

Comparative Study of Long-Term Monitoring Systems and Introduction to Emerging Smart FRP Technology



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Abstract This article presents feasibility and performance evaluation of three types of sensors systems, namely conventional wired sensor, wireless monitoring sensor and fibre optic sensor systems, to perform long term structural health monitoring of infrastructures. The short-term evaluation of the sensor systems showed comparable data. However, while all three systems were capable to record long-term continuous data, the fibre-optic system performed better than the conventional wired and wireless sensor technology. The article further reports the introduction of a novel smart fibre-reinforced material with an embedded fibre optic sensor for long term structural health monitoring of structures.

Keywords Fiber optic sensors · Fiber reinforced polymer · Long term structural health monitoring

1 Introduction

Structural Health Monitoring (SHM) is a technique to proactively manage structural health by diagnosing deterioration and damage at its onset and delivering an effective response to operational incidents, accidents, natural hazards, or other emergencies. A large number of studies are being conducted for the development of new sensors capable of acquisition of dynamic data [1]. Typically, sensor systems are classified under three major categories, namely, Conventional Wired Sensor (CWS) System, Wireless Monitoring Sensor (WMS) System and Fiber Optic Sensor (FOS) System.

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The present section provides a brief introduction, merits and demerits associated with each of the SHM systems.

1.1 CWS System

In the case of CWS Systems, different transduction mechanisms (e.g. piezo-electric, piezoresistive, capacitance) are designed to be used within a conventional wired network, and each individual sensor output voltage is transferred to a centralized data acquisition unit containing appropriate charge amplification, analog-to-digital converters, signal processing (e.g., anti-aliasing filtering), and demultiplexing. Traditional SHM often uses CWS systems but are usually expensive due to the necessity of continuous maintenance and are not always suitable for sensing remote structures. Moreover, power and wiring constraints imposed by these systems can increase the acquisition costs of such datasets, impose significant setup delays, and limit the number and location of sensors due to costs and installation logistics.

1.2 WMS System

Wireless sensors for SHM are an emerging new technology that promises to overcome many disadvantages pertinent to conventional wired sensors. WMS Systems are a possible alternative for traditional CWS systems since they enable dense in situ sensing and simplify the deployment of instrumentation. WMS acquisition is advantageous for enabling instrumentation in inaccessible places, reducing installation and maintenance costs while expanding its use in situations where large wired systems are not feasible. Batteries have historically powered WMS, and, as a result, the limiting factor in their overall lifespan has always been the battery lifetime. However, alternative solutions can be listed, such as the use of solar panels and the development of sensors that convert ambient vibrations into electromagnetic energy. Sazonov et al. [2] reported a field test in which the self-powered sensors were used on a rural highway. The sensors were shown to be self-powering even during periods of low traffic.

1.3 FOS System

FOS techniques and lasers have been under significant development in recent years and are now available in the market. They are characterized by an easy installation and data-collecting concept. These techniques often allow very delicate measuring in harsh conditions and in applications that were not possible in the past. FOS allows for

measurements that have been unpractical or too costly with the traditional sensor technology. Hundreds of measuring points along the same fibre, the distributed sensing, insensitivity to electromagnetic fields, and the fact that there is no need for protection against lightning are some of the advantages over the electrical-based counterparts [3, 4].

Table 1 provides a comprehensive comparison of CWS, WMS and FOS systems for their application in long-term SHM of infrastructures.

2 Selection of Sensor System

The selection of a CWS, WMS and FOS system requires to meet certain criteria before classifying it as a viable option for SHM applications. Many factors contribute to the selection process of a sensor node including, but not exclusively, the application, operational environment, the measurement type (strain, vibration, temperature, ultrasonic, etc.), sensor size and range, power consumption, robustness, and the lifetime of the sensing element [5].

In the CWS system, each node must contain several components for its efficient and reliable usage. The various components required include bus cables, sensing unit, signal processing unit, and ethernet connection with a Desktop/Laptop that is continuously powered. Power management/source system for the CWS system is mandatory for its reliable and efficient operation. With the presence of an energy source, powering the sensor will not be an issue despite the level of energy needed and the operation time. However, in the absence of an energy source, particularly when monitoring structures in remote areas, an alternative energy source must exist, or an alternate system such as WMS should be selected.

In WMS system, internal batteries are used to supply charge to the piezo-electric sensors, keeping in mind the limited lifetime that the batteries have before needing to be replaced. The energy consumption of the node, when an internal battery is used, affects the system outputs, such as the duration and frequency of data collection. A microcontroller can regulate the sleep and wake-up time for the sensor during or when an incident happens, such as traffic or crowd loading on a bridge, wind load on a high-rise building, or a bird strike on an aircraft nose. The WMS system relies on electrical and magnetic fields to convert the charge into measurements. It may not be effective in a highly electromagnetic environment, like metro lines or electric towers. WMS require the identification of network for data uploading and the positioning of sensors to cause minimum signal interception.

Thus, in cases where the sensors are to be multiplexed or placed close to each other, or the sensors are to be installed in a highly corrosive or electromagnetic environment, FOS system is preferred. FOS further provides the ability to perform direct embedment operations into construction materials to create ‘smart materials’ [3, 6].

Table 1 Comparison of CWS, WMS and FOS systems for long term SHM

Param	CWS	WMS	FOS
Data transmission	In CWS, a complex network of multiple sensors is brought to a single node/gateway. Thus, the sensors require continuous connection to the loggers, creating a complex wired network. The gateway is generally hard-powered and transmits data through ethernet or using IEEE communication	WMS sensors provide sensor-to-screen solutions with built-in transmitters within the sensor itself and can transmit data through radio frequency	In terms of data transmission, FOS is similar to the CWS system. The sensors are connected to a high-speed laser-based interrogator
Resistance to corrosion	In case of CWS and WMS system, the instrumentation is typically manufactured using metal wires and are susceptible to corrosion		FOS technology is non-metallic in nature and is not susceptible to corrosion
EM waves susceptibility	In case CWS, if the entire system is connected using bus cables/wires, the chances of EM waves susceptibility is limited	WMS technology transmits data using an unlicensed frequency band of 2.4 GHz. Thus, presence of high voltage electrical lines may cause interference issues	FOS technology is based on light-waves. Thus, the presence of electromagnetic radiations does not contribute to signal loss
Multiplexing capability	In case of both CWS and WMS, each parameter to be measured (strain, acceleration, etc.) require independent communication to gateway whether using bus cables (CWS) or wireless (WMS). Thus, in CWS, the system requires a complex cable network and increases the chances of short-circuiting, while WMS may have interference issues		Multiple FOS can be multiplexed into a single array to record strain at several locations using a single channel of the optical interrogator
Embedding capability	CWS and WMS cannot be utilized to create smart materials since the morphological structure of such sensors are too big to be embedded		Unpackaged FOS can be embedded into construction materials to create smart materials to serve the dual purpose of taking load and measuring load

(continued)

Table 1 (continued)

Param	CWS	WMS	FOS
Electrical input	Most loggers in the CWS technology are hard-powered using an external DC supply	WMS have a built-in lithium-ion battery. The batteries can be replaced and the life of WMS can be extended for another 10 years	FOS systems utilizes laser interrogators. Thus similar to CWS, FOS systems also require hard-power
Installation	The sensors that operate on CWS technology require armoured jelly cables, nodes, and junction boxes. Thus, the installation is time-consuming and extremely difficult	WMS is based on self-adhesive or bracket mounts. Thus, the WMS can be mounted on a surface in a record time of 1–2 min	Installation of FOS system is comparatively faster than CWS but slower than WMS
Physical and environmental protection	Generally, CWS system comes with IP65 rating; however the bus cables connecting the gateway to sensors are not IP65 rating. Thus, the system becomes redundant after a few years	Typically, WMS has ingress protection with IP65 and above rating and are protected against rain, snow, and UV radiation	Similar to CWS, the sensors and gateway in the FOS system are IP65 and above. Although rodent-proof high-quality FOS cables are available to connect gateway and sensors, they are always at a greater risk of damage

3 Selection of Type of Sensor

Designing of the sensor network is crucial to select the type and number of sensors. The type of sensors highly depends on the application and the structure to be monitored. For instance, when using an accelerometer to measure the level of vibration, the interest will be more on understanding the global behaviour of the structure, i.e., the shift in the modal frequencies that may be used to identify the presence of damage. Vibration-based methods have been implemented already on many structures, mainly civil infrastructure, albeit these methods are not effective in providing a qualitative assessment about the health state of the structure. On the other hand, when strain sensors or ultrasonic transducers are considered, the focus is more on the local assessment of any damage that may be present within the structure. These techniques can detect small surface and embedded defects such as corrosion, fatigue cracking, impact damage, etc.

4 Research Significance

The present study reports a pilot investigation conducted to examine the capabilities and challenges of three different sensor systems but not mutually exclusive approaches to monitor a column specimen.

In this study, the intended functionality of different systems has been evaluated on its ability to identify potential changes in the structure and to provide decision-making support. Furthermore, to advance the research in the field of FOS system, a novel technique of potential embedment of Fibre Bragg Gating (FBG) based fibre optic strain sensors into the fibre-reinforced polymer (FRP) has been briefly discussed.

5 Specimen Identification

The instrumented specimen was essentially a part of another study involving seismic evaluation of a periodic column under controlled dynamic loading. The column specimen was fabricated with alternate layers of rubber and concrete bonded together using engineering adhesives. Long term data analysis has been performed on the column specimen under intermittent dynamic loads. Figure 1 shows the instrumented column specimen with various sensors installed at pre-decided locations (as discussed in Sects. 5.1 through 5.3) and the associated logging system.



Fig. 1 Instrumented column specimen and associated data logging systems

5.1 Vibration Sensor

A single vibration sensor (single or multi-axis accelerometer) in some cases may provide the information needed, for instance, in the case of determining the global modal frequencies and damping on a bridge structure. However, more sensors are needed to determine the mode shapes. The main requirement for a successful application of vibration-based methods is to identify the range of the targeted natural frequencies and mode shapes and overcome spatial aliasing [7]. In the present study, three mutually exclusive vibration monitoring sensors have been installed at the top location of the specimen, as shown in Fig. 2.

First, a spring-mass damping based CWS has been installed and connected to CF2000 FFT analyzer through bus cables. Second, a WMS has been installed next to the CWS that communicates to a wireless gateway using an unlicensed band of 2.4 Ghz. Finally, a Fabry–Perot technology-based FOS has been attached at the

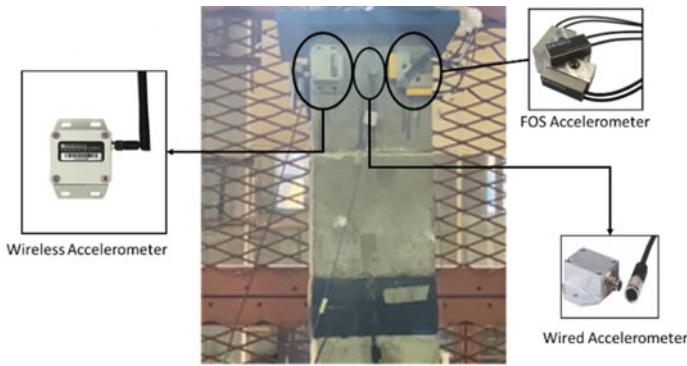


Fig. 2 Accelerometers installed on specimen



Fig. 3 Strain sensors installed on specimen

same location and connected to an optical interrogator using rodent-proof fibre optic cables.

5.2 Strain Sensor

Currently, the sensors used for SHM of civil engineering infrastructures mainly include vibrating wire sensors, resistance strain gauges and FBG sensors [8]. The measurement accuracy of the vibrating wire sensor is relatively low, and it is easily affected by the magnetic field and surrounding environment. The resistance strain gauge is characterized by high measurement accuracy, a wide measuring range and a simple structure. However, it has a distinct non-linearity when subjected to a large strain and weak signal. These shortcomings severely limit its application, especially in long-distance monitoring and harsh environments. FBG sensing technology has developed rapidly in recent years. It is characterized by high measurement precision, immunity to electromagnetic interference, stability of long-term sensing and so on. Therefore, the FBG sensing technology favours the long-term SHM.

In the present study, two commercially available FBG based strain sensors have been installed at the centre (front and back) of the column specimen between the two concrete cubes separated by a rubber layer. Additionally, a linear-potentiometer (LP) representing the CWS system has been attached next to the front FBG sensor to perform a comparative analysis of the recorded strain data.

5.3 Temperature Sensor

Long term continuous temperature measurement is typically used for continuous detection of leakage at pipelines, vessels and mass concrete structures. In the present study, an FBG based temperature sensor has been attached to the front surface of the column specimen. Additionally, a wireless resistance temperature detector (RTD) sensor has been attached at the back surface of the specimen as shown in Fig. 4.

6 Loading Protocol

The specimen has been mounted on a hydro-controlled uniaxial shake table. Two different types of loading protocol have been selected to investigate the sensor systems mounted on the specimen, namely, free vibration and forced controlled vibration.

In case of free vibration, the specimen has been manually displaced by providing a gentle push at the top of the specimen. The specimen has been allowed to vibrate

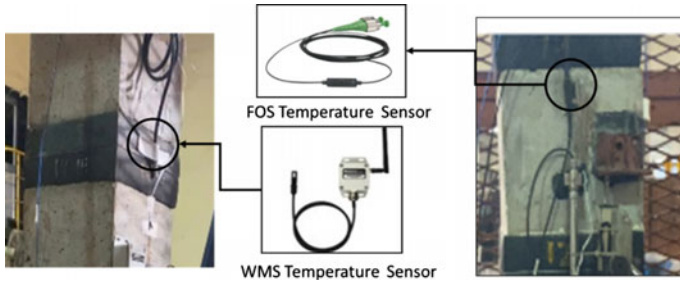


Fig. 4 Temperature sensors installed on specimen

freely under the applied load. The procedure of free vibration has been repeated four times a day in intervals of 2 h from 1100 and 1700 h.

The metamaterial-based concrete column has been designed to impede frequencies over a bandgap ranging between 5 and 10 Hz. Thus, the forced vibration tests have been conducted at a nominal frequency of 2.5 Hz and 0.1 g. In the case of the forced vibration test, the controlled load has been applied two times in a day from 1100 and 1700 h. However, in the present study, the data recorded only during the free vibration investigation has been reported.

7 Results and Discussion

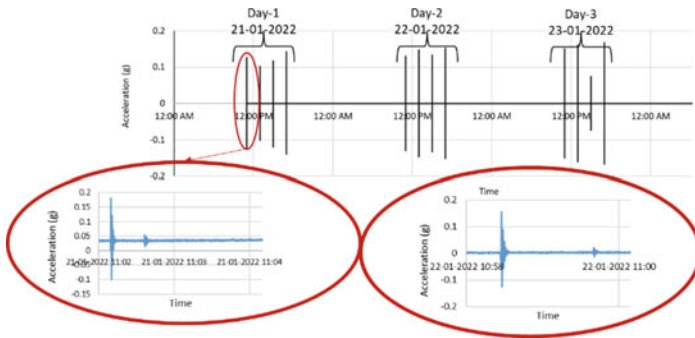
The data from individual sensors and systems have been continuously monitored. However, the CWS system has been switched on only when the load has been applied. The present section briefly discusses the results obtained from the individual systems.

7.1 Free Vibration Long-Term Acceleration Data

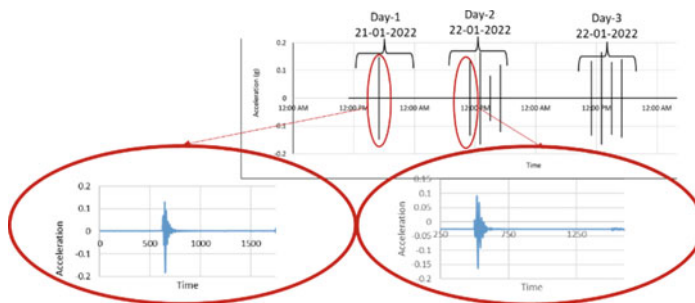
During the free vibration investigation, the specimen has been first displaced manually along one of the transverse directions (Y-direction) and allowed to vibrate freely. Subsequently, after the specimen stabilized, it has been displaced along the orthogonal direction (X-direction) and allowed to vibrate freely. During the free vibration test, acceleration and strain information from the sensors have been automatically recorded in the respective logging systems.

Figure 5 reports the acceleration v/s time history recorded by FOS, WMS and CWS accelerometer. It can be observed from Fig. 5a, b that both FOS and CWS accelerometers appropriately recorded the acceleration response of the system during the free vibration investigation. However, the acceleration response recorded by WMS accelerometer (Fig. 5c) during the free vibration investigation has been observed to be negligible (varying between 993 and 994 μg). This indicates that the WMS

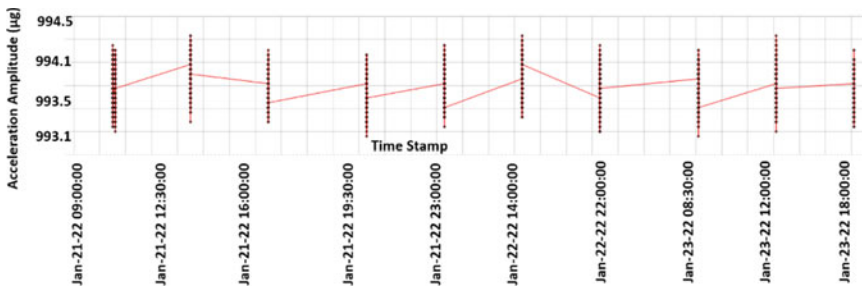
system failed to record the acceleration values during the free vibration test. This is essentially due to the fact that the WMS accelerometers are micro-electromechanical systems (MEMS) based accelerometers. These accelerometers get activated only when a particular threshold value is exceeded and is maintained for a particular duration. The concept of MEMS accelerometers is designed to be implemented in bridges so that minor vibrations due to vehicular movements are unaccounted and only meaningful data is stored in the server.



(a) Acceleration vs Time History from FOS System



(b) Acceleration vs Time History from CWS System



(c) Acceleration vs Time History from WMS System

Fig. 5 Acceleration versus time history from individual sensor systems

The acceleration data from the sensor systems has been post-processed to estimate the time period of the instrumented column (Table 2). The typical free vibration period for the column specimen has been estimated using the data obtained from the FOS system to be approximately 0.90 s along both X and Y directions.

Table 2 reports the peak 'g' value and 'time-period' obtained from the CWS accelerometers connected to the FFT analyzer. The FFT has been turned on only during the application of free vibration. The readings during first three-displacement cycles could not be recorded by the CWS accelerometers due to an instrument error. It can be observed from Table 2 that both FOS and CWS accelerometers reported almost identical values of time-period indicating the robustness of the two systems in sensing short-term vibrations.

7.2 Free Vibration Long Term Strain Data

Strain measurements have been performed in the present investigation by using FOS and CWS systems. FOS strain measurement system has been selected as a complementary solution to the resistance strain gauge, vibrating wire strain gauges and accelerometers. The combination of different types of technology, especially the combination of strain and acceleration measurement results, can facilitate the measurement of long-term deflection of bridges at inaccessible locations, allowing accurate analysis of the dynamic behaviour. The peaks in Fig. 6 shows the strain information from FOS and CWS system during each manual displacement. The front and back FOS strain sensor readings have been observed to be approximately equal and opposite in nature. The strain readings gradually reduced to zero as the system came to rest.

Table 3 compares FOS strain measurements with the peak strain values recorded by the LP connected through CWS technology. The displacement from LP has been utilized to estimate the peak strain readings. In most cases, the maximum front strain readings from the CWS system have been observed to be comparable to the maximum front strain readings from FOS.

7.3 Free Vibration Long Term Temperature Data

The temperature measurement plays a crucial role in structures constructed in extreme environments with a high-temperature variation. Further, massive concreting generates a high-temperature gradient that may affect the gain of concrete strength. Thus, it is paramount to monitor temperature of structural members and systems continuously for taking decisive actions.

Figure 7 shows the 24-h temperature variation recorded by FOS and WMS systems. The noisy data shown in Fig. 7a is due to the higher sampling rate which has

Table 2 Peak acceleration and time period from FOS and CWS systems

Day	Date	Time	Dir	Acceleration						CWS									
				FOS			Y			X		Y							
				Peak (g)	Time per. (s)	Time Per. (s)	Peak accl. (g)	Time Per. (s)	Time Per. (s)	Peak accl. (g)	Time per. (s)	Peak accl. (g)	Time per. (s)						
Day 1	21-01-2022	11:00 AM	Y	0.01	0.93	0.87	0.18	Instrument error	0.03	0.85	0.18	0.85							
			X	0.20	0.93	0.05	0.90												
		01:00 PM	Y	0.20	0.87	0.30	0.84												
			X	0.29	0.90	0.20	0.80												
		03:00 PM	Y	0.34	0.87	0.45	0.83												
			X	0.43	0.90	0.33	0.90												
		05:00 PM	Y	0.39	0.95	0.52	0.87						0.03	0.85	0.18	0.85			
			X	0.48	0.93	0.38	0.80						0.13	0.88	0.03	0.93			
		Day 2	22-01-2022	11:00 AM	Y	0.03	0.90						0.87	0.15	Instrument error	0.03	0.83	0.16	0.85
					X	0.11	0.87						0.02	0.90					
01:00 PM	Y			0.11	0.90	0.27	0.87	0.03	0.83	0.19	0.90								
	X			0.23	0.90	0.13	0.83	0.19	0.92	0.02	0.85								
03:00 PM	Y			0.23	0.90	0.38	0.87	0.03	0.90	0.18	0.88								
	X			0.33	0.90	0.25	0.90	0.14	0.92	0.10	0.90								
05:00 PM	Y			0.29	0.87	0.44	0.87	0.03	0.85	0.16	0.87								
	X			0.37	0.93	0.29	0.83	0.13	0.88	0.04	0.92								
11:00 AM	Y			0.09	0.90	0.16	0.87	0.03	0.83	0.16	0.85								
	X			0.11	0.87	0.01	0.87	0.16	0.92	0.03	0.87								

(continued)

Table 2 (continued)

Day	Date	Time	Dir	Acceleration								
				FOS			CWS					
				Peak (g)	Time per. (s)	Y	Peak accl. (g)	Time Per. (s)	Y	Peak accl. (g)	Time per. (s)	Y
		01:00 PM	Y	0.08	0.90	0.24	0.03	0.90	0.19	0.83	0.90	0.90
			X	0.19	0.90	0.08	0.18	0.90	0.02	0.90	0.85	0.85
		03:00 PM	Y	0.18	0.90	0.23	0.02	0.90	0.18	0.87	0.88	0.88
			X	0.22	0.90	0.16	0.15	0.90	0.05	0.92	0.90	0.90
		05:00 PM	Y	0.14	0.90	0.30	0.03	0.90	0.16	0.90	0.90	0.90
			X	0.25	0.90	0.13	0.15	0.90	0.02	0.90	0.87	0.87

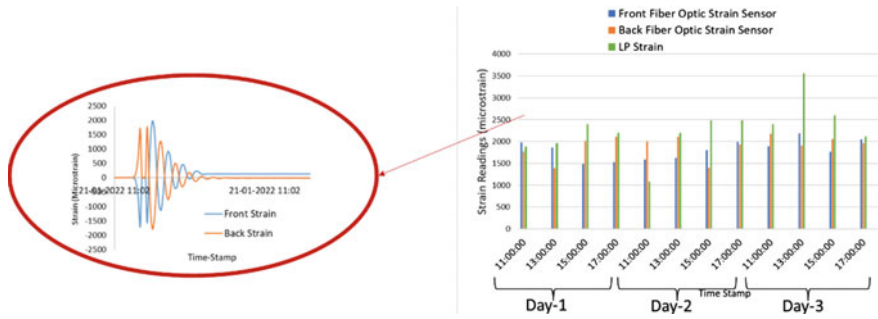


Fig. 6 Strain versus time history from FOS and CWS system

been selected to record the ambient temperature variations in the present investigation. Such high sampling rate is necessary to record the acceleration response from the FOS which is connected to the same interrogator through the same algorithm. The mean temperature variation recorded by both FOS and WMS on the column specimen has been observed to vary between 25 and 29 °C.

8 Introduction to Smart FRP

It has been observed in the present study that the FOS system can offer many potential advantages over the CWS and the WMS systems for SHM applications. The examination and comparison of the characteristics of the FOS system to conventional techniques reveal the dynamics of FOS systems in predicting minute disturbances in the column specimen. However, the current cost of access to customized FOS monitoring systems and services is exceptionally high. Hence, it is difficult to consider and include advanced SHM measures using the FOS system at this cost.

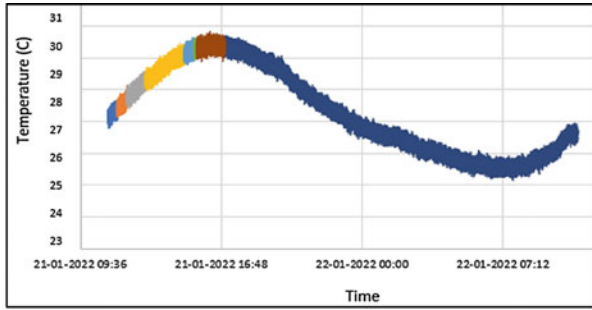
The primary motivation of using FOS in SHM is to benefit the future design of new buildings and protect the overall economics of building maintenance, as a consequence of better understanding of the assessment of existing buildings along with their adaptation and restoration protocols. With practising engineers, industry, and academia working in tandem, it is necessary to reduce the cost of the FOS system so that greater benefits can be accrued to society. While a commercially packaged FBG sensor consists of stainless-steel packing, a smart FRP packaged FBG sensor would cost significantly lower. This is due to the fact that the cost of FRP is substantially lower than the cost of stainless steel itself.

A novel manufacturing technology for the embedment of the FOS in pultruded FRP bars has been developed in an ongoing investigation in order to utilize them as the smart sensing element in concrete and steel structures. The finished product (referred to as ‘smart FRP bar’) has been manufactured by designing a FOS layout to be embedded into the FRP bar and subsequently modifying the open-resin pultrusion line that allows the sensor embedment within the composite bar and the subsequent

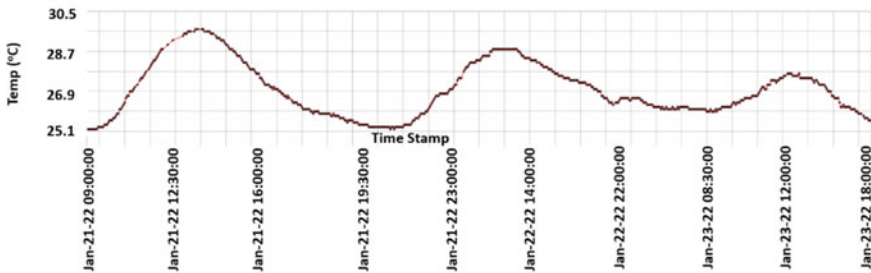
Table 3 Peak strain from FOS and CWS systems

Day	Date	Time	Dir	Strain							
				FOS				CWS			
				Front strain ($\mu\epsilon$)		Back strain ($\mu\epsilon$)		Max disp. (mm)	Max + Strain ($\mu\epsilon$)		
				Max+	Max-	Max+	Max-				
Day 1	21-01-2022	11:00 AM	Y	1980	1699	1776	1786	7.52	1880		
			X	1710	2129	79	252	8.48	2120		
		01:00 PM	Y	1864	1278	1387	1892	7.84	1960		
			X	880	493	118	113	1.6	400		
		03:00 PM	Y	1490	1932	2014	1407	9.6	2400		
			X	1079	1316	162	170	1.12	280		
		05:00 PM	Y	1529	1951	2106	1625	8.8	2200		
			X	1267	782	81	0	1.28	320		
		Day 2	22-01-2022	11:00 AM	Y	1582	1976	2003	1739	4.32	1080
					X	742	608	124	103	1.6	400
01:00 PM	Y			1629	2050	2107	1756	8.8	2200		
	X			826	714	194	260	1.28	320		
03:00 PM	Y			1808	1488	1404	1689	9.92	2480		
	X			1210	1854	462	333	0.64	160		
05:00 PM	Y			1986	1909	1931	1777	9.92	2480		
	X			724	526	377	247	0.64	160		
Day 3	23-01-2022			11:00 AM	Y	1888	1992	2181	1246	9.6	2400
					X	1050	934	0	400	1.28	320
		01:00 PM	Y	2190	2029	1903	1355	14.24	3560		
			X	1082	381	309	381	0.64	160		
		03:00 PM	Y	1768	2074	2064	1647	10.4	2600		
			X	1368	1488	423	565	2.72	680		
		05:00 PM	Y	2046	1841	1961	1405	8.48	2120		
			X	1039	447	133	226	0.96	240		

recovery of the associated fibre-optic leads. The present embedment technique has been validated by embedding a single optical fibre among 160,000 continuous reinforcing fibres impregnated with epoxy resin. The prototype sample has been subsequently tested using a FOS fault detector and by-passing a laser light through the FC/APC adaptor (as shown in Fig. 8).

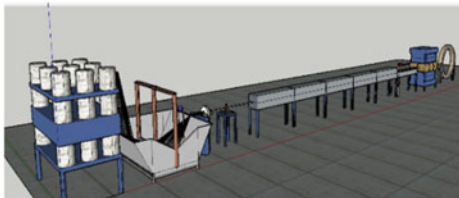


(a) FOS System

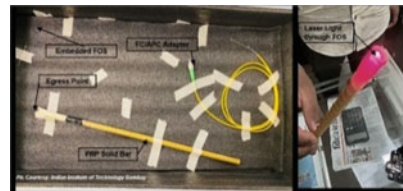


(b) WMS System

Fig. 7 Temperature versus time history



(a) Modified Pultrusion Line



(b) Finished Smart FRP

Fig. 8 Smart FRP bar prototype

9 Summary and Conclusions

Preventive intervention using SHM is always efficient, less disruptive and economical than undergoing structural intervention by retrofitting. This is certainly true for the maintenance of ageing civil infrastructure where repair costs can become astronomical. With the increasing volumes and quality of data becoming available, intelligent monitoring of ageing assets is feasible. Insights from this data can be used to better

understand asset health and detect early warning signs so that proactive maintenance can be undertaken—saving time, money and improving worker and public safety.

The pilot investigation reported in this paper contributed towards testing three independent mutually exclusive sensor technologies, namely CWS, WMS and FOS to perform long-term continuous monitoring of infrastructure systems. The measured data can be used as an input for an in-time monitoring system which can be used for operational functions as well as for the management of the bridge maintenance, by complementing and targeting the information gathered with routine inspections.

The study concluded that although the FOS system showed satisfactory results for acquiring real-time data without any discrepancies, the commercial aspects of FOS system limit its feasibility in SHM applications. Thus, a detailed investigation has been undertaken to develop an FRP packaged FBG sensor that is cost-effective and technologically advanced.

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