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REAL-TIME STRUCTURAL HEALTH MONITORING FOR CONCRETE BEAMS: A COST-EFFECTIVE 'INDUSTRY 4.0' SOLUTION USING PIEZO SENSORS

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REVIEWERS' COMMENTS AND AUTHORS' RESPONSE

The authors wish to extend thanks to the referees once again for their constructive comments and suggestions. These minor comments have now been addressed and a final file resubmitted for your consideration using the 'tracked changes' feature within MS Word. Once again, thank you.

No.	Reviewer	Authors' Response
	Editor Comments	
1	We are almost ready to accept your manuscript for publication, however there are a few minor points to be addressed.	Thank you – this has certainly been a thorough process.
	Referee No.1	
2	Accept - The authors have certainly made significant effort in addressing some of the reviewer's earlier comments, and the quality of the manuscript has significantly improved from the 'originality' and 'contributions' perspectives.	Thank you for the constructive comments and suggestions offered during the writing and revision of this manuscript. Your assistance is much appreciated.
	Referee No.2	
3	The authors have made effort to improve the paper, further change would be made to expand the research implication section and make sure the originality are aligned with the research aims and objectives.	The research implications section has been expanded to include new text and an additional citation viz: *"Hitherto, Industry 4.0 has received scant academic attention within extant literature but has already been successfully adopted in more technologically advanced sectors such as manufacturing (Al-Saeed et al., 2020). The research presented therefore provides a useful case study of Industry 4.0 adoption and thus serves to generate wider polemic debate and discussion within the contemporary construction and civil engineering management discipline."*
4	The rationale of this research study is interesting and meaning to the industry. However, the solid explanations or examples of its research implications are neglect. The results and implications of this research can be seen as practical. More discussions on its implications on theory and real work practices are looked	Again, further new text has been added to the practical implications section viz: *"For industry practitioners, the accurate structural health monitoring of concrete structures has been an historically expensive and time consuming process. By combining technologically advanced*

	forward.	*industry 4.0 digital technologies with novel low-cost sensors an automated hybrid analysis system developed during this research demonstrates enormous potential to revolutionise the structural health monitoring of concrete structures. More specifically, The developed system redefines structural health monitoring of concrete with some significant practical implications implications viz:…"* And again at the and of this section viz: *"Cumulatively, the compelling evidence reported upon in this paper should stimulate wider academic research and development and possibly expansion of the advanced Industry 4.0 technologies adopted to other areas of construction and civil engineering management."*

REAL-TIME STRUCTURAL HEALTH MONITORING FOR CONCRETE BEAMS: A COST-EFFECTIVE 'INDUSTRY 4.0' SOLUTION USING PIEZO SENSORS

ABSTRACT

Purpose: This research paper adopts the fundamental tenets of advanced technologies in industry 4.0 to monitor the structural health of concrete beam members using cost effective non-destructive technologies. In so doing, the work illustrates how a coalescence of low-cost digital technologies can seamlessly integrate to solve practical construction problems.

Methodology: A mixed philosophies epistemological design is adopted to implement the empirical quantitative analysis of 'real-time' data collected via sensor-based technologies streamed through a Raspberry Pi and uploaded onto a cloud-based system. Data was analysed using a hybrid approach that combined both vibration characteristic based method and linear variable differential transducers (LVDT).

Findings: The research utilises a novel digital research approach for accurately detecting and recording the localisation of structural cracks in concrete beams. This non-destructive low-cost approach was shown to perform with a high degree of accuracy and precision, as verified by the LVDT measurements. This research is testament to the fact that as technological advancements progress at an exponential rate, the cost of implementation continues to reduce to produce higher accuracy 'mass-market' solutions for industry practitioners.

Originality: Accurate structural health monitoring of concrete structures necessitates expensive equipment, complex signal processing and skilled operator. The concrete industry is in dire need of a simple but reliable technique that can reduce the testing time, cost and complexity of maintenance of structures. This was the first experiment of its kind that seeks to develop an unconventional approach to solve the maintenance problem associated with concrete structures. This study merges industry 4.0 digital technologies with a novel low-cost and automated hybrid analysis for real-time structural health monitoring of concrete beams by fusing several multidisciplinary approaches in one integral technological configuration.

KEYWORDS

Structural health monitoring, Industry 4.0, piezoceramic sensor, Internet of Things (IoT), concrete, construction industry.

INTRODUCTION

Extant literature acknowledges the significance of implementing long-term structural health monitoring (SHM) (Sheikh *et al.,* 2016) systems for civil infrastructures, in order to secure structural safety and issue incipient warnings of structural damage prior to costly repair (Li *et al.,* 2016). To underscore the scale of this operations and maintenance activity, the concrete repair industry in the US is estimated to generate 25 billion USD per year (Al-Mahaidi and Kalfat 2018). Indeed, over 25% of Canadian concrete bridges are deemed to be structurally deficient (Cusson *et al.,* 2011), and 85% of high-rise buildings in New South Wales (NSW) built after 2000 had some form of structural failure (Randolph *et al.,* 2019). SHM refers to a non-destructive process of implementing a damage identification and diagnosis strategy (Sohn *et al.,* 2003). In the context of concrete members (cast in-situ or prefabricated), SHM refers to the detection of abnormalities or deformities (i.e., arising via deterioration, damage or failure) and provides information regarding structural health and integrity of concrete members for continued use (Agarwal *et al.,* 2017; Zou *et al.,* 2019).

The structural health of concrete members relies on several factors, including temperature (both external and internal), humidity, moisture content, applied stresses, and boundary conditions during manufacturing and its life cycle (Strangfeld *et al.,* 2017; Tran *et al.,* 2017). Structural members' design normally takes these factors into consideration (Ghodoosi *et al.,* 2018). However, conditions are likely to change during the service life of concrete members, with the potential to significantly affect the overall health of the structure, providing the likelihood of deformations and failure (James *et al.,* 2019). Moreover, designers can implement little control over the external conditions confronting concrete during its curing process (Joshi 2019; Moon *et al.,* 2016).

In the current practice, several innovative and non-destructive methodologies have been developed to address the above challenges, including c-scan (Liu *et al.,* 2019); x-rays (Marzec and Tejchman 2019); linear variable displacement transformers (LVDT) (Mohandoss *et al.,* 2019); conventional microscopes (Jang *et al.,* 2019). The aim is to identify and/or monitor structural deficiencies and cracks present in concrete structures especially aging infrastructure elements with an objective of provide early warning and redressal in the event of incipient partial or complete structural collapse. However, these techniques utilise large-sized (indeed, cumbersome) and expensive equipment that provide localised solutions, thus rendering them impractical and generally unattractive to industry practitioners (Sun *et al.,* 2004; Yan *et al.,* 2013). Moreover, existing techniques, for the most part, provide partial solutions to the monitoring requirements of the concrete industry. For example, LVDT sensors will provide insufficient information regarding the cause of the observed displacement (Subramanian and Murugesan 2019), and microscopes can only observe and measure localised surface deformations without any indication of below surface deformations (Bernard 2019).

The latest development in the field of SHM (Sheikh *et al.,* 2016) came from sensors and sensor-based networks, data acquisition and communication, signal processing and data and information management (Li *et al.,* 2016). Researchers have also suggested the use of several forms of embedded and surface sensors in concrete to assess the concrete quality, economically (Taheri 2019b).

Piezoceramic, or piezoelectric sensors represent one viable option for monitoring the structural health of concrete structures by measuring the voltage generated by physical stress or strain on the sensor itself (Li *et al.,* 2019). These sensors can either be embedded into a concrete member before casting or it can be attached to the external surface facilitating its use on both new and pre-existing structures (Xu *et al.,* 2015). But the extent of its applicability has been hampered by the delay in signal processing development (Gao *et al.,* 2016), the use of complicated signal analysis techniques like Fourier transform (Wang *et al.,* 2019) and wavelet analysis (Jiang *et al.* 2017), which make the translation of its output, from research laboratories to industrial practice, difficult. These issues remain unresolved within extant literature. To address the above shortfalls, this research provides an innovative and low-cost industry 4.0 methodology for monitoring the structural health of concrete structural members. Associated objectives to be realised are to: 1) facilitate early detection and localisation of internal cracks in concrete members through real-time monitoring using Internet of Things (IoT) tools; 2) provide an economically viable tool for real-time data monitoring of concrete quality in a visually-engaging manner; 3) provide an affordable and accurate solution for industry practitioners; and 4) as a result of fulfilling the previous objectives, preserve the health, safety and welfare of building occupants.

STRUCTURAL HEALTH MONITORING OF CONCRETE MEMBERS

Various methods for SHM are applied across the industry to observe, record and analyse physical changes to structural members throughout their lifecycle (Lynch *et al.,* 2016). Currently, conventional methods include different tests such as a simple human eye detection of surface defects (Ghodoosi *et al.,* 2018) or a compressive strength test which only provides results after a 28 day curing period (Yildirim *et al.,* 2015). The prevalence of such conventional testing methods in the construction industry has led to unpredictability and unreliability in assessing the structural health of concrete infrastructure (Asprone *et al.,* 2018). Moreover, these methods are proven cumbersome with low efficacy and increasingly, are deemed impractical (Ghodoosi *et al.,* 2018; Oesterreich and Teuteberg 2016). A list of major conventional methods on construction sites has been tabulated in Appendix 1, along with the limitations affecting each method as well as an associated costs comparison. As illustrated in Appendix 1, visual-based observation techniques such as the human eye, fibrescope, borescope, hand-held magnifier or stereo microscope are labour intensive and do not offer detailed or quantitative information about interior defects occurring internally within concrete members. Acoustic techniques such as the rebound hammer, ultrasonic pulse velocity (UPV), impact echo, spectral wave analysis, crosshole sonic lagging or parallel seismic have various limitations. These limitations include: the need for two-sided access to members; an inability to detect anomalies at a greater depth; limitations in resolution and imaging; complex signal processing; exorbitant costs of equipment; and the need for specialised training to operate acoustic equipment (Kaiser *et al.,* 2004). These facts make such techniques unsuitable for practical use in concreting operations (Giri 2019). Set against this contextual backdrop, a paradigm shift has occurred in the market, where new low-cost and highly accurate digital methods are designed based on including sensors that can be embedded internally in new structures or on the surface of already existing structures (Li *et al.,* 2016).

Sensor-based methods

The contemporary concreting industry has progressively moved away from cumbersome SHM tools and techniques (Zinno *et al.,* 2019). Researchers are hence, actively looking for innovative Industry 4.0 solutions for monitoring of structures with the use of smart materials and sensors (Lehmhus *et al.,* 2019) efficiently and economically; where Industry 4.0 represents a coalescence of digital and automated technologies working in unison (Edwards *et al.,* 2017). In terms of utilisation of digital techniques for monitoring of concrete members, a series of research in digital SHM is redefining the way that structures are monitored and maintained (Concepcion *et al.,* 2017). Appendix 2 presents various sensing techniques used in SHM of concrete members, their method, principle, application and limitations as well as associated costs for comparison purposes (Sheikh *et al.,* 2016). As illustrated, most existing techniques are complex, expensive and operators require rigorous training to possess competency in these techniques. In the commercial market similar products are developed as: SmartRock2 (195 USD) for monitoring concrete strength; BlueRock (350 USD) for monitoring relative humidity to optimise curing; and SmartRock Plus to monitor temperature and strength of early age concrete in real-time and SmartBox (3500 USD) for monitoring electrical resistivity to provide useful information regarding water content and the setting and hardening time of concrete by Giatec Scientific, Canada (Giatec Scientific, 2020). Additionally AOMS, Canada provides similar concrete sensors, LumiCon (4000 USD) for monitoring temperature, strength, relative humidity, evaporation rate, maturity and temperature differential (AOMS Technology, 2020). However, until now there has not been a similar product for IoT-enabled structural health monitoring of concrete structures. This study proposes a novel technique with the help of a pilot study to address this research and provide industry with a viable accurate solution at an extremely affordable cost. Low-cost piezoceramic sensors ($2.22 AUD each) and a raspberry pi model B 3+ ($54 AUD) as a controller are identified as a viable alternative package for monitoring the structural health of concrete members.

Piezoceramic Sensors

Piezoceramic sensors have been utilised heavily for SHM in the aircraft industry (Chang 2016; Shen *et al.,* 2006), automobile (Martinotto *et al.,* 2016) and manufacturing (Hossain *et al.,* 2016) industries. Various studies have also assessed the suitability of piezoceramic elements in assessing structural health of concrete members (Feng *et al.,* 2018; Xu *et al.,* 2018a; Zhao *et al.,* 2016). The economical and easy applicability of piezoceramic sensors make them a viable option for SHM of concrete members in real-life projects (Shen *et al.,* 2006). Piezoceramic elements are devices which create a voltage reaction when undergoing external stress due to vibration, soundwaves, or mechanical strain (Pan *et al.,* 2019). Acting as a sensor, actuator, accelerator or transducer within the concrete member, the piezoceramic sensors detect the electrical energy converted from mechanical energy and convert it into a voltage output (Ballas and Schoen 2017). The mechanical energy developed from changes to the mechanical properties of a member (i.e. when a crack begins to form within the structure) is converted into electrical voltage fluctuations by the piezoceramic sensor (Xu *et al.,* 2018b). As a crack grows in a concrete beam after loading, for example, the displacement from the original size and shape of the structure changes and then can be verified using an LVDT (Suárez *et al.,* 2019).

There has been growing interest in using piezoceramic sensors in SHM for concrete members (Han *et al.,* 2015; Song *et al.,* 2007) even though Taheri (2019a) explored the advantages and disadvantages of varying SHM techniques with piezoceramic sensors. For example, water solubility and high humidity environments can affect the sensor (Mikulik and Linderman 2019). Moreover, Dong *et al.,* (2019) suggest that the use of piezoceramic sensors may affect the mechanical properties of the concrete structure when they are embedded. In terms of installation, sensors embedded with no protection have corroded (Taheri 2019b). As cement continually reacts with water and develop strong bonds between mix components to build the final concrete strength, a protective layer is necessary to protect the embedded sensors from its boundary, moisture damage, and corrosion (Sanches *et al.,* 2019). That said, these barriers can readily be overcome with cost-effective techniques. For example, Yan *et al.* (2013) discussed coating the piezoceramic patches in insulation as a method of preventing damage due to water or moisture. Yan *et al.* (2013), also embedded sensors into smaller sized concrete blocks to form a concrete smart aggregate and avoid physical damage that may occur to the delicate patches (where the latter may be damaged during curing of concrete members). In summary, although piezo elements have limitations of being fragile and non-water resistant, their economic feasibility and simplicity of usage provide strong arguments for using them on real-time SHM projects.

RESEARCH PHILOSOPHY

This overarching epistemological design for this research is to utilise a mixed methods philosophy to examine the phenomena under investigation (Al-Saeed *et al.* 2019) (e.g., the application of low-cost piezoceramic sensors to conduct real time SHM of concrete structures). Whilst interpretavism (Roberts *et al.* 2019) informs the research direction and methods of measurement employed (via qualitative analysis of literature), positivism is employed to conduct quantitative analysis of empirical data (Edwards *et al.* 2019). This combination of philosophies ensures that a scientifically robust research instrument is adopted.

Research Approach

When piezoceramic sensors are used to measure the mechanical properties of concrete, one of three common methods are often adopted: the impendence based method; the vibration characteristic based method; and the lamb-wave based method (Stojić *et al.,* 2012). In this study, a hybrid method utilising the principles of the vibration characteristic based method is adopted to analyse the vibrational voltage feedback from surface-attached piezoelectric elements. This data is then correlated to strain displacements measurements collected by a LVDT electric strain gauge to assess crack detection and occurrence in four test sample members under various loading conditions. The hybrid approach is a novel combination of traditional LVDT testing and piezoceramic sensor vibrational voltage feedback to provide an accurate and early detection of cracks (Jeong-Beom and Fu-Kuo Chang 2004).

For data analysis, signal processing techniques were adopted including Fourier transform (ul Haq *et al.,* 2017), Hilbert-Huang transform (Wei *et al.,* 2016) and wavelet analysis (Jain *et al.,* 2016). The wavelet method, an extension of the Fourier transform method, is commonly adopted within the field of electrical engineering as a valid and robust technique due to its developments in analysing non-stationary signals (Komorowski and Pietraszek 2016). However, Fourier transform, Hilbert-Huang transform and wavelet analysis methods require extensive mathematical computation and signal processing. Hence, for the purposes of this study, a simple hybrid analysis technique that correlates vibrational voltage feedback from piezoelectric elements and simple LVDT strain gauge displacements is adopted to facilitate easy adoption by industry practitioners.

Concrete member design

The design of the reinforced concrete beams follows a standard design procedure and complying with the Australian Standards AS3600-2009, for Reinforced Concrete

Structures (see Standards Australia (2011) for details). The concrete test specimens are 150 × 150 × 500 mm in size and are reinforced with 4 × 7.6 mm steel bars and five stirrups of the same diameter along the length of the beam. The beam will have 25 mm cover on all sides (refer to Figure 1). The mix-design and material composition of the M25 grade concrete members are provided in Table 1.

<Insert Figure 1 and Table 1 about here>

Decoding Raspberry Pi and electronic components used

The main components used in the present 'Industry 4.0' study include: a Raspberry Pi; piezoceramic sensors; a breadboard; analogue to digital converter; and two 16-bit multiplexers (refer to Figure 2).

<Insert Figure 2 about here>

- A Raspberry Pi is used as a computing unit to code the sensors and receive the data from these sensors. The Raspberry Pi microcontroller is a low cost, credit card-sized computer that plugs into a computer monitor or TV, and uses a standard keyboard and mouse, and uses much lesser power than other equivalent computing units (Raspberry Pi Foundation 2019).
- A piezoceramic sensor is a device that uses the piezoelectric effect to measure changes in pressure, acceleration, temperature, strain or force by converting them to an electrical charge. When a piezoceramic sensor is struck, it 'rings' like a bell but instead of sound it, it outputs a voltage spike that can be monitored in real-time.
- A breadboard comprises of a board in electronics that facilitates the prototyping of the circuit connecting the piezoceramic sensors to the Raspberry Pi.
- The analogue to digital converter (ADC), is utilised to convert the analogue data received from the piezoceramic sensor into digital signals that are passed to the Raspberry Pi.
- Two 16-bit multiplexers allow the simultaneous real-time data streaming from 13 piezo element sensors (with a maximum capacity of 2 X 16= 32 piezo element sensors).

Screenshots of the data streaming on SmartWorks cloud platform is provided in Figure 3. The major electronic and IT activities of the experiment included (ref. Figure 2):

- Hardware connections and developing circuits for connecting sensors to the Raspberry Pi;
- Coding the sensors and Raspberry Pi; and
- Attaching the sensors to the specimen and conducting the test.

<Insert Figure 3 about here>

EXPERIMENT AND ANALYSIS DESIGN

The concrete mix components have been prepared, weighed, and dry mixed before adding the water using a lab scale mixer at Deakin's concrete laboratory. Then, the wet mix has been poured into the prepared moulds. Demoulding the hardened concrete samples conducted on the next day while all samples have been cured for 28 days in water baths so that the concrete can develop its full strength before testing. The piezoceramic sensors are then attached to the pre-determined locations on the surface of the beams (refer to Figures 4 and 6). One beam will be tested in flexure under three-point loading set up. This beam will act as a benchmark to ensure that: 1) the sensors have been coded correctly; 2) there are enough sensors distributed throughout the beam; and 3) the sensors collect the relevant data.

Following the testing of the initial beam, essential changes on the test set up will be made to ensure correct test procedure is carried out for the remaining beams. As the data collected by the piezoceramic sensors is to be verified, LVDTs were set up for use throughout the flexural testing of each of the beams in locations relevant to those of the sensors. As the project concept highlights the use of microscopes for verification throughout the testing, DSLR (digital single-lens reflex) cameras will instead be used throughout testing to magnify points of interest along the beam as the loads are applied to show when surface deformations occur. Furthermore, surface cracks were visually monitored and measured to use as further reference material when comparing several results.

After the test, surface cracks of a smaller size (such as micro cracks < 10μm) usually verified with the use of a microscope, and will be inspected visually via DSLR camera footage for the four beams. While testing the beams, three standard concrete cylinders, prepared from the same concrete mix of each beam and cured at the same condition, have been tested for compressive strength to verify the quality/grade of the concrete used for each beam.

<Insert Figure 4 about here>

Sensor Setup

Sensors were attached to each beam externally using adhesive tape to ensure optimised surface contact between the sensors and the concrete beam. The four beams included 13 sensors for each beam with five on the front and rear faces of the beam, one on the base and two on the top (ref. Fig. 5 and 6). The final beam included five sensors where there were two on each of the front and rear faces and one on the base of the beam (refer to Figure 5).

<Insert Figure 5 about here>

Setting up the sensors involved attaching the wiring by ensuring the male end of a wire was touching the exposed wire from the sensor and securing with tape. Each sensor initially had three wires attached to each of the protruding wires. Once the sensors are secured to the beam, the wires are connected to a breadboard which in turn is connected to the Raspberry Pi. Where the wire length previously connected to the sensors was not long enough, further extensions are attached ensuring that the length ends with a male connection point. Figures 5 and 6 illustrate the location of sensors attached to the beam while Figure 4 provides the overall test setup for conducting the experiments.

The incorporation of sensors in the setup, as shown in Figure 5, has been conducted carefully due to a number of reasons. First, it was anticipated that because the sensors will collect data within a range of 20 – 50 mm, they were placed in the region of expected large damage on the beam. As the beam would be placed under three-point bending with the load applied at the span centre, the majority of sensors were positioned within this area where the applied maximum bending moment is located. The sensors positioned at the quarter lengths on beams one – three to allow for verifying data with the lasers positioned at these lengths on the soffit of the beam.

Three-point bending test

The test is performed on the beams to achieve the ultimate flexural load. This is the maximum transverse load and the corresponding bending moment that the beam can tolerate before full structural failure. The testing frame is self-supported type and provide a full circle of loading system, while the loading has been introduced through a hydraulic jack with load cell to monitor the actual applied load. The testing frame has also LVDT attached to the system to monitor beam deflection during the test. All outputs have been connected to a control panel and data acquisitioning system to capture the load-displacement relationship of each test. During the testing, and due to the load action of the applied bending moment, excessive deformation, such as beam deflection and concrete cracking, are expected around the mid span region where the bending moment has peaked. Therefore, the piezoceramic sensors were attached towards the mid-section of the beam. The materials have the property of generating an electric charge when subjected to a mechanical strain (direct effect for sensor) and conversely, generate a mechanical strain when subjected to an applied electric field (Taheri 2019b). In the experiment, the piezoceramic sensors were proposed as the sensors used for monitoring the SHM of the concrete beams. The first three beams had thirteen piezoceramic sensors, attached to the beams soffit at a distance of 100 mm. The fourth beam had five sensors attached to it. The size of a piezoceramic sensor is 2mm in diameter. During the experiment, the test starts with load control at a rate of 0.016 MPa/second, while it has been changed to deflection control of 1 mm/minute at the later stages to ensure capturing the full load-deflection relationship and to avoid sudden failure and damages to the instrumentations. This allowed the beam to gradually undergo safe and observable crack detection without significant damage to the sensors. The ultimate load at which the structures failed was recorded as 88.37 kN , 83.31 kN, 78.71 kN and 89.61kN for test samples 1, 2, 3 and 4 respectively. The time to final failure was recorded as 1170 s, 1036 s, 978 s and 1116 s respectively for each of the four samples.

FROM EXPERIMENTS TO FINDINGS

Final testing was carried on once the entire setup was ready. The beam was placed on the testing frame and ensuring that the marking were made in such a way that 13 sensors are connected to the correct location. A total of ten sensors on the face of sides of the beam were connected and two sensors were connected on the top surface and one sensor was connected on the bottom face of the beam (ref. Fig. 5 and 6). The load was gradually applied on the beams and the code was run at the start of loading and the loading on the beams continued till the specimen failed due to excessive deformation and concrete crushing. Data streams from the piezoceramic sensors were collected for all four samples in SmartWorks platform (refer to Figure 3) with technical support provided by AltAir Solutions Company (Agarwal and Alam 2018).

Test Beam 1 (control test)

Beam 1 had 13 sensors attached on the surfaces when the load was applied. Figure 7 shows that voltage of the piezoceramic sensors (namely sensor 1 to until sensor 13) with respect to time intervals where the cracks occurred. At initial time instant, the voltage fluctuation of the sensors is ignored. This is because the sensor fluctuations are due to the load being applied to the beam and not because any cracks were being formed. Figure 7 illustrates the strain displacement of Beam 1 measured using LVDT. The three major displacement spikes marked are the points of significant localised deformation (i.e. cracks) at loads equivalent to 24.7 kN, 45.632 kN and 50.664 kN and stress equivalent to 4.94 MPa, 9.13 MPa and 10.13MPa. When analysed clearly there was a huge voltage difference in sensors 1, 3, 4, 7 and sensor 13 where the cracks occurred. The piezoceramic sensor 2 was constant where there was no cracks formed and hence, there was no change in the voltage. The base voltage that the sensor generates in constant stage would be 0.60 V. The increase in voltage is observed at locations where cracks are viewed through DSLR camera recordings. The time interval of the camera footage is matched with the recorded sensor readings and it is observed that voltage spikes match that of observed surface cracks at similar time instant. In fact the voltage spikes occur a few seconds before the surface cracks are observed on camera. Also certain micro-cracks and internal cracks which cannot be registered on camera or even on a microscope are easily detected through the piezoceramic sensors through minor voltage spikes. After a time interval of 1080 seconds, when the load applied was 88.37kN (as measured by the load cell), final structural failure occurred and all the sensors were observed producing high voltages at that particular time instant (ref Fig.6) which is evident in the graph.

<Insert Figure 6 and 7 and 8 about here>

The analysis of graphs in Figures 7 proves that when there was a change in voltage in the sensors, there was an observable change in displacement at that particular time instant. Hence, the working sensors can detect even internal crack occurrence effectively. Also, the location of the sensors is helpful in determining the localisation of the occurred crack as shown in Figure 3. Similar tests are repeated for beams 2, 3, 4 respectively with similar displacement graphs obtained for the respective beams with the piezoceramic sensors detecting a spike in voltage at each of the major displacement spikes. Additionally, minor voltage spikes were observed which signify the occurrence of internal micro-cracks at that particular location. Hence, the piezoceramic sensors were successful in both real-time crack detection and localisation of cracks in concrete members.

THEORETICAL AND MANAGERIAL IMPLICATIONS

The multidisciplinary approach (using Industry 4.0 advanced technologies) adopted towards solving an important maintenance issues associated with the construction industry has some significant theoretical and managerial implications. Specifically, the work provides an economical and multi-featured addition to extant literature in the area of non-destructive testing (NDT) techniques (as outlined in Appendices 1 and 2). It also redefines the construction managerial landscape by ensuring remote maintenance assessment of concrete structures can be achieved without the need for on-site assessment. Such an approach could improve the cost efficiency of facilities management operations. F~~o~~rom a novel ~~theroectical~~theoretical perspective, the work provides an insightful case study of tentative steps towards adopting an Industry 4.0 application in the concrete industry that could facilitate modernisation of this sector. Hitherto, Industry 4.0 has received scant academic attention within extant literature but has already been successfully adopted in more technologically advanced sectors such as manufacturing (Al-Saeed *et al.*, 2020). The research presented therefore provides a useful case study of Industry 4.0 adoption and thus serves to generate wider polemic debate and discussion within the contemporary construction and civil engineering management discipline.

PRACTICAL IMPLICATIONS

For industry practitioners, the accurate structural health monitoring of concrete structures has been an historically expensive and time consuming process. By combining technologically advanced industry 4.0 digital technologies with novel low-cost sensors an automated hybrid analysis system developed during this research demonstrates enormous potential to revolutionise the structural health monitoring of concrete structures. More specifically, t~~T~~he developed system redefines structural health monitoring of concrete with some significant practical ~~implictions~~implications viz:

- Retrospective quality control for concrete can be conducted seamlessly and in real-time but also shared remotely among all the stakeholders.
- Significant time savings (and by implication, cost savings) can be made in turnaround time required to obtain test results.
- Enhanced accuracy of test results and enhancement of the reliability of results achieved, trough removing subjective judgement and labour-based activities from the procedure.
- Improved interoperability of data generated when linked to new developments in the field like Building Information Modelling (BIM) and Digital Engineering (DE).
- Enhanced transferability of data across the supply chain to better inform practitioners involved in the post-construction stages and assist decision making on maintaining concrete structures.
- Facilitate lower construction costs and completion times, through omitting unnecessary and repeated operator controls in traditional monitoring and control systems.
- In long-term, improve durability and minimise the cost of repair and maintenance of concrete structure and reduce material waste that occurs due to the low quality of concrete.
- Ensure compliance with the relevant regulations and quality standards and in the long-term, improve the image and reputation of construction companies among the communities they serve.

Cumulatively, the compelling evidence reported upon in this paper should stimulate wider academic research and development and possibly expansion of the advanced Industry 4.0 technologies adopted to other areas of construction and civil engineering management.

CONCLUSIONS

SHM of concrete is a significant research frontier that seeks to provide structural safety to both existing and future concrete structures providing an insurance against structural failure disasters. SHM plays a vital role due to the increase in the number of aging buildings or structures. While previous methods included traditional techniques to assess the structural integrity of concrete structures, current techniques have harnessed sensor-based techniques to provide real-time monitoring of concrete structures. However, many of these techniques suffer from the limitations of economic infeasibility or complex signal-processing techniques. This study investigates the application of low-cost piezoceramic sensors to detect deformations within the concrete structure (i.e., cracks and fractures) due to the member being placed under physical strain. Presently this method has been used on large scale infrastructure projects or some critical projects (Park *et al.,* 2003; Su *et al.,* 2018). The results of this study prove that piezoceramic sensors could detect both internal and external cracks and assist in real-time monitoring of concrete structures. This study also serves as a real-life application of Industry 4.0 in the construction sector and consequently, reveals how technology can automated this process moving forwards.

Future Work Recommendations

The demonstrated method is suitable for an autonomous continuous monitoring system because the data acquisition procedure can be computerised and requires minimal user interference. However, this approach being a preliminary scoping study had several limitations and some significant lessons for future studies. The use of wired sensors and its complex and sensitive circuit could potentially lead to delays and damage to devices. Hence, adequate protection of sensors and the development of wireless sensors is crucial for translating research into heavy duty industry applications. Adequate sensor concrete adhesion must be ensured to ensure reliability of collected readings – longitudinal research is therefore needed to assess the longevity and robustness of possible glues and/or resins that could be used. Studies investigating the exact range and lifespan of piezoceramic sensors could also further assist in fine-tuning this technique for industrial use. An analysis regarding suitable density of sensors by optimising the code used in the high stress region to capture the strain mapping could lead to more accurate indication of the critical regions of the structural element.

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Figure 1 - Reinforced concrete beam design

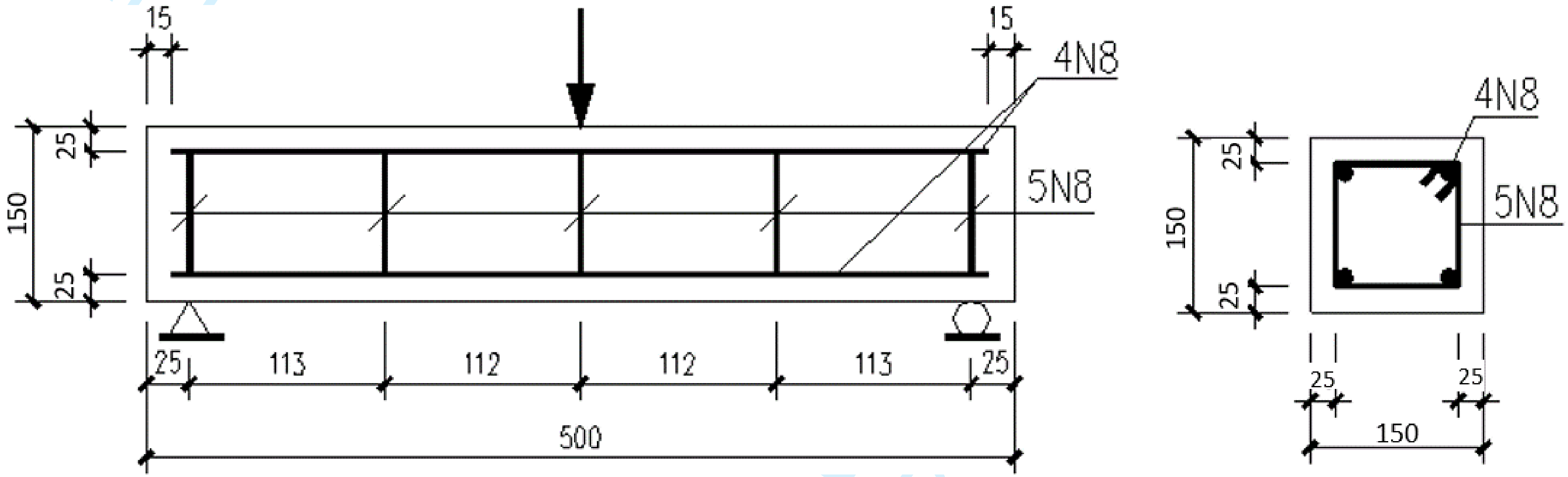


Table 1 - Concrete Mix design, material quantities

Material	Ratio	Total Weight (kg)
Cement	0.185	26.119
Water	0.075	10.589
Coarse Aggregate	0.377	53.277
Fine Aggregate, Sand	0.363	51.250
TOTAL	1	141.186

Figure 2- IoT ecosystem for connecting piezoceramic sensor to cloud server

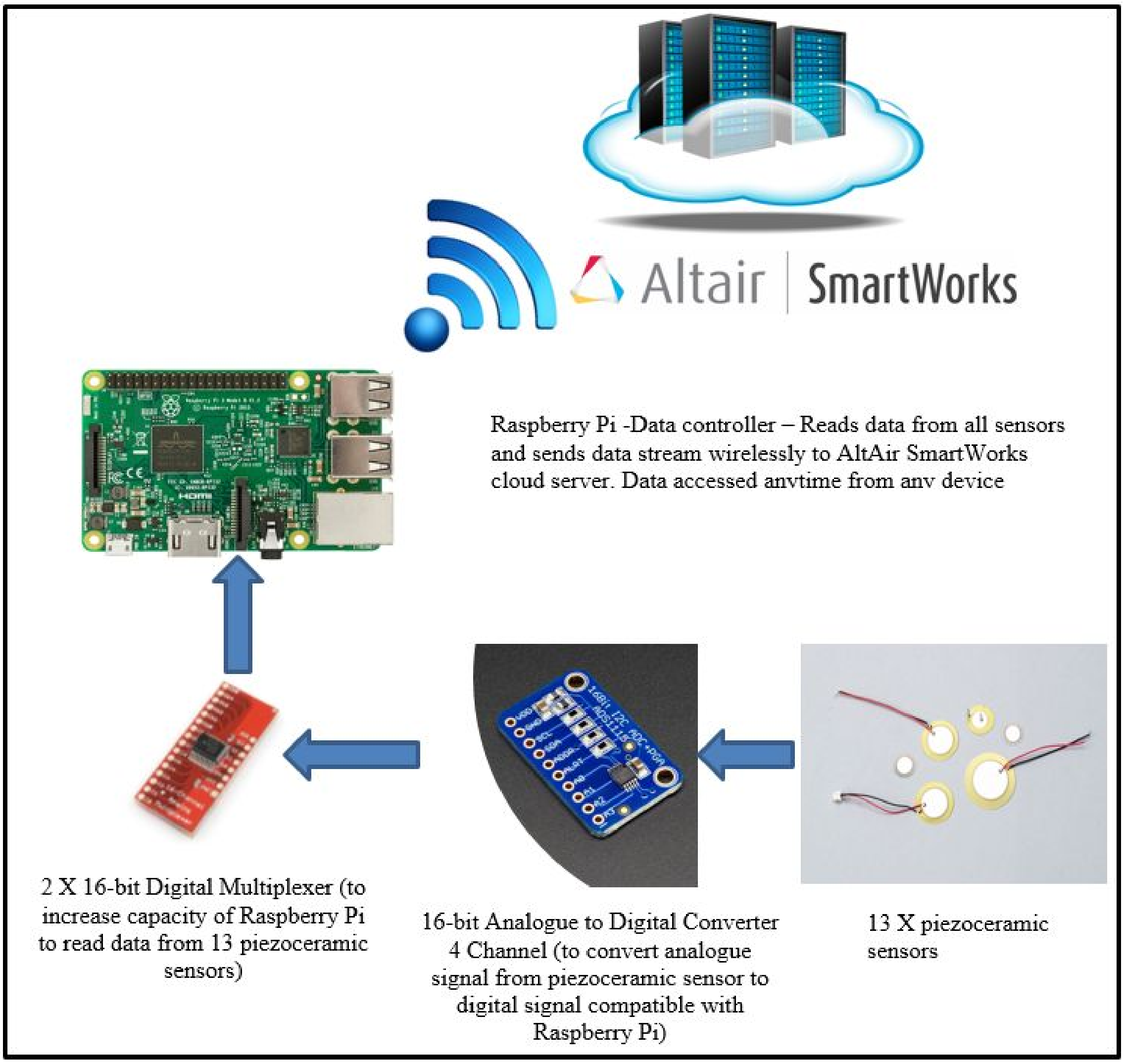
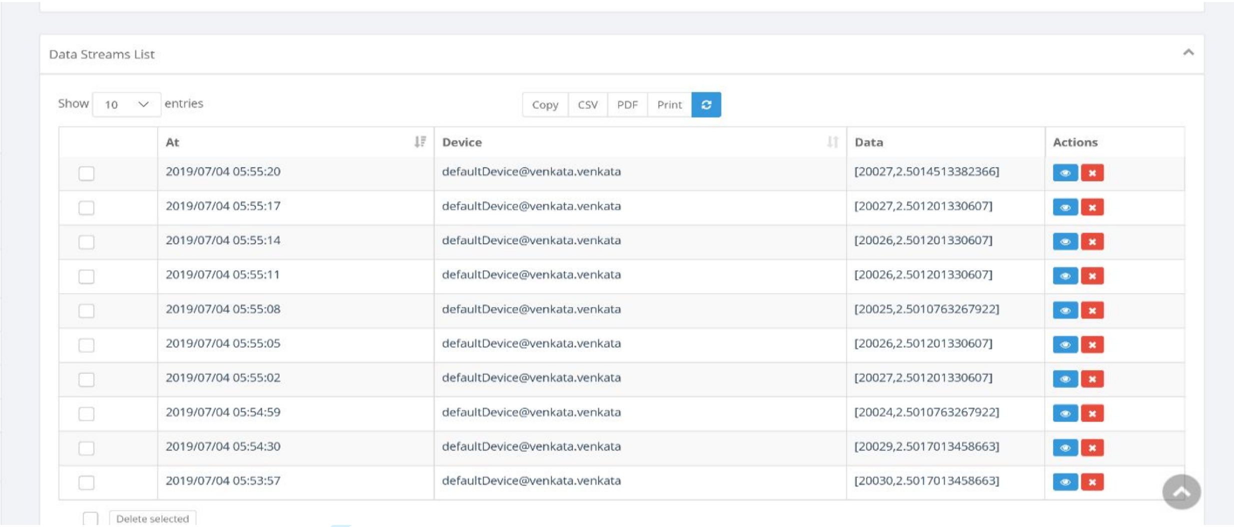


Figure 3 - Screenshot of AltAir SmartWorks datastream program running code and results in numbers (voltage)



	At	Device	Data	Actions
	2019/07/04 05:55:20	defaultDevice@venkata.venkata	[20027,2.5014513382366]	
	2019/07/04 05:55:17	defaultDevice@venkata.venkata	[20027,2.501201330607]	
	2019/07/04 05:55:14	defaultDevice@venkata.venkata	[20026,2.501201330607]	
	2019/07/04 05:55:11	defaultDevice@venkata.venkata	[20026,2.501201330607]	
	2019/07/04 05:55:08	defaultDevice@venkata.venkata	[20025,2.5010763267922]	
	2019/07/04 05:55:05	defaultDevice@venkata.venkata	[20026,2.501201330607]	
	2019/07/04 05:55:02	defaultDevice@venkata.venkata	[20027,2.501201330607]	
	2019/07/04 05:54:59	defaultDevice@venkata.venkata	[20024,2.5010763267922]	
	2019/07/04 05:54:30	defaultDevice@venkata.venkata	[20029,2.5017013458663]	
	2019/07/04 05:53:57	defaultDevice@venkata.venkata	[20030,2.5017013458663]	

Figure 4 - Experimental Setup with three-point bending machine, piezoceramic sensors attached to Raspberry Pi and connected to monitor to run the code

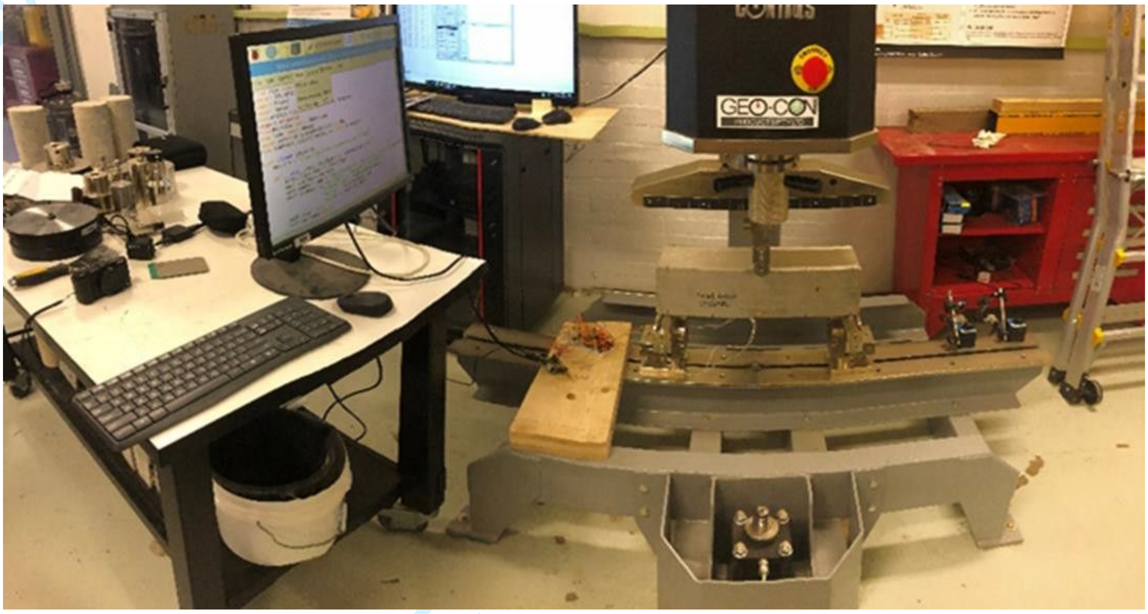


Figure 5 - Layout of sensors on each beam (Not to Scale)

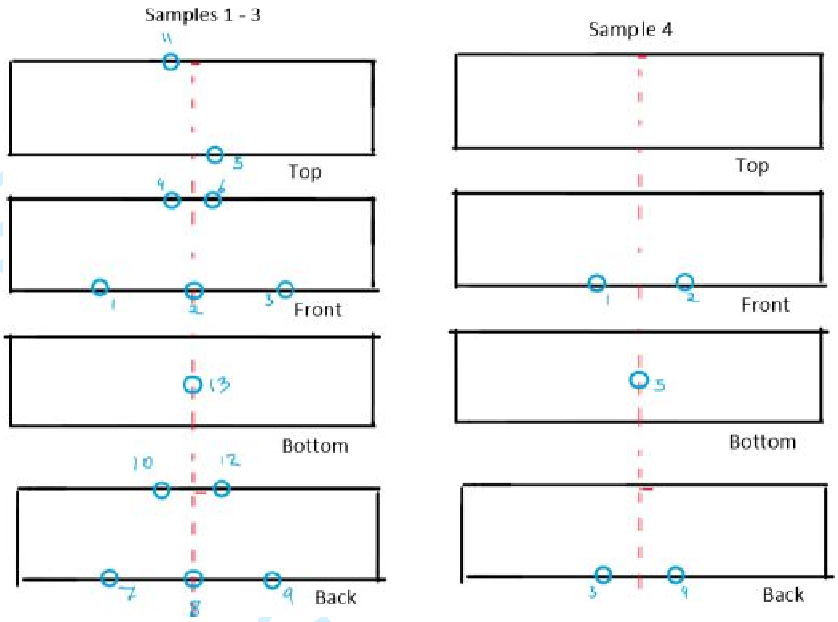


Figure 6- Sensor arrangement for beam 1

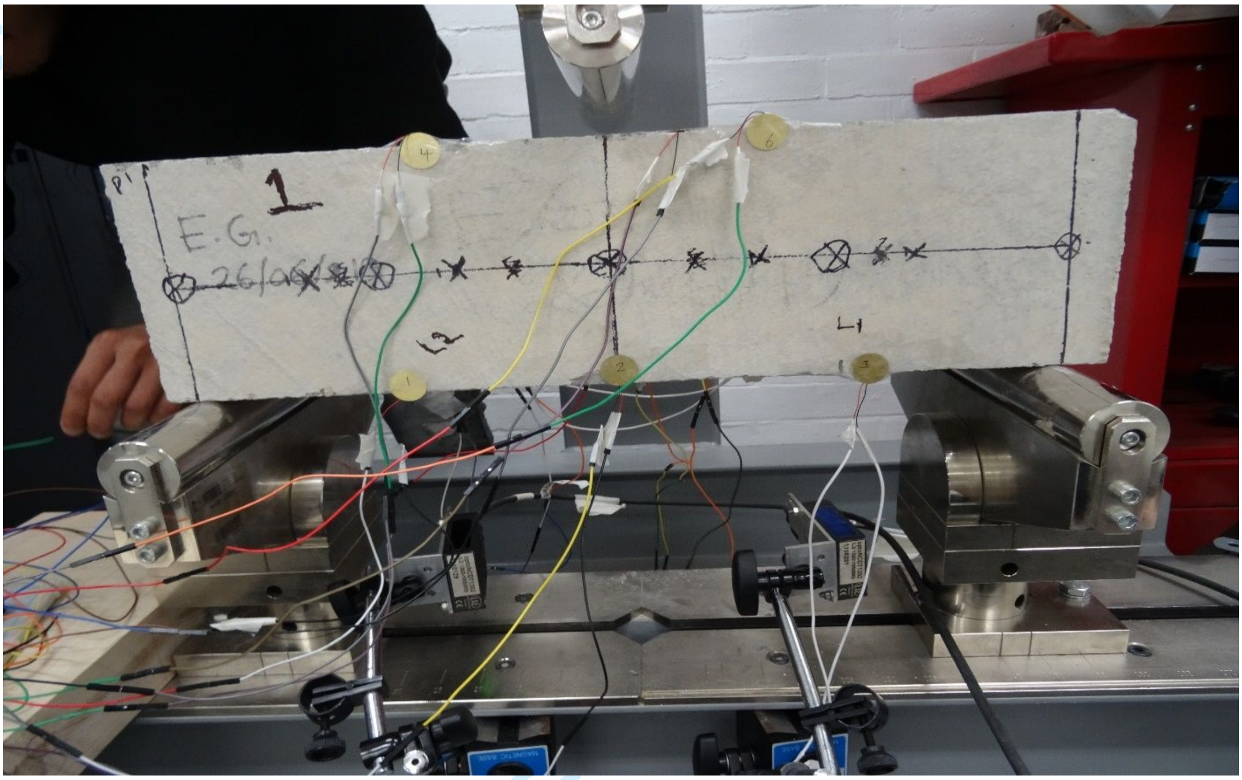


Figure 7- Load Displacement curve for beam 1

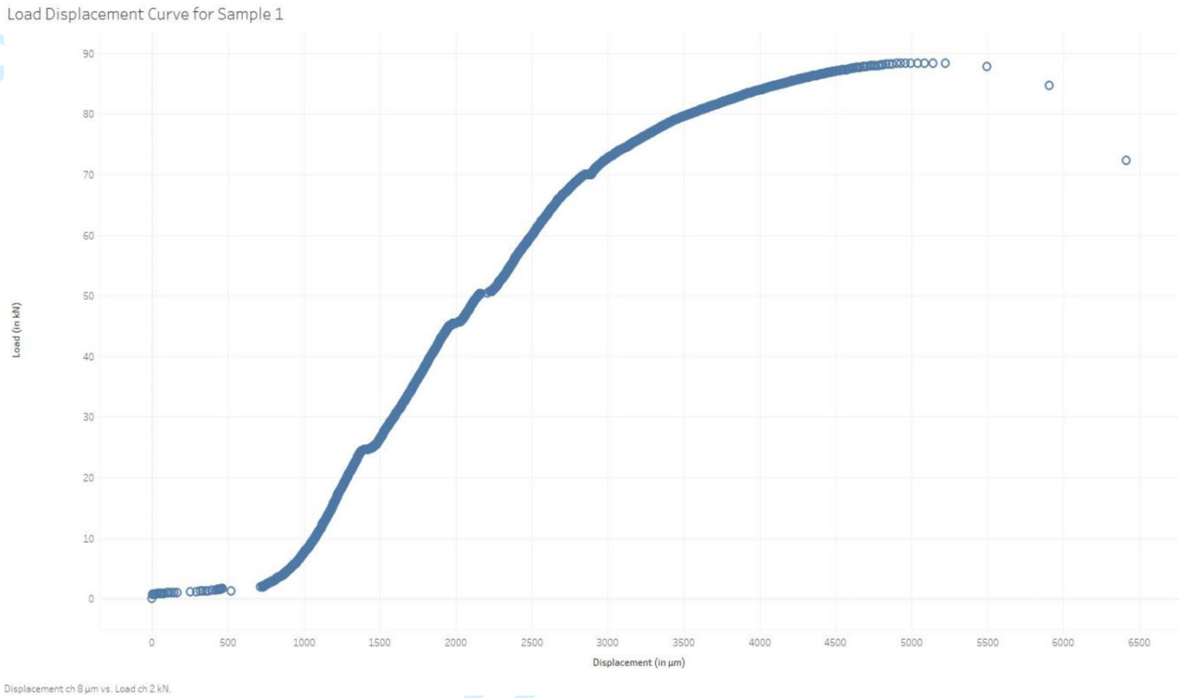
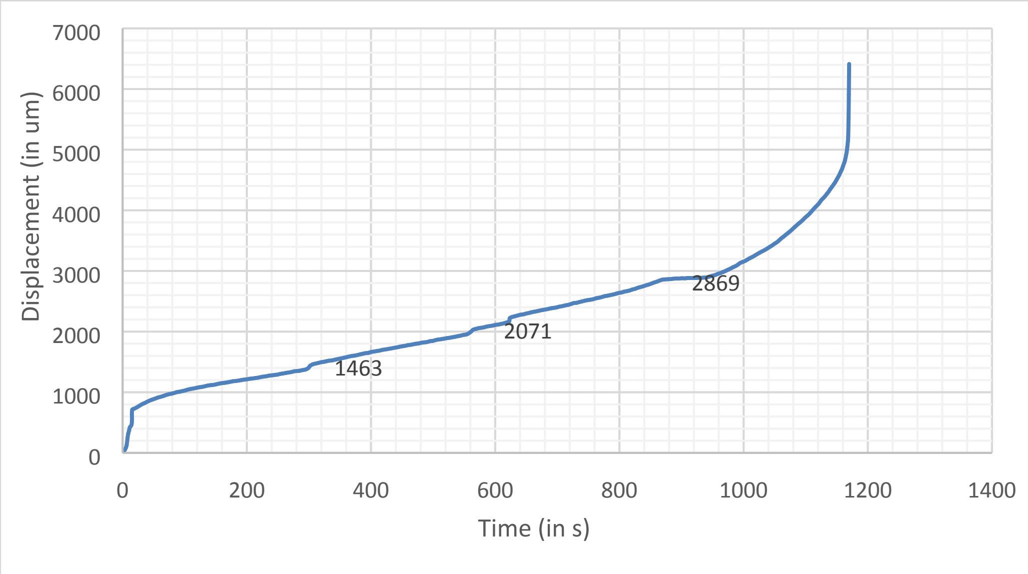
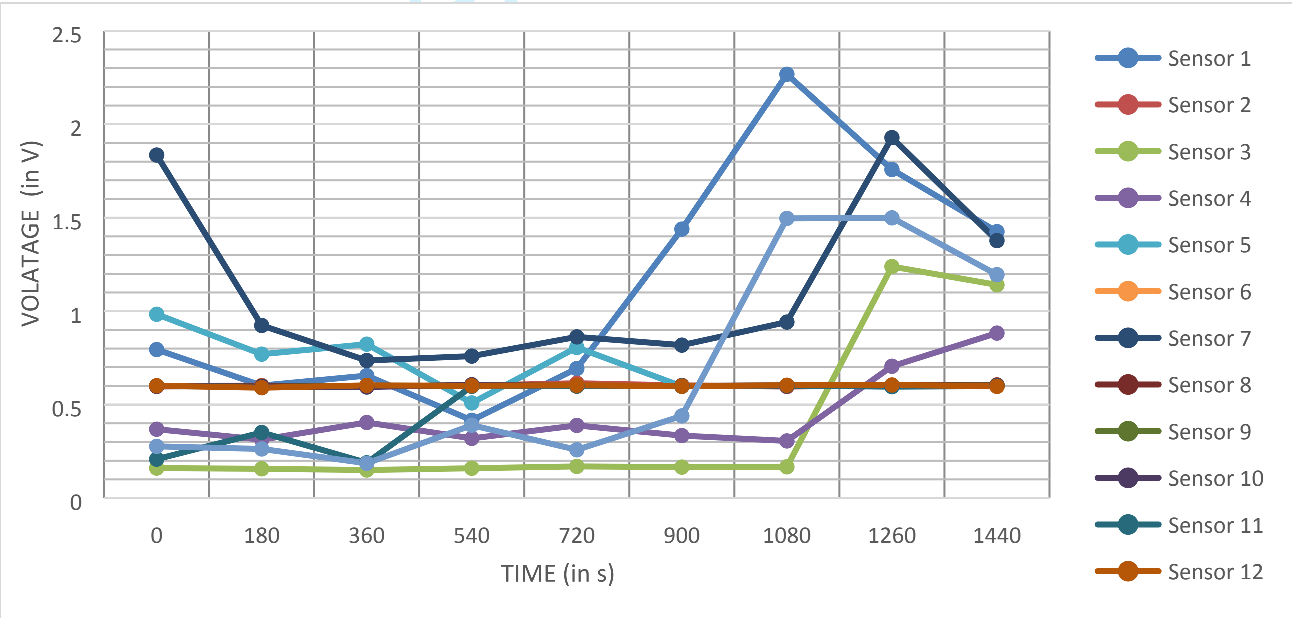


Figure 8 - Test 1 Sample 1 Sensor Readings vs LVDT strain displacement readings on beam 1





Appendix 1 - Major traditional SHM methods

Observation Technique	**Method and Principle**	**Cost of apparatus (in AUD)**	**Application**	**Limitations**	**Reference**
Human eye	Principle of photography.	Nil	Rapid detection of superficial flaws like cracking, seepage, spalling, exposed reinforcement, staining, moisture ingress, beam delamination, concrete deterioration, and reinforcement corrosion.	Labour intensive, doesn't offer detailed or quantitative information about interior defects.	(Davis et al. 1998), (Park et al. 2001), (Gokhan 2013)
Hand-held magnifier	Principle of magnification.	$36			
Stereo microscope	Combination of fixed and pancreatic magnification.	$2000-4000			
Fibrescope	Total internal reflection.	$290			
Borescope	Using lens attached through an adapter to a CCD camera for viewing real-time video.	$100-60,000			
Rebound hammer/sonic echo	Hammer impact on surface and receiver monitors reflected stress wave. Time-domain analysis is used to determine travel time.	$1500	Determine the length of deep foundations (piles and piers), location of cracks or constrictions (neck-in).	Confuses necking and bulging. Does not measure diameter; unable to detect defects in shafts >30 m.	(Alani, Aboutalebi & Kilic 2014)
Ultrasonic pulse velocity (UPV) test	Measure the travel time of a pulse of ultrasonic waves over a known path length.	$2,247	Determine the relative condition of concrete based on measured pulse velocity.	Requires two-sided access to members; does not provide information on depth of defect.	(Davis et al. 1998)
Ultrasonic echo	Emission of a short pulse of ultrasonic waves and measurement of the arrival of reflected echo pulse by adjacent receiver.	$12,334	Locate delaminations and voids in relatively thin elements.	Primarily a research tool with limitations in penetration depth, resolution, and imaging capabilities.	(Niederleithinger et al. 2019)
Impact echo	Receiver.	$11,560	Locate a variety of defects within concrete elements such as delaminations, voids, honeycombing or measure element thickness.	Current instrumentation limits members to less than 2 m thickness.	(Kachanov et al. 2019)
Spectral analysis of surface waves	Impact used to generate a surface wave, and two receivers monitor the surface motion with a subsequent signal analysis	$10 per meter	Determination of stiffness profile of a pavement system and depth of deteriorated concrete.	Involves complex signal processing.	(Rodriguez-Roblero et al. 2019)

Observation Technique	Method and Principle	Cost of apparatus (in AUD)	Application	Limitations	Reference
	determination of wave speed which leads to calculation of the elastic constant of layers.				
Impedance lagging	Use of complex signal (time and domain) analysis allowing.	$150-300	Determine the approximate 2D shape of deep foundation.	High-quality data requirement, full analysis requires lab environment.	(Paquet 1991)
Crosshole sonic lagging	Transducers positioned within tubes cast into deep foundation or holes drilled after construction.	$200-400	Determine the location of low-quality concrete along the length of the shaft and between transducers. With drilled holes permits direct determination of shaft length.	Pre-placed tubes or coring required, the edge of shaft defects may not be detected.	(White, Nagy & Allin 2008)
Parallel seismic	Receiver is placed in hole adjacent to foundation. Foundation is struck with a hammer and signal from the receiver is recorded.	$ 33,800	Determine the foundation depth and determine whether it is of uniform quality.	Signal stops at first significant anomaly. Edge defects may be bypassed.	(Rashidyan, Maji & Ng 2019)
Chain drag and hammer sounding	Involves dragging lengths of chain across the top of a concrete surface with a distinctly hollow, drum-like sound heard when delaminations are encountered.	$30	Easy and quick superficial investigation of surface defects.	Labour intensive, efficiency and reliability dependent on operator expertise, usually used in conjunction with other tests like acoustic techniques or radar.	(Barnes, Trottier & Forgeron 2008)

Appendix 2 - Review of sensor-based techniques for structural health monitoring of concrete members

Sensing Technique	**Method and Principle**	**Cost of apparatus (in AUD)**	**Application**	**Limitations**	**Reference**
Strain Gauge	Can be mechanical, electrical (LVDT), acoustic or electrical displacement. Measures the reaction of the structure to the applied load.	$600	Monitor crack growth, thermal stress (in conjunction with temperature sensor), provide real-time monitoring of strain.	Unsuitable for dynamic tests due to its slow response time, constant electric supply necessary and avoidance magnetic disturbances required, low fatigue life.	(Kaklauskas et al. 2019b)
Piezoceramic*	Conversion of mechanical vibrations emitted from even micro cracks to measurable electrical voltage.	$2.22 per sensor + $50 controller	Ability to measure variations in parameters such as acoustic emission, temperature, strain, force, pressure, or acceleration.	Fragile, unsuitable for humid environment, low life-span, bonding of sensor with concrete member.	(Pan, Wong & Su 2019)
Shape memory alloy	Utilize the shape memory effect (SME) to revert to their original shape upon heating after being deformed; use magnetic field sensing technique to monitor the structural health of concrete members.	$60-70 per sheet	Used in near surface-mounted strengthening reinforcement (NSM) to enhance serviceability and easy monitoring of prestressed concrete.	External magnetic disturbances from reinforcement could distort readings.	(Abouali et al. 2019)
Temperature and humidity	Measurement of temperature and humidity parameters through negative temperature coefficient (NTC) thermistors, resistance temperature detector (RTD), thermocouples, infrared sensors, thermometers, change-of-state sensors, silicon diodes and semiconductor-based sensors.	$29 per sensor + $50 controller	Optimising concrete curing process, minimising thermal stress, drying shrinkage, autogenous and plastic shrinkage.	Most temperature sensors are unable to survive in harsh alkaline concrete environment; problems of signal transmission stability, antenna design, electrical power, maintenance, database size, or the influence of structural strength.	(Chang & Hung 2012)
Bulk form	Entire structure made of self-sensing concrete using carbon fibre or polyvinyl alcohol fibres or carbon nanotubes.	$16,600/kg for 0.5wt. % multiwall carbon nanotube(MWNT)	Monitor the extent of fatigue damage, self-monitoring own strain, crack detection and propagation prediction of deflection of bridges.	Expensive filler materials of carbon nanofiber, polyvinyl alcohol. Need to monitor loading results in lab environment.	(Howser, Dhonde & Mo 2011; Zhang et al. 2004)

Sensing Technique	**Method and Principle**	**Cost of apparatus (in AUD)**	**Application**	**Limitations**	**Reference**
Coating form	One surface of structure/component covered with a layer of self-sensing composite.	\$8000/kg for 0.034wt. % sand-coated MWNT	Compressive and tensile strain monitoring of concrete members, early warning system of fracture, ultimate load, and rigidity.	Although it could act as a potential strain sensor but it couldn't act as a feasible damage sensor due to the low strains experience by concrete.	(Baeza et al. 2013)
Sandwich form	Both top and bottom layers of a structure/component covered with self-sensing concrete layers.	\$10,000/kg for 0.1% MWNT	Within elastic stage, sandwich concrete members capable of stress and strain monitoring of both compressive and tensile zones.	Expensive filler materials of carbon nanofiber, polyvinyl alcohol. Need to monitor loading results in lab environment.	(Wu, Dai & Wang 2007)
Embedded form	Self-sensing concrete is prefabricated into standard small-size sensors which is then embedded into the structure.	\$8210/kg for 0.05% MWNT	Stress and strain of both compressive and tensile zones within elastic range, loading , deflection, crack and damage extent of concrete members.	Difficult to prefabricate embedded concrete sensors, laboratory environment required for monitoring of loading characteristics.	(Fan et al. 2011)
Bonded form	Small sensors made of self-sensing concrete attached to concrete members using adhesive materials.	\$8000/kg for 0.034wt. % sand-coated MWNT	Composites could act as strain sensors even for severely damaged structures near collapse.	Adhesive material not waterproof, long-lasting feature of bonded.	(Camacho-Ballesta et al. 2019)
Fibre Bragg Grating (FBG)	Periodic variation of the refractive index along the fiber length formed by exposure of the core to an intense optical interference pattern.	\$15-50 per m^2	Measurement stability and leading/interconnecting insensitivity; inherent immunity from signal intensity fluctuations.	Expensive, fragile, specialist expertise in construction and deployment of fibres and need for several repeaters to boost the signal.	(Moyo et al. 2005)
Hybrid sensors	Combination of two or more fibre optic sensors (FOS) to monitor multiple parameters simultaneously (e.g. strain and temperature).	\$1500-3000	Hybrid optical fiber sensors having capability of discriminating between strain, temperature and thermal strain provides one-stop solution for SHM applications.	Complicated interrogation techniques are required for analysis of multiple parameters.	(Patrick et al. 1996), (Kaklauskas et al. 2019a)
Direct transmission radiometry	Measure the intensity of high-energy electromagnetic radiation after passing through concrete.	\$600-1200	Easy and rapid determination of in-place density with minimal operator skill and portable equipment.	Available equipment limited to path lengths below 300mm. Requires access to the inside member of opposite faces.	(Bień, Kamiński & Kużawa 2019)
Backscatter	Measure the intensity of high-energy	\$600-1200	Suitable for fresh or hardened	Precision of density measurements	(Venkatraman

Sensing Technique	Method and Principle	Cost of apparatus (in AUD)	Application	Limitations	Reference
radiometry	electromagnetic radiation that is backscattered (reflected) by near-surface region of a concrete member.		concrete. Portable equipment facilitates rapid testing.	lower than direct transmission. Material chemical composition affects measurements.	& Raj 2019)
Radiography	Recording of the intensity of high-energy electromagnetic radiation on a photographic film.	$1500-4000	Provides an internal structural view of studied object.	Difficult to identify cracks perpendicular to the radiation beam. Gamma-ray penetration limited to 500mm of concrete. Bulky and expensive X-ray equipment.	(Anton, Komárková & Heřmánková 2019)
Covermeter	Low frequency alternating magnetic field applied on the surface of structure and depth of reinforcement cover is gauged from alteration of the magnetic field.	$800-1500	Locate embedded steel reinforcement, measure the depth of cover, estimate diameter of reinforcement.	Accuracy of estimated cover depth affected by bar size and spacing, unable to detect presence of second layer of reinforcement, only ferromagnetic objects can be detected.	(Cikrle et al. 2019)
Half-cell potential	Measure voltage between steel reinforcement and standard reference electrode.	$3000-4000	Detect corrosion of reinforcement.	Embedded reinforcement to be electrically connected, no indication of corrosion rate, concrete should be moist.	(Garcia & Deby 2019)
Polarization methods	Measure current required to change the voltage between reinforcement and standard reference electrode; measured current and voltage provide resistance value which is related to corrosion.	$70-140	Determination of instantaneous corrosion rate of reinforcement located below test point.	No standards for interpreting test results, concrete surface to be smooth and uncracked and free of impermeable coating.	(Khajehnouri et al. 2019)
Penetrability methods	Measure fluid flow rate into concrete under prescribed condition which depends on the penetrability characteristics of concrete.	$2000-10,000	Compare alternative concrete mixtures, assess adequacy of curing process. Includes ISAT, Figg Water absorption, covercrete absorption test, CLAM water permeability, Steinert Method, Fig Air permeability, Schonlin Test and Surface Airflow test.	Does not provide coefficient of permeability, affected by surface coatings, concrete surface is damaged, long test time.	(Yang et al. 2019)
Infrared thermography	Infrared radiations highlight defects in concrete through noticeable temperature difference.	$230-300	Locate delaminations in pavements and bridge decks and detecting moist insulation in buildings.	Expensive, requires proper environmental conditions, depth and thickness of sub-surface defect cannot	(Rocha, Póvoas & Santos 2019)

Sensing Technique	Method and Principle	Cost of apparatus (in AUD)	Application	Limitations	Reference
				be measured.	
Radar	Electromagnetic waves transmitted and the reflection time provides a measure of dielectric properties of the material.	$1500-3000	Locate metal embedments, voids beneath pavements, regions of high moisture content and determination of member thickness.	Cracks And delaminations not easy to detect unless moisture also present, limited penetration depth, large data obtained needs to be properly processed by experience operator.	(Mehdinia et al. 2019)
pH sensor	Measurement of hydrogen-ion content of concrete using reference electrodes, embedding potentiometric pH electrodes or FOS (fire optic) pH sensors.	$100- 200	Corrosion monitoring of concrete sewers, tidal or splash zones in maritime structures.	Brittleness, chemical instability of chromophore at high or low pH values, indicator leaching and subsequent drifting of signal, unreliable and long response time.	(Chang & Hung 2012)
Corrosion sensor	Measurement of diffusion of Cl- ions alongwith pH level using electrodes.	$1400-1800	Monitoring reinforcement corrosion, external chemical attack on underwater marine concrete structures carbonation and chlorine penetration type corrosion.	Low sensitivity, unreliability, elongated response time, incompatibility in hostile environments, contamination of electrodes, requirement for periodic maintenance, short service life and, focus only on the local corrosion rather than the spatial scale corrosion of concrete members.	(Karthick et al. 2019)