Skin-like Sensor Enabled Bridge Structural Health Monitoring System

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Abstract

Structural Health Monitoring (SHM) has an important role in the management of transport infrastructure. However, most SHM techniques are based on data obtained from dense networks of point-based sensors (rather than sparse networks of spatial sensors) and so, in relative terms, they are costly to implement. Most commercially available strain sensors have a limited maximum range - typically 1% to 2% - and are not well-suited to providing information of a severe loss of structural integrity. The SENSKIN project develops a dielectric-elastomer and micro-electronics-based skin-like sensor, based on the use of a large highly extensible capacitance sensing membrane and advanced micro-electronic circuitry, for monitoring transport infrastructure - such as bridges. The sensor will provide spatial measurements of strain of more than 10% and is being designed to (a) require low power to operate, (b) be easy to install (c) have a comparable or lower cost than conventional strain sensors, (d) allow simple signal processing, and (e) have the ability to self-monitor and self-report. The system will support the new and emerging technology of Delay/Disruption-Tolerant Networking to secure that strain measurements acquired will reach the base station even under extreme conditions where communications may be disrupted. SENSKIN also develops a Decision-Support-System (DSS) for proactive condition-based structural interventions under normal operating conditions and reactive emergency intervention following an extreme event. In assessing potential rehabilitation options, the DSS will use the data supplied by the SENSKIN sensors together with advanced structural analysis models, whilst taking account of the lifecycle economic, social and environmental implications. The overall monitoring system will be evaluated and benchmarked on actual bridges of Egnatia Highway (Greece) and Bosporus Bridge (Turkey). This paper describes the concept and principles of the SENSKIN sensing system, and its various components with attention to end-user requirements, specifications and system architecture.

1 INTRODUCTION

Currently there is limited use of sensors to monitor the stability of transport infrastructure. Reliance is instead placed on visual inspections to gather information to determine the condition of infrastructures. To complete the assessment of the load-carrying capability of a structure, visual inspections are supplemented by measurements of structural section sizes. Inspections can be slow to complete and usually require the closure (partially or totally) of a network node or link, and/or expose the inspector to a dangerous working environment. Detailed assessments (a) are particularly slow and expensive, (b) are usually based on simplistic and conservative models of structural behaviour, and (c) do not provide a rapid, convenient means of determining structural stability following a major incident. Furthermore, the quality and reliability of the visual information and measurements depend upon the expertise of the inspector, and often the inspector is unable to gain access to all parts of a structure. Structural Health Monitoring (SHM) technologies have a major role in the management of transport infrastructure. Currently used SHM technologies and methods rely only on the use of dense networks of point sensors to monitor a structure, which is costly (and sometimes not practicable). At the same time, conventional sensors fail at relatively low strains and their communication system is unreliable in extreme service conditions: thus, they do not provide a fool-proof alarm of an imminent structural collapse.

1.1 SENSKIN EC Project

SENSKIN is an EC co-funded project that operates in the framework of EC-FP7-Transport (MG-8.1a-2014 - Smarter design, construction and maintenance). SENSKIN includes a consortium with all the expertise needed in the lifecycle from research to innovation, as well as real-life end-users that can provide solid feedback on the project results. The list of partners of the consortium has been presented below:

Partner Name	Short Name	Country
Institute of Communication and Computer Systems	ICCS	Greece
University of Potsdam, Applied Condensed-Matter Physics Group	UP	Germany
Egnatia Odos A.E.	EOAE	Greece
RISA Sicherheitsanalysen GmbH	RISA	Germany
TECNIC S.p.A.	TECNIC	Italy
Democritus University of Thrace	DUTH	Greece
Mistras Group Hellas A.B.E.E.	MGH	Greece
University of Stuttgart	USTUTT	Greece
TRL Limited, Transport Research Laboratory	TRL	UK
State Enterprise State Road Scientific Research Institute	DNDI	Uktraine
Forum Des Laboratoires Nationaux Europeens De Recherche Routiere	FEHRL	Belgium
Teletronic Rossendorf GmbH	TTRONIC	Germany
Turkish General Directorate of Highways	KGM	Turkey

The consortium includes partners that (a) have already developed a first generation of 'sensing skin' with very encouraging results (UP), (b) have already developed relevant sensor near electronics (TTRONIC), (c) have developed LCAs and LCCs for construction works (USTUTT), (d) have developed algorithms for the assessment of deteriorating structural systems in the context of several previous research projects (TECNIC, RISA) and (e) have developed and implemented relevant wireless sensor network architectures (DUTH). The work in SENSKIN is totally market driven (there are three major end users in the consortium: EOAE, KGM and FEHRL (including members that belong to Highway Departments)[1].

SENSKIN aims to: (a) develop a dielectric-elastomer and micro-electronics-based skin-like sensing solution for the structural monitoring of the transport infrastructure that will offer spatial sensing of reversible (repeated) strains in the range of 0.012% to more than 10%, that requires little power to operate, is easy to install on an irregular surface, is low cost compared to existing sensors, allows simple signal processing and includes the ability of self-monitoring and self-reporting. (b) use the new and emerging technology of Delay Tolerant Network to secure that strain measurements acquired through the 'sensing skin' will reach the base station even under extreme environmental conditions and natural disaster events such as, high winds or an earthquake, where some communication networks could become inoperable. (c) develop a Decision-Support-System for proactive condition-based structural intervention under operating loads and intervention after extreme events. It will be based on an accurate structural assessment based on input from the strain sensors in (a) above and will examine the life-cycle economic, social and environmental implications of the feasible rehabilitation options and the resilience of the infrastructure to future changes in traffic demand that these options offer. (d) Implement the above in the case of bridges and test, refine, evaluate and benchmark the monitoring system (integrated a and b) and package (integrated a, b and c) on actual bridges.

1.2 Challenge and Requirements

During the early stages of the SENSKIN project and in very close collaboration with the project end-users, the consortium has identified, consolidate and structure the end-user requirements for the bridge monitoring and assessment solution, that have in turn led to the definition of the SENSKIN system specifications and architecture. The main use of the SENSKIN SHM system is to gather information from the actual bridge (sensing data) and evaluate the extent and severity of damage being below critical threshold levels in maintaining safety. This will be advantageous when choosing actions required maintaining the safe use of the bridges following an unusual or severe in-service loading event. Currently, most bridge managers/operators rely heavily on visual inspections to detect and quantify the extent and severity of damage. However, there are a number of shortcomings with this approach – including [2]:

- The subjectivity, variability, and (in general) conservatism of visual inspections;
- The intermittent and variable nature of information provided by relatively widely-spaced inspections;
- The difficulties and cost of accessing all the critical structural elements of a bridge;
- The difficulties of relating the visual condition of a structure to its continued safe use.

The requirements of the SENSKIN solution include some particular functional and operational characteristics that can be summarised below for the application of the sensors on concrete and steel structure bridges. A major requirement for the sensors has to do with the sensors’ welding, bolting or chemically fixing (by glue) to ensure structure following. As the SENSKIN sensor is a surface/skin type sensor, monitoring all across its attached sensing area, its fixing by glue or other proper adhesive seems mandatory. Welding is in general not accepted in steel bridges in operation, as they are coated for protection against corrosion. The welding of minerals of different electric resistance can cause corrosion intrusion as well. The type, material and properties of the adhesive that will be used for attaching rigidly and robustly the new sensor on the steel bridge element surfaces should at least provide [2, 3]:

- Durability to support long term monitoring;
- High fatigue strength under repeatedly applied reversible loads;

- Resistance if exposed to UV radiation (chemical attack, adverse temperatures, moisture);
- Fast curing;
- High bonding strength on steel, without failure high reversible strains (10%).

2 SKIN-LIKE MONITORING SENSOR

The sensing assembly of the SENSKIN monitoring system basically consists of two integral parts – namely the sensor itself and the electronic module of the Data Acquisition System. The two parts are described below in sections **2.1** and **2.2**, respectively.

2.1 SENSKIN soft-capacitor sensor

The principle of operation of the skin-like capacitive sensor is based on the monitoring of the capacitance changes caused by the sensor's deformation [4, 5, 6]. It is well known that the capacitance C of a uniform parallel-plate capacitor can be written as:

$$C = \varepsilon\varepsilon_0 A/d, \qquad (1)$$

where A is the area of the capacitor, d is its thickness, and ε and ε_0 are the relative dielectric permittivity of the sensor material (*i.e.* of the capacitor dielectric) and the vacuum dielectric constant in the SI system of units, respectively. If any of the above parameters change the capacitance will change as well. Thus, if the capacitor is attached to any substrate the lateral deformations of the substrate will cause the sensor capacitance to change. In order to accommodate large substrate strains, the capacitor needs to be rather soft, *i.e.* it has to be able to change its linear dimensions within the limits of elastic deformation, and the electrodes [7] should also remain conductive over the whole designed or expected range of movement. In order to fulfil these requirements, we have developed a soft capacitive sensor that is made from silicone-rubber films with compliant electrodes that are also based on the same material. Because the elastomer material is essentially incompressible, the increase in the area A in Equation (1) will necessarily be coupled with a decrease in the thickness d. Both processes combined lead to a fairly linear increase in the capacitance when the sensor is stretched in either the length or the width direction, for example. The capacitive-sensor design and its fabrication procedure can be seen in Figure 1 and the exploded Figure 2, respectively.

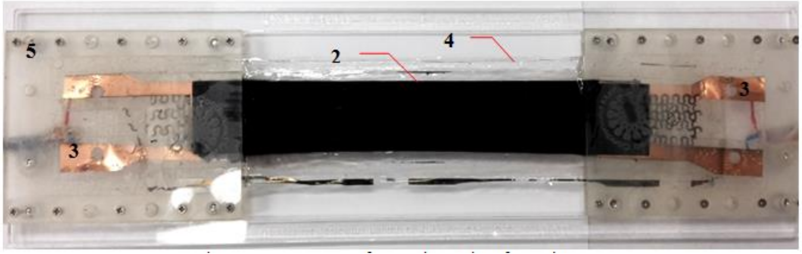

Figure 1: SENSKIN soft capacitor. View from above.

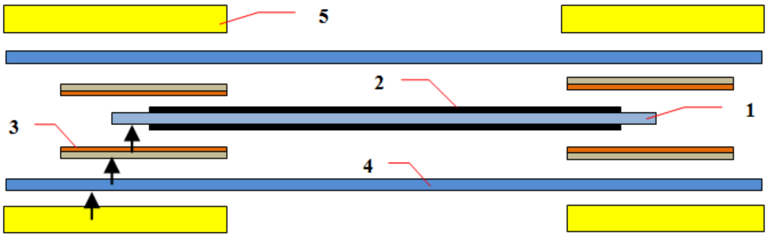

Figure 2: SENSKIN soft capacitor. Exploded view of a typical cross section.

Fabrication procedure: The silicone film (1) (Wacker Chemie Elastosil, 50µm thick) supplied on a liner by the manufacturer is sprayed on one side with a hexane-based solution

of the not-yet-cross-linked silicone components, filled with carbon nanoparticles. After evaporation of the solvent and cross-linking of the composite electrode coating, the film carries a highly stretchable conductive layer (2) with typical electrical resistances as low as 0.1 - 10 kΩ across 15 cm length. After attaching polyester (PETP) frames with electrical terminals (3), the whole sensor is sealed with a silicone protective layer (4) by means of blade casting (so-called doctor blading). The outer frames (5) are used for mounting the sensor in the ZWICK linear testing machine. The terminals (3) on both sides of the sample can be used to either measure the capacitance of the sensor or the resistance of the electrodes. Obviously, the sensor mounted on real transport-infrastructure objects will only need either the right or the left set of terminals to measure the capacitance. Thus, in practical applications, the sensor will be shorter and will not need the mounting frames (5).
Sensor parameters: The active electroded area is 15x3 cm^2. The capacitance without pre-stretching is between 2.3 and 2.5 nF. Typically, the sensitivity is between 2 and 2.5 fF per µstrain. The resistance of the electrodes changes within 0.02-0.07 Ω per µstrain. Being made of soft elastomer materials, the sensing capacitors can withstand mechanical strains in excess of 300% without losing their integrity. Electrical operation has been proven to function well within a 100% strain limit.

2.2 Data Acquisition System

Challenging for the data acquisition is the measurement of relatively small changes in capacitances induced by stretching, compared with the large basic capacitance of the sensing element. First realized prototypes of sensor with basic capacities between 2.3 and 2,5nF achieve a strain sensitivity of 2...2,5fF/micro strain. A resolution of 100 micro strain is required. A limiting constraint is the relatively high contact resistance of the sensor, ranging from some 100 ohms up to 10k. So for data acquisition there is a need for Capacitance to Digital Converter (CDC) with high resolution and huge dynamic range. We choose the CDC circuit PICOCAP 02 of Acam Electronics which enables a lot of free programmable parameters. The PICOCAP 02 module consists of an analog part and a subsequent digital signal processor (DSP). The DSP module enables low level signal processing like averaging and supports adaption of sensor parameters as well as the requirements of the measurement technology by programming on assembler level. By the analog part the RC discharge times of an internal resistor of the Acam circuit and the unknown sensor capacity on the one hand and a reference capacitor on the other hand are measured. The sensor capacity we find by comparing the discharge cycles. Disadvantageous for this measurement principle are the resistances of stretchable electrode of sensing capacitor which influences measurement result significantly. Therefore the system including sensor has to be calibrated and the calibration results has to be memorized in the DSP. In first tests by combining a demo of KIT Pico Cap 02 and a prototype sensor this measurement principle was realized. The interface between DSP and the communication modules is implemented via SPI bus and some status lines.

2.3 SENSKIN Monitoring Combined with Conventional Strain Monitoring

Field evaluation and benchmarking of the skin-like monitoring system will be carried out in lab trials as well as in field trials that will take place in two actual bridges: (a) in Bosporus 1 suspension bridge in Istanbul, which is currently instrumented with a sophisticated Structural Monitoring System (SMS) composed of numerous strain and displacement sensors, accelerometers, tilt meters and thermocouples and (b) in Egnatia Motorway ravine bridge G4, of the west sector of Egnatia Motorway section, in Krystalopigi, Greece, which is currently un-instrumented. To meet the needs of the second trials Mistras Group Hellas will develop and instrument the Egnatia's Motorway bridge with a fully autonomous SMS system composed of current state-of-the-art SMS system developed by Mistras Group, Inc. and high quality strain sensors intended for axial, shear and torsional strain monitoring in steel and concrete sections of the bridge. The conventional strain sensors will be placed next to the innovative skin-like sensors aiming to perform parallel measurements that will be fed to the central database of the SENSKIN system and will be used as a reference point for the evaluation and benchmarking of the technical performance of the innovative skin-like sensor. The sensor will be evaluated against conventional strain sensors in terms of measurements quality (accuracy, sensitivity, noise threshold); useful range of measurements; sensor response against temperature and humidity variations and finally robustness, durability and life expectancy of the sensor when subjected to cyclic loading and various weather conditions. In addition, the technical and operational performance of the complete SENSKIN system consisting of the skin-like sensor, acquisition, communication and data transmission modules will be assessed under normal and extreme operating conditions where loss of valuable measurements shouldn't occur. Furthermore user friendliness of the complete system, interpretability of the system's output to support engineering assessment and ability to self-monitor and self-report hardware and software faults will be investigated. Finally, cost analysis of components and resources required for bridge instrumentation with both systems will be performed aiming to minimize the overall cost for instrumenting new and in-service bridges.

3 SENSKIN COMMUNICATION SYSTEM

Both reporting and controlling functionalities of the SENSKIN platform are supported by the SENSKIN communication system. In particular, the purpose of the communication system is threefold: first, to deliver reliably collected sensor data to the DSS, second, to deliver in a timely manner configuration commands or other operational requests to the monitoring system, and, third, to guarantee the availability and integrity of the sensor data.

3.1 Network Architecture

In practice, the placement of SENSKIN nodes across a bridge might cover an area of several kilometers. This fact constitutes a potent argument against employing a wired-based solution for the SENSKIN communication system, as that would imply: i) high installation costs, ii) a time-consuming deployment process that often requires tampering the structure itself and iii) various scalability issues originating mainly from the difficulty in adding extra nodes after the initial deployment of the system. By taking into consideration these drawbacks, along with end-user requirements, we decided for the SENSKIN communication system to be solely based on wireless telecommunication technologies.

A distinctive characteristic of all wireless telecommunication technologies is that they present certain communication range limitations. These limitations, in conjunction with the respective energy consumption profiles of these technologies, exclude the option of deploying a centralized network infrastructure, leading us to adopt instead a mesh networking architecture. Forming a wireless mesh network allows the communication system nodes to: a) form an ad-hoc network, meaning that they are able to communicate directly, without relying on any fixed network infrastructure, such as access points and ii) to participate in routing by relaying data for other nodes, so the determination of which nodes relay data is made dynamically on the basis of network connectivity. Apart from any deployment considerations, mesh networking is also useful from another perspective in the context of SENSKIN platform: in case of major catastrophic events, where bridge parts may have been damaged or even detached, data from isolated sensors could be flushed to an external ad-hoc node, acting as a failsafe data-harvesting element. Figure 3, presents a schematic representation of the SENSKIN communication system network architecture including its basic elements: SENSKIN, Gateway and Failsafe nodes.

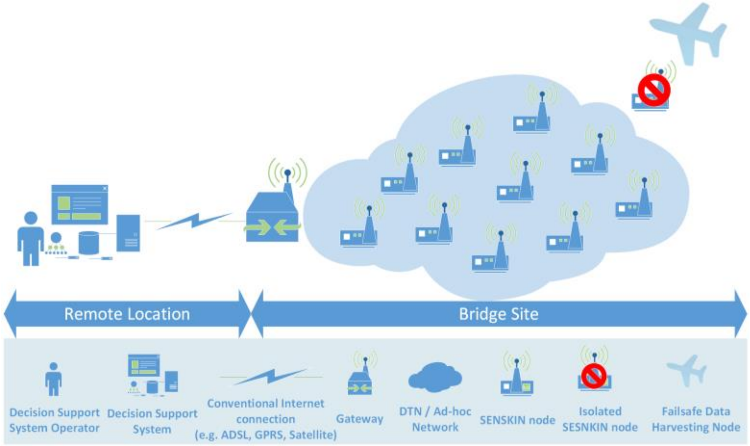

Figure 3: SENSKIN communication system network architecture

3.1.1. Delay/Disruption-Tolerant Networking

Although the concept of mesh networking is certainly helpful for the communication scenario investigated in the context of the SENSKIN project, it does not constitute the complete solution to the problem, especially when the specificities of the SENSKIN system (e.g. battery powered devices, open deployment environment etc.) are taken into account. Mesh networks are in general sensitive network structures, as they are prone to problems of intermittent connectivity due to power scheduling, node failure, and packet losses from unpredictable external factors, such as interference.

Apart from the communication issues within a mesh network, the connection of the gateway to the Internet might also present its own challenges. It is not uncommon for bridges to be located at places where communication infrastructure to the Internet is only available intermittently (e.g. remote places where only a satellite link is available) or it is not sufficient to cover monitoring needs due to the employment of low-capacity links (e.g. GPRS links).

In this context, we adopt the Delay/Disruption-Tolerant Networking (DTN) architecture [8], as a solution that could act synergistically with mesh networking to address the majority of the aforementioned problems. DTN architecture provides reliable data communication across failure-prone networks by specifying delay/disruption-tolerant network mechanisms, such as store-and-forward data forwarding, multi-path routing and hop-by-hop reliability.

3.2 Communication System Elements

SENSKIN communication system is composed by three different elements:

i) SENSKIN nodes: These are essentially SENSKIN devices placed at different locations of a bridge site. Each SENSKIN device is equipped with a communication module. Each communication module implements the network stack presented in Figure 4.

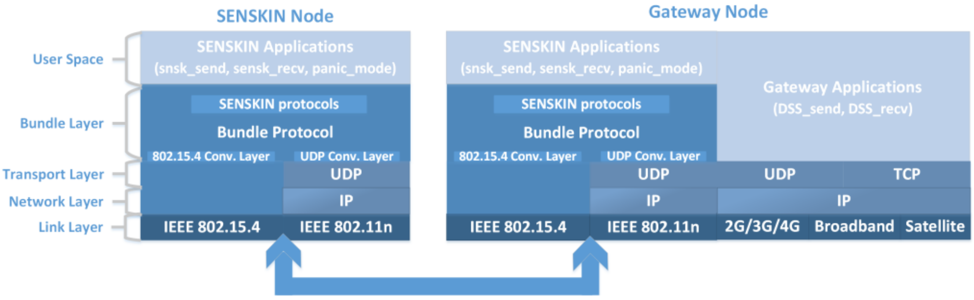

Figure 4: SENSKIN and Gateway nodes network protocol stack

At link layer, communication modules adopt a dual interface approach, by employing in particular the IEEE 802.11 and 802.15.4 standards, to provide both a performance- and energy-efficient solution. Bundle Protocol (BP) runs on top of them [9]. BP constitutes the basic protocol through which a delay tolerant networking architecture can be established among the nodes of a network. Through appropriate convergence-layer protocols, BP can run directly over IEEE 802.15.4. The same does not stand true for IEEE 802.11, where a UDP/IP stack is employed to allow BP pass its data over IEEE 802.11. SENSKIN-related protocols, which constitute custom-tailored solutions for supporting SENSKIN system operation logic, run at the Bundle layer. Finally, all SENSKIN communication applications used for sending and receiving data, along with certain panic communication mechanisms, which are planned to be developed in the context of SENSKIN project, run at the application layer.

ii) Gateway(s): Gateway nodes employ a dual network protocol stack that allows them to serve as a middleware platform for interconnecting the deployed SENSKIN nodes network with a remote administration facility. The first network stack is identical to the one employed by the SENSKIN nodes, while the second one employs mobile telecommunications, broadband or satellite link layer protocols, along with conventional Internet protocols, such as TCP, UDP and IP.

iii) Failsafe node(s): Failsafe nodes are similar devices to gateways in terms of operational capabilities with their basic difference being that that they are mobile.

4 REHABILITATION PLANNING AND DECISION SUPPORT

For the purpose of operationalization of sensor data for bridge rehabilitation planning, an expert system (see Figure 5) will be developed within the SENSKIN project. Calculation modules, a specific SENSKIN database, the end-user interface and measurements from the sensors will be linked via an orchestration module.

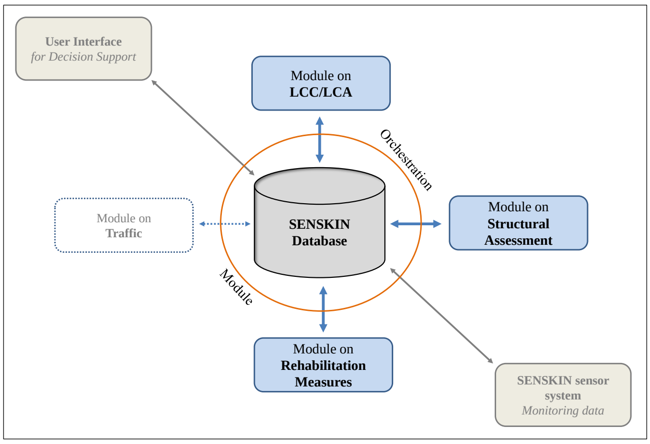

Figure 5: Expert system for decision support on rehabilitation planning

The orchestration module will ensure efficient and accurate data exchange between the single applications as well as initiate inquiries for specific background operation of the calculation modules. The calculation modules (e.g. for LCA, LCC and Structural Assessment) themselves will integrate existing approaches and new methodological advances for bridge rehabilitation planning. Methods such as life cycle assessment (LCA) and life cycle costing (LCC) will be connected with bridge structural condition assessment. Therewith, the technical and/or economic decision (oftentimes state-of-the-art) for or against specific measures will be extended by the assessment of environmental implications and external effects of bridge rehabilitation works. Parametrical and probabilistic risk-assisted scenario analysis will support pro-active decision making during bridge service life under operating and future loads (e.g. changes in traffic demand) as well as after extreme events (e.g. strong winds, earthquake). The SENSKIN database, as central information storage, will provide respective input data and will receive output data from calculation or information modules (e.g. sensor data, environmental and economic profiles, condition states for different bridge elements etc.). The user interface will serve for graphical visualization of results on singular (e.g. solely environment) or integrated analysis (e.g. optimized rehabilitation path combining structural, economic, social and environmental aspects) based on end-user specification. End-user, seeking for decision support on rehabilitation planning, shall benefit in this way from:

- an easy-to-use approach without need for in-depth knowledge;
- the possibility for integrated (as well as customized) economic and environmental assessment of different bridge rehabilitation measures including external effect;
- a lifecycle-based pro-active decision support on when and what rehabilitation measure to undertake as well as
- the modular and interoperable system approach, enabling for efficient communication (e.g. data exchange) as well as future expansion or integration (e.g. as part of a Bridge Management System or connected to other external calculation modules).

5 SYSTEM EXPERIMENTAL EVALUATION

The performance characteristics of the SENSKIN system will be determined through carefully controlled tests. Such tests will calibrate the change in electrical output of the sensor (capacitance and/or resistance) to variations in (a) applied load, and (b) ambient temperature. Amongst other things, the tests will quantify (a) variations in the applied load regime, (b) changes in the measured output due to repetitive load cycles, and (c) changes in the output with time under fixed boundary conditions. The sandwich construction of the system complicates the calibration exercise. The exercise has to investigate - as best can be - transient or permanent slip within the sensing membrane, and between the encapsulation and the substrate. For a number of reasons, current test standards for calibrating conventional strain gauges and various types of extensometers are not applicable to the SENSKIN system. It is necessary, therefore, to develop new test protocols to calibrate the system. Four rigs of the type shown in Figure 6 have been built to investigate the characteristics of the system subject to uniaxial loading. Note that although subject to a uniaxial strain, the output from a sensor bonded to the steel coupon (highlighted in the figure) is affected by the strain developed in the orthogonal direction. Tests are planned to be undertaken using 250mm long, 50mm wide *SENSKIN* sensors: that is, of a size that could be used for monitoring structural elements of a bridge. In addition, it is planned to design and construct a larger test rig to determine the performance of the system to bending.

Figure 6: Uniaxial test rig (load applied by torque wrench)

The output from the *SENSKIN* system has to be compared to the strains/displacements measured by an independent means. The two methods for calibrating sensors are through the use of (a) conventional sensors (principally, strain gauges), and (b) photogrammetric techniques. Because the former would not deliver all the requirements of the test programme, the latter will be adopted for most of the tests. Following the calibration exercise, a number of larger-scale tests will be undertaken in which sensors will be attached to steel or concrete beams, and/or frames: these tests will mimic rather extreme loading conditions on in-service structural elements. Outline arrangements for tests on beams and frames have been developed, but details of this part of the programme hinge on the results from the calibration tests.

6 CONCLUSIONS

This publication has presented the concept of operation and system modules of the SENSKIN monitoring solution that is currently being developed in the framework of the SENSKIN EC co-funded project. The project is currently in the first stages of developments regarding the prototyping of the skin-like sensor, the delay-tolerant communication system as well as the structural and maintenance decision support modules. The developments are closely following the system requirements, specifications and system architecture. As an imminent next step we can mention the prototyping of the SENSKIN sensor that will be tested at the labs of TRL. In parallel the communication system components are being integrated.

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