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Strain monitoring system for steel and concrete structures

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Abstract

The present work is part of a collaborative H2020 European funded research project called SENSKIN, that aims to improve Structural Health Monitoring (SHM) for transport infrastructure through the development of an innovative monitoring and management system for bridges based on a novel, inexpensive, skin-like sensor. The integrated SENSKIN technology will be implemented in the case of steel and concrete bridges, and tested, field-evaluated and benchmarked on actual bridge environment against a conventional health monitoring solution developed by Mistras Group Hellas. The main objective of the present work is to implement the autonomous, fully functional strain monitoring system based on commercially available off-the-shelf components, that will be used to accomplish direct comparison between the performance of the innovative SENSKIN sensors and the conventional strain sensors commonly used for structural monitoring of bridges. For this purpose, the mini Structural Monitoring System (mini SMS) of Physical Acoustics Corporation, a comprehensive data acquisition unit designed specifically for long-term unattended operation in outdoor environments, was selected. For the completion of the conventional system, appropriate foil-type strain sensors were selected, driven by special conditioners manufactured by Mistras Group. A comprehensive description of the strain monitoring system and its peripheral components is provided in this paper. For the evaluation of the integrated system's performance and the effect of various parameters on the long-term behavior of sensors, several test steel pieces instrumented with different strain sensors configurations were prepared and tested in both laboratory and field ambient conditions. Furthermore, loading tests were performed aiming to validate the response of the system in monitoring the strains developed in steel beam elements subject to bending regimes. Representative results obtained from the above experimental tests have been included in this paper as well.

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Keywords: Structural health monitoring; strain sensors; strain gauges; bridges; steel and concrete structures

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1. Introduction

Nowadays, Structural Health Monitoring (SHM) is a key issue for managing the transport infrastructure mainly because increasing traffic demands, need to be accommodated on existing infrastructure with widespread signs of deterioration, while climate changes may negatively affect the infrastructure loading (Alampalli and Ettouney (2008)). Current SHM techniques rely on point-based sensing, as opposed to spatial sensing, requiring a dense network of such point-sensors which increases the monitoring cost. Furthermore, conventional sensors fail at relatively low strains and their communication system is unreliable in extreme service conditions thus, they do not provide a foolproof alarm of an imminent structural collapse (http://www.senskin.eu/). Therefore, the need to develop sensing devices capable of measuring strains in a surface area (as opposed to discrete points), as well as, a reliable communication system which will ensure a robust and reliable delivery of data between sensing nodes and base station, is required.

The present work is part of a collaborative H2020 EU-funded research project, SENSKIN, aiming to achieve the above requirements though the development of novel maintenance techniques, that will enhance bridge performance by improving safety, service continuity in case of disruptive events, capacity, resiliency to changes in traffic demand and climate, cost-effectiveness, sustainability and reliability. The SESNKIN system will be field-evaluated and benchmarked in the Bosporus 1 bridge in Istanbul and the ravine bridge G4 on the Greek Egnatia Motorway, against a conventional health monitoring solution developed by Mistras Group Hellas.

The main objective of this paper is to implement the autonomous and fully functional strain monitoring system, based on commercially available off-the-self components, that will be used for long-term comparison with the SENSKIN system. A presentation of the SENSKIN technology, as well as a detailed description of the conventional strain monitoring system accompanied by its peripheral components including appropriate strain sensors for steel and concrete application and conditioners, is provided in this paper. In addition, representative results obtained from a series of experimental tests carried out in both laboratory and field ambient conditions are presented, aiming to evaluate the overall system's performance and long-term behavior of sensors. Finally, the serious benefits of potential combination of strain-based installations with Acoustic Emission SHM is discussed.

2. SENSKIN project solution

The SENSKIN technology comprises of the following parts (Loupos et al. (2016; 2017)):

- A novel, wireless skin-like sensor accompanied by its Data Acquisition Unit (DAQ) that offers spatial sensing of irregular surfaces and can monitor large strains. The sensor, which is demonstrated in Fig.1, is made from a thin dielectric-elastomer membrane coated on both sides with compliant electrodes and is encapsulated between soft protective elastomer layers. The sensor is practically an all-silicone device that is very suitable for measuring large deformations via monitoring the changes in its capacitance.

Fig. 1. View of the novel SENSKIN sensor accompanied by its Data Acquisition Unit (DAQ).

- Emerging Delay Tolerant Networking (DTNs) communication systems that will guarantee the delivery, availability and integrity of the sensor data even during hostile communication conditions, such as in the case of an earthquake. In the emergency that may follow an extreme event, the sensor data will be preserved through (so-called) panic protocols and forwarded to the processing station without loss of availability or accuracy.
- A Decision-Support-System for proactive condition-based structural intervention under operating loads and intervention after extreme events. The system will be integrated to provide decision support on the timing and type of rehabilitation based on the identified damage, structural condition and available rehabilitation options.

3. Conventional strain monitoring system

3.1. Mini Structural Monitoring System (mini SMS)

Based on structural bridge engineering needs and SESNKIN project requirements, the Mistras Group Inc. mini Structural Monitoring System (mini SMS), illustrated in Fig.2, was selected. The Structural Monitoring System (mini SMS), is a comprehensive data acquisition unit designed specifically for long term unattended operation in outdoor environments. The system is configurable with 32 current input (4-20mA) channels and is armed with many features, including data collection, alarming, historical trending and data storage. Each channel provides voltage (24 V) and signal transmission which allows to connect to all kinds of sensors and signal sources using 4-20 mA current loops from strain gauges, Acoustic Emission, temperature sensors, vibration, displacement, inclinometers and various other transducers, offering solution for a wide range of applications of SHM of structures. Complete with an Ethernet output for network communications, the mini SMS can send alarms and reports remotely via e-mail and has a battery backup in case of loss of power.

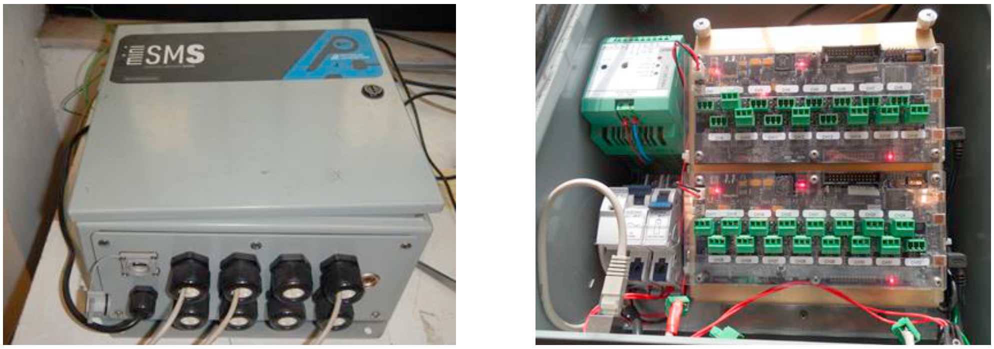

Fig. 2. External view (left image) and inside view (right image) of the 32-channel mini SMS conventional monitoring system.

The mini SMS is packaged in NEMA 4/IP66 wall mounted steel waterproof box with dimensions 31x36x17 (cm) and overall weight of approximately 10 kg. The system is based on a high performance industrial embedded computer with Windows 7 operating system, large internal storage capacity, multiple communication interfaces, Gigabit Ethernet, as well as battery charge controller plus Wi-Fi and cellular modem as options. Furthermore, it features 8 digital outputs for alarms and 8 digital inputs for trigger control. In addition, the system supports Smart Sensors through HART protocol, and a low system consumption of 10-60W (depending on the number of sensors), an analog to digital (ADC) resolution of 16 bit and an output voltage of 24V.

The system uses Mistras' SMS data acquisition software that provides data acquisition capabilities tailored specifically to long-term unattended usage for structural monitoring. The main screen of the mini SMS Graphical User Interface (GUI) is presented in Fig.3. The layout consists of five separate plots, each showing a user-selectable set of channels. Different channels can be grouped together, and recorded data can be displayed in real-time. The settings of each channel are customised through the same user-friendly GUI, where all the parameters such as sensor type, units, multipliers, offsets, triggering levels and alarms for each channel can be set individually.

3.2. Strain Gauge Conditioner (SGC)

For the completion of the conventional system, special Strain Gauge Conditioner (SGC) Modules, model 9383, developed by Mistras Group Inc. were procured. The 9383 SGC is available as single channel board with screw terminal connections for interfacing to 350 Ohm strain gauges. The SGC generates a 4-20mA output, contains a trimmer potentiometer for zeroing the 4-20mA output, and is configurable to accept 1/4 bridge, 1/2 bridge or full bridge strain gauge configurations. For the protection against environmental conditions, aluminum IP rated enclosures were used to host the single-channel SGC modules, as shown in Fig.4a. Furthermore, multiple SGCs can be mounted into an IP rated enclosure creating an environmentally rugged, multiple channel strain gage interface such as the four-channel solution demonstrated in Fig.4b.

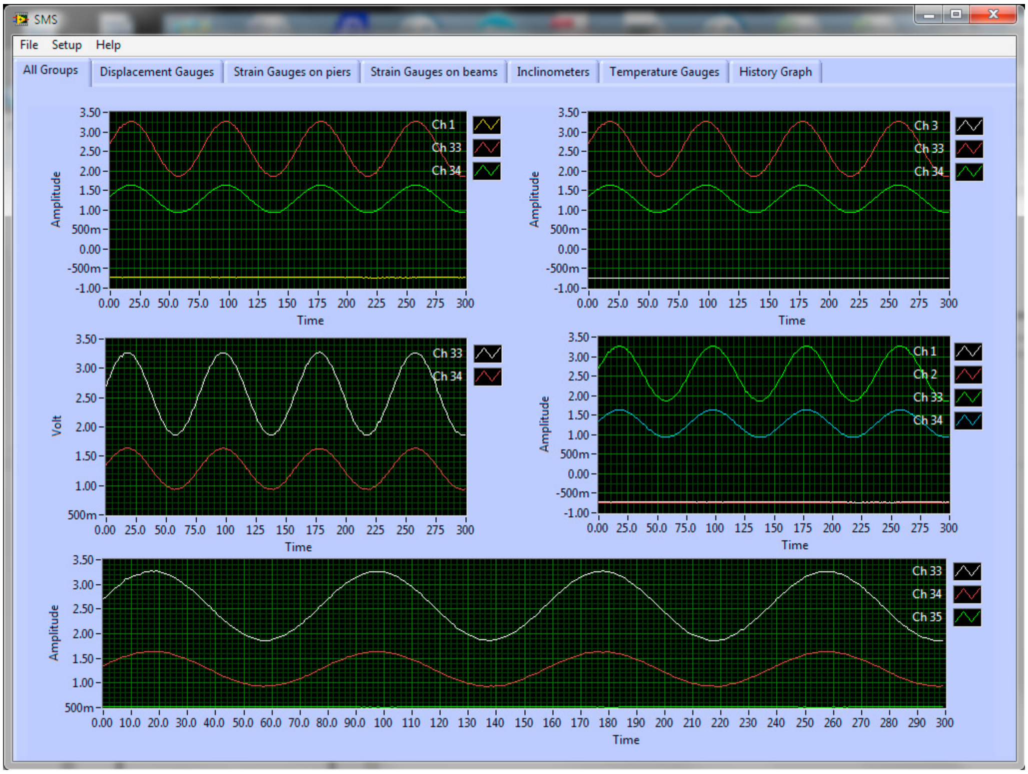

Fig. 3. Mini SMS GUI main screen - Typical presentation of recorded data.

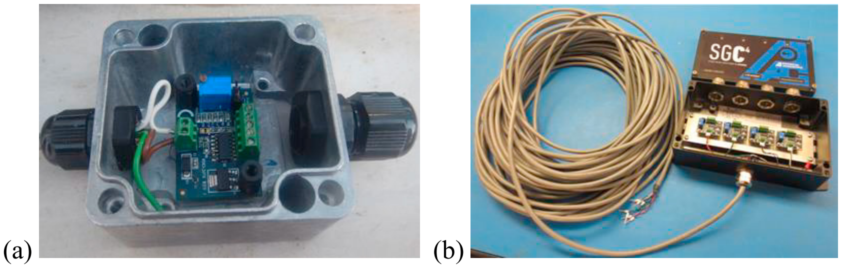

Fig. 4. Single-channel SGC module (a) and four-channel SGC module (b) housed in waterproof enclosures.

3.3. Conventional strain sensors

The initial step in preparing for any strain gauge installation is the selection of the appropriate gauge for the task that will meet specified test requirements. Basically, the selection process consists of determining the available combination of parameters that is most compatible with the environmental and any other operating conditions, and at the same time best satisfies the installation requirements such as the type of strain measurement and loads (static or dynamic), direction of principle strains, if known, expected strain levels, specimen material, accuracy and stability required, temperature variation during the test, elongation, test duration, ease of installation and environmental conditions (Vishay Precision Group 2010). Following the above selection criteria and the evaluation of actual bridge structural needs, HBM linear pattern strain gauges with constantan grid lengths in the rage from 6mm to 10mm were selected for steel applications. In the case of inhomogeneous materials such as concrete, it is commonly essential to comply with the recommendation to use a grid length at least five times as long the largest aggregate grain size, corresponding to lengths up to 150mm. Furthermore, the selection of higher 350-Ohm against 120-Ohm gauge resistance was preferable, in that it reduces the heat generation rate by a factor of three.

3.4. Integrated system

A typical strain gauge connection to the system is shown in Fig.5a, where a four-channel SGC is used to drive 1/4 bridge, 1/2 bridge or full bridge configurations of strain gauges. Each configuration is considered as one channel and allocates one of the 32 available current input channels provided by the system. An image of the integrated system in laboratory environment is presented in Fig.5b, demonstrating the connection of a single-channel SGC to the mini SMS board, used to drive a 1/4 bridge configuration of linear strain gauge bonded on a test metal plate.

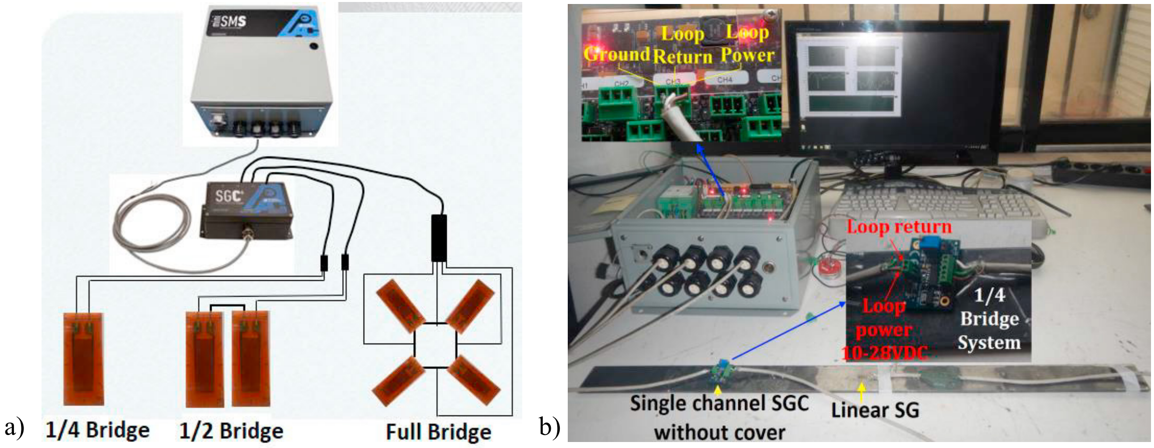

Fig. 5. (a) Typical strain gauges configurations with mini SMS. (b) View of the integrated system in laboratory.

4. Experimental testing

For the experimental tests, several SG bridge systems were set-up and installed on test steel plates. A thorough preparation of the plates surface prior to the sensors mounting, careful sensors bonding, and proper application of protection were performed using appropriate accessories and in accordance with manufacturers' recommended installation procedures (Hoffman (1996)). Indicative types of bridge systems are presented below (Hoffman (1989)):

- Quarter Bridge Strain Gauge Configuration: 1 active-gauge 3-wire system
  This system is suitable for ordinary uniaxial strain measurement providing an x1 output signal. An image of this configuration in lab is shown in Fig.6, illustrating a linear strain gauge with 6mm grid length bonded on a test metal plate. An additional identical configuration was prepared, that was covered with protective agents and placed in the field. A thermocouple was also attached on the plate in the field for recording ambient temperature.
- Half Bridge Strain Gauge Configuration: Orthogonal 2-active-gauge system
  This system is used for axial strain measurement yielding an output signal multiplied by the factors of (1+ν), where ν: Poisson's ratio. This configuration is suitable for eliminating the error due to thermal output and compensate for temperature effects. An image of this configuration is shown in Fig.7, where two linear pre-wired strain gauges are bonded on a test metal plate at a right angle and connected to adjacent sides of the Wheatstone bridge circuit. The above configuration was further covered with protection and placed in the field.
- Half Bridge Strain Gauge Configuration: Active-dummy 2-gauge system
  The active-dummy method uses the 2-gauge system, where an active gauge is bonded to the test object and an identical dummy gage is mounted on an unstrained specimen made of the same material as the test object and is sub-

jected always to the same temperature conditions as the active gauge. This is a temperature compensation method and can be alternatively applied as a 2-gauge system in which the active gauge is bonded on the test plate and the dummy gauge is not glued, but just affixed to the surface using i.e. with adhesive tape at an adjacent position.

Fig. 6. Quarter bridge SG configuration: 1 active-gauge 3-wire system in lab (left image) and in the field (right image).

Fig. 7. Half bridge SG configuration in lab. Orthogonal 2-active-gauge system with two linear pre-wired SGs 6 mm grid length at a right angle.

A series of experimental tests were carried out aiming to investigate the influence of various factors such as temperature variation, bonding material, strain gauge length and type of bridge configuration on the long-term stability (zero drifting) of strain measurements and sensors in both laboratory and field ambient conditions. (Espion and Halleux (2000)). Furthermore, loading tests were performed for the validation of the performance and response of the system in monitoring the strains developed in steel beam elements subject to loading and bending regimes. For the visualization and manipulation of the recorded mini SMS data files, NOESIS^{TM} was used, that is a powerful software developed by Mistras Group Hellas, available for advanced data handling, classification and processing. Representative results obtained from the experimental tests of the integrated system are presented below.

5. Results and discussion

Depending upon the test temperature and the required accuracy in strain measurement, it is, sometimes, necessary to make corrections for thermal output, even though self-temperature-compensated gages are used as the ones reported here, which are designed to minimise the error over the normal range of working temperatures. The above is evident in Fig.8, where a representative set of unstressed data recorded for approximately 21 hours from the two above-described test plates instrumented with the same Quarter Bridge SG Configuration (presented in Fig.6) in laboratory and outdoor environment is provided.

More specifically, the blue and red lines of the top diagram correspond to the data obtained from the test pieces placed indoors and in field, respectively, while the red line on the bottom graph represents ambient temperature data recorded from the thermocouple that was attached on the plate in the field. A deviation of the zero point is observed for the 1-active-gauge 3-wire system at field ambient conditions, that was found to be on the order of approximately 45 microstrain for a temperature variation (increase) of approx. 30 ^{o}C, with respect to the same bridge system placed indoors that appears very stable in near-zero condition.

The above results indicate the need for deployment of proper SG bridge systems capable of providing effective temperature compensation when strain measurements are to be made in outdoor environments. For this purpose, a series of additional tests were carried out aiming to identify the most appropriate configuration to be used on-site, not only in terms of performance and accuracy, but also in terms of applicability considering the bridge access restrictions and measurement needs. The results obtained, indicated that the most effective compensating solution would be the orthogonal 2-active-guage system in half bridge arrangement presented in Fig.7. A set of unstrained data recorded for a period of 10 days at outdoor conditions is illustrated in Fig.9, verifying the efficient long-term behavior of the orthogonal 2-active-guage system (blue line) and much more limited zero-point deviation occurring with temperature variations, compared to the quarter bridge 1-active gauge system (red line). However, it should be noted that in all strain-measurement applications which involve mounting the compensating gauge on the test object itself, a priori knowledge of the expected strain distribution at the two locations, is required.

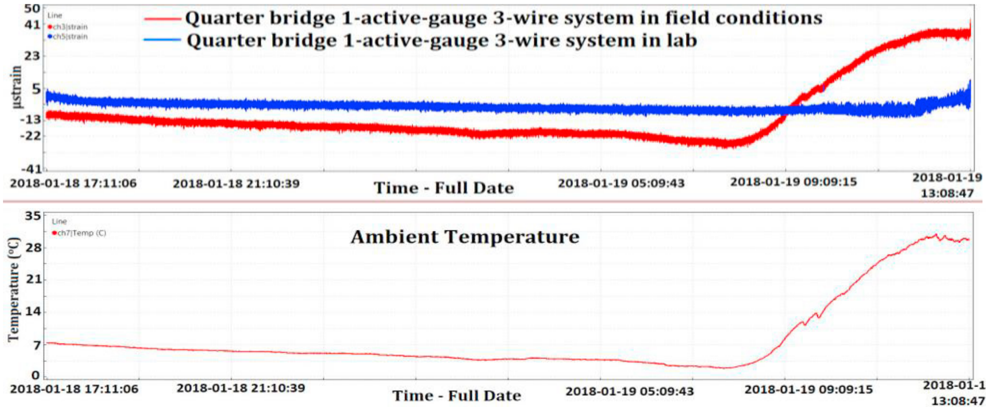

Fig. 8. MiniSMS microstrain data and temperature data of ¼ SG bridge systems versus time in laboratory and outdoor ambient conditions.

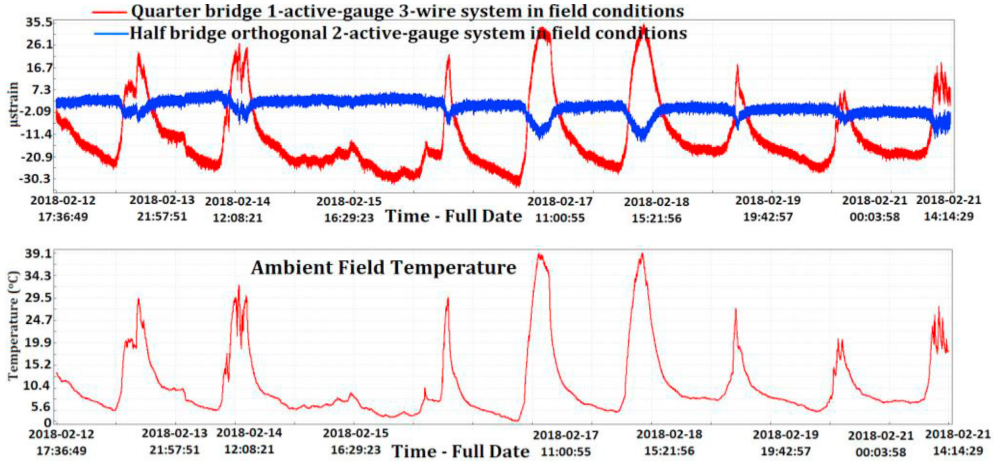

Fig. 9. MiniSMS microstrain and temperature data of ¼ and ½ SG bridge systems versus time in field ambient conditions.

In order to investigate the effect of bonding material on the strain measurements, an identical 1-active-gauge 3-wire system to that shown Fig.6 was attached on a steel plate, using however a different adhesive (that was the commercial LOCTITE glue) than that recommended by HBM manufacturer (that was the X60 superglue). Data were recorded in laboratory environment for a period of approximately three days during which the test piece remained unstrained. A significant drift of the zero value, independent of the temperature variation of ±5°C in laboratory, was observed, compared to the respective system of Fig.8 that exhibits stability, indicating the inappropriate performance of the LOCTITE glue and verifying the suitability of the HBM superglue.

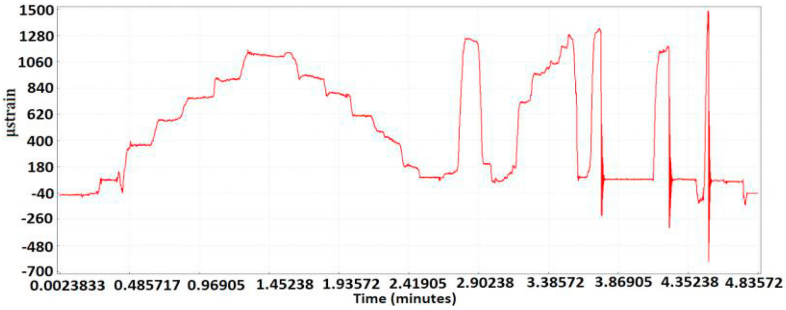

Fig. 10. MiniSMS microstrain data of ¼ SG bridge configuration subjected to bending.

In order to evaluate the performance and overall response of the integrated system in strain monitoring, loading tests were performed on the above test steel plates by subjecting them to bending loads manually by hand. Fig.10 illustrates a representative set of recorded data clearly indicating the strain levels developed in a metal plate instrumented with a quarter bridge SG configuration, that was subjected to five repeated loading-unloading bending cycles for a total test duration of 5 minutes. As it can be seen, during the "recovery" periods, corresponding to the periods following unloading where the strain in the sample exhibits movement back to near zero strain, the output strain signals also recover rapidly to near zero condition.

6. Conclusions and future development

In the present work, a fully functional conventional strain monitoring system has been implemented by Mistras Group Hellas as part of SENSKIN European research project actions, that will be installed on a bridge on the Greek Egnatia Motorway for long-term comparison with the innovative SENSKIN system and will also be used in the reference system testing that will take place in Bosporus 1 Bridge, Turkey. A detailed overview of the mini SMS system's hardware along with the peripheral components employed for the completion of the system including conventional metal and concrete strain sensors and signal conditioners has been presented in this paper. The results obtained from the various experimental tests led to significant conclusions towards the determination of the most appropriate strain gauges and bridge configurations to be used on-site in terms of applicability, appropriate bonding, effective temperature compensation, environmental durability, long-term stability and strain measurement needs. Through the implementation of manual loading tests, the effective performance and accurate response of the system in strain monitoring was validated, as well.

The monitoring system reported in this work accepts all types of sensors with 4-2 mA current loop including, among others, acoustic emission (AE), thus offering solution for a wide range of applications of SHM of structures. The application of AE is widely used as an effective, viable solution in the remote monitoring of bridges worldwide, capable of providing early detection of active cracks and damage evolution and predicting the time to structural collapse (Watson et al. (2004); Tamutus et al. (2015)). Therefore, the potential combination of strain-based installations with AE SHM systems would be of great benefit since, it will additionally offer real-time detection and location of micro-cracking and monitoring of possible damage propagation in critical points of the structure. The crack growth estimation through AE activity combined with strain monitoring would provide a powerful tool for fatigue crack detection and through life damage assessment with potential for improving structures safety and sustainability.

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References

Alampalli, S., Ettouney, M., 2008. Role of structural health monitoring in bridge security. Bridge Structures 4(3,4), 143-154.

Espion, B., Halleux, P., 2000. Long-term measurements of strains with strain gauges and stability of strain gauge transducers. Reports in Applied Measurement (RAM) 2000/1. Hottinger Baldwin Messetechinik GmbH, Darmstadt, ISSN 0930-7923.

Hoffman, K., 1996. Practical hints for the installation of strain gauges. Hottinger Baldwin Messetechinik HBM GmbH Publisher, Darmstadt.

Hoffman, K., 1989. An introduction to measurements using strain gauges. Hottinger Baldwin Messetechinik HBM GmbH Publisher, Darmstadt.

Loupos, K., Amditis, A., Tsertou, A., Damigos, Y., Gerhard, R., Kalidromitis, V., Camarinopoulos, S., Lenas, S-A., Anastasopoulos, A., Lenz, K., Hill, M., Adesiyun, A., Frankenstein, B., 2016. Skin-like Sensor Enabled Bridge Structural Health Monitoring System. 8th European Workshop On Structural Health Monitoring (EWSHM 2016), 5-8 July 2016, Spain, Bilbao.

Loupos, K., Damigos, Y., Amditis, A., Gerhard, R., Rychkov, D., Wirges, W., Schulze, M., Lenas, S-A., Chatziandreoglou, C., Malliou, C., Tsaoussidis, V., Brady, K., Frankenstein, B., 2017. Structural Health Monitoring for bridges based on skin-like sensor. IOP Conf. Ser.: Mater. Sci. Eng. 236 012100

Tamutus, T., Gostautas, R., Watson, J.,2015. Does Structural health monitoring provide safety and maintenance or confusing data? Materials Evaluation 73 (3), 354-359.

Vishay Precision Group, Micro-Measurements, 2010. Strain Gauge Selection: Criteria, Procedures, Recommendations. Tech Note TN-505-4.

Watson, J.R., Cole P.T., Anastasopoulos, A., 2004. Condition Assessment of Concrete Hinge Joint Bridges. 3rd International Conference on Emerging Technologies in NDT, 26-28 May 2003, Thessaloniki, A. A. Balkema, Netherlands 2004, ISBN 90 5809 645 9 (Volume) - 90 5809 645 7(CD), 281-285.