1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.73

PUFJ and FRPU earthquake protection of infills tested in resonance

Arkadiusz Kwiecień[1], Zoran Rakicevic[2], Aleksandra Bogdanovic[3], Filip Manojlovski[4], Angela Poposka[5], Antonio Shoklarovski[6], Theodoros Rousakis[7], Alper Ilki[8], Matja Gams[9], Alberto Viskovic[10]

[1] *Professor* of CUT, Cracow University of Technology, a*kwiecie@pk.edu.pl*
[2] *Professor*, University Ss. Cyril and Methodius in Skopje, Institute of Earthquake Engineering and Engineering Seismology, *zoran_r@iziis.ukim.edu.mk*
[3] Assoc. Prof. Dr., University Ss. Cyril and Methodius in Skopje, Institute of Earthquake Engineering and Engineering Seismology, *saska@iziis.ukim.edu.mk*
[4] *Assistant*, University Ss. Cyril and Methodius in Skopje, Institute of Earthquake Engineering and Engineering Seismology, *filipmanojlovski@iziis.ukim.edu.mk*
[5] *Assistant*, University Ss. Cyril and Methodius in Skopje, Institute of Earthquake Engineering and Engineering Seismology, *angela@iziis.ukim.edu.mk*
[6] *Associant Professor*, University Ss. Cyril and Methodius in Skopje, Institute of Earthquake Engineering and Engineering Seismology, *antonio@iziis.ukim.edu.mk*
[7] *Associant Professor*, Democritus University of Thrace, *trousak@civil.duth.gr*
[8] *Professor*, Istanbul Technical University, *ailki@itu.edu.tr*
[9] *Assistant Professor*, University of Ljubljana, *matija.gams@fgg.uni-lj.si*
[10] *Associant Professor*, G. D'Annunzio University of Chieti – Pescara, *a.viskovic@unich.it*

Abstract

The main objective of this paper is to present the efficiency of an innovative seismic protection of masonry infills in RC frame structures, based on polyurethane flexible joints (PUFJ). The proposed repair and strengthening method was assessed and validated through forced vibration testing of a full-scale building. The test specimen examined dynamically in the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology – IZIIS in Skopje, North Macedonia, is fully symmetrical one storey 3D frame with 4 infill masonry walls, designed according to current Eurocodes. One symmetrical pair of infills, walls type B, was tested out-of-plane and had three interfaces (left, right and top) injected with PUFJ. The other symmetrical pair of infills, walls type C, was tested in-plane and had all 4 interfaces bonded with prefabricated PUFJ laminates as frame-infill joints. It should be noted that the test specimen had previously been subjected to a series of shake table tests for the purpose of another experiment. The foundations-to-column and column-to-slab joints had already yielded, and the infills had heavy damage. Then they were repaired using emergency (quickly applied) fiber reinforced polyurethane (FRPU) coating and were subjected again to a series of shake table tests. Therefore, the concrete members and the wall infills had been significantly damaged before the present tests. The experimental testing activities for this, second stage of research were conducted by the method of forced vibrations.

Key words: forced vibrations, experimental testing, polyurethane, RC, masonry

1 Introduction

The concept of building reinforced concrete frame structure with block or brick infills is common around the world. At first, the load bearing RC elements are constructed (foundations, columns, beams and slabs) and infills are erected afterwards. The infills are not considered load bearing elements during the design and in reality are lightly loaded with the additional vertical live loads. Post earthquake inspections show that the damage pattern of wall infills is usually characterized by diagonal shear cracks or out of plane collapse or joint sliding or combination of the above [1, 2, 3]. In general, non-structural infill walls are more vulnerable, and develop damage earlier compared to the RC bearing members. In some cases, infills may cause detrimental failure of RC columns and even building collapse. Further, even for moderate earthquakes, the cost of repair of infills is very high leading to urgent need of consideration of the influence of the non-structural infill walls to the behaviour of the structures in general.

Major reason for the infill damage is the insufficient capabilities of the stiff elements to bear the forces due to the relatively large displacement imposed by the RC members. The stress concentrations on the contact between the RC elements and walls cause damages at very small inter-storey drifts.

To take advantage of the polymer properties, such as deformability and extreme bonding, researchers are exploring their potential use in repair and strengthening of the structural members [4, 5].

This paper presents forced vibrations testing of a full scale 3D RC frame with four masonry infills. One symmetrical pair of infills, walls type B, had three interfaces (left, right and top) injected with polyurethane flexible joints (PUFJ). The other symmetrical pair of infills, walls type C, had all 4 interfaces bonded with prefabricated PUFJ laminates as frame-infill joints. The building was previously subjected to shake table tests, and then repaired and strengthened with polyurethane flexible joints – PUFJ and fiber reinforced polyurethane – FRPU and retested again on the shake table. In other words, the specimen (with PUFJ and FRPU) already damaged during the shake table tests was tested again by the forced vibration tests summarized in this paper.

The proposed repair and strengthening method is assessed and validated through forced vibration testing method in the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology – IZIIS in Skopje, North Macedonia. The infill walls with PUFJ and FRPU, already damaged during the shake table tests, were subjected to in-plane (type C) and out-of-plane (type B) excitation simultaneously in long-duration harmonic vibration tests.

A brief introduction to the results from the forced vibration testing and dynamic properties by ambient vibrations method are presented.

The long-duration tests confirmed the effectiveness and the potential that PUFJ interfaces and FRPU coating have regarding the response of the structure to earthquake or harmonic excitations.

2 Test specimen and testing methodology

The test specimen was fully symmetrical reinforced concrete one by one bay frame structure, with inherent damage on the foundation-to-column and column-to-slab joints due to previous history of experimental testing activities performed on shake table [6, 7]. The experimental testing activities presented herein, focus on the efficiency of the innovative seismic protection system by the technique of forced vibrations, generating harmonic excitations on the top of the structure (Fig. 1).

2.1 Description of the tested model structural elements

The test specimen, Fig. 1a, was fully symmetrical 3D frame RC structure of 4 identical columns with cross-section a/b=20/20cm, reinforced with 8 longitudinal rebars Ø10 and double perpendicular stirrups Ø8/5cm. The beams (b/d=20/20cm) were incorporated in the slab and comprised of 8 longitudinal rebars Ø10 with Ø8/5cm stirrups. The foundation beams constructed to fix the model to the ground were b/d=40/40cm with 10 longitudinal rebars Ø18 and Ø8/15cm stirrups. The slab, d=20 cm, was reinforced with Q503 steel rebar mesh. The materials quality was concrete C30/37 and rebars B500C. The structure was designed according to current Eurocodes.

2.2 Description of the tested model infills

Infills as non-structural elements were constructed of KEBE Ortho Block K100 system with half bricks at both ends of every second layer using Mounting Mortar M10 [6].

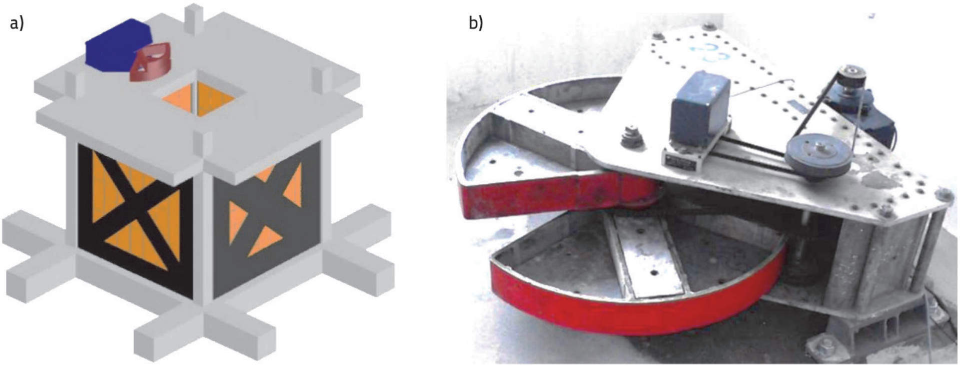

Figure 1. Test specimen with vibrations generator (a); Vibrations generator – shaker (b)

The walls were divided in two types: B and C (Fig. 2a). The first parallel infill walls of type B was built with 2 cm gap between the bricks and RC columns and slab. After brick laying, the RC interface was filled with Sika ZP Primer and the gaps were sealed with thin longitudinal Sika PS sheets. The final step consisted of injection with Sika PM, left to cure to form the PUFJ.

The second parallel infill walls of type C was built on PUFJ Sika PM laminates, already glued to the RC structure on all 4 sides, connecting with RC elements (columns, slab and foundation) with cross section b/d=2/10cm.

Additional emergency interventions using FRPU have been undertaken in the previous experimental campaign [4]. During the previous testing campaign conducted using shake table, the specimen experienced damage and was repaired with FRPU as shown in Fig. 2. The FRPU was applied on the damaged walls around the contact of the wall and RC elements and two diagonal stripes at the inner and outer part of the infills. As shown in Fig. 2b, the stripes installed on infills type B were 50 cm wide and the diagonal and perimeter stripes on the infills type C were 35 cm and 20 cm wide, respectively. The repaired specimen was tested again on the shake table up to the shake table limit [7]. The damaged specimen after the shake table tests was not repaired again before forced vibration tests.

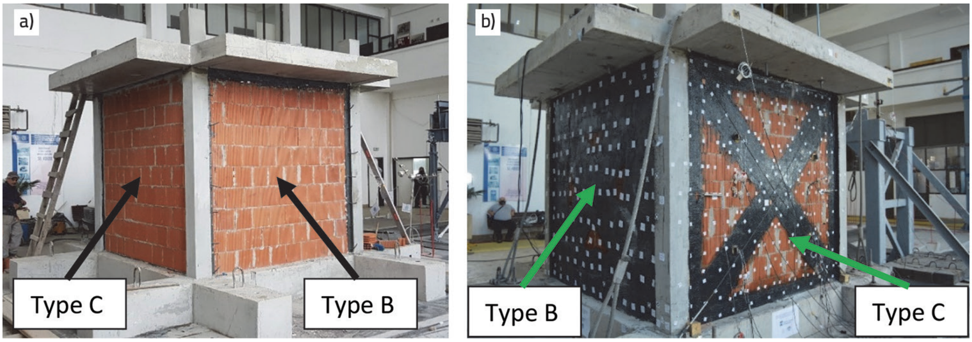

Figure 2. Built with PUFJ – before testing on the shake table (a) and FRPU strengthened test specimen after testing on the shake table – just before forced vibration tests (b)

2.3 Testing methodology and the theory behind

The experimental testing activities were conducted by the technique of forced vibrations, generating harmonic excitations at the top of the structure. The purpose was to simulate the desired drift as if a specific seismic event would have caused. After several forced vibration tests, the dynamic properties of the specimen were determined by the ambient vibrations technique. Similar testing technique was used by the authors before on actual structures in the field [8]

The theory of forced harmonic vibrations provides a basis to determine experimentally the natural frequencies, mode shapes and damping of a structure as well as to apply a specific harmonic excitation at desired level of a structure. The forced vibrations are produced by vibration generators, shakers, with different capacities in terms of produced force and frequency range, all depending on the purpose of the tests and the specific needs.

The harmonic character of the motion is achieved by the special design of the generators themselves. Fig. 1b shows the shakers used for this experimental activity, having the form of two flat baskets rotating in opposite directions around a single vertical axis. By placing various number of weights in the baskets, the magnitudes of the rotating mass can be adjusted. The two counter rotating masses, are shown schematically in Fig. 3 as lumped masses with eccentricity e. Their locations at is shown on the left-hand side in Fig.3 and at time *t* on the right-hand side in Fig.3. The x-components of the inertia forces of the rotating masses cancel out, and the y-components combine to produce a force - equation (1).

$$p(t) = (m_e e\omega^2)\sin\omega t \qquad (1)$$

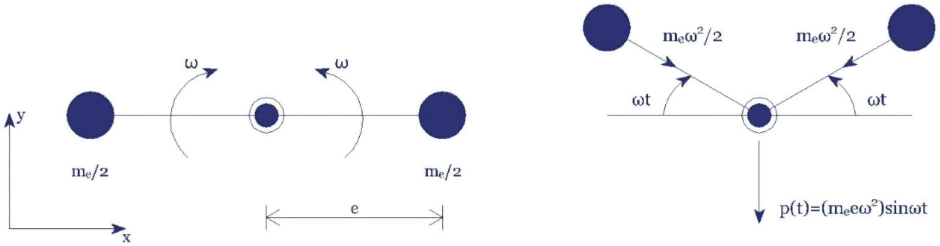

Figure 3. Rotating mases - scheme presentation

The force has the maximum value at the moment of overlapping of the baskets, and opposite, minimum value equal to zero when the angle that the baskets close is equal to π. This dynamic force can be transmitted to the structure by fixing the vibrations generator to the specimen. The amplitude of this harmonic force is proportional to the square of the excitation frequency ω. Fig. 4 shows a vibration generator consisting of two rotating baskets. Each basket is composed of three parts: two identical parts which are intended space for „L" plates and one part which is intended space for „S" plates. One "L" plate weighs 20kg, and one „S" plate weighs 10kg.

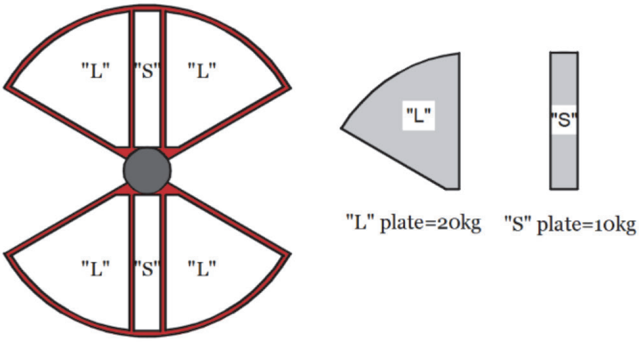

Figure 4. Vibrations generator, "L" plate and "S" plate (additional mass)

For example, the case of "L-1 + S-1" requires two "L" plates and one "S" plate in one basket, which must also be put in the other basket. So, for the mentioned case, total weight of 100kg should be used. Furthermore, for the case "L-0 + S-0", the baskets are rotating empty. A full list of the performed tests, containing type of excitation and load case description is presented in Table 1.

Table 1. List of the performed tests

Test No.	Name	Type of excitation	Load case
1	FV Test 01	Harmonic forced vibrations	S-1 + L-0
2	FV Test 02	Harmonic forced vibrations	S-1 + L-0
3	AV After Test 2	Ambient vibrations	Ambient
4	FV Test 03	Harmonic forced vibrations	S-3 + L-0
5	AV After Test 3	Ambient vibrations	Ambient
6	FV Test 04	Harmonic forced vibrations	S-4 + L-0
7	AV After Test 4	Ambient vibrations	Ambient
8	FV Test 05	Harmonic forced vibrations	S-2 + L-0
9	FV Test 06	Harmonic forced vibrations	S-3 + L-0
10	AV After Test 6	Ambient vibrations	Ambient
11	FV Test 07	Harmonic forced vibrations	L-3
12	FV Test 08	Harmonic forced vibrations	S-4 + L-1
13	FV Test 09	Harmonic forced vibrations	S-1 + L-0
14	AV After Test 9	Ambient vibrations	Ambient

2.3.1 Measuring devices and instrumentation

The instrumentation of the tested model comprised of 23 accelerometers (acc), 2 linear potentiometers (LP) and 10 linear variable differential transformers (LVDT) measuring acceleration, total and relative displacements, respectively. Their exact positions on the specimen are shown in Fig. 5.

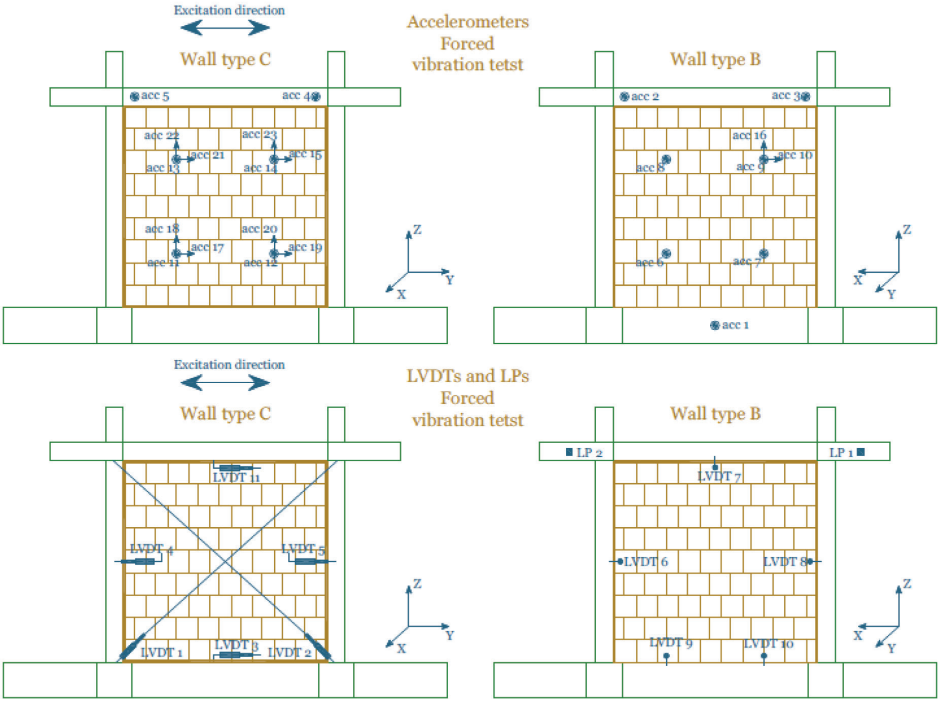

Figure 5. Instrumentation scheme

3 Results and discussion

The results from the performed tests are divided into two categories. Firstly, the results of ambient vibrations measurements are shown and secondly, the results of forced vibrations tests are shown.

3.1 Ambient vibrations

Ambient vibrations were measured after the forced vibrations tests, test 2, test 3, test 4, test 6 and test 9, to observe the change of the dominant frequencies. The predominant frequencies for the specimen are defined using ARTeMIS Modal [9] post-processing software. Operational modal analysis was performed, hence the natural frequencies and the mode shapes of vibrations were determined using the Peak Picking technique and the Enhanced Frequency Domain Decomposition technique. The frequencies and damping obtained with ambient vibrations after each test are described in Table 2.
The mode shape in X direction (perpendicular to the excitation) is clear translation during all ambient vibration measurements except for the last ambient vibrations test, when the mode shape has significant contributions of rotation. Following Table 2, it could be noticed that the natural frequency (mode 1 in X direction) decreased from 4.303 Hz after

test 3 to 2.895 Hz after test 10. This is due to the stiffness degradation of the model of 55 % (calculated according to [7]), caused by gradual further development of damages in the structure and FRPU. The mode shapes in Y direction are translation with noticeable rotation. The main reason of the appearance of 2 different mode shapes in Y vibration is the difference of the stiffness of the walls and RC columns (different configuration and initial conditions), which was observed during the testing. During the ambient vibrations measurements, the appropriate frequencies in Y direction drop from 5.282 Hz and 7.401 Hz to 3.932 Hz and 5.82 Hz, respectively due to the stiffness degradation of the model of 45 % and of 38 %, respectively).

Table 2. Frequencies and damping obtained with ambient vibrations technique

Test No.	**Frequency** [Hz]	**Damping** [%]	**Comment**
3 (after FV test 2)	4.303	3.866	Translation X
	5.282	1.686	Combined – Translation Y + visible rotation
	7.401	2.461	Combined – Translation Y + visible rotation
5 (after FV test 3)	4.157	3.825	Translation X
	5.139	2.019	Combined – Translation Y + visible rotation
	6.772	2.576	Combined – Translation Y + visible rotation
7 (after FV test 4)	4.117	3.263	Translation X
	4.745	2.151	Combined – Translation Y + visible rotation
	6.708	2.615	Combined – Translation Y + visible rotation
10 (after FV test 6)	2.895	5.071	Translation X
	4.166	2.748	Combined – Translation Y + visible rotation
	6.69	2.367	Combined – Translation Y + visible rotation
14 (after FV test 9)	3.932	2.25	Combined – Translation Y + visible rotation
	4.876	1.496	Combined – Translation X + visible rotation
	5.82	1.823	Combined – Translation Y + visible rotation

3.2 Forced vibrations

Table 3 presents the top displacements and accelerations of selected forced vibrations tests for the top in-plane transducers such as accelerometers acc2 and acc3 and linear potentiometers LP 1 and 2. The presented frequencies in Table 3 are output values for the frequency of the specimen (obtained by acc2 and acc3) whereas the presented acceleration and roof displacement values are the peak values measured during testing. Furthermore, as noticeable, some of the performed tests are divided into several segment, due to the duration of the test as well as the change in the input frequency of the shakers.

From the results of Test 01 it could be noticed that maximum acceleration and displacement are measured when the specimen is excited in his natural frequency (around 4.5-5.0 Hz).

Also, from the acceleration and displacement of segment 1 and 2 of Test 01, it could be noticed that the deformed shape of the specimen is not clear translation. The reason behind could be the wall's different stiffness. In segment one the maximum acceleration and displacement is measured in acc2 and LP2 respectively (along one wall of type C), whereas in segment two the maximum acceleration and displacement is measured in acc3 and LP1 respectively (along the second wall of type C).

Table 3. Maximum accelerations and top displacements of selected forced vibration tests

Test No.	Segments	**Acceleration** [g]		**Displacement** [mm]		**Frequency** [Hz]
		acc 2	**acc3**	**LP1**	**LP2**	
FV Test 01	1-S1	1.16	0.7	6.4	12.1	4.0÷5.0
	1-S2	0.58	1.32	10.98	4.56	5.3
	1-S3	0.65	0.41	4.73	8.15	4.2
	1-S4	0.23	0.14	1.99	3.58	3.8
FV Test 03	2-S1	1.25	0.68	8.48	21.21	3.0÷4.0
FV Test 06	6-S1	0.067	0.04	1.37	4.07	2.0
	6-S2	1.12	0.36	5.96	27.92	2.9
	6-S3	0.27	1.1	13.12	5.13	4.3
	6-S4	1.1	0.34	6.24	28.99	2.9
	6-S5	0.3	1.35	16.8	6.4	4.0÷4.5
	6-S6	0.27	0.21	5.02	8.34	3.0
	6-S7	0.99	0.41	9.46	28.87	2.6
FV Test 09	9-S1	0.77	0.51	13.78	30.15	2.2

It could be seen from Table 1 that tests with several different combinations of loads in baskets were performed, in order the specimen to be excited with different force. Following Table 3, maximum displacement of 30.15mm (drift of 1,3 %) is recorded during Test 09. The plots on the Figures 8 and 9 show the time history of acceleration measured at points where acc2 was placed during the Test 01 and Test 09. For clearer presentation and analysis of the results, the plot of the Test 01 is segmented in 4 parts, and their recorded peaks of acceleration with dominant frequency are presented in Table 3.

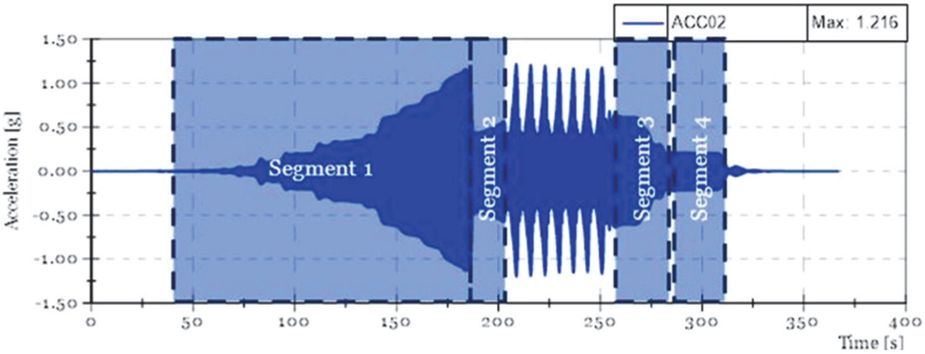

Figure 8. Acceleration time history of FV Test 01, accelerometer 02, marked segments

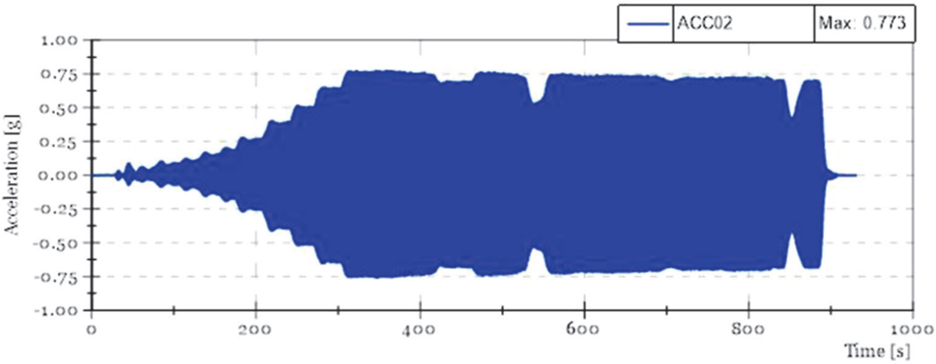

Figure 9. Acceleration time history of FV Test 09, accelerometer 02, full plot, non-segmented

4 Conclusions

The implementation of flexible joints on the concrete – masonry contact, during the process of erection of the buildings or as a part of post building interventions, could significantly contribute to better seismic response. The main reason is the stress redistribution in the joints, protecting infills and concrete frames against serious damages caused by stress concentration. Long-duration (up to 10 minutes) of strong harmonic forced vibrations in resonance with various adjusted modes (up to 1,35g, up to 30 mm - drift of 1,3 %) were not able to collapse the tested structure (previously examined on the shake table [7]) nor increase already existing damages significantly to make the structure unstable. Additional drop of stiffness degradation was less than 55 % after all resonance excitations, and the structure remained in safe and stable condition (protected by the infills against collapse). Change of natural frequency of the system, was also observed.

Another major contribution is the ability of the FRPU to prevent in- and out-of-plane collapse of the infill walls subjected to long duration harmonic forced vibrations but also to significantly contribute to the zones of tension developed in the diagonals of the walls when exposed to horizontal forces. Extreme dynamic tests with resonance proved that PUFJ and FRPU systems are functional, efficient and durable anti-seismic protection of masonry infills in RC frame structures, allowing the protected structure to withstand many earthquakes and aftershocks without collapse.

Acknowledgements

Financed from the Dean Grant 2020 from Faculty of Civil Engineering, Cracow University of Technology (Poland).

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