enhance the behaviour of infill walls. This system is based on the isolation/decoupling of infill walls from the surrounding frame. Through comprehensive experimental campaigns and numerical simulations, the system was tested and refined to provide a practical solution to the challenges posed by infills. The paper presents this decoupling system, offering information anticipated to be valuable to the earthquake engineering community by proposing a solution for infill walls that could yield significant improvements in the future.

2. Behaviour of masonry infill walls in the February 2023 Kahramanmaras earthquakes

On Monday, February 6, 2023, at 4:17 in the early morning hours, a seismic event of magnitude 7.7 struck the central part of Turkey and the northwest part of Syria. The earthquake's epicenter was in close proximity to the town of Pazarcik, with a hypocenter at a depth of 8.6 km. Later on the same day, around 13:24, another powerful earthquake, measuring 7.5 in magnitude, occurred at a depth of 7.0 km. The epicenter for this second earthquake was near the town of Elbistan, situated approximately 95 km north-northwest of the epicenter of the initial earthquake. Subsequent to these destructive earthquakes, more than 18,000 aftershocks were recorded by June 2023, with three exceeding a magnitude of 6.0 and over twenty having a magnitude greater than 5.0. These aftershocks exacerbated existing damage and, in certain instances, led to the collapse of structures previously weakened by the initial seismic events.

The geographic location of Turkey, situated at the convergence of three tectonic plates (Anatolian, Arabian, and African), has historically exposed the region to destructive earthquakes dating back to ancient times. The epicenter of the first earthquake was identified along the East Anatolian Fault, a geological feature notorious for triggering numerous devastating earthquakes of significant magnitude. Intriguingly, this fault was responsible for two notable earthquakes with magnitudes of 5.7 and 6.8 in 2020. It's noteworthy that the earthquakes in Kahramanmaraş caused a fault slip along the East Anatolian Fault spanning over 300 kilometers, resulting in substantial damage and building collapses in settlements near the fault, irrespective of their distance from the epicenter.

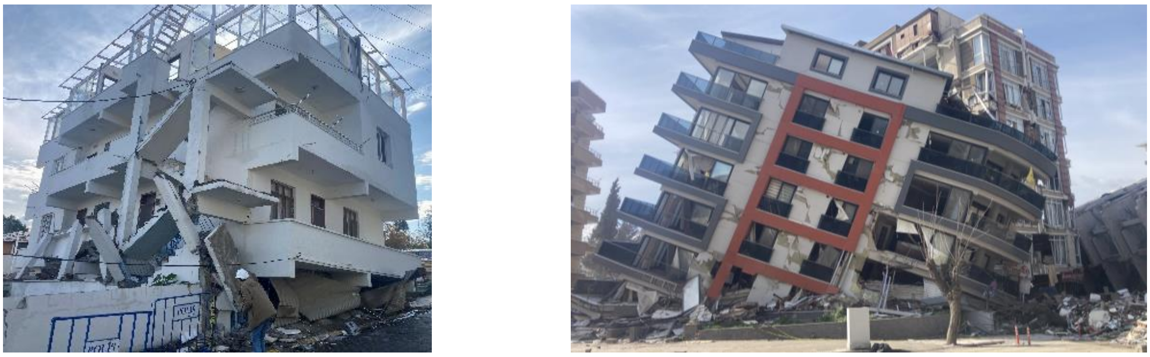

a) b)

Figure 2. Collapse of RC buildings: a) three story residential building in Arsuz and b) overturning of RC frame building with 8 stories that is 3 years old.

This study specifically examines the predominant type of damage—masonry infill—following the earthquake. A more in-depth analysis of the earthquake's effects is available in the seminar conducted on May 29, 2023 (SUZI&ETH 2023). The team members conducted on-site visits within the earthquake's epicentral zone to document characteristic damage types on both buildings and infrastructure. The most substantial structural damage was identified in RC frame structures with masonry infill. Masonry infill damage was widespread in RC frame structures throughout all areas affected by the earthquake. Notably, buildings with a dual system (RC frames with walls) as well as RC wall system also exhibited infill damage. A key observation from the team was that RC frame structures with masonry infill exhibit excessive flexibility, rendering them unsuitable for medium and high-rise buildings. The connection between infill and frame was identified as a critical point influencing the out-of-plane (OOP) collapse of infills. Figure 1 provides a visual representation of significant infill damage, specifically out-of-plane collapse, observed in numerous residential buildings.

Soft-story collapse was often observed on the field and it usually occurred in case of open ground floor and masonry infill wall in upper stories (Figure 2a). The inclusion of commercial spaces on the ground and first floors, coupled with a sparse distribution of structural elements, triggered the "soft story" effect, sometimes resulting in the tilting of buildings. Often in ground floors there was a garage. In several cases, overturning of structures was initiated by partial ground floor collapse due to soft-story (Figure 2b).

Instances of the "short column" effect (Figure 3), arising from the interplay between columns and partially infilled masonry panels, have been observed. In such cases, the interconnection of the masonry infill with the RC column, combined with restricted deformations of the column along its height, resulted in an escalation of shear force in the "free" section of the column. Despite the inclusion of 15 cm spaced and 135-degree hooked ties, shear cracks emerged. A notable limitation was the insufficient reinforcement of the RC column, which solely featured external ties, while the presence of internal ties was anticipated.

Figure 3. “Short column” effect due to interaction between RC column and partial height infill

Figure 4. Hospital in Iskenderun: Damage and collapse of infills

Instances of inadequate performance in non-structural elements, such as infill walls and brick façade walls within RC frame structures, have been noted. During the earthquake, infill walls experienced both in-plane and out-of-plane loading, leading to a substantial decrease in the load-bearing capacity of the infill under out-of-plane loading. Additionally, there was a loss of proper contact between the frame and the infill. The utilization of polyurethane foam at the connection between the infill and the RC frame (Figure 4) often caused damage and collapse of the infill. It is noteworthy that this method of connecting infill to the surrounding RC structure has gained significant popularity across numerous construction sites, despite the evident drawback that polyurethane foam does not establish a durable connection between the wall and the structure. Consequently, any perpendicular acceleration to the wall plane can result in the infill becoming dislodged in an out-of-plane direction. In this case (hospital in Iskenderun – Figure 4), failure of infill walls caused the hospital to be mail functional although building did not have big structural damage.

It's crucial to emphasize that the nature of damage was not dependent on the type of masonry units used, as most infill walls exhibited similar forms of damage, including diagonal cracks, and in numerous cases, out-of-plane (OOP) collapse (Figure 5 and Figure 6a). In addition to the risks associated with the damage and fracture of infill walls, which pose a substantial threat to the safety of building occupants, another significant concern was that the collapse of these walls obstructed staircases and other evacuation routes, both inside and outside the building. The fracture of infill walls emerged as a notable impediment to the reoccupation of the building. The area around staircases also serves as an example of non-structural elements in the building that were frequently damaged (Figure 6a).

Figure 5. Damage of infill walls made of hollow concrete blocks and hollow clay blocks.

a) b)

Figure 6. a) AAC infill damage blocking escape routes at stairwells and b) damage and collapse of infill walls on the lower stories

The team members were profoundly impacted during their visit to Antioch (Antakya), where they witnessed a scene of complete destruction and catastrophe. In March 2023, extensive efforts were underway to clear and demolish nearly all structures damaged by the earthquake. According to local engineers, the surrounding settlements situated on the foothills of the mountain did not suffer significant damage, most likely owing to a different soil type.

A significant number of collapsed residential buildings were RC structures. RC buildings with frames and/or a dual system of frame/wall endured notable damage to their masonry infill, which, in many instances, collapsed OOP on the lower levels (Figure 6b). This occurrence resulted from the combined effect of IP and OOP loading on the infill walls. The deflection of the RC structure caused IP loading on the infills in the form of displacement arising from interstorey drift. Additionally, due to acceleration acting on each floor, inertia forces acted perpendicular to the wall surface (OOP load). Interstorey drift was most significant in the lowest stories, causing IP damage to infill walls and/or the detachment of infills from the surrounding RC elements. Damaged infill walls were highly susceptible to OOP loading, and detached infills without a connection to the RC frame were even more vulnerable to OOP loads, which did not need to be high to induce infill collapse in the OOP direction.

It is crucial to highlight that, even several months after the earthquake, a significant level of fear persists among the population. Many residents continue to reside in tents, despite the possibility of rehabilitating or repairing their homes (houses or apartments). The apprehension is fueled by the lingering fear of subsequent earthquakes and the potential collapse of buildings that endured strong earthquakes in February 2023. Furthermore, conversations with the local population revealed that many are hesitant to return to structurally undamaged buildings with substantial masonry infill damage. Their reluctance is understandable, considering the lasting impact of the earthquake, characterized by noise, cracking, and falling of infill walls, which undoubtedly leaves a strong impression of insecurity regarding these structures. This sentiment is further supported by images collected from inside homes (Figure 7). Given this on-the-ground situation, decisions are being made to demolish many buildings because the damage to masonry infill gives the impression of complete destruction.

Figure 7. Infill damage inside the buildings

In summary, this chapter briefly outlined several reasons motivating the efforts of numerous researchers and practicing engineers to address the issue of masonry infill damage under seismic actions. While this topic has been under study for decades, it has now evolved into a pressing concern that must be addressed to prevent such disasters in the future.

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

Considerable efforts have been dedicated to comprehensively studying the behaviour of infill walls in RC frames, employing both experimental and numerical methods with the goal of devising enhanced solutions. Among the various proposed improvements, the most promising approach involves the isolation of infill walls. This method achieves in-plane separation of infills from the frame, enabling deformation while delaying the engagement of infills making them non-interacting. While creating gaps between infills and frames achieves in-plane separation, additional devices are required for ensuring proper out-of-plane strength. This approach presents design advantages by minimally altering current practices and has gained traction in recent years.

Decoupling prevents infill activation during frame deflections, treating it as non-structural. Flanagan (1994) found a 1-inch gap between column and infill didn't reduce ultimate load, but it postponed its occurrence to a higher level of drift. Charleson (2012) proposed separation gaps to address "short column" issues in rigidly connected masonry infills. He noted separation just from columns is insufficient as infills prevent beams from bending during building sway. He added that poor infill performance in past earthquakes prompts isolated infills in seismic areas. Kuang and Wang (2014) suggested an air gap to isolate masonry infills from columns, and steel connectors for preventing out-of-plane failure. However, findings in Marinković and Butenweg (2022), show that steel anchors for out-of-plane support cause local failures and sudden infill collapse. Tsantilis and Triantafillou (2018) examined RC frames with infill panels isolated using thin cellular layers, resulting in less severe damage than traditionally infilled frames. Paulay and Priestley (1992) proposed isolating infills with a deformable strip, emphasizing connections for out-of-plane forces. Bennett et al. (1996) observed Northridge earthquake's masonry infill performance, stressing the need for large enough gaps to prevent infill activation and highlighting the difficulty of providing free in-plane movement with out-of-plane anchorage.

While the undeniable effectiveness of decoupling solutions in enhancing seismic performance is acknowledged, their limited practical application is hindered by economic constraints, encompassing material and installation expenses for integrated components. Despite these challenges, this approach remains valid, prompting the need for continued efforts in solution development. Consequently, updated guidelines for masonry walls prioritize enhanced seismic performance and incorporate provisions for decoupling (non-interacting) infill panels from surrounding RC frames as a viable option.

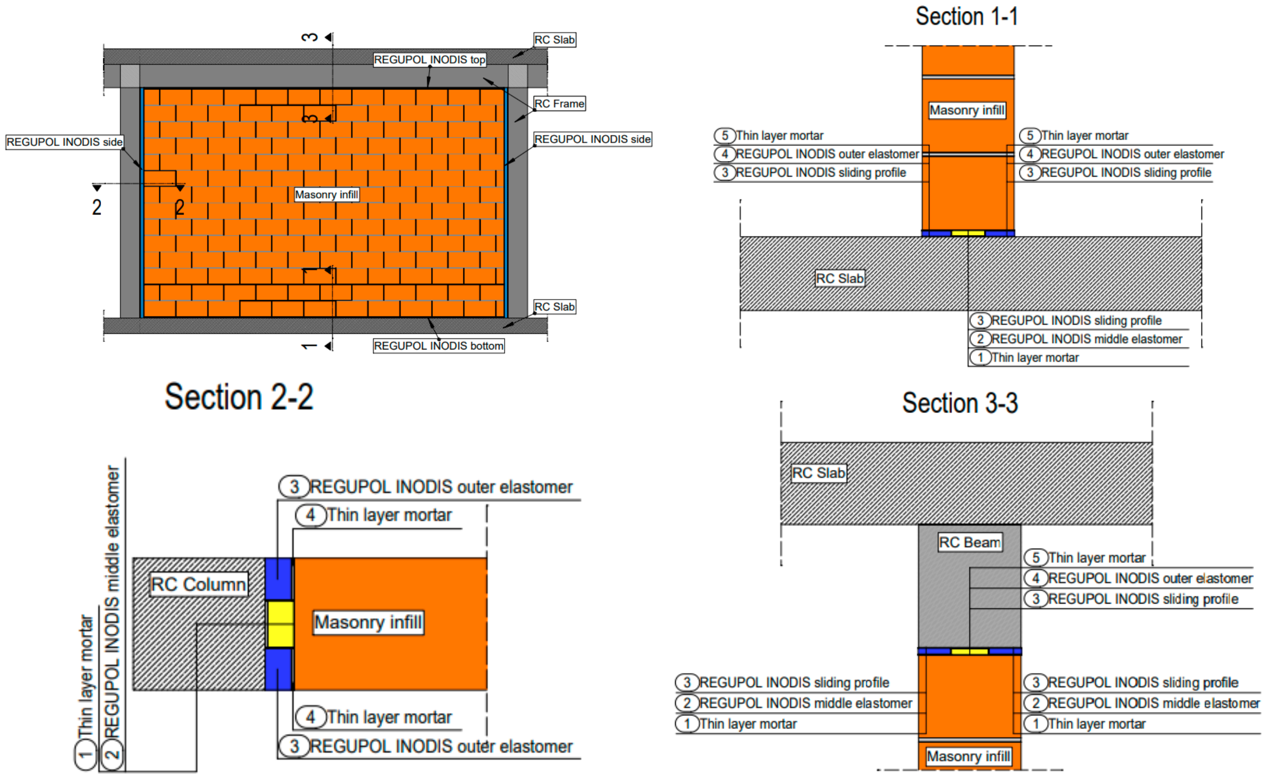


Figure 8. REGUPOL INODIS system

These circumstances have driven research and solution development to improve adverse interactions between masonry infill walls and concrete structures. This paper introduces a system aligned with this research objective, striving to devise a practical construction measure that effectively addresses these challenges. The aim is to provide engineers with a straightforward application without relying on complex numerical models.

Over the last decade, extensive research and thorough testing have been undertaken to develop a solution that enhances the seismic safety of infills. The devised system aimed to ensure seismic safety under various loads, practical on-site installation, adaptability for different brick types, and economic efficiency. To address these criteria, a decoupling approach is in the prior work of Marinković and Butenweg (2019) and further updated. The primary objective of the decoupling system is to enhance both the IP drift capacity and the load-bearing capability against OOP forces resulting from seismic activity. The decoupling system (Figure 8) comprises three recycled rubber strips. The central strips are affixed with mortar to the surrounding RC frame, while the outer side strips are attached to the masonry bricks using a thin layer of mortar for secure adhesion. Thicker strips with lower stiffness characteristics are placed between the masonry infill and columns, effectively absorbing the IP deformation of the frame and delaying interaction with the infill. Thinner rubber strips with higher compression and shear stiffness are positioned at the top and bottom of the infill wall, playing a crucial role in maintaining OOP stability. This design enables significant IP drifts and substantial OOP loads concurrently by adjusting rubber stiffness and thickness to different seismic loads. Rubber joints enhance building damping capacity due to their viscoelastic behaviour. Importantly, the proposed concept extends to any type of units and masonry infills with openings, requiring no supplementary measures for such cases.

4. Testing campaign

An experimental campaign was conducted on 18 specimens, all subjected to tests on full scale RC frames with infills. The objective was to examine their behaviour under separate and combined in-plane (IP) and out-of-plane (OOP) loads. The tests encompassed full infill walls as well as infills with windows and doors (Figure 9). Subsequently, the results from nine tests on RC frames with decoupled infills (D1-D9) were compared with those from nine tests on RC frames with traditional infills (T1-T9), as extensively detailed in Milijaš et al. (2023). It is crucial to note that the only primary distinction between tests T1-T9 and D1-D9 lies in the application of the decoupling system in the latter, while maintaining consistent infill configurations and loading protocols. This enables a direct comparison of experimental outcomes on RC frames with traditional and decoupled (non-interacting) infills. Due to space constraints, this paper focuses on presenting results on specimens with openings (window and door) under combined IP and OOP loading (T5, D5, T6, D6, T8, D8, T9, D9).

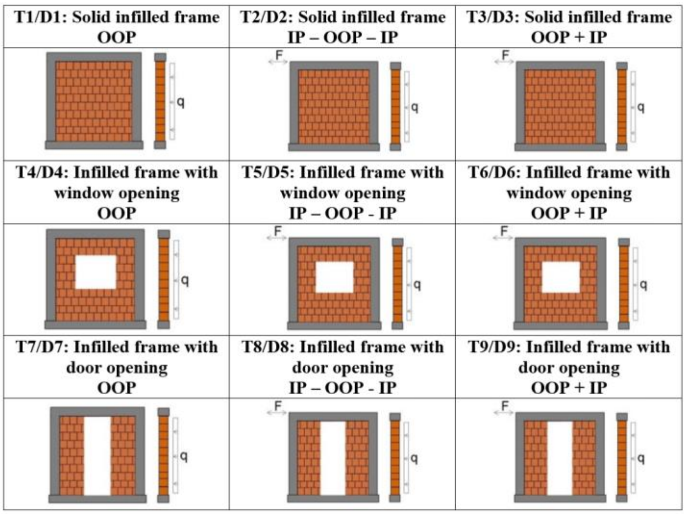
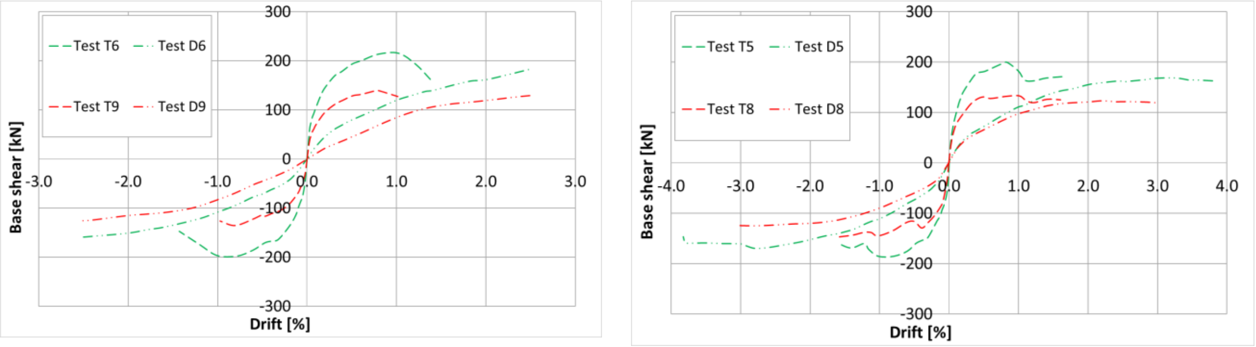


Figure 9. Specimen configurations and loading conditions investigated during the testing campaign

In the experimental setup, vertical forces were applied to the columns of the RC frame using unidirectional hydraulic jacks concealed by a crossbeam connected to two steel rods per column. Cyclic IP loading was implemented by a pair of servo hydraulic-controlled actuators, each with a 250 kN capacity and a stroke of ±200 mm, providing a combined capacity of 500 kN. Four horizontally positioned steel tie rods along the top beam, anchored to a stiff steel plate, facilitated the transmission of cyclic displacement. OOP loading involved the use of four airbags positioned between the infill wall and a timber reaction wall. Load cells with a 500 kN capacity were attached to each rod to measure the applied OOP force. The RC frames were anchored to the laboratory strong-floor using two anchors at both ends of the bottom beam, preloaded with 400 kN.

The RC frame utilized in the experimental campaign was constructed from concrete with a strength class of C30/37 and reinforcing steel B500B. The columns were designed with a quadratic cross-section measuring 25/25 cm, while the beams featured a rectangular cross-section of 25/45 cm. Detailed information regarding the distribution of reinforcement and characteristics of bricks, mortar, and masonry materials can be found in Milijaš et al. (2023). For the construction of masonry infills, Thermoplan SX10 clay bricks with narrow vertical voids were employed. The bricks were laid in Maxit 900D thin layer mortar, applied exclusively to the bed joints. Head joints were dry tongue and groove connections, following common practice. In the case of traditional infills, connections between the infills and the columns were filled with mortar.

Figure 10 presents envelope curves of the IP force-displacement cyclic hystreses and it can be seen that much higher IP drifts are reached in tests on decoupled infill specimens. The results indicate that, in the case of traditional infills, the initial stepwise cracks emerge in the lower parts of piers at 0.2% of in-plane drift. As the in-plane drifts increase, diagonal shear cracks develop through joints and bricks on both piers. This progression leads to the formation of triangular-like pieces of masonry that begin to detach from the rest of the infill. At 0.8% of in-plane drift, the observed damage level is considered a significant damage limit state, as defined by Morandi et al. (2018). Moreover, at 1.1% of in-plane drift, the damage to the infill in test T8 corresponds to the near-collapse limit state (NCLS) conditions introduced by Morandi et al. (2022). Due to severe damage to the infill, there is no contribution to the in-plane load capacity of the frame from an in-plane drift of 1.1% up to the maximum attained in-plane drift of 1.6%. At 1.6% of in-plane drift, the detached masonry parts fall down in test T8, while in test T9, the same failure type occurs even sooner, at 1.0% of in-plane drift due to the adverse effects of simultaneous loads. Traditional infills with door openings exhibit detrimental crack patterns, rendering them more vulnerable to seismic actions than full traditional infills. On the contrary, decoupled infills with full-height door openings remain completely isolated up to ultimate in-plane drifts of 3.0% and 2.5% in tests D8 and D9, respectively. Since no cracking appears on infills, both tests are stopped due to significant damage to the RC frames, a common occurrence for these drift levels. Decoupled infills with door openings can fully absorb RC frame deformations under in-plane loads.



a) b)

Figure 10. Envelops for: a) sequential loading tests on traditional infills (T6 and T9) and isolated infills (D6 and D9), b) simultaneous loading tests on traditional infills (T5 and T8) and isolated infills (D5 and D8)

In tests T5 and T8, traditional infills with window and door openings reach significant damage (Morandi et al. 2018b) and near-collapse limit state conditions (Morandi et al. 2022) at around 0.8% and 1.1% of in-plane drift, respectively (Figure 10b). Unstable triangular-like parts of masonry emerge next to openings, significantly impacting the out-of-plane behavior of infills in tests T5 and T8. As a result, the out-of-plane capacity of traditional infills with window and door openings in these tests decreases by 3.7 times after an in-plane drift of 1.1%. Similar poor performance is observed in simultaneous loading tests on traditional infills with window (T6) and door opening (T9). In test T9, the detrimental effects of in-plane and out-of-plane load interaction are especially pronounced, with one infill pier falling out of the wall plane like a rigid body at the load combination of 1.0% of in-plane drift and 21 kN of out-of-plane force. In contrast, the damage level to the masonry infill with a window opening in test D5 is limited. After an in-plane drift of 2.0%, the decoupled infill withstands the out-of-plane force with stable vertical arching. In test D8, an in-plane drift of 3.0% is reached without any damage to the decoupled infill with a door opening. Finally, after 3.0% of in-plane drift, the right and left piers are subjected to out-of-plane loads, reaching exceptionally high forces of 16 kN and 15 kN, respectively, due to the formation of stable vertical arching. It's essential to note that the out-of-plane forces applied to infills in tests D5 and D8 do not represent the out-of-plane capacities.

The effectiveness of the decoupling system is evident in simultaneous loading tests as well. In test D6, the decoupled infill with a window opening reaches an out-of-plane force of 45 kN applied simultaneously with 2.5% of in-plane drift. Considering that the pure out-of-plane test was terminated at an out-of-plane force of 63.2 kN, this demonstrates that in-plane and out-of-plane load interaction has a relatively small effect on the in-plane drift and out-of-plane capacity of the decoupled infill with a centric window opening.

5. Conclusions

This paper explores the devastating effects of earthquakes that occurred in Turkey in February 2023, with a specific focus on masonry infill walls, which emerged as the predominant source of damage in these seismic events. The paper draws attention to the poor behaviour of infills, utilizing data collected during reconnaissance missions in the affected areas. Representative examples are presented, and characteristic failure types are summarized, supported by field data and accompanying photographs. The evident impact of earthquakes on RC structures with infill walls underscores the urgent need for a solution to address the substantial financial losses, delays in recovery efforts, and threats to lives resulting from the damage and collapse of these infills during seismic events.

The analysis of data collected on the field goes in a line with the literature review and reveals that the influence of in-plane (IP) loads, including detachment at unloaded corners, degradation of frame-infill connections, and damage to masonry infill, is a key factor contributing to the failure of masonry infills. Frame-infill connections, often deficient in practice, particularly in adequately filling the remaining gap at the top, further exacerbate the situation. Even well-executed connections may experience gaps at the top due to mortar shrinkage, hindering effective arching action between the frame and infill. While this issue has been studied for decades, it has now become a pressing concern that demands resolution to avert future disasters.

In response to this challenge, an innovative decoupling system is introduced as a solution to enhance the seismic performance of masonry infills. The core concept involves isolating the infill walls from the surrounding frame, preventing their interaction during frame deflection. Notably, the system excels in simultaneously providing IP decoupling and robust out-of-plane OOP resistance. The effectiveness of the system is validated through comprehensive full-scale experimental tests, covering scenarios with and without window and door openings. The results, compared directly with traditional infills, highlight the advantages of the decoupling system, showcasing improved seismic performance.

This groundbreaking solution employs recycled rubber material, offering a cost-effective approach applicable to various brick types and 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. This 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.

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