IWSS2020
1st Italian Workshop on Shell and Spatial Structures
25th – 26th June 2020 – WEB MEETING
endorsed by

Permanent monitoring of thin structures with low-cost devices

Donato ABRUZZESE, *Andrea MICHELETTI, Alessandro TIERO, Sreymom VUTH

Department of Civil and Computer Sciences Engineering, University of Rome Tor Vergata, Rome, Italy (abruzzese@uniroma2.it, micheletti@ing.uniroma2.it, tiero@uniroma2.it, sreymom.vuth@hotmail.com)

Abstract

Recently, structural monitoring technology invested in methodologies that give direct information on structures' stress state. Optic fiber, strain guages, pressure cells give real-time data on the stress condition of a structural element, often determining the area where peak stresses have been reached. In addition, stresses can be recorded in a data log for "post-event" analysis, as well as for taking into account the lifelong stress state of the structure.

Beams and columns of a reinforced concrete frame can be effectively monitored for flexural loads. Differently, thin shells are most of the time under membrane regime, and, when properly designed, they rarely move to the bending regime.

Our proposal is to monitor the stress in thin structures by small-sized low-cost devices able to record the stress history at key locations, sending alerts when necessary, with the aim of ensuring safety against the risk of collapse, or simply to perform maintenance/repairing activities. The application examples are given as laboratory tests performed on a reinforced concrete plate, a masonry panel, and a steel beam. Results shows that the permanent monitoring control of stresses can be conveniently carried out on new structures using low-cost devices of the type we designed and realized in-house.

Keywords: structural health monitoring, new constructions, permanent monitoring, stress measurement, low-cost sensors

1. Introduction

The monitoring of structures has been always a demand more than a suggestion of structural designers, even though the owners are often afraid about the installation cost of expensive devices with a not completely clear and reliable efficiency. Indeed, construction experts and builders would much like to have a continuous real-time picture of the structure's conditions, and if a reliable structural health control system could be available, they would use it. There are at least two motivations which brought people to refrain from installing complicated electronics devices on a structure. One is the belief that structural 'damages' are not so menacing and impending on our life; the other one is the difficulty to understand the real 'daily' advantages of such an electronic system, which could be embedded and hidden in our steel or reinforced concrete homes, hospitals, factories, theatres, commercial centres, etc.

In fact, a permanent monitoring system would provide an up-to-date information on the condition of the structure, like the one we get from our car dashboard every day, and in the same way could send an alert in case of problem, whether the situation is critical or not, suggesting us what part of the structure is suffering. It is the same approach followed in the design of the car sensors and checking system that put us in the safest possible driving condition. Monitoring of structures, or *structural health monitoring* (SHM), has followed the development of modern electronics, trying to take advantage of its typical positive aspects: *miniaturization* of components, which allows for the use of sensors and devices embedded in the structure or with negligible size; *communication* via different platforms, such as WiFi, Bluetooth, high frequency radio; *large dissemination* of more friendly electronic components which do not require, in most cases, a strong experience as electronic enginee.

If at the beginning the Internet of the Things (IoT) has been used as simple additional experimental system, at present the use of multiple electronic devices allows one to design the monitoring system with specific requests, according to the typology of the structure or the individual structure element, the construction material, the stress to investigate, the static or dynamic behavior, the interval time for the registration, and, finally, the communication architecture to send the remote information to the central control point [1,2,7,8]. Despite the large number of the possible variables to be considered for a suitable and reliable structural control system, we can now state that the civil engineer, or structural designer, is enabled to be responsible of the design correct SHM architectures, requiring consultancy from the electronic engineer only for limited needs. Definitely, the architecture of the monitoring system cannot be designed by electronic engineers only, since the monitoring system is related to the type of stress, location, duration, and frequency acquisition of the data. Unltimately, it is clear that the interpretation of the data, once collected in a suitable way, is a duty of the structural engineer. This is also very important, since requires a high knowledge about structures, loads, material, restraints. A good list of statement, rules and referring values (i.e. yield point of the material) will make the structural control much more efficient. Of course the IoT electronic devices could be selected and the entire architecture could be optimized by the electronic engineers, but it is strongly suggested, if not unavoidable, that the engineers cooperate together.

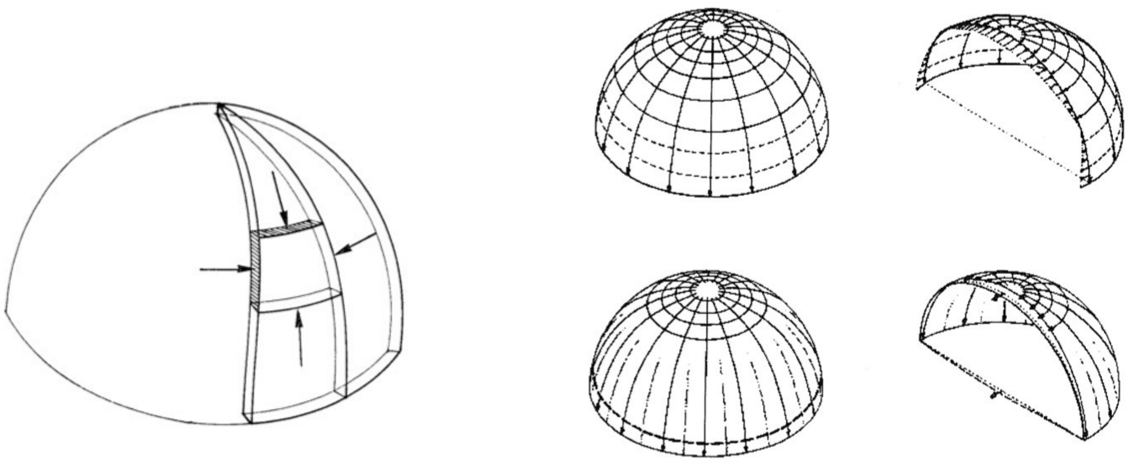
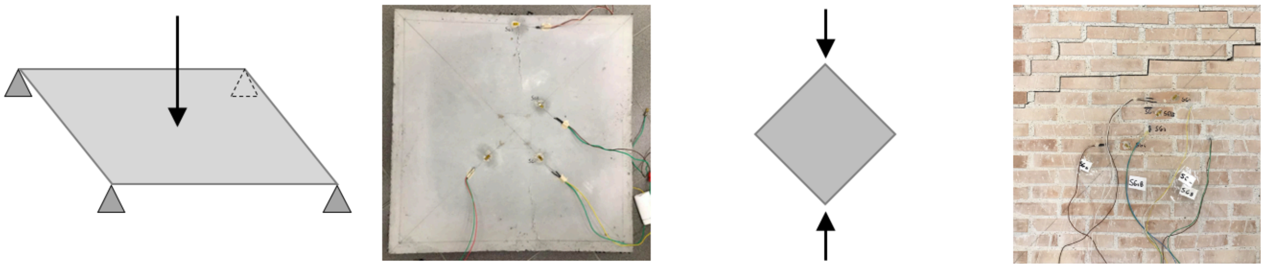


Figure 1 – The typical σ_φ and σ_θ membrane stress in a shell.(left). Stress in a masonry vault (right) [6]

Monitoring bidimensional structures is a very interesting and challenging goal for engineers. The possibility to control current stresses instantaneously, as well as accumulated stresses, for a long time, can give to the structural engineer the feeling of a permanent knowledge of the structure. We know that sometimes complicated or irregular shapes of thin shells are difficult to model, since the presence of the double curvature, for instance, implies a strict but not clear relation between the two stress directions (Fig.1). To have a permanent knowledge of the local stress in some peculiar point of the structure allows comparing the theoretical and numerical results with the real ones expressed by the structure under loads. The continuous control of the stress, connected also to different load cases, produces an amount of information useful to adjust the relevant parameter included inside the numerical simulation, like Young elastic modulus or behavior of the restraints, and it results in a more reliable model of the reality.

In this work the application examples are given as laboratory tests performed on: a steel beam (three-point bending test), a reinforced concrete plate (bending test, Fig 2, a, b), and a masonry panel (diagonal compression test, Fig 2, c, d). Results shows that a permanent monitoring control of stresses can be conveniently carried out on new structures using low-cost devices of the type we designed and realized in-house. In the next section, the experimental setup of each of the test is described, together with the components layout of the low-cost wireless sensing device proposed. Section 3, illustrates the results of the tests, while in Section 4 the maintenance and safety advantages of permanent monitoring are discussed. Our conclusions follows in the last section.



(a) (b) (c) (d)

Figure 2: Five-point out-of-plane bending test (a) on an instrumented FRP concrete plate brought to fracture (b). In-plane diagonal compression test (c) on an instrumented masonry panel brought to fracture (d).

2. Experimental testing of low-cost devices

The development of a suitable and affordable family of devices connected to the IoT for monitoring structures led us to design and realize sensors which should meet standard technical requirements and a satisfactory level of precisión and reliability. Then the sensors and the connected control device have been tested in laboratory, making performance comparisons with more conventional lab instrument, traditionally adopted for reading strain-gauge measurements. The comparative machine available in the Department of Civil and Computer Sciences Engineering at University of Rome Tor Vergata is a MGC MagicPlus from HBM Italia equipped with Catman software. In all the following tests the MGC device has been considered as the reference point as the most advanced and reliable machine available for such measurements. The low-cost device the we present here, designed and realized in-house, is composed by a signal acquisition/conditioning system and a processing/communication system. The signal acquisition/conditioning system (Fig. 3, a) is composed by two strain gauges from HBM Italia and the associated Wheatstone bridges, signal amplificators, and analog-to-digital converters, all obtained from cheap off-the-shelf components. The processing/communication system (Fig.3, b) is composed by an Arduino Mega microcontroller (slave) and a ESP8266 Wi-Fi module (master). Figure 3(c) shows the web-browser graphic interface implemented on and broadcasted by the Wi-Fi module.

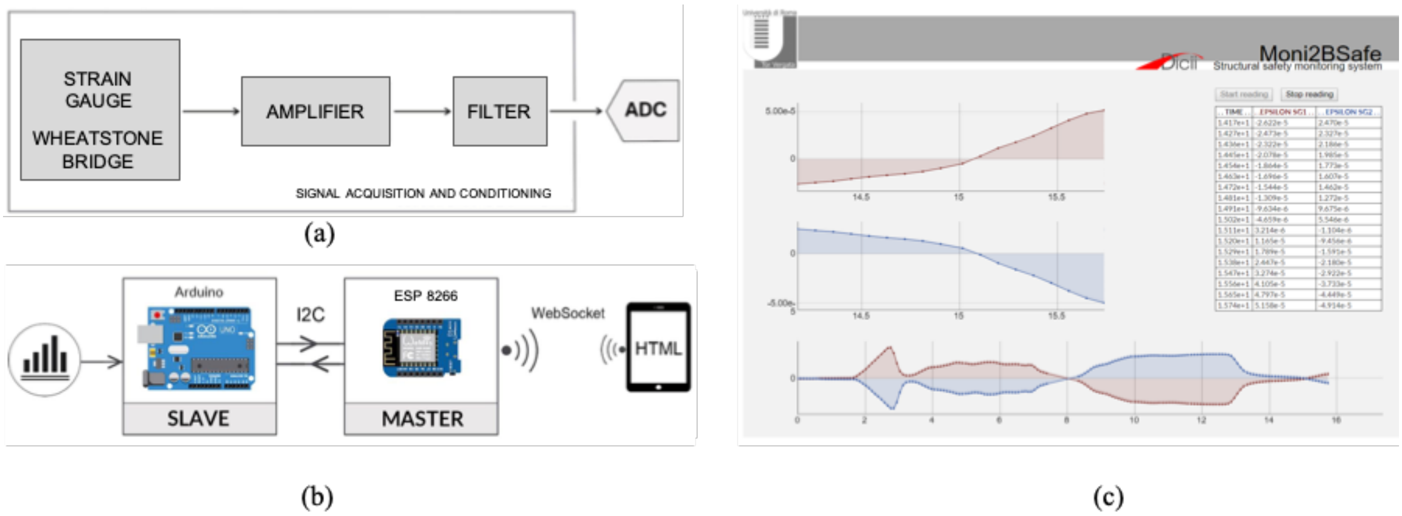
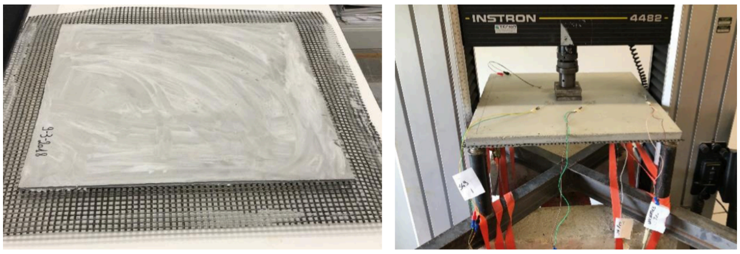


Figure 3: Low-cost device (a) Sensor layout. (b) Communication layout. (c) Web browser interface.

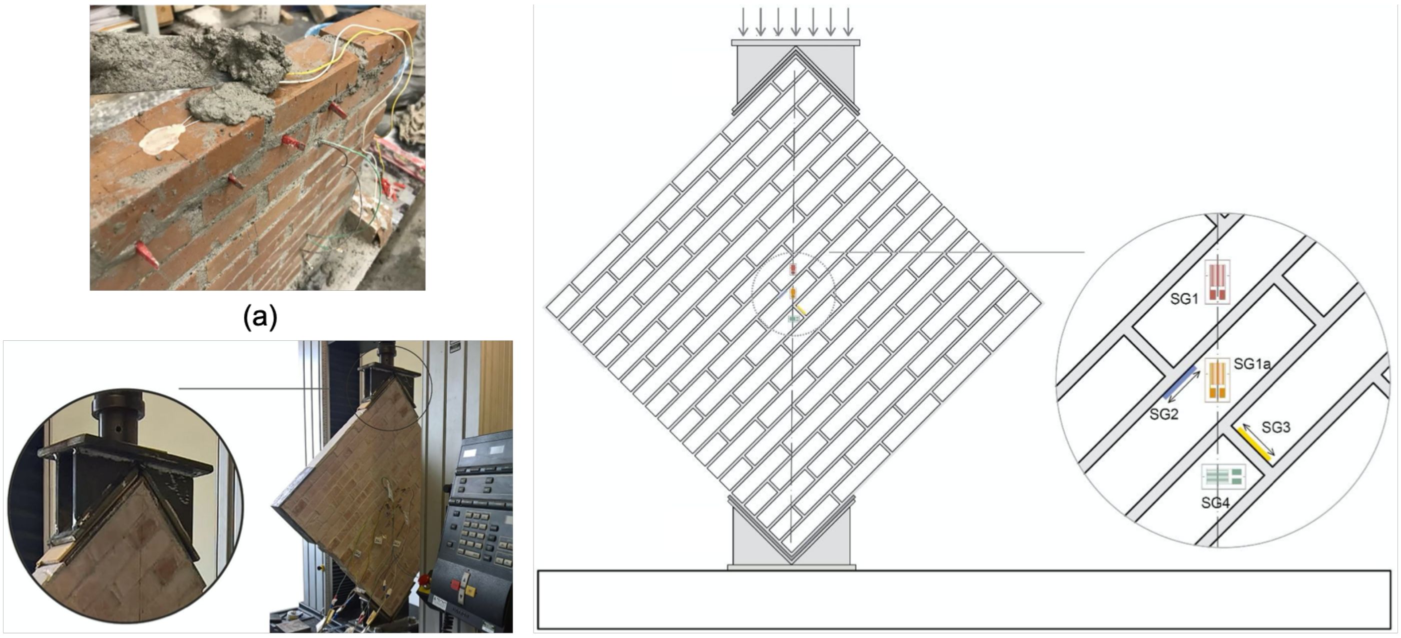
We present here three basic test setups. The first test is a standard three-point bending test carried out on a simply supported steel beam of 200cm span, and 4x1cm2 rectangular cross-section, with a pair of strain gauge positioned at 5/12 of the span. One strain gauge has been connected to the MGC and the other one to the low-cost device. Following a *soft-device* procedure, we hang at midspan certain weigths of increasing size and recorded the readings of the strain gauges at each loading step.

The second and third test have been carried out on square thin structural elements, after installation of the strain gauges at suitable positions. In both tests the load has been applied using an Instron 4482 testing machine. The second test regarded a thin square FRP concrete plate, shown in Fig. 4, supported at the corners and loaded orhtogonally to the mid plane (five-point bending test). The thin plate was cast in high performance concrete (40 MPa) and reinforced by a bidirectional carbon fiber net. Two strain gauges were positioned on the top surface of the plate along the diagonals, in simmetric positions so as to compare their measurements. The third test regarded a scaled-down brick masonry panel, shown in Fig. 5, tested in a shearing load case (diagonal compression test). The masonry panel did not have any reinforcement, in order to reproduce the behavior of actual masonry. Strain gauges were applied in the central region of the panel (Fig.3, c), with two of them applied on the top and side brick surface at the mortar joint (SG2 and SG3, see detail in Fig. 3, c). Two straig gauges (SG1 and SG1a in Fig.4) were positioned along the vertical on two adjacent central bricks. The SG1 and SG1a sensors are used for the performance comparison, and they were connected to the HBM MGC and to the low-cost device, respectively. In order to apply the load, angular steel reinforcements for stress redistribution were attached at two opposing corner of the panel, while two steel pieces of adequate stiffness, specially designed to fit such angular reinforcement, were attached to the testing machine (see detail in Fig.3 b).



(a) (b)

Figure 4: The realized FRP concrete square plate (a) and five-point bending test setup (b).



(a) (b) (c)

Figure 5: Realization (a) and diagonal test setup (b, c) of a reduced-scale masonry panel, together with sensors placement. The strain gauges SG1a and SG4 are read with the proposed low-cost system.

3. Results

The results of the three tests described in the preceeding section are presented in the following tables and figures, showing a satisfactory agreement between the low-cost and the laboratory measurement instruments.

Table 1 and the plot in Fig. 6 show the results of the three-point bending test on the simply supported steel beam. The difference in the measured strain values remains equal to or below 3% except for the first three loading steps, while the absolute difference is small for all the loading steps.

Load (N)	L-C device µm/m	MGCPLUS µm/m	% difference %	Nominal value µm/m
1.00	3.36	2.76	-18.0%	2.976
3.00	10.02	9.15	-8.7%	8.929
5.00	16.44	15.55	-5.4%	14.881
8.31	27.06	26.26	-3.0%	24.732
12.31	39.83	38.66	-2.9%	36.637
17.31	55.94	54.39	-2.8%	51.518
22.31	71.62	70.35	-1.8%	66.399
24.31	77.33	77.36	0.0%	72.351

Table 1: Comparison between the strain measurements of low-cost device and laboratory equipment on a simply supported steel beam.

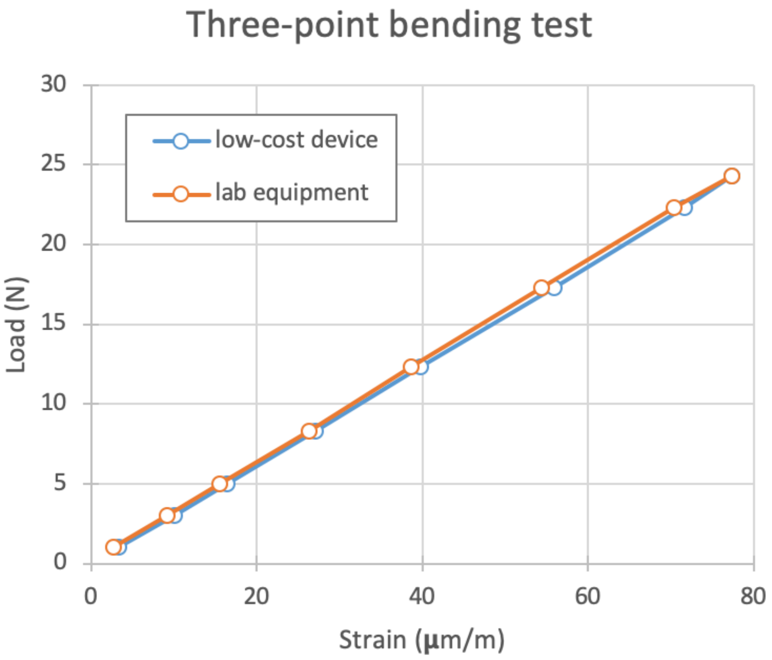
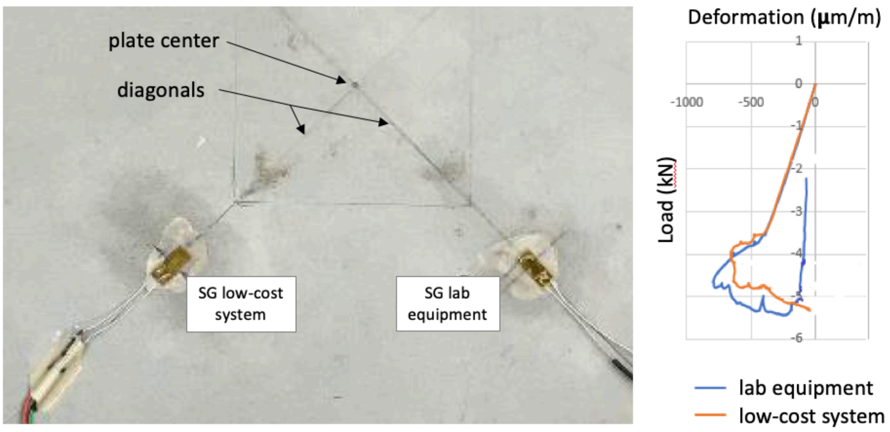


Figure 6: Comparison between the HBM MGC and low-cost device. Strain values for the simpy supported steel beam with an increasing load applied at mid span.

Figure 7 (a) shows the symmetric placement of the strain gauges on the FRP concrete plate of the second test, while Fig. 7 (b) reports the two corresponding load-vs-deformation plots recorded by the two measurement systems. One can observe that the two plots are almost superposed along linear portion.



(a) (b)

Figure 7: Results of the five-point bending test for the FR concrete plate: symmetric placement of strain gauges (a); comparison of load-vs-deformation plots (b). Measurements carried out with laboratory equipment, in blue (dark grey), and with the proposed low-cost device, in orange (light grey).

As to the results of third test, Fig. 8 reports the load-vs-deformation plots for the five strain gauges installed on the masonry panel, along with the load-vs-displacement plot for this test. In particular, the SG1 and SG1a curves, corresponding to the sensors located along the main diagonalof the panel and used in the performance comparison, remain close to each other, while the visible difference between the two can be ascribed to the non-symmetric placement of the sensors. It is also worth noticing that the low-cost system was also able to detect the two cracking event which occurred during the test.

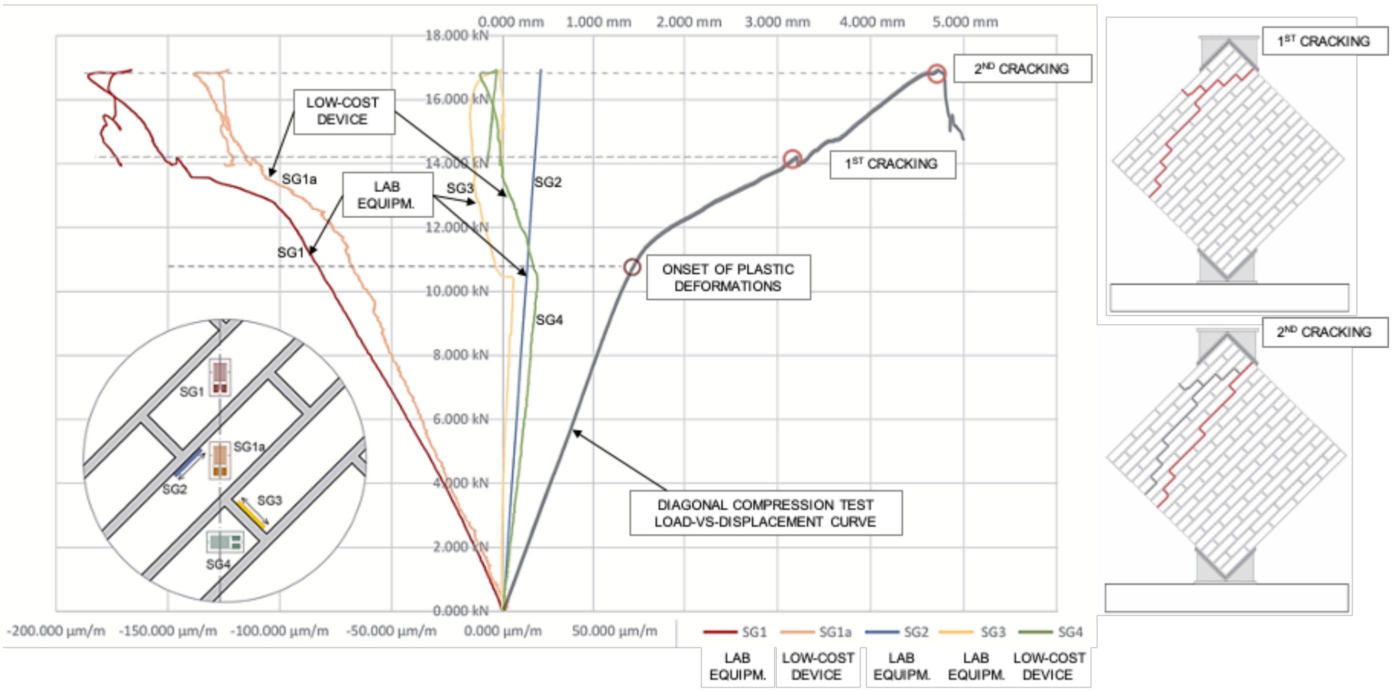


Figure 8: Results of the diagonal compression test of a reduced-scale masonry panel.

The experiments showed that there is a quite good agreement between the two system, a results which is promising for future research and applications. Moreover, the values of the measurements obtained with the low-cost device developed in-house as compared to the ones obtained with the HBM MGC reference lab equipment, show that there is an very limited error, taking into account in particular that the ratio between the costs of the two systems is of the order of 1/100.

4. Discussion: maintenance and safety advantages of lifelong monitoring

Our main goal is the installation of embedded deformation sensors inside concrete shells, for instance, but not far from the inner and external skin; in this way the membrane stresses can be recorded. But by using also new types of sensor in the middle of the thickness of the shell, able to measure the local curvature of the thin shell, such as the one shown in Fig. 9 (top), we could get the local bending moment. Moreover, by installing two sensors along two directions, we would be able to obtain the bending moment along these directions.

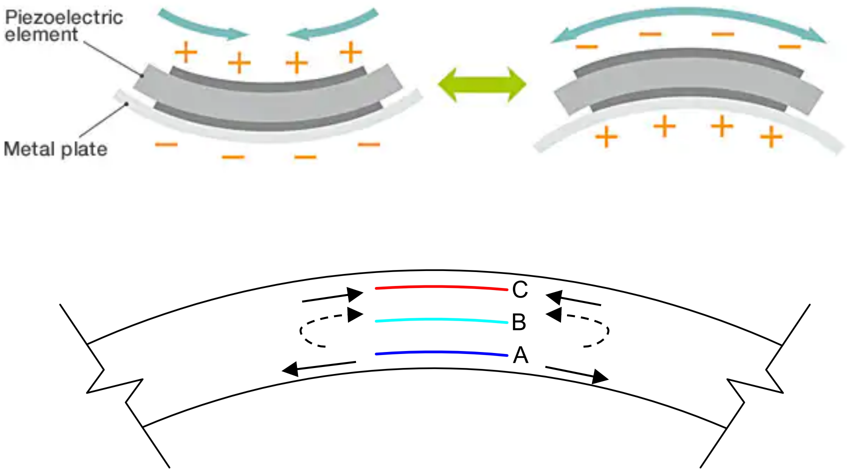


Figure 9: Top: piezo-actuator (PiezoHapt^{TM}, TDK courtesy). Bottom: cross section of concrete thin shell. A and C are deformation sensors measuring the local normal stress; B is a sensor measuring the local curvature the thin shell.

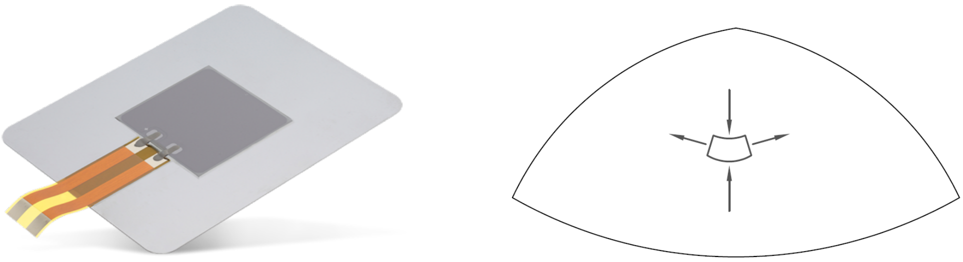


Fig. 10 – New thin piezo Haptic actuator (TDK courtesy) for flexural applications (left). Possible application point of the piezo-haptic actuator/sensor on a double curvature shell (right).

Compact actuators enlarge the sensory capabilities of SHM. The new piezo-actuators available nowadays [3,4,5] are based on multilayer piezo plates with cost-effective copper inner electrodes. When activated, the piezo plates expand only slightly along the z axis, but owing to the constant volume deformation in the piezoelectric effect, such plates contract simultaneously along both the x and y axes, providing information about membrane stress but also about flexural behavior of the structure.

Sensors like that belong to the family of the *piezoelectric haptic actuators* (figs.9-10). This kind of sensor can work as actuator as well as sensor. In the latter case they can inform us about deformation, which in this case could be the curvature. From the curvature we can recover the local moment, according to the geometry of the structural element. It is quite clear, at this point, what kind of monitoring information we could retrieve with this family of sensors. From the standard deformation sensor we can achieve the membrane stress, which should be the most important stress in a thin shell; from the piezo-haptic actuators we can get information about the additional, usually of small entity but very important, bending moment.

Fig. 11 – The TWA terminal in NewYork, by Eero Saarinen (1962).

Fig. 11 shows the famous TWA terminal in NewYork, by Eero Saarinen (1962). It is a marvelous example of a double curvature shell, quite difficult to analyze unless using finite element modeling, since simplified procedures and simulations could not be satisfactory. Then a good distribution of sensors as mentioned above could give local information on the shell stress and describe instantly but also permanently the real behavior of the structure. It is evident that real-time measurements could help even the structural designer to better calibrate the numerical finite element model, in order to make its predictions more reliable.

The large use of structural health monitoring systems achieve two main goals: improving maintenance, and increasing safety of the whole structural system. Today it is mandatory to install alerting devices on cars, instruments and other tools, in order to help preventing damage to people and goods. We are surrounded by green and red leds informing us about whether a situation is safe or not. We also often have some acoustic alarm to alert us about the danger. The question is, why we cannot use the same approach for structures, in steel or reinforced concrete, in order to improve the safety of our homes, offices, and service and entertainment buildings? And if for one second we want to forget about safety, what about maintenance? We know that if we buy a car, after several thousand kilometers we need to change the tires, and perform a small or large maintenance activity, with car technicians. This means to increase the safety, of course, but it also means that if we do not perform the maintenance activity at the right moment (when the green light becomes orange, for instance) we know that the damage will become bigger and the maintenance cost will increase. Therefore, the duty of a well-designed monitoring system is: to inform us about building structural health, about the structural elements to be more carefully checked, to suggest when the structure needs to be repaired and where, and finally to increase the global safety of the construction.

5. Conclusions

Among traditional, and often not feasible, structure's control techniques we can include the embedded electronic monitoring systems consisting mainly in deformation sensors which provide information about local stresses, also recordable as permanent information on the lifelong stress condition of the structure. A suitable structural monitoring system, a corresponding well dimensioned communication system and a stress database will definitely provide an increasing value of the construction, and a comfortable safety level. The cost of such devices and sensors and the related control panel are now really affordable and limited to about 1-2 % of the cost of the entire structure, according to our estimates.

In this work, we analyzed and demonstrated the application of a low-cost SHM system to a concrete thin plate and a masonry panel. Thin shells, and mostly concrete thin shells, are still a way for the architects to express the freedom of the architectural composition, resulting in eye-catching complex shapes. These are difficult to analyze with standard models, but require shape modeling software and taylored finite element structural codes. Needless to say, these considerations about SHM can be extended to other, different, types of structures adopting appropriate devices and control software.

Acknowledgements

The contribution to this work given by the students Manuel Cosentino, Damiano Forconi, Gian Marco Grizzi, Gianluca Scarano, Davide Bracale, Daniele Paradisi, during the preparation of their Bs/Ms Theses, is gratefully acknowledged.

The Authors wish to acknowledge the University of Rome Tor Vergata and the Department of Civil Engineering and Computer Sciences of the same university for partly supporting this research within the funding program "Mission Sustainability", project title "Structural safety monitoring system and structure-embedded event log system for new and existing buildings" (project id # E86C18000340005).

References

[1] D. Abruzzese, A. Micheletti, A. Tiero, M. Cosentino, D. Forconi, G. Grizzi, G. Scarano, S. Vuth, P. Abiuso, “IoT sensors for modern structural health monitoring. A new frontier”, *Procedia Structural Integrity*, vol. 25, pp. 378-385, 2020.

[2] H. S. Tzou, H.-J. Lee, S. M. Arnold, , "Smart Materials, Precision Sensors/Actuators, Smart Structures, and Structronic Systems", *Mechanics of Advanced Materials and Structures*, 11: 367–393, Taylor & Francis Inc ed., 2004

[3] Clinton Y. K. Chee, Liyong Tong, Grant P. Steven, “A Review on the Modelling of Piezoelectric Sensors and Actuators Incorporated in Intelligent Structures”, *Journal of Intelligent Material Systems and Structures,* Volume: 9 issue: 1, page(s): 3-19, January 1, 1998

[4] Q. Wang, N. Wu, “A review on structural enhancement and repair using piezoelectric materials and shape memory alloys”, *Smart Materials and Structures*, Vol.21, N.1, 2011

[5] D. Biqin, “Cement-based piezoelectric ceramic composites for sensor applications in civil engineering”, *PhD Thesis, University of Hong Kong of Science and Technology*, 2005

[6] F. Ottoni, “La lunga vicenda delle fabbriche cupolate. Note storiche sulla stabilità, tra dibattito e sperimentazione”, *PhD Thesis*, Università di Parma, 2008

[7] E. Panzardi, A.Pozzebon, V.Vignoli, T.Addabbo, A.Fort, M.Mugnaini, “A city-scale IoT architecture for monumental structures monitoring”, in *Measurement*, Volume 131, January 2019, Pages 349-357

[8] S. Nižetić, P. Šolićb, D. López-de-Ipiña, G. de-Artazac, L. Patrono, “Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future”, in *Journal of Cleaner Production*, Volume 274, 20 November 2020, 122877