Fidler, P., Vardanega, P. J., Long, P., Webb, G., Stehle, J., & Middleton, C. (2013). Construction monitoring constraints and challenges: A feasibility study. In Y. L. Xu, S. Zhu, Y. Xia, Y. Q. Ni, S. S. Law, J. H. Yin, & Z. Q. Su (Eds.), Structural Health Monitoring for Infrastructure Sustainability: Proceedings of the 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure, 9-11 December 2013, Hong Kong, China. Hong Kong, China: Department of Civil and Environmental Engineering - The Hong Kong Polytechnic University.

The 6th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Hong Kong | 9-11 December 2013

CONSTRUCTION MONITORING CONSTRAINTS AND CHALLENGES: A FEASIBILITY STUDY

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ABSTRACT

This paper presents a study of the constraints and challenges faced by the authors when invited to study the feasibility of developing a monitoring system to provide specific information sought by the designer and contractor during the construction of the new 225m high, 48 storey steel-framed Leadenhall Building, located at 122 Leadenhall Street in London. The original goal of the study was to develop a system to assist with the active alignment of the building during construction, a key aim being to determine if the diagonal bracing members were in tension or compression. Installing strain gauges directly onto the steel bracing members was not permitted due to concerns regarding the integrity of the intumescent paint coating. A laboratory study to investigate the ability to measure strain directly from the paint surface was undertaken. Aesthetic concerns also imposed further restrictions on what could be attached to the structure. This feasibility study did result in the development of a new wireless sensor to measure temperature and optionally strain. In order to allow the sensors to be unobtrusive they were designed to fit within holes already present in the steel sections, originally used for attaching lifting equipment during erection of the steel frame. This exploratory study demonstrates that such collaborations can yield outcomes which, while not originally envisaged, nevertheless have the potential to benefit the research organisation, the designer and the contractor. This paper demonstrates how a bespoke wireless sensor platform can be rapidly developed using existing technologies to fit the needs of an individual project. The potential for use on future construction projects of a similar nature is also highlighted and future research directions discussed.

KEYWORDS

Steel-framed building, wireless sensor networks, construction engineering, intumescent paint, strain measurement, temperature measurement.

NOTATION

ADC	Analogue to Digital Converter
ERS	Electrical Resistance Strain
I^2C	Inter Integrated Circuit
PCB	Printed Circuit Board
RTC	Real Time Clock
TCXO	Temperature Compensated Crystal Oscillator
SHM	Structural Health Monitoring
SPI	Serial Peripheral Interface
SRAM	Static Random Access Memory

INTRODUCTION

The Leadenhall Building is a 225m high, 48 storey steel-framed-structure constructed in a very tight space near Liverpool Street Station in London. The geometry of this structure was controlled during construction using a process known as 'active alignment' in which the large diagonal bracing members at each end of the main building frame shown highlighted in Figure 1 are adjusted in length at set stages of construction to ensure the building remained within the required geometrical tolerance for verticality. At key stages during construction, the contractor has the option to jack apart the connections between the diagonal members in order to add or remove metal shims as needed to make adjustments to the vertical alignment of the building. If the diagonal members are in tension such jacking is not required. During these ‘active alignment’ operations it would be beneficial to the contractor to know prior to attempting any jacking, whether the individual diagonal members are in compression or tension. While this could be considered a simple construction engineering task, the constraints imposed on this particular project made development of a system with the required capability difficult. However, the resulting feasibility study documented in this paper discusses possible resolutions to some of these concerns which would have the potential for adoption on future construction projects with similar constraints.

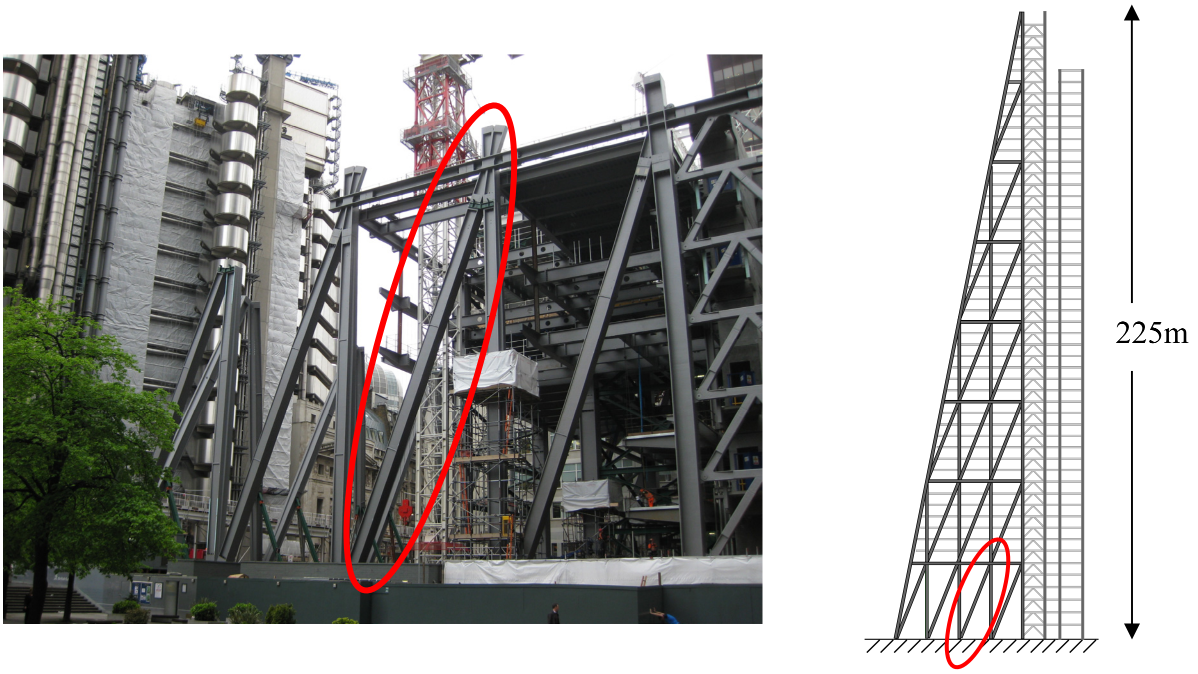


Figure 1. Left: Photograph of the Leadenhall building during construction (9th May 2012)
Right: Sketch of major structural components of the completed building (not to scale)

MONITORING AIMS

Papers discussing the limitations and challenges of using SHM systems have been published (e.g. Maser, 1988; Farrar & Worden, 2007 and Catbas et al 2007). However, the project constraints highlighted some interesting challenges not usually discussed in the aforementioned literature reviews. As a result of an extensive literature review, Webb and Middleton (2013) suggested that there are four categories of SHM studies:

(a) Anomaly Detection
(b) Damage Detection
(c) Threshold Check
(d) Model Validation

A fifth category could be postulated, namely (e) Sensor Demonstration studies.

Tension or Compression?

The primary goal of the study was to determine the feasibility of using a SHM system to determine whether the diagonal bracing members were in tension or compression. Applying the aforementioned categories, this is a *Threshold Check* task (as well as a *Sensor Demonstration* study). The threshold value to be checked is actually the crossing of a zero point (i.e. zero strain). Therefore the need to know an initial zero point strain reading prior to imposition of structural load, and/or the strain history of the bracing-member is essential to be able to achieve the aim of the monitoring project.

Temperature Measurement

A secondary goal of the study was to measure temperature at many locations on the building. The performance of the building components was specified by the designers at an assumed uniform 20°C. It is highly unlikely that this *uniform* temperature would ever occur in reality, with wind and sunlight acting on the building causing local variations in temperature throughout the structure. In particular, the surface temperature of the steel members is likely to vary considerably. An accurate temperature profile is essential for validation of many assumptions in the building's structural model and can assist the surveyor in an accurate determination of the alignment of the building during construction. While the monitoring system would assist the contractor during the construction phase, the ability to furnish the client, contractor and/or designer with long-term strain and temperature measurements would be of interest for those trying to better understand the performance of such structures. Therefore, it may be advantageous for any system developed to be robust enough for long-term deployment.

Constraints

By the time the research efforts had begun in earnest it soon became clear from discussions with the contractor (and a subsequent site visit to the steel fabrication yard) that it would not be possible to alter the steel beam fabrication process to allow for strain gauges and wiring to be installed on the beams prior to the application of the intumescent paint coating. The beams are fabricated and painted near Wigan, Greater Manchester, and then shipped to the site in London and immediately lifted into place (there is no provision for onsite storage at the Leadenhall Building site). As strain gauges can only measure changes in strain from the time they are first installed, a 'zero' reading would need to be taken prior to site delivery or during the erection process. In any event it must occur prior to any imposition of structural loads. The imposed constraints meant that the chance of getting a true 'zero' reading was very unlikely. Another option considered was analysis of vibration measurements of the diagonal members but it was concluded that the low frequencies would probably make data extraction and interpretation difficult. However, the use of vibration measurements may warrant future research. The contractor would not allow any of the intumescent paint to be removed either before or after installation. Therefore, any strain measurements would have to be taken from strain gauges attached to the paint coating, not directly onto the steel.

Initial studies generated concerns about the reliability of measuring strain using strain gauges attached to the surface of the intumescent paint. It was not known if such measurements would vary linearly with load in the same fashion as strain measurements taken directly on the steel. Therefore, a laboratory study was also undertaken as part of the wider feasibility study. Some preliminary results of this laboratory testing program are described later in the paper.

Other monitoring constraints included concerns on the adverse aesthetics of visible wires, thus suggesting that any monitoring system should be wireless. The many benefits of wireless systems are outlined in Lynch & Loh (2006) and Lynch (2007). Aesthetic concerns also meant that large sensor boxes mounted on the building frame exterior were not permitted. It had been suggested that small magnetically mounted boxes could be used, as these could be removed post-construction. Although this was an interesting suggestion, difficulties attaching magnets to the intumescent paint made this option problematic. It was eventually discounted on safety grounds as it could not be guaranteed that magnetically mounted boxes would not detach during construction.

DEVELOPMENT OF A 'BOLT' MOTE

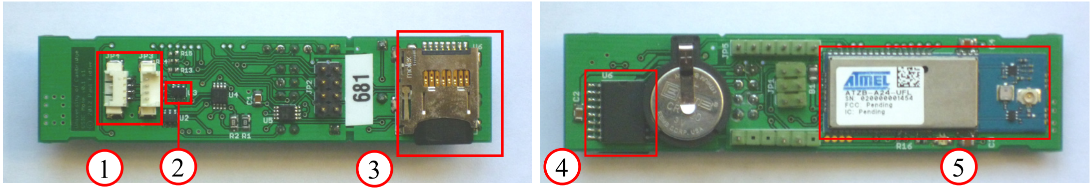
The lower-level diagonal bracing members are steel box sections and have a group of four M30 holes at two locations along their length for attaching a lifting plate with bolts. These holes are only used when lifting the steel box sections into place during construction. Given the requirements that any monitoring system be hidden or discreet it was proposed that the wireless sensor electronics and batteries could be largely hidden from view by fitting them through these M30 bolt holes.

Choice of Microcontroller

Researchers from the Centre for Smart Infrastructure and Construction (CSIC) at the University of Cambridge were already familiar with using Atmel AVR devices for wireless mesh networking having previously used Crossbow/Memsic Micaz and Iris motes. There are a number of wireless modules now available that integrate an Atmel AVR microcontroller with an IEEE 802.15.4 radio and either a chip antenna or a U.FL antenna socket. Using one of these modules immediately simplifies the design as the RF circuitry is already provided by the module: in a sense a lot of the difficult circuitry is pre-fabricated. Of the various wireless modules available, the Atmel Zigbit was chosen because, at only 18mm wide, it was the narrowest then available that could reasonably be soldered by hand. It incorporates an ATmega1281 microcontroller connected to an AT86RF230 radio on a single module with a castellated edge suitable for soldering directly to another PCB without additional pins or sockets. The Dresden Elektronik deRFmega128 module based on an ATmega128FRA1 microcontroller and radio chip has more SRAM (16KB) and a completely integrated radio, but this is 20.5mm wide and hence was not considered suitable for this project. Dresden Elektronik now sell a narrower module at just 13.2mm based on a ATmega256RFR2 microcontroller-radio. However this has pads underneath the module, rather than a castellated edge, making it difficult to solder by hand. Also, these smaller modules do not include the option of a U.FL connector for an external antenna.

Data-Logging

In previous wireless sensor deployments undertaken by the authors difficulties had been encountered with both the reliability of the wireless mesh networking (described in Hoult et al 2008) and with the data logger. These had resulted in data being lost. For this reason using on-board storage was considered, with each wireless sensor also capable of acting as its own data-logger. A microSD card socket, real-time clock (RTC) and coin-cell battery were therefore included on the board. This data-logging capability is however optional and this entire section of the PCB is designed so that it can be removed if not required. The RTC used is a Dallas Semiconductor DS3231 and incorporates a Temperature Compensated Crystal Oscillator (TCXO). The microSD card can be accessed using the SPI bus from the ATmega1281 while the RTC uses the I^{2}C bus. Figure 2 shows the locations on the board of some of the aforementioned devices.



1) Vertical and Horizontal I^{2}C connectors for external TMP100 sensors
2) Internal TMP100 temperature sensor
3) microSD card and socket
4) DS3231 Real-time clock
5) Atmel Zigbit module with U.FL connector

Figure 2. Temperature sensor board (left) underside; (right) topside

Temperature

Understanding overall temperature distribution is important for predicting/monitoring performance and geometry. Temperature is measured using three TMP100 I^{2}C temperature sensors. One of these sensors is mounted on the main PCB to measure ambient temperature within the hollow steel diagonal member. The other two are on flying leads, one intended to be attached directly to the steel surface inside the diagonal member and the other to measure external ambient temperature. The TMP100 temperature sensor was selected as it is one of the smaller digital temperature sensors available. Small size was important as space was at a premium on the main PCB. Furthermore, since one of the sensors was to be used to measure outside ambient air temperature, where it would be visible, small size was also important to minimise the perceived adverse visual impact. There is also a temperature sensor in the DS3231 Real-Time Clock (RTC) chip. Using the I^{2}C bus meant that in principle the two sensors on flying leads could be replaced by any other I^{2}C-based sensor, such as a STS21 temperature only or SHT21 temperature and humidity sensors from Sensirion. The nature of the I^{2}C bus also makes it simple to add additional sensors in the future, whereas adding extra sensors to the SPI bus would require additional chip select lines. Another option would have been to use an analogue temperature sensor but analogue readings may have been adversely affected by the wiring to the sensor and would not have had as much flexibility to migrate between different sensor types.

Strain

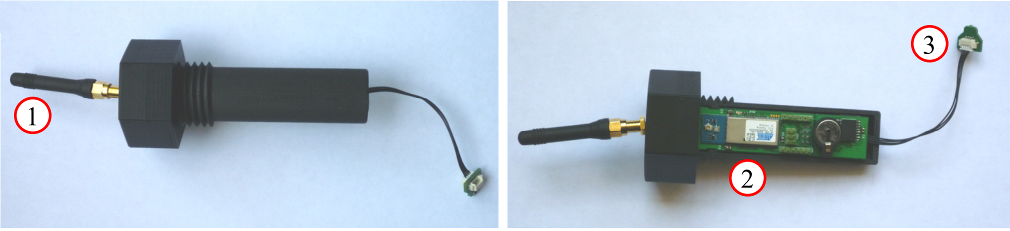
Strain measurements may be taken via an optional daughter board based on an Analog Devices AD7780 24-bit single channel ADC. The board includes a Texas Instruments INA122 instrumentation amplifier and permits the connection of Electrical Resistance Strain (ERS) gauges in either quarter, half or full bridge configurations.

Software

The software for the wireless board was based on the Contiki platform (described in Dunkels et al 2004). Contiki includes a port for the Atmel Zigbit modules as well as driver code for the AT86RF230 radio and several options for wireless mesh networking. FatFS (ChaN, 2013) was used for logging data to the microSD card. The researchers developed application code to take periodic readings from the temperature sensors, RTC and 24-bit ADC, which are then logged to the microSD card and transmitted over the radio. Care must be taken to disable the radio when reading from the SPI peripherals. The radio shares the SPI bus with these peripherals and the low-level radio driver code for the AT86FR230 actually reads from the bus in the radio interrupt handler. Although the AD7780 ADC also uses the SPI bus, it has no chip select line – analogue to digital conversions begin once power is applied to the chip. Power to the entire daughter board is controlled by switches on the main board.

Packaging Concept

The initial concept for the packaging was that the batteries and circuit boards would be fed through the M30 bolt holes in a tube, with only a small external temperature sensor and the antenna remaining outside. However, access and safety requirements lead to the development of a hollow plastic bolt to fit the M30 lifting holes. The initial prototype (produced on a rapid prototyping machine) is shown in Figure 3.



1) External antenna
2) Temperature board hidden in bolt housing
3) TMP100 temperature sensor on a flying lead

Figure 3. Temperature sensor board mounted in M30 bolt housing

LABORATORY TESTING

A laboratory program was undertaken to determine if strain measurements from gauges attached to the intumescent paint surface varied in the same fashion as those taken from gauges attached directly on the steel during load-controlled testing. The influence of temperature on the strain readings has as yet not been studied in the laboratory.

Experimental Design and Set-up

Figure 4. Beam 1 prior to testing

The laboratory testing program had the following aims: (1) to compare ERS gauges attached to the paint coating with gauges attached directly to the steel, (2) test the new temperature sensor for the wireless bolt mote, and

(3) test the use of the 24-bit ADC daughter board to measure strain. The 500 tonne, screw jacked controlled AMSLER rig located at the Cambridge University Engineering Department (CUED) laboratories (Figure 4) was used to perform four point bending tests on sample steel I-beams coated with the same intumescent paint coating that is used on the Leadenhall beams. The ERS gauges were attached to a data logger (a Solartron SI3535D Data Acquisition System) in a quarter bridge configuration. Five beam specimens were tested. All had varying nominal thicknesses (approximately 5 to 14 mm) of intumescent paint coating which can vary over the steel beam surface. Furthermore, on the building itself the specified minimum paint thickness varies with the vertical location on the building. Measurements from the five beam specimens indicate that the variability of paint thickness is approximately plus or minus 2 mm.

Strain Measurement on Intumescent Paint

On the web of each beam a run of three strain gauges was installed both on the surface of the paint and directly on the surface of the steel (where the intumescent paint had been removed) (see Figure 4). The central gauge was installed at the neutral axis of the beam section (where theoretically zero strain should be measured). The outer gauges were located closer to the flanges. The tension zone strain readings for each beam are displayed on the charts depicted in Figure 5. For each beam a load controlled test was conducted from 0 to 800kN with readings of strain (on the paint and on the steel) taken every 50kN (the load was increased in approximately 50kN steps). The load was then reduced in 50kN steps back to around 50kN. This process was then repeated. For each beam test there is a distinct shift between the ERS readings on the paint and on the steel. The strain readings on the intumescent paint appear to vary from approximately 1.1 to 1.4 times lower than those taken directly on the steel (Table 1). Also shown in Table 1 are average paint thicknesses for each beam specimen and the average temperature in the room measured during the testing.

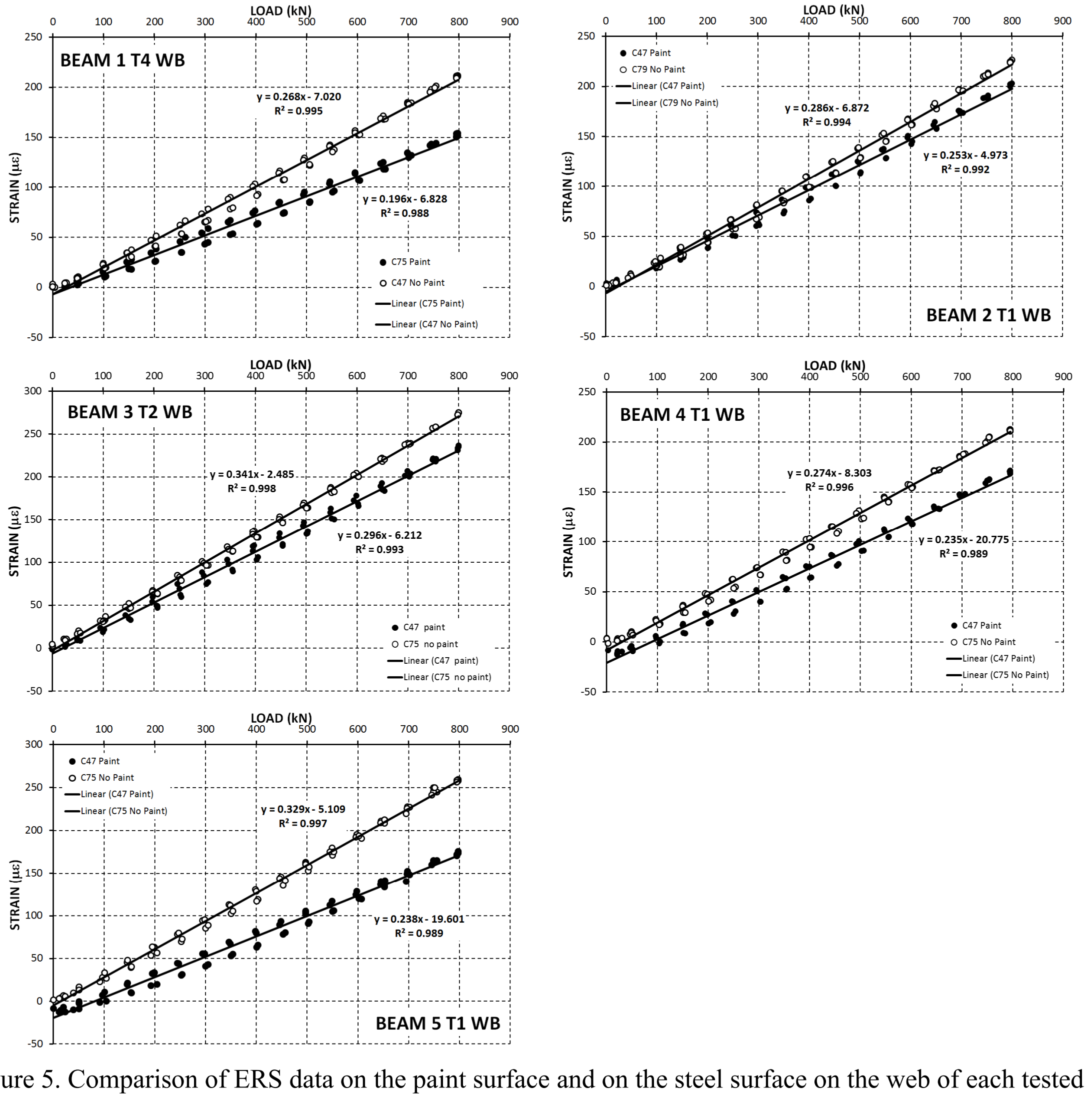


Figure 5. Comparison of ERS data on the paint surface and on the steel surface on the web of each tested beam

Table 1. Slope ratios computed from Figure 5 and average test temperatures and average paint thicknesses for the five beam specimens tested

	Average[1] Paint Thickness mm	**Average[2] Test Temperature °C**	**Slope Ratio**
Beam Test 1	13.6 (45)	17.7	1.4
Beam Test 2	5.0 (18)	16.1	1.1
Beam Test 3	10.9 (20)	17.1	1.2
Beam Test 4	13.6 (46)	18.4	1.2
Beam Test 5	10.7 (26)	19.3	1.4

[1] values in brackets are the number of measurements used to compute the average value
[2] based on measurements from External 1 TMP100 and External 2 TMP100 only

Temperature Sensor Validation

Figure 6 shows temperature readings taken by each of six active sensors during Beam Test 4. The lowest two plots of temperature readings are from two thermocouples (Thermocouple 1 and Thermocouple 2) resting on the surface of the beam and measured using the same data logger used to take the strain readings (the thermocouples were used in this test as controls). The other four temperature plots are recorded by the wireless temperature sensor board. This board has one on-board TMP100 temperature sensor (Internal TMP100), and two further temperature sensors on flying leads (External 1 TMP100 and External 2 TMP100). The DS3231 RTC also has a built-in temperature sensor (RTC Temp DS3231). The Internal temperature sensor (TMP100) consistently reads higher than the other sensors. This is probably due to warming by the Zigbit module (the temperature sensor is located directly underneath). During the laboratory tests no effort was made to minimise the power consumption of the Zigbit module - it was essentially on all the time, hence the observed warming is not unexpected. The two external TMP100 sensors readings are within a degree or so of those measured by the thermocouples, well within the plus or minus 2°C accuracy claimed in the TMP100 datasheet (Texas Instruments, 2007). Although the temperature sensor in the DS3231 RTC has a resolution of 0.25°C it is only accurate to plus or minus 3°C. The temperature reading from this sensor is only updated internally once every 64 seconds (Maxim Intergated Products Inc., 2013) regardless of how often it is actually read by the software. This sensor could be used as a means of 'sanity checking' the other sensors, but should probably not be relied upon for anything else. In Figure 6 the DS3231 RTC temperature data remains stable despite the TMP100 sensors all showing a slight spike in temperature at about 11:38 a.m., when the experimental setup was being checked between two cycles of loading.

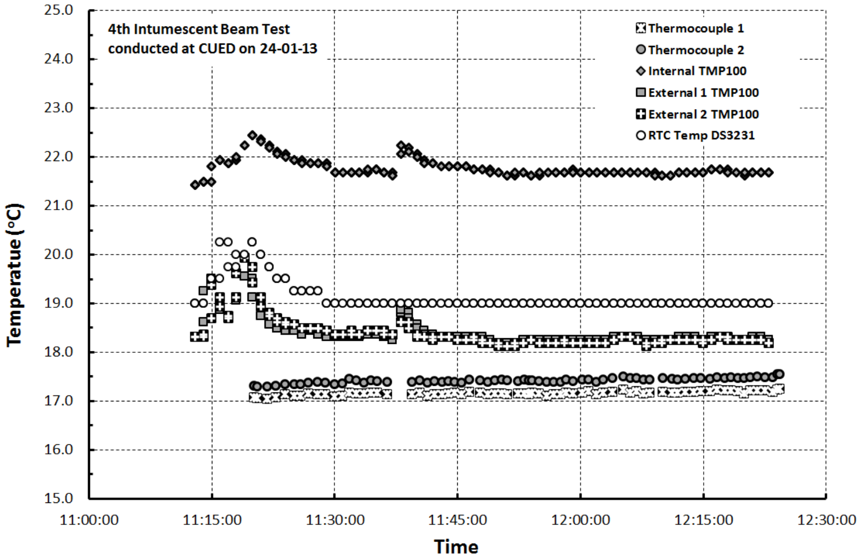


Figure 6. Temperature data taken during Beam Test 4

Strain Measurement with the New Board

For the majority of the experimental program the ERS strain gauges had been connected to the Solartron data logger. For the final beam test however it was decided to disconnect one of the strain gauges located on the bottom flange (labelled C65 on Figures 7 and 8) from the data logger and instead connect it to the one of new wireless motes in order to test functionality of the 24-bit ADC daughter board. Sufficient data had already been obtained in a previous test on this beam for the study of the effect of the paint on the strain readings. This final test was purely to validate wireless strain measurement using the new mote. Figures 7 and 8 show the strain readings from the other two ERS gauges on the bottom flange (labelled C63 and C67) measured using this conventional data logger system, compared with the strain measured using the ERS gauge connected to the ADC board on the wireless mote. Results from the previous tests indicated that the slopes of the fitted lines drawn through load versus strain data from these ERS gauges should be comparable. Figures 7 and 8 both clearly show that the strain readings are indeed comparable when the strain gauge is logged using the new wireless sensor board.

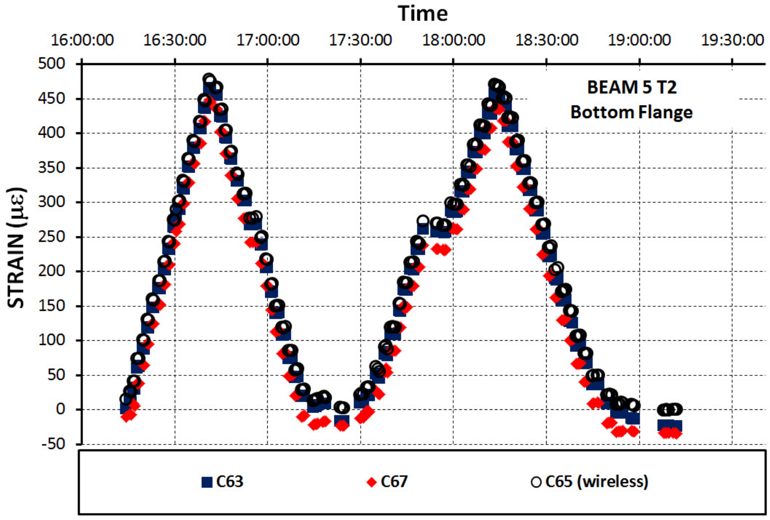


Figure 7. Comparison of strain readings from the new wireless sensor compared to strain gauges read using the Solartron data logger – strain versus time (load varying)

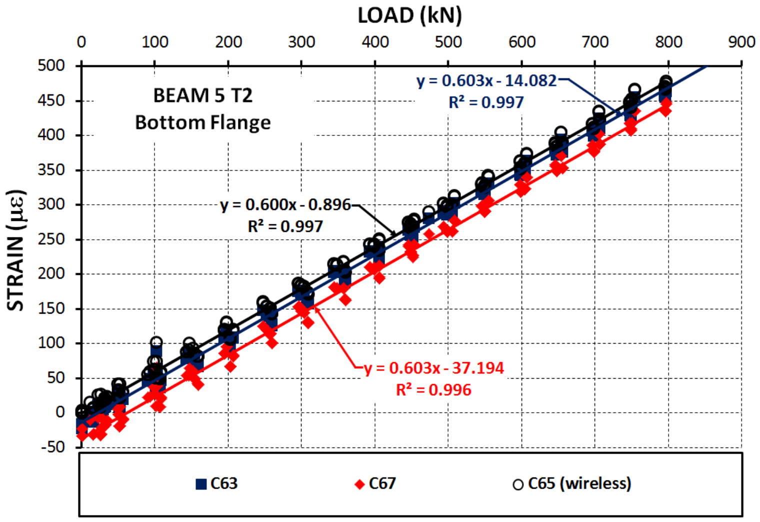


Figure 8. Comparison of strain readings from the new wireless sensor compared to strain gauges read using the Solartron data logger –strain versus load

SUMMARY

This paper has outlined some of the challenges faced with developing a solution for the measurement of strain and temperature on intumescent paint coated diagonal bracing members on the Leadenhall Building during the construction phase. This feasibility study provides some useful conclusions if a similar challenge is presented in the future.

The following concluding remarks are made:

(a) There is some indication that installation of ERS gauges on intumescent paint is a possible option. However, the potential for creep and drift with diurnal and seasonal temperature changes means that further testing is needed to determine how viable this option actually is for a real structure.
(b) Installation of strain gauges under the paint would be a more robust solution. However, this requires early recognition of the need for such a monitoring system in the detailed design stage, given the difficulties of altering specifications once fabrication has commenced. The inability to maintain such a solution (no access once the paint is applied) means that this may not be a desired solution if the robustness of the sensor system must be guaranteed.
(c) A ‘zero’ point or ‘reference’ point is necessary for successful threshold check studies as in this project. In this case the ‘zero’ point is the threshold being sought – without it the main aim of the monitoring cannot be realized. The strain gauges could be zeroed at many stages during the installation of the diagonal bracing members but a zero point must be measured before the imposition of structural loads on the members themselves.
(d) The demand for installation of a wireless solution is acceptable if indeed the system is only to be used during construction. For a longer-term deployment battery life and the need for access to the installed motes remains a major constraint for wireless solutions.
(e) While not originally envisaged in the early stages of the project – the development of the instrumented bolt has yielded a new sensor board to discretely mount temperature sensors which could be adapted for use with other packaging.

ACKNOWLEDGMENTS

This work was supported by EPSRC Grant no: EP/I019308/1: Innovation Knowledge Centre for Smart Infrastructure and Construction. Thanks are also due to Mr Karl Wilkinson from Laing O’Rourke who provided site access and for his helpful advice. Thanks to Mr Martin Touhey and Mr Peter Knott for their technical services and helpful suggestions, to Mr John Gradwell for arranging a visit to see the steel fabrication and painting process and to Miss Yu Ge for helping install the thermocouples during the fourth beam test.

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