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SEISMIC BEHAVIOUR OF A REINFORCED MASONRY INFILL MADE WITH AN INNOVATIVE NEW BRICK UNIT: RESULTS OF A SHAKING TABLE TEST

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Abstract. *Within the framework of INSYSME project (www.insysme.eu) [1], an innovative solution for infill walls has been developed by the authors and XALKIS S.A.. A special, vertically perforated, brick unit has been designed and produced. The innovative brick unit was granted a patent (No. 1008797) by the Greek Patent Office. Vertical holes are located close to the faces of the masonry unit, to serve two needs, namely (a) the enhancement of the out-of-plane bearing capacity of the infill, using vertical reinforcement and (b) the positioning of installations (electrical and plumping). Horizontal or horizontal and vertical reinforcement is provided. The horizontal reinforcement is positioned in the bed joints during the construction of the wall, whereas the vertical reinforcement is placed (in the special vertical holes) after the construction of the wall. Additionally, simple sliding connectors may be used to prevent out-of-plane collapse.*

In order to assess the performance of the proposed solution, an experimental campaign is carried out on a one-bay masonry infill. A specimen is constructed and tested on the shaking table, in the facility of the Laboratory of Earthquake Engineering/NTUA, in a reduced scale of 1:2. The aim of this investigation was to obtain quantitative data about the seismic behaviour of the infill constructed with the innovative brick unit, and to compare it with its quasi-static behaviour (in-plane and out-of-plane tests on full scale specimens).

In the present paper the experimental results of the shaking table test are presented and commented upon.

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1 INTRODUCTION

Brick masonry infills, widely used as enclosures to RC buildings, offer an economic and durable solution, as they may ensure adequate insulation properties, whereas they contribute to the seismic behaviour of the structural system. Traditionally, enclosures and partition walls in RC structures are considered as non-structural elements and, thus, they are not explicitly taken into account in the aseismic design of buildings, even though theory and practice have repeatedly proven that masonry infills may affect in a positive way the seismic behaviour of buildings, provided that possible negative structure-infill interaction is avoided [2].

On the other hand, the behaviour of the infills themselves is significant both from the Public safety and economy point of view [3]. In recognition of this fact, EC8 [4] includes (qualitative) guidance for the improvement of the seismic behaviour of infill walls. Quantification of the EC8 [4] rules, as well as innovative infill systems-fully documented through experiments and analysis-is the aim of the EU-funded project INSYSME.

Within the framework of the European Project INSYSME, one of the two innovative solutions for infill walls developed by the authors and a brick manufacturing industry XALKIS S.A., INSYSTEM 2, aims at enhancing the in-plane and out-of plane deformability of the infill wall. A special, vertically perforated, brick unit has been designed and produced. The innovative brick unit was granted a patent (No. 1008797) by the Greek Patent Office. In order to evaluate the system performance in-plane and out-of-plane tests on one-bay infilled frames are performed. Shaking table tests of frames were also envisaged. More specifically, one-bay infilled frame (scale 1:2), constructed with the proposed enclosure wall INSYSTEM 2, is tested on the earthquake simulator of the Laboratory of Earthquake Engineering, NTUA. Uniaxial (separately along X or along Y direction) and biaxial (along the two horizontal axes) tests were performed, in order to characterize the seismic behaviour of the infills in relation to the behaviour of the frame, and obtain information on the systems performance.

This paper presents shaking table test results on INSYSTEM 2 behaviour (scale 1:2). The results are compared with the results of a full scale frame against in-plane cyclic actions [5].

2 DESCRIPTION OF SPECIMEN AND TEST SETUP

2.1 Description of Specimen

INSYSTEM 2 consists in a single leaf clay masonry infill. A mortar joint is provided along the surrounding infill-to-RC concrete interfaces. The enclosure is not fixed to the RC frame elements. A detailed description of the developed system is provided elsewhere [5]. In the present paper, only a summary of the characteristics of the infill solution is presented.

In the system presented here (INSYSTEM 2: System with reinforcement), horizontal or horizontal and vertical reinforcement is provided to the infill. As already mentioned, a special unit was designed by NTUA and XALKIS and produced by XALKIS (Figure 1). The horizontal reinforcement is laid during the construction of the wall in bed mortar joints, whereas the vertical one is placed (in special cavities) throughout the height of the wall after the construction of the infill is completed. Although the idea of reinforcing the infill wall is quite common, the use of the available on the market vertically perforated bricks allows for positioning of the horizontal reinforcement, whereas (as the infill is constructed after the completion of the RC structure) only external vertical reinforcement can be provided to the infill ([6], [7], [8], [9], [10]). The out-of-plane collapse of the wall is prevented by special sliding connectors, if the aspect ratio of the infill dictates such a need. The sliding connectors are anchored to the RC frame elements. On the contrary, they are not connected to the infill wall, while the reinforcement is not anchored to the RC frame.

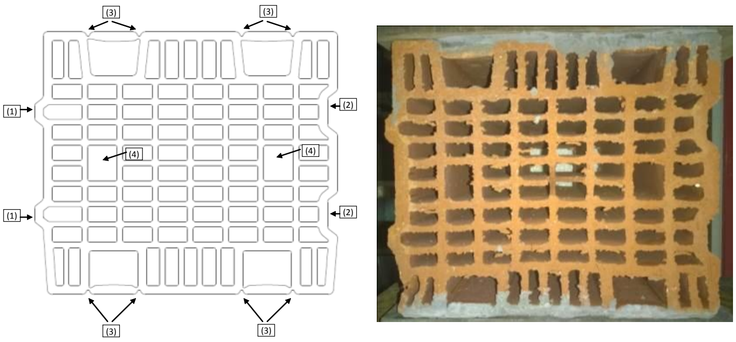


Figure 1: Unit shape.

a) b) c)

Figure 2: Construction of the scaled specimen INSYSTEM 2: a) Positioning of the horizontal reinforcement, b) View of the infill wall, special cavities for the vertical reinforcement, c) Cavities filled with cement mortar.

In order to study the seismic response of the developed infill solution, namely INSYSTEM 2, one-bay RC frame at reduced scale, equal to 1:2 following the similitude laws, has been constructed and tested [11]. The model was built with a length scale of 1:2 with the same material properties as the real frame. The prototype structure consists of a one bay RC frame, having 2 columns (with dimensions 0.3x0.3m^2), one beam (with dimensions 0.3x0.5m^2) and a slab (with dimensions 2.1x2.1m^2, thickness equal to 0.16m). The length of the RC frame equals to 3.3m, whereas its height is 2.70m. Thus, the dimensions of the enclosure are 2.7mx2.2m (length x height). Since the real and the scaled model have the same material properties and both systems are subjected to gravity acceleration, then the acceleration and stress scale equals to 1. Taking into account the scale, additional mass of 3.0Mgr was placed on top of the specimen. It is important to underline that by respecting the similitude laws, the results of the reduced scale specimens may be extrapolated to the prototype structure.

The dimensions of the constituents composing the infill, namely brick units, mortar joints, and diameter of the horizontal and vertical reinforcement, were reduced appropriately to respect the scale factor. As there are no brick units available in the market with the required (reduced) dimensions and the desired shape, it was decided to cut an existing unit, available in the market under the name K100, to adequate smaller parts and use it for the scaled models.

INSYSTEM 2 was designed to host horizontal and vertical reinforcement. In the scaled specimen, the horizontal reinforcement (4Φ5 per wall face) was placed in the horizontal bed joints during construction of the wall, whereas the vertical reinforcement (3Φ8 per wall face) was placed in special cavities at the exterior parts of the wall (Figure 2). The vertical reinforcement was placed after the construction of the wall. In order to form these special cavities, K100 was cut into the following dimensions: 90x110x110 [mm^3] (length x width x height).

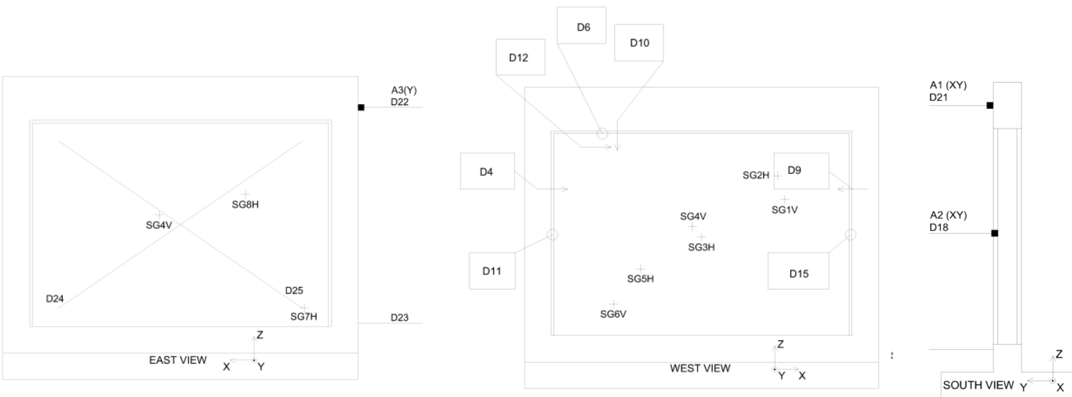
2.2 Test setup

The specimen was securely fastened on the shaking table. A steel frame was designed (Figure 3), in order to allow the in-plane deformation of the infilled frame and prevent the out-of plane displacement of the columns. The steel frame was securely fastened on the RC footing and was designed to sustain an out of plane force equal to the maximum shear force that may be applied by the shaking table. As mentioned above, to respect the similitude laws and, hence, to make possible the extrapolation of the results from the model to the prototype, additional masses (3Mgr) were placed at the top of the specimen.

The measuring devices are shown in Figure 4. In detail, accelerometers were placed at the top of the RC frame and at the center of the infill wall (measurements along both directions). Absolute displacements in both horizontal directions were measured at the top and foot base of column (D22, D23), as well as at the center of the infill wall (D18). Moreover, the relative in-plane and out-of plane displacement between the frame and the infill walls were also measured. The horizontal and vertical reinforcement was provided with strain gauges (SG1 to SG8), to assess its contribution to the overall behaviour of the structure. Finally, the acceleration and displacement of input motion were recorded during each test.

a) b) c)

Figure 3: Test setup: a) View of the specimen, the steel frame and the additional masses can be seen, b) Side view of the steel frame, c) The arrangement that allows the in-plane sliding of the RC frame and prevents the out of plane movement of the columns of the RC frame.



a) b) c)

Figure 4: Measuring devices of acceleration and displacement.

2.3 Test procedure. Seismic input and test protocol

The specimen was subjected to a series of scaled motions with increasing maximum acceleration, until significantly damaged. Uniaxial (separately along X or along Y direction) and biaxial (along the two horizontal axes) tests were performed. The input motions were time scaled (i.e. $1/\sqrt{2}$) according to the similitude laws. Needless to mention that, prior to the application of the selected seismic inputs, the dynamic properties of the specimen were measured through sine logarithmic sweep excitation of low amplitude (0.04g). Sine sweep tests were performed separately along X and Y directions. This procedure was repeated during the experimental procedure, in order to detect changes in the dynamic properties of the specimens.

For the shaking table tests, three real earthquake records and an artificial time history were applied. The following records of seismic events were used: (a) An aftershock of Kefalonia earthquake (1983): The event occurred in Argostoli on March 1983 (Magnitude Ms=5.5). The Lateral component was used in X-direction, while the Long Component used in Y direction, (b) Jensen Filter Plant (JFA) record of the Northridge, USA (1994) earthquake: The component JFA-292 was applied in the horizontal X-direction. In case of biaxial excitation, the JFA -022 component was imposed along the Y-direction, (c) Kalamata earthquake (1986): The accelerograms were recorded on hard soil. The longitudinal component was used for the shaking table tests, (d) Artificial time histories: The duration of strong motion was about 30sec and the maximum acceleration was equal to 1g.

The time histories of the time scaled earthquakes and the corresponding acceleration response spectra for 5% damping are shown in Figures 5 to 8. All input motions were selected taking into account that the major spectral amplifications occur for frequencies close to the frequencies of the fundamental modes of models in both directions. When further increase of base motion was not possible (the capacity of the shaking table was reached or the dynamic characteristic of model was modified due to damages), another seismic input was applied. The testing procedure is presented in Table 1.

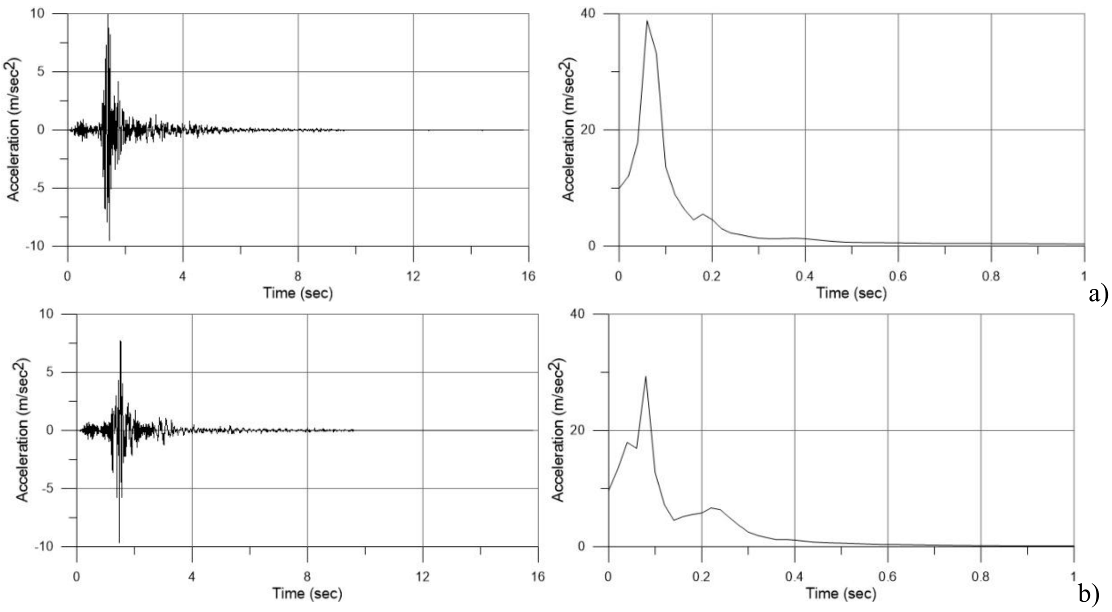


Figure 5: Argostoli earthquake: Acceleration time history and corresponding response spectrum for 5% damping: a) Longitudinal and b) Lateral Component.

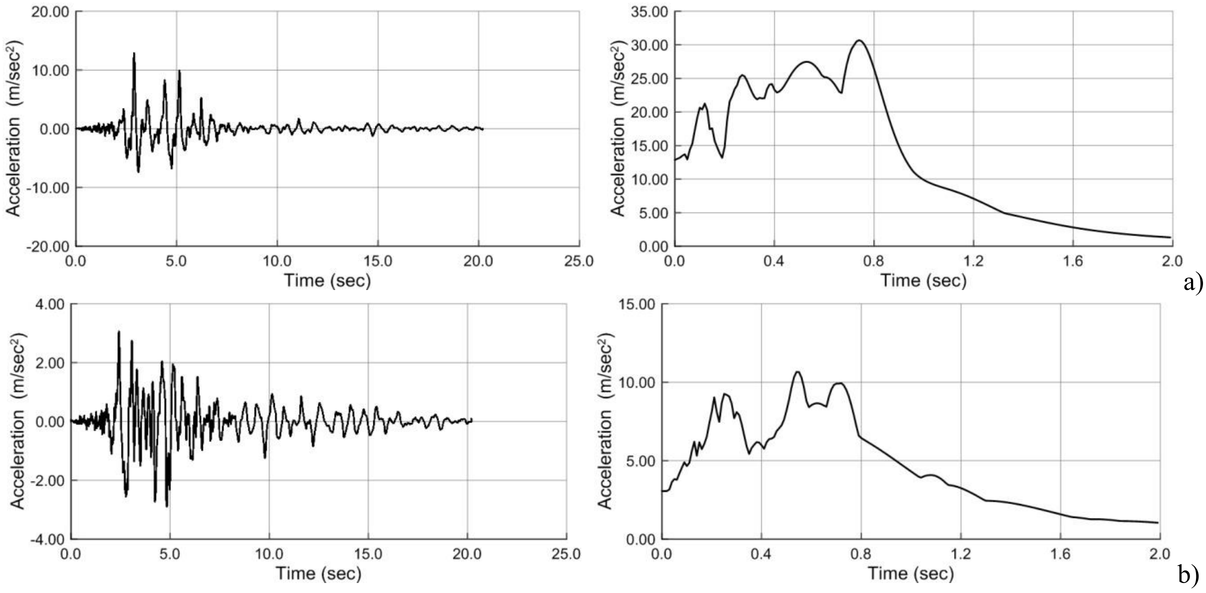


Figure 6: JFA record: Acceleration time history and corresponding response spectrum for 5% damping: a) JFA-292 component and b) JFA-022 component.

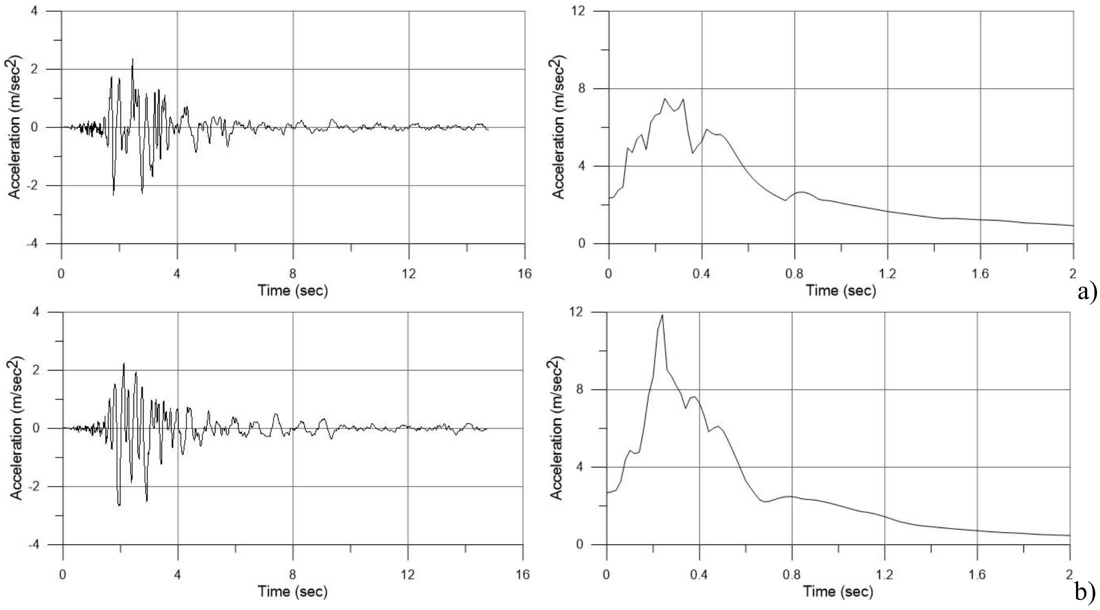
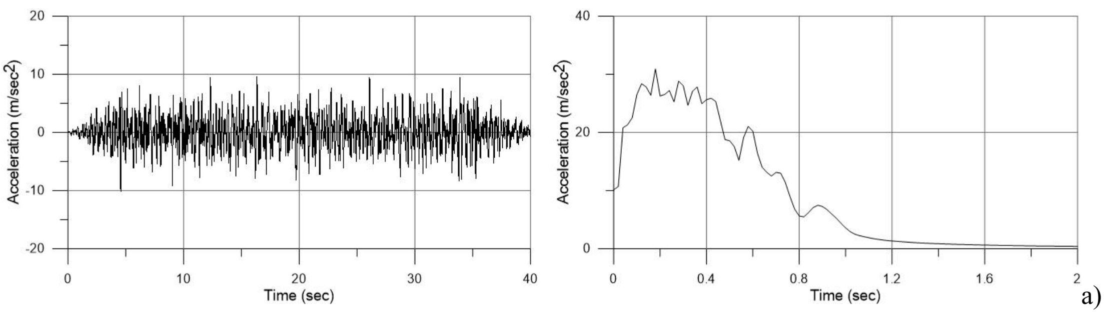


Figure 7: Kalamata earthquake: Acceleration time history and corresponding response spectrum for 5% damping: a) X and b) Y direction.



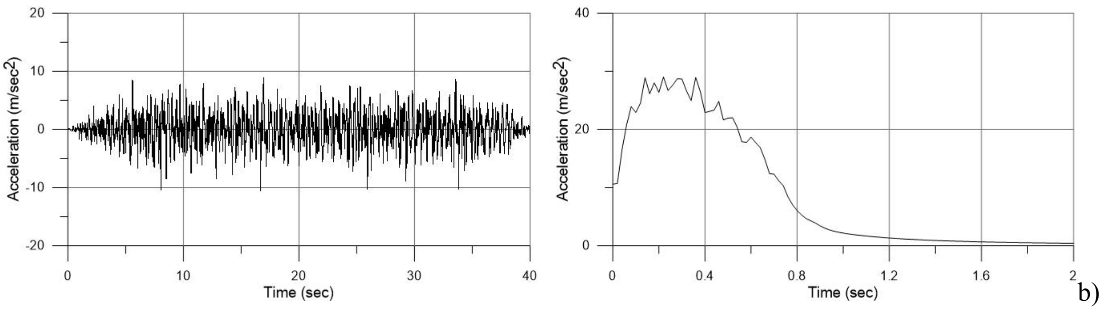


Figure 8: Artificial earthquake: Acceleration time history and corresponding response spectrum for 5% damping: a) X and b) Y direction.

No. of test	Excitation	Direction of excitation	Base acceleration [g]/(%)	
			X	Y
1	Sine sweep	X	0.04	–
2	Sine sweep	Y	–	0.04
3	Argostoli	X	0.05g/ (5%)	–
16	Argostoli	X	1.09g/ (102%)	–
17	Sine sweep	X	0.04	–
18	Argostoli	XY	0.64g/ (50%)	0.70g/ (50%)
24	Argostoli	XY	1.01g/ (102%)	1.76g/(102%)
25	Sine sweep	X	0.04	–
26	JFA	X	0.14g/ (10%)	–
32	JFA	X	1.64g/ (102%)	–
33	JFA	X	1.64g/ (102%)	–
34	Sine sweep	X	0.04	–
35	Kalamata	X	0.09g/(30%)	–
37	Kalamata	X	0.27g/(100%)	–
38	Artificial	X	0.22g/ (20%)	–
40	Artificial	X	1.22g/(100%)	–
41	Artificial	XY	0.59g/(50%)	0.71g/(50%)
42*	Artificial	XY	(100%)	(100%)
43*	Artificial	X	(100%)	–
44**	Artificial	X	1.09g/ (100%)	–

*Test stopped
**During these test the instrumentation was removed from the specimen

Table 1: INSYSTEM 2 specimen. Test protocol.

3 EXPERIMENTAL RESULTS

3.1 Observed damages

The following Figures 9 to 12, present the damage pattern of the specimen. Damage occurred after reaching the maximum acceleration of each test series, i.e. after completion of Test 16 (Argostoli earthquake: 1.09g(X)), Test 24 (Argostoli earthquake: 1.01g(X)/1.76g(Y)), Test 35 (JFA earthquake: 1.63g(X)), Test 40 (JFA earthquake: 1.22g(X)) and Test 44 (Artificial earthquake: 1.09g(X)).

During the first series of uniaxial tests (Tests 3-16), only separation of the infill wall from the RC frame is recorded, as well as minor cracking along limited number of bed joints. It is noted that the joints with the horizontal reinforcement (at the lower part of the infill) are the first ones to present cracking. Shear cracks at the RC beam are also evident (Figure 9).

After the first biaxial test series (Tests 18-24), cracking along bed joints is more pronounced, while also cracking along limited number of head joints has been recorded. Cracks on RC frame (i.e. beam and columns) are recorded as well (Figure 10).

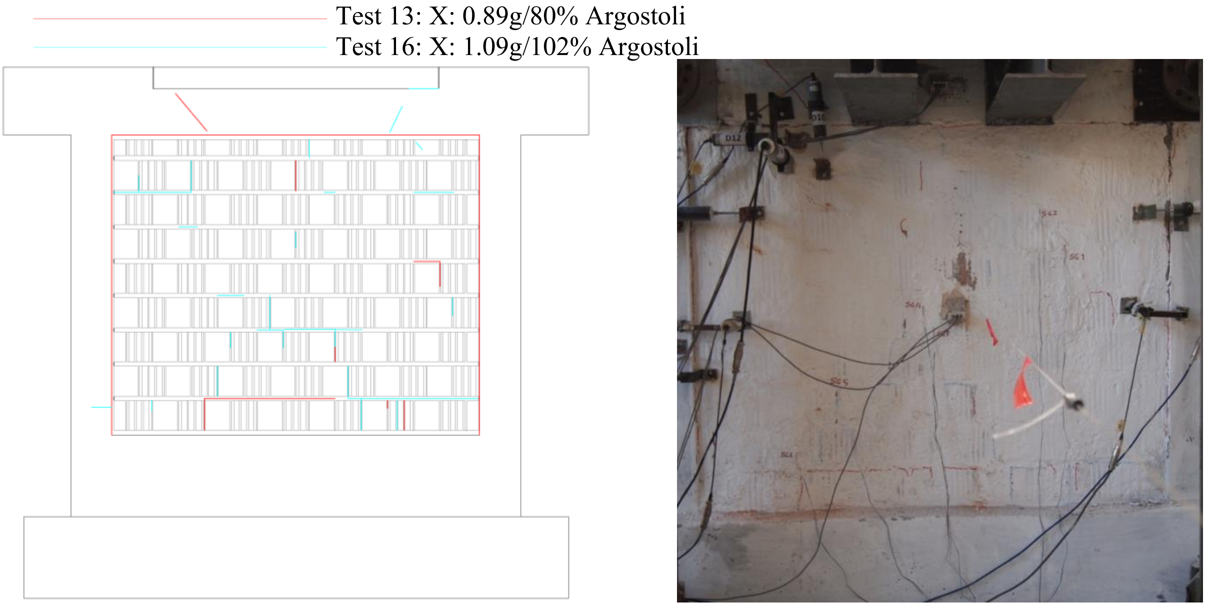


Figure 9: Crack pattern after the first uniaxial test series (Tests 3-16).

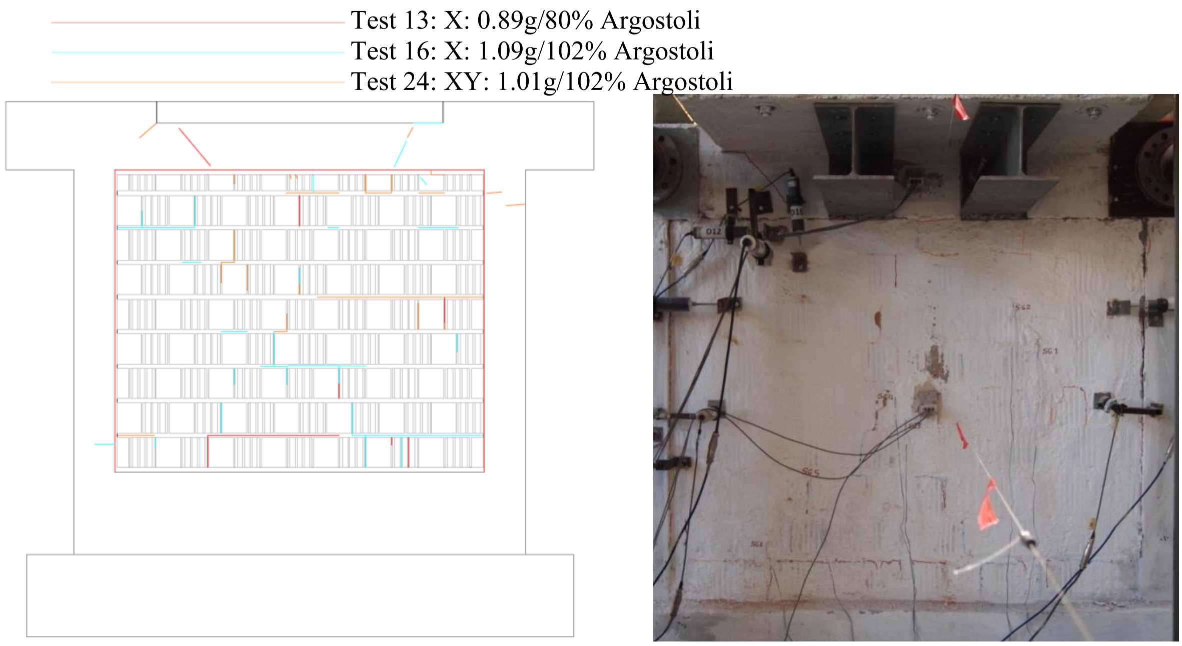


Figure 10: Crack pattern after the first biaxial test series (Tests 18-24).

After the second uniaxial test series (Tests 26-40), shear cracks appeared in the infill. It is noted that cracking of the bricks has not yet occurred, whereas the damage is concentrated along the bed and head joints. The damages up to this point, can be considered as repairable. It is noted that after the second series of uniaxial tests, only one single biaxial test has been performed. Minor damage has been recorded during this test, which was of small intensity. It is noted that damage on the RC frame slab is recorded, mainly due to the anchors used for the fastening of the additional masses (Figure 11).

After the completion of all test series (Tests 41-44), limited cracking and crushing of the bricks of the upper rows is recorded. Diagonal cracking is more pronounced, while also the cracks along the reinforced bed joints are well formed (Figure 12).

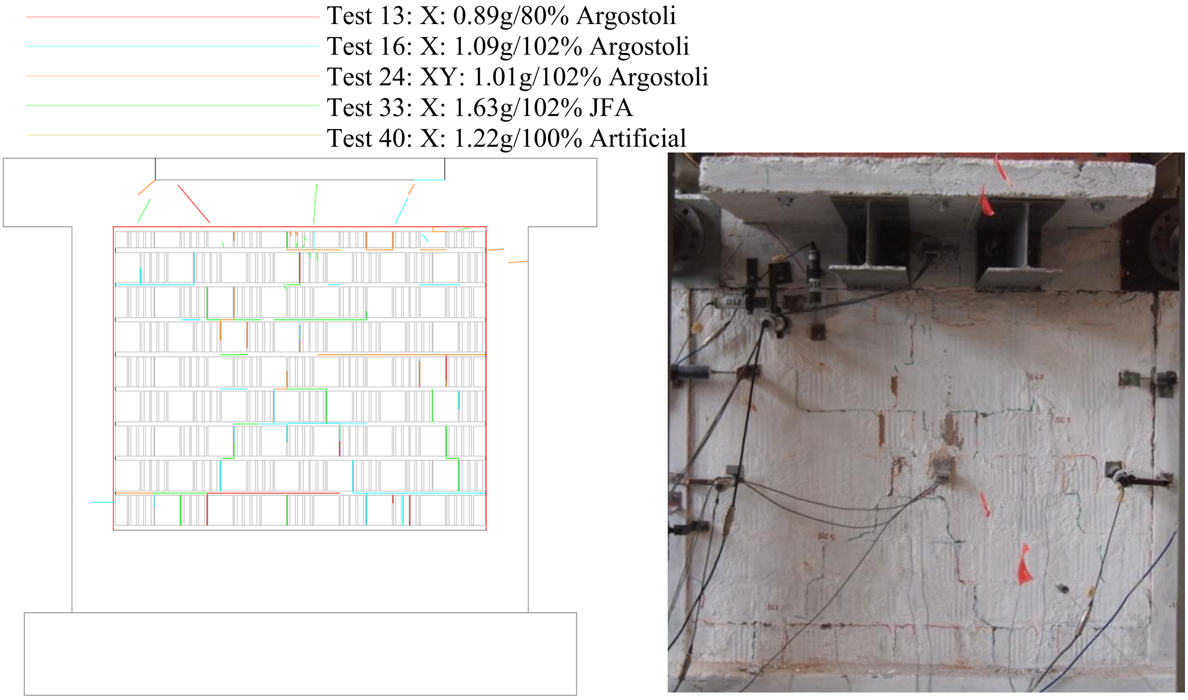


Figure 11: Crack pattern after the second uniaxial test series (Tests 26-40).

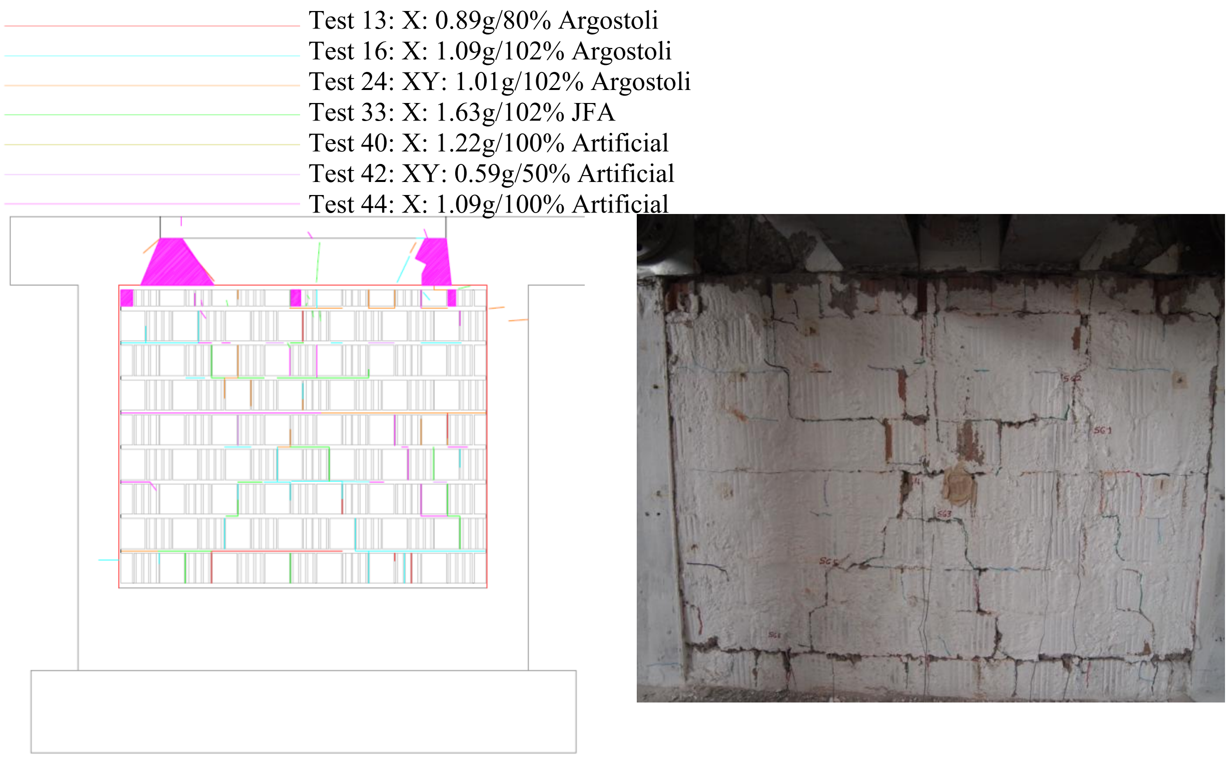


Figure 12: Crack pattern after the after the completion of all tests (Tests 36-42).

3.2 Dynamic Characteristics

The resonance frequencies and the corresponding damping ratio of INSYSTEM 2 are given in Table 2. The frequency along X-direction (along the infill) equals to 16.09Hz, whereas that along Y-direction equals to 13.30Hz. The corresponding damping ratio is 2.18% and 4.30% along X and Y direction respectively. As expected, due to the occurance of damage on the infill and the RC frame, the frequencies measured along X direction were significantly reduced (by approx. 85% after Tests 16 and 24, and more than 150% after Test 33).

Test No.	Direction	Frequency (Hz)	Period (sec)	Damping (%)
1	X	16.09	0.06	2.18
2	Y	13.30	0.075	4.30
17	X	8.72	0.11	8.63
25	X	8.48	0.12	8.64
34	X	6.44	0.16	7.20

Table 2: INSYSTEM 2 specimen. Resonance frequency and damping ratio.

3.3 Hysteretic response and maximum accelerations

In Figure 13 hysteresis loops are shown for the longitudinal (X) direction (Uniaxial excitation along X direction: Tests 9 to 16). The maximum applied base acceleration along X direction was approx. equal to 1.10g. Slightly higher was the maximum response acceleration recorded at the top of the beam of the frame (1.33g). Moreover, one may observe, that the infilled RC frame (a) may sustain drift values of the order of 2.4 [‰]; (b) is able to absorb seismic energy (as confirmed by the form of the hysterisis loops), whereas; (c) its the stiffness remains intact, after the initiation of cracking and under increasing imposed excitations.

Similarly, Figure 14 shows the hysteresis loops for the longitudinal (X) and transversal (Y) direction (Biaxial excitation along X and Y direction: Tests 18 to 24). The maximum applied base accelerations were approx. equal to 1.0g and 1.7g along X and Y directions respectively. One may note: (a) A significantly higher stiffness of the system along Y direction as compared to that along X direction. This may be explained by the fact that the model has suffered in-plane damage during Tests 9 to 16, as well as by the positive effect of the presence of the horizontal and vertical reinforcement in the out-of-plane response of the infill; (b) The significant capacity of the infill to absorb seismic energy along both directions. This feature is more significant along Y direction, due to the contribution of the reinforcement that offers significant ductility to the infill; (c) The similar displacements of the model along both directions (approx. 3.3mm). Again, the decrease of the stiffness (along both directions) is rather insignificant during the entire first series of seismic tests, although the acceleration was gradually increasing and so did the recorded damages.

By applying the JFA earthquake (an excitation with different dynamic characteristics) to the already damaged model, the infilled frame presents a different response (Figure 15). Actually, the system exhibits reduced capacity to absorb seismic energy along X direction during uniaxial Tests 27 to 33. The maximum applied base acceleration along X direction and the maximum response acceleration recorded at the top of the beam are approx. equal to 1.6g, whereas the proposed system may sustain drift values of the order of 8.3 [‰].

The application of the Artificial earthquake to the model (Tests 38 to 40), results to hysteresis loops typical for ductile behaviour (large hysteretic damping), as well as to a gradual decrease of the stiffness (Figure 16). In this case, the maximum applied base acceleration along X direction and the maximum response acceleration recorded at the top of the beam reached 1.20g and 1.50g respectively.

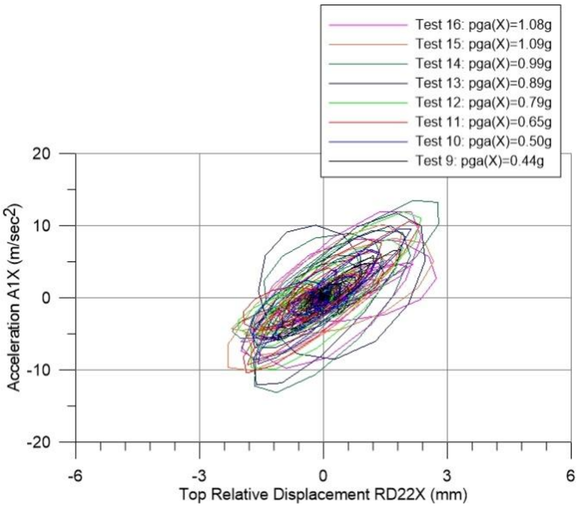


Figure 13: Uniaxial Tests 9-16. Absolute acceleration versus top relative displacement along X direction for Argostoli base motion.

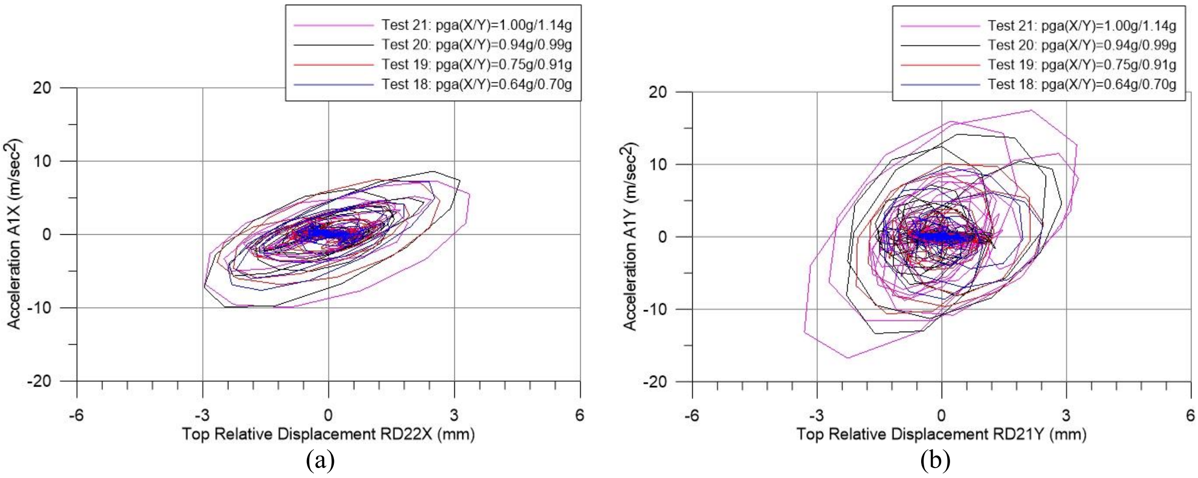


Figure 14: Biaxial Tests 18-21. Absolute acceleration versus top relative displacement along a) X and b) Y direction for Argostoli base motion.

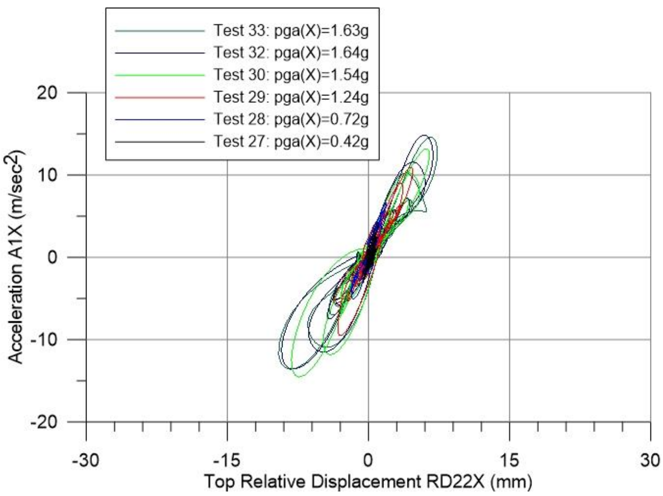


Figure 15: Uniaxial Tests 27-33. Absolute acceleration versus top relative displacement along X direction for JFA earthquake component 292 base motion.

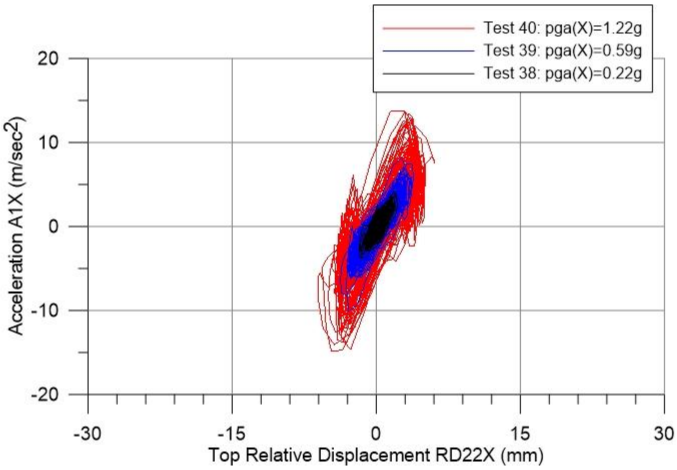


Figure16: Uniaxial Tests 38-40. Absolute acceleration versus top relative displacement along X direction for Artificial base motion.

3.4 Drift

Drift values along X and Y direction, were calculated for the uniaxial and biaxial excitations applied to the specimen. Those calculations were based on measurements taken by the displacement transducer D22 (X-direction) and D21 (Y-direction). The drift values (Table 3) show that for the dynamic tests a maximum in-plane drift of the order of 8‰ was reached.

	Uniaxial X Tests 9-16	Biaxial XY Tests 18-21	Uniaxial X Tests 27-33	Uniaxial X Tests 38-40
Max/Min displacement (mm)	2.79/-2.31	3.35/-2.95 (X) 3.29/-3.30 (Y)	7.32/-9.54	6.08/-6.06
drift [‰]	2.4	2.9 (X) 2.9 (Y)	8.3	5.3

Table 3: In-plane and out-of plane maximum/minimum displacement [mm] and drift values [‰].

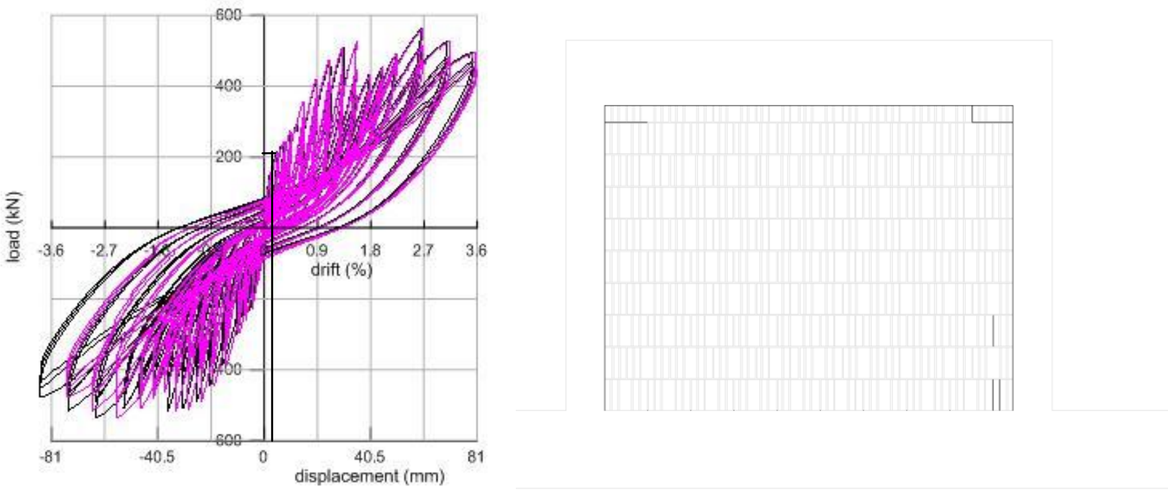
4 EXTRAPOLATION OF THE RESULTS TO THE PROTOTYPE STRUCTURE - COMPARISON WITH QUASI STATIC TESTS.

By respecting the similitude laws [11], the results of the reduced scale specimen may be extrapolated to the prototype structure. Given that the real and the scaled model have the same material properties and both systems are subjected to gravity acceleration, then the acceleration and stress scale equals to 1. According to similitude laws, the results may be extrapolated to the prototype structure by multiplying the force scale by 4 and the length (and thus, the recorded deformations) by 2. It is noted that, the estimated drift values for the scaled specimens are the same for the scaled and the prototype structures.

In the following section, a comparison between the behaviour of the shaking table specimens and that of the quasi static in-plane test [5] is attempted. For this purpose, the results of the scaled specimens are extrapolated to that of the prototype structure. One should mention that the comparison is carried out only for the first test series along X direction (uniaxial shaking table tests using Argostoli earthquake). Afterwards, a direct comparison between the results is not possible, given that the load history applied to the models is quite different (for the shaking table tests biaxial tests were performed, whereas for the quasi static tests the in-plane and out-of plane behaviour of the RC infilled frames was investigated separately) and thus, the response of the models (which is affected by the load history) differentiates.

For the first uniaxial test series (Tests 9-16), the maximum recorded acceleration of the scaled model was approx. 13m/s^2 and was obtained at a displacement almost equal to 2.5mm. Thus, for the prototype structure the recorded value of acceleration corresponds to a base shear equal to 190 KN. This force corresponds to a displacement equal to 5mm.

From the quasi-static tests [5], the resistance of the RC infilled frame was almost 210KN and was obtained at an applied displacement equal to 5mm (Figure 17a). Thus, a good agreement between the dynamic and the quasi static tests is obtained. Moreover, the crack pattern of the specimen tested on the shaking table (Figure 9) is quite similar to that observed from the quasi static tests at the same value of displacement (approx. 5mm) (Figure 17b). In both cases a detachment of the infill from the RC frame occurs and some cracks are formed along the joints of the infill.



a) b)

Figure 17: INSYSTEM 2, quasi static in-plane tests: a) Hysteresis loops obtained from quasi-static tests, b) Crack pattern for displacement equal to 5mm for in-plane cyclic loading.

5 CONCLUSIONS

On the basis of the shaking table tests, taking also into account the quasi-static tests performed on the full-scale infilled frames, one may conclude that:

(a) Shaking table test has confirmed the basic features of the behaviour observed during the quasi-static in-plane and out-of-plane tests, in terms of maximum resistance, crack pattern and drift values.

(b) INSYSTEM 2, developed at NTUA, was able to sustain significant in- and out-of-plane motions keeping its integrity, absorbing seismic energy and undergoing more or less repairable damage.

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