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EXPERIMENTAL VERIFICATION OF INOVATIVE TECHNIQUE FOR SEISMIC RETROFITTING OF TRADITIONAL MASONRY BUILDINGS

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Abstract

Despite the extensive use of modern construction materials, old masonry buildings, characterized by high consumption of energy and a high risk of partial or complete destruction during earthquakes, still represent a great majority of both residential and public building stock in many earthquake - prone countries, such as the countries in the Balkan region. Improvement of seismic resistance and energy efficiency of these buildings is very important and actual topic worldwide.

In providing the earthquake protection of existing structures, the experts are permanently challenged by the fast development and the improved performance of new materials and techniques. However, the implementation of particular retrofitting or strengthening methodology depends on the extent it has been investigated. The delicate problem of proving the effectiveness of the selected consolidation, retrofitting or strengthening system can be successfully overcome by using the methodology of design assisted by testing, which as methodology, has been recently codified in all Eurocodes.

The main goals of the research project realized by the Institute of Earthquake Engineering and Engineering Seismology UKIM-IZIIS, Skopje, in collaboration with the RÖFIX Company, Austria, have been the following:

1. Assessment of the vulnerability of structure of traditional masonry building representative for the territory of the Balkan region
2. Experimental investigation of the efficiency of the proposed methodology for seismic and energy efficiency upgrading of traditional masonry buildings using innovative *System RÖFIX SismaCalce*
3. Definition of the process for implementation of the proposed methodology in real buildings

For experimental verification of the retrofitting methodology, shaking table testing of a 1:2 scaled model of a hypothetical masonry building has been performed both in its original and retrofitted state. The models were tested under three types of earthquakes to predict the prototype behaviour under different earthquake conditions. The both models were subjected to the same experimental programme, however, due to the obviously higher resistance of the retrofitted model, the tests were continued under higher intensities of input excitation. Comparison the final test results points out that for about triple excitation level, the damage level of the repaired model is considerably lower.

This paper presents the experimental shaking table programme and the outcome of its realization.

Keywords: traditional brick masonry, shaking table testing, seismic retrofitting, energy efficiency, innovative materials

1. Introduction

Traditional stone and brick masonry structures, whether or not they are historic monuments, have low ductility, and, due to their stiff and brittle structural components, are usually severely damaged during strong earthquakes. The main reasons for damage or collapse are the lack of ductility of the masonry components, high displacements that the structure cannot afford, and amplification of dangerously high frequencies due to their dynamic behaviour in response to earthquake action making them vulnerable to those harmonies of the ground motion. In the majority of cases, past and recent earthquakes have caused most of the damage to masonry buildings, and most of the loss of human lives has occurred due to the collapse of masonry buildings. Therefore, masonry buildings are not considered as earthquake resistant. Nowadays, despite the extensive use of modern construction materials like reinforced concrete and steel, masonry buildings still represent a great majority of both residential and public building stock in many earthquake-prone countries, such as the countries in the Balkan region.

In order to improve the behaviour of these masonry structures in response to earthquake forces, strengthening measures that emphasize the use of reinforcing steel have been widely adopted in building codes. In this practice, steel reinforcement is placed within piers and walls at critical areas to compensate for the lack of tensile strength and ductility and to increase the stiffness of these elements. Horizontal bands are provided at different levels in order to ensure "box-like" action and to reduce the possibility of "out-of-plane" failures. These strengthening concepts have met with success by greatly decreasing the potential of collapse. However, these methods are quite intrusive and time consuming, may require the partial disassembly of building elements, can destroy valuable and irreplaceable interior finishes, and can also alter the external appearance of a building. In spite of these interventions, masonry structures can still be cracked during earthquakes of medium or higher intensity.

In providing the earthquake protection of existing structures, the experts are permanently challenged by the fast development and the improved performance of new materials and techniques. However, the implementation of particular retrofitting or strengthening methodology depends on the extent it has been investigated. The delicate problem of proving the effectiveness of the selected consolidation, retrofitting or strengthening system can be successfully overcome by using the methodology of *design assisted by testing*, which as methodology, has been recently codified in all Eurocodes.

2. Objectives and Experimental Programme

Providing both the earthquake resistance and energy efficiency of existing buildings was the triggering issue for developing an innovative technology called *System RÖFIX SismaCalce* by the company RÖFIX, member of Fixit Gruppe from Austria. It combines the system *RÖFIX Sisma* for seismic upgrading and the *multilevel RÖFIX system* for thermal insulation; applied together they enable earthquake resistant and completely thermal insulated structure. Experimental investigation of the efficiency of this newly developed *System RÖFIX SismaCalce* in repair and seismic retrofitting of existing traditional masonry structures was the main subject of the research programme elaborated and performed by IZIIS in collaboration with the RÖFIX Company, Austria and the SINTEK Company, Skopje, [1]. Apart from the (i) laboratory testing of masonry unit and mortar specimens for definition of their strength characteristics, and (ii) quasi-static testing of series of masonry wall samples in lime-cement mortar, in its original and retrofitted state, for definition of mechanical characteristics and failure mechanism, the experimental programme includes:

- Design and construction of the model to a scale 1:2 of hypothetical 2-storey brick masonry building, for shaking table testing,
- Shaking table testing of the model in its original (non-retrofitted) state, (model BM) under different levels and frequency content of seismic excitation, to introduce damage to the model,
- Design of seismic upgrading of the model using the innovative *System RÖFIX SismaCalce*,
- Shaking table testing of the model in its retrofitted state, (model BM-SR) up to the level close to failure, depending of the maximum capacity of shaking table.

3. Experimental Shaking Table Tests on 1:2 Scaled Non-retrofitted Model BM

To experimentally verify the methodology for seismic retrofitting of traditional masonry structures pertaining to historic buildings, a model of a hypothetical prototype structure was constructed and tested on the seismic shaking table in the Dynamic Testing Laboratory of IZIIS. Two story brick masonry structure with RC floor structure was proposed as prototype structure, (Fig. 1), representative for the large number of residential, but also public buildings that have been usually constructed in the second half of XX century on the territory of former Yugoslavia and beyond in the Balkan region.

3.1 Design and construction of the 1:2 scaled traditional brick masonry model - BM model

The geometrical scale of the model was selected based on the characteristics of the seismic shaking table and the precisely defined objectives of testing, i.e., based on the following criteria:

K1 - proportions of the shaking table (4.5 m x 4.5 m)
K2 - allowed total height of the model (10m)
K3 - allowed total weight of the model (400 kN)
K4 - realistic reproduction of nonlinear behaviour
K5 - realistic reproduction of the failure mechanisms

Satisfying these criteria, the following three main scales were adopted:

- geometrical scale l_r = 1:2,
- scale for the bulk density of the material ρ_r = 1,
- scale for the stresses E_r = 1

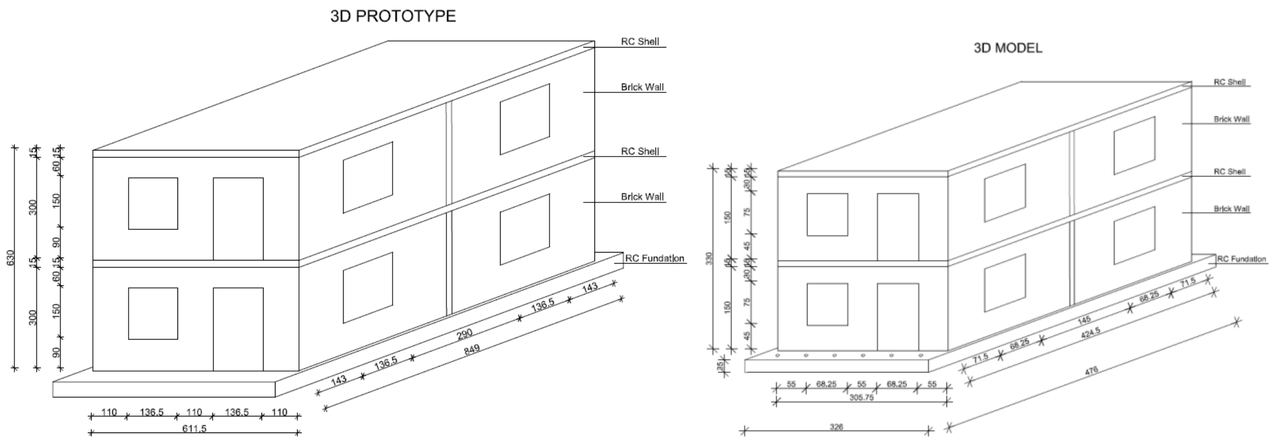


Fig. 1 - 3D view of hypothetical prototype and model to a scale 1:2

Computed were the scales of all the remaining physical quantities in model analysis of problems on dynamics of structures (Table 1). The considered structures have relatively low levels of axial stresses at the base which justifies the adoption of a model with neglected gravity forces ($g_r \neq a_r$, gravity acceleration cannot be simulated). In such a case, the scales of all the quantities of interest are expressed only in relation to the geometrical scale l_r adopting a material identical to that of the prototype. The comparison between the characteristics of the model and the hypothetical prototype, i.e., the comparison of the designed and the obtained scales is given in Table 2. By satisfying the scale for the bulk density in constructing the model to a scale of 1:2, used were original construction materials with physical-mechanical characteristics of material almost equal to those of the prototype, prepared according to the designed proportions.

Scanning the main characteristics, it is clear that almost ideal similarity between the model and the prototype has been achieved by modeling. Thus, conditions were created to interpret the results obtained from testing of the dynamic response of the model, relating them directly to the prototype. The way in which the prototype is selected enables application of the acquired knowledge in seismic analysis of a large number of such buildings in the considered region which is the main purpose of the performed investigations.

Table 1 - Scaling factors for the parameters of the model used for dynamic analysis (expressed via l_r, ρ_r , σ_r)

Physical quantity	*Scale*
Length, displacement	l_r
Acceleration	$a_r = \sigma_r / l_r \rho_r = 1/ l_r$
Time	$t_r = l_r / (\rho/ \sigma)_r^{0.5} = l_r$
Frequency	$f_r = (\sigma/\rho)_r^{0.5} / l_r = 1/ l_r$
Mass	$m_r = l_r^3 \rho_r = l_r^3$
Force, weight	$P_r = l_r^2 \sigma_r = l_r^2$
Stress	$\sigma_r = 1$
Mass density	$\rho_r = 1$
Deformation	$\varepsilon_r = 1$
Modulus of elasticity, shear modulus	$E_r = \sigma_r = 1$
Poisson's coefficient	$\nu_r = 1$
Damping coefficient	$\mu_r = 1$

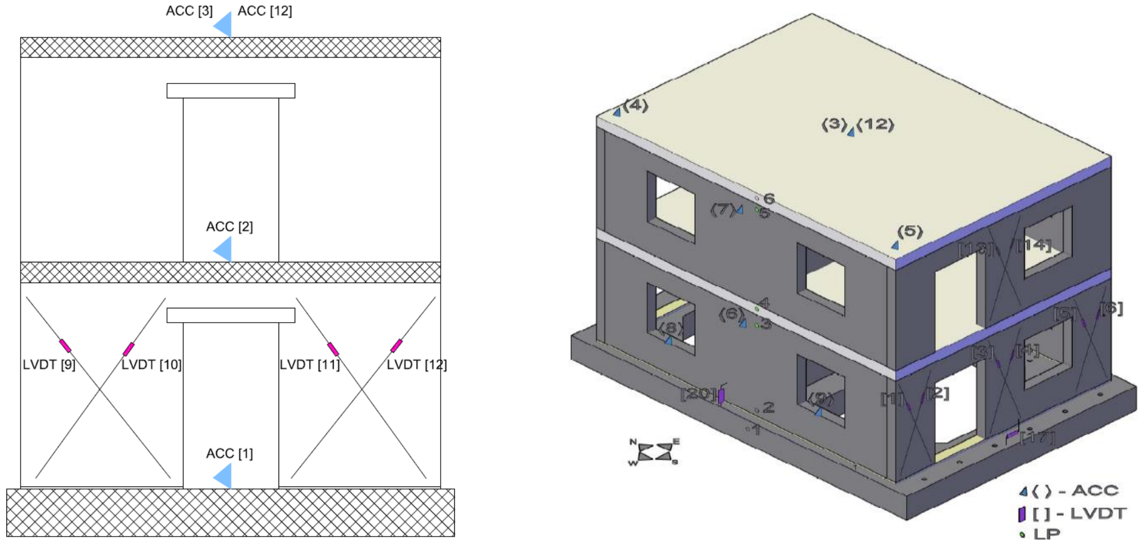
Table 2 - Main characteristics of the model and the prototype

Characteristics	**Unit of measure**	**Prototype Xp**	**Model Xm**	**Xp/Xm**	**Design scale**
Proportions at plan, L / W	m	8.49/6.11	4.24 /3.06	2	2
Total height	m	6.60	3.30	2	2
Total volume - walls - plates	m^3	39.50 14.50	4.93 3.15 (+3.3)	8 4.5 (2.3)	2^3=8
Bulk density -masonry -concrete	kN/m^3	18.50 25.00	19.50 25.00	0.94 1	1
Total weight	kN	1093.2	256.5	4.2	2^2=4
Area of the walls at plan	m^2	8.45	2.11	4	2^2=4
Average σ_o for the walls	kN/m^2	129.4	121.6	1.06	1
Total mass -masonry -concrete	kNs^2/m	74.5 36.9	9.8 8 (+8.4)	7.6 4.6 (2.25)	2^3=8
Compressive strength of: - mortar - brick	MPa	- -	15.50 20.10	- -	1 1
Bending strength of: - brick - mortar	MPa	- -	11.80 11.40	- -	1 1
Frequency in E-W direction Frequency in N-S direction	Hz	-	10.95 17.00	-	2^{-1} =0.5

In accordance with the designed proportions, the model was constructed in the Dynamic Testing Laboratory of IZIIS using a traditional technology of construction of brick masonry structures. A reinforced concrete platform with proportions of 3.26 m x 4.76 m and a thickness of 0.30m was constructed as a foundation for the model for the purpose of its construction and transport, (Fig.2). Dimension of the model are length 4.24m, width 3.06m and height 3.30m. Structural system consists of five bearing walls, four facades and one middle wall. The walls were constructed in a running bond, with the thickness of 12.5 cm, while the thickness of the vertical and horizontal mortar layers is 0.5 cm. Bricks with designed proportions of 12.5 x 6 x 3.25 cm have been used for the construction of the walls. It was decided to procure the required number of bricks with standard dimensions, 25 x 12 x 6.5 cm, and prepared the bricks for model construction in the required dimensions by cutting. Preparation and baking of the bricks were performed mechanically, in the furnace of ”Elenica” factory from Strumica, which has a long experience in production of bricks of standard and nonstandard proportions. Lime-cement mortar which is the main bonding material for the structures that represents the hypothetical structure has been prepared with lime: cement: sand ratio equal to 1: 1: 3. The river sand with fraction 0-2 cm was used as filler. Water from the water supply system was used.

Fig. 2 - Construction and transportation of the brick masonry non-retrofitted model, BM

The floor and roof structure are constructed as reinforced concrete one, with the thickness of 15 cm. Additional 12 cm of RC plate was constructed because of satisfying the criteria for normal stresses, ($\sigma r=1$). The additional 12cm thick plate is constructed in such a way that it is not connected to the walls and has a role of additional load. Thus, the level of normal stress in the walls is very similar as that in the prototype structure, (Table 2). After being completed and dried for a period of 30 days on the place where it was constructed, the model was transported and connected to the shaking table by 90-tons auto crane, (Fig. 2) and properly instrumented. The model response was monitored by high speed data acquisition system consisting of 12 accelerometers (ACC), 20 displacement transducers (LVDT) and 6 linear potentiometers (LP), providing information about accelerations at different levels and points, relative displacements, deformations at selected points. The instrumentation set-up is presented on Fig. 3



Middle wall 3D-view

Fig. 3 - Instrumentation of the BM model

3.2 Test Procedure

The shaking table tests of 1:2 scaled model BM required special testing program consisting of several test phases, considering the expected information about the dynamic behaviour of the prototype and the effectiveness and justification of applied strengthening method and technology. The same testing procedure was applied for original, (BM) and for retrofitted model (BM-SR), consisting of two main phases:

1. Tests for definition of *dynamic characteristics* of the model, before and after performing seismic tests at each phase, in order to check stiffness degradation of the model produced by micro or macro cracks developed during the tests;
2. *Seismic testing* by selected earthquake record until heavy damage. The tests are performed in several steps, increasing the input intensity in order to obtain the response in linear range, as well as to define the initial crack state, development of failure mechanism and possible collapse of the model.

The dynamic characteristics of the both non-retrofitted and retrofitted model were checked before being subjected to earthquake excitation by ambient vibration technique. After the placement of the models on the shaking table, random excitation test was applied by shaking table only in E-W direction of the model. The seismic response tests were performed applying three different types of earthquakes: earthquakes Petrovac, Montenegro, 1979 and El Centro, California, 1949, as far distance earthquakes and earthquake Northridge, California, 1994, as a local type of earthquake. The both models, non-retrofitted and retrofitted one, were tested under these three types of earthquakes to predict the prototype behaviour under different earthquake conditions. According to the adopted modelling principles, the whole-time scale has to be reduced, i.e., the scale of the input excitations is reduced 2 times. Considering the importance of defining the first crack state, the crack development as well as failure mechanism and damage of the non-retrofitted model comparing to that of the retrofitted model, detailed visual inspection of the models was performed, the cracks were marked and the frequencies of the models were checked.

3.3 Testing of the non-retrofitted model BM

Definition of *dynamic properties* of the original model was first step of experimental testing, which enabled acquiring of important information about the achieved stiffness (natural frequencies) of the model. Natural frequencies were defined for both orthogonal directions of the model, N-S and E-W by applying ambient vibration measurements, (Fig. 4). The first natural frequencies of original model for E-W and N-S direction are 10.95Hz and 17.0Hz, (Table 3).

Table 3 - Natural frequencies for original non-retrofitted model BM

direction	type of excitation	Initial Frequency (Hz)	Frequency after final test (Hz)
E-W	ambient vibration	10.95	8.7
	random excitation	10.18	6.5
N-S	ambient vibration	17.00	12.2

The main objectives of *experimental shaking table testing* of model BM simulating the existing state of the hypothetical prototype structure can be summarized as follows: (1) evaluation of the vulnerability of the considered buildings, i.e., damages under different earthquake intensities, and (2) investigation of effectiveness of the proposed retrofitting methodology. In order to achieve the upper stated goals, a programme was adopted for experimental testing under earthquake excitations performed by gradual increase in intensity for the purpose of monitoring the progressive development of cracks, the modification of the dynamic characteristics, the phases of behaviour and the failure mechanisms as well as determination of the elasticity limit, i.e., the occurrence of the first cracks.

The model has been subjected in its W-E direction to three characteristic earthquakes (El Centro, Petrovac N-S, and Northridge). The application of the earthquakes was done gradually, increasing the peak ground acceleration (PGA) and using the time histories scaled in compliance with the principles of model analysis. Table 4 shows the selected experimental tests starting with moderate to destructive intensities. The dynamic response of the model is given through the maximum accelerations and relative displacements recorded for the second story.

Table 4 - Specification of selected experimental test on the non-retrofitted model BM

Earthquake	span %	acc_{max}^{input} (g)	acc_{max}^{top} (g)	LP^{top} (mm)	LP^{top}-$LP^{foun.}$ (mm)	damage
El Centro	50	0.14	0.22	10.5	0.494	-
Petrovac	36	0.16	0.26	6.4	0.34	
Northridge	16	0.18	0.34	13.5	0.26	-
El Centro	65	0.18	0.26	13.7	0.89	
Petrovac	40	0.18	0.29	6.9	0.58	
El Centro	75	0.21	0.35	16.4	0.91	initial cracks
Petrovac	45	0.20	0.32	7.8	0.77	
Northridge	20	0.21	0.42	17	0.98	
El Centro	80	0.27	0.52	11.6	1.2	development of cracks
Northridge	25	0.23	0.47	21	1.04	
Petrovac	50	0.22	0.41	8.9	1.14	
Petrovac	70	0.32	0.61	12.2	1.29	
Petrovac	75	0.35	0.71	13.9	1.54	

The first visible cracks occurred during the application of the Petrovac earthquake with acc_{max}=0.20 g. Visible horizontal crack occurred along the contact of the foundation slab with the west and east wall due to overstressing the tensile strength. The rest of the masonry was without any visible crack. The state of stresses, deformations and damages can be estimated as a state of initial nonlinearity of the principal structure. With next several tests the existing cracks became wider and initial fine diagonal cracks occurred on the north and south window corners. After this loading phase, only the time history of the Petrovac earthquake was applied with an intensity of acc_{max}=0.22-0.35g, which resulted in heavy damages to the building, (Fig. 4). Analyzing the induced damages, it may be concluded the main failure mechanism is transferred in the lower zone and in the final stage it results in occurrence of typical shear cracks of the order of 0.5 - 2.5 cm due to dominant shear stresses. Damages are further on expanded to the bearing walls, mainly the north and the south, but also the middle wall, which are in the direction of the excitation. The stretching direction of cracks confirms the above stated facts about the type of failure.

Fig. 4 – Damage to the model after final test (acc_{max}=0.35g)

Considering the general behaviour of the model under dynamic effects and under the last applied effect inducing considerably large cracks (Petrovac 75, acc_{max}=0.35 g), it is concluded that the building behaves as a rigid body in the elastic range. At the state of occurrence of the first shear cracks, the loads acting on the walls in the excitation direction are considerably increased which results in larger cracks occurring in these walls, (in plane failure mechanism) and development of damages up to a state close to failure. This was proved also by the decrease in natural frequency (stiffness degradation) from 10.95 to 8.7 Hz and from 17.0 to 12.2Hz for E-W and N-S direction, respectively, (Table 3).

4. Experimental Shaking Table Tests on 1:2 Scaled Retrofitted Model BM-SR

4.1 Repair and seismic retrofitting of the model using *System RÖFIX SismaCalce*

The repair and seismic retrofitting of the damaged BM model was undertaken using *System RÖFIX SismaCalce*; first the model was repaired by injection of lime-cement based mixtures, then it was retrofitted by the innovative technique that was originally developed, and for this particular case designed and applied, by the RÖFIX Company. The chronology of retrofitting consists of:

- applying of the layer of RÖFIX SismaCalce NHL- based mortar as primer,
- applying of RÖFIX SismaProtect anti seismic eq-grid on the outer side of the walls,
- applying of the RÖFIX SismaDur mortar for facade finishing.

The eq-grid was applied with 10-15 cm overlapping in the following order, (Fig. 5):

- around the roof and floor slab,
- above the window and door corners,
- around the foundation slab,
- from the top of the walls to the foundation with required overlapping.

For decreasing of the effect of rocking during seismic tests, additional detailing of retrofitting methodology was proposed to the specialists from the RÖFIX Company, providing anchoring of the eq-grid into the foundation by placing of steel profile (L) along the perimeter of the bottom of the facade walls and its anchoring by bolts under angle of 45^0 on regular distances of 15-20 cm.

Fig. 5 – Retrofitting of the model using *System RÖFIX SismaCalce*

4.2 Testing of the retrofitted model BM-SR

Investigations of the dynamic characteristics were carried out on the repaired and retrofitted model applying the available equipment for ambient and random vibrations, (Table 5). For the repaired model a frequency of $f^{E\text{-}W}$=11.48 – 13.7 Hz were obtained. From the comparison of results, it can be concluded that the repair and retrofitting slightly increased the model stiffness, however, the main mode of vibration remains unchanged.

Table 5 - Natural frequencies for retrofitted model BM-SR

direction	**type of excitation**	**Frequency (Hz)**
E-W	ambient vibration	13.77
	random excitation	11.48
N-S	ambient vibration	16.62

The repaired and retrofitted model was subjected to the same series of dynamic tests for the purpose of direct comparison of the quantities of interest and proving the efficiency of the applied method of strengthening. However, due to the higher resistance of the retrofitted model, the tests were continued under higher intensities of input excitation. Table 6 shows the selected experimental tests starting with moderate to damaging intensities.

Table 6 - Specification of selected experimental test on the retrofitted model BM-SR

Earthquake	span %	acc^{input} (g)	BM-SR acc^{top} (g)	BM-SR LP^{top} (mm)	BM-SR LP^{top} - $LP^{foun.}$ (mm)	damage
El Centro	50	0,14	0.21	9.6	0.39	-
Petrovac	36	0.16	0.25	5.7	0.29	
Northridge	16	0.18	0.21	12.8	0.21	
El Centro	65	0.18	0.25	13.5	0.81	
Petrovac	40	0.18	0.28	6.4	0.52	
El Centro	75	0.21	0.32	15.9	0.86	
Petrovac	45	0.20	0.30	7.0	0.73	
Northridge	20	0.21	0.28	15.8	0.62	
El Centro	80	0.27	0.37	10.9	1.11	-
Northridge	25	0.23	0.33	20	0.79	
Petrovac	50	0.22	0.36	8.4	0.94	initial fine cracks
Petrovac	70	0.32	0.55	11.9	1.60	
Petrovac	75	0.35	0.51	12.2	1.64	
Petrovac	100	0.51	0.91	16.9	2.80	
Petrovac	120	0.60	1.09	20.3	2.98	further propagation of initial cracks
El Centro	100	0.31	0.41	21.7	1.35	
Petrovac	150	0.82	1.29	23.9	4.26	
Petrovac	180	0.92	1.58	28.9	11.40	damage development
Petrovac	220	1.035	1.76	36.99	20.10	
Petrovac	260	1.22	2.1	44.7	26.40	
Petrovac	250	1.21	1.88	43.4	28.50	

The response of the retrofitted model was different from that of the original model. The building behaves as a rigid body during all the performed tests. Characteristic was the increased elasticity limit and slight reduction of displacements at the top. Although there was deterioration in bearing capacity and stiffness of the model structure under maximum very strong seismic effects, the complete stability of the model structure was not disturbed at all, while the damage was such that it was repairable.

What was different from the behaviour of the original model is the absence of the visible rocking effect along the vertical plane, so the intensity of induced vertical acceleration was negligible. It can be explained by modified interaction of the model with the shaking table due to the applied retrofitting and detailing of the anchoring of the eq-grid to the foundation.

The first fine cracks occurred during the application of the Petrovac earthquake with acc_{max} = 0.35g. Visible horizontal crack occurred about 60 cm above the foundation, i.e. along the line of the bottom of the windows on first floor. This was characteristic for the N-E, S-E and N-W corners, (Fig. 6). With gradual increase of acceleration level of the Petrovac earthquake up to 0.50 g, it is concluded from the behaviour of the model BM-SR that the nonlinear state starts after this level. Compared to the effects of the same time histories of the earthquakes applied to model BM, it is concluded that the level of elasticity, that is the linearity limit is increased for about 100%.

In order to obtain the stages of nonlinear behaviour and estimate the damage level for higher expected earthquake intensities, the tests were carried out applying Petrovac earthquake with gradual amplitude of up to acc_{max} = 1.22g. For this very high acceleration level characteristic was further propagation of the initial cracks as well as occurring of additional cracks along the contact line of the walls with foundation (Fig. 6). However, stability of the complete building is preserved.

Fig. 6 - Damage of BM-SR model after final test, (left: S-E corner, right: South wall)

4.3 Summary of shaking table test results

The comparison of the main dynamic characteristics of the original, (BM) and the retrofitted model (BM-SR) leads to the conclusion that there is slight stiffness increase of the retrofitted model, which contributes to its less intensive dynamic response.

Structural response of the original and retrofitted model for an acceleration level of about 0.20g, shows that in the original model nonlinear cracks occur, while for the retrofitted model, for same excitation level, complete elasticity without any cracks is evident, (Tables 4 and 6).

For an applied acceleration level of about 0.35 g, the original model (BM) shows large nonlinear damage and this state is considered to be similar to the state of ultimate load carrying capacity. For the same level of the retrofitted model, it is the beginning of the nonlinear state.

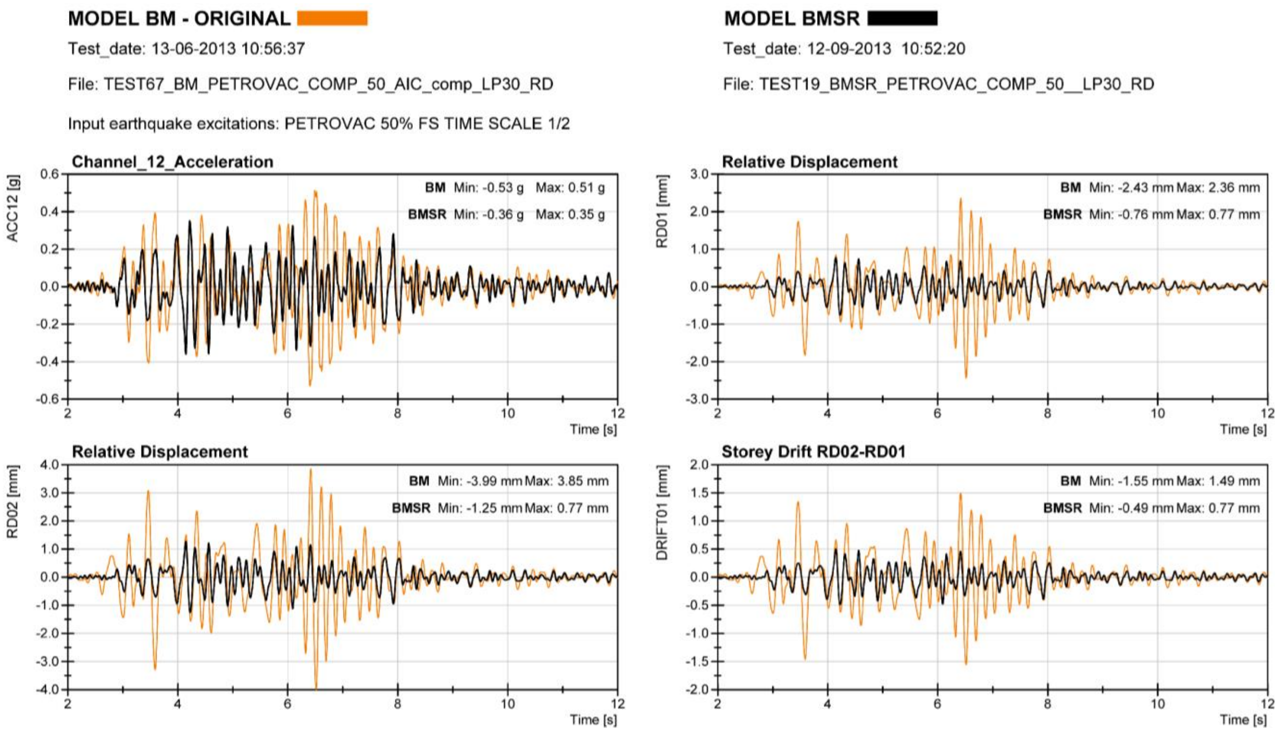


Fig. 7 - Comparison of the results for original and retrofitted model, Petrovac, acc_{max}=0.35g

The retrofitted model shows qualitative differences in respect to dynamic behaviour. The rocking effect along the vertical plane and high level of induced vertical acceleration, which was characteristic for the original model, was negligible in the case of retrofitted model. The BM-SR model shows complete integrity and "box-like" behaviour even during the last most intensive shaking table tests. The comparison of the results from the tests with Petrovac earthquake with acc_{max}=0.35g for both models is shown on Fig. 7; the BM model is close to failure, while the BM-SR is in initial nonlinearity. It is evident that both the output acceleration and relative displacement are greater in the BM than in the BM-SR model; the difference increases with the increasing of the intensity of input excitation.

Finally, for maximum expected effects of the Petrovac earthquake (acc_{max}=1.22g), the structure of the retrofitted model is entering deeper into the nonlinear state, however, taking into account the complete integrity of structure due to the retrofitting, this state is far from the failure boundary. Comparing the levels of maximum applied effects to the models points out that for about triple excitation level, the damage level of the retrofitted model is considerably smaller.

5. Concluding Remarks

Masonry buildings, dominantly with no or low-code implemented, still represent a great majority of both residential and public building stock in many earthquake-prone countries, such as the countries in the Balkan region. These structures with unknown level of seismic stability have high potential to be severely damaged during strong earthquakes. To investigate the efficiency of the innovative methodology for seismic retrofitting of traditional masonry building using *System RÖFIX SismaCalce*, an ample experimental study was performed within the research project that has been realized by the IZIIS, Skopje, in collaboration with the companies RÖFIX, Austria and SINTEK, Skopje.

For experimental verification of the retrofitting methodology, shaking table testing of a 1:2 scaled model of a hypothetical masonry building has been performed both in its original and retrofitted state. The both models were subjected to the same experimental programme, however, due to the obviously higher resistance of the retrofitted model, the tests were continued under higher intensities of input excitation. Comparing the levels of maximum applied effects to the original (BM, 0.35g) and the retrofitted model (BM-SR, 1.22 g) points out that for about triple excitation level, the damage level of the repaired model is considerably smaller. The overall stability of the model structure was not affected, and the experienced damage level is not beyond repair even for the highest intensity of input excitation.

Taking into account the previous results a general conclusion can be made that the proposed methodology of repair and retrofitting of the structure using *System RÖFIX SismaCalce* is very efficient and contributes to the overall improvement of dynamic behaviour of the masonry structures, which is verified through the experimental results. It enables increasing of the load carrying and deformation capacity of the structure up or even higher than the required protection level.

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