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DETECT-AGING blind prediction contest: a benchmark for structural health monitoring of masonry buildings

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Abstract

The installation of monitoring systems on buildings allows analyzing variations in structural parameters over time, creating room for detection of damage. Structural Health Monitoring (SHM) systems have the potential to support pro-active risk management, where structural interventions are planned if specific thresholds related to target performance losses are achieved.
DETECT-AGING is a research project of relevant national interest that was funded by the Italian Ministry of University and Research (MUR) through the PRIN 2017 programme. The project started in September 2019 and involves the universities of Bologna, Genova, Napoli Federico II, and Perugia. The main goal of the project is to develop a new analytical-instrumental approach aimed at the quantitative assessment of the effects of aging and material degradation on structural safety of cultural heritage, with special focus on masonry structures. Based on a combined use of structural models and health monitoring systems, indications and operational tools will be provided for the identification and quantification of structural damage, supporting the management of built cultural heritage. To this purpose, a two-storey masonry building, having a single room with a vault at the first floor and a timber roof, was built with the aim of being monitored and progressively and will be damaged during the project. It is equipped with a hybrid SHM system managed by the University of Perugia, which is based on both vibration and strain measurements. The present paper illustrates the main features of the case-study building and presents the results of the experimental program aimed at characterizing the mechanical properties of masonry the materials used. The final part of the paper presents a blind prediction contest based on prediction of modal features of the building in different damaged configurations.

Keywords: Masonry buildings, Structural health monitoring, Aging, Degradation

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1. Introduction

Unreinforced masonry (URM) buildings constitute the majority of the Italian building heritage (ISTAT. 2014) and represent one of the most vulnerable construction types (Dolce et al. 2021). Many studies have underlined their seismic vulnerability (Augenti and Parisi, 2010; Cattari et al. 2012; D'Amato et al., 2020; Fiorentino et al., 2017; Parisi and Augenti, 2013) but the consequences of damage accumulation due to aging, degradation and soil settlements, in terms of structural safety have received much less attention from researchers. Masonry deterioration problems include several phenomena such as blistering, chipping, efflorescence, flaking, peeling, and pitting (Grimmer, 1984), which are caused by extreme weather, pollution and moisture. Causes of deterioration include aging and may also be related to construction deficiencies and geotechnical problems.

As damage grows, it may reach a level that affects the structure operation to a degree that is no longer acceptable for users. In terms of time scales, damage can occur during a specific event, such an earthquake, or accumulate incrementally over long periods of time such as that associated with corrosion or with foundation settlements. Clearly, this definition is not meaningful without a comparison between two different states of the structure under consideration, one of which is assumed to represent the initial, and often undamaged, state.

The adoption of Structural Health Monitoring (SHM) systems on buildings allows analyzing the variations of some structural parameters over time and, therefore, may allow detecting the activation of some of the aforementioned damage mechanisms. SHM systems have the potential to support pro-active risk management, planning structural interventions when specific thresholds related to a target performance loss are achieved, rather than intervene on a periodical basis or after a harmful event (reactive management). The literature on the application of SHM systems to masonry buildings is mainly focused on detection of seismic damage (Macías et al., 2020; Kita, 2019) while the potential of SHM systems in identifying other forms of damage has not been widely investigated (see e.g. La Mendola et al., 2021).

This paper presents the DETECT-AGING (Degradation Effects on sTructural safEty of Cultural heriTAGe constructions through simulation and health monitoring) project, which started in September 2019 and involves the universities of Bologna, Genova, Napoli Federico II, and Perugia. The main goal of the project is to develop a new analytical-instrumental approach aimed at the quantitative assessment of the effects of aging and material degradation on structural safety of cultural heritage, with special focus on masonry structures. Based on a combined use of structural models and health monitoring systems, recommendations and operational tools will be provided for the identification and quantification of structural damage, to support the management of built cultural heritage.

The research unit of Bologna built a scaled model of a two-storey masonry building having a single room with a vault at first floor and a timber roof. The specimen building is equipped with a hybrid SHM system managed by the University of Perugia, which is based on the acquisition and processing of both vibration and strain measurements. While vibrations are measured by means of commercial seismic accelerometers mounted at strategic locations of the load-bearing structure, strains are monitored through self-sensing sensors of newly conception, called "smart bricks", which are fully integrated within the masonry. The paper illustrates the main features of the specimen building and presents the experimental program that will be carried out, involving artificial degradation and controlled construction defects.

2. The building specimen

The model building is a two-storey masonry building (Fig. 1) with in-plan dimensions of 4.72 m × 3.5 m at the ground floor and a total height of 4.67 m. The construction is irregular in plan, in order to increase the complexity of its modes of vibration, but regular in elevation. There are two openings on wall A and one opening on wall C at both floor levels. Walls are 250-mm thick and composed of double-wythe clay bricks and lime mortar. The masonry has a Gothic bond pattern (Fig. 2b) in which header bricks are located in the middle of the stretcher brick in both the lower and upper courses. Head joints and bed joints are both 10-mm thick. All door openings were sized with height of 1.25 m and width of 0.85 m. Six fir timber lintels (type C24) with dimensions 250 mm × 100 mm × 1050 mm were installed on top of all openings.

A masonry polycentric vault with thickness of 125 mm was built at the first floor level, using gravel as fillings material (Fig. 3b). Four ties made of steel S235, with a diameter of 18 mm and a length of 3.75 m, are located 390 mm above the springer line of the vault. At the ends of each tie there are two diffusion square steel plates with dimensions 400 mm × 400 mm × 25 mm. On the roof level there is a wooden slab and a single straight-sheathed timber floor, composed of 5 fir wood beams type C24 (dimensions 200 mm × 280 mm × 3250 mm) and a single layer of planks with a cross section of 250 mm × 50 mm. Both slabs are rectangular with plan dimensions of 3.00 × 4.22 m^2. Walls A and C are connected with the wall D, but are separated from the wall B with a full height plastic film. In order to simulate different degrees of wall-to-wall connection, 18 threaded steel bars type-M8 are used to connect the wall B to the walls A and C (Fig. 3a). By tightening steel nuts on these bars, is possible to partially restore connections between walls. The model building is supported by a steel foundation, designed in order to simulate a settlement of wall D. The foundation is made of two C-shaped assemblies of steel beams (Fig. 4). The first is fixed and supports the wall B and most of the walls A and C, while the second is hinged supported by 2 steel hinges and 2 hydraulic jacks. The reduction of oil pressure in the hydraulic jacks allows the simulation of soil settlement.

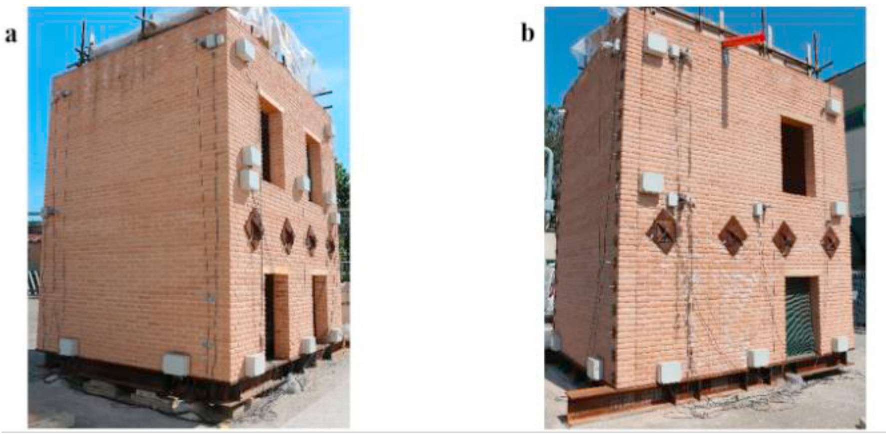

Fig. 1. (a) Facades D-A and facades B-C (b) of the building.

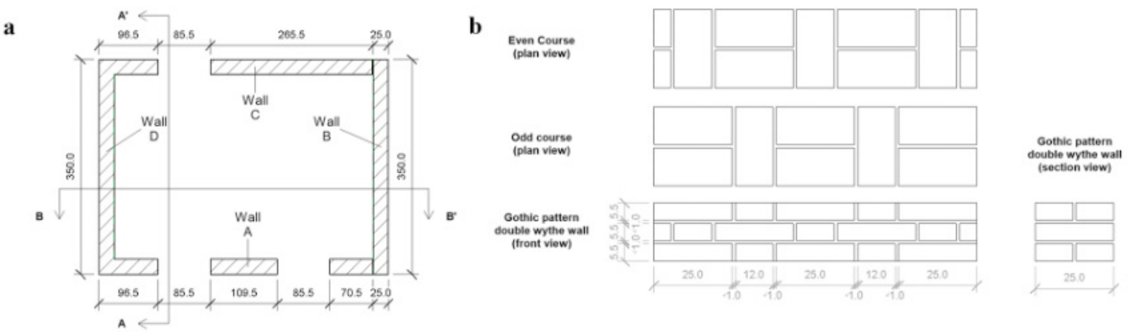

Fig. 2. (a) Plan view of level 0, scheme of walls and sections; (b) Gothic bond pattern of masonry walls. Distances are measured in cm.

3. Material Properties

The blocks used for the masonry walls are clay bricks with dimensions 25 cm x 12 cm x 5.5 cm [9]. Their mechanical properties were obtained from tests on 20 specimens. From each of them, 8 cylindrical specimens with a diameter of 3.8 cm, 4 parallel and 4 perpendicular to the bed face of the brick, were tested in compression. The compressive strengths parallel ($f_{b,c//}$) and orthogonal ($f_{b,c\perp}$) to the bed face are reported in Table 1.
Mortar is made using pre-mixed mortar available on the market, with the addition of fine sand to decrease strength but keeping an adequate workability. This mix derives from an experimental program carried out at the university of Bologna (Ferretti et al., 2020). The mortar strength was evaluated by means of three-point bending and compression tests on 144 specimens with dimensions 4 cm × 4 cm × 16 cm. Table 1 shows the average value and the coefficient of variation of the mortar flexural tensile strength ($f_{m,fl}$) and compression strength ($f_{m,c}$).
The mechanical parameters of the masonry were obtained from compression tests (Fig. 5a) on three small double wythed walls with dimensions 51 cm × 51 cm × 25 cm. Each specimen was equipped with 3 vertical and 1 horizontal linear displacement transducers on both faces (Fig. 5a). Fig. 6a shows the normal stress versus horizontal (*H*) and vertical's (*V*) strain diagrams obtained. Strains were calculated dividing the measured elongation/shortening by the

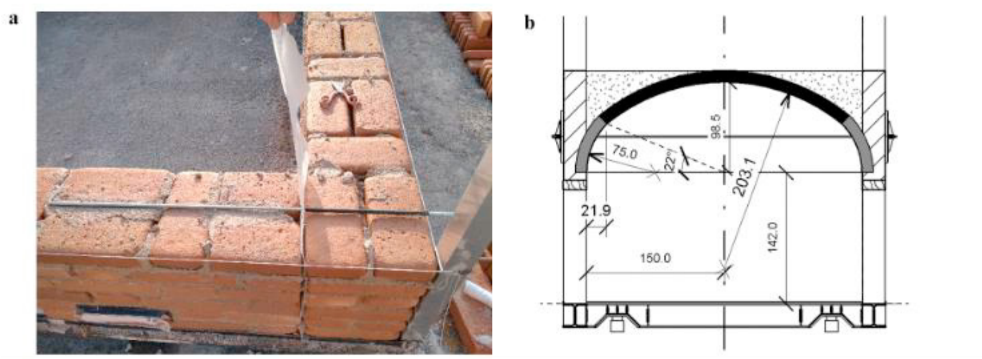

Fig. 3. (a) Particular of connections between wall A and C; (b) geometry of polycentric vault. Distances are measured in cm.

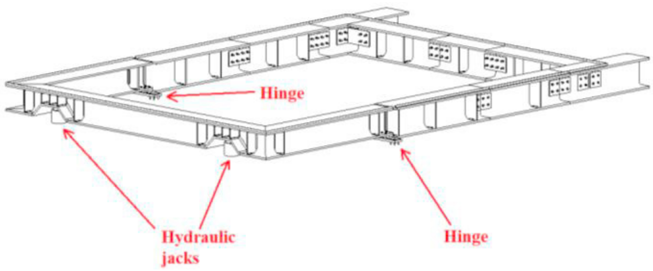

Fig. 4. Steel foundation and settlement's system.

Table 1. Average values and coefficient of variation of bending and compression strength of mortar.

	Average (MPa)	C.o.V. (%)
$f_{b,c//}$	27.8	12.4
$f_{b,c\perp}$	22.4	13.3
$f_{m,fl}$	1.26	2.3
$f_{m,c}$	2.82	3.2

gage length, while stresses were obtained dividing the applied force by area of the cross-section of the wall. Furthermore, diagonal compression tests were carried out on two double-wythe walls with dimensions 129 cm x 129 cm x 25 cm. On these specimens 1 vertical linear transducer and 1 horizontal transducer were installed on both faces (Fig. 5b). Figure 6b shows the tangential stress versus angular strain diagrams obtained. Strains were calculated dividing the measured elongation/shortening by the gage length while shearing stresses are computed as $\tau = 1.05 \cdot F/A$, where F indicates the applied force and A the cross-section area of the specimen. Those tests allow the assessment of the average values (Table 2) of compressive (f_{wc}) and tensile (f_t) strengths of masonry, Young's modulus (E), Poisson's ratio (ν), diagonal shear strength (τ_{el}) and shear modulus (G).

4. Structural Health Monitoring of the building

4.1. Description of the SHM system

SHM refers to the process of a continuous assessment of the health conditions of a structural system, aiming at improving its integrity, by detecting potential manifestations of damage, before this may reach a critical state, possibly detrimental for structural safety. SHM involves sensors which are permanently attached to a structure to collect data over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features allow to determine the current state of system health.

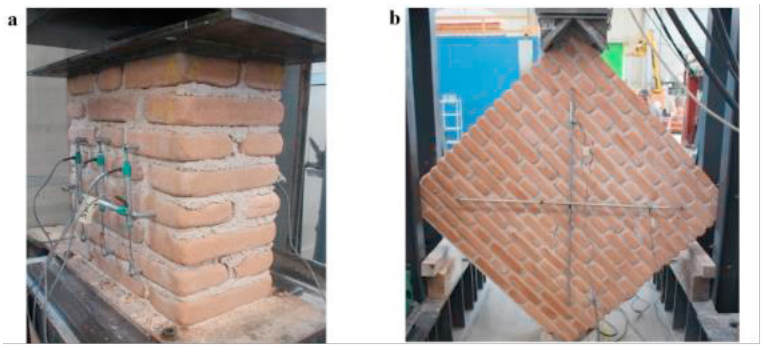

Fig. 5. (a) Compression test; (b) Diagonal compression test.

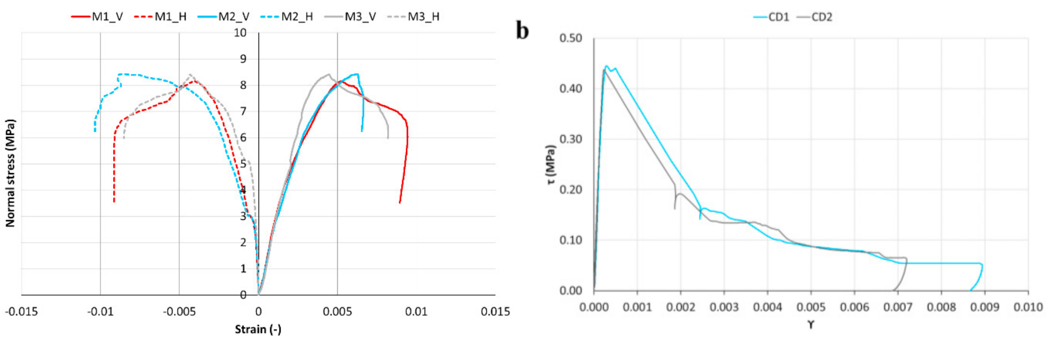

Fig. 6. (a) Normal stress versus horizontal (H) and vertical (V) strains; (b) Tangential stress versus angular strain

Table 2. Average values of masonry mechanical parameters.

f_{wc} (MPa)	E (MPa)	ν (-)	f_t (MPa)	τ_{el} (MPa)	G (MPa)
8.33	2976	0.34	0.21	0.44	2493

The building is equipped with a hybrid SHM system managed by the University of Perugia, which is based on the acquisition and processing of both vibration and strain measurements. In particular, the permanent vibration-based SHM system consists of six seismic accelerometers, model PCB 393B12, deployed on Façade A at the first floor level (h=237cm from the ground) and roof slab (h=419cm from the ground) by means of steel plates anchored to the masonry. Fig. 7 shows the position of accelerometers in plan. Sensors are connected to a CompactDAQ ethernet chassis, model NI cDAQ-9188, mounting three data acquisition modules NI-9234 (24-bit resolution, 102 dB dynamic range, and antialiasing filters), used to perform acceleration measurements every 10 minutes with a sampling frequency of 100 Hz. The duration of each acquisition is 10 minutes. A LabVIEW code automates the system also pushing acceleration measurements on a Network Attached Storage (NAS) connected to a remote PC, which analyzes data in real-time fashion through the MOVA/MOSS software (Macías et al., 2020).

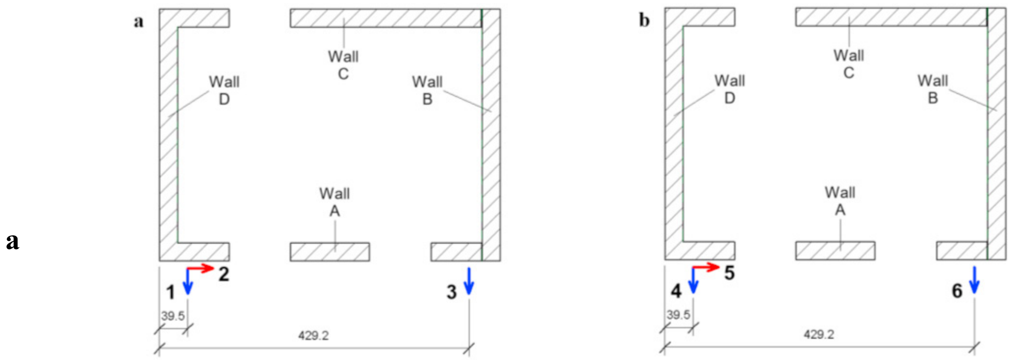

Fig. 7. Position of accelerometers in plan at level 0 (a) and level 1 (b). Distances are measured in cm.

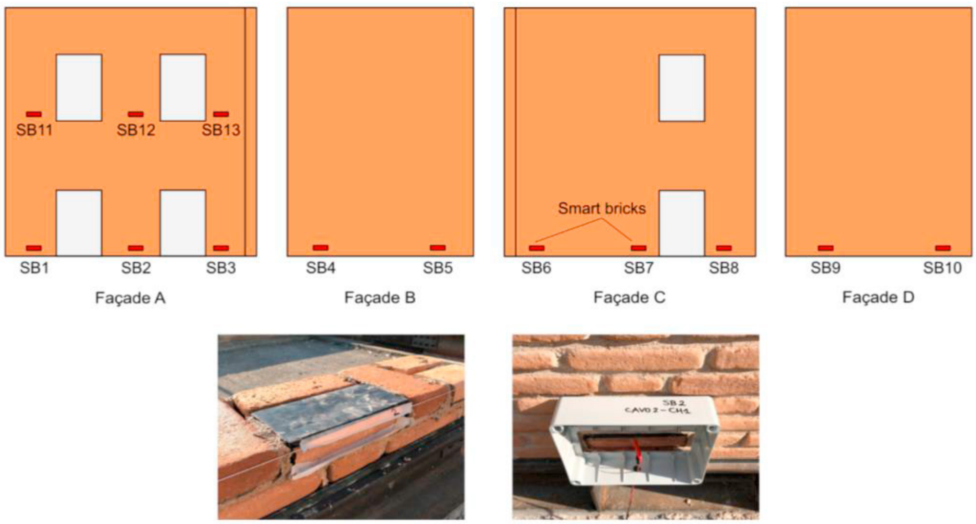

Fig. 8. Position of smart bricks in elevation.

The permanent strain-based SHM system consists of thirteen smart bricks, a novel class of self-sensing bricks developed by the research unit of Perugia (Meoni et al., 2019; 2021) and capable of providing strain measurements through the processing of their electrical outputs by means of a tailored electromechanical model (Meoni et al., 2020). Smart bricks were fully integrated within the masonry during the construction phase of the specimen building by following the deployment scheme depicted in Fig. 8. A recently developed multi-channel measurement technique (Meoni et al., 2020) is used for performing simultaneous electrical measurements from the sensors every 10 minutes with a sampling frequency of 10 Hz and for retrieving strain measurements through the real-time processing of the acquired electrical outputs. Even this monitoring system is connected to the NAS by allowing the further processing of the data from smart bricks via the MOVA/MOSS software. Temperature and relative humidity measurements are also carried out through specific sensors installed on the specimen building. Finally, inside the building, at the tie level, there is a probe measuring temperature and relative humidity. Two couples of 6-mm strain gauges are installed on each tie, measuring strains every 10 minutes.

5. Blind prediction contest

In order to tests the damage identification capabilities of the SHM system and the reliability of different types of numerical models, a blind prediction contest has been launched. The following types of damage or variation of the structural system will be induced in the building:

- variations of the quality of connection between walls A-C and B (Fig. 2);
- variation of the stiffness of the roof floor, through the application of a second layer of timber planks;
- partial release of one or more steel ties;
- simulated settlement of wall D;
- removal of part of the mortar in the horizontal joints of some masonry piers.

Modal features and different damage parameters will be estimated during the tests. Researchers are invited to predict the variations in modal frequencies and shapes induced by damage, average strains and displacement in some points of the structure, and damage patterns in the masonry elements. Further details on the blind prediction contest can be found on the site “https://eventi.unibo.it/detectaging”.

6. Conclusions

This paper has presented the main features of the model building constructed within the DETECT-AGING project, which is being used to investigate the ability of SHM systems to detect non-seismic damage due to degradation, ageing and soil settlements. The paper presented the main features of the construction and the adopted SHM system employing conventional accelerometers and innovative strain-sensing bricks. Before the end of the project, different tests will be carried out on the building by implementing artificial degradation, stiffness variations and soil settlements. The results of the tests will be used to evaluate the accuracy of the predictions of numerical models through a blind prediction contest. Specifically, researchers are invited to predict the variations in terms of modal frequencies and shapes produced by the different forms of damage.

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