Application of IoT based Techniques in Concrete- A review

Ankit Kayal[1], **Prof (Dr.) Biman Mukherjee**[2] **Souvik Sharma**[3]

[1] M.Tech Students, Department of Structural (Civil) Engineering, Narula Institute of Technology

[2] Professor, and former Head of the Civil Engineering Department, Narula Institute of Technology

[3] Assistant Professor, of the Civil Engineering Department, Narula Institute of Technology

Abstract

Structural health monitoring (SHM) and damage assessment of civil engineering infrastructure is an extremely complicated job. Strength of structures is impacted by numerous parameters, starting from the stage of material production up to placing in situ, then followed by the level of workmanship, removing of formwork, and final concrete curing. Technology advancement with high availability of Wi-Fi resulted in SHM shift from conventional methods of traditional wiring to the use of the Internet of Things-based real-time wireless sensors. Structures' health can be comprehensively assessed through the effective utilization of real-time test data on structures collected from various forms of IoT sensors, which are used to monitor several health parameters of structures and are available in cloud-based data storage systems. The sensor data can later be used for applications such as the forecasting of the deterioration of masonry construction, the prediction of the early-stage compressive strength of concrete, the forecasting of the optimum time for the removal of formwork, vibration and curing quality control, crack detection in buildings, pothole detection on roads, determination of construction quality, corrosion diagnosis, identification of various typologies of damage and seismic vulnerability assessment. This review paper covers the applications of the wireless IoT technology in monitoring civil engineering infrastructure. Besides this, several case studies on real structures and laboratory investigations for monitoring the structural health of civil engineering constructions are discussed.

Keywords: Structural Health Monitoring (SHM), Wireless Sensors, Real-time Monitoring, Masonry Deterioration Forecasting, Concrete Strength Prediction, Formwork Removal Optimization, Vibration Monitoring, Curing Quality Control, Crack Detection

Introduction

Monitoring and assessing the condition of civil engineering infrastructure is crucial for the economic growth of a country since the long service life and timely maintenance of structures can reduce the reconstruction costs substantially. Infrastructure structural performance deteriorates with time, both due to short-term effects such as improper curing, vibration, shrinkage cracks, and poor workmanship during or shortly after construction, and long-term

effects such as material degradation, weathering, rebar corrosion, water seepage, changing loading conditions, environmental degradation, and crack formation.

Hence, SHM is crucial throughout the entire service life of a structure. Real-time, nondestructive SHM can contribute to the extension of service life of civil infrastructure through detection at early stages of damage and monitoring key factors that may become causes for future issues. Various types of civil engineering structures and potential factors that could curtail their service lives are discussed in the paper, along with possible mitigations of those risks through IoT-based SHM for sustainable infrastructure longevity.

The construction industry worldwide has been underperforming, incurring an annual productivity loss estimated at $1.6 trillion. Research reveals that approximately 57% of labor hours in construction are spent on non-value-added activities, a stark contrast to the 26% observed in the manufacturing sector. Innovative technologies provide viable solutions to tackle these inefficiencies. Therefore, integrating "technology-enabled" processes powered by the Internet of Things (IoT) into the construction industry is essential. This integration aims to reduce uncertainties and systematically optimize operations [1–4].

Although lacking a universally accepted definition, the IoT traces its origins back to 1982, when a modified Coke vending machine was connected to the Internet to monitor the inventory level. It was later popularized as the term "IoT" by Kevin Ashton in 1999, and it was specifically within the context of supply chain management. IoT is a network of physical devices, equipped with sensors, actuators, and communication capabilities that enables data collection, synthesis, and processing on a unified platform. It allows users to access the domain-specific software and services very smoothly [5–7].

IoT represents a human-designed technology driven by intelligent virtual objects that can understand their surroundings and interact autonomously with nearby devices without direct human input. In other words, IoT refers to a network of sensors, devices, and appliances communicating their physical state and environmental data over the Internet. The proliferation of smart devices and IoT technologies is paving the way for developing intelligent and sustainable infrastructure.[40] IoT enhances efficiency in the construction industry across all phases, from material production and design to construction, operation, and maintenance [8]. As a labor-intensive sector, construction generates significant employment opportunities with relatively low capital investment, playing a crucial role in reducing unemployment, particularly in low-income countries [9].

By enabling real-time data collection and sharing across critical resources—such as machinery, personnel, materials, and tasks—IoT fosters the development of intelligent applications across a wide range of industries. In construction, IoT applications include transportation and traffic systems, fleet tracking, logistics chain management, smart cities, industrial automation, collision avoidance systems for vehicles, energy efficiency initiatives, waste management, smart buildings, homes, offices, and environmental monitoring [10–12].

Despite these opportunities, the construction industry has historically lagged in adopting new technologies compared to advanced industries such as manufacturing, aviation, and electronics

[13]. While IoT has driven transformative benefits in sectors like automotive, mining, defense, agriculture, and manufacturing, its adoption in the construction sector remains relatively slow, highlighting a critical area for growth and innovation [14].

Study of IoT-Based Technologies in Civil Engineering Construction

IoT in Structural Health Monitoring (SHM)

Monitoring and evaluating the condition of civil engineering infrastructure is very important to a nation's economic growth. Maintenance and proper repair can prevent costly reconstruction by making structures last longer. With time, there are several reasons why infrastructure deteriorates, which include:

Short-term causes: Poor curing, vibration, shrinkage cracks, and poor workmanship during or after construction.

Long-term effects: Material degradation, weathering, rebar corrosion, water seepage, environmental stress, loading conditions, and crack formation.

For overcoming these challenges, SHM has to be applied throughout the life cycle of civil engineering infrastructure. Real-time, non-destructive monitoring through SHM allows for the early detection of damage and the identification of causes that may cause future deterioration, thus extending the service life of infrastructure. Incidents abound in highlighting the aftermath of inadequate SHM. For example, collapses of formwork shoring systems have led to worker fatalities on multiple construction sites [22]. One notable incident occurred in April 1978 when the collapse of a reinforced concrete (RC) cooling tower in Willow Island, West Virginia, USA, caused 51 workers to fall to their deaths. Investigations revealed that the premature removal and inadequate anchoring of the scaffold, combined with insufficient concrete strength, were probable causes of the disaster [23].

Wireless sensors and IoT have become more significant for upgrading SHM throughout engineering fields. Strategically positioned sensors transfer the acquired data to the cloud, providing the authorities with the capability of monitoring real-time damage-sensitive parameters. The alert mechanism identifies sudden changes and facilitates efficiency in processes currently applied to SHM systems [24–28]. It helps to directly transfer data into cloud platforms by applying IoT technology for remote accessibility, high device connectivity, and detailed analysis of critical parameters.

IoT-based SHM further advances by incorporating artificial intelligence, which supports smart supervision without human intervention [29–31]. Data gathered from IoT sensors predict various structural health indices that guarantee the long-term stability of engineering structures. The IoT technique has been used to monitor heritage structures, nationally significant buildings, and mass concrete structures through techniques like image processing, vibration analysis, and crack detection. This synergy between IoT and SHM plays a central role in infrastructure protection and in optimizing the effort for maintenance.

IoT in concrete technology

The performance of concrete structures is mainly evaluated in terms of their mechanical and durability properties, which are very crucial for assessing their health and overall functionality. Inadequate management of fresh concrete mixtures can impede the development of strength during later stages of their lifespan. IoT-based wireless sensors provide a solution by enabling real-time assessment of mechanical and durability performance. These sensors reduce the need for core-cutting operations and do away with the requirement of sample extraction and testing on-site, thus saving costs.

Some of the factors that decrease the service life of concrete structures include slow strength development, poor quality control, improper placement of concrete, plastic cracks, premature or improper removal of formwork, and inadequate cover to reinforcement leading to corrosion [22]. Embedded IoT sensors measure the temperature in fresh concrete from within the concrete; such temperatures are then correlated with the heat of hydration to estimate early-age strength using maturity index methods [23–26]. Small, compact dimensions enable these sensors to be embedded in foundations and columns, beams, and slabs of buildings, where strength is monitored at various stages of its gain. Smart aggregates of piezoceramic material have even been used as strength assessment through wireless sensors by researchers [27–32]. Concrete curing is another application of IoT technology in automating processes. Wei et al. [33] designed an automatic water-spraying system for concrete curing in Hunan, China. Perry et al. [34] utilized a network of eleven thermocouple sensors in determining the strength of a concrete foundation using the maturity index approach.

The optimum time to remove the scaffold after casting of concrete is decided based on compressive strength. Several research studies used IoT to measure slab displacements and gave alarms when it crosses the excessive threshold value for safety of the laborers [25]. The correct time to remove the scaffold from post-tensioned concrete structures is quite important since appropriate stress transfer occurs in them [26–31].

The presence of voids also affects the durability of concrete structures, and thus proper vibration during concrete placement is required. Over-vibration or under-vibration should be avoided to maintain quality. Wang et al. [33] used IoT combined with convolutional neural networks (CNN) to predict the vibration quality of concrete. IoT-based corrosion monitoring systems have been used to monitor parameters such as chloride ion concentration and pH levels, which may predict the long-term performance of reinforced concrete structures based on the presence of reinforcement bar corrosion [34, 35].

Yang et al. [56] utilized IoT to track temperature and relative humidity in the automated curing of concrete. The relative humidity threshold was set at 80% and temperature at more than 45°C for the application of fogging spray. Similarly, John et al. [27] used an IoT system to monitor atmospheric temperature, internal concrete temperature, and relative humidity in concrete specimens, identifying critical thresholds where plastic shrinkage cracks begin to form under hot weather conditions.

Challenges in use of IOT-based technologies for SHM & Concrete Technology

While IoT-based SHM has tremendous advantages and versatile applications, it also faces challenges across different structures. One major drawback is the sensor's battery life, which must be prolonged for long-term operations. Strategies like configuring the microcontroller to be in sleep or low-power mode for long durations and sending data in small packets only when the microcontroller is active may address this issue [24].

The installation of IoT infrastructure, including sensors, communication networks, and data analytics platforms, often requires significant upfront investment. This cost can be a deterrent, especially for smaller projects or organizations with limited budgets. Integrating IoT devices with existing construction processes, tools, and software systems can be challenging due to compatibility issues, lack of standardization, and differences in communication protocols.[15] IoT sensors and devices in concrete structures must withstand harsh environments, including exposure to high temperatures, moisture, vibrations, and corrosive elements. Ensuring their durability and performance over the structure's lifespan is a critical challenge. The transmission and storage of data generated by IoT devices expose construction projects to potential cybersecurity threats. Unauthorized access to sensitive project data or system disruptions could result in significant risks. The transmission and storage of data generated by IoT devices expose construction projects to potential cybersecurity threats. Unauthorized access to sensitive project data or system disruptions could result in significant risks.[20]

The lack of clear regulations and industry standards for IoT deployment in construction can create barriers to adoption and complicate compliance with safety and quality standards. Addressing these challenges requires collaborative efforts from industry stakeholders, researchers, and policymakers to develop cost-effective, reliable, and scalable IoT solutions tailored to the specific needs of concrete technology.[39] IoT devices, especially sensors embedded in concrete, require power sources to operate. Ensuring long-term energy efficiency or developing sustainable power solutions, such as energy harvesting, remains a challenge.[37]

Conclusion

In conclusion, the adoption of IoT in civil engineering and the construction industry holds immense potential to revolutionize traditional practices, address inefficiencies, and foster the development of intelligent and sustainable infrastructure. By enabling real-time monitoring, data-driven decision-making, and enhanced operational efficiency, IoT-based technologies can significantly reduce costs, optimize resource utilization, and extend the service life of critical infrastructure.

While the challenges involved in high cost of implementation, data security threats, and aversion to change remain, there are more impactful benefits that come with IoT change. These encompass enhanced safety, higher productivity, and environmental sustainability. To

bridge this gap between potential adoption and current deployment, policymakers, industry stakeholders, and technology providers will need to pull together to work on scalable and cost-effective standards for IoT applications.[1]

Depending on how the construction industry can adapt to embracing more innovation and leveraging IoT to align with the present global trends toward smarter cities, sustainable practices, and advanced automation, this industry will be able to progress to unprecedented levels of performance - long-term economic growth and societal progress.

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