Robotic Installation of Wireless Strain Gauges into Precast Concrete Elements

Tresor Tshimbombo
Civil and Environmental Department
University of Strathclyde
Glasgow, United Kingdom
t.tshimbombo.2018@uni.strath.ac.uk

Marcus Perry
Civil and Environmental Department
University of Strathclyde
Glasgow, United Kingdom
m.perry@strath.ac.uk

Chris Hoy
COWI UK Limited
Glasgow, United Kingdom
chhy@cowi.com

Efi Tzoura
Highways England
Bristol, United Kingdom
Efi.Tzoura@highwaysengland.org.uk

Christos Vlachakis
Civil and Environmental Department
University of Strathclyde
Glasgow, United Kingdom
christos.vlachakis@strath.ac.uk

Jack McAlorum
Civil and Environmental Department
University of Strathclyde
Glasgow, United Kingdom
jack.mcalorum@strath.ac.uk

***Abstract*— This paper outlines our group's recent progress in the robotic deployment of wireless sensors within concrete precast elements. This study is focused on the automated installation of embedded vibrating wire strain gauges (VWSGs), interrogated by a wireless node. This paper outlines the initial development of our robotic process and the magnetic sensor packaging which is used to encapsulates wireless nodes and VWSGs. The system has been deployed onto an oiled metallic formwork, to simulate conditions found in precast factories. The magnetically attached sensor packaging can withstand loads imposed during the pouring of concrete and its vibration. The results of this pilot study are promising and could allow robotics to be successfully integrated into precast processes so that smart precast segments can be produced at scale.**

Keywords—automated inspection, smart structure, structural health monitoring, Robotic deployment, construction.

I. INTRODUCTION

Structural health monitoring (SHM) of large civil infrastructures is a key component of asset management. SHM is a arguably not a new field in civil engineering, with a variety of applications worldwide both on existing and new infrastructures. Efforts are being made to establish infrastructure-tailored specifications for the design and execution of SHM systems. Such specifications are being developed at a rapid speed [1]. There are, for example, standards established for highways bridges [2] which specify the types, quantity, and positioning of sensors on the infrastructure. Although such specifications are an enormous help, there is still the challenge of applying them consistently and reliably in an infrastructure or across same types of infrastructures. The present work addresses this challenge by proposing a robotic installation of sensors. Sensors play a crucial role in the process of monitoring structure behaviour. They can be surface-mounted or embedded into components to measure engineering (strain and stress) or environmental features (temperature, moisture) [3]–[11]. Sensors are generally installed manually on-site, tying them to rebars, when embedded into concrete, or attaching them (by screwing or gluing) on the surface of the component to be monitored. This comes with unavoidable downfalls such as diminished accuracy, heavy reliance upon expert workforce, and probable delays to the infrastructures' commissioning.

Despite heavy and increasing adoption in other sectors such as aeronautics, automobile, food, electronics and pharmaceutical, the use of robotics in construction and civil engineering is still in its infancy [12], [13]. The reasons for this could include the lack of adapted robotic solutions or the level of inertia in the construction industry that can make innovation challenging. Therefore, the authors could find no evidence of demonstrations of the robotic installation of embedded sensors into concrete.

This paper will present an initial methodology of the automatic installation of sensors embedded into precast concrete elements to measure strain and temperature. This study is part of a project on the design and fabrication, at lab-scale, of smart precast tunnel segments using the Lower Thames Crossing [14] as a case study for design. Wireless electronics will be embedded and surface mounted onto concrete segment using robotics on a lab-scale production line. This will make the components smart, so that they can track their location, loads, and performance through their service life.

This study presents combined advantages both from the asset management point of view and from the fabrication of smart precast elements point of view. Sensors installed in and on smart precast elements will serve as a key components to continuously monitor the structural and physical behaviour of the infrastructure, and trigger the maintenance responses if needed. This will contribute in making the infrastructures more reliable in the long run. Integrating robotics in the repetitive process of deploying sensors in the production line of precast elements will bring more precision, accuracy, and flexibility to changes. Incidentally, robotics comes with additional benefits in terms of time and safety. The reduction or suppression of site works interventions after erection of the smart elements will help to save time and the removal of human operators from moulds during the deployment of sensors in the production plants will reduce risks of hazards.

II. BACKGROUND

The concrete precast industry is highly mechanised and already involves a reasonable level of automation to perform tasks such as lifting forms or preparing their interior surfaces before casting concrete. There are two main mode of production of prefab elements: the static method and the carousel technique. The main difference between the two is in the latter, the mould move during the process on a carousel system. In either case, though, the process of fabricating

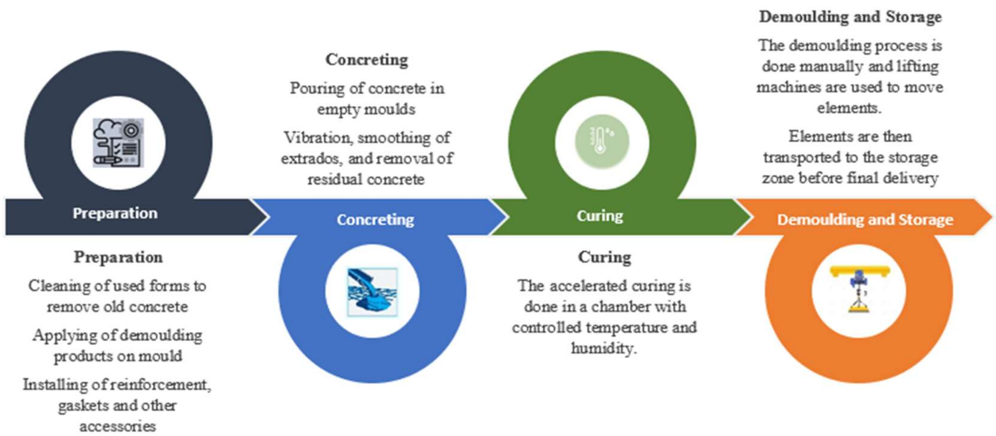

Fig. 1. Flowchart of prefab tunnel segment manufacturing

prefab elements is very similar and can be summarized in four main steps as illustrated in Fig. 1:

- the preparation;
- the concreting;
- the curing process;
- the demoulding and storage.

Although certain level of automation can be involved in many of the mentioned steps. However, the integration of robotic solutions that could be of interest to our application of robotically installing sensors into prefab elements could intervene in the preparation phase as it will be further demonstrated. In the following lines, we present a brief theoretical background on the components intervening in the robotic deployment of sensing elements.

A. Vibrating wire strain gauge

In this work, we have opted to develop a process for the robotic installation of vibrating wire strain gages (VWSGs). VWGS are the most common types of sensors used in concrete based infrastructures to measure strain. Even though their operating principle was discovered later than the one governing widely popular resistive strain gauges (RSG), they quickly became the preferred choice of sensors embeddable into concrete for long-term strain measurement [15]. The operating principle is of a tensioned wire which tension (strain) varies with its resonant frequency. The change in the stress of the wire attached at the two extremities will lead to a change in resonant frequency [16]. The first part of equation (1): $f_0 = (1/2L)(\sigma/\rho)^{1/2} = (1/2L)(E\varepsilon_0 g/\rho)$, where L, σ, ρ are respectively the length of the vibrating wire, the stress, and the density, gives a general equation that can be used to correlate the resonant frequency f_0, to a variety of structural parameters. The second part of equation (1), where E, ε_0, and g are respectively the modulus of elasticity, the strain, and the gravitational acceleration, obtained using the Hooke's law, gives an indirect measure of the wire strain once its corresponding resonant frequency is known.

VWSGs are made of three basic elements as shown in Fig. 2. The vibrating wire, the plucking coil and the end blocks. To measure the strain, the coil plucks (excites) the wire with a pulse varying frequency to vibrate at his resonant frequency. The corresponding resonant frequency is then correlated to strains values through a calibrated equation provided by manufacturers.

In addition to being a mature technology, the VWSGs present many advantages over RSG, especially for long-term applications on concrete infrastructures. They are generally more accurate [17] and robust [10], [18], they produce stable measurements [19] with low drift [20] in the long-term, and they have a lower failure rate. Table 1 compares VWSG and RSG regarding some key features and shows the motivation behind them being the technology choice for this project.

B. Wireless transmission

VWSGs are not, by default, wireless sensors. Wireless transmission is preferred when robotically deploying sensors as: i) wires would themselves require management by the robot; ii) when embedded into concrete, wires can provide pathway for water ingress into a concrete structure, and this can lead to leakage of barriers, the accelerated corrosion of reinforcement, or the damage of the sensors.

Wireless communication within civil infrastructure SHM has grown considerably in the last two decades. As a matter of terminology, it is worth noting that a standalone wireless

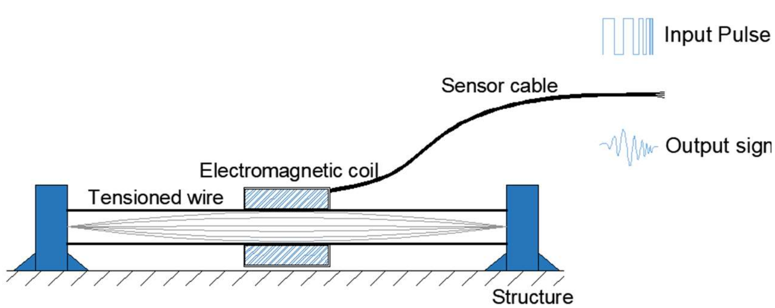

Fig. 2. Schematic representation of a VWSG

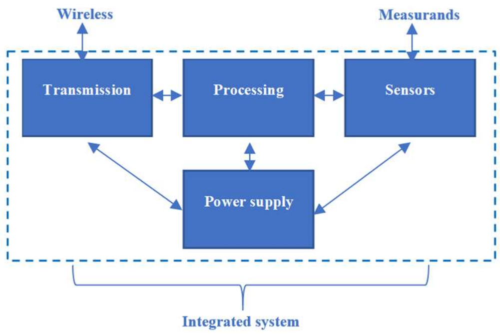

Fig. 3. Standalone wireless system

sensor system (including sensor, processing, power supply, and transmission), see Fig. 3, can often be referred to as a wireless node [3], [21]. This terminology is the same used in this paper. Wireless nodes are an attractive alternative to cables for several reasons. They offer more flexibility in their deployment and can, therefore reduce the overall cost of installation compared to wired systems [8], [21], [22]. However, wireless nodes embedded in a dense and/or humid material as concrete are faced with challenges such as the propagation loss of electromagnetic waves. Also, metallic elements (reinforcement bars and metallic fibers) can generate electromagnetic interference with the electronics when embedded into concrete [23].

C. *Robotic installation of sensors*

There are currently some real-world applications of the use of robotics in the construction industry. They range from novel technologies such as 3D-printing, construction robots, or the automation of some precast concrete plant processes. The production of concrete precast elements occurs in a more controlled environment (temperature, space distribution, sequencing of operations) than on-site operations. The intensive use of machinery for key operations such as lifting, transporting, or concrete mixing not only improves safety, but also optimizes efficiencies in production. In the manufacture of a large number of the same type of elements such as tunnel segments, these considerable features make it possible to produce 'copies' numerous segments with high accuracy. This adoption of some level of automation in precast plants makes it easier to integrate robotics. As for robotic applications in the prefab industry, there are already market solutions consisting of robotic arms used in the preparation process to install and remove shutters and delineate location to install forms [24].

III. METHOD

A. *Robotic technology*

The robotic deployment of sensors has not been explicitly demonstrated according to the authors' best knowledge. However, the process of deploying them could consist of a simple pick and place operation that existing technology can easily perform. In this study, the robotic installation of a wireless sensor to measure strain is conducted using a collaborative robot which features are provided in the following lines. The strain sensors robotically deployed should:

- cause minimal disturbance to the whole element;
- be sufficiently sensitive to capture accurately even small variations of the measured property;
- move as little as possible form their initial position, even after vigorous vibration.

a. b.

Fig. 4. a. Typical Universal Robot (https://www.universal-robots.com/products/ur10-robot/)
b. Robotiq Gripper Model Hand E (https://robotiq.com/products/hand-e-adaptive-robot-gripper)

Fig. 5. VWSG Geokon Model 4204

At the lab-scale wireless sensor deployment is realized using a universal robot UR10 (See Fig. 4a). It is a collaborative robotic arm widely used in modern manufacturing plants. It has a reach of 1.3 meters and a payload of up to 10 kg. A UR10 was chosen for its affordability, ease of programming, and built-in safety features that allow the robot to work in the space as a human operator without barriers. An appropriate end-effector (Fig. 3b) was also chosen to pick-and-place embeddable sensors. Of the three options (magnetic grippers, vacuum grippers, and finger grippers) we opted for a finger gripper that offers a higher IP resistance, a larger range of motion (hence more flexibility in what can be picked up), and a higher level of customizability.

B. *Sensor*

In this study, the Geokon vibrating wire strain gage Model 4202 (Geokon Inc., 2018) in Fig. 4 will be used to monitor concrete strain. With a 57 mm length, it is recommended for direct embedment in mortar and small aggregate concrete. This is an important feature for the study of concrete-based models such as the one to be fabricated in the lab. The rest of technical features are reported in Table 2.

C. *Standalone wireless system*

The first iteration towards a physical standalone wireless sensor is represented in Fig. 6. It includes:

- a *VWSG Geokon Model 4202* previously described;
- a *vibrating wire (VW) interface Geokon Model 8960-01* [25] that allows the VWSG to be queried via industry standard Modbus Remote Terminal Unit protocol over a simple half-duplex RS-485 connection;
- a *RS-485 Module* connected to the VW interface

TABLE I. COMPARATIVE TABLE OF RSG AND VWSG

Features	**Conventional sensors**	
Sensor type	**RSG**	**VWSG**
Resolution (με)		0.4-1
Range (με)	3000-10,000	
Accuracy (με)		1-2% (FSR) [16]
Linearity	0.3 - 0.5% Full Scale Reading (FSR) [28]	
Typical failure rate	Up to 70% after 7 years [29]	Up to 30% after 25 years [29], [30]
Apparent elastic modulus (N/mm^2)	40-1000 [31]	390-82,390 [16]
Temperature ranging	-20 to 180	-20 to 200
Sampling frequency (Hz)	170Hz	0.5-20Hz
Estimated Cost (£)[a]	40-330	40-100

[a]Sensor without interrogation system

- a *Microcontroller board Arduino Mega 2560* [26] to process the signal and transmit the signal.

All the components are connected to a computer via USB cable serving a power supply for the whole system. As for now, the interrogation system cannot communicate wirelessly and use instead a cable communication to interface with the computer. The final standalone wireless sensor should be compact and include smaller microcontroller board with wireless capability and an autonomous power supply.

IV. PILOTS RESULTS

This study aim was to present and demonstrate a novel approach of using robotics to install embedded VWSGs into precast elements. In this section, some pilots results obtained so far, are briefly presented in the following with the primary objective of demonstrating our approach.

A. *Wireless standalone container: magnetic box*

This box which 3D model can be seen on Figure 7 was 3D-printed in plastic and represent the container of miniaturised electronics to interrogate the VWSGs. The cover is made of 4 holes to fit in Neodymium magnets and provide a strong adhesion of the box on a metallic surface before, during, and after casting concrete. The box position did not change even after intense vibration applied to concrete.

B. *VWSGs measurement*

To assess initial performance of the electronic parts of the standalone system and the collection of data from the sensor, the VWSG was placed in a tensile testing machine and submitted to controlled cycles of tractions and compressions. This demonstration had a double purpose of verifying that the measurement could be collected from a lab-made interrogation system and that the sensor response was stable under repetitive cycles of loadings. Fig. 8 contains the results of the test.

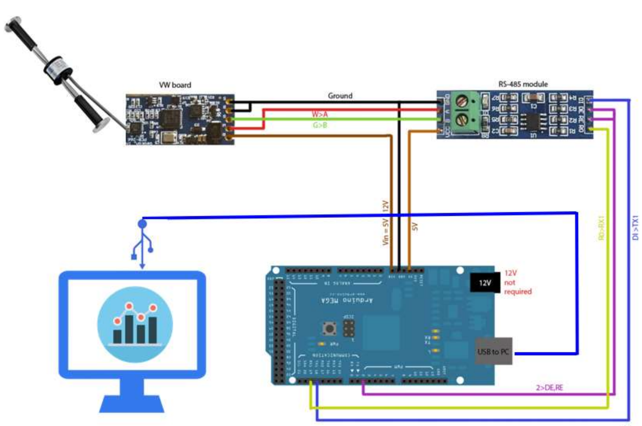

Fig. 6. Pinout of standalone sensor to read strain from VWSG.

TABLE II. TECHNICAL SPECIFICATIONS VWSG GEOKON MODEL 4202 [16]

Length (mm)	57mm
Nominal range	3000 με
Effective Modulus	4205.80 N/mm^2
Resolution	±0.1 με
System Accuracy	±2.0% FSR
Thermal Coefficient	12.2 με
Frequency Range	1400-3500 Hz
Coil Resistance	50 **Ω**
Temperature range	-20 to +80 ℃

C. *Robotic deployment of VWSGs*

As with the rest of the box, the VWSGs token to demonstrate the process of robotically installing the sensor was 3D printed and attached to the box to form the wireless standalone system. This way the whole set of elements could be gripped by the robot and installed at the designated location. This exercise was repeated in different occasions varying the speed of the robot. In the demonstration of the embedding process in [27], it is possible to see the pick-and-place realised by the robot, the pouring and vibration of concrete and ensued vibration.

V. CONCLUSIONS AND FUTURE WORK

This paper briefly presented preliminary results on robotic deployment of wireless vibrating wire strain gauges

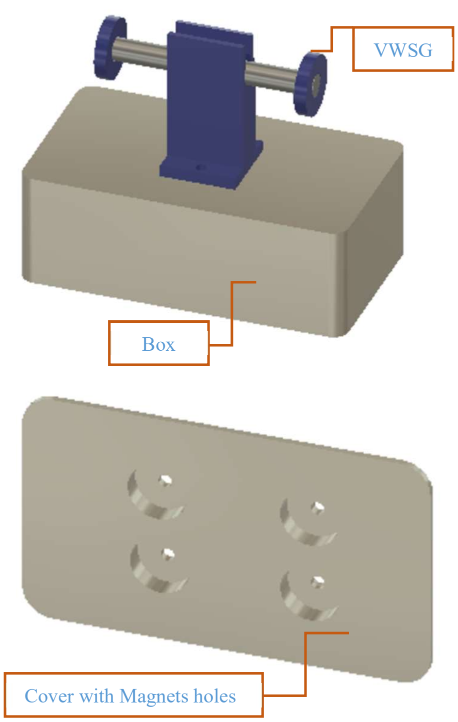

Fig. 7. 3D model of the standalone wireless box

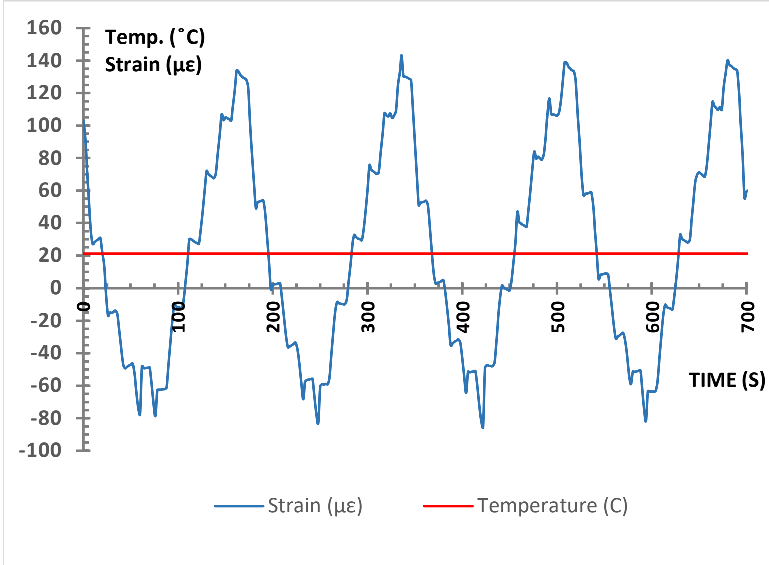

Fig. 8. Strains and Temperature measurement from the VWSG under controlled loading in the tensile testing machine.

embedded into concrete. Wireless interrogation was achieved using a standard microcontroller board type Arduino. Using 3D-printed elements, it was possible to mimic the real sensor and the enclosure containing the electronics and use them to tune the automate deployment process. Using a low cost six-axis robotic arm, the enclosure can be gripped and placed at a designated location and onto the oiled metallic surface of a formwork, and held in place by neodymium magnets embedded into the to the cover of the box. This whole set up remained immobile during concrete pouring and vibration. In addition, results from the demonstration of the strains and temperature measurement have been presented showing a regular evolution of strains under controlled loadings.

In future work, further steps will be undertaken to miniaturize the size of the enclosure and select an appropriate material adapted to withstand loading and avoid stress concentration during the installation process and service life. At the same time, appropriate small size microcontroller platforms should be further investigated.

REFERENCES

[1] P. Cawley, "Structural health monitoring: Closing the gap between research and industrial deployment," *Struct. Heal. Monit.*, vol. 17, no. 5, pp. 1225–1244, Sep. 2018, doi: 10.1177/1475921717750047.

[2] F. Moreu, X. Li, S. Li, and D. Zhang, "Technical Specifications of Structural Health Monitoring for Highway Bridges: New Chinese Structural Health Monitoring Code," *Front. Built Environ.*, vol. 4, p. 1, Mar. 2018, doi: 10.3389/fbuil.2018.00010.

[3] S. Taheri, "A review on five key sensors for monitoring of concrete structures," *Constr. Build. Mater.*, vol. 204, pp. 492–509, Apr. 2019, doi: 10.1016/j.conbuildmat.2019.01.172.

[4] N. C. Yoder and D. E. Adams, "3 - Commonly used sensors for civil infrastructures and their associated algorithms," in *Woodhead Publishing Series in Electronic and Optical Materials*, vol. 55, M. L. Wang, J. P. Lynch, and H. B. T.-S. T. for C. I. Sohn, Eds. Woodhead Publishing, 2014, pp. 57–85.

[5] B. Glišić and D. Inaudi, *Fibre optic methods for structural health monitoring*. John Wiley & Sons, 2007.

[6] Y.-K. An, M. K. Kim, and H. Sohn, "4 - Piezoelectric transducers for assessing and monitoring civil infrastructures," in *Sensor Technologies for Civil Infrastructures*, vol. 55, M. L. Wang, J. P. Lynch, and H. Sohn, Eds. Woodhead Publishing, 2014, pp. 86–120.

[7] K. J. Peters and D. Inaudi, "5 - Fiber optic sensors for assessing and monitoring civil infrastructures," in *Woodhead Publishing Series in Electronic and Optical Materials*, vol. 55, M. L. Wang, J. P. Lynch, and H. B. T.-S. T. for C. I. Sohn, Eds. Woodhead Publishing, 2014, pp. 121–158.

[8] C. R. Middleton, "Technologies for bridge monitoring," in *Bridge Monitoring*, London: ICE Publishing, 2016.

[9] C. Fernando, A. Bernier, S. Banerjee, G. G. Kahandawa, and J. Eppaarchchi, "An Investigation of the Use of Embedded FBG Sensors to Measure Temperature and Strain Inside a Concrete Beam During the Curing Period and Strain Measurements under Operational Loading," *Procedia Eng.*, vol. 188, pp. 393–399, 2017, doi: https://doi.org/10.1016/j.proeng.2017.04.500.

[10] Y. Ge, M. Z. E. B. Elshafie, S. Dirar, and C. R. Middleton, "The response of embedded strain sensors in concrete beams subjected to thermal loading," *Constr. Build. Mater.*, vol. 70, pp. 279–290, Nov. 2014, doi: 10.1016/j.conbuildmat.2014.07.102.

[11] K. Kesavan, K. Ravisankar, S. Parivallal, P. Sreeshylam, and S. Sridhar, "Experimental studies on fiber optic sensors embedded in concrete," *Meas. J. Int. Meas. Confed.*, vol. 43, no. 2, pp. 157–163, Feb. 2010, doi: 10.1016/j.measurement.2009.08.010.

[12] M. Gharbia, A. Y. Chang-Richards, and R. Y. Zhong, "Robotic technologies in concrete building construction: A systematic review," in *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*, 2019, pp. 10–19, doi: 10.22260/isarc2019/0002.

[13] B. Nematollahi, M. Xia, and J. Sanjayan, "Current progress of 3D concrete printing technologies," in *ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction*, 2017, pp. 260–267, doi: 10.22260/isarc2017/0035.

[14] Highways England, "Lower Thames Crossing - Route - Highways England." https://highwaysengland.co.uk/our-work/lower-thames-crossing/route/ (accessed Nov. 20, 2020).

[15] B. Glisic, "One Hundred Years of Strain Sensing in Civil Structural Health Monitoring," in *Structural Health Monitoring 2019 Enabling Intelligent Life-cycle Health Management for Industry Internet of Things (IIOT)*, 2019, pp. 1704–1714.

[16] Geokon Inc., "Model 4200 Series Vibrating Wire Strain Gages Instruction Manual," 2018, [Online]. Available: https://www.geokon.com/content/manuals/4200-4202-4204-4210_Strain_Gages.pdf.

[17] X. You, Lin Xu; Yong, *Structural Health Monitoring of Long-Span Suspension Bridges*. London: CRC Press, 2011.

[18] S. A. Neild, M. S. Williams, and P. D. McFadden, "Development of a vibrating wire strain gauge for measuring small strains in concrete beams," *Strain*, vol. 41, no. 1, pp. 3–9, Feb. 2005, doi: 10.1111/j.1475-1305.2004.00163.x.

[19] P. Sreeshylam, K. Ravisankar, S. Parivallal, K. Kesavan, and S. Sridhar, "Condition monitoring of prestressed concrete structures using vibrating wire sensors," *Int. J. COMADEM*, vol. 11, no. 3, pp. 46–54, 2008.

[20] A. Simon, A. Courtois, T. Clauzon, E. Coustabeau, and S. Vinit, "Long-term measurement of strain in concrete : durability and accuracy of embedded vibrating wire strain gauges," *SMAR 2015 Third Conf. Smart Monit. Assess. Rehabil. Civ. Struct.*, no. September, 2015.

[21] D. Huston, *Structural sensing, health monitoringm and performance evaluation*, vol. 369, no. 1. Burlington, Vermont, USA: Taylor & Francis, 2011.

[22] P. J. Bennett, Y. Kobayashi, K. Soga, and P. Wright, "Wireless sensor network for monitoring transport tunnels," *Proc. Inst. Civ. Eng. - Geotech. Eng.*, vol. 163, no. 3, pp. 147–156, Jun. 2010, doi: 10.1680/geng.2010.163.3.147.

[23] S. Jiang and S. V. Georgakopoulos, "Optimum wireless powering of sensors embedded in concrete," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2 PART 2, pp. 1106–1113, Feb. 2012, doi: 10.1109/TAP.2011.2173147.

[24] Weckenmann, "All products," 2019. https://weckenmann.com/en/products/all-products (accessed Feb. 06, 2020).

[25] Geokon, "Modbus Vibrating Wire Interface." Accessed: Nov. 23, 2020. [Online]. Available: https://www.geokon.com/content/datasheets/8960-01C-Addressable-VW-Interface.pdf.

[26] "Arduino Mega 2560 Rev3 | Arduino Official Store." https://store.arduino.cc/usa/mega-2560-r3 (accessed Nov. 23, 2020).

[27] T. Tshimbombo, "Robotic installation Magnetic Box - YouTube," 2020. https://www.youtube.com/watch?v=dGQTODdub6U&feature=youtu.be&ab_channel=TresorTshimbombo (accessed Nov. 23, 2020).

[28] T. M. I. Lab, "Internal strain of concrete, synthetic resin Civil engineering design KM Strain Transducers A B C D E Red KM-30 KM-50F."

[29] E. Cuelho, J. Stephens, and M. Akin, "SEVEN - YEAR EVALUATION OF THREE INSTRUMENTED BRIDGE DECKS IN SACO, MONTANA," 2010. [Online]. Available: http://www.mdt.mt.gov/research/docs/research_proj/threedecks/final_report.pdf.

[30] B. N. Grainger, "The Strain Behaviour of Prestressed Concrete Reactor Pressure Vessels Over 20 Years," Surrey, UK, 1989. Accessed: Jul. 30, 2020. [Online]. Available: https://repository.lib.ncsu.edu/bitstream/handle/1840.20/29486/DC_250340.pdf?sequence=1.

[31] L. Tokyo Sokki Kenkyujo Co., "TML Strain gauges 2017," *Tech Note*, p. 98, 2017, [Online]. Available: ase.au.dk/fileadmin/www.../Strain_gauges/TML_Strain_Gauge_Catalog_2017.pdf.