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Research paper

Earthquake protection of reinforced concrete structures with infill walls using PUFJ and FRPU systems

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Abstract: Advancements in technology and material sciences lead new solutions to be used in civil engineering. PolyUrethane Flexible Joints (PUFJ) and Fiber Reinforced PolyUrethanes (FRPU) are among those innovative solutions. PUFJ implemented systems comprise of seismic preventive buffer material between masonry infill walls and reinforced concrete (RC) frames, whereas FRPU solution is designed for covering the wall surfaces with thin composite strips. Both methods are primarily developed for increasing the ductility capacities of buildings while sustaining the overall structural strength without compromising on the safety of these systems against earthquakes. In this article, test results of the quasi-static cyclic experiments as well as dynamic tests on the shake tables including harmonic forces operating in resonance are presented. Moreover, numerical analyses are performed in order to comprehend the behavior of PUFJ implemented frames constituted with different masonry materials than above which are under various loading conditions. The outcomes confirmed the high efficiency of the proposed solutions, which at the same time meet the strict requirements of the modern seismic standards.

Keywords: anti-seismic protection, cyclic and resonance loading, polymer flexible joints, dynamic tests on shake table, PUFJ and FRPU, RC frames with infills

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1. Introduction

Masonry in general, is a world-wide assimilated construction technique being preferred for the ages. Various underlying reasons can be mentioned in this regard, such as; easy accessibility, different formation and configuration options, fireproof and thermal insulation features are some of those. Although new construction methods have been developed particularly after the industrial revolution, humankind did not abandon the ancient fellow – masonry, but instead we have transformed the way of arranging blocks in modern buildings. That being said, utilization of the masonry in multi-story buildings is one of the most common types of infill wall solutions across the globe. Additionally to the aforementioned advantages of masonries, infilled systems in frame buildings are popular due to several other reasons including but not limited to; enabling to create dwellings and architectural purposes.

Despite its popularity, structural engineers most often neglect the effects of infill walls during design process or merely consider these members as the source of additional weight [1–3]. It is particularly due to the complexity of simulating infill walls as well as lack of knowledge regarding the possible adverse effects. Another reason is that these walls are considered as non-structural components and designing phase primarily focus on the structural parts [4]. This approach might be appropriate in many circumstances if vertical loads are the only concern. However, in today, it is a known fact that dynamic characteristics of the bare-framed buildings drastically change upon constructing infill walls in structural systems [5–7]. Lateral load capacity of a building, especially during ground-shakes, is directly related to two main parameters, i.e. mass and inertia, which infill walls substantially have effects on it. General perception is that infill walls constitute an auxiliary load carrying source, thus their impact on the dynamic features might be taken as a positive contribution. On the other hand, recent studies reveal that negative effects might outweigh the positive ones, especially if the infills are severely damaged and eventually lose their load carrying capacities [8]. Earthquake reconnaissance reports exhibit the fatal consequences of this drawback from real-life events, where multi-story buildings were either partially or totally collapsed because of the infill wall related failure mechanisms such as; torsional irregularities, soft-story effects and short-column shear damages on columns [9, 10]. In the next section, one of the recent earthquakes occurred in 2020 in Petrinja, Croatia is briefly investigated particularly focusing on the masonry failures.

2. Petrinja 2020 earthquake damages on buildings

Earthquakes are among the most catastrophic events beyond human control, in which building structures fail and deteriorate, often contributing to an increase in the number of casualties. The task of engineers is to design structures in accordance with the current standards so that they are resistant to exceptional loads, such as earthquakes. Unfortunately, many buildings have been constructed in the recent centuries without sufficient anti-seismic protection. These are especially brick structures. The inertial forces generated by the ground movement during an earthquake lead to various damage mechanisms in buildings that have been widely described in the world literature in recent decades. The last major earthquakes in Europe occurred in the Balkans in 2020, and the damage they caused have been very well documented in [11].

Historically, the Balkans are located in a seismic area where a strong earthquake occurred in 1880 near Zagreb [11], with the magnitude of $M = 6.4$ – based on the seismic moment scale, corresponding to an intensity of level VIII on the European Macroseismic Scale. It resulted in numerous deaths and significant damages to the brick residential buildings and historic cathedrals. On March 22, 2020, in the morning, two tremors in Zagreb with the magnitude of $M = 5.4$–5.5 (successive half an hour apart) caused numerous damages to the buildings, including the collapse of vaults and parts of towers in historic churches. Fortunately, there were no fatalities [11]. At noon on December 29, 2020, a relatively stronger earthquake struck the town of Petrinja (approx. 47 km away from Zagreb), caused 7 victims. Its magnitude $M = 6.4$ was similar to this in 1880. The damage in the town was significant due to the low quality of the buildings, mostly made of brick (Fig. 1).

Fig. 1. The Petrinja center immediately after the earthquake in December 2020 (left) and after the removal of debris in October 2021 (right)

Damages to the masonry structures of many buildings in Petrinja were reflecting the characteristics of typical failures in the seismic areas, with the concentration of cracks in the plane of the walls (in-plane – Fig. 2) as well as damages resulted in the falling off entire fragments of the walls from the structure (outside their plane – the so-called out-of-plane), mainly in the upper parts of the gable walls (Fig. 3). The latter damage was caused by the lack of connection of the gable walls closing the attics (formed by wooden roof trusses) with stiffening structural elements perpendicular to these walls. Often, out-of-plane damage to these elements was caused by the wooden elements of the roof truss [12], hitting these walls while moving under the influence of inertia forces generated by the earthquakes (Fig. 4).

Solutions proposed by Croatian engineers to reconstruct damaged gable walls [12] are based on the use of technology very popular in seismic areas – reinforced concrete frames with infill walls – Fig. 5. Structures of this type comprise of a reinforced concrete frame as the load-bearing skeleton, in which the brick infill walls are the non-structural elements.

Fig. 2. Wall damage (in-plane) in the center of Petrinja (October 2021)

Fig. 3. A closed school building in the center of Petrinja with out-of-plane gable damage (October 2021)

Fig. 4. Destroyed out-of-plane gable walls after the Zagreb earthquake (March 2020), caused by the impacts of wooden roof truss elements [12]

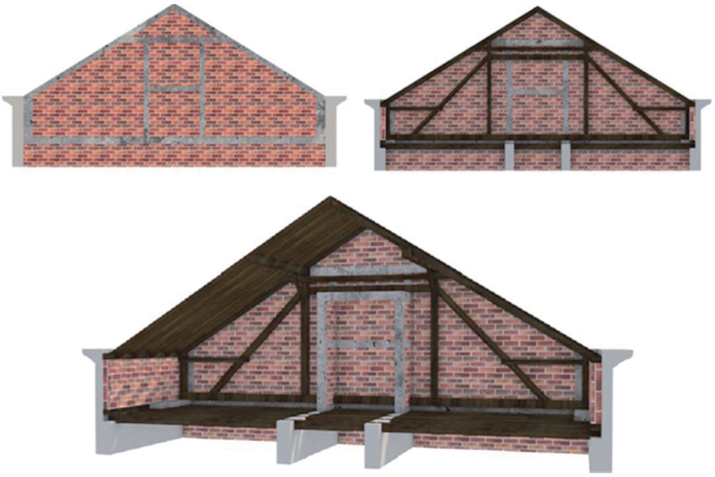

Fig. 5. Proposed reconstruction of the damaged gable wall with the use of reinforced concrete frames with brick infill walls [12]

3. The behavior of infill walls during an earthquake

The concept of building as reinforced concrete frame structure filled with masonry block or brick elements is common all over the world in the seismic areas (Fig. 6). First, load-bearing reinforced concrete elements (foundations, columns, beams and slabs) are constructed, and then the infills are made. These infill walls are not considered as load-bearing elements during design, but in fact they are lightly loaded with the additional vertical loads transferred by the frame. However, in the dynamic nature of such a structure during earthquakes, these walls play a role as the secondary load-bearing elements, especially in terms of stiffening the entire building [13].

Fig. 6. Structures of buildings in seismic areas made of reinforced concrete frames with brick infill walls (Bhaktapur, Nepal – 2016)

Infill wall related damages are natural outcomes of the interaction forces arising between the frames and masonries. Both surrounding frames and walls typically have brittle intrinsic characteristics, though frames are usually required to be designed relatively ductile [14]. When seismic loads trigger the displacement demands on buildings, it is expected that those elements response in a similar manner. On the other hand, the desired phenomenon cannot be successfully satisfied in many instances, since either frames or infill walls get damages that jeopardize the composite behavior. Frame-to-masonry bonding is the crucial aspect at this point. Because, sustaining wall stability requires sufficient connection to the surrounding frame, which in return provides a strong wall contribution to the seismic performance. Moreover, the connection detailing should also satisfy the conditions of protecting masonry induced frame damages, especially in case of strong bricks presence. In Fig. 7, typical infilled system damages are illustrated.

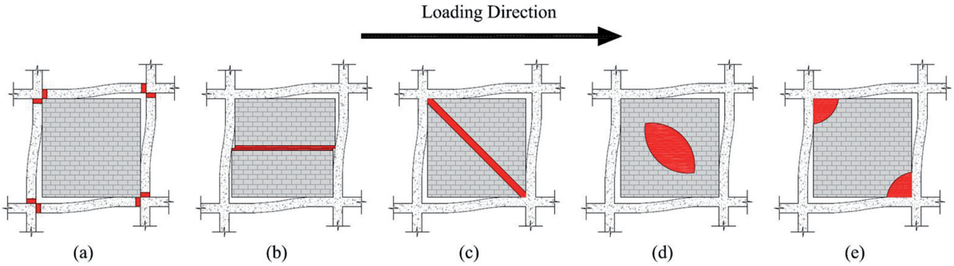

Fig. 7. Common infilled system failure mechanisms; frame damage (a), horizontal shear (b), diagonal crack (c), mid-height diagonal compression (d) and corner crushing (e)

Post-earthquake inspections show that the infill wall damage pattern is usually characterized by the oblique fractures caused by the in-plane shear or out-of-plane collapse, slippage of joints between the masonries and reinforced concrete frame (Fig. 8) or a combination of the above [8, 9, 15], leading to their falling out of the frames. In general, non-structural infill walls are more prone to damages and fail faster compared to the reinforced concrete load-bearing elements. Moreover, even in the case of moderate earthquakes, the cost of repairing the infills is very high, which leads to an urgent need to consider the impact of non-structural infill walls on the overall behavior of the buildings [16] and to use innovative solutions to protect those from the damages occur during the repeated strong ground-shakes.

The main reason of the failure of infills is the insufficient ability of transmitting forces of the rigid elements due to the relatively large displacement imposed by the reinforced concrete columns. Stress concentrations at the contact of reinforced concrete elements with the infill walls cause damages even at very small horizontal drift levels, below 0.5% [17].

In order to prevent such damages, researchers have started to propose alternative solutions recently. Studies mostly offer load or deformation capacity increment of the systems by means of utilizing carbon fiber reinforced polymer (CFRP) wrapping sheets on the walls [18–20], special connection detailing for separating masonries from the frames [21] or enhancing the sliding capacity of infills with special joints [22]. In this paper, two other innovative solutions are proposed and the details are given below.

Fig. 8. Detachments at the joint of the infill wall and the reinforced concrete frame and damage to the wall corners (school in Petrinja after the earthquake in December 2020)

4. PUFJ and FRPU methods as effective protection solutions of the infill walls against earthquakes

The technology of Polymer Flexible Joints (PFJ) was developed at the Faculty of Civil Engineering of the Cracow University of Technology [23], which is capable of simultaneously carrying heavy loads and large deformations (Fig. 9a) and dissipating energy thanks to its visco-elastic features. Accordingly, flexible joints for securing the structures in seismic areas were developed, in cooperation with the foreign partners. These are PolyUrethane Flexible Joints (PUFJ) and Fiber Reinforced PolyUrethanes (FRPU). Their high efficiency has been verified by the cyclic push-over experiments [17, 24], tests on a seismic table [25, 26] and harmonic dynamic force resonance excitations [16]. The behavior of PUFJ and FRPU protected structures was also analyzed using numerical models [13, 27, 28].

The PUFJ joints are made of a two-component polyurethane compound from the Sika P family, which can be applied as an injection, e.g. when repairing cracks in masonry structures (Fig. 9b) or as an interface element in the connection of reinforced concrete frames with the infill walls (Fig. 9c), where the interface can also be made as a prefabricated PUFJ joint (Fig. 9d). The FRPU composite is constructed of a glass fiber mesh embedded in a polyurethane matrix (Fig. 9e, f, g).

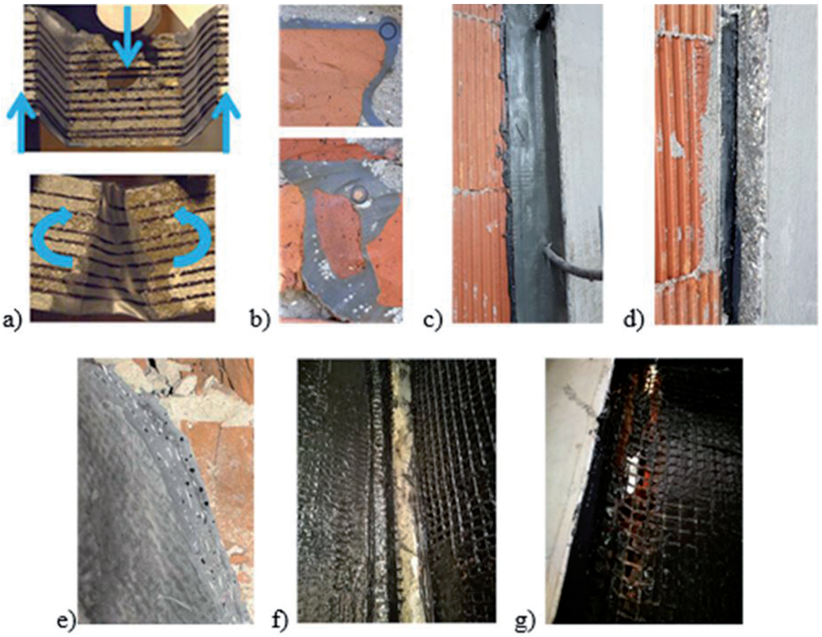

Fig. 9. Various forms of PUFJ and FRPU (description in the text)

4.1. Cyclic push-over tests of the frames with PUFJ and FRPU implemented infills

Cyclic push-over tests (cyclic shear) were carried out at the ZAG Laboratory in Ljubljana (Slovenia) on reinforced concrete frames filled with the masonries made of clay blocks. Four types of systems shown in Fig. 10 were tested. On the test stand (Fig. 11a), cyclic shear was forced according to the protocol shown in Fig. 11b. Examples of type B frame hysteresis loops are shown in Fig. 11c, while a comparison of the envelope of these loops for A, B and C frame types is presented in Fig. 11d.

The classic frame connected to the wall with a rigid mortar (type A) was tested until the wall detached from the surrounding frame around the entire perimeter (risk of out-of-plane

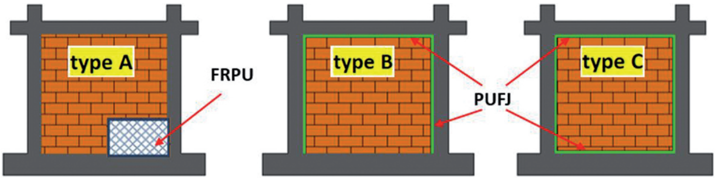

Fig. 10. Schemes of tested reinforced concrete frames with infill walls: type A (rigid connection with mortar) without and with FRPU reinforcement (left), type B with injection PUFJ on 3 edges (in the middle), type C with prefabricated PUFJ on 4 edges (on the right)

damage – compare the real structure in Fig. 8), and then the wall was strengthened on both sides with FRPU (rescue intervention) and tested to the maximum drift capacity. Type B was created by cutting 3 furrows 2 cm wide on the upper and side edges of the wall, which were then filled with injection PUFJ (simulation of wall protection in an existing building). In type C, the inside of the frame was first lined with 2 cm thick prefabricated PUFJ, and then the wall was built (simulation of wall protection in a newly constructed building). A detailed description of the tested elements and the performed tests is presented in [24].

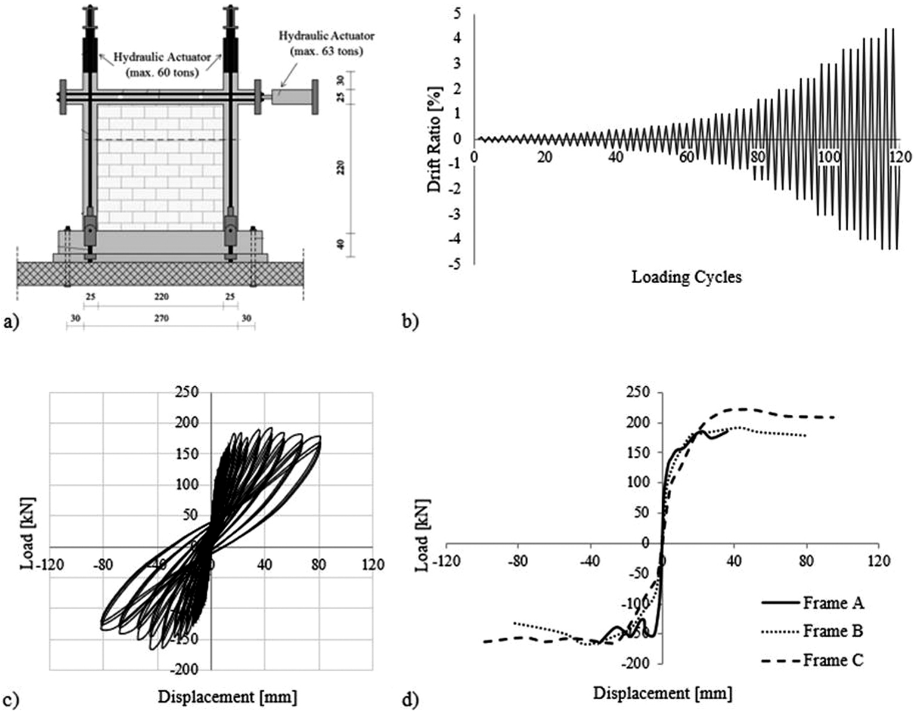

Fig. 11. Test stand at ZAG for cyclic shear tests with dimensions of the tested element (a), cyclic load protocol (b), exemplary hysteresis loops for the B type frame (c), hysteresis loop envelopes for the tested A, B and C frames (d) [24]

Type B and C frames, with walls bonded by PUFJ joints, showed a very high resistance to the cyclic loads with large horizontal displacements (up to 100 mm) and drifts (up to 4%), and retained the ability to further transfer vertical and horizontal loads (limit of the operating range of the actuator was reached) without the risk of out-of-plane failure, and the operation ability of the frames were remained ductile (Fig. 11d). The damage to the corners (Fig. 12a, b) indicates a redistribution of stress concentration by PUFJ, and the out-of-plane test of the damaged B and C frames, subjected to dynamic harmonic excitations in resonance (for 10 minutes), did not cause the out-of-plane failure of the damaged walls (Fig. 12c).

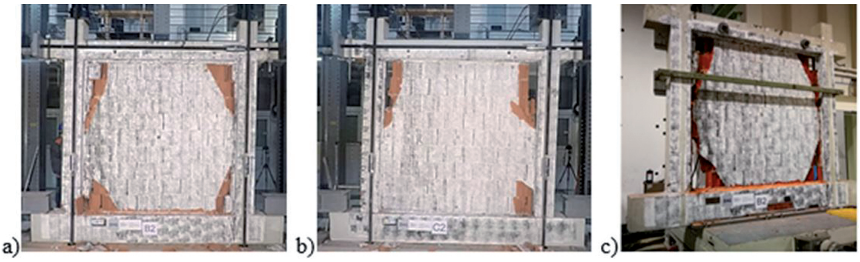

Fig. 12. Damaged frames after cyclic shear tests in the frame plane (in-plane): type A (a), type B (b) and no additional damage in the frame type B after the action of out-of-plane dynamic harmonic loads in resonance – for 10 minutes (c)

For comparison, the A-type wall was completely detached from the frame with a drift of 0.5% and chipping of the edge at 1.6%, which could cause the wall to fall out of the frame plane.

The test was stopped for the installation of the FRPU reinforcement – (Fig. 9g, and Fig. 13a). Frame type A, strengthened with FRPU (A2R) showed an additional significant increase in the load capacity and ductility (Fig. 13c) compared to the damaged frame type A without FRPU (A2) reinforcement – Fig. 13b. Moreover, even a significant drift of the frame after the FRPU intervention (Fig. 13a) did not cause any major damage, which could lead to the wall falling out of the frame plane (Fig. 9g). This was also confirmed by the visual inspection after a cyclic test in an attempt to remove the reinforced wall from the reinforced concrete frame [17].

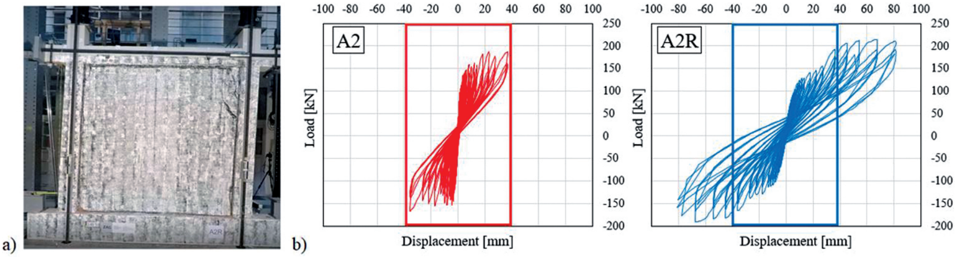

Fig. 13. The maximum drift (3.6%) in the plane of the frame (in-plane) of the A2R element of the reinforced FRPU (a), comparison of the hysteresis loop of elements without FRPU – A2 and with FRPU – A2R (b)

It should be noted that all infilled frames equipped with PUFJ or FRPU systems were able to transfer significant amounts of shear forces (190–220 kN), even under very large drifts of the structure (3.5–4.0%) repeated cyclically (Fig. 11d and 13b), without losing the connection between the frame and the infill wall. The latter condition is a design requirement according to [29] and [30], with Turkish Standard [30] adding the condition to ensure that the structure shall be safely drifted to a level of at least 2%. PUFJ and FRPU technologies fulfill these conditions with a considerable margin. Moreover, they are able to dissipate significant amounts of energy in each cycle while maintaining the load capacity.

4.2. Numerical in-plane analyses for testing different materials and loading conditions

In order to evaluate the PUFJ performance under conditions other than the aforementioned tests, various numerical models were created which enabled to perform analyses without the need of additional costly experiments. For this purpose; single-bay and single-story frames with real-size dimensions were numerically tested for both traditionally designed stiff (STF) mortar used systems and PUFJ implemented ones. The frames and masonries were identical for each type, whereas frame-to-masonry connection detailing constituted the only difference. Accordingly for each model, rectangular shaped masonry wall with the edge lengths of vertical 1950 mm and horizontal 2000 mm was surrounded by the RC frame. Unlike the above tests carried out at the ZAG laboratory where hollow clay bricks were utilized, the wall for the numerical analyses was created by forming Polish Bonarka solid brick units with dimensions of 65 × 120 × 250 mm in single wythe vertically, thus the wall thickness of 120 mm was achieved. Detailing of the RC elements and joints was similar of the ZAG tests. Material properties were adapted from the previous experimental [31, 32] and numerical [27] results.

In terms of support and loading conditions, the frames were restrained at the bottom beam level and the rest of system was able to move freely in any direction. First, all frames were exposed to the vertical loads affecting on columns. Two different load levels were considered. Total amount of 900 kN and 60 kN loads were distributed equally on the columns, for representing bottom and upper stories in a building, respectively. In this way, behavior of the enclosed infill walls was aimed to be investigated under two extreme conditions in terms of contribution to the surrounding frame. Following that, while the vertical loads were still effective, the frames were loaded with the same horizontal cyclic excitations regardless of the vertical load magnitude. The loading was done by means of forcing the frames on top-beam level with gradually increasing displacement targets reaching up to 100 mm (4.5% drift).

Outcomes were evaluated in terms of the horizontal load carrying capacities and corresponding energy absorption levels. For the case of load capacities, peak values of the hysteresis curves were utilized; whereas for the latter one, total area swept under the load-displacement cyclic loops were calculated. The results are presented in Table 1.

According to the results; it was established that PUFJ could support frames for carrying loads up to the levels of conventional constructed infill walls or even higher (peak load for the STF frame was around 5% higher than the PUFJ frame for the case of 900 kN vertical loading, whereas PUFJ frame could carry 13% higher horizontal forces when 60 kN vertical loading was effective). PUFJ exhibited promising results in this aspect, since no significant strength drop was observed compared to the traditional method. Other than that, PUFJ implementation in this numerical study exhibited better performance of absorbing the seismic energy compared to its traditional counterpart (between 12% and 18% – depends

Table 1. Results of the cyclic numerical analyses

Frame	Vertical Load [kN]	Max. Load [kN]	Relative Max. Load [%]	Energy [kNm]	Relative Energy [%]
PUFJ	900 kN	179.3	94.3	26.2	100
STF		190.2	100	21.6	82.4
PUFJ	60 kN	129.1	100	18.9	100
STF		112.3	87	16.6	87.8

on the vertical loading) hence it is in alignment with the modern engineering requirements that suggest the displacement-based design (DBD) approach [33–35]. Finally, flexible joints were also effective of preventing local damages on the infill walls, since hyper-elastic elongation abilities of this joint method could resist the high displacement demands and the wall stability could be sustained visibly better than the traditionally constructed stiff joint implemented frame. This can be seen from the damage status of the infill walls examined by means of comparing the plastic strains of PUFJ and STF type of frames in Fig. 14 and Fig. 15.

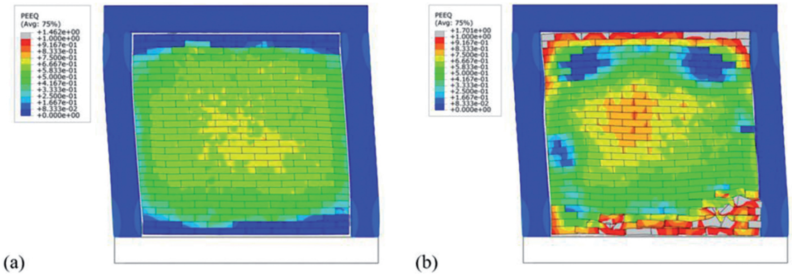

Fig. 14. Plastic strain diagrams on the masonries for the case of 900 kN vertical load; PUFJ (a) and STF (b) frames

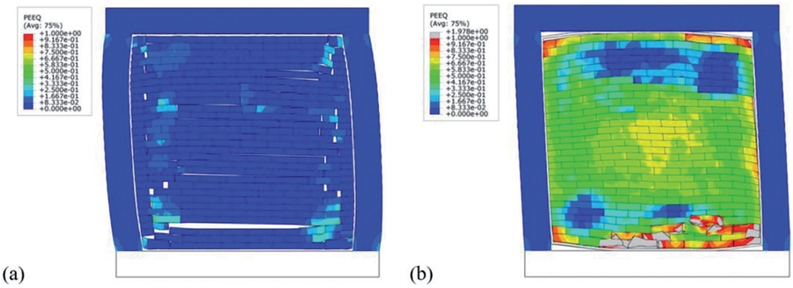

Fig. 15. Plastic strain diagrams on the masonries for the case of 60 kN vertical load; PUFJ (a) and STF frames (b)

4.3. Dynamic tests of a building with PUFJ and FRPU implemented infills – shake table results

Dynamic tests of the infill walls with PUFJ and FRPU were carried out in the laboratory of IZIIS Skopje in North Macedonia as a part of the H2020 SERA project. A symmetrical building with B and C type walls was tested in 4 phases (Fig. 16). The most serious (in-plane) damages occurred on the B walls at the end of Phase I (Fig. 17a) when the C walls were tested in out-of-plane mode (Fig. 16a). In Phase II, the damaged B walls were strengthened by FRPU (B_FRPU) and tested in-plane again. Between Phases II and III, the building was rotated by 90 degrees around its vertical axis due to the fact that the shake table had only the single-direction loading ability. In Phase III, the C walls were tested in-plane and the B_FRPU walls out-of-plane. In Phase IV, the moderate cracked C walls were strengthened by FRPU (C_FRPU) and tested in-plane again (Fig. 16b). Repeating seismic excitations on the shake table were unable to collapse the tested building.

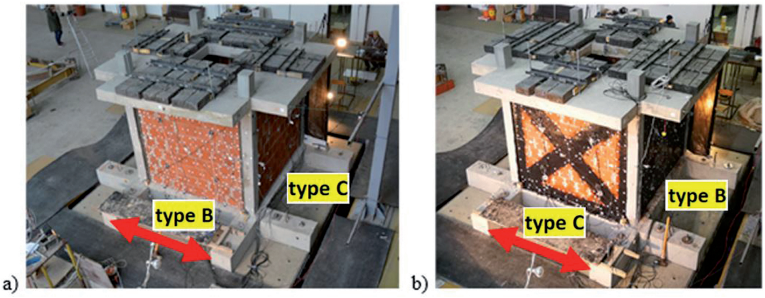

Fig. 16. The building with PUFJ and FRPU implemented infill walls on the shake table: Phase I – B (in-plane) and C (out-of-plane) (a), Phase IV – B_FRPU (out-of-plane) and C_FRPU (in-plane) (b)

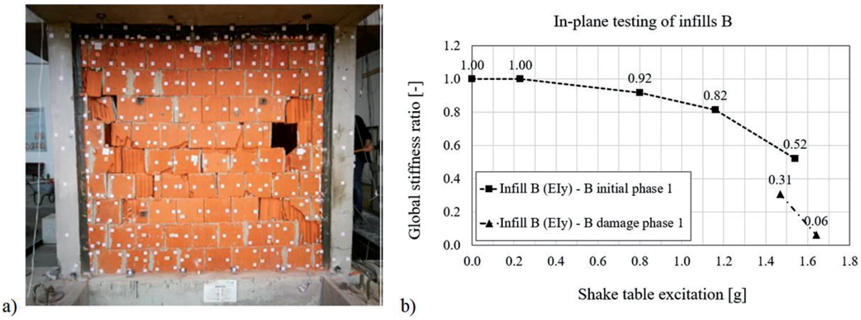

Fig. 17. Phase I: final damage to the B-type wall (a), gradual degradation of the building stiffness (b)

The subsequent phases of the experiment on the seismic table, together with the maximum values recorded during the tests, are presented in Table 2. The recorded values indicate that the PUFJ joint sustained the stability of the very badly damaged B-type walls in the plane of the frame at accelerations above 1.5 g and building drift of 3.7% (well above the standard requirements of 2%) – Phase I. In the same phase, the C-type wall resisted the out-of-plane excitation of the same level without any damage. The global stiffness of the tested building was degraded to the level of 6% of the initial stiffness (Fig. 17b), which was caused by the work in resonance between the 2.5–4.0 Hz band, dominant in the given scaled Kefallonia 2014 seismic excitation.

Table 2. Maximum values recorded during the shake table tests

Testing phase	Infill type (excitation direction)	Table acc. [g]	Slab acc. [g]	Slab displ. [mm]	Drift [%]
I	B (in-plane)	1.64	1.52	88.9	3.7
	C (out-of-plane)				
II	B_FRPU (in-plane)	0.39	0.89	38.9	1.6
	C (out-of-plane)				
III	B_FRPU (out-of-plane)	0.35	0.48	16	0.7
	C (in-plane)				
IV	B_FRPU (out-of-plane)	0.95	1.25	21	0.9
	C_FRPU (in-plane)				

At the end of Phase I, the severely damaged B-type walls were strengthened with FRPU on both sides and the Phase II test was conducted, but to a level that was safe for the building. After rotating the building by 90 degrees, the C in-plane walls were tested until the bonds of the joints between the blocks on the wall were opened – Phase III. After the FRPU intervention on the surfaces of the C-type walls, the tests were continued in Phase IV up to the maximum load capacity of the seismic table (limitation caused by the failure of the actuator). Following the implementation of FRPU strengthening on the walls and upon the completion of the tests in all phases, the building maintained its global stiffness at the level of 52%, despite the presence of plastic hinges at the ends of reinforced concrete columns, thanks to the cooperation with PUFJ and FRPU masonry walls. More details can be found in [25] and [26].

4.4. Dynamic tests of a building with PUFJ and FRPU implemented infills – harmonic forcing in resonance

The building made of PUFJ and FRPU implemented infill walls, sustained in a good condition after the tests on the shake table, was subjected to another loading by the harmonically variable resonance forces. Despite several minutes of continuous dynamic excitations (sweeps) with different set resonant frequencies (a total of over 2 hours of work in resonance) and the reduction of global stiffness to the level of approx. 10–15%, the building retained its elastic nature and global stability, without any signs of the wall out-of-plane instability (Fig. 18a). The only significant damage was the cut of glass fibers on the FRPU composite in the center of the C-type wall (Fig. 18b). The loss of symmetry of stiffness in the building and its considerable reduction did not negatively affect its seismic resistance, as shown by the recorded measurement results at the end of the study (Fig. 19), as the PUFJ and FRPU systems helped to maintain its integrity until the end of the study.

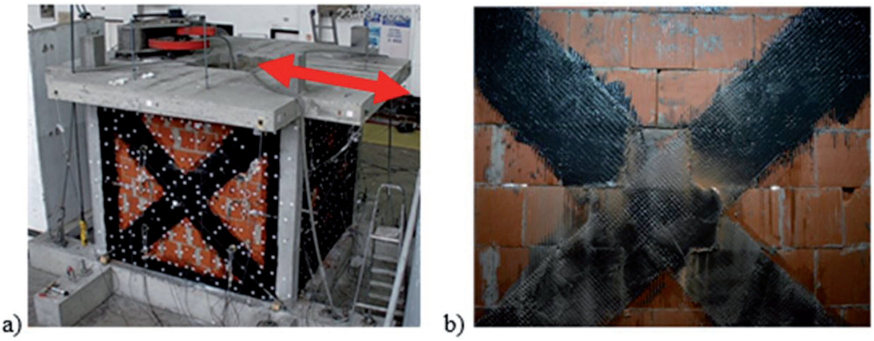

Fig. 18. Building after completed examination (a), FRPU damage in the center of the C-type wall (b)

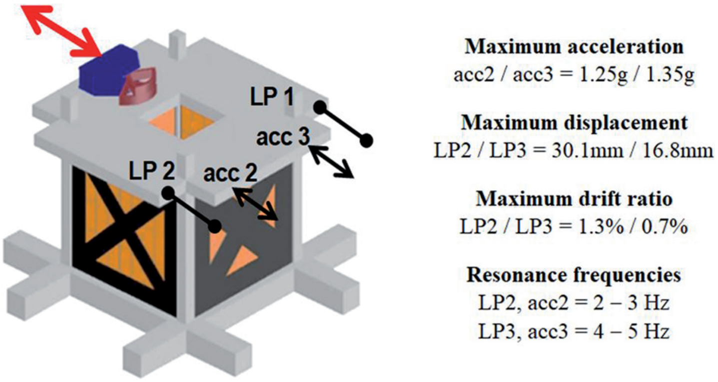

Fig. 19. Recorded dynamic response of the building with asymmetric stiffness

5. Conclusions

The presented research results, concerning innovative PUFJ and FRPU systems for fastening filling walls to reinforced concrete frames, have confirmed their high efficiency as permanent anti-seismic protection. One-time installation of these systems is able to protect property and human life during repeatedly repeated earthquakes and at the same time meet the strict requirements of modern seismic standards, which was also confirmed by the experts in the earthquake engineering [16, 26, 28]. Properly adjusted PUFJ and FRPU systems can be also used in other structures (timber, masonry) threatened by extreme loadings in areas of hurricanes and mining damages.

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Ochrona przed trzęsieniami ziemi konstrukcji żelbetowych ze ścianami wypełniającymi przy użyciu systemów PUFJ i FRPU

Słowa kluczowe: ochrona antysejsmiczna, obciążenie cykliczne i rezonansowe, polimerowe złącza podatne, testy dynamicznena stole sejsmicznym, PUFJ i FRPU, ramy żelbetowe ze ścianami wypełniającymi

Streszczenie:

Postępy w technologii i materiałoznawstwie prowadzą do nowych rozwiązań wprowadzanych w inżynierii lądowej. Wśród tych innowacyjnych rozwiązań znajdują się podatne złącza poliuretanowe (PUFJ) i poliuretany wzmocnione włóknami (FRPU). Systemy PUFJ instalowane są pomiędzy murowanymi ścianami wypełniającymi a ramami żelbetowymi jako anty-sejsmiczny element buforowy, natomiast systemy FRPU są przeznaczone do wzmacniania powierzchni ścian cienkimi pasami kompozytowymi. Obie metody zostały opracowane w celu zwiększenia ciągliwości budynków, przy jednoczesnym utrzymaniu ich ogólnej nośności, a tym samym w celu zwiększenia bezpieczeństwa użytkowania tych budynków w trakcie trzęsień ziemi. W artykule przedstawiono wyniki badań elementów w skali naturalnej pod quasi-statycznymi obciążeniami cyklicznymi oraz obciążeniami dynamicznymi na stole sejsmicznym i pod działaniem sił harmonicznych w rezonansie. Ponadto zostały przeprowadzone analizy numeryczne, mające na celu poznanie zachowania się podobnych konstrukcji z innymi materiałami murowymi współpracującymi z PUFJ, które poddane zostały różnym warunkom obciążenia. Wyniki potwierdziły wysoką skuteczność proponowanych rozwiązań, które jednocześnie spełniają surowe wymagania współczesnych norm sejsmicznych.

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