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INTELLIGENT MONITORING WITH UNMANNED AERIAL VEHICLES FOR ADVANCED CONCRETE REPLACEMENT STUDIES

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Abstract

In this study, the seamless integration of intelligent monitoring systems and Unmanned Aerial Vehicles (UAVs) is rigorously evaluated, unveiling a ground-breaking approach in the field of advanced concrete replacement. The Concrete Depth Model (CDM) is introduced as a paradigm in real-time structural monitoring, its effectiveness demonstrated between May 1, 2021, and June 10, 2021. Enhanced by Falcon8 UAVs, the CDM enabled meticulous data capture and analysis, particularly in areas of strain, displacement, and steel reinforcement stress. The empirical data reveal a detailed landscape of structural integrity. In regions marked by sensor failures, alternative monitoring points were employed to ensure comprehensive data capture, affirming that the concrete's structural parameters remained within safe limits. The rebar stress measurements further corroborated the consistency and reliability of the data. Sensors within the replacement columns consistently registered readings within 60% of the maximum allowable thresholds. Additionally, transient spikes observed in upper column sensors were found to stabilize within predefined alert thresholds, affirming the structural integrity maintained throughout the replacement process. The CDM's precision, as evidenced by the consistency in sensor and UAV data, underscores its capacity to significantly elevate both safety and operational efficiency in concrete replacement projects. This research contributes valuable academic insights and introduces a practical, data-driven model for the construction industry, heralding a new era in intelligent construction methodologies characterized by enhanced safety, precision, and efficiency.

Keywords: Concrete depth model, Intelligent construction, Structural integrity, UAV.

1. Introduction

Concrete replacement technology is a cornerstone for structural reinforcement and modification across various construction projects. However, traditional methods of concrete replacement pose significant challenges, such as the inability to monitor column deformation and stress states in real-time and evaluate the overall structural integrity. These limitations critically impede the efficiency and precision of concrete replacement techniques and call for urgent research interventions.

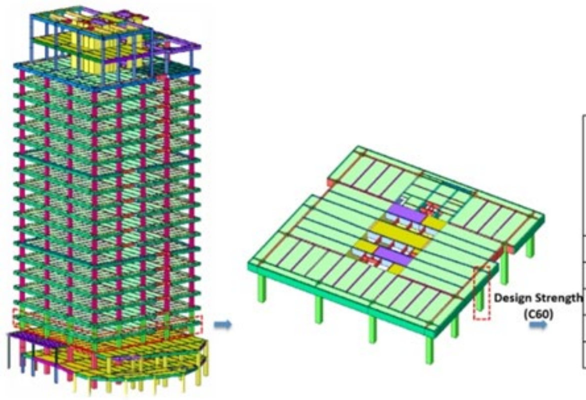
This study focuses on intelligent solutions to address these issues and proposes a concrete replacement approach that integrates intelligent monitoring systems and UAV technologies. Intelligent monitoring systems, characterized as disruptive technologies, can monitor and record structural deformations, stress levels, and overall health conditions. UAV technologies offer an efficient means for real-time monitoring, contributing significantly to implementing concrete replacement technologies [1]. Utilizing these intelligent systems and UAVs, we can perform real-time monitoring of concrete deformations and stress conditions and, based on holistic structural health assessments, provide accurate data support and decision-making guidance for designing and implementing concrete replacement technologies.

The scholarly landscape reveals concerted efforts in enhancing concrete materials and leveraging UAV for civil engineering applications. Research such as [2, 3] has advanced our understanding of sustainable concrete replacements, notably through partial substitutions like fly ash, metakaolin, and tailings. Concurrently, studies by [4, 5] have introduced innovative approaches to acid-resistant and green concretes, respectively. On the technological front, UAVs have proven to be a game-changer in data collection and monitoring, with works like [6, 7] demonstrating their utility in energy-efficient propulsion and industrial-grade applications.

Recent strides in Artificial Intelligence (AI), as discussed by [8, 9], have further augmented UAV capabilities, particularly in navigation and control. The recent work of [10, 11] represents a significant milestone by matching UAV technology with intelligent monitoring for efficient crack detection in concrete structures. These collective advancements form a foundation upon which this paper seeks to build, aiming to integrate intelligent monitoring and UAVs in advanced concrete replacement studies.

The subject property, henceforth referred to as Jiaxiuzhou Tower A, is a key residential development within the 2019 Jiaxiuzhou-025 project, managed by Jiaxing Aowen Real Estate Development Co., Ltd. Situated in Youchegang town, Jiaxing City, the tower is strategically located at the intersection of Chayuan Road to the east and Mashi Road to the north. Structurally, the edifice employs a shear wall configuration anchored on a pile foundation and ascends to a height of 78.5 meters. It encompasses 27 floors above ground and a single subterranean level, with residential occupancy designated up to the 20th floor.

As elucidated in Fig. 1, inspection outcomes have pinpointed subpar concrete strength in the vertical elements of the 10th and 11th floors. To remediate this structural concern, the project envisions targeted concrete replacement, thereby aligning the tower's vertical components with the requisite strength and durability specifications as per design and utilization norms.



Specimen number	Specimen size(mm)		Compressive strength of concrete (MPa)
	Diameter	Height	
1	67	67	25. 6
2	67	67	31. 7
3	67	67	18. 9
4	67	67	44. 7
5	67	67	40. 8

Fig. 1. Model of low-strength concrete position.

2. Design of Concrete Replacement Technology

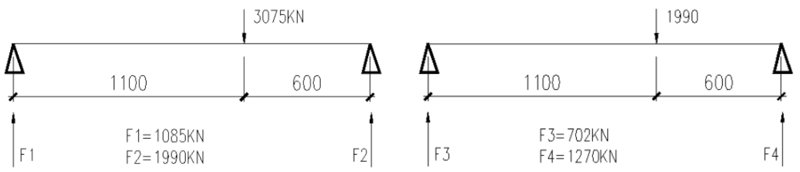
This study elucidates an intricate scheme for concrete replacement, amalgamating intelligent monitoring systems with UAV technologies. This integration aims to augment the construction process in terms of efficiency, safety, and long-term durability. Employing phased construction methodologies coupled with strategic steel bar reinforcement, the scheme facilitates a rigorously controlled and methodical approach to concrete substitution. The intelligent monitoring apparatus serves as the linchpin for real-time surveillance of critical structural metrics, while simultaneously interfacing with UAVs for high-fidelity, on-site observation and exigency management. Subsequently, the unified application and assessment module further refines the edifice's seismic resilience through expert adjudication and data-driven analytics, thereby ensuring the structure's enduring safety and stability.

2.1. Methods of concrete replacement

The present methodology introduces a Sequential Construction Protocol, a meticulously designed approach that involves the systematic removal of aged or substandard concrete and the segmented casting of superior-strength replacement material. This protocol not only ensures the quality of the new concrete but also minimizes structural risks during the replacement process. Complementary to this is the Steel Bar Reinforcement strategy. Before the new concrete is cast, supplementary steel bars are welded to the existing ones. This dual-phase approach serves to bolster the structure's overall load-bearing capacity and enhances its seismic resistance, thereby contributing to both immediate and long-term stability.

The implementation of a Sequential Construction Protocol and precise column displacement planning are foundational to maintaining structural integrity and safety in the concrete replacement process. The protocol entails a systematic removal of aged or substandard concrete and the segmented casting of superior-strength material. The columns, measuring 1000 mm by 1000 mm and situated between the third and fourth floors along the 5-4/5-C axis, were initially designed for C60 concrete grade but were implemented with C25 and bear a load of 12300 kN. A phased replacement, conducted in four segments, ensures structural integrity is preserved throughout the process. Each jack is calculated to bear a load of 800 kN, a figure derived considering the reduced column cross-sectional area and corresponding load.

Complementing this process is the Steel Bar Reinforcement strategy, where additional steel bars are welded to the existing structure prior to the casting of new concrete. This augmentation not only enhances the column's load-bearing capacity but also improves its seismic resistance, assuring both immediate and long-term stability. This complex, yet meticulously planned process is visually and descriptively presented in Fig. 2, offering a comprehensive insight into the intricate methodology and implementation procedures that underpin the project's success.



(a) **(b)**

Fig. 2. Simplified calculation steps for beams with (a) 3075 kN; (b) 1990 kN.

2.2. Intelligent structural monitoring system

To address the challenges associated with real-time and long-term structural monitoring, the framework incorporates an advanced Intelligent Structural Monitoring System. This system leverages a network of cutting-edge sensors and employs state-of-the-art data analytics tools for the continuous assessment of essential structural parameters, such as deformation, stress, and temperature. In addition to real-time surveillance, the system is equipped with Automated Safety Alerts, a feature that instantaneously triggers warning protocols when anomalous or hazardous structural changes are detected. Furthermore, the system's utility extends beyond project completion, remaining operational to continuously evaluate the structure's integrity and provide actionable recommendations for either repair or further reinforcement, ensuring long-term safety and durability.

2.3. Integration with UAV technology

For the purpose of this study, Falcon8 UAVs are deployed as a critical component in both the inspection and monitoring phases, seamlessly interfacing with the existing intelligent monitoring system. Specifically, these UAVs execute high-precision aerial inspections prior to and during construction phases, facilitated by their high-pixel camera systems. These cameras capture exhaustive, multi-angle aerial imagery of the vertical components on the 10th and 11th floors, thereby providing an unparalleled depth of structural information. The data collected are instantaneously transmitted to the intelligent monitoring system and can be further processed through TOPCON Context Capture software for the generation of high-precision 3D models.

As detailed in Table 1, the Falcon8 UAV system is equipped with a range of features designed for optimal performance and safety in diverse operational conditions. Moreover, the captured images undergo specialized non-destructive stitching algorithms and are fed into image processing software, where defects such as cracks are automatically identified, quantified, and compared against existing models for precise dimensional and locational analysis. In emergency scenarios, the Falcon8 UAVs are capable of swift and accurate problem localization, thereby enhancing the robustness of the project's emergency response measures. Additional details regarding the hardware and software configurations of the Falcon8 UAVs employed in this study are delineated in Fig. 3.

Table 1. Specifications and features of the Falcon8 UAV system.

Feature	Description
Camera	SonyA7R 36 MP full-frame camera
Gimbal	180° rotatable gimbal for top and bottom views
Sensors	31 sensors ensuring high safety
Stability	Resistant to level 6 winds and magnetic interference
Transmission System	High-definition image transmission
Weight	Only 2.3 kg, portable and easy to operate

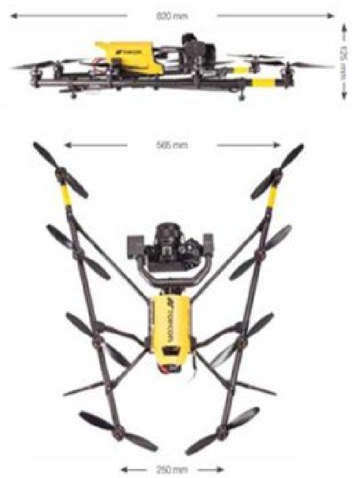


Fig. 3. Falcon8 UAV used in the proposed intelligent monitoring system.

2.4. Integrated application and evaluation mechanism

Within the framework of this study, a harmonized operational platform is established to facilitate seamless collaboration between the intelligent monitoring system and UAV. This integrated approach aims to guarantee an uninterrupted, real-time, and precise data flow, which is crucial for effective decision-making and emergency response. Concurrently, the structural integrity, particularly seismic performance, undergoes rigorous evaluation through a combination of data analytics and expert assessment. This multi-faceted validation serves not only to confirm the immediate efficacy of the concrete replacement methods but also to optimize the long-term stability and safety of the engineering initiative.

2.5. Reinforcement measures

To ensure the rigorous standards of quality and efficiency required for this engineering project, the employment of a superior grade of ordinary concrete is advised for structural replacement procedures. This strategic adjustment aims to significantly augment the edifice's load-bearing capability as well as its seismic resilience.

2.5.1. Concrete strength design

The concrete grade is selected based on the following strength design equation:

$$f_c = k_1 \times f_c^{'} \tag{1}$$

In this equation, f_c signifies the actual compressive strength of the concrete, f_c' denotes the standard cubic compressive strength, and k_1 is a correction factor. This equation allows for the flexible selection of the correction factor and standard cubic compressive strength, tailored to meet both design and field conditions.

2.5.2. Rebar mass and protective layer thickness

The following equations dictate the mass of the reinforcing bars and the thickness of the protective layer post-replacement:

$$m = A_s \times l \times p \tag{2}$$

$$h = C_m + \partial_m + \Delta h \tag{3}$$

In these equations, m represents the mass of the rebar, A_s is the cross-sectional area of the rebar, $l$is the length of the rebar, p is the density of the rebar material, is the minimum thickness of the concrete protective layer, h denotes the thickness of the protective layer, C_m is the minimum thickness of the concrete protective layer, ∂_m is the minimum diameter of the rebar, and Δh is the allowable thickness error.

2.5.3. Rebar cross-sectional area

The cross-sectional area of the reinforcing bars is calculated as:

$$A_s = n \times \pi \times \frac{d^2}{4} \tag{4}$$

Here, A_s represents the cross-sectional area of the rebar, n is the number of rebars, and d is the diameter of the rebar.

In terms of project management, a meticulous plan has been devised to oversee the replacement of 18 shear walls and four columns, a process anticipated to span 45 days. A staggered replacement methodology is employed, scheduling the substitution of either a shear wall or column at bi-daily intervals. To uphold the integrity, pace, and quality of the undertaking, regular engineering consultations are scheduled, engaging all team divisions to facilitate cohesive and informed decision-making. Additionally, systematic assessments of the implementation progress are instituted to guarantee the project unfolds in accordance with the predetermined quality, efficiency, and timeline benchmarks.

3. Implementation Plan for Intelligent Monitoring System

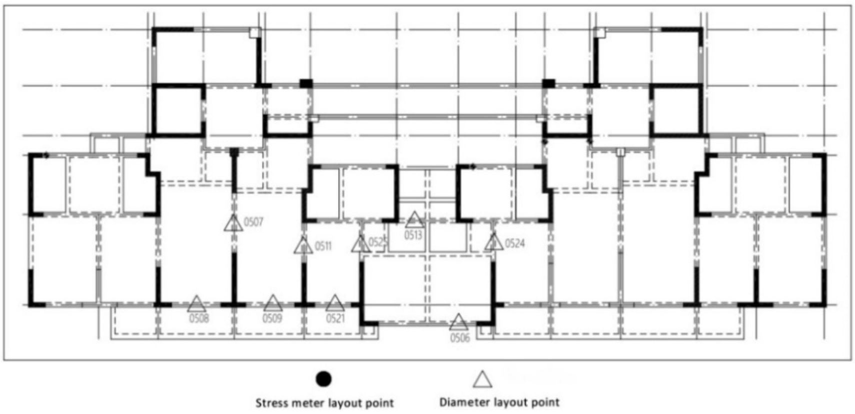
In this case study focusing on deformation and monitoring issues in concrete replacement engineering, an innovative sensor deployment strategy is proposed, as illustrated in Fig. 4. Throughout the engineering process, structural health monitoring sensors are deployed in critical structural locations such as the concrete chipping area, rebar reinforcement zone, concrete pouring sector, and curing region. These sensors are capable of real-time monitoring of various parameters, including stress, displacement, and temperature in concrete and steel reinforcement, thereby accurately reflecting structural deformations.

Additionally, these sensors are wirelessly connected to a data processing centre, enabling real-time data collection and analysis, which offer timely and precise scientific support for ensuring construction safety and quality. To enhance the reliability and accuracy of the structural health monitoring system, machine learning algorithms are integrated for deep learning and pattern recognition of the collected data, thus enabling predictive modelling of potential structural deformations and providing advance warnings to mitigate safety hazards induced by deformations. The adoption of this strategy significantly improves the construction quality and safety in concrete replacement engineering, thereby positively contributing to the overall project efficiency.

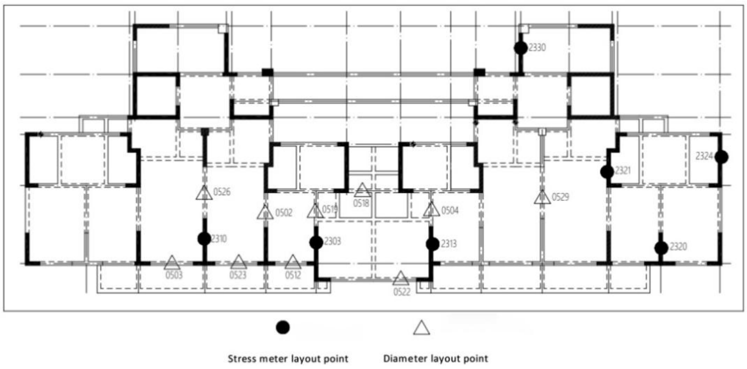
3.1. Sensor deployment

In the context of concrete replacement engineering, we have deployed a set of high-precision sensor equipment. This ensemble includes vibration sensors, stress-strain sensors, and temperature sensors, among others. These sensors are strategically placed at various critical nodes across the construction site, enabling real-time monitoring of the entire project. To exemplify, the temperature sensor system we employed has an accuracy of ±0.1 °C and a sampling rate of 1 Hz-specifications that traditional devices often fail to meet. Such precise sensor data form the cornerstone of the entire intelligent monitoring system.

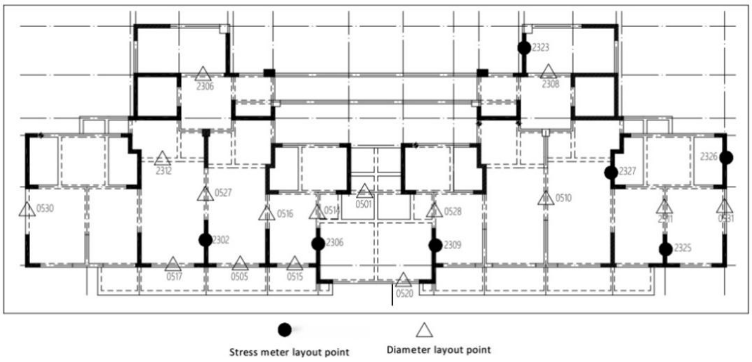
Additionally, as depicted in Fig. 5, a simulation analysis model of sensor deployment during the construction phase is provided. In this simulation, multiple sensors are placed evenly on the building to detect stress level of each part of the building. This model integrates the placement of these sensors with various construction sequences, offering an analytical framework for the spatiotemporal deployment of sensors throughout the construction process.



(a) Floor 9 plane sensor layout.



(b) Floor 10 plane sensor layout.



(c) Floor 11 plane sensor layout.

Fig. 4. Sensor layout diagram on (a) floor 9; (b) floor 10; and (c) floor 11.

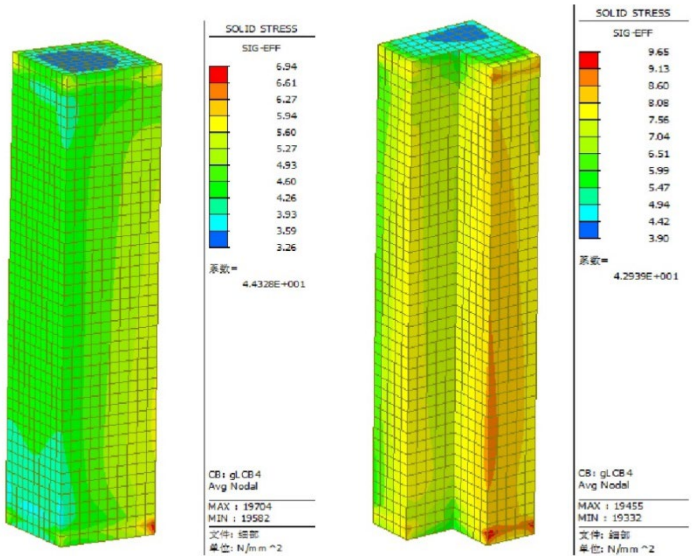


Fig. 5. Simulation and analysis model of sensor deployment.

3.2. Data processing and predictive modelling

Advanced data processing techniques and algorithms are employed for real-time analysis of the collected data. The employed methodologies encompass deep learning, pattern recognition, and predictive modelling, among others. For instance, leveraging deep learning algorithms on historical data enables us to forecast deformation trends in concrete and reinforcing steel. Such predictive analytics facilitate timely adjustments in construction strategies, preempting potential issues.

Furthermore, the integration of Cloud Computing and IoT technologies enhances the system's capability for real-time processing and transmission of voluminous data sets, thereby facilitating remote monitoring. Cloud computing provides ample computational resources to handle large-scale data processing, while IoT technologies enable ubiquitous access to project data, achieving comprehensive and round-the-clock monitoring of the engineering project. These components coalesce into a holistic, autonomous, intelligent monitoring system.

3.3. Comprehensive system architecture

The architecture of the system is characterized by a multilayered design, integrating various technological components to optimize data management and decision-making processes. The Data Collection Layer is equipped with high-precision sensors, including those for vibration, stress, and temperature, complemented by Falcon8 drones, ensuring real-time and accurate data acquisition. This layer is integral for capturing comprehensive and multi-dimensional data critical for subsequent analyses. The Data Transmission Layer, leveraging the advancements in cloud computing and IoT technologies, ensures the seamless and real-time transmission of data, enhancing the system's responsiveness and adaptability. In the Data Processing and Analysis Layer, deep learning and pattern recognition algorithms are employed to analyze and interpret the data, facilitating insights that are both profound and actionable.

Finally, the Prediction and Decision-Making Layer is tasked with the generation of predictive models for displacement and stress states, derived from sophisticated algorithmic analyses. These models are instrumental in facilitating informed decision-making, ensuring the structural integrity and safety of the construction.

3.4. CDM predictive model

The integration of sophisticated algorithms plays a pivotal role in enhancing the precision and efficiency of concrete displacement and stress state predictions. Utilizing K-Means Clustering in the pattern recognition algorithm, initial cluster centroids are established, followed by the iterative assignment and updating of data points and centroids until specific termination criteria are fulfilled. This algorithm is instrumental in identifying intricate patterns associated with displacement and stress states.

In parallel, the Support Vector Machine (SVM) is employed as a predictive model algorithm. The process initiates with data normalization, followed by the application of kernel functions for data mapping, and the optimization of the objective function to delineate the optimal separating hyperplane, culminating in an evaluation of the model’s accuracy. The objective function of the model is given by Eq. (5).

$$J(\theta) = \frac{1}{m}\sum_{i=1}^{m} L\left(y^{(i)}, \hat{y}^{(i)}\right) \quad (5)$$

where $L(y^{(i)}, \hat{y}^{(i)})$ is the loss function, $y^{(i)}$ is the actual value, while $\hat{y}^{(i)}$ is the predicted value.

The pragmatic application of these advanced algorithms is epitomized in the CDM, which was implemented and assessed during the concrete replacement project of the Jiaxiuzhou Tower A within the 2019 Jiaxiuzhou-025 plot overseen by Jiaxing Aowen Real Estate Development Co., Ltd. The CDM's efficacy, marked by enhanced accuracy in displacement predictions and augmented construction efficiency, was rigorously evaluated against traditional methodologies. The results underscored the CDM's superior performance, underscoring its substantial practical value and broad application prospect in the realm of concrete replacement and structural integrity monitoring.

3.5. Advanced intelligent monitoring and early warning protocols

In the context of the concrete replacement initiative, the incorporation of the sophisticated CDM has proven instrumental in amplifying the precision and effectiveness of early warning mechanisms. The system is calibrated to initiate alerts when the evaluated concrete strength plunges below 80% of the stipulated design threshold, equating to a critical limit of 22 MPa. This advanced monitoring infrastructure is adept at real-time identification of construction anomalies, including but not limited to poor flowability, layer separation, or the emergence of cracks. Upon the detection of such irregularities, the CDM instantaneously triggers the activation of a meticulously designed early warning mechanism.

This protocol is orchestrated around a three-tier warning system, each level corresponding to varying degrees of severity and requisite responsive actions. The specific operational workflow and responsive actions associated with each warning tier are comprehensively delineated in Fig. 6. Specifically, if anomaly detected, the system would identify four security levels, corresponding to blue (lowest), yellow, orange, and red (highest) alerts. This integration of intelligent monitoring and responsive early warning mechanisms underscores a pivotal advancement in ensuring the structural integrity, safety, and quality of concrete replacement projects.

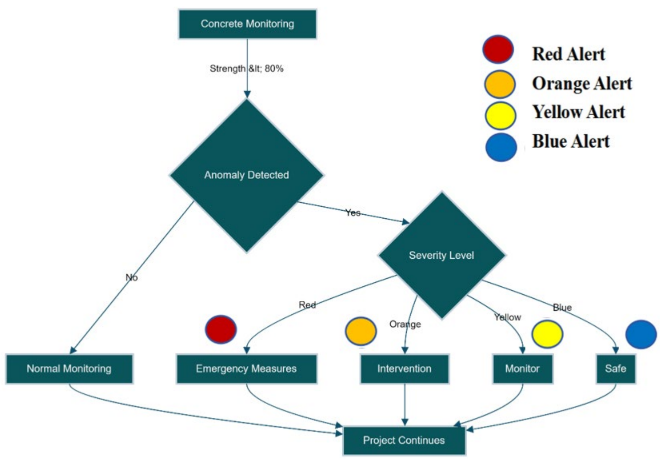


Fig. 6. Intelligent monitoring and alert mechanism in concrete replacement project.

4. Results and Discussions

The success of the concrete replacement project hinged on an intricate monitoring data statistical scheme designed for operational continuity and enhanced quality assurance. This was achieved through the implementation of a systematic sensor arrangement and a comprehensive data acquisition protocol that enabled the real-time tracking of essential structural parameters such as strain, displacement, and steel reinforcement stress.

During the period from May 1, 2021, to June 10, 2021, Fig. 7 illustrates the strain measurements across multiple sensors, revealing a consistent pattern of behavior within the material's expected stress-response curve. Figure 8 captures the axial forces on the steel reinforcement, offering insight into the load-bearing capacity and the stress distribution throughout the structure. Meanwhile, Fig. 9 delineates the deformation of concrete beams, with each sensor tracing the extent of deformation over time, highlighting areas of potential non-elastic behavior and confirming overall structural resilience.

These figures collectively present a detailed narrative, underpinned by calibrated alert thresholds informed by industry standards, historical data, and anticipated responses to extreme stress scenarios. Despite challenges such as isolated sensor malfunctions, specifically with IDs 2010RB2320 and 2010RB2326, the robust sensor network proved its effectiveness in ensuring uninterrupted data acquisition, as evidenced by the comprehensive depiction of the monitoring points in the figures.

The lower bull leg region's sensor outages were compensated for by alternative monitoring points, validating that the concrete's stress parameters were maintained within the elastic range. Such diligence in data consistency is corroborated by the rebar stress measurements illustrated in the figures, with each sensor's readings within 60% of the maximum permissible thresholds, illustrating a state of nominal construction conditions.

Additionally, transient spikes observed in the data from upper column sensors were noted to stabilize well within the established alert thresholds. This demonstrates the robustness of the structural integrity, even amidst the dynamic conditions of the concrete replacement operations. The comprehensive data, as summarized in Table 2, provides an enriched understanding of the structural integrity and safety metrics, reinforcing the reliability and precision of the Concrete Depth Model (CDM) in intelligent construction methodologies.

Table 2. Sensor types with corresponding IDs.

Type of Sensor	Sensor IDs
Concrete Strain Gauge (unit: micron)	2010RB2328, 2010RB2321, 2010RB2325, 2010RB2327 2010RB2324, 2010RB2320, 2010RB2323, 2010RB2326
Steel Bar Meter (unit: N)	2010RB2404, 2010RB2407, 2010RB2408, 2010RB2401 2010RB2405, 2010RB2406, 2010RB2409
Displacement Sensor (unit: mm)	2010RB2315, 2010RB2319, 2010RB2310, 2010RB2317 2010RB2314, 2010RB2316
Inclinometer (unit: degree)	2010RB2305, 2010RB2301, 2010RB2304, 2010RB2307 2010RB2303

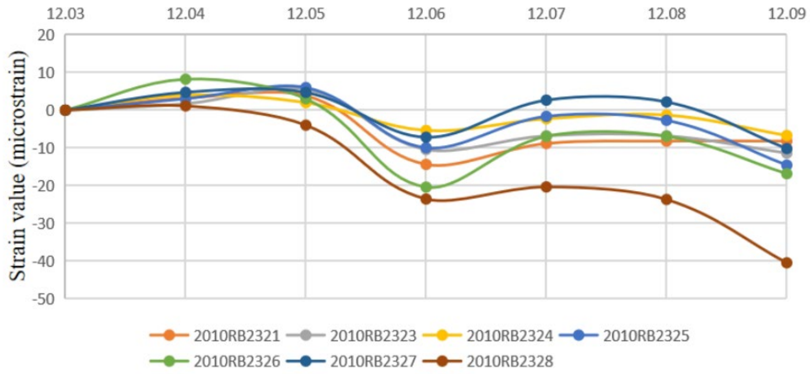


Fig. 7. Concrete strain measurement during monitoring phase.

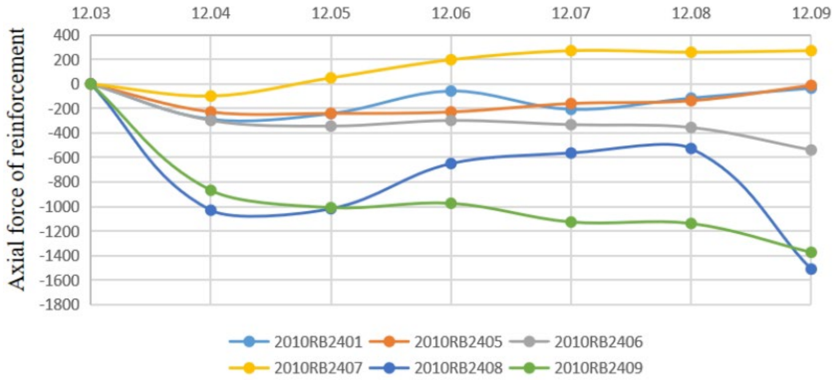


Fig. 8. Axial force of reinforcement measurement during monitoring phase.

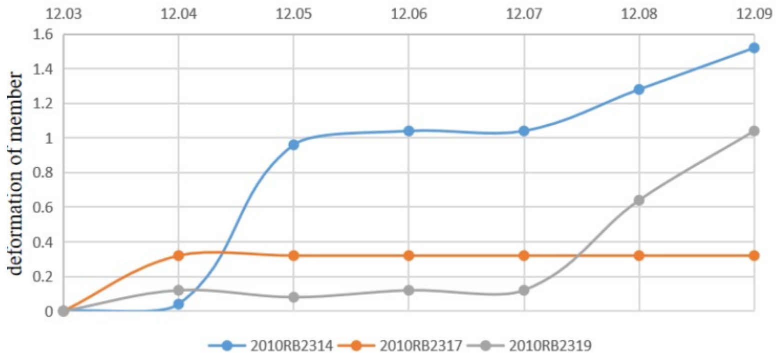


Fig. 9. Concrete beam deformation measurement during monitoring phase.

5. Conclusion

In this intricate study, the CDM was conceived and meticulously executed, marking a pivotal stride in the intelligent monitoring landscape. The CDM is emblematic of an advanced surveillance ecosystem, intricately engineered to capture and analyze cardinal parameters pivotal to the integrity and safety of concrete replacement projects. Data, scrupulously harvested between May 1, 2021, and June 10, 2021, was instrumental in evaluating key structural facets including strain, displacement, and the stress dynamics of steel reinforcements. Our findings, detailed and robust, unveil a narrative of operational excellence and reliability.

A few isolated sensor malfunctions and data anomalies notwithstanding, the overarching data landscape was marked by consistency and adherence to predefined safety parameters. These empirical insights, rooted in rigorous data analytics, attest to the CDM's formidable capacity to augment both safety protocols and operational efficiency. The integration of drone technology accentuated the model's data acquisition capabilities, ushering in a new paradigm of precision and comprehensiveness in monitoring. The cumulative insights derived offer the construction domain an innovative, data-centric model, proven to enhance the precision of structural health assessments and inform engineering decisions that are both timely and rational.

The academic and practical implications of this study are expansive. We envisage subsequent phases of research to be centered on refining the CDM, amplifying its adaptability to a diverse array of architectural edifices and engineering contexts. The future trajectory will also see an intensified integration with avant-garde technologies, including the Internet of Things and cloud computing, fostering an ecosystem where data accuracy, real-time insights, and predictive analytics converge to define the future of safe and efficient construction endeavors.

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