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Shaking Table Tests on Multi-leaf Stone Masonry Structures: Analysis of Stiffness Decay

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Abstract The influence of the natural hydraulic lime-based grout on the dynamic behaviour of injected multi-leaf stone masonry elements is discussed in the paper. Shaking table experiments on two stone masonry buildings, tested before and after grout injection, have been performed. The paper focuses on the analysis of both the recorded accelerations and related displacements, at the bottom and at each further storey. This leads to evaluate the stiffness of the unstrengthened and injected structures. The input at increasing PGA allowed the stiffness decay to be studied, simulating a gradual damaging of the structures. These results were also interpreted in the light of both computed frequencies and mode shapes. Finally, the comparison among these results, obtained from all the models, allows to deepen the knowledge concerning the effects induced by the lime-based grout injection and on its capability to modify the dynamic behaviour, when intervening on a damaged (repairing) or on an undamaged (strengthening) structure.

Keywords: Shaking table test, multi-leaf stone masonry, stiffness, lime grout, injection

Introduction

A wide part of ancient buildings in Italy, as well as in several further European Countries, is represented by masonry structures. The decay conditions, in which part of these buildings is, make often necessary structural interventions to preserve their integrity. Among several causes of damage, safeguarding historical structures from earthquakes has an important role. In order to limit the destructive effects of the seismic events, several intervention techniques were developed during the years. However, most and less recent earthquakes occurred in Italy (Lunigiana and Garfagnana 1995; Umbria and Marche 1997; Abruzzo 2009) confirmed limits and consequences of some intervention techniques (Modena 1997, Corradi et al. 2002, Binda and Saisi 2005). The observed damages, induced by a conceptually wrong strengthening technique, underline the wide importance in deepening the effects of these operations.

Past researches, carried out by the University of Padua in collaboration with the Polytechnic of Milan, highlighted a wide use of multi leaf-stone masonries as structural system and, in particular, of three-leaf elements (Binda et al. 1999, 2003, Gardin 2007). This construction system is particularly diffused in the minor historical centres. Of all the techniques suitable in case of this masonry typology (Binda et al. 1997, Modena and Valluzzi 2006), the grout injection was considered. Indeed, this technique is able to limit the local separation of layers and the out-of-plane mechanisms, typical failure modes of this masonry typology. Several studies were performed in the quasi-static field (Vintzileou and Tassios 1995, Valluzzi 2000, Toumbakari 2002, Vintzileou and Miltiadou-Fezans 2008), involving different types of admixtures, normally cement- or lime-based, while limited investigations were developed in the dynamic field (Benedetti 1980). These researches clarify that the lime-based grouts may provide a wider overall compatibility with the historical materials (Valluzzi et al. 2003). Moreover, they are able to increase the overall strength of the injected elements without affecting further mechanical parameters, such as elastic modulus and stiffness, that is often the case of the cement-based ones.

Shaking table tests were thus performed for an in-depth study concerning the influence of the hydraulic lime-based grout injection on the dynamic behaviour of multi-leaf structures (Mazzon et al. 2009). This paper investigates the stiffness variation of injected structures, widening the results and the considerations previously obtained in terms of frequencies, mode shapes and damping factors.

Building Models and Experimental Set-up

The experimental program expected the realization of two building models with equal geometrical characteristics. Due to both the pay load and geometric dimensions of the shaking table, the specimens were built considering a reducing scale factor of 2:3. As a consequence, they had a rectangular floor plan, 2.40m by 2.80m, and an overall height of 3.60m. Both models were realized with the same masonry typology, namely three-leaf stone masonry. Furthermore, double planking wooden floors were realized to reproduce the effects of a not-rigid diaphragm, as in the case of historic structures, and steel ties limited the out-of-plane behaviour of masonry piers. The first model, named UnReinforced Masonry (URM) model, was tested in unstrengthened conditions, while the second one was injected before the test, through a hydraulic lime-based grout, and it was named Strengthened Masonry (SM) model. Finally, since the URM model was not led to the collapse, it could be repaired, through grout injection and local rebuilding, and tested again. This was named Repaired Masonry (RM) model.

All the models were equally instrumented to monitor both accelerations and displacements of most relevant points of the structure (Fig. 1). A first acquisition system of accelerations was externally fixed to the structures, at corners, while a parallel group of sensors was internally fixed, to the timber beams. Both series of accelerometers were placed at the bottom of the structures and at each floor level. The displacement of a hundred points of the external surface of the structures (Fig. 1) was monitored via an optical system, through the triangulation of the directions recorded by several isolated cameras, placed around the structure. The record of the earthquake occurred on 1979 April 14th in Montenegro was employed as input. The signal was properly processed, considering the adopted scale factor, and was input at increasing percentage of the original PGA. The SM model could suffer the highest input, up to 0.70g, while the weakest situation is represented by the URM model, that sustained only 0.45g. An intermediate condition is given by the RM model, that could attain 0.60g. A preliminary dynamic identification, involving frequencies, mode shapes and damping factors could be performed (Mazzon et al. 2008).

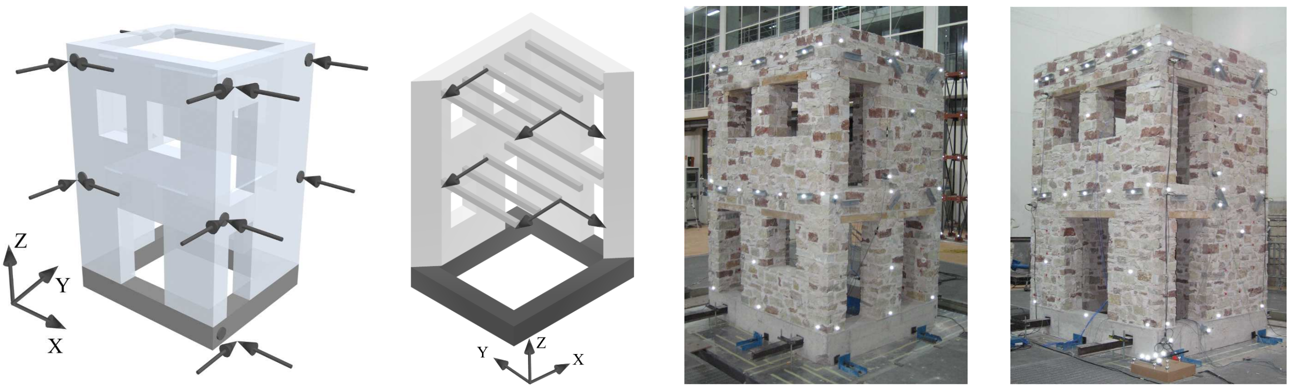

Figure 1: From left to right (i, ii) series 1 and 2 of accelerometers, (iii, iv) disposition of markers

Analysis of Data

Data Processing The acquired measurements were initially depurated from noise induced by both the acquisition system and low vibrations of the shaking table at the lower seismic inputs. For these reasons a high-pass filter at 2Hz was firstly applied. Further combinations of low-pass filtering were

performed at 20Hz and 25Hz. A final pass-band filer between 2Hz and 20Hz was chosen. This range includes all the fundamental frequencies, that vary between 5Hz and 15Hz, of all the tested structures. The reliability of both acquired displacement data and their subsequent processing was verified through some preliminary analyses. Firstly, data were processed to restore the fluctuation of measurements around a mean value equal to zero (linear-base correction). Subsequently, the displacements were differentiated twice and compared with the recorded acceleration signals. Furthermore, an additional comparison of these data in the frequency domain confirmed their complete agreement. A later analysis, involving energetic considerations, included the calculation of the Arias Intensity of both recorded and computed accelerations. The limited deviation of these results verified the reliability of data and confirms that any relevant information was lost.

Structural Oversimplification and Methodologies of Analysis Two sensors in the same position at each floor level, for displacements and accelerations, were chosen to obtain the best compatibility of acquired data. This allows to analyze the original signal instead of a processed one (obtaining acceleration from displacement or vice-versa). The overall behaviour of each storey was considered equal to that represented by data obtained at the corresponding floor level. Starting from this oversimplification, the overall mass of each storey was considered as concentrated at these points.

On the basis of the above mentioned considerations, the hysteretic relationship between shear forces and consequent displacements on both orthogonal directions could be computed, with the exception of some seismic inputs, for which data were unreliable. The stiffness calculation was performed via two different methods: (i) maximum displacements and (ii) linear regression. The first methodology only considers the maximum absolute displacements and the related shear force, while the second method involves all data achieved during the test. Since the results provided by both methods manifested a noticeable difference and the coefficient of determination resulted quite low (method (ii)), the second process was repeated using different data. Firstly, the analysis was repeated per each second of the input, while a subsequent study was performed considering the part of the time history with the highest intensity. This last method provided the best results, with both the highest coefficient of determination and the best accordance with the results of the first applied analysis. Values and trends obtained from this process will be discussed in the following sections.

Analysis of Stiffness Degradation

URM The stiffness values show an overall decreasing trend (Fig. 2). Nevertheless, up to 0.25g, the stiffness behaviour at both storeys and directions appear as similar, manifesting a comparable reduction. The stiffness of the first storey in both directions is higher than that of the second one and this may be mainly due to both a lower presence of openings and a higher vertical load acting on the considered wall section. Over 0.25g a sudden drop can be noted, even if the decrease is different on orthogonal directions and unlike floor. Indeed, the highest stiffness reductions are concentrated on the first storey in the Y direction and on the second floor in the X direction, where the heaviest damage could be seen in the model. For seismic accelerations higher than 0.30g and up to the end of the experiment, the stiffness decrease is limited. This confirms that the damage suddenly occurred and involved the whole structure, even if with noticeable differences among the parts. Furthermore, comparing the overall decrease per level and direction, no substantial difference can be seen (Fig. 2). In all cases, these reductions are higher than 50%, particularly at the second storey.

RM The overall stiffness trend for the RM model appears more complex than that of the URM one (Fig. 3). A general reduction can be seen, even if few localized increases are present. Furthermore, one should note that the lime grout injection allows the initial stiffness of the URM model to be completely recovered on the RM structure. Between 0.20g and 0.30g a general reduction of values takes place and, over 0.35g, all computed stiffness values exhibit a monotonic decrease, which is greater for the first storey in both orthogonal directions. Indeed, over 0.35g, both quantities show an overall decrease higher than that manifested up to this seismic level. In this case, the stiffness decay

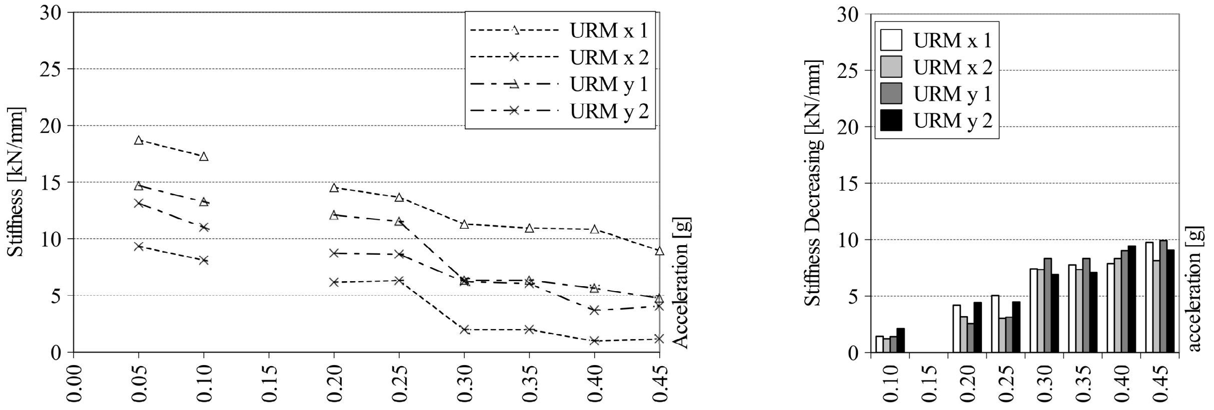

Figure 2: URM, Stiffness trend and decrease at increasing seismic intensity

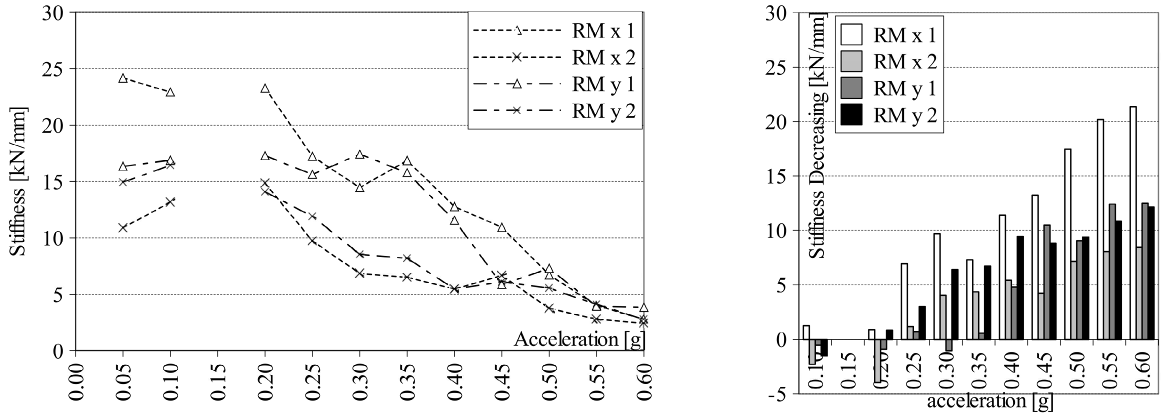

Figure 3: RM, Stiffness trend and decrease at increasing seismic intensity

gradually develops along the whole test and this is not mainly concentrated during a single step. This can be explained in the light of the overall damage, which similarly occurred gradually on the structure. Furthermore, the computed decrease makes clear a certain diversification in the damage position. Indeed, the first floor exhibits the highest stiffness degradation, particularly in X, even if also that of the second storey is noticeable. In all cases an overall decrease higher than 70% can be seen. Finally, it should be noted that a higher overall decrease is allowed, if referred to the URM model, while at the same load level the decay is similar.

SM The initial conditions of this model are similar to those of the URM one. The overall behaviour is decreasing, even if in several steps a noticeable increase can be seen (Fig. 4). Up to 0.20g, stiffness values exhibit a substantial invariance. The first important considerations can be drawn on the basis of the effects manifested between 0.20g and 0.35g. Within this range, a clear increase of stiffness at first storey should be noticed, while the second one manifest a general decrease. Over a seismic acceleration of 0.40g and up to 0.55g, a high and overall stiffness reduction takes place and values settles in a similar range. Over 0.55g, as a consequence of the insertion of brace elements in X, due to stability problems of the model, the stiffness was increased (Fig. 4). However, the overall behaviour at both storeys on the considered direction is similar and the total reduction in this second part is very limited if compared with that up to 0.55g. The analysis of the stiffness decay (Fig. 4) shows that, during the first phase, the highest overall decrease is concentrated at the first storey and, particularly, along the heaviest solicited direction, namely X. The stiffness decay of the SM model at 0.45g appeared more similar than that of the RM one to the overall behaviour of the URM structure. Furthermore, the strengthening allowed the highest overall stiffness decrease to be attained.

Overall Dynamic Characteristics The stiffness decay manifests a close relationship with further identified dynamic characteristics. Particularly, frequencies (Fig.5) and mode shapes show a similar overall trend (Mazzon et al. 2009).

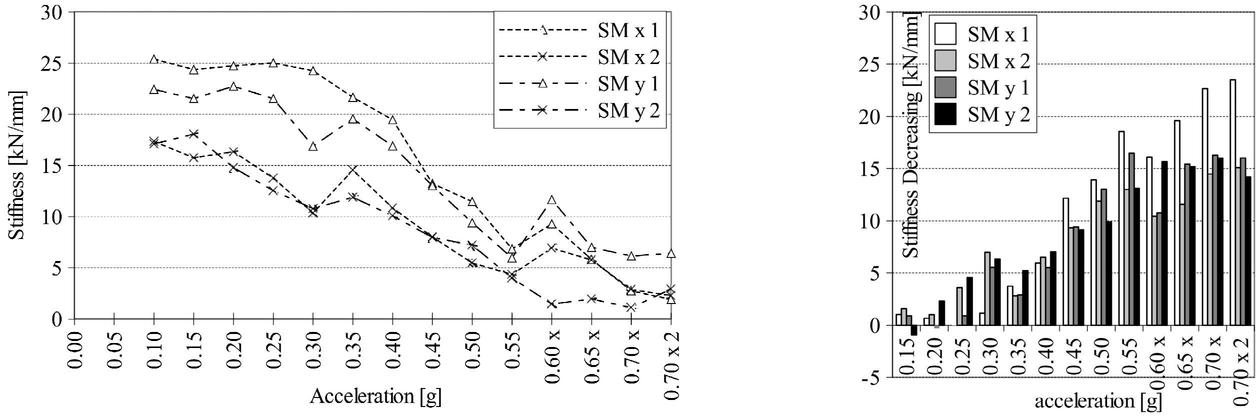

Figure 4: SM, Stiffness trend and decrease at increasing seismic intensity

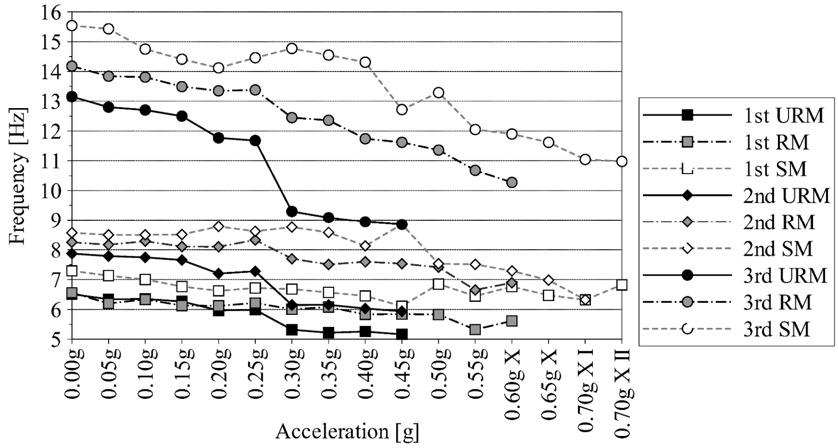

Figure 5: Frequency trend for all models at increasing seismic intensity

The frequencies of the URM model shows a sudden drop over 0.25g (Fig. 5). Moreover, the differentiated stiffness decrease, above observed, is confirmed and related to the computed mode shapes. Indeed, the normalized modal deformation manifest an increase at the first floor level (Y direction), while it is reduced on the orthogonal direction, namely absolute modal displacements at the second storey increased. This is in agreement with the localized sudden stiffness decrease, occurred at 0.25g and above described.

The stiffness increase on the RM model, between 0.05g and 0.10g, could also be seen particularly for the first and second frequencies (Fig. 5). The following monotonic decrease reflects the overall stiffness trend. Particularly, the most noticeable decrease can be seen at 0.30g on both analyses. Finally, the high decreases of modal deformations at first storey in X and at the second floor level in Y are in agreement with the stiffness results above commented, confirming their reliability and the mutual reliance among stiffness, frequencies and mode shapes.

Lastly, the identified frequencies for the SM model (Fig. 5) behave similarly to the stiffness trend. Indeed, all modes, particularly those higher, exhibit a localized increase in the same range of accelerations observed in Fig. 4. In case of both stiffness and frequencies, the percentage reduction on SM model was lower than that of other structures, if the same load level is considered. Equally, the identified mode shapes show a wider decay at the second storey in Y and at the first one in X.

Conclusions

The results presented in the paper highlighted the wide effectiveness in intervening via hydraulic lime-based grout injection on multi-leaf stone masonry structures. Firstly, the starting dynamic behaviour is only limited affected by the injection of this type of admixture. Indeed, the SM model exhibited a limited initial stiffness increase, due to the strengthening. This is also confirmed by the

initial stiffness of the RM model, that is very close to that of the URM structure. This is a fundamental feature, since it implies that the injection does not modify neither the vibrational modes nor the fundamental frequencies, as confirmed by the preliminary dynamic identification. Furthermore, the injection allows a higher seismic load to be sustained as well as a lower overall stiffness decay. Moreover, the results obtained in case of strengthening (SM) appeared more similar to the original model (URM) than those computed in case of repairing (RM). The analyses also demonstrated the capability of the lime grout injection, when intervening in a damaged structure (RM), in recovering the initial stiffness of the original unstrengthened one (URM). These results are widely confirmed by the comparison with the further identified dynamic characteristics. As a consequence of the above mentioned considerations, the best result is obtained in the case of strengthening, while repairing represent an intermediate situation if compared to the unstrengthened case.

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