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Effectiveness of injections evaluated by sonic tests on reduced scale multi-leaf masonry building subjected to seismic actions

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Abstract

The results of the application of NDT on two reduced-scale (2:3) buildings subjected to shaking table tests at the laboratory of ENEA (Rome) are presented. The models have two storeys and are made of three leaves stone masonry and timber floors, connected to the walls by steel ties. One model was strengthened by injections before test, in order to compare the effectiveness of the intervention in increasing its strength. The models reproduce the typical pattern of buildings in historical centres, where the use of poor materials (especially mortar) and the lack of strong connections among them, is responsible of their high seismic vulnerability. To pursue preservation criteria, compatible grouts were proposed, based on natural lime-mortar binders. A preliminary phase of materials characterization was performed (on stones, mortar and grouts), and non-destructive investigation methods were also applied. Particularly sonic waves, before and after injection, applied as direct and tomographyc tests, allowed identifying the grout penetration pattern and validating the intervention.

Résumé

Les résultats de l'application de NDT sur deux édifices, réalisés en échelle réduite et sujets à une épreuve dynamique dans le laboratoire ENEA en Rome, sont présentés. Les modèles ont deux étages et ils ont été réalisés utilisant une maçonnerie constituée de trois strates en pierre et sols en bois, reliés aux murs avec des barres en acier. Le premier modèle a été renforcé par des injections avant l'épreuve, afin de comparer l'efficacité de l'intervention en la réduction du collapse. Les modèles reproduisent le schéma typique des bâtiments historiques, où l'usage de matériaux pauvres et l'absence de forts liens entre eux, est responsable de leur grande vulnérabilité sismique. Pour suivre les critères de préservation, l'utilisation de coulis compatibles, à base de liants de chaux naturelle, a été proposée. Une phase préliminaire de caractérisation des matériaux a été effectuée (sur pierres, mortier et liants de chaux naturelle), et des méthodes non destructives d'auscultation ont également été appliquées. En particulier les ondes sonores, avant et après l'injection, appliquées soit en mesure directe, soit en et tomographie, ont permis d'identifier la pénétration du coulis et de valider l'intervention.

Keywords Non Destructive Techniques, experimental investigation, stone masonry.

1 Introduction

Sonic tests are a non-destructive method widely employed to detect qualitative characteristics of materials. This technique consists in transmitting stress waves, within 20Hz and 20kHz frequency range, across a material. A qualitative relation among sonic velocity, dynamic elastic modulus, Poisson's ratio and density of studied material can be found [1]. Nevertheless, equations are depending on several aspects, such as the investigated matter and its homogeneity. For these reasons a preliminary calibration of mathematical relationships is required. Moreover, the method needs a proper resolution to be reliable for the diagnosis [2].

Preliminary examinations and qualitative investigation of structures are a wider field in which sonic waves are employed. It has been already demonstrated that sonic tests can be usefully applied to perform local analyses. Moreover qualitative informations on the consistency of masonry [3,4,5] can be obtained. Main applications of sonic technique aim to identify internal cohesion among materials and to detect internal voids or structural damages. These investigations lead to important indications for the most suitable strengthening method. Sonic tests [7] can be usefully applied to control goodness of intervention.

The paper presents the application of sonic techniques on two stone masonry buildings. The experimental campaign involves dynamic tests on building models. The study aims at investigating the strengthening influence of lime grout injection. Sonic tests were employed before interventions to explore the masonry quality and the strengthening feasibility. A further application, after repairing, permitted to control the improved masonry characteristics and the homogeneity of lime grout penetration [8]. Additional tests will be carried out after shaking table tests to deepen the capability of sonic analyses to detect cracks and masonry damage.

2 Experimental program

The experimental program expected the realization of two reduced scale (2:3) stone masonry buildings (Figure 1). A simplified typical and common historical structure, more diffused in the north-east region of Italy, was considered as prototype. The two storeys models have regular floors 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. Three-leaf stone masonry typology was adopted for walls. Main aspects of masonry are: absence of transversal connection between external layers and incoherence of the internal leaf, constituted by stone fragments and characterized by 12% of voids [8]. These masonry characteristics allow a strengthening intervention employing injections of lime grout. This repairing intervention aims at binding the incoherent masonry core and, consequently, improving the monolithic behaviour of walls.

The main aim of the research is to study the influence of lime grout injection on the overall behaviour of structure. Within this wider study, sonic investigations allow both the evaluation of masonry injectability and the estimation of change in main characteristics of stonework.

A preliminary wide research [9] on more than 400 historical structures was carried out, with the Polytechnic of Milan, to detect the typical cross section of three leaves stone masonry. The study leads to choose an overall deepness of 50cm in natural scale, reduced to 33cm in case of scaled structures. The investigation focused also in the identification of typical strength of materials employed in historical constructions. A comparison within literature review, a previous similar experimental campaign [10] and the present study, was carried out (Table 1). The characteristics of historical and reproduced mortar are similar, guaranteeing a correct replication of overall behaviour of historical masonry. A similar elastic modulus between mortar and lime grout permits a complete mechanical compatibility.

First model, named URM (UnReinforced Masonry), was tested as built while the second structure, named SM (Strengthened Masonry), was injected before test. Direct and tomographyc tests were carried out on both models in the same chosen positions. The aim of sonic investigations was characterizing masonry quality according to cataloguing proposed by [3] and [4]. Sonic tests performed before intervention permitted both to control the injection feasibility and to check voids presence. Sonic tests executed after strengthening allowed to verify the uniform diffusion of lime grout and the effectiveness of strengthening, measuring the increased sonic velocity.

An instrumented impact hammer with hard tip, producing stress waves with frequency up to 1kHz, was used as excitation source. Piezoelectric accelerometers with measurement range of ±0.5g and frequency range between 0.05 and 4000Hz were employed as sensors. A National Instruments PXI was utilized as system acquisition combined with LabVIEW commercial software for analyses and results of directs sonic tests. Successively, a software developed at the University of Padua [11] was employed to elaborate sonic tomographies.

Four direct sonic investigations were planned in likewise panels of each specimen (Figure 1). A rectangular mesh of 66cm by 99cm was employed with a step of 33cm, equal to the overall masonry thickness. This set up allowed 12 acquisition points per each test. Direct sonic tests were performed by measuring the transit time in all of the “corresponding” sonic paths, meaning with the term “corresponding” the pairs of points positioned at the same location in opposite sides of the wall section. Investigations were carried out in the largest parts of the structure: positions 1 and 3 are placed on second floor while 2 and 4 on first one. Locations 1 and 2 are vertically aligned to control likenesses and differences of masonry characteristics, due to unlike storey.

Two sonic tomographies were also carried out in the same pier (Figure 1) to control and to compare results with those obtained from direct sonic investigations. Tomography “A” was realized placing sensors on three sides, using a two by six mesh. Tomography “B” involved four sides, with a two by nine mesh. In both cases acquisition points were equally spaced of 16.5cm, corresponding to half of the overall masonry thickness. Sonic tomographies were realized by measuring the transit time in all of the possible sonic paths in the individuated horizontal cross-section, according to the considered acquisition grid. Results were elaborated considering simultaneously all the recorded transit times [11]. It was therefore possible to detect the fastest and slowest paths and, consequently, the most compact and disaggregated areas of considered masonry section.

Table 1. *Characteristics of materials employed in different experimental campaigns*

Material	Test	Binda [9]	Valluzzi [10]	Actual campaign
Stone	Compression	111 MPa	164 MPa	212 MPa
	Flexure	-	32 MPa	29 MPa
	Tensile	4.67 MPa	-	-
	Young’s Modulus	-	-	64.3 GPa
Mortar	Compression	3.34 MPa	1.6 MPa	3.7 MPa
	Flexure	-	0.8 MPa	1.3 MPa
	Tensile	1.48	-	-
	Young’s Modulus	-	2695 MPa	6130 MPa
Lime grout	Compression	-	3.2 MPa	12.8 MPa
	Flexure	-	0.4 MPa	3.8 MPa
	Young’s Modulus	-	7250 MPa	6580 MPa

3 Results before strengthening intervention

Direct sonic tests, carried out before strengthening interventions on both URM and SM models, highlight sonic velocities under 1000m/s. These results denote weak masonry conditions, according to [3] and [4] proposals. Particularly positions 2 and 4, on first storey, present higher velocities than positions 1 and 3, situated on second floor (Figure 2). This difference is due to masonry dead loads, that caused a natural compacting of material in lower storeys. These weak conditions are related to the wide voids presence on the masonry core. Noticeable is position 4 where sonic velocities are higher than 2000m/s. This fact is due to the mesh position. Actually higher velocities can be found on lateral sides, corresponding to the pier edges. In these positions stones are posed transversally to the section. Existing lower velocities of about 1000m/s on the middle of the pier, where no transversal connection is provided, validate this thesis. Other tests, placed away from piers edges do not present this unusual behaviour. Figure 3 demonstrates as at the piers edges, where masonry continuity is present, velocities are greater than 1800m/s. In the central zone higher transit times confirm the incoherence of core masonry. Time records between points on opposite long sides are predominant on measures obtained between perpendicular faces. This overall behaviour make difficult to detect the central core. Moreover, mean tomographic velocity results greater than velocities from direct sonic tests. All the results of sonic tests carried out on URM and SM models are therefore similar, confirming the possibility to strength masonry by injections.

4 Results after strengthening intervention

Direct sonic tests, performed after injections on SM model, denote as the mean velocity widely increased: all sonic velocities are ranging between 2200m/s and 2900m/s. This fact indicate a quite good masonry quality and a drastic decreasing of voids presence.
Figure 4 shows the quantity [$10^{-3}m^3$] of injected lime grout in each injection point of panels. This quantity was different in each injection point. This confirms the great variability of voids in the masonry core. Nevertheless Figure 5 highlights as the free diffusion on lime grout can lead to an homogeneous distribution of sonic velocities. Light differences were found in limited parts of investigated panels. Particularly low values found on the base of position 2 can be ascribed to local problems of lime grout penetration because of too small core fragments. Besides, position 4 (Figure 5) shows as on lateral zones a limited increasing

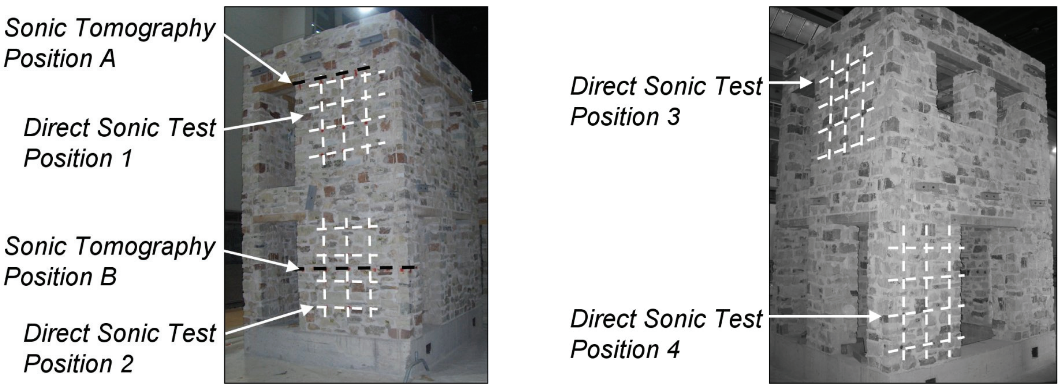

Figure 1. *Building models and sonic tests position*

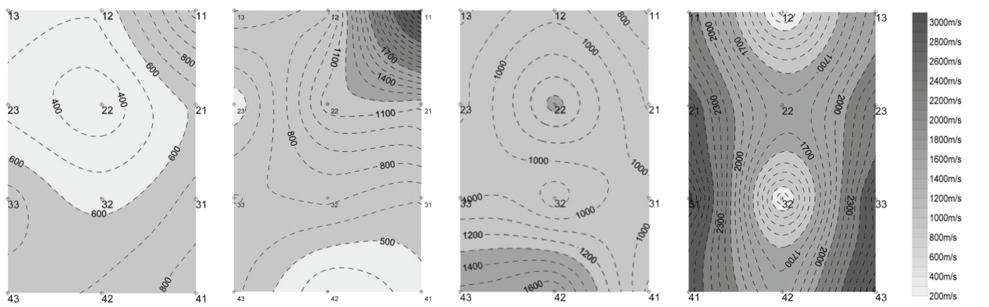

Figure 2. *SM model: direct tests before injection. From left to right: position 1 to 4*

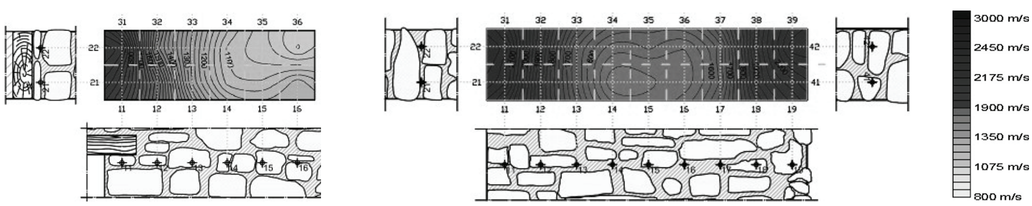

Figure 3. *SM model: sonic tomographies before injection. Position A (left), B (right)*

can be found. This lower increase of velocity indicates as in the pier edges not much voids are present. More voids are obviously concentrating in the middle, where greater increasing are evident. This conclusion can be also deduced from the analysis of injected quantities: more lime grout was injected in the middle of panel. This confirms the previous comments. Moreover, no velocity increase was found between the second and the first storey.

Sonic tomographies confirmed analyses obtained from direct tests. The considered sections show an homogeneous distribution of velocities. Therefore different velocities between pier edges and central zone, as highlighted before strengthening, were eliminated. Tomographies carried out after injections indicate lower velocities than those obtained from direct sonic tests. This is due to the alternative elaboration of different signals in the same areas.

By considering the totality of sonic results after strengthening, it can be confirmed that lime grout is freely distributed and permeated the great part of voids percentage. Moreover an homogeneous velocity distribution and improved compacting (Figure 5) can be reached, even starting from worse and heterogeneous conditions (Figure 2).

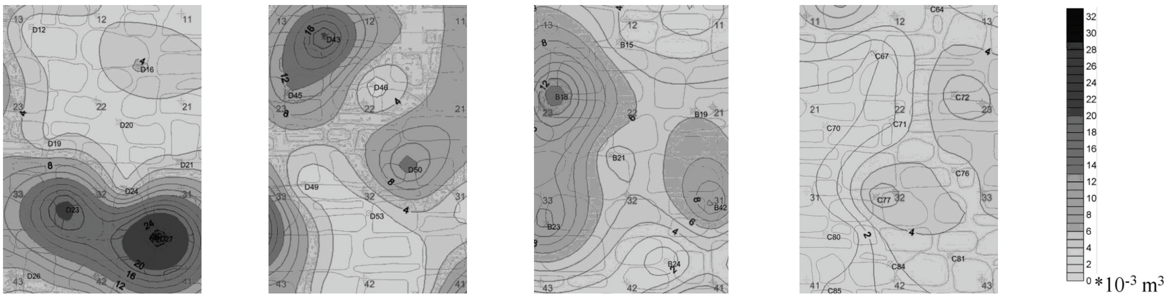

Figure 4. *Maps of injected grout quantity. From left to right: position 1 to 4*

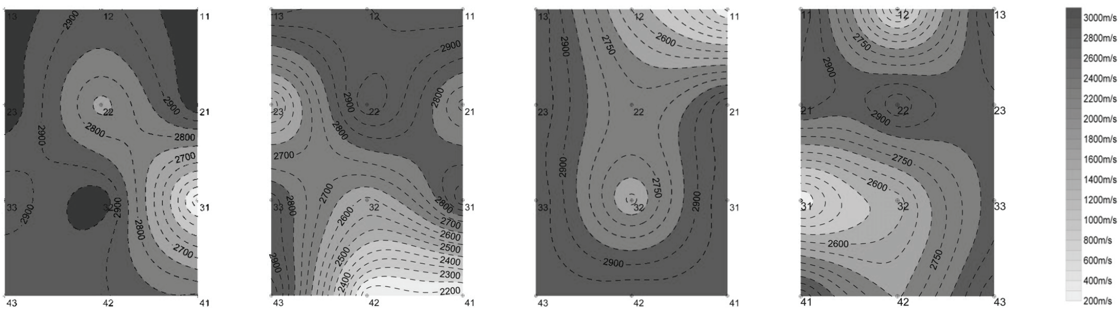

Figure 5. *SM model: direct tests after injection. From left to right: position 1 to 4*

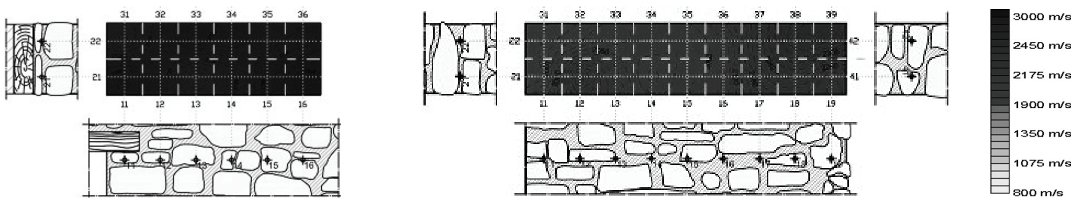

Figure 6. *SM model: sonic tomographies after injection. Position A (left) and B (right)*

5 Conclusions

The paper establish as sonic investigations can be employed in multi-leaf masonry to detect voids presence. A limited application of direct sonic tests in a point of structure can not provide sufficient elements to detect its characteristics. However, the application of this technique in different parts of the model and the comparison of their results help to qualitatively understand masonry characteristics and detect voids.

Sonic tomographies provide a deeper masonry knowledge, even if an adequate thickness should be accounted. A comparative assessment, such as the monitoring of injection process and the employing of sonic tests after intervention, leads to evaluate the strengthening effectiveness. Finally, areas where injection more difficultly penetrated can be detected.

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