Smart reinforcement steel bars embedded with low-cost MEMS sensors for strain monitoring

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ABSTRACT: Structural health monitoring (SHM) plays an increasingly important role in the condition assessment of civil engineering structures and infrastructures. Currently, the SHM of reinforced concrete constructions with embedded devices is mainly performed using electrical, optics or resonant chord extensometers. The difficulty of installation, the cost of the devices and the uncertainties in longterm robustness and reliability push for alternatives toward low cost devices which could be easy to install and use. In this paper, an innovative system is proposed consisting of reinforcement bars embedded with low cost MEMS which make them sensitive to axial strains. These steel bars replace the ordinary reinforcement combining both structural and monitoring functions. Experimental laboratory tests are performed on the single element under monotonic and cyclic load and results are discussed.

1 INTRODUCTION

Structural health monitoring (SHM), combining various sensing technologies with data acquisition and processing capabilities, plays an increasingly important role in the condition assessment of civil engineering structures and infrastructures (Spencer et al. 2017). Applied to both existing and new constructions, continuous on-line SHM increases the quality and safety of structures and reduces their maintenance cost (Farrar et al. 2007). On the one hand, monitoring the long-term degradation of aging structures allows for the adoption of optimal preventive policies and for the early detection of dangerous behaviors or incipient damages, so as to mitigate repair and down-time costs. On the other hand, observing the structural response after extreme events, such as earthquakes, hurricanes or fires, provides for a rapid and objective assessment of the structural integrity, imperative and urgent in those circumstances.

SHM is a fast-developing area in civil engineering. The innovation in the SHM technologies as well as the development of large-scale SHM systems have been a great subject of interest within the engineering and academic communities over the last two decades. The rapid aging of the existing structural and infrastructural asset in North America and Europe, the increasing use of complex and slender paradigms for the building of new constructions, and the limits of current non-destructive testing (NDT) techniques are the factors driving the growth of the global SHM market, which is expected to increase, according to recent surveys, from 700 M$ in 2015 to 3.400 M$ by 2022, at an average annual rate of 25%.

However, despite its great potential, SHM is still not applied in large scale and in a systematic manner to civil structures and infrastructures. One significant reason for this is the lack of reliable and affordable generic monitoring solutions (Glisic et al. 2013). But the major deterrent probably resides in the complexity and cost of monitoring large-scale constructions, which entails installing and interrogating large numbers of sensors as well as managing huge amounts of data. In this context, the advancement in sensor technologies, the spread of smart materials and structures, and the development of wireless communication platforms are the key opportunities for SHM growth, sketching out a future where every structure will be permanently, pervasively and (nearly-) automatically monitored since its construction.

Currently, various sensor types exist for SHM purposes, including electric strain sensors, fibre optic sensors (FOS), piezoelectric sensors, GNSS-based sensors, accelerometers, inclinometers, acoustic emissions and wave propagation devices, etc. Each of them has a preferable domain of use, as well as genuine challenges when deployed in real-world applications.

Focusing on the SHM of reinforced concrete (r.c.) structures and infrastructural systems, and aiming at improving the cost-effectiveness of existing sensing technologies, this paper presents a new concept of smart rebar, combining both structural and strain-sensing capabilities by virtue of the incorporation, in the core of the rebar, of an ordinary low-cost embedded MEMS sensor, currently available on the market but never used in this application field before. According to this concept, a cavity is produced in the reinforcing bar (rebar) and is equipped with a pressure and temperature MEMS sensor, so that the axial deformation of the rebar can be deduced by the volume variation of the cavity, on its turn reconstructed from the pressure and temperature variations. The new sensing system shows significant advantages over current strain-measurement devices, proving cheap, durable, easy to install, robust to mechanical shocks and chemical aggression, and requires simple interrogating equipment. This paper reports the theoretical framework of the new concept and the results of a preliminary test campaign.

2 DESCRIPTION OF THE MEASURING SYSTEM

2.1 Current r.c. strain sensing technologies

The basic idea of the proposed system is to use low-cost existing micro-sensing devices, commonly used to other purposes, to estimate the strain in r.c. structures, by exploiting in an original way the well-known physical laws of deformable continuum systems.

Strain monitoring of r.c. structures can be achieved by focusing on either the concrete matrix or the reinforcement steel rebars. Because of the intrinsic large scatter in the micro-mechanical properties of concrete, which depends on the peculiarities of the different mix components (aggregates, cement paste, voids and interface transition zones), and because of the influence of micro-crack and rheological phenomena at smaller scales, the concrete-oriented approach practically implies using either macro-sensors (having dimensions multiple of the nominal aggregate size) or small sensors mounted on macro skeletons. In both cases, the average strain along either the macro-sensor or the skeleton length is measured, and a perfect sensor/concrete adhesion is required. As a result, a steel-oriented approach aimed at strain measurement appears preferable. It is generally done by a direct measure of strain by means of a local transducer.

In current practice, such a transducer is either an electric strain gage glued on the longitudinal lug of the rebar (or rather two strain gages placed on the opposite sides of the rebar), or a FOS (e.g. a local Bragg grating type sensor or a distributed FOS) glued on the surface of the rebar or incorporated in a longitudinal groove drilled along the bar. In both cases, compensation of temperature effects is needed.

Critical stages for these devices are the sensor installation and the concrete casting. Both strain gages and FOS can be damaged during these stages, or even during in-service operation as a consequence of cracks formation or steel-to-concrete slip. The glueing agent itself can be compromised by chemical aggression, mechanical action or ageing. In the case of FOS, the protective encapsulation and/or packaging, needed to prevent standard glass fibres from contact with the alkalin environment of the concrete mixture, result in a difference between the strain of the concrete matrix and the strain sensed by the fiber (Quiertant et al. 2012). Moreover, the installation of distributed FOS requires specialized personnel, and the glueing process can be discouragingly time-demanding (Barrias et al. 2016).

2.2 *The new concept*

In this study, aiming to solve the aforementioned issues, the axial deformation of the rebar is measured by an appropriate MEMS sensor which, instead of being applied on the surface of the rebar, is embedded in a small cavity drilled in its core. The sensor measures both the pressure and the temperature of the fluid contained in the cavity. An elongation of the rebar results in a proportional variation of the volume of the cavity, which on its turn determines pressure and/or temperature variations in the cavity. By measuring the latter variations through the sensor, the volume variation can be computed by applying the appropriate thermodynamic state equation to the fluid contained in the cavity, and the axial elongation can be consequently deduced based on a previous calibration. As long as the fluid is air, the state equation can be accurately approximated by the ideal gas law as follows:

$$pV = nRT \tag{1}$$

where $p = p(t)$ is the absolute pressure within the cavity, $V = V(t)$ is the cavity volume, n is the number of moles of the fluid in the volume, R is the ideal gas constant, $T = T(t)$ is the absolute temperature within the cavity, and t is time. Because n and R are constant during the elongation, the volume deformation $\Delta V/V$ can be computed, at any time t, from the monitored values of p and T, according to the following relation:

$$\frac{\Delta V}{V} = \frac{T + \Delta T}{T} \frac{p}{p + \Delta p} - 1 \tag{2}$$

In general, the volume deformation $\Delta V/V$ can be caused by a variation of either the rebar axial load or the rebar temperature, or of both. The simultaneous knowledge of both T and $\Delta V/V$ can be used to discriminate between the two causes, provided that an appropriate calibration is preliminary conducted, and therefore to eventually determine the elastic strain in the rebar.

2.3 *The low cost sensors*

A widespread type of MEMS is the barometric sensor, which usually integrates pressure and temperature sensors. Nowadays barometric MEMS are commonly employed in smartphones and smartwhatches, IoT devices, wearable and fitness session instruments and others, thanks to their small dimensions (2x3x1 mm^3). These MEMS are easily available on the market at a cost of about 2 \$. The vacuum technology used for their construction allows to measure the absolute pressure, ranging between 260 hPa and 1260 hPa. This is a valuable characteristic since it establishes an absolute reference for the measuring system over time.

2.4 The system in detail

The measuring system is based on a Patent (Tondolo 2016). In this paper, it is applied on a ribbed steel reinforcing bar in which a cavity is obtained as a transversal drilled hole. The latter determines an internal volume, filled with air, which hosts an hard PCB mounting a barometric pressure sensor LPS25H by STMicroelectronics®. An electrical feedthrough is provided at the entry of the cavity, connecting the hard PCB inside with a soft PCB outside, which on its turn communicates with the acquisition system, exchanging power and data. The cavity is perfectly sealed, and the soft PCB is lodged into a groove machined all along the longitudinal lug of the rebar. A longitudinal section of the system is schematized in Figure 1.

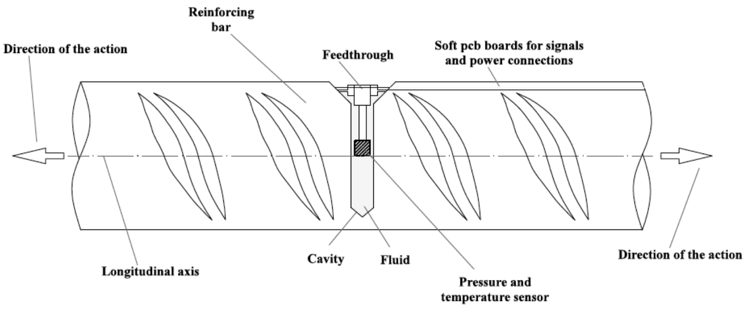


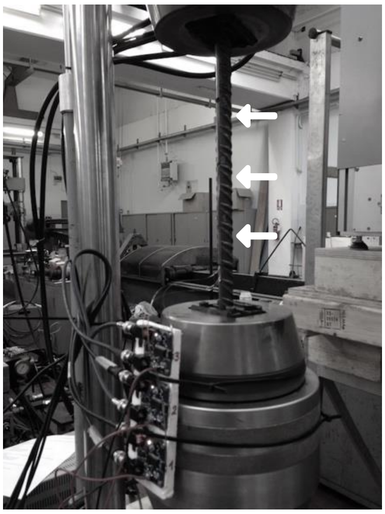
Figure 1. Longitudinal section of the system.

The cavity determines a reduction of the rebar section and therefore a critical point for stress increase and concentration. The consequent reduction in resistance and/or ductility may not represent a significant drawback, as long as the exact reproduction of the original rebar mechanical properties is deemed inessential.

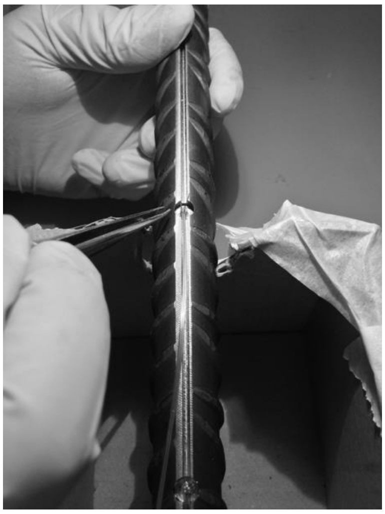
3 EXPERIMENTAL TESTS

3.1 Description of the components

The experimental tests focus on a ribbed reinforcing steel bar instrumented to be a smart bar with the monitoring system described in the previous paragraphs. Figure 2 shows a setup of the system during the experimental test. It consists of a ribbed rebar having 20 mm diameter, equipped with three measuring units spaced 8 cm each other (pointed out by three white arrows in Figure 2a). A closer look at the ingress to one of the units is provided in Figure 2b. A longitudinal groove 2 mm in depth and width is machined into the rebar to host the soft PCBs which connect the pins of the feedthrough to the converter boards (clearly visible at the bottom of Figure 2a). The converter boards acquire the digital pressure and temperature signals coming from of the embedded systems and transform them into analog inputs for the HBM Spider 8 acquisition system.



(a)



(b)

Figure 2. The experimental setup.

3.2 Temperature calibration test

A preliminar test is carried out to analyze the response of the three measuring units to temperature variations at constant axial load. The aim is to find the relation existing between $\Delta V/V$ and T in the absence of axial load variations. The instrumented rebar is placed into a temperature controlled chamber (Angelantoni Challenge 250) and subjected to slow temperature variations (1K/6min), approximately spanning 30K between 287K and 317K. Figure 3 shows the experimental curves obtained for the three measuring units (denoted as, respectively, S_1, S_2 and S_3), where the volume deformation $\Delta V/V$ is plotted as a function of the absolute temperature T.

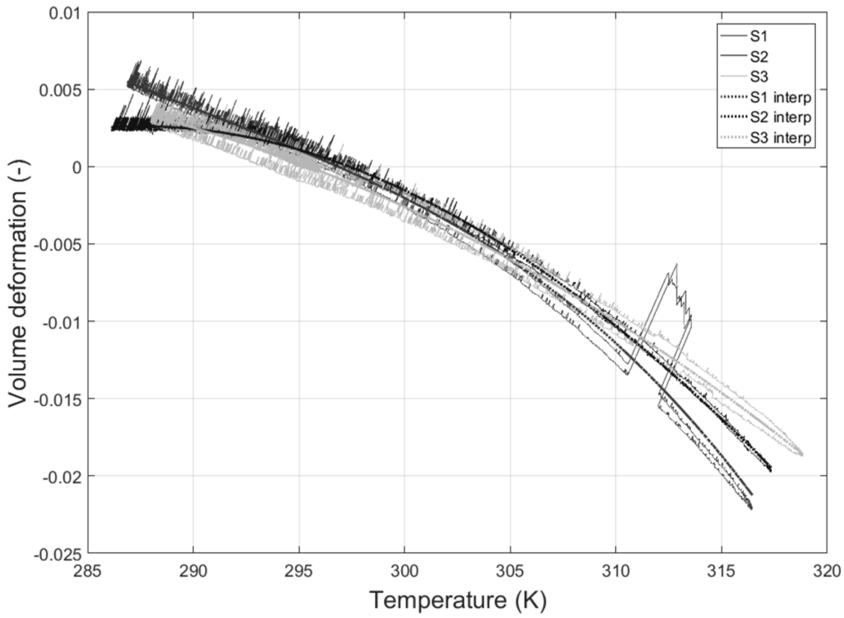


Figure 3. Temperature calibration for the three measuring units.

Except for an electrical interference experienced by the unit S_1 (between 310K and 315K), the curves are similar. A nonlinear relation is found for each unit, which can be closely fitted by a cubic interpolation (see Figure 3 curves named interp), as reported in Figure 3. These relations can be used to take into account the part of $\Delta V/V$ which does not depend on the axial load but solely on the rebar temperature variations induced, for instance, by environmental factors.

3.3 Load test

A uniaxial tensile load test is performed with a universal testing machine MTS with a maximum capacity of 250 kN. Considering the dimensions of the holes hosting the sensors (4 mm of diameter and 18 mm of depth) and the presence of the longitudinal groove, which further reduces the effective sectional area, the rebar transversal section is 24% smaller than the original section. In order to avoid the insurgence of any plastic strain during the tests, assuming a stress intensity factor equal to 3, the maximum applied load is limited to 40 kN. A complete loading and unloading cycle is performed, through 8 steps of 5 kN, corresponding to about 20 MPa of tensile stress on the net transversal section of the rebar. The load variations are applied instantaneously and maintained for about 30 s. In Figure 4 the time histories of p and T are reported for the three measuring units.

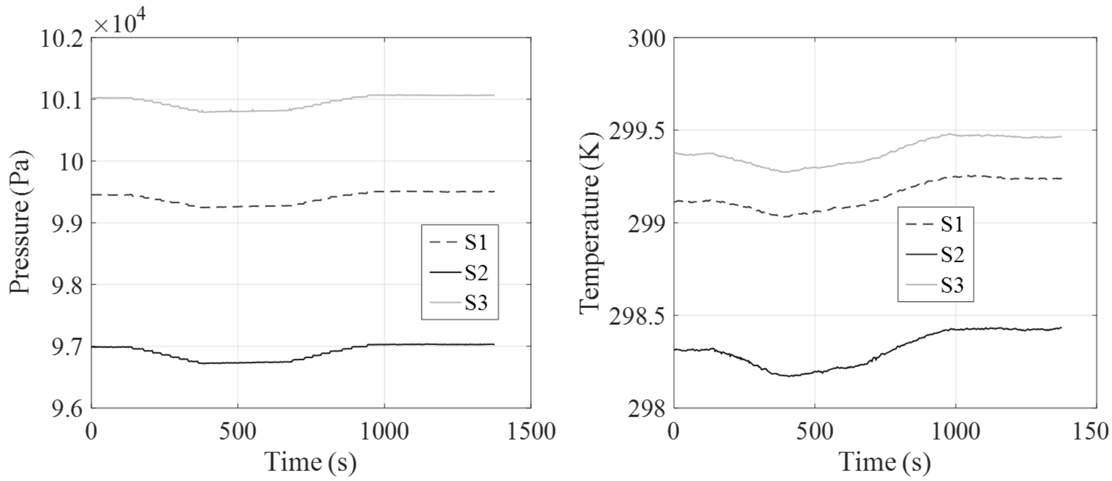


Figure 4. Pressure and temperature variations during the loading and unloading cycle.

Remarkably, a shift is visible between the final and the initial temperature values, certainly attributable to environmental changes (the loading test is not conducted in temperature-controlled conditions). A temperature variation is also apparent during the test, as a result of the thermodynamic changes occurring inside the cavities during loading variations. This shift is responsible, according to paragraph 3.2, for a part of the total $\Delta V/V$ variations observed during the test. In Figure 5 the time histories are reported of the applied axial load (on the left) and of the total deformation $\Delta V/V$ (on the right), computed for each measuring unit according to Eq. (2). As a result of temperature variation, a drift in the $\Delta V/V$ curves is visible, making their descending branches not exactly specular to their ascending counterparts.

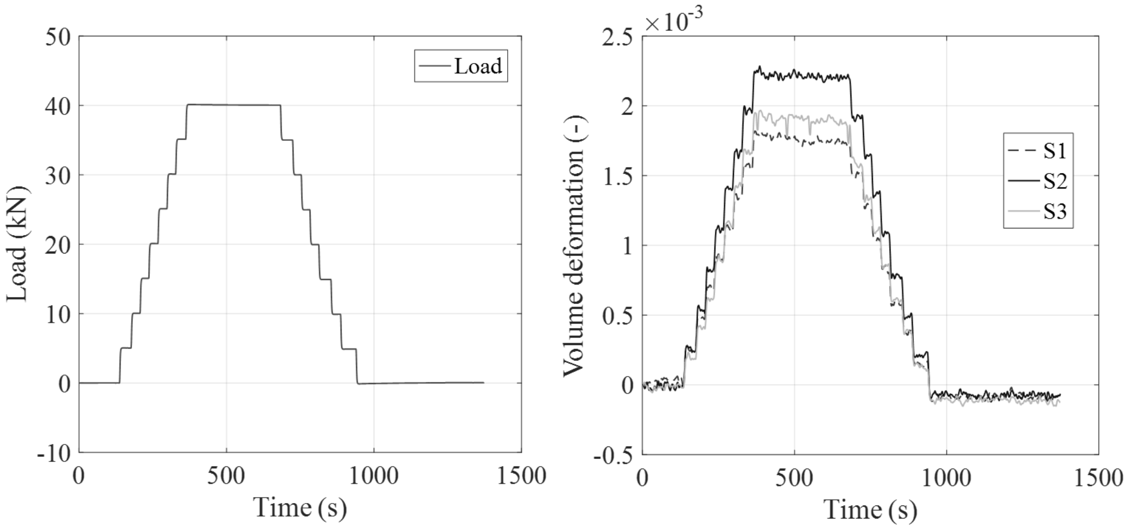
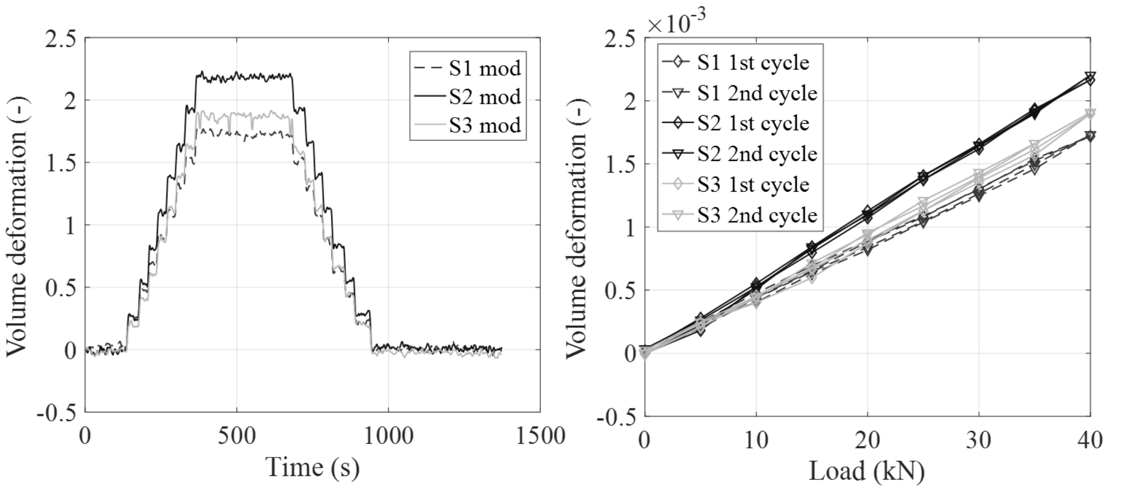


Figure 5. Axial load and total volume deformations during the loading and unloading cycle.

The drift can be compensated by subtracting from the total $\Delta V/V$ the part of it which depends on temperature variations, computed according to the previous calibration. In Figure 6a the corrected $\Delta V/V$ is shown, accurately following the axial load trend. In Figure 6b, the corrected $\Delta V/V$ is reported as a function of the axial load, for each load step. A second experimental load cycle is represented too, in order to check the consistency of the results. A substantial proportionality and a negligible hysteresis can be appreciated.



(a) (b)

Figure 6. Corrected volume deformations as a function of either time (a) or the applied axial load (b).

4 DISCUSSION

The results reported in the previous paragraphs are encouraging to continue testing and developing the proposed technology. Every load level, either in loading and unloading phases of repeating load cycles, can be reliably and uniquely associated to a volume deformation level, derived from temperature and pressure measurements. Linearity and lack of hysteresis are obtained. It is woth noticing that the tested prototype employs ordinary commercial MEMS sensors easily available on the market and not specifically intended to SHM applications.

5 CONCLUSIONS

This work presents the preliminary experimental testing of a new measuring system capable to monitor stress/strain variations in steel rebars. The system is based on measuring pressure and temperature variations of the fluid contained in a sealed cavity drilled in the hosting rebar. Pressure and temperature are registered by using commercial barometric MEMS sensors.

Tests are conducted by submitting the instrumented rebar either to controlled temperature variations (at constant axial load) or to load variations (at freely varying environmental temperature conditions). Results show a valuable sensibility and a clear linearity of the response of the system with respect to the applied load.

The presence of the cavity modifies the surrounding mechanical continuity and therefore a new profile for the reinforcing bar at the instrumented site is needed to compensate the missing material and to reduce the stress concentration.

These encouraging results push forward to continue its development and testing on r.c. specimens. Due to its peculiarities in terms of cost, installation and robustness, the proposed technology can be considered as a reliable alternative to traditional devices. The final aim is to obtain a smart reinforcing rebar for monitoring r.c. structures that combines structural and sensing functions.

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