Automated Manufacturing of tunnel segment

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ABSTRACT

This project aim to robotically deploy vibrating wireless strain gauges (VWSG) into small scale steel fibre reinforced concrete (SFRC) tunnel segment making it smart. The VWSGs connected to an autonomous wireless node can establish ad-hoc modular networks with other smart segments and the segment properties can be tracked through their whole lifecycle. The main objective pursued are: (i) the design, the implementation, and the performance assessment of the robotic process of installing the sensors; (ii) the design, the fabrication and the mechanical testing of smart segment under cyclical loadings.

Keywords: Smart tunnel segment, construction automation, structural health monitoring, concrete tunnel segment, sensors.

1. INTRODUCTION

As in many areas of life, technology has been increasingly used over the past 30 years to improve task performance, limit risk, and reduce costs. Notoriously slow to adopt innovation, the construction sector is catching up at an accelerating pace. Although, the adoption of technology during the design phase is now well established, there is still a lag for the commissioning, operation and maintenance phases. This opens a window of opportunity for innovation. Two of such innovations are the use of robotics and structural condition monitoring.

On the one hand, and since the successful introduction of the first automobile automated assembly line by Ford Motor Company, many fields ranging from the foods industry to manufacturing of cutting-edge microchips have successfully adopted automation in their respective areas. Tasks originally performed by a group of skilled and unskilled workers are now taken over completely or partially by robots. In construction too, automation has seen some successful attempts of adoption. One such successful application is the automated process of manufacturing repeatable precast components such as concrete tunnel segments. In general, robots are used to move and assemble metal formwork, demarcate concrete pouring areas, and smoothen surfaces of hardening elements.

On the other hand, continued improvements in sensor technology and increases in processing and communication technology have made SHM adoption more viable for some critical civil infrastructure. Until recently, this technology was primarily installed on damaged or somehow affected existing structures that required close monitoring, it is for example the case of old bridges of great economic importance or historic buildings. In some other cases, sensors are installed to monitor the infrastructures after a natural disaster (flood) or before, during and after the construction of new infrastructure in the vicinity. Sensors are increasingly used during the construction phase to monitor the evolution of the concrete strength from concrete temperatures using the maturity method. There are even several commercial applications [2], [3] used in hundreds of worksite around the globe and the adoption is on the rise.

Monitoring can be global (monitoring the entire structure) or local (focusing on a few critical sections) for both existing and newly constructed structures. While wires are commonly used to power sensors, collect and transmit collected data from sensors, battery-powered wireless nodes are increasingly becoming an option that opens up more possibilities. One such possibility is to use sensor nodes on precast concrete elements so that their properties can be tracked from the moment they leave the manufacturing plant.

In this article our aim is to demonstrate and present a performance assessment of tunnel segment robotically instrumented with vibrating wire strain gauges (VWSG). The resulting elements are called smart segments. First, we designed a suitable robotic process for attaching the VWSG to the segmental formwork and implemented a performance evaluation strategy. A series of mechanical tests were then performed to evaluate the reproducibility and stability of the strain measurements of the fabricated smart segments.

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2. METHODOLOGY

2.1 Design and packaging of VWSG

To measure the internal strains in the precast concrete segment, the VWSGs were selected because of their easy availability and their long-term stability and general accuracy. We have selected the model Geokon 4202, recommended for mortars and micro concrete (aggregate size no greater than 10mm) [4]. VWSGs operational principle is based on the physical principle of a vibrating wire which correlates the resonating frequency of a wire to the strain. Excitation pulses sent through a coil at mid-span of the wire serve to pluck the wire up to its resonating frequency. An ad-hoc interrogative system made of a VWSG addressable board, an Arduino micro controller and an RS-485 interface board.

The sensor packaging has been adapted to both host the VWSG and the downsized interrogation system as shown in the Figure 1.

Figure 1. New packaging for the VWSG node.

2.2 Robotic sensor deployment

The robotic process, illustrated in Figure 2, of installing the magnetic box is a simple pick and place (PnP) using a 6-axis manufacturing robot type COBOT with a generic gripper which fingers have been adapted. The experiments will involve the following 4 scenarios:

- Robotic PnP with Magnetic Box
- Robotic PnP with Non Magnetic Box
- Manual PnP with Magnetic Box
- Manual PnP with Non Magnetic Box.

Figure 2. Robotic PnP of magnetic box with a 6-axis robotic arm

In order to provide a statistically significant sample, 100 points are collected for each scenario.
The box has been slightly modified as shown in Figure 3 to improve the picking point by the robotic arm. The rest of the experimental set up, is made of a steel plate positioned on the testing table covered with the box template printed on a paper and a NIKON D3200 camera mounted on a slider supported by two tripods.

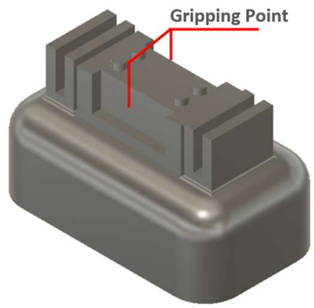


Figure 3. Modified box to improve the gripping

After Picking and posing the box at the targeted destination, either manually or robotically, a photo of the box is taken. Photos previously taken are then used to extract geometrics information such as ΔX, ΔY and $\Delta \Theta$ as defined in Figure 4. coordinates of this centre point are then subtracted from the coordinates of the centre of the template, resulting in ΔX and ΔY.

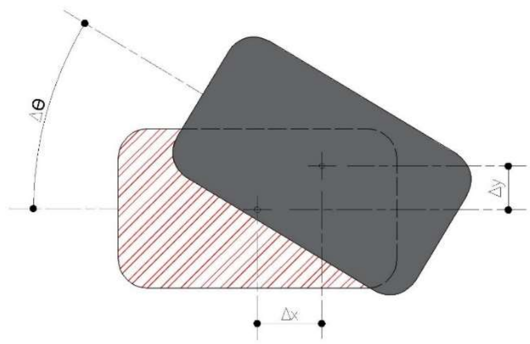


Figure 4. Illustration of geometric deviations

2.3 Smart segment

Full scale tests of concrete structures or components to determine their mechanical or physical properties are not uncommon for important and complex infrastructures and are nowadays used in combination with computer models for optimised designs [5]. They can be used to validate the design assumptions in order to update them or just to design from scratch through the incorporation of data from full scale tests conducted on laboratory specimens. Although it is preferable for the models under study to have same dimensions as the prototype, the higher cost involved in the fabrication, handling and testing of particularly large or complex components makes the use of reduced-scale models more suitable.

Here, the specific goal is to conduct cyclical flexion and compression tests on small-scale smart tunnel segment, based on the Lower Thames Crossing project (LTC) [6] , and later characterise such segment in regard of their mechanical properties. For convenience, we chose to work with standard tunnel segments. The chosen segment type is downsized based on practical considerations related to the easiness of its handling during the casting, the transport, and the testing.

The segment is made of steel fibre reinforced concrete (SFRC) which composition is presented in Table 1. And the SFRC compression [7] and flexion [8] properties, in Table 2.

Table 1. Steel Fibre Reinforced Concrete mix composition

Components	**Fibre concrete**
Cement (CEM II 32.5R)	350 kg
Water	158 l
Coarse aggregate	1200 kg
Sand	600 kg
Fibres	40 kg
Superplasticiser	1.4l

Table 2. SFRC mechanical properties

	Compression	Flexion			
	f_C [N/mm2]	f_L [N/mm2]	f_{R1} [N/mm2]	f_{R2} [N/mm2]	f_{R3} [N/mm2]
Average	40.3	4.39	3.98	4.63	5.24
Characteristics		3.16	3.30	3.24	3.40

2.3.1 Smart segment characterization

To evaluate smart segment performance, a series of flexion tests, shown in Figure 5, will be conducted up until 50% of the failure load. The flexion test will evaluate sensors response under flexural behaviour generated by temporary loadings (demoulding, stacking, transport, and positioning).

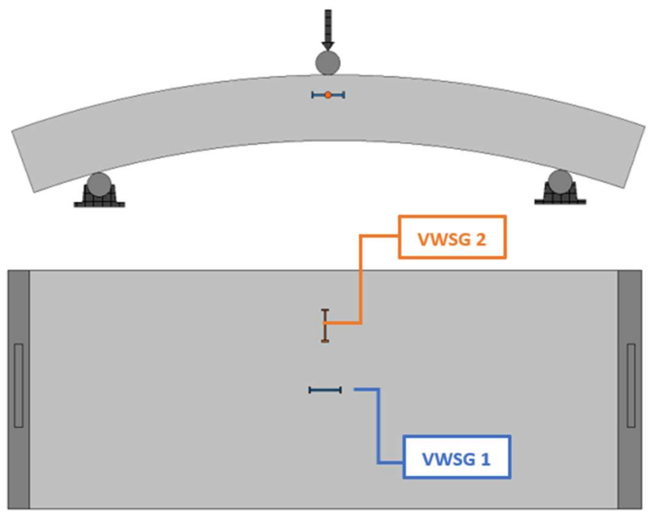


Figure 5. Smart segment set up before 3-point-bending test

The assessment of the smart segment process will consist of evaluating strains transfer using a straight beam approximation and a FE based model as theoretical model. The smart segment was submitted to 10 cycles of loading with the following same sequencing of loads: 0-2kN-4kN-6kN.

3. RESULTS AND COMMENTARY

3.1 Robotic performance evaluation

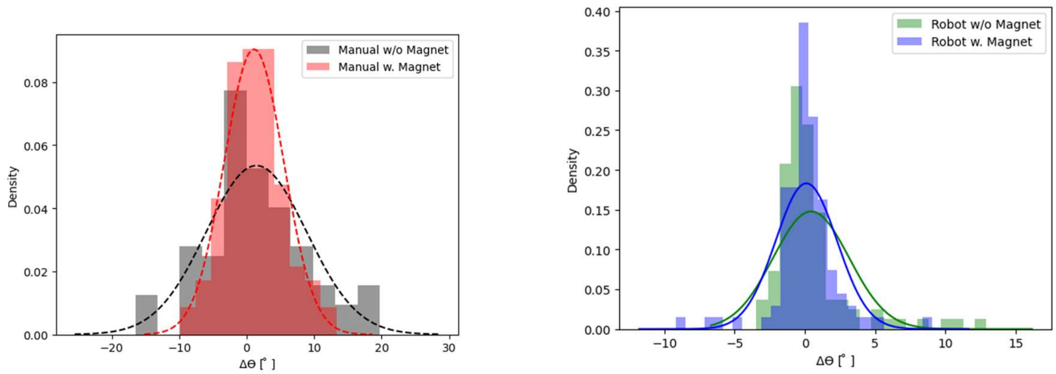
3.1.1 Geometrics errors

The distributions of angular errors, in Figure 6, show that a smaller dispersion for both robotic PnP compared to manual operations. Also, in both manual and robotic PnP, the use of magnets help to improve the accuracy of the PnP.

3.1.2 Strain variations

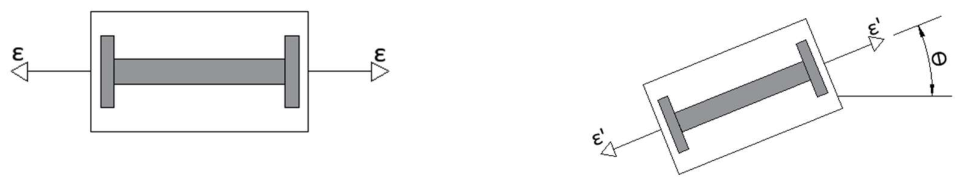
For a unitary strain, as shown in Figure 7. VWSG Strain transformation (a) ideal state (b) rotated state on the VWSGs embedded into the concrete, the only geometric parameters inducing the variation of strain is the angle variation ϴ. Using Equation (1), we can transform the initial strain when the box is at the perfect location to the rotated state.

The average and standard deviation of the strain losses for the 4 scenarios presented in Table 3 show that the drop in strain due to angular deviation introduced by the PnP process follows the same pattern as previously with the angular errors. In all the four scenarios though, the average of the strain loss relative error remains below 2%.



(a) (b)

Figure 6. Distributions of angular deformation of the box with different scenarios. (a) The two scenarios using the robotic arm (b) the two scenarios of manual PnP



(a)

(b)

Figure 7. VWSG Strain transformation (a) ideal state (b) rotated state

$$\varepsilon' = \frac{\varepsilon}{2}(1 + \cos 2\theta) \tag{1}$$

Table 3. Average and standard deviation (STD) of the strain loss for different scenarios

Type of PnP	**Average**	**STD**
Robot with magnets	0.144%	0.405%
Robot without magnets	0.226%	0.7001%
Manual with magnets	0.624%	0.994%
Manual without magnets	1.721%	2.525%

3.2 Smart segment

The loading pattern for the cyclical testing of the smart segment equipped with two VWSGs is shown in Figure 8. When compared to calculated strain using a straight beam approximation and the finite element model, the strain transfer, which is the slop of the trend lines of the plots in Figure 9, for both the straight beam approximation and the FE model is less than 1.

4 CONCLUSION

This paper presented the automated making of smart segment. It started with a brief description of the state of automation in the prefab industry emphasizing on tunnel segment. Later on, a brief description of the VWSG was presented as well as an ad hoc design of the magnetic box that will host both the sensors and the electronics to interrogate the sensors. After, the automated process to deploy the sensors and to evaluate their performance was also discussed. We finally examined the characterization of smart segments. The results obtained show the clear advantage of using robotic for sensors deployment over a manual process. The angular errors that can be correlated to strain losses showed tighter statistical distribution with relative strain loss relative error of less than 2%. Smart segment equipped with VWSG showed a regular behavior during a repetitive three-point-bending test. The strain transfer of both embedded sensors when compared to a straight beam approximation and an FE model was inferior to 1.

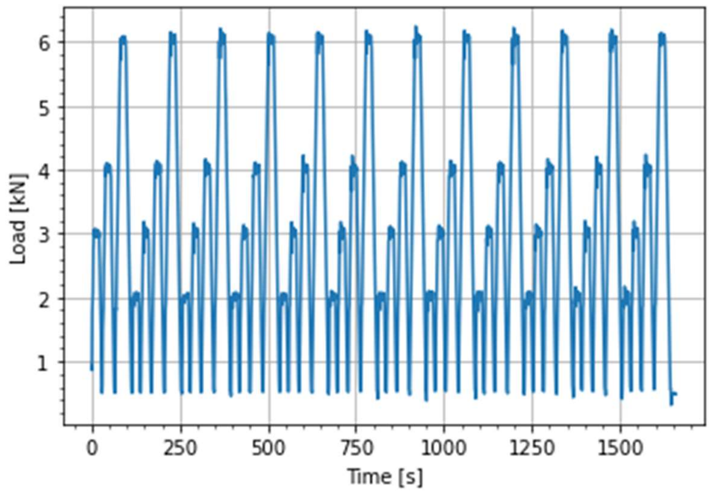
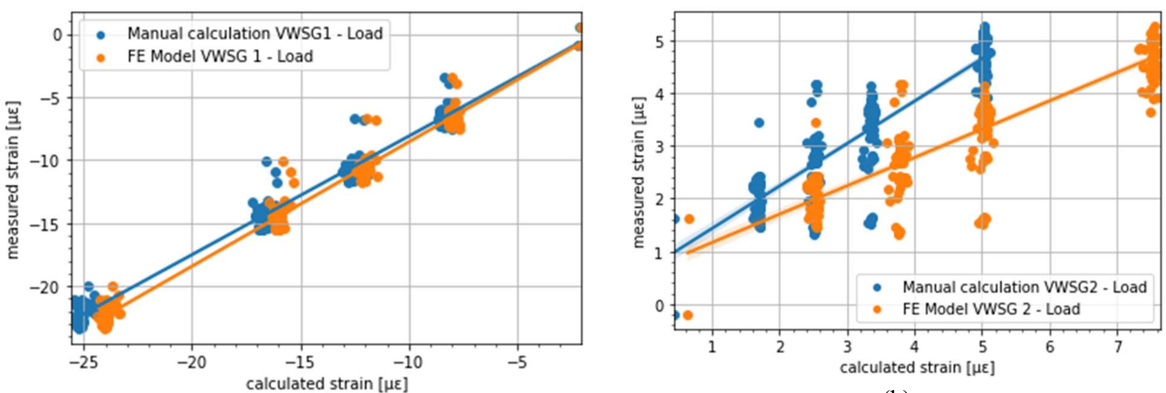


Figure 8. Cyclical loading of the smart segment



(a)

(b)

Figure 9. Strain transfer plots for (a) VWSG 1 and (b) VWSG 2

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