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EXPERIMENTAL TESTING OF TWO NOVEL STRESS SENSORS FOR SHM OF MASONRY STRUCTURES

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Keywords: Structural health monitoring; unreinforced masonry walls; piezoelectric stress sensors; capacitive stress sensors; experimental testing.

Abstract. *The paper presents an experimental study on the performance of two types of stress sensor for their possible use in structural health monitoring (SHM) of masonry constructions. Ceramic piezoelectric sensors and capacitive sensors were installed in mortar bed-joints of two series of masonry specimens made of calcarenite stones and clay bricks. The specimens were tested under uniaxial compression, assessing the effectiveness of the sensors in recording the stress state variation in terms of vertical stresses within different types of masonry. Experimental results show that, although both the ceramic and capacitive sensors were initially designed to be embedded in concrete elements, their application in mortar joints ensures a good agreement with records by standard measurement devices. Results also demonstrate the possibility to extend the application of these devices to existing masonry structures, where SHM becomes a challenging issue.*

1 INTRODUCTION

Recent natural disasters and aging-related damage of structural elements and materials have pointed out that an adequate diagnostic system is required to detect relevant changes in structural behavior that can potentially affect safety of a structure [1-3]. A permanent monitoring system can be useful to reveal damage and its propagation, supporting decision-making to keep safety levels above prescribed thresholds. The idea of monitoring new and existing structures, if applied over a large territorial scale, can produce significant advantages [4-6] in controlling safety of strategic and residential buildings, which many times have masonry primary structures, especially in historic cities. In last years, the evolution of low-cost sensors derived from telecommunication industry, the development of high-speed Internet communication, the advent of cloud-based computing and of big data platforms making use of artificial intelligence, provided a new enhanced scenario for structural health monitoring (SHM). This kind of monitoring has been implemented using different devices, such as contactless sensors with high-resolution cameras, drones and contact robotic sensors [7]. Sensing technology is largely employed in the field of automotive and aerospace engineering. On the contrary, SHM has been rarely applied in structural and infrastructure engineering for a long time, because of the instrumentation costs, uncertain possibility to ensure long-term monitoring, complexity of the installation, and sometimes a difficult interpretation of results.

Recently, special attention has been paid to new-generation low-cost sensors, based on Micro Electro-Mechanical Systems (MEMS) technology. These sensors work with micro-movements of micrometric mechanical systems that are electronically read. MEMS include inclinometers, accelerometers and magnetometers. Inclination and vibration measurements are used to support the condition-based safety assessment of structures and infrastructure. Besides MEMS technology, new stress sensors based on piezoresistive or capacitive technologies delineate an emerging category of monitoring devices. Piezoresistive stress sensors with ceramic sensing package have been already used imbedded in concrete structures, while capacitive stress sensors are available only as prototype and are still under test. The state of the art enhances the optimization of the sensors' layout for health monitoring of new structures by incorporating a sensor network that has been already designed [8]. Both the sensors are thought to be used in new and existing structures although with different modalities of installation.

The current paper presents two innovative monitoring devices [9] which are tested for their possible implementation within unreinforced masonry structures. The proposed devices are piezoresistive and capacitive, low-cost, stress sensors. Capacitive sensors provide a sensing ceramic package working with the deformation of piezoresistive elements arranged on the ceramic plate. Capacitive sensor consists of two conductive plates with a thin dielectric foil between them. The capacitance, measured in picofarads (pF), changes with the variation of distance between the plates subject to vertical strains. The experimental program has been carried out on calcarenite and clay brick masonry wall specimens was addressed to test the capacity of the sensors to reveal strain variations. Data recorded by the sensors have been compared to those provided by a standard (reference) measuring device.

2 PROPOSED CERAMIC AND CAPACITVE SENSORS

The ceramic sensors tested in the experimental campaign include embedded electronic circuits as shown in Figure 1a, which are based on a microcontroller with embedded memory flash to read the low electrical signal of piezoresistive bridges and to convert the electrical signal into a digital value. Since ceramic is a perfectly elastic material, a direct calculation of the stress in a given direction is possible in the field of the elastic service stresses without any direct measure of deformation. The sensor was initially designed to be embedded inside concrete casting tied to the rebars. Its application within concrete structures under short-term loading is discussed in [10-12]. In a second experimental campaign the sensor was tested under long-term loading [13]. The effectiveness of these sensors to be employed within masonry mortar joints is explored in the current paper, providing also details about installation modalities.

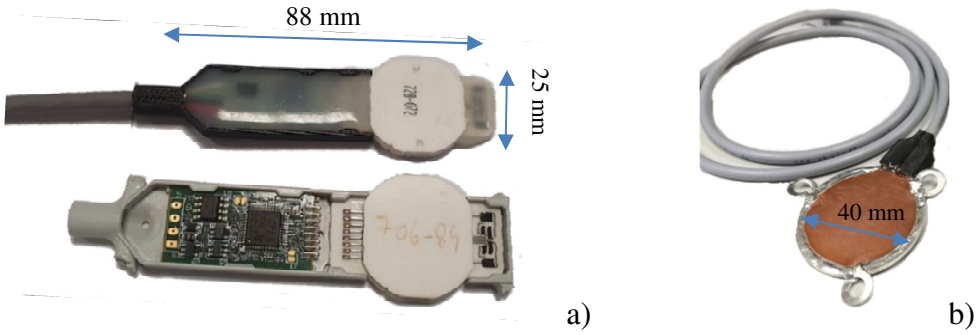


Figure 1: The proposes stress sensor: a) ceramic; b) capacitive.

A new capacitive stress sensor [14] is also proposed and tested in the paper for the same purposes. The capacitive sensor here discussed (Fig. 1b) consists of a parallel-plate capacitor with Kapton as a dielectric layer and, in this case, the sensing area is the plate surface. It is noteworthy observing that, the sensing surface can be realized as big as needed to be comparable with the dimensions of the wall. The capacitance, C, of a parallel plate capacitor is given by the following expression:

$$C = \frac{\varepsilon A}{d} \tag{1}$$

where ε, A and d are the permittivity of the gap, the area of electrodes, and the gap between the electrodes, respectively. The dielectric used in the sensor is the Kapton, which has a dielectric constant value ε_r = 3.4. The variation of the capacitance is related to the variation in strain according to the variation of the distance between the electrode plates. The sensor reader is a signal conditioning electronics which converts the capacitance signal to voltage, current or frequency. The reader used for capacitive sensors makes use of a microcontroller and it is located outside the sensing part. Capacitive sensors offer different advantages including high sensitivity, high stability, low temperature sensitivity, low production costs and durability.

3 EXPERIMENTAL TESTING OF SENSORS IN MASONRY WALLS

The experimental program consisted of twelve specimens. Six of them were made of calcarenite bricks extracted from Sabucina quarry (Southern Italy). The other six specimens were made of solid clay bricks. Calcarenite and clay bricks had bricks had the same size of 250×120×50 mm^3. The compressive strength the bricks was also experimentally obtained by compressive tests carried out according to UNI EN 1926 [15] and UNI EN 772 [16], respectively. In detail compressive tests were carried out on six cubes of calcarenite and six cubes of clay with side of 100 and 50 mm, respectively. The average compressive strengths obtained from the tests were 11.80 MPa and 23.39 MPa for calcarenite stones and clay bricks, respectively. All specimens were fabricated with a premixed cementitious mortar an average compressive strength of 8.36 MPa. Each specimen was made by seven rows of clay or calcarenite units (250×120×50 mm^3) and interposed mortar joints having a thickness of 10 mm.

Capacitive and ceramic sensors were pre-installed within the specimens during their construction according to three patterns shown in Figure 2, which are also summarized in Table. 1.

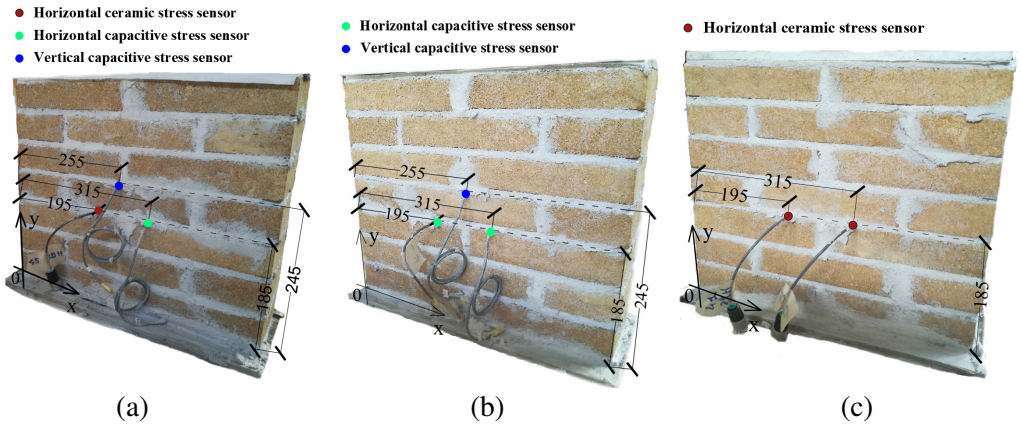


Figure 2: Monitoring patterns (dimensions in mm): (a) two horizontal and one vertical capacitive sensors; (b) two horizontal stress sensors (one ceramic and one capacitive) and one additional vertical capacitive sensor; (c) two horizontal ceramic sensors.

Table 1: Specimens and sensors setups.

ID sample	Masonry type	Sensors Set-up
SP1_C	Calcarenite	2 horizontal capacitive stress sensors
SP2_C		
SP3_C		1 horizontal capacitive stress sensor + 1 horizontal ceramic stress sensor
SP4_C		
SP5_C		2 horizontal ceramic stress sensors
SP6_C		
SP1_L	Clay	2 horizontal capacitive stress sensors
SP2_L		
SP3_L		1 horizontal capacitive stress sensor + 1 horizontal ceramic stress sensor
SP4_L		
SP5_L		2 horizontal ceramic stress sensors
SP6_L		

In detail, sensors were installed in the mortar bed joints close to the mid-height of each specimen (Figure 2). The three different measuring patterns provided: two capacitive stress sensors in SP1 and SP2 specimens; two ceramic stress sensors in SP5 and SP6 specimens; one ceramic and one capacitive stress sensor in SP3 and SP4 specimens. Capacitive sensors were also installed in vertical joints but the results from these sensors will not be commented in this paper.

Figure 3 shows the positioning phases of ceramic and capacitive sensors within the mortar joints. This phase was crucial as it was necessary to place sensors avoiding any type of rotation and translation.



(a) (b)

Figure 3. Installation of the sensors in the mortar bed-joints: (a) ceramic sensors; (b) capacitive sensors.

The masonry wall specimens so arranged were subjected to compressive loads, recording the response of the monitoring system to the stress state variation in the masonry. Load data acquisition was performed by means of an integrated load cell. Two initial pre-loading cycles were carried out in the range 20 - 100 kN to achieve adequate contact between the specimen and machine and also to observe the capacity of the sensors in recognizing also cyclic stress variations.

4 EXPERIMENTAL RESULTS

4.1 Results by ceramic sensors

For the sake of space, a reduced number of results are presented in the paper. Figures 4a and 4b show the experimental results for calcarenite and clay brick masonry specimens equipped with ceramic stress sensors (specimens SP5_C, SP6_L). Results are compared in terms of stresses vs. the acquisition time. Both the sensors and the machine load cell recorded one data per second, so the two data sets are overlapped in the same diagram. The comparison between sensors readings and the reference stresses evaluated by the load cell have shown quite good matching both in the preloading phase and in the monotonic load phase up to the peak stress.

However, moderate discrepancies were also revealed, for instance, sensors placed in specimen SP5_C seem to measure lower stresses with respect to those actually occurring. This was manly observed in correspondence of the lower load levels (before 1000 sec). Better accordance was found for specimen SP6_C and bricks masonry.

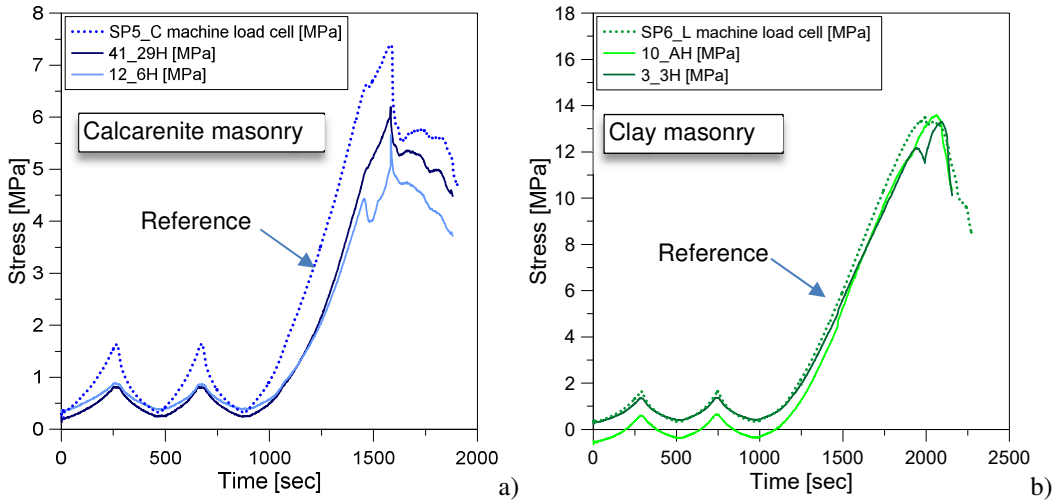


Figure 4: Comparison between ceramic stress sensor results and load cell data: a) calcarenite masonry; b) clay masonry.

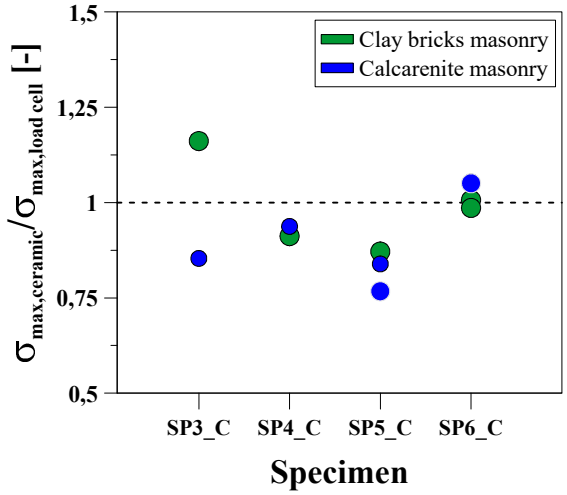


Figure 5: Comparison between reference compressive strengths and maximum stresses recorded by ceramic stress sensors for calcarenite and clay brick masonry specimens.

In Table 2 the values of the maximum compressive strengths provided by the ceramic stress sensors ($\sigma_{max,ceramic}$) are also shown and compared to those recorded by the machine load cell ($\sigma_{max,load\ cell}$) for all the specimens (not only those shown Figure 4).
Figure 5 summarizes the ratios between compressive strength recorded by ceramic stress sensors ($\sigma_{max,ceramic}$) and reference compressive strength ($\sigma_{max,load\ cell}$), highlighting a limited scattering of results with an average underestimation of 15% and 7.7% and an average overestimation of 5% and 8.4% for calcarenite and brick masonry specimens, respectively.

Table 2: Compressive strengths of specimens by ceramic sensors and load cell.

Specimen	$\sigma_{max,load\ cell}$ (MPa)	$\sigma_{max,\ load\ cell}$ Avg. / STD (MPa)	$\sigma_{max,ceramic}$ (MPa)	$\sigma_{max,\ ceramic}$ Avg. / STD (MPa)
SP3_C	6.96	7.01 / 0.37	5.94	6.38 / 1.32
SP4_C	7.19		6.74	
SP5_C	7.39		6.20 5.67	
SP6_C	6.52		6.87 6.85	
SP3_L	12.46	13.8 / 0.51	14.47	13.48 / 0.74
SP4_L	13.62		12.42	
SP5_L	15.63		13.62 *	
SP6_L	13.50		13.59	

*data considered unrealistic.

4.2 Results by capacitive sensors

For the sake of space, a reduced number of test results are presented in the following. Figures 6a and 6b show results for calcarenite and clay brick masonry respectively, equipped with capacitive stress sensors (SP1_C, SP2_C, SP1_L, SP2_L). In Fig. 6, experimental data by sensors are plotted against two vertical axes, that is the axis of vertical stresses, referred to data recorded by the testing machine load cell and the axis of capacitance, referred to data recorded by capacitive stress sensors. The sampling frequency of data by capacitive sensors was 2 Hz, that is two times that of the testing machine. To ensure the consistency of the two measurements, capacitive sensors data are represented as one per second. Results from capacitive stress sensors showed a stepped trend. This is related to the resolution limit of the acquisition system. Despite measures by the sensors are referred to capacitance values, it should observed that the global trend was correctly interpreted. This can be observed comparing stresses and capacitance trends in the two pre-load cycles, the ascending loading branch and peak. In some cases, the sensors were also able to record the post-peak behaviour.

To date, results of measurements by capacitive stress sensors and stresses recorded by the load cell cannot be compared since, these sensors are still in a prototyping status and a reliable transformation function from capacitance to stress has not been yet defined. Because of the same reason, experimental capacitance plots start from different values, in fact, the capacity of each device at zero deformation is different as the prototypes are hand-assembled. In some cases, the sensors also followed the load history with different slopes. This occurs because, as expressed by Eq. (1), the relationship between the capacitance and the electrode distance is nonlinear, implying that, for Δd intervals the corresponding capacitance range ΔC varies in a significant way.

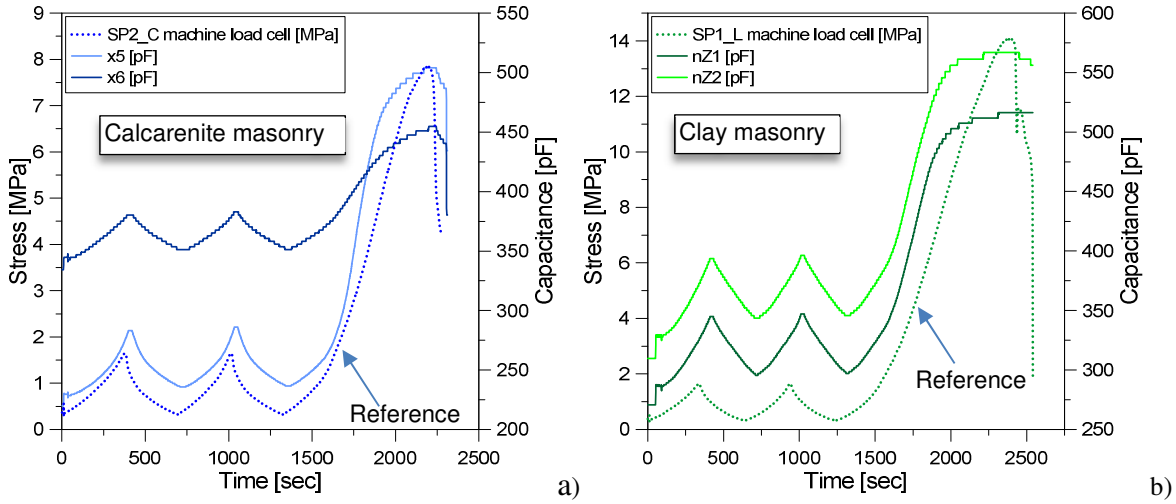


Figure 6: Comparison between capacitive stress sensor results and load cell data: a) calcarenite masonry; b) clay masonry.

5 CONCLUSIONS

The paper presented the results of an experimental program aimed at testing two novel stress sensors embedded in masonry for their possible implementation in structural health monitoring. Two types of sensor were evaluated, namely, a piezoelectric (ceramic) sensor and a capacitive sensor. Those monitoring devices were initially designed to be embedded in reinforced concrete structural elements, so the aim of the paper was to assess their effectiveness for structural health monitoring of masonry structures.

Experimental tests were carried out on twelve masonry specimens. Six of those specimens were made of calcarenite brick masonry, the others of clay brick masonry. The specimens were tested in simple compression after cyclic pre-loading phase. Peak strength varied from 6.52 to 8.21 MPa and 12.46 to 15.63 MPa, for calcarenite and clay brick masonries, respectively.

Results have highlighted that ceramic stress sensors have shown very good agreement with the stresses recorded by the load cell. Comparisons in terms of average peak stress evidenced a good accuracy, showing an underestimation of 10% in the case of calcarenite stone masonry and only 3% in the case of clay brick masonry. Moreover, standard deviations by sensor readings were lower than 1 MPa, also showing a limited dispersion despite the uncertainties related to the heterogeneity of masonry and potential local shortcomings of installation. Therefore, experimental results confirmed the suitability of ceramic sensors to be installed in masonry structures, without any need for additional calibrations with respect to that performed for the same sensors applied to concrete structures.

As regards capacitive sensors, since their calibration is still ongoing, results were compared in a more qualitative way. Sensor readings in terms of capacitance showed more pronounced correlation with recorded stresses up to a threshold of 9 MPa. After, a highly nonlinear relationship was observed, demonstrating that a full characterization is needed to define a robust analytical stress-capacitance relationship. It should be also noted that such a nonlinear

relationship between capacitance and electrode distance is not necessarily a weakness, but a possible starting point to take into account when realizing a family of sensors with different load working ranges as a function of potential different applications. Finally, it is noteworthy observing that the tests here presented were carried out up to the achievement of the peak loads of masonry. However, the application of the stress sensors for SHM is generally related to serviceability load conditions. In this context, the better results obtained for the lower stress ranges indicate a promising SHM tool. Both ceramic and capacitive sensors showed a positive response, demonstrating their ability to be regularly implemented in SHM of new masonry structures and potentially also existing masonry structures.

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