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Structural health monitoring of civil engineering structures by using the internet of things: A review

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ABSTRACT

Structural health monitoring (SHM) and damage assessment of civil engineering infrastructure are complex tasks. Structural health and strength of structures are influenced by various factors, such as the material production stage, transportation, placement, workmanship, formwork removal, and concrete curing. Technological advancements and the widespread availability of Wi-Fi networks has resulted in SHM shifting from traditional wire-based methods to Internet of Things (IoT)-based real-time wireless sensors. Comprehensive structural health assessment can be performed through the efficient use of real-time test data on structures obtained from various types of IoT sensors, which monitor several health parameters of structures, available on cloud-based data storage systems. The sensor data may be subsequently used for various applications, such as forecasting masonry construction deterioration, predicting the early-stage compressive strength of concrete, forecasting the optimum time for the removal of formwork, vibration and curing quality control, crack detection in buildings, pothole detection on roads, determination of the construction quality, corrosion diagnosis, identification of various damage typologies and seismic vulnerability assessment. This review paper summarizes the applications of the wireless IoT technology in the monitoring of civil engineering infrastructure. In addition, several case studies on real structures and laboratory investigations for monitoring the structural health of civil engineering constructions are discussed.

1. Introduction

Monitoring and assessing the conditions of civil engineering infrastructure are crucial for the economic development of a country because a long service life and the timely maintenance of structures reduces reconstruction costs substantially. The structural performance of civil engineering infrastructure decreases over time because of immediate or short-term factors after or during construction period, such as inappropriate curing, vibration, shrinkage cracks, and workmanship, and long-term effects, such as material degradation and weathering, rebar corrosion, water seepage, loading conditions, environmental degradation, and crack formation. Therefore, structural health monitoring (SHM) from the initial to the final stages of service life is crucial. Service life can be prolonged through the real-time nondestructive SHM of civil infrastructure to identify damage locations in the initial stages of service life and monitor control factors that might lead to future damage. Factors that may limit the service life of different types of civil engineering structures and applications of IoT-based SHM are presented in Fig. 1.

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Several case studies [1–4] have reported the collapses and damages of civil engineering structures because of inadequate SHM. For example, in 1864, the Dale Dyke Dam in the United Kingdom collapsed because of the formation of embankment cracks, and this collapse resulted in the deaths of at least 240 people [5]. In the 1940s, the Tacoma Narrows Bridge collapsed because of the activation of the twisting mode (aeroelastic flutter) of vibration by wind [6]. Furthermore, collapses of the formwork shoring system have led to the deaths of construction workers at many construction sites [7]. In April 1978, a reinforced concrete (RC) cooling tower in Willow Island, Virginia, USA, collapsed, which led to 51 workers falling from the roof of the tower [8]. According to the post-collapse assessment, the probable reasons for the aforementioned collapse were the premature removal and inappropriate anchoring of the scaffold and the inability to achieve the required concrete strength to support the loading conditions. Incidences of structural collapses in the past 5 years include the Florida International University pedestrian bridge in 2018 [9] because of the excessive tightening of cables, which caused crack growth collapse, and Xinjia Express Hotel in 2020 [10], which occurred because of the illegal construction of an additional story and resulted in the deaths of 29 people. The aforementioned cases highlight the importance of real-time SHM.

Several studies [11–25] have indicated the importance of wireless sensors and the Internet of Things (IoT) for SHM in various engineering domains. Wireless IoT sensors can be installed at selected locations and transfer data to a cloud-based platform; therefore, they can alert relevant individuals and authorities regarding unusual changes in monitored damage-sensitive parameters and thus improve the efficiency of existing SHM systems. IoT technologies provide a mechanism for transferring real-time data to cloud platforms so that the collected data can be remotely accessed, connectivity between devices can be improved, and parameters of interest can be calculated. IoT technology aims to inspect structures with SHM data being retrieved online; thus, can be used to examine structures for future generations SHM systems. Additionally, apart from the IoT-based SHM systems summarised in the review paper, there exist alternative methods and possibilities for SHM. Examples are smart and functional materials [26,27], smart aggregates [28–30], printed sensors and structures [31–34], screen-printed sensors [35], carbon-based nanomaterials [36–40], infrared thermography [41,42], radar-based SHM [43,44], sonic/ultrasonic testing [45,46], LIDAR [47,48], 3D laser [49–51], computer-vision [52–55], radiographic techniques [56], global navigation satellite system [57], three-dimensional digital image correlation [58, 59], smartphones [60–62] and many more techniques at local and global levels. These solutions should optimize the time for building health intervention with possible retrofit solutions, which would prevent major collapses.

The application of the IoT in SHM can help increase the service life of buildings and bridges and thus facilitate the creation of sustainable infrastructure worldwide, which would pave the way for smart cities [63,64]. Thus, monitoring structural health parameters of interest by using low-cost, self-powered IoT sensors [65] is crucial. Abruzzese et al. [13] envisioned the installation of IoT sensors as part of legal and structural code provisions to gain knowledge on the current health of structures for designing measures to prolong their service life. This aim can be achieved by adopting digital technologies under the Construction 4.0 framework, such as machine learning, the IoT, and data science [66,67], to improve current SHM practices for achieving the SHM 4.0 revolution. The new technologies have low cost and are practical for measuring the response of large-scale structures.

IoT-based monitoring sensors exhibit high potential for SHM and smart supervision applications in civil engineering [68–70] because they are supported by artificial intelligence technologies and their use does not require human intervention [71]. Several factors have contributed to the increased use of the aforementioned sensors. These factors include a reduction in the costs of IoT-based monitoring sensors with their miniaturization, low power consumption and ubiquitous connectivity, improvements in cloud computing capabilities, and rapid advancements in data science. The data collected from IoT sensors are used for predicting various

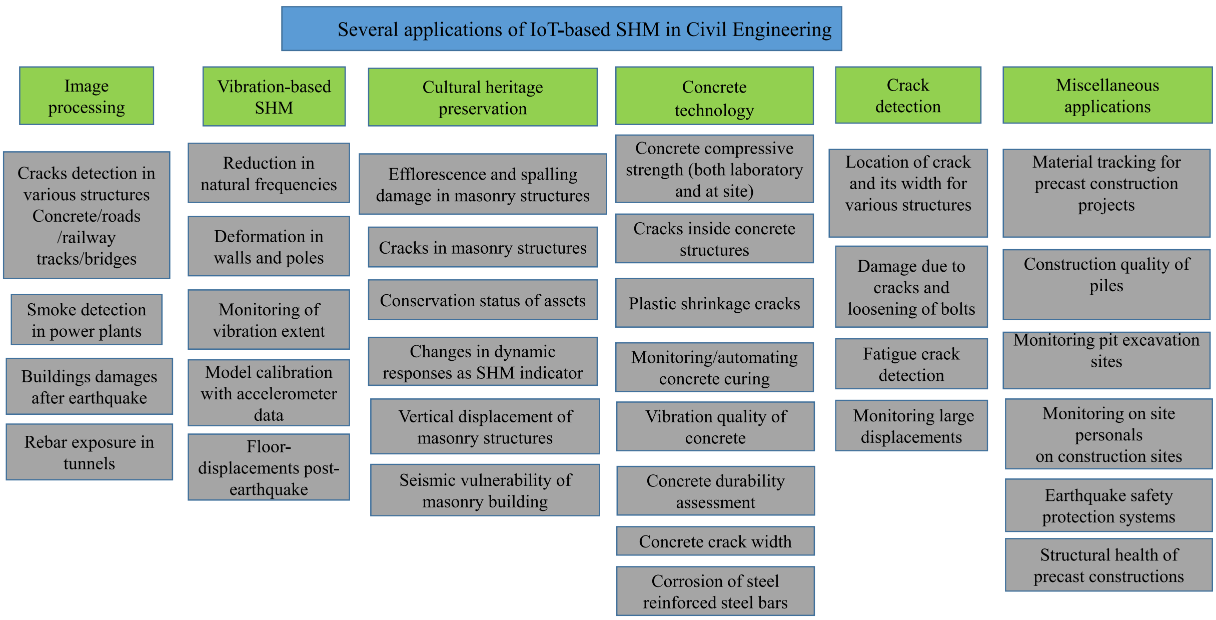

Fig. 1. Examples of applications of IoT-based SHM methods for civil engineering structures.

structural health indicators that affect the life-long integrity of civil engineering infrastructure. Moreover, efficiently monitored buildings provide high returns on investments in terms of energy conservation [72] and maintenance costs. The IoT has been used in the SHM of civil engineering infrastructure only in the past few years. Tables 1–6 summarize state-of-the-art IoT applications used for SHM at laboratory and field scales. Fig. 2 illustrates a sample IoT system that can be used for the SHM of civil engineering infrastructure, which includes aspects from parameter identification to decision-making for maintaining structural health. Monitoring the temperature of a concrete surface to forecast the compressive strength of the structure represents an indirect application of IoT for SHM; however, measuring the crack width of a concrete surface represents a direct application of IoT for SHM. The aforementioned parameters serve as key performance indicators (KPIs) for determining the structural integrity of concrete constructions.

Studies have examined the usage of the IoT in civil engineering. Ghosh et al. [153] explored the potential capabilities of the IoT in the construction industry. They identified the importance levels of main research areas in the IoT for the smart construction sector. Alavi et al. [154] conducted a state-of-the-art review on the applications of the IoT in the development of smart cities. Awolusi et al. [155] analyzed the application of wearable sensing devices and the IoT for enhancing the safety of workers at construction sites. They proposed the use of various types of sensors for physiological monitoring, environmental sensing, proximity detection, and location tracking to mitigate construction hazards for enhancing the safety of the construction workplace. Jia et al. [156] and Gao et al. [157] investigated the IoT technologies used in smart buildings and their implementation challenges. Tang et al. [158] integrated building information modeling (BIM) and IoT device integration to improve construction and operational efficiencies. Taheri [159] reviewed five key sensors, including wireless sensors, used in the SHM of concrete infrastructure. Tokognon et al. [160] reviewed a framework based on IoT technologies and data management for SHM; however, they did not review any case studies on the application of the aforementioned framework in civil engineering. Dave et al. [161] proposed combining the IoT with BIM to improve the information flow in construction activities. Studies have examined the use of IoT technologies in various civil engineering applications but the present review paper focuses solely on the SHM of civil engineering structures by using the IoT.

Many IoT sensors have been modified and customized for the SHM of various types of civil infrastructure as stated in Section 3 and briefly mentioned in Fig. 1. The use of state-of-the-art IoT technologies can improve real-time SHM of structures and increase

Table 1
Review of the literature on the use of the IoT and other methods in the SHM of concrete structures.

reference	case study sample	monitored input from IoT sensor/sensors used	SHM indicator
[73–76]	concrete cylinder/cube specimens in laboratory	internal concrete temperature sensors, moisture sensor	early age compressive strength of concrete
[77]	case study of a 250 m super high-rise building	concrete temperature history	strength of concrete structure with time
[78]	wind turbine reinforced concrete foundations	temperature at 5 locations	concrete strength
[79]	concrete cylinder lab specimen	embedded piezoceramic sensor to capture harmonic amplitude	early-age strength monitoring
[80]	laboratory testing of concrete and brick structure	ultrasonic pulse velocity	damage in concrete structure correlated by reduction in ultrasonic pulse velocity
[81]	concrete specimens (40cmx10cmx10cm)	embedded smart temperature sensors (SmartRock) and PZT sensors	concrete strength through maturity method and UPV velocity
[82]	20 box-section beams	temperature and humidity	compressive strength of the concrete, no early-age cracks, better appearance
[83]	cement concrete laboratory specimen	atmospheric and concrete temperature, relative humidity	plastic shrinkage cracks
[84]	side wall concrete curing project at subway station in China	wind speed, temperature, humidity condition	appearance of drying shrinkage cracks
[85]	railway precast beam tensioning construction	piston displacement data during tensioning, retraction value measurement	tension force for pre-stressed concrete beams
[86]	concrete columns	concrete temperature, atmospheric temperature, relative humidity	early age compressive strength deciding the minimum striking time of vertical formwork
[87]	concrete formwork with a scaffold shoring system	slab settlement, overall lateral displacement, column axial force, column tilting angle	stability of scaffold shoring system for concrete formwork
[88]	both laboratory and civil construction site	temperature profile inside the concrete structure	concrete curing
[89]	laboratory concrete samples	concrete surface temperature and dampness (%), anemometer, humidity and temperature sensor (air)	concrete curing efficiency
[90]	arch dam in China	infrared sensor for vibration depth, camera sensor for concrete surface image	three-category classification model for vibration quality (unqualified, middle, and qualified)
[91]	proposed in concrete mixing plant	sensor for weight measurement, temperature and humidity sensors	concrete mix quality
[92]	proposed conceptual framework	various parameters that controls the penetration of CO_2 and chloride Cl^- ions	concrete durability
[93]	proposed application on reinforced concrete structures	pH and chloride Cl^- ion concentration	corrosion of reinforcement bars
[94]	proposed application on dams	temperature sensor, geophone sensor, pressure sensor, turbidity sensor, crack width sensor	unusual change in values of monitored parameters
[95]	indoor pedestrian steel bridge	gyroscope + accelerometer sensor, strain sensor, temperature and humidity sensor	spikes in values of monitored parameters

Table 2
Review of the literature on the use of the IoT and other methods in image processing.

Reference	case study sample	monitored input from IoT sensor	SHM indicator
[96]	reinforced concrete buildings damaged after earthquakes	image data of several damage typologies	four different damage types
[97]	spillway tunnel	images of a spillway tunnel collected by UAV	rebar-exposure defect
[98]	real field bridges and tunnels	digitally obtained images	cracks in concrete structures
[99]	real bridge deck	entire bridge deck pictures using cell phone camera	global crack map
[100, 101]	bridge structures	collected bridge crack photographs	cracks in bridges
[102]	railway tracks	ultrasonic sensors to measure distance between railway tracks, real-time video processing	rail surface defects (cracks, squats, corrugations, and rust)
[103]	laboratory prototype	RF transmitter and receiver, IR sensors	cracks in a railway track
[104]	dataset images from CRACK500 and GAPs384	IoT mobile sensor (for images)	road crack detection
[105]	medieval city walls in Siena Italy	displacement sensor	alert message after excess crack displacement
[106]	wall of residential building	moiré crack gauges	changes in moire pattern for crack growth indicator
[107]	fire smoke image dataset (both in operating and fire environment)	monitoring image of the power plant using IoT equipment	fire smoke detection in power plants

Table 3
Review of the literature on the use of the IoT and other methods in cultural heritage conservation.

reference	case study sample	monitored input from IoT sensor	SHM indicator
[108]	masonry buildings in China	real time image collection using smartphone camera	efflorescence and spalling damage in masonry structures
[109]	castle in San Fili Italy	piezoelectric accelerometer sensors	changes in natural frequency
[110]	two masonry churches	location, identification (intended use, use condition), typological, dimensional data, photographic data with crack identification	vulnerability index related to seismic vulnerability
[111]	specimen wall and masonry castle	LVDT for wall, piezoelectric accelerometric sensors for castle	vertical displacement of masonry wall exceeding limit values
[112]	Church in Sarajevo	heat detector, temperature sensor, gas and humidity sensor, air pollution sensor, vibration sensors, ultrasonic sensors, xylophage sensors	alert ceilings for undesirable values
[113]	historical library at University of Salamanca Spain	sensor nodes for 27 parameters including bioclimatic (temperature, CO_2, luminosity), structural (e.g. crack width) and biological	admissible tolerances limits and key performance indicators (KPI) for various assets to monitor conservation status
[114]	Science museum, University of Coimbra, Portugal	Oxygen Sensor, Nitrogen Oxide Sensor, Humidity Sensor, thermal sensor	sudden change in monitored parameters
[115]	historical library of the University of Salamanca	humidity and temperature sensors, xylophagous sensors, solar radiation sensor, carbon dioxide sensor, presence detector sensor, metrological station (MS) for recording outside air temperature, humidity, barometric pressure, wind direction and velocity, precipitations, rain duration, hail, solar radiation and carbon dioxide levels	monitoring of tolerance ranges (color coded for easy interpretation)
[116]	San Frediano bell tower in Lucca, Italy	three-axial acceleration, temperature, and humidity	increase in the power spectral energy
[117]	Church in Matera Italy	temperature and humidity sensor	ongoing structural monitoring of assets
[118]	Jeronimos Monastery in Lisbon	indoor temperature, relative humidity, CO_2	mechanical degradation of permanent collections
[119]	monument scaled model (1:20)	temperature and relative humidity sensor, IR flame sensor	early warning of disasters
[120]	relics from Changsha Museum	acceleration sensors, temperature and relative humidity sensors	damage during transportation of cultural relics
[121]	Church in Spain	temperature and relative humidity sensor nodes	artwork degradation
[122]	three ancient buildings in Italy	accelerometer sensor, temperature and humidity sensor, strain-gauge, displacement and wind speed transducer, unmanned aerial vehicle (UAV) for image acquisition	environmental and mechanical data, cracks in the structural components of the building

automation in industry. The benefits and limitations of IoT-based monitoring are described in Section 4. Section 4 which also presents ideas on how to improve the performance of IoT-based monitoring for civil infrastructure. Ultimately, this paper summarizes state-of-the-art applications of the IoT in both academia and industry. The findings of this review are beneficial for researchers and SHM professionals when developing IoT applications for SHM. Employing IoT-based approaches to monitor the real-time structural health status of various components of buildings over long- and short-term periods will aid in reducing the maintenance cost and extending the remaining service life of structures.

Table 4
Review of the literature on the use of the IoT and other methods in vibration-based damage detection.

Reference	case study sample	monitored input from IoT sensor	SHM indicator
[123]	three reinforced concrete beams	displacement sensor, dynamic measurements using accelerometers, strain sensor	reduction in natural frequencies for damage detection
[124]	proposed system for various concrete members	vibration sensor (integrated six-axis accelerometer), gyroscope, flex sensors, piezo board	deformation in walls, poles etc
[125]	cantilever structure (aluminum bar)	digital triaxial accelerometer (ADXL355)	increase in damage indicator
[126]	proposed application in dams	images, temperature & moisture sensor	parameters exceeding threshold limits
[127]	Volumni Hypogeum archeological site	two triaxial MEMS accelerometer	vibration of a structure
[128]	simply supported steel beam	three-axial acceleration sensors	monitoring modal shape and natural frequency
[129]	bridge in Tunisia	temperature variation sensor, humidity sensor, gas sensor, accelerometer	vibration monitoring
[130]	four- and eight-story buildings	acceleration dataset of building response to earthquakes	floor displacement post-earthquake
[131]	proposed implementation in structures	accelerometer sensor	observing non-linear vibrations

Table 5
Review of the literature on the IoT and other methods in crack detection.

Reference	case study sample	monitored input from IoT sensor	SHM indicator
[132]	aluminum sheet	two piezoelectric sensors mounted on opposite ends of metal sheet	damage location and width
[133]	reinforced concrete members	IoT sensors for crack monitoring	crack width
[134]	simply supported aluminium beam (33 cm, 2.5 cm × 0.2 cm)	piezoelectric transducers (actuator and a sensor)	cracks in beam
[135]	aluminium sheet	two PZT sensors	values exceeding threshold
[136]	concrete beam members	13 piezoceramic sensors	localization of structural cracks in concrete beams via voltage difference
[137]	unmanned gate crossing and aluminium frame track	IR sensor, pressure sensor	warning of crack or no crack
[138]	laboratory notched aluminum bar specimen	fiber Bragg grating (FBG) rosettes, fiber-optic sensor (FOAE) for acoustic emissions monitoring	monitoring crack initiation and extension
[139]	numerically modelled steel frame	piezoelectric strain and acceleration sensors	damages due to cracks and bolt loosening
[140]	steel truss structure of civil engineering machinery	strain sensor nodes at jib crane	fatigue crack detection
[141]	steel bridge	acoustic emission sensor	crack-related activities owing to high frequency acoustic emission
[142]	reinforced concrete beam and Wuxi west bridge in China	displacement sensor (−5 cm - +5 cm)	larger displacements indicating problems

Table 6
Review of the literature on the IoT and miscellaneous applications.

Reference	case study sample	monitored input from IoT sensor	SHM indicator
[143]	laboratory-scaled 6-storey test frame	3-axis wireless accelerometers (ADXL345) sensor to detect ground motions	detecting earthquake P-waves
[144]	prefabricated construction (PC) slab and a PC wall panel	RFID sensor for current location, strain sensor	PC structural performance during installation
[145]	real-life construction project in Hong Kong	RFID, GPS	tracking of the materials for precast project
[146]	public housing project in Hong kong	radio frequency, identification (RFID) sensor, GPS sensor	on-site assembly rightness in prefabricated construction
[147]	tunnel in Nanning city China	vibrating wire sensor (precision 0.025 mm)	settlement control
[148]	actual pit excavation engineering site	settlement of the building elements such as columns, walls, pile, gas pipeline	monitoring pit excavation engineering site (strut force and wall pressure)
[149]	suspension bridge model	FBG sensors	load position and intensity
[150]	case construction project	thermal infrared sensor, radio-frequency identification (RFID) sensor & trigger, thermal infrared sensor	real-timely monitoring the on-site persons
[151]	gravel pile	laser sensor, Beidou positioning antenna, electromagnetic current transformer	analysis of control parameters for monitoring construction quality
[152]	underground metro construction site in China	RFID-based positioning technology sensor, ultrasonic sensor	changing of hazard energy

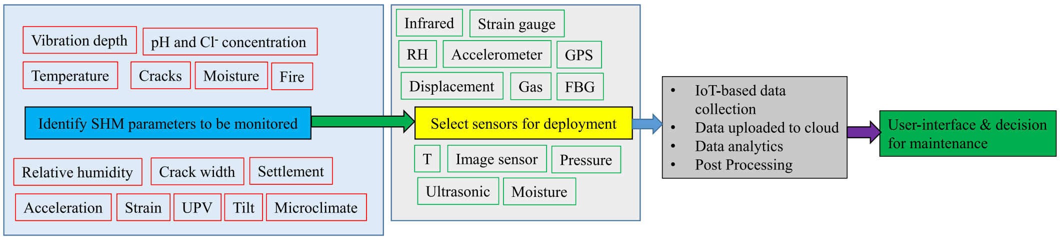

Fig. 2. IoT system for the SHM of buildings.

2. IoT architecture for SHM

IoT systems have a robust architecture to serve their intended purposes. Furthermore, the quality of the developed infrastructure governs the applicability of IoT systems. Various types of IoT systems used for different engineering applications are based on similar frame-works and data flows. An IoT-based SHM system mainly consists of five layers, as illustrated in Fig. 3. The "things" in IoT can be a building and must be connected to the Internet, with embedded sensors and actuators measuring SHM parameters and passing it on through IoT gateways. The next stage involves data collection by data acquisition systems, which filter massive amounts of data for further analysis. The third layer analyzes the data through, e.g. using machine learning techniques, for visualization. Then, the visualized data are transferred to cloud-based platforms, which analyze such data for providing additional insights. The five layers of an IoT-based SHM system are described as follows:

Layer 1 (sensors and actuators): Layer 1, which is the core layer of the IoT framework, is primarily responsible for the generation and collection of data on things through sensor nodes. Sensors and actuators are the core components of this physical layer, in which sensors monitor parameters required for building condition assessment and monitoring, such as temperature, relative humidity, crack image data, and acceleration. The decision regarding the intervention to be adopted is taken according to the analysis of the monitored sensor data. Sensors can be placed inside or outside the civil infrastructure that must be subjected to continuous health assessment. The actuators perform an action according to the data received from the sensors. For example, for the real-time monitoring of concrete curing according to the input obtained from temperature and relative humidity sensors, these can instruct the external curing machine ("actuator") to spray water to maintain the curing process of concrete. Section 3 presents details on the aforementioned application and describes the sensor responsible for measuring the SHM parameters. The sensors used in layer 1 must be calibrated to measure the relevant SHM parameters.

Layer 2 (internet gateways and network communication): Layer 2, namely the core IoT layer, comprises microcontrollers that receive data from sensors. Various developmental kits, such as Arduino, Raspberry Pi, and NodeMCU, are available in the market for this layer. These kits can be connected to suitable operating systems for task execution. The data fed into a microcontroller are processed to determine whether these data are appropriate for SHM applications. Layer 2 comprises data acquisition systems and Internet gateways. Data acquisition systems collect data from sensors, locally preprocess the collected data, and then send the pre-processed data to cloud-based platforms for processing after wirelessly squeezing the data into useful bundles for the next stage. Layer 2 acts as an intermediary level between the connected devices and the cloud platform.

Layer 3 (data analytics and cloud computing): Layer 3 is an edge computing layer that uses machine learning techniques to preprocess data before sending them to the cloud. A data center can store and analyze large quantities of data. For example, layer 3 can perform computations for temperature sensor data for concrete and predict the developed early-stage compressive strength.

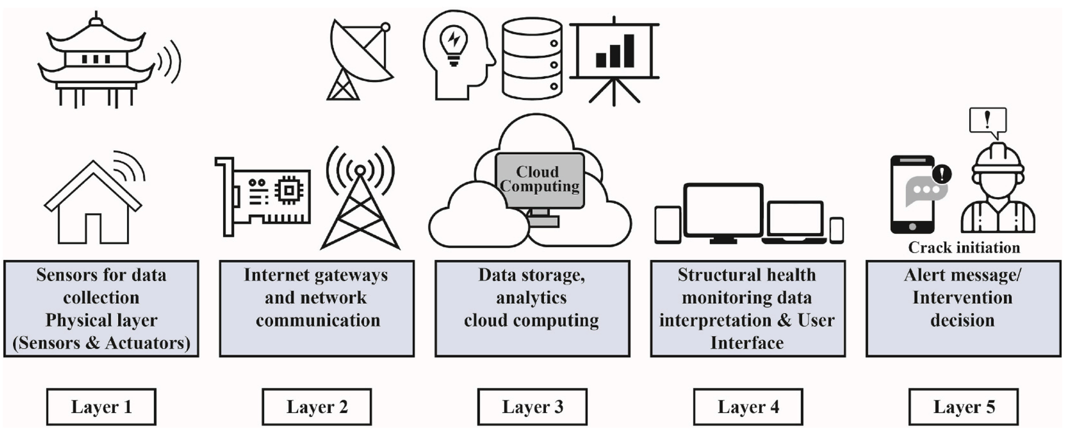

Fig. 3. IoT architecture for SHM applications.

Layers 4 and 5 (SHM data interpretation and session/message, respectively): Layers 4 and 5 analyze the preprocessed data from layer 3 to provide a broad meaningful picture to broadcast the appropriate response to the cloud. For example, the data computed by layers 4 and 5 can provide an estimate regarding the concrete vibration quality. When the quality deteriorates to a certain level, an alert message is sent to vibration equipment so that an appropriate action can be taken. In case of cultural heritage buildings, when the indoor climate deviates from recommended values, an alert message is sent to take proper action.

3. Review of IoT-based technologies used in civil engineering constructions

Numerous types of IoT-based sensors are used in various applications. This section presents an overview of the most popular types of IoT-based sensors used in SHM. Some monitored properties, such as curing and vibration, might not be directly related to mechanical properties; however, these factors may affect these properties and performance in the long term. Moreover, this section describes the applications of image-based (for crack identification) and vibration-based IoT-based methods in the SHM of infrastructure.

The data collected by IoT-based sensors may vary considerably and include e.g. relative humidity, acceleration, or video and audio data. These data can be used to determine parameters that affect the safety and performance of structures, such as the compressive strength, and the surface defects identified on the surfaces of buildings from images collected by an IoT system. These techniques enable the monitoring of the control factors required for developing SHM-based monitoring solutions.

Sections 3.1-3.6 reviewed the applications of rapidly evolving IoT-technologies deployed for real-time SHM applications in civil engineering field. Tables 1–6 have summarised the most recent applications of IoT-based SHM to monitor health of the structures. The sections are summarised and grouped accordingly on the basis of the similar applications of IoT are clubbed together such as, in SHM of concrete constructions (Section 3.1), image-based IoT (Section 3.2), cultural heritage SHM (Section 3.3), vibration-based damage (Section 3.4) and crack detection (Section 3.5), and some miscellaneous applications (Section 3.6). The review will raise awareness among engineers and enable them to tap the emerging IoT-based SHM for their benefit.

3.1. IoT in concrete technology

Monitoring of the mechanical and durability properties of concrete plays a crucial role in assessing the health of concrete structures. The inappropriate handling of the early-stage concrete mix can result in inadequate strength development in concrete in the later stages of its service life. This section discusses how IoT-based wireless sensors are used for assessing the mechanical and durability

Fig. 4. (a) IoT-based-real-time monitoring of concrete samples in a laboratory for calibrating maturity constants [77], (b) automatic concrete curing system developed by Yang et al. [82] to increase the curing efficiency and reduce the number of shrinkage cracks, (c) sample images classified according to concrete quality by a CNN [90], (d) embedded SmartRock sensor for obtaining temperature data [81], (e–f) application of a vibration quality control system based on an IoT sensor for concrete structures [90].

properties of concrete in real time. These sensors are increasingly used by project managers on site for the nondestructive evaluation of mechanical properties and sample climatic conditions [162]. Therefore, the aforementioned sensors reduce the need to conduct core sampling or the need to be present on site for sample extraction and testing; thus, these sensors reduce costs. Insufficient development of compressive strength with time, inadequate quality control, early removal of construction formwork, corrosion of rebars, inappropriate curing, and the formation of cracks can drastically reduce the service life of concrete structures.

For monitoring the early-stage compressive strength of concrete, IoT-based sensors are used to detect the temperature inside the concrete mix [163]. This temperature is correlated with the heat of hydration and concrete age, which can be used with the maturity index method [164] endorsed by the American society for testing and materials [165] and adopted by Carino [166] for estimating the early-stage compressive strength of concrete. This method is used for different grades and mixes used in large concrete placements [167], sprayed concrete [168], polymer concrete [169], curing at variable temperatures [170,171], and improving the estimation of compressive strength in the late stages of curing [172]. Many researchers have monitored the early-stage compressive strength of fresh concrete in laboratory samples [73–76], and some studies have monitored the early-stage compressive strength of concrete used in buildings. Zuo et al. [77] implemented an IoT-based remote real-time monitoring system on an under-construction, 250-m super high-rise RC building and concluded that this system can be applied remotely in real time with high accuracy. Inspired by the success of temperature-based sensors in the estimation of the compressive strength of concrete and in calibration through laboratory testing (Fig. 4a), commercial pocket-size, miniature Wi-Fi-enabled waterproof devices have been developed that are already used in industrial applications [173–175]. These devices can be easily embedded in various structural members, such as beams, columns, and slabs. Perry et al. [78] employed a network of 11 thermocouple sensors to determine the strength of an concrete foundation by using the maturity method. In addition to the maturity index, which is a function of the temperature and time, smart aggregates embedded with piezoceramic material are used for determining the compressive strength by adopting wireless sensors [79,176–180]. Misra et al. [80] proposed an SHM system for predicting the damage in concrete and brick specimens on the basis of Lamb wave amplitudes. Ultrasonic pulse velocities from both the aforementioned two types of specimens were compared with benchmark values to obtain an estimate of the damage inside laboratory specimens. Tareen et al. [81] performed a comparative study on the performance of smart temperature sensors and piezoelectric sensors (Fig. 4d). Yang et al. [82] conducted IoT-based monitoring of the concrete temperature and relative humidity when implementing automated concrete curing equipment (Fig. 4b). They selected a threshold value of 80% for relative humidity and $> 45^{\circ}C$ for temperature to add a fogging spray to concrete. John et al. [83] adopted an IoT system to measure atmospheric temperature, concrete internal temperature and relative humidity for concrete specimens to determine the critical point for the initiation of plastic shrinkage cracks in hot weather conditions. Wei et al. [84] developed an intelligent curing system to send the controlling instruction for water spraying in a concrete curing project in Hunan, China.

Several studies [181–183] have estimated the optimum time for removing the scaffold shoring system and impending post-tensioning methods in concrete constructions [85]. The aforementioned optimum time depends on the compressive strength, with the scaffold shoring system being removed after the required compressive strength is developed [86,184]. A delay in the removal of the scaffold shoring system increases the project costs on a day-to-day basis. Su et al. [87] used an IoT-based system for monitoring slab displacements. This system triggers an alarm when slab displacements exceed permissible values so that workers risk is reduced.

Several monitoring technologies are used for ensuring the success of the curing process of concrete. Before using IoT-based sensors, Barroca et al. [185] adopted a wireless sensor network to measure the internal temperature and internal humidity of a concrete cube. Cabezas et al. [88] developed and field-tested a concrete curing monitoring system based on a small embedded wireless sensor installed inside a concrete structure. Lo et al. [89] conducted a comparative study of various curing techniques ranging from traditional to IoT-based techniques. Studies have determined the advantages of IoT-based curing over manual curing in preventing plastic shrinkage cracks. Moreover, IoT-based curing requires less water than does manual curing. The vibration of concrete to remove air voids and ensure its appropriate compaction is crucial in concrete construction projects. The presence of air voids drastically reduces the strength of concrete and thus affects the performance of civil engineering infrastructure. Therefore, real-time monitoring methods have been developed for checking whether a concrete mix is undervibrated or inappropriately vibrated [186]. Wang et al. [90] adopted a hybridized approach that involves combining the IoT with convolutional neural networks (CNNs) to predict the vibration quality for fresh concrete. In their framework, the IoT is used to measure the vibration depth and capture images of concrete surfaces (Fig. 4e and f). Moreover, a CNN is used to determine the vibration duration and classify captured images into three categories (unqualified, middle, and qualified in Fig. 4c) according to a dataset of 15k images. Cai et al. [91] proposed an innovative IoT-based method to control the production process of concrete mixing plants for improving the quality and production efficiency.

The corrosion of steel is one of the most crucial phenomena that must be monitored to check the health status of structures, as it decreases the load-carrying capacity of RC members substantially. Taffes et al. [92,93] employed an IoT-based corrosion monitoring system for predicting the long-term durability of concrete structures. This system can predict the long-term durability of concrete structures because it can detect the corrosion of rebars by monitoring factors that control the Cl^{-} ion concentration and pH values inside concrete.

Furthermore, some laboratory [94] and on-site [95] SHM systems exist for monitoring unusual changes in monitored parameters, such as acceleration and crack width. These SHM systems are installed to inspect various components of a structure and set an alarm if the monitored parameters exceed permissible values.

3.2. IoT coupled with image processing

The IoT has been coupled with image processing techniques for various applications ranging from crack to fire detection. These techniques can detect intrinsic details that are not visible to experts performing surveys by using visual aids. Moreover, techniques based on drone-based inspections can be used to detect structural damage at inaccessible locations where operators cannot reach.

Spencer et al. [187] summarised the recent advances in computer-vision techniques for SHM of structures. Cracks and fires have direct effects on the structural health of civil engineering infrastructure [188]. Thus, the structural damage initiated by cracks and fire must be detected in time so that concerned authorities can make appropriate repairs to avoid long-term stability problems. Early repair of the aforementioned damage can increase the remaining service life and thus ensure adequate safety of a structure. Automated techniques based on convolutional neural networks (CNNs) with different deep learning (DL) frameworks are extensively used for detecting cracks in civil engineering structures. Mondal et al. [96] employed R-CNNs to classify four types of damages, namely spalling, cracks, exposed reinforcements, and buckling, in data obtained from buildings damaged after earthquakes through mobile internet. Feng et al. [97] employed DL and images captured by an unmanned-aerial vehicle (UAV) for detecting real-time rebar exposure in a spillway tunnel. Nair et al. [98] employed a two-stage damage detection method based on image processing techniques. The data required for their study were captured from an IoT Web-based server. In the first stage of the aforementioned method, the presence or absence of cracks is identified, In the second stage, an efficient thresholding strategy is used to increase the crack detection accuracy. A crack detection accuracy of up to 96% was achieved after the second stage. Sharma [99] used a crack inspection system for detecting cracks on the deck of a bridge. This system comprises a mobile robot (Fig. 5a) fitted with a camera for capturing images of the deck of a bridge in real time. The captured images are then processed using the Laplacian of Gaussian algorithm to identify cracks and generate crack maps. Zhang et al. [100] and Chehri et al. [101] adopted an intelligent bridge crack detection method for structural diagnosis. This method involves processing photographs of a bridge by using a CNN. Iyer et al. [102] designed a prototype system for the SHM of rails. This system uses an ultrasonic sensor for detecting cracks, corrugations, and squats and a Raspberry Pi camera for capturing images. The aforementioned multirobot system uploads sensor data though IoT technology, and the data are then classified using the computer-vision-based OpenCV software program. Furthermore, a prototype system as shown in Fig. 5b was tested in the laboratory in Ref. [103] for the detection of cracks in railway tracks.

In addition to cracks in bridges and railway tracks, IoT-based SHM systems have been used to detect cracks on roads [104]. Alfarraj [104] employed an IoT system based on a bio-inspired deep learning approach for road crack detection. This system analyzes images collected by a smart mobile camera sensor and achieved a prediction accuracy of almost 100% in Ref. [104]. Addabbo et al. [105] described IoT infrastructure that can be used in the large-scale monitoring of monuments for measuring displacements with a resolution of 10 μm, whose prototype is shown in Fig. 5c. The alert system helps in deploying low-cost sensor nodes for smart city applications. Rathnam et al. [106] employed the Moiré effect to detect cracks in concrete structures from Moiré pattern images. These images, which can be uploaded to a cloud-based platform by using a smartphone, are processed using an image processing algorithm to determine the displacement magnitude with an accuracy of $\pm$0.05 mm. Rui et al. [107] monitored the anomalies in input images captured by a video camera installed at an IoT power plant to detect fire smoke. The deep CNN employed for fire smoke detection exhibited an accuracy of 97% and 95% for the training and testing datasets, respectively.

3.3. IoT in cultural heritage preservation

Cultural heritage preservation is important for local economies as well as for traditional beliefs, customs, and cultural identities. Numerous people are directly or indirectly employed in the tourism sector, which may account for a considerable portion of a country's gross domestic product. Therefore, historic buildings should be appropriately inspected, and accurate damage diagnosis should be conducted for them. Failure to conduct such diagnosis may lead to the importance of historical buildings being diminished, which would affect the livelihood of people and the cultural identity associated with these buildings.

Many historic buildings that flourished in the past are at risk because of the damage accumulated in them. This damage is caused by various hazards, such as earthquakes [189], owing to the high vulnerability of these buildings. The SHM of masonry constructions, which constitute the majority of this heritage, is a challenging task because of the heterogeneity of construction materials, complex structural geometries, and the existence of various collapse mechanisms. Therefore, several parts of a structure must be monitored to obtain an accurate indicator regarding its health.

The use of wireless IoT [190–196], modern IoT [197–200], and augmented reality (AR)-assisted [201–205] methods for inspecting monuments and other infrastructures are gaining popularity in many parts of the world. Napolitano et al. [206] developed an application prototype to combine image-based documentation with AR to several SHM case studies such as bridges and buildings for better visualization of several damage pathologies and sensor data. Yu et al. [207] realised VR technology with IoT to restore the ancient kiln and ceramics in historical site in China. In another study [203], NDT methods were integrated with AR to assess the SHM of bridge infrastructure by collecting data of damage deterioration's. Several indicators that change with the age of a building, such as

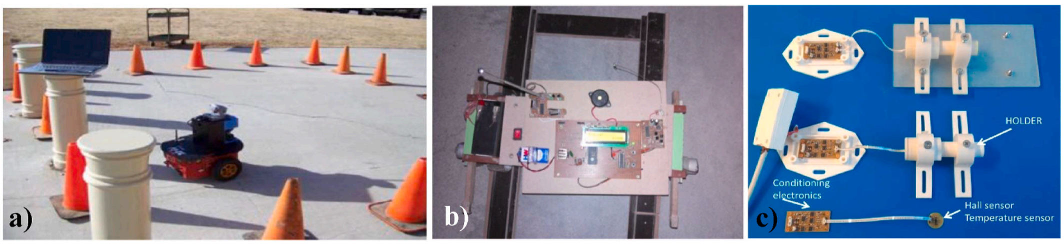

Fig. 5. (a) mobile robot for inspecting cracks on bridge decks [99], b) prototype laboratory circuit employed by Ref. [103], and (c) sensor prototype for monuments monitoring [105].

material deterioration, can be estimated quantitatively. The use of nondestructive techniques with machine learning techniques can considerably increase the accuracy of the SHM of historical constructions. In this regard, IoT-based smart platforms [208] and resilient preservation [209] can be used to obtain data from several parts of historic structures for detecting various damage typologies, such as spalling and efflorescence [108], in these structures. Wang et al. [108] used a mobile phone to conduct on-site damage detection. Images were captured using a smartphone and sent to a workstation for automatic damage detection based on deep learning. Lamonaca et al. [109] proposed a calibrated finite-element method model to identify damage in the Castle of San Fili, Italy, from data obtained from accelerometer sensors. Uva et al. [110] investigated the seismic vulnerability of masonry churches from data that were acquired using a computer platform [quality detection platform (QDP)] and mobile phone, which were connected through an IoT framework. The aforementioned QDP assesses the seismic vulnerability by using the macroelement approach and adopts the analytic hierarchy process to calibrate the relative importance of each factor in each collapse mechanism. The photographs obtained from the mobile adopted in Ref. [110] were used to correlate possible crack patterns with their associated overturning and in-plane mechanisms by studying the matrix of pathologies. Scuro et al. [111] conducted a case study on the IoT-based SHM of two masonry cultural heritage structures, out of which one was experimental diagonal compression testing of specimens simulating an antiseismic technique of using a masonry infilled wall comprising fictile tubules (a special type of brick, characterized by a cylindrical shape and a hollow core) used in the past, while other was a preliminary vibration-based damage identification of a Castle in Calabria, Italy. For the first structure, two linear variable differential transformers (LVDTs) were used to record horizontal and vertical displacements. Moreover, the response of the second structure was measured using accelerometers. Both tests carried out have their data gathered though IoT compared from numerical finite-element models, one for load–displacement diagrams and another for evaluating natural frequencies for first three modes of masonry castle.

Several researchers [210–214] have established that appropriate climate control and optimum indoor climate is required inside heritage buildings for preserving and prolonging the life of cultural movable works, such as wall paintings. The combined effect of factors such as relative humidity, temperature, fire, moisture ingress, pests, and ultraviolet radiation contributes to the long-term damage of assets in heritage buildings. Maksimovic et al. [112] developed an SHM system containing various sensors to measure the climate and vibration parameters of a church in Sarajevo, Bosnia and Herzegovina, for improving the microclimate inside the church. Mora et al. [113] implemented historical BIM as a solution to monitor KPIs though IoT monitoring. Tse et al. [114] monitored the temperature, humidity, and indoor air quality for a museum in Portugal by using a self-adaptive system, whose sensors turn off when their use is not required or the museum is closed. The aforementioned authors also used their system in the historical library at the University of Salamanca for monitoring several parameters, such as temperature, humidity, CO_2 concentration, luminosity, and solar radiation, to inspect the structural health. For example, excessively high temperatures can accelerate the degradation and discoloration of assets such as books or manuscripts. Sanchez et al. [115] implemented their PlusCare system at the library of the University of Salamanca, which integrates the IoT, 360° panorama images, and point cloud data. The system monitors 27 parameters through sensor hotspots, whose updated values are displayed on a three-dimensional (3D) point cloud for SHM, 360 panorama images, and point cloud data. The systems adopted by Mora et al. [113] and Sanchez et al. [115] are equipped with color coding scales so that nonexperts can easily interpret the structural health of a structure. Barsocchi et al. [116] deployed IoT sensor nodes at the top of the San Frediano bell tower to monitor the effects of bell movements on the tower. Data related to three-axial acceleration, temperature, and humidity were obtained using sensors and sent to a message queuing telemetry transport broker. The data were subsequently relayed to a cloud MySQL database and MongoDB database.

Lerario and Varasano [117] developed a cloud-based IoT platform for the static monitoring of the environmental effects causing the deterioration of the Saint Domenico Church in Matera, Italy. The data obtained through such monitoring would facilitate the creation of a digital twin model [215] of the aforementioned church in the future. Silva et al. [118] implemented low-cost sensor devices on an Arduino platform to obtain temperature, relative humidity, and CO_2 readings in compliance with EN 15 757 standards [216] for monitoring the interior climate of a church in Portugal. Spasova et al. [119] used a prototype of an IoT-based solution for detecting damage in a monument in Varna, Bulgaria. Zhang et al. [120] monitored environmental parameters and the vibration of cultural relics during their transportation to ensure their safe movement. Perles et al. [121] monitored the temperature and humidity inside a church in Spain to identify objects in the church that were affected by adverse environmental conditions. Bacco et al. [122] implemented a

Fig. 6. Interface of a futuristic IoT–UAV integrated system for SHM [122]: (a) building in Old Fortress in Leghorn [122]; and (b) its VR reconstruction showing sensor damage data in real time [122] (http://moscardo.isti.cnr.it/).

monitoring system developed in the MOSCARDO project to detect potential structural deterioration in heritage buildings. This system integrates virtual reality (VR), an IoT architecture and an unmanned aerial vehicle (UAV). Environmental and mechanical data were collected from IoT sensors; the UAV was used for the 3D reconstruction of the heritage buildings with the exact positions of sensor nodes; and a 3D online VR tool was used for monitoring the current status of the building (Fig. 6a and b).

3.4. IoT in vibration-based SHM

In vibration-based damage detection techniques, damage is assessed by monitoring the changes in natural frequencies and mode shapes caused by damage. The response of civil infrastructure is captured by sensors to measure changes in sensitive modal parameters. Any change in the global modal parameters can help the identification of damage. For example, changes in mass, stiffness, and damping can be identified from the natural frequencies and mode shapes captured by accelerometers. Mishra et al. [217,218], Ramos et al. [219,220], Pena et al. [221], and Barman et al. [222] have detected damage in 3D trusses, masonry structures, cantilever beams, plates, and double-story buildings on the basis of changes in natural frequencies and mode shapes. Barontini et al. [223] used a multiobjective optimization algorithm to solve the inverse damage detection problem for historic constructions. The use of wireless accelerometers with high sensitivity and low noise [224,225] is becoming popular in IoT-based SHM. Thus, the IoT-based SHM of a structure can be conducted by measuring the vibrational response of the structure in real time.

Danish et al. [123] investigated the integration of the IoT into the real-time SHM of an RC beam. The data obtained from accelerometers (acceleration response and fast Fourier transform graph) and strain gauges were compared with data for the undamaged state to determine the damage status of the RC beam. Paul et al. [124] proposed a portable structure analyzer that can be mounted on several load-carrying members and joints of RC structures. This analyzer can monitor the inclination of members and provide alerts for excessive deformations and overinclined members, which can ensure safe evacuation. Muttillo et al. [125] concluded that a 2.5-mm engraving in an anchored cantilever beam (Fig. 7a) led to the damage indicator increasing by 24.65. Shukla and Lingaraj [126] proposed an IoT-based approach involving the use of microcontrollers and sensors to detect cracks in dams through continuous monitoring. They employed moisture, temperature, and vibration sensors to detect damage in dams when the moisture or vibration value exceed the corresponding threshold. De et al. [127] developed a sensor node system to monitor vibration locations on site for detecting potential risk situations. Testoni et al. [128] used five three-axial acceleration sensors on a simply supported steel beam (Fig. 7b) to obtain data that could be processed using signal processing techniques and Raspberry Pi for determining modal shapes and natural frequencies of vibration. In addition to laboratory-scale structures, vibration-based diagnostics has been conducted for monitoring bridge health [129]. Ibrahim et al. [130] deployed an IoT-based network of distributed sensors for capturing inter-story drift ratio, as floor displacement is identified as main governing parameter according to codal standards for post-disaster SHM. Chowdhry et al. [131] used a simple accelerometer to capture nonlinear vibrations for performing SHM.

3.5. IOT for crack detection

Abdelgawad and Yelamarthi [132] mounted pairs of piezoelectric sensors to detect the extent and locations of damage in structures through a combination of the pulse-echo and pitch-catch techniques. Their proposed method exhibited an accuracy of 99% and 92% for damage location and damage extent, respectively. Lee and Lee [133] predicted the widths of cracks in structural members by using the IoT and an analytical model. The responses of various parts of a simply supported aluminum beam were captured using two lead zirconate titanate (PZT) transducers (one sensor and one actuator, as shown in Fig. 8 and compared with that of an undamaged part by adopting the cross-correlation damage index [134]. If the obtained cross-correlation damage index was 0.95–1, the structure was deemed healthy, whereas a cross-correlation damage index of less than 0.5 triggered an alarm. Mahmud et al. [135] used a combination of the pitch-catch and pulse-echo techniques to determine the location and extent of damage in an aluminum sheet by adopting two PZT sensors. Ghosh et al. [136] demonstrated the performance of low-cost piezoceramic sensors in recording the localization of cracks and fractures in concrete beams. Dhande et al. [137] proposed a crack detection system consisting of infrared sensors for the automatic closing and opening of unmanned railway crossings. The intensity of light reaching these sensors is directly correlated to the

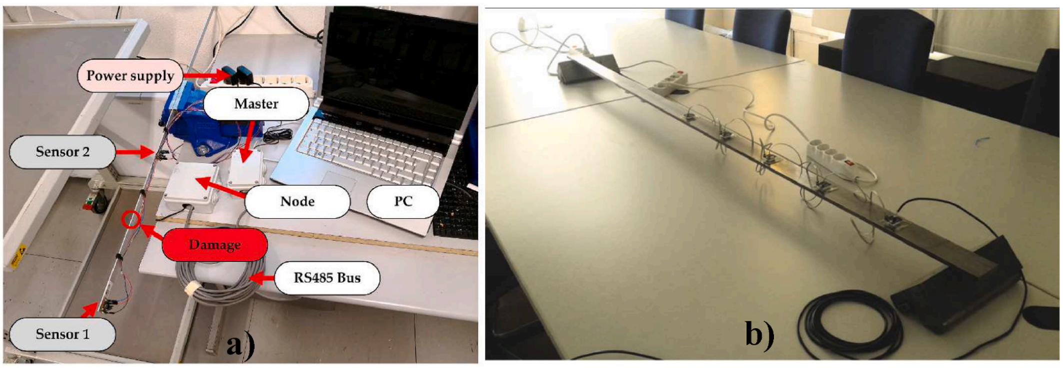

Fig. 7. (a) Experimental setup used in Ref. [125] for an aluminum bar (damage in the red circle: 2.5-mm engraving; the two accelerometers are marked as sensor 1 and 2) and (b) simply supported beam with five sensor nodes used in Ref. [128] (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

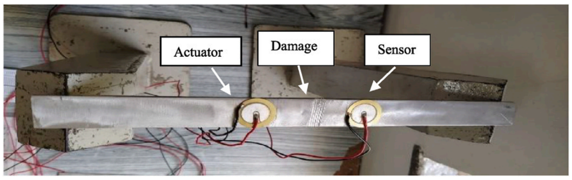

Fig. 8. Simply supported beam with two PZT sensors used in Ref. [134] (the damage increased with the crack width).

extent of cracks in the railway track.

For the detection of damage in structures, Nguyen et al. [138] suggested the implementation of passive principal strain direction monitoring by adopting wireless fiber Bragg grating (FBG) rosettes. The aforementioned method can be integrated with the IoT. In Ref. [138], considerable agreement was noted between the strains predicted using a numerical finite-element model and those measured using FBG sensors. Hasni et al. [139] employed an intelligent damage detection approach to detect the damage induced by bolt loosening and cracks in a steel frame. The voltage output obtained through wireless transmission was compared with the benchmark value obtained for the undamaged structure to estimate the damage extent. Yasuda and Miyazaki [140] used an IoT-based remote automatic monitoring system and a weldable strain sensor to detect fatigue cracks in a steel truss structure and jib crane. They adopted the SI–F method, in which abnormal values indicate the onset of fatigue damage, for damage analysis. Mukherjee et al. [141] developed an IoT-based acoustic emission sensor for the SHM of bridges. Hou and Wu [142] designed a wireless, low-cost, and IoT-based SHM system for monitoring bridge displacement. The accuracy of the aforementioned system was ensured by calibrating it by using a wired sensor.

3.6. Miscellaneous applications of the IoT in civil engineering

IoT-based SHM can be used to capture crucial parameters that directly or indirectly affect the health status of civil engineering structures in other applications. Lin et al. [143] connected a base isolation system with the IoT to allow an earthquake warning system to modify the properties and the effectiveness of a base isolation system which can be locked by employing shear keys in absence of an earthquake event (i.e., in the standby mode) and retractable shear keys in the activated mode. The working of the aforementioned technology is based on the differences in the traveling speeds of P and S waves, and it provides an early earthquake warning. The aforementioned authors conducted a laboratory test on a six-story test frame excited on a shaking table and demonstrated a reduction in floor responses for earthquake time histories; thus, the proposed technology can enable the development of next-generation earthquake mitigation devices.

Prefabricated members are widely used in civil engineering structures, especially in bridges; therefore, these members must have satisfactory structural performance to ensure the durability of the structure. Zhao et al. [144] proposed a cloud-based BIM system with IoT technologies for monitoring the stress and strain levels of structural components. In the system, a strain sensor is attached to a structure to monitor the real-time strain levels at lifting points during installation. The results obtained with this system were validated using finite-element analysis. In addition to SHM-related applications, other applications of the IoT in prefabricated construction include IoT-enabled BIM for tracking labor, equipment, and material statuses by using radio-frequency identification (RFID) technology for ensuring a smooth construction process [145]. Zhong et al. [145] reported significant reductions in waiting time, order picking time, and paperwork in a smart construction project in Hong Kong that employed an IoT-enabled BIM framework. Li et al. [146] integrated the IoT with BIM to improve the efficiency of prefabricated constructions by collecting real-time information from an RFID system and a global positioning system (GPS) for better tracing the construction status and quality control.

The IoT also has some applications related to geotechnical engineering. Xie et al. [147] developed an IoT-based mobile application for detecting dangerous settlements during tunnel construction for a railway station in China. Their application included an instant messaging tool that provided alerts regarding dangerous ground movements according to real-time data obtained from high-precision, vibrating-wire sensors rather than data obtained using analytical and numerical methods.

Wang et al. [148] developed an early warning system regarding the structural health of buildings by using a combination of technologies, such as the IoT, BIM, early warning systems (EWS), and cloud-based services. They applied this system at an underground pit excavation site for a six-story office building, where EWS existed according to predefined threshold values. Various types of sensors, such as steel stress gauges and earth pressure cells, were used to monitor building settlement and parts of the excavated pit. Mohapatra et al. [149] used an FBG with the IoT to monitor the strain distribution and load localization in the model of a suspension bridge.

The IoT is also used in applications related to monitoring intrusions of unauthorized people in construction projects [150], monitoring the construction quality of gravel piles [151], safety barrier systems at metro tunnel construction sites [152], slope and landslide monitoring systems [226–228], monitoring the potential risk for landslides and boulder falls [229], the conservation of objects in cultural heritage monuments [230], the monitoring of petrol pipelines [231], guyed towers [232] and facade system [233], the prediction of soil moisture [234], the SHM of tunnels [235], the inspection of construction sites [236], checking instrument functionality [237], expediting fire safety operations using immersive VR/AR with IoT [238] and underground engineering safety [239–241].

4. Challenges in the use of IoT-based technologies for SHM

Although IoT-based SHM has salient features and diverse applications, some hurdles exist in its implementation for various structures. For example, the battery life of sensors must be prolonged to ensure their long-term use. This problem can be overcome through solutions such as setting the microcontroller in the sleep/low power mode by increasing sleep time [242] and sending data in small packets whenever the microcontroller is functional. The problem of battery life can be overcomed by using energy harvesting techniques [243,244] to self-power IoT sensors equipped with self-charging energy storage units. Recently, some new technologies using Ambient Backscatter Communication Systems are used for communication between IoT devices using RF of TV and cellular transmissions further reducing power communication [245]. Furthermore, green energy harvesting management strategies, optimising current battery usage and models can significantly reduce power consumption and thus prolong the service life of the IoT sensors [246]. Their reliance on Wi-Fi connectivity is also challenging in several locations, which limits its applicability. As pointed out in Section 2 the system is composed of several interdependent layers, so any malfunction in one layer can lead to fail in the entire IoT-SHM system.

Setup problems, such as inappropriate wiring, deposition of impurities and faulty sensors can result in incorrect readings being obtained for a monitored structure. These incorrect readings might trigger false alarm leading to a false SHM assessment. Moreover, problems caused by hacking and bugs in the system may lead to errors in the entire monitoring framework. The privacy of data on IoT-based SHM systems is also a concern [247,248]. A latency problem exists in which a delay is experienced in transmitting data from the client to the server [249], This problem must be overcomed by performing data analysis at local levels [250] and employing a fog (or intermediate) layer [251,252]. The presence of inherent uncertainties in the empirical formulas used for the estimation of SHM indicators might also cause errors in the prediction of the service life of a building.

Moreover, civil engineers might encounter problems in integrating IoT-based SHM systems with cloud-based-platforms and integrating machine learning with the IoT for data analytics. Data analytics techniques can help in eliminating erroneous sensor readings by a predefined rule criteria for filtering. All the data gathered might not be used for calculation of SHM parameters by choosing proper sampling interval for calculation. Furthermore, choice of the appropriate ML technique for a particular application is an important issue that has to be addressed to get meaningful insights about data. Civil engineers need to be trained for implementing these IoT solutions in modern constructions, which many constructions companies might be negligent to provide the training, as it might lead to adding costs and time to projects. An exponential growth in the data collected from relevant devices might lead to data management and storage problems, which could be managed by relevant data management solutions [253]. Furthermore, the integration of AR/VR with the IoT, which is currently in the early stages, must be improved with regard to the interface for interaction and data retrieval. The big data analytics equipped with their own tools and machine learning techniques can facilitate processing of large SHM data gathered from these devices within proper time-frames. Finally, attention should be focused on the quality of IoT sensors so as to minimise maintenance charges, electronic components, and designed circuit to ensure the accurate recording of data throughout the SHM process for a building.

In addition to the aforementioned issues, issues exist with regard to the provisions, device heterogeneity across various platforms [254] and guidelines of industries and building codes for the adoption of the IoT. Building codes must include provisions to embed IoT-based SHM sensors in the structure for monitoring purposes. Because provisions for IoT-based sensors are not included in relevant standards, construction professionals tend to exhibit a lack of interest in including these sensors in building designs. IoT applications in small-scale construction projects where most workers accidents happens owing to poor safety records is still non-existent. In such sites, their usage will provide an additional safety layer, thus reducing accidents and reducing risks. IoT-based earthquake warning systems can be used for the protection of historical monuments because they have higher vulnerability to vibrations than modern constructions. Fire detection methods based on deep learning that involve real-time image processing can reduce the response time of firefighters considerably and prevent the destruction of buildings because of fires. No suitable standards or code provisions exist regarding communication among different IoT devices on a common platform. Thus, considerable scope exists for the improvement of the application of the IoT in SHM. For example, customized circuits boards can be developed for specific applications of the IoT in SHM.

Although IoT-SHM has to come a long way to became the standard in SHM, in some areas its deployment is ever growing. Several commercialised products having custom-made circuit board are already catering the demand of engineering professionals. With application areas such as monitoring cultural assets and concrete SHM specifically for early strength, IoT-based accelerometer solutions have seen a rise, while there exists considerable potential for its application in other areas such as automatic concrete curing systems and IoT-based drones to inspect buildings for damages, which can take live video of the buildings and detect the typology of damages in real-time. Despite the limitations highlighted, the technologies such as cloud computing and increase Wi-Fi connectivity will help to realise IoT-SHM to its full potential.

5. Conclusions and discussion

This review paper describes the several applications of the IoT in the SHM of civil engineering constructions. Different sensors can be adopted for monitoring various factors that might influence the long- and short-term integrity of a structure. IoT technologies can be used to obtain real-time SHM data from different sensors regarding the parameters that influence the structural health of civil engineering infrastructure. These technologies can be adopted for automating the SHM process to increase the service life of structures. The IoT can be combined with VR for the superior visualization of sensor locations in structures and the superior monitoring of these sensors through a Web-based SHM interface. Thus, the IoT can increase the accuracy of SHM and consequently enable civil engineering professionals to make well-informed decisions regarding the health statuses of buildings. Alert messages can be sent to construction managers when the safety thresholds for a parameter are exceeded. Furthermore, time and cost are saved in several stages of the SHM process, which paves the way for predictive maintenance rather than reactive maintenance. Furthermore, hybrid approaches, such as coupling the IoT with a CNN, VR, or an UAV, can be deployed to achieve superior SHM results. For example, image data can be coupled with infrared sensor data, rather than relying on a single type of data, to obtain more accurate quality results.

This review paper indicates considerable potential exists for the deployment of the IoT in field settings. The IoT revolution would increase the application of the IoT in civil engineering applications, and future applications will be broader and may require incorporation into building design codes. Furthermore, developments in other research fields, such as image processing and VR, would improve the IoT-based SHM of civil engineering structures. Some doubts remain regarding the accuracy of certain parameters and methods for identifying the structural health of infrastructure. For example, the early-stage maturity method is applicable only over a few days. Moreover, various factors that affect the structural health of structures may not be captured by sensors. Researchers must appropriately calibrate sensors according to laboratory results to ensure a match between field and laboratory results as well as determine appropriate threshold limits for monitoring parameters. Despite these limitations, IoT-based SHM has considerable potential for use in construction monitoring, modal-based identification procedures, concrete strength determination, and automatic equipment development for quality control in the civil engineering industry. Improvements in SHM procedures would reduce the economic losses and the number of deaths caused by structure collapses by enabling a rapid response for post-disaster stabilization and repair. In summary, IoT-based SHM systems can enhance the safety of structures and meet the current needs of the civil engineering industry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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