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SHAKING TABLE TESTS ON TWO MULTI-LEAF STONE MASONRY BUILDINGS

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ABSTRACT

An experimental campaign concerning the dynamic behaviour of historical stone masonry buildings in unreinforced condition as well as strengthened condition was carried out. Natural hydraulic lime based injection was used as strengthening. Two identical two-stories models, made of three-leaves stone masonry and wooden floors, were built in reduced scale of 2:3.

About 25 seismic inputs, divided in two shaking table tests, were performed: first model was tested in unreinforced conditions, while the second building was strengthened before the experiment using natural hydraulic lime based injection.

A preliminary investigation on the effectiveness of applied strengthening techniques in both damaged and undamaged structures was carried out. The variation of dynamic and modal parameters, damping factors and crack pattern were computed. For this reason “random” and “swept sine” inputs were applied to stress the structure and to extract modal parameters.

The analyses highlighted the capability of the hydraulic lime grout injections to substantially increase the ultimate strength without modifying the structural behaviour. Main results and a synthesis of obtained data are presented.

KEYWORDS: shaking table, stone masonry, multi-leaf, strengthening, dynamic identification.

INTRODUCTION

Masonry is a widespread structural system in Europe. Several masonry types were utilized differing for material, as brick and stone, for building system, such as multi-leaf or monolithic masonries, and different structural systems. All these typologies are widely employed on both historical and modern constructions and they are employed in monumental as well as in common structures. Nowadays, several historical and more recent masonry structures need strengthening interventions because of different causes as age and/or natural occurrences. Among these, preserving historical structures from seismic events has an important role. Most recent italian seismic events (Lunigiana and Garfagnana, 1995; Reggio Emilia, 1996; Umbria and Marche, 1997; Piedmont, 2000; Molise, 2002; Piedmont, 2003; Salò, 2004) confirmed limits and consequences of some intervention techniques [1]. Damages, due to conceptually wrong strengthening interventions, highlight as these operations should be deeply investigated before their application. Shaking table tests represent last validation phase of an intervention technique.

Since the 80's, several seismic tests were carried out to clarify the dynamic behaviour of historical masonry structures [2-5], but few experimental campaigns were performed on strengthening techniques [6-10]. Finally, the high costs, necessary to build the specimens and to test models on the shaking table, lead to investigate scaled structures [11, 12]. The higher the considered scale factor, the lower representative and reliable are the obtained results, because of problems in reproduce the real behaviour of considered prototype structures [13].

This paper aims at investigating the influence of strengthening by hydraulic lime grout injection in three-leaves stone masonry structures. The study focuses on how injection modifies dynamic characteristics of strengthened buildings besides on the change of both damping factors and mode shapes.

DESCRIPTION OF BUILDING MODELS

The experimental program expected the realization of two reduced stone masonry buildings (scale factor of 2:3). A simplified typical and common historical structure, widespread in the north-east region of Italy, was considered as prototype. The two storey models (Figure 1) have plan dimensions of 2.40m by 2.80m, and a total height of 3.60m. Double planking wooden floors were employed to simulate a non-rigid diaphragm and three-leaves stone masonry typology was adopted for walls. Main aspects of the calcareous stonework are the total absence of transversal connections between external layers and the incoherence of the internal leave. The masonry core is constituted by calcareous stone fragments, allowing the presence of about 12% of voids [14]. These masonry characteristics permit a strengthening intervention employing natural hydraulic lime based injection. The use of this grout aims at binding the incoherent core and improving the monolithic behaviour of walls. A preliminary wide research was carried out at University of Padua [15], to detect the typical cross section of three leaves stone masonry typology and to define its mechanical characteristics.

First model, named URM (UnReinforced Masonry), was tested as built, while the second model, named SM (Strengthened Masonry), was injected before test. The URM model did not collapse during the experiment. This allowed repairing the building using injections, repointing of cracked mortar joints and local reconstruction of damaged parts, particularly of corners.

EXPERIMENTAL PROGRAM

The experimental campaign was carried out at the ENEA Research Centre ("la Casaccia") in Rome. The applied seismic input was the record of the earthquake occurred on 1979 April 14th in Montenegro. The PGA (Peak Ground Acceleration) was of 0.22g in the interested interval, between 0.1s and 0.5s in the graph of spectral acceleration. It was decided a priori to utilize a natural record, so that the input pattern was realistic also in the time domain. This record well simulates the highest acceleration demand in the Italian Code for new constructions in seismic regions. Both recorded components, N-S and E-W, were considered during the tests in two horizontal orthogonal directions, while no vertical component was provided.

The followed method to scale physical sizes and mechanical characteristics was proposed by Tomaževič [13]. The geometrical dimensions are reduced, acceleration is amplified and time is contracted respecting the scale ratio, while the material characteristics between real and scaled structures are equal. A brief resume is given in Table 1.

Tests were carried out at increased PGA of 0.05g, for each succeeding step. Experiments were stopped when stability problems of models arisen due to the heavy damage. After each seismic load two different inputs were utilized to identify dynamic characteristics of specimens. The first test was realized using ambient vibration, while the second one using a random vibration with a maximum PGA of 0.05g.

Data presented in the following sections are only referred to ambient vibration records. Frequencies, mode shapes and damping factors were computed utilizing these data. For each case two different analysis methods were employed. First calculation was carried out on frequency domain using the commercial software ARTeMIS Extractor [16], based on Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD).

Figure 1: Stone masonry building

Table 1: Scale factors

Quantity	General equation	Simple model Tomaževič (1992)	Sonda, Stoppa (1992)	Zanardo (1998)
Length (L)	$S_L = L_P/L_M$	3/2	3/2	3/2
Strain (ε)	$S\varepsilon = \varepsilon_P/\varepsilon_M$	1	-	1
Strength (f)	$S_f = f_P/f_M$	1	-	1
Stress (σ)	$S_\sigma = f_P/f_M$	1	1	1
Young’s Modulus (E)	$S_E = S_\sigma/S_\varepsilon$	1	-	1
Sp. Weight (Γ)	$S_\Gamma = \Gamma_P/\Gamma_M$	1	1	2/3
Force (F)	$S_F = S_L^2 S_f$	9/4	-	9/4
Time (t)	$S_t = S_L\sqrt{(S_\Gamma S_\varepsilon/S_f)}$	3/2	3/2	$\sqrt{(3/2)}$
Frequency (Ω)	$S_\Omega = 1/S_t$	2/3	2/3	$1/\sqrt{(3/2)}$
Displacement (d)	$S_d = S_L/S_\varepsilon$	3/2	-	3/2
Velocity (v)	$S_v = S_\varepsilon\sqrt{(S_f/S_\Gamma)}$	1	1	$\sqrt{(3/2)}$
Acceleration (a)	$S_a = S_f/S_L S_\Gamma$	2/3	2/3	1

Second analysis was carried out on time domain using a software developed by Prof. V. Denoel, University of Liege [17], based on the Stochastic Subspace Identification (SSI). In both analyses three modes were computed: 1st one corresponds to flexural mode in Y direction, 2nd to flexural mode in X direction and 3rd is the torsion mode (Figure 2).

The sensor location was similar in all tests (Figure 2), even if with some difference due to the different number of employed accelerometers and local problems of positioning.

UNREINFORCED MASONRY MODEL (URM)

First test was carried out on the URM model with the aim to understand the dynamic behaviour of unreinforced structures. Its result constitutes the reference point to evaluate the achievable increase in term of dynamic strength using injection as strengthening technique.

The URM model could suffer a maximum PGA of 0.45g. Up to 0.25g any crack could not be seen, while over this acceleration level the cracks widely increased. Besides local problems, such as separation between external masonry layers and out-of-plane rupture of specimen corners, occurred. At the end of the experiment a very diffuse crack pattern was observed (Figure 3). Only a small number of cracks, positioned on the second floor of the structure, presented a large extension and an opening of few centimetres.

All computed frequencies for the URM model are generally decreasing and this reduction is greater for higher modes (see 0.25gI in Figure 4). Due to a sudden stop of the shaking table, after 0,25gI, the step 0,25g was repeated. This step was named 0,25gII. Particularly, a rapid drop is evident between steps 0,25gI and 0,25gII. The corners of the model damaged and after this step a widespread crack pattern took place. The overall decrease of 1st, 2nd and 3rd modes is 25.5%, 33.8% and 47.4%, respectively. Frequencies calculated for all steps using different identification methods are very close to each other, denoting the goodness and the reliability of the results.

The range of damping factor's variation is limited between 1.5% and 4% (Figure 5). An overall increasing trend can be detected, even if few steps showed a decrease of damping factor if compared with the previous step. A general trend is clearly identifiable up to 0,25gI. For higher PGA it is difficult to understand the behaviour of damping factors, even if they can be considered constant. Finally 1st and 2nd modes show a higher damping values, settled at about 2.5%-3%, than 3rd mode, settled at around 2%. However, 3rd mode shows a more regular

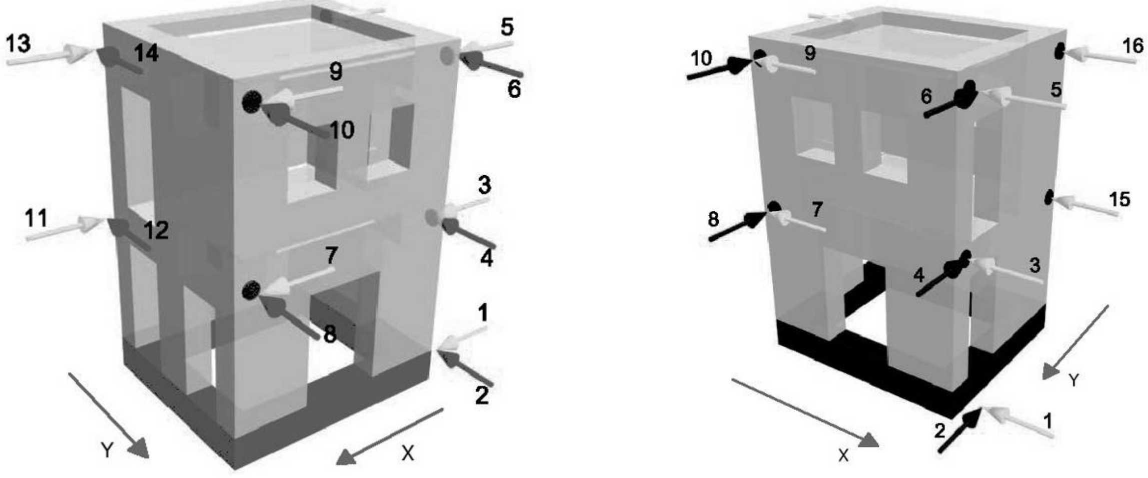

Figure 2: Sensor location in URM and SM models

development. Differently from computed frequencies, EFDD and SSI methods provide slightly different results for damping factors, particularly in the case of 1st mode. Trend and values calculated with both methods for 3rd mode are very close.

Mode shapes show a very different behaviour from that detected for frequencies (Figure 6). Before 0,25gI the deformation can be considered constant for all modes, while over this step it becomes larger. The normalized deformation increases shifting from 0.67 to 0.77 and therefore its vibration mode essentially changes. This is clearly shown in the case of 2nd mode: the heavy damage, localized on the second floor, can be detected noting the larger deformation at this level than that calculated for the first floor.

STRENGTHENED MASONRY MODEL (SM)

The SM model was strengthened using hydraulic lime grout injection before carrying out the shaking table test. This experiment aims at understanding the dynamic behaviour of a historical structure strengthened before a seismic event.

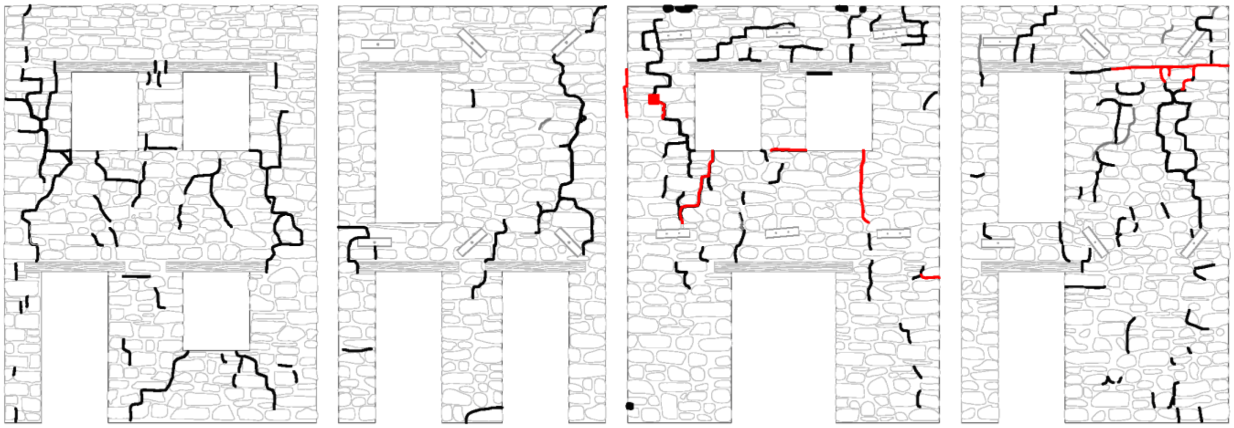

Figure 3: Crack pattern on URM model at the end of the experiment

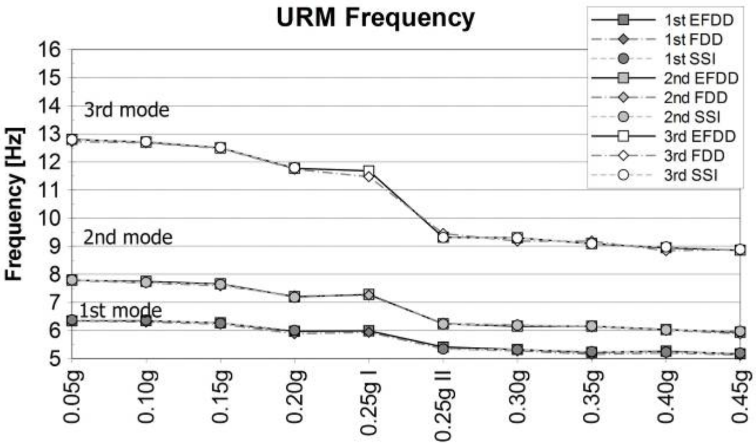

Figure 4: Frequency trend for URM model

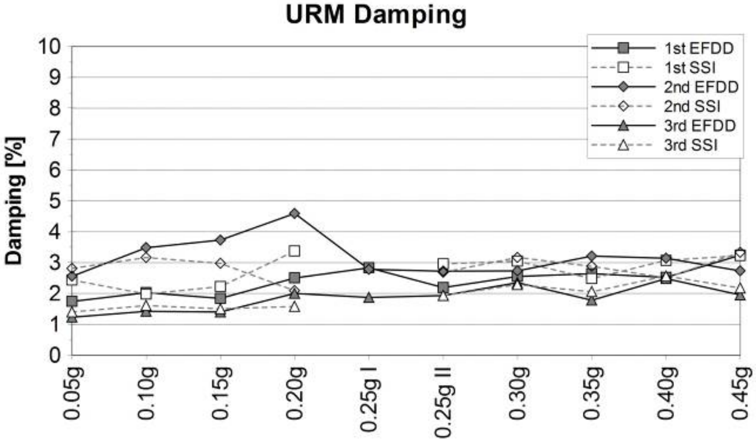

Figure 5: Damping trend for URM model

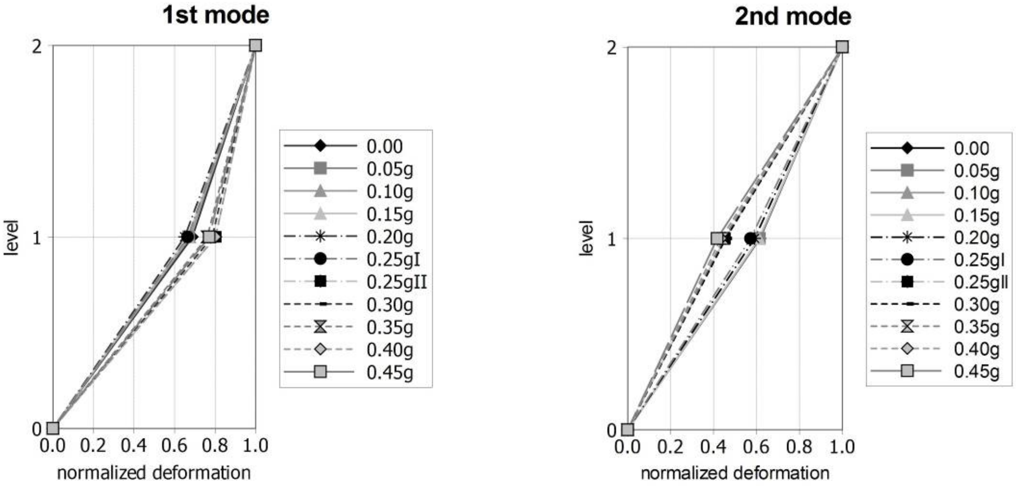

Figure 6: Mode shapes of URM model: a) 1st mode and b) 2nd mode

The SM model could suffer a maximum PGA of 0.70g. The test was divided into two parts: the dynamic input was applied in both horizontal directions up to 0.55g, while over this acceleration, up to 0.70g, it was input only in X direction. This changing was due to the out-of-plane rupture of a masonry pier, repaired before continuing with a unidirectional test. Few cracks appeared in the model during increasing steps and no separation between external masonry layers could be seen. Macro-elements started to appear in the model for highest accelerations; stability problems of the model (Figure 7), arisen at 0.70g, prevent to continue the experiment.

The overall behaviour of all frequencies is decreasing, even if a limited increase can be seen at 0,50g for all modes (Figure 8). This progression is clearly evident for 3rd mode. All modal frequencies decrease up to 0.20g. Over this acceleration value, up to 0.40g, all frequencies exhibit an increase: about 1Hz for 3rd mode, while first two modes had a small increment. This behaviour can be attributed to the settlement of material caused by seismic load. Over 0.30g two different trends can be highlighted: between 0.30g and 0.40g and from 0.55g up to the end. In the first interval frequencies exhibit a lower decreasing than that computed in the second interval. This enhancement denotes the increased damage in the structure.

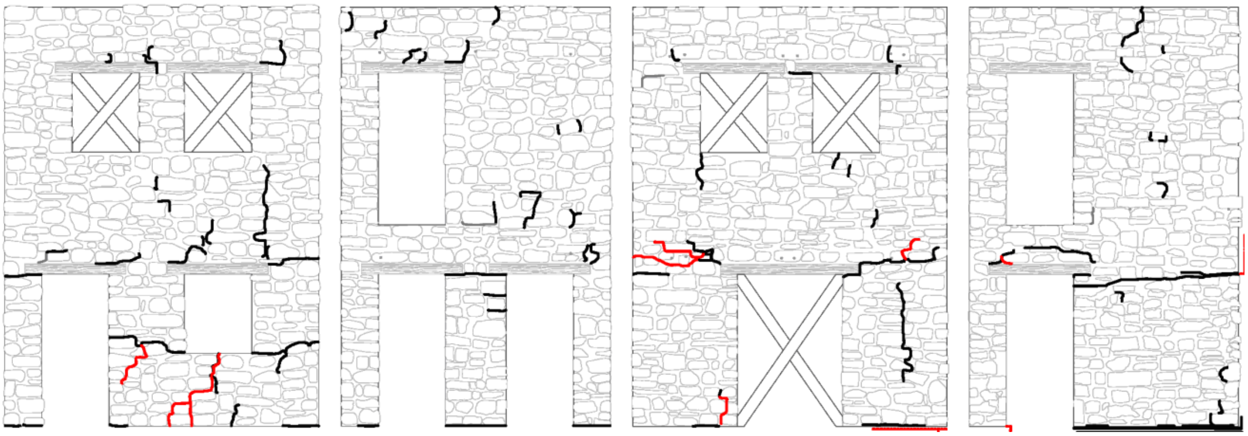

Figure 7: Crack pattern on SM model at the end of the experiment

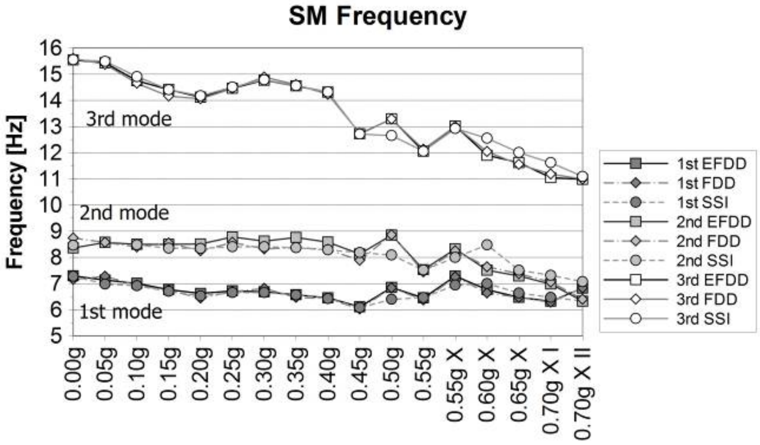

Figure 8: Frequency trend for SM model

The increase of all frequencies over 0.55g can be ascribed to the insertion of wooden diagonals in the openings in X direction (Figure 7) to induce a rupture in a selected pier. This changed dynamic characteristics of model. The overall decrease for 1st, 2nd and 3rd mode is of 14.1%, 24.3% and 39.2%, respectively. Only in the case of few steps SSI method provided results slightly dissimilar to those obtained from EFDD and FDD methods. Overall behaviour of all methods is very close to each others.

Damping factors range between 2% and 9%. Particularly, damping factors for 2nd and 3rd modes (Figure 9) show a high increase. The trend of damping factors can be divided in three phases even if the limits of these intervals are different for each mode. First part shows the increase of damping, second phase highlights a decreasing trend and last interval indicates an about constant damping value ranging between 2% and 4%. It should be underlined as damping factors for 2nd and 3rd modes increase from initial step up to 0.30g. This acceleration value corresponds to the beginning of the decreasing phase of frequencies. This can be related to the damping augment during the material settlement. This damping factor decreases over this acceleration level, denoting as structure completely developed its dissipative capacity. SSI method shows a trend similar to that identified using EFDD method, even if with a slight difference in values.

Mode shapes show a limited range of variation up to 0.45g, denoting as the SM model preserve almost unaltered its dynamic characteristics (Figure 10). Over 0.45g the deformation of second floor starts to increase, particularly for 1st mode. This fact is probably due to the concentration of cracks at first floor. Finally, it should be noted that the increase of modal deformation on the SM model gradually changes. Differently, on the URM model a sudden drop is clearly evident after the arising of severe damaging.

EFFECTIVENESS OF STRENGTHENING INTERVENTION

The comparison between results of elaborations carried out on the URM specimen and strengthened structure, so that the SM model, leads to evaluate the effectiveness of strengthening using natural hydraulic lime based injection.

Firstly, injection of hydraulic lime grout changes the rupture mode. The URM shows a very diffuse crack pattern, particularly at second floor, whereas the SM is characterized by

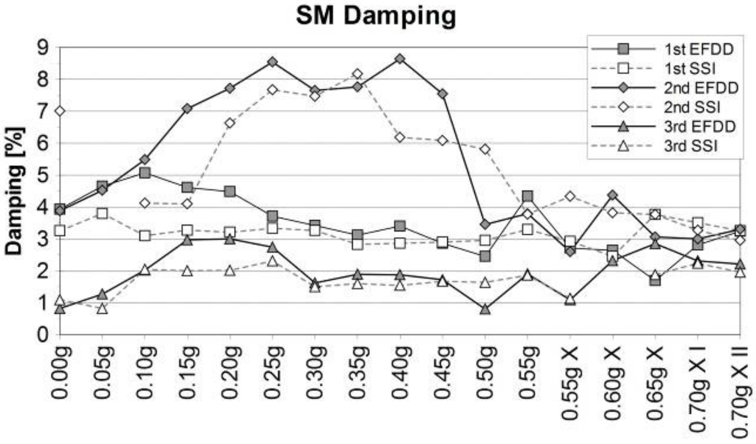

Figure 9: Damping trend for SM model

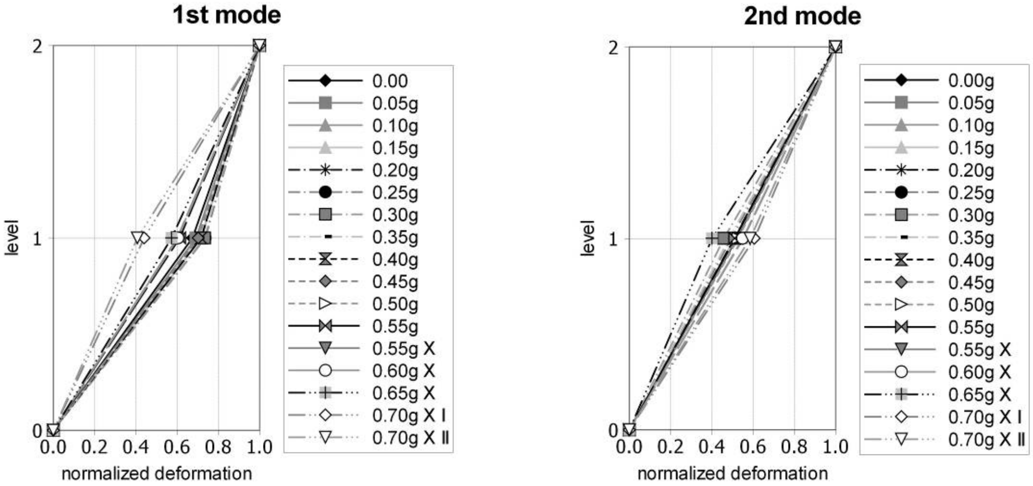

Figure 10: Mode shapes of SM model: a) 1st mode and b) 2nd mode

concentrated cracks with greater width. A localized damaging facilitates the repairing interventions; differently, the numerousness of damaged zones on the URM model makes the restoration difficult.

Frequencies of the URM model showed a higher decrease than those of the SM building. This highlights as injection can better preserve dynamic characteristics of structures and permits to reach a higher PGA. It is also important to note that the URM and the SM structures show similar starting frequencies. Slight differences of initial frequencies between two models can be imputed to the fact that measures are computed on two different structures. Finally, it can be concluded that injection permits to restore initial conditions without affecting vibration frequencies of unstrengthened structures.

All damping factors of the URM model have lower values than those computed for the SM building. Differently form the SM building, an unique increasing trend on damping can be detected for the URM structure. However, this growth is very limited and there is no substantial increase in dissipation. Although injection does not modify initial frequencies, as explained above, it permits to increase damping factors in the SM model (Figure 4 and Figure 8).

Finally, injection also allows a more monolithic behaviour. A wider modal deformation is detected in the case of the URM structure, comparing mode shapes of two buildings.

CONCLUSIONS

Injection can appreciably reduce local problems, such as separation of external layers and out-of-plane ruptures. Besides injected model could suffer a higher PGA, with reference to the URM model. The investigated strengthening intervention allows a limited crack pattern without modifying dynamic characteristics of original structure. In effect, injecting the model modifies neither the initial frequencies of the original structure nor the modal deformations. In addition, injection can limit the frequency decrease and it allows a lower damaging in the SM model. For these reasons injection of natural hydraulic lime based injection can satisfactory improve the safety level of a structure. Strengthened model shows high damping factors, indicating a good capacity in dissipating seismic energy, up to the developing of a heavy crack pattern. Subsequently to the arising of severe damage, no difference can be seen about damping between strengthened and unreinforced structures.

However, it should also be noted that, generally, damping factors from shaking table tests become larger than those of actual structure. A deepen study on damping factors can provide additional information and it can lead to identify the correct value to be used in real cases. Further investigations should be carried out, particularly on energy dissipation. These studies will allow to understand and to evaluate the benefits using injection of hydraulic based lime grout, particularly when preventing seismic event.

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REFERENCES

1. Corradi, M., Borri, A., Vignoli, A. (2002) “Strengthening techniques tested on masonry structures struck by the Umbria–Marche earthquake of 1997–1998”, Construction and Building Materials 16 (2002) 229–239.
2. Turnšec, V., Terčelj, S., Sheppard, P., Tomaževič, M. (1978). “The seismic resitance os stone masonry walls and buildings”. Proc. Of 6th European Conference on Earthquake Engineering, Vol. 3, Dubrovinik, 1978, pp. 255-262.
3. Benedetti D., Carydis P., Pezzoli P. (1998). “Shaking table tests on 24 simple masonry buildings”, Earthquake Engineering and Structural Dynamics, Vol. 27, pp 67-90.
4. Yi, T., Moon, F. L., Leon, R. T., Kahn, L. F. (2006) “Analyses of a Two-Story Unreinforced Masonry Building”, Journal of Struct. Eng., Vol. 132, No. 5, May 2006, pp. 653-662.
5. Terčelj, S., Boštiančič, J., Shepaprd, P., Turnšec, V. (1976). “Seismic resistance of typical stone- masonry buildings in the Kozjansko region”, Report ZMRK, Ljubljana, 1976.
6. Tomaževič, M., Weiss, P., (1994) “Seismic Behavior of Plain- and Reinforced-Masonry Buildings”, Journal of Structural Engineering, Vol. 120, No. 2, February 1994, pp. 323-338.
7. Modena, C., La Mendola, P., Terrusi, A. (1992). “Shaking table study of a reinforced masonry building model”, proc. 10th World Conference on Earthquake Engineering, Balkema, Rotterdam, 1992.
8. Zarnić, R., Gostić, S., Crewe, A., Taylor, C. A. (2001) “Shaking table tests of 1:4 reduced-scale models of masonry infilled reinforced concrete frame buildings”, Earthquake Engng Struct. Dyn. 2001, 30, pp. 819-834.
9. Juhasova, E., Sofronie, R., Bairrão, R. (2008). “Stone masonry in historical buildings – Ways to increase their resistance and durability”, Engineering Structures, Vol. 30, pp. 2194-2205.
10. Krestevska, L., Tashkov, Lj., Gramatikov, K., Landolfol, R., Mammana, O., Portioli, F., Mazzolani, F. M. (2008) “Shaking table tests on the large scale model of Mustafa Pasha Mosque without and with frp”, proc. of Structural Analysis of Historic Construction, Bath, England, 2008, pp.383-391.
11. Tomaževič, M., Velechovsky, T. (1992) “Some aspects of testing small-scale masonry building models on simple earthquake simulators”, Earthquake Engineering & Structural Dynamics, 21 (1992) 11, Jhon Wiley & Sons, pp. 946-963.
12. Jha, A., Sedaghati, R., Bhat, R. (2006). “Analysis and dynamic testing of structures subjected to vibration and shock using scale models”, Canadian Aeronautics and space Journal, Vol. 52, n° 3, pp 95-108.
13. Tomaževič, M., Lutman, M., Weiss, P., Velechovsky, T. (1992) “The influence of rigidity of floors on the seismic resistance of old masonry buildings”, Report ZRMK, Ljubljana, 1992.
14. Bresolato, F., Pasin, N. (2008) “Indagini sperimentali con prove soniche su murature in pietra consolidate mediante iniezioni” (in italian), MSc Thesis, U. of Padua, Italy, July 2008, 600p.
15. da Porto, F., Valluzzi, M. R., Modena, C. (2003) “Investigations for the knowledge of multi-leaf stone masonry walls”, 1st International Congress on Construction History, Madrid, Spain, 20-24 January 2003 Vol. II, pp. 713-722.
16. ARTeMIS SVS, ARTeMIS Extractor, Release 4.1, Structural Vibration Solutions A/S, Aalborg East, Denmark.
17. Denoel, V., Butz, C., Jakobi H. & Feldmann M., “Experimental determination of dynamic properties of the concrete foundation of a cement roller mill”, Experimental Vibration Analysis of Civil Engineering Structures, EVACES 07, Porto, Portugal, 2007.