CONSTRUCTION INDUSTRY COUNCIL
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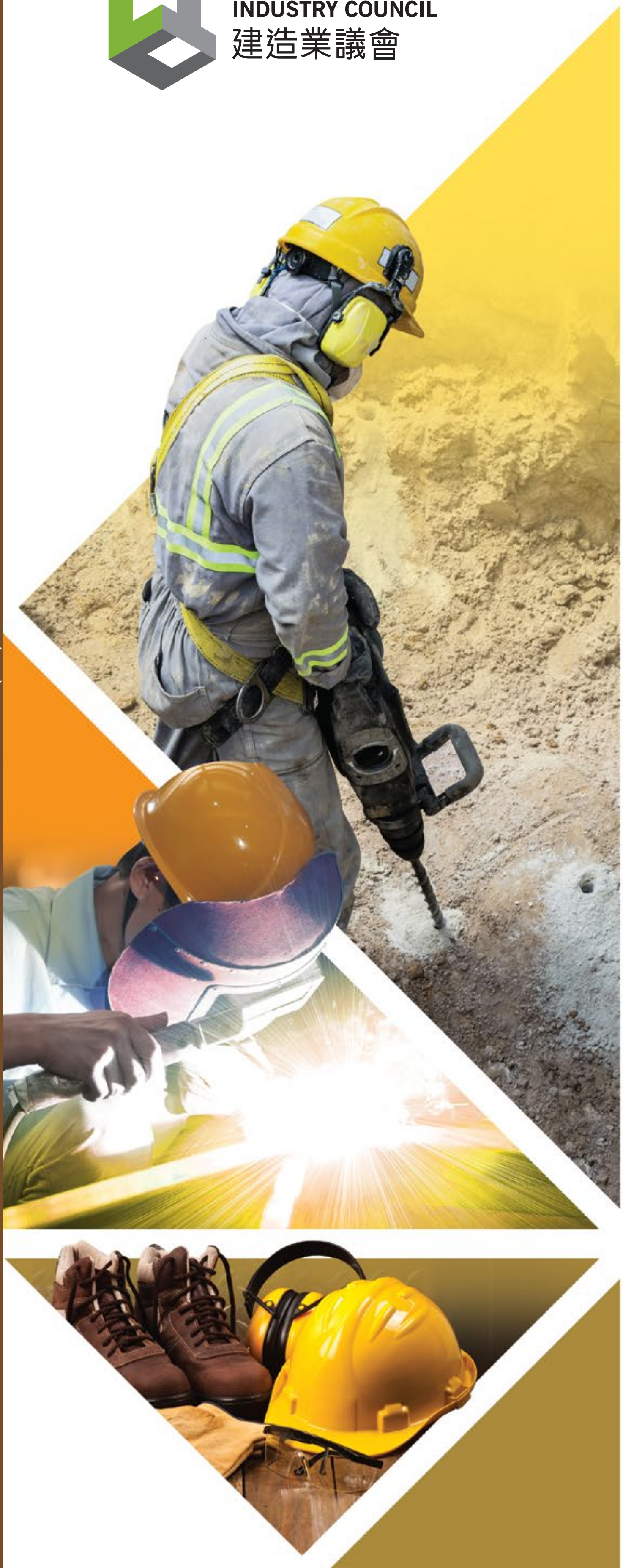
OPTIMAL USE OF INTERNET OF THINGS (IOT) TECHNOLOGY TO PREVENT FAILURE (COLLAPSE) OF TEMPORARY SUPPORT SYSTEM IN CONSTRUCTION



RESEARCH SUMMARY

Construction Industry Council   Optimal Use Of Internet Of Things (IoT) Technology To Prevent Failure (Collapse) Of Temporary Support System In Construction   Research Summary

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PREFACE

Since 1949, the year that the Chu Hai College of Higher Education was founded, the Department of Civil Engineering ('the department') has offered civil engineering programmes to equip students with in-depth knowledge and practical training for the pursuit of a career in the civil engineering and construction industry. More than 1,500 students have since graduated from the programme. Over the years, graduates have made tremendous contributions to the civil engineering and construction industry in various capacities. In particular, the outstanding achievements of the College's graduates in the field of structural engineering, especially related to the construction of the world's most renowned bridges, reflect the success of the department.

The civil engineering profession is at a crossroads as it enters the 21st century. Emphases on some aspects are shifting. In addition to the emphasis on massive infrastructure developments, more concern is now placed on maintenance and revitalisation. Similarly, sustainable development and environmental concerns have considerably expanded the role and functions of civil engineering. On the other hand, with the advancement of digital technology, modern civil engineers have had to acquire knowledge of innovations and technology developed in other related disciplines for improvements in safety and cost-effectiveness. Keeping up with and ahead of these changes, the department continues to upgrade its curriculum to be both current and innovative.

The new campus of the College provides space and equipment to facilitate the development of the department's research capability. The department is now taking a leading role in the application of Internet of Things (IoT) and digital technologies for the improvement of construction safety, monitoring of infrastructures and provision of a safer urban living environment. At present, there are three prominent and distinctive IoT projects being undertaken by the department.

The first one is the research project presented by this summary report. It is a project for the improvement of the safety of scaffolding falsework used for the construction of tall buildings. This research project is supported and funded by the Construction Industry Council.

Last year, the department, as an innovative technology service provider, was also contracted to carry out the force and deflection monitoring work on the SkyBridge at the Hong Kong International Airport. This contract is due for completion in the third quarter of 2021.

Recently, in partnership with a local innovative technology company, the department was the winner of an open competition project sponsored by the Urban Renewal Authority to protect residents living in urban environment against infection by pathogens. The project is now at the completion stage. The outcome is the successful development of an IoT-based ventilating pipe sanitisation device utilising ultraviolet c-band radiation to inactivate pathogens. The first batch of sanitisation device products are installed at the rooftops of a residential building at 12 Soy Street, Mongkok, Kowloon and the building of the old Central Market, Central, Hong Kong.

RESEARCH HIGHLIGHTS

The use of Internet of Things (IoT) technology has been growing rapidly in recent years. This technology, when suitably applied, can greatly enhance safety in construction and improve efficiency and management at a lower cost. One example of such use is the development and validation of a real-time construction monitoring system and an application software platform which would allow users to view and use the data for various purposes. However, a lot of research still needs to be done to ensure that customised IoT methodology can be applied correctly, efficiently, and effectively in a number of specific areas. This summary report gives a brief overview of a research project planned to study how IoT technology can be adopted in wide-scope applications to enhance the safety of construction falsework systems.

Failure of a temporary support falsework system is the kind of serious accident which often causes heavy casualties and injuries. Even with stringent safety codes of practice and regulations implemented, collapses still occur in both demolition and new construction work from time to time. Failure of falsework accidents occur not only in Hong Kong, but also on construction sites all over the world.

The following are two typical failure cases in demolition and new construction work which occurred in Hong Kong.

One noteworthy demolition accident case occurred on 29 October 2001 at Sze Shan Street, Yau Tong, shown in Figure 1. The entire structure collapsed, from the sixth floor all the way to the ground floor, killing six workers and injuring eight others. The investigation following the incident identified multiple factors as having caused the accident, of which the top three were: overloading caused by the piled-up debris; inappropriate use of the support props for stabilising the structure; and a resonance effect produced by the hydraulic breakers.

Likewise, a new construction falsework failure case occurred during the third phase of development at the Hong Kong Science and Technology Park in 2013, as shown in Figure 2.

These collapse cases suggest that safety codes of practice and regulations alone are not enough to prevent similar cases from occurring.

Figure 1 – Collapse of Falsework at Sze Shan Street, Yau Tong

Figure 2 – Collapse of Falsework at Hong Kong Science and Technology Park Phase 3

Figure 1 and 2 show the devastation of construction sites after falsework collapse

Prior to an accident involving temporary structures, there will usually be a transition period during which the supporting structure starts to lose stability. This is indicated by abnormal changes in key supporting members' internal force and verticality (inclination), which ultimately intensify to exceed safety limits and finally result in a collapse failure.

If instantaneous data on the force and inclination of each load-bearing member could be obtained, appropriate actions could be taken to avoid an accident. However, in order to achieve this, the answers to four important questions on the use of temporary structures must also be obtained:

- How are the load and inclination of key support members to be reliably measured?
- How is change measured in load distribution in the entire temporary support system, as affected by site activities?
- How can the load and inclination information be delivered to relevant parties in a timely manner?
- How are the initial load and inclination of key support members controlled?

If changes can be detected and analysed rapidly, timely warnings can be issued and corrective and remedial measures carried out in time to prevent accidents. In a less beneficial scenario, this could offer more time for evacuation to avoid casualties. Addressing these questions is thus essential in avoiding accidents in construction works involving temporary structures.

Regarding the use of temporary support in demolition works, the "Code of Practice for Demolition of Buildings, Year 2004" provides guidelines on shoring and load capacity of floor slabs with respect to loads on temporary supports, and specifies propping requirements such as prop spacing and the number of consecutive floors requiring propping (Department, 2004). However, determining the load distribution among floor slabs and support props is a very complicated problem theoretically (Lam L. C., 2002). Almost all practising engineers use "rule of thumb" for the design of temporary support systems, and there is currently no means of knowing the exact load on each support member and the load distribution in the entire supporting structure.

The inclination of support members is also not a regular monitoring item under current practice, though changes in this are a clear sign of loss of stability. Even though monitoring is possible, the current method to monitor inclination is labour-intensive and involves long reporting delays. Measurements are prone to human errors and cannot be conducted continuously due to labour costs, limited working hours, and weather conditions. Furthermore, the measurements also take time to reach engineers, technicians, and workers. In short, current industry practices are still unable to provide a solution to any of the questions raised above.

However, recent technological advancements in various fields, e.g., power electronics, wireless radio frequency transmission, etc., have made it possible to build a real-time monitoring system and integrate Internet technology into its architecture. The developed Internet of Things Construction Monitoring System (IoTCMS), which is the backbone supporting the studies in this project, is the result of this integration. The system comprises of the following parts (Lam, Lam, Li, Chu, & Lee, 2019):

I. Sensing units which will be integrated onto falsework for construction. These sensing units have integrated force sensors and inclination sensors to measure load and inclination of the prop or support structure on which they are mounted.

II. A processing unit which collects data from sensing units, processes the monitored data, analyses collected data for changes and under/overloading situations, reports sensing units' data to users, and also receives instructions from users.

III. A communication backbone which provides a secure channel for data transmission between the processing units and users, and also involves a cloud server handling data traffic to ensure reliable communication.

IV. Front-end access for users to review and monitor load and inclination measurements in the falsework structure, and to also control monitoring settings such as reading frequency.

Preliminary laboratory testing of the IoTCMS showed promising results as the system was able to reliably and accurately measure inclination and load on a test prop, present measurements on users' mobile devices instantly, and issue appropriate warnings immediately. Initial conclusions suggest that continuous real-time monitoring with the IoTCMS can play a significant role in achieving higher safety standards in construction works involving temporary structures. Figure 3 below shows a simplified schematic view of the system.

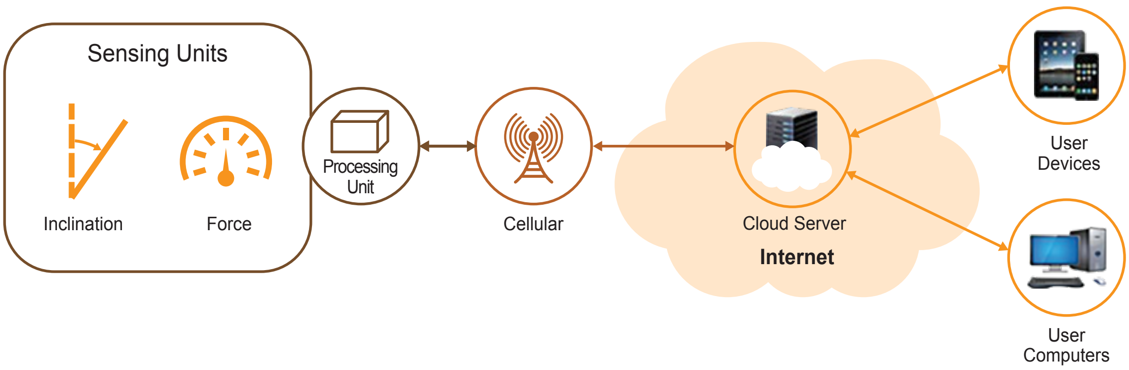

Figure 3 – Simplified Schematic View of IoT System

To ensure the technology is applicable on a real construction site, a large-scale test of the system, demonstrating loading across an entire structure, still has to be conducted. In particular, because key structural members are numerous, methods of using the minimum number of sensor points to achieve effective monitoring is an important subject to research.

The research work described in this report is an attempt to perform actual physical full-scale tests on construction sites utilising an IoTCMS to expose the problems that may emerge in future applications. With the experience gained from the tests, standardised method statements can be drafted and proposed for adoption by the industry for safety enhancement in the use of temporary support falsework systems.

One significant achievement of this research project is the successful improvement of the sensing units, previously designed for the monitoring of telescopic props used in demolition falsework systems, enabling them to also monitor the portal frame-type scaffolding systems used for new construction works. Thus, the modified IoTCMS is the answer and solution to the four questions listed on page five of this report.

An important finding in this research is the revelation that traditional assumptions of uniformly distributed loading, on which the design of a falsework system is based, may lead to hazardous situations. Uneven settlement and continuous beam effects are the major causes. These situations can be avoided, or alleviated to a large extent, by adjusting the loading in each load-supporting vertical member of a scaffolding portal frame module to balanced values. This can be achieved with the help of the real-time force values which are captured by the multi- purpose sensor devices and issued to the user interface by the IoTCMS described in this report. An optimal deployment pattern for the sensing devices is also proposed in this report.

Finally, as an important extension in the further development of this IoTCMS, it is proposed to integrate IoTCMS with a Building Information Modelling (BIM) system such that, during construction, the construction process information can also be captured and monitored spatially in real time. The ability to provide spatial information in addition to load and inclination information would give stakeholders a comprehensive view of the conditions at the site.

CONTENTS

1 INTRODUCTION

1.1 Background

The use of Internet of Things (IoT) technology has been growing rapidly in recent years. This technology, when suitably applied, can greatly enhance safety in construction and improve efficiency and management at a lower cost. One example of such use was the development and validation of a real-time construction monitoring system and an application software platform that allowed users to view and use the data for various purposes. However, a lot of research still needs to be done to ensure that customised IoT methodology can be applied correctly, efficiently, and effectively in a number of specific areas.

Prior research has shown that IoT technology can be applied to carry out real-time monitoring of construction site conditions such as the underground water table, inclination of a retaining wall, construction noise levels, construction site air quality, etc. Despite an IoT construction monitoring system (IoTCMS) having been developed to monitor the force and inclination of telescopic props used in a temporary support system, and preliminary laboratory testing of the IoTCMS which showed promising results, a large-scale test of the system that demonstrates loading across the entire temporary support system has yet to be conducted.

In particular, because key structural members are numerous, the variety of ways to use a minimum number of sensor points to achieve effective monitoring is an important subject to research.

1.2 Aims and Objectives

The objective of this research project is to establish a reliable methodology or system so that instantaneous data on the force and inclination of each load-bearing member can be obtained. With such information, appropriate actions could be taken to avoid an accident.

In order to achieve the above-mentioned objective, the activities of this research project are planned with aims to:

i. capture and adjust force and inclination of key support members before a construction project begins;

ii. continuously monitor force and inclination of key support members, along with load distribution in the entire support structure system throughout the construction work;

iii. devise effective means of capturing critical load and inclination data with a minimal amount of devices; and

iv. assess the effectiveness of the IoTCMS in fostering a safer working environment in construction sites.

1.3 Scope

The scope of work for this research project was extended substantially after inclusion of monitoring for formwork scaffolding used in new building construction. The following list is a summary of the work items included.

i. Review the design concept and principles of the monitoring sensor devices mounted on telescopic props which are used as key structural components of the falsework system for demolition works.

ii. Conduct a thorough study on the requirements of the revised sensor devices for monitoring scaffoldings for new construction work.

iii. Oversee and manage the progress of the production of the revised sensor devices.

iv. Carry out laboratory tests to inspect and check the fabricated sensor devices to ensure they meet the design criteria and requirements.

v. Design and oversee the fabrication of a special apparatus for speedy calibration of the sensor devices.

vi. Calibrate sensor devices before carrying out site tests.

vii. Conduct an analytical review of various causes of failure of falsework for new construction work.

viii. Carry out site monitoring tests of falsework for new construction work.

ix. Ascertain the effectiveness of the IoTCMS in site tests.

x. Analyse the test results.

xi. Report the test results with the method statement on how falsework safety can be enhanced, recommendations on future improvement of the IoTCMS and conclusion of this research project.

2 RESEARCH METHODOLOGY

In the original research proposal, the type of falsework system planned to be used to carry the tests was the popular temporary support system widely used in demolition work. Multiple sensors were to be deployed in a falsework system consisting of a forest of props. Continuous simultaneous measurements using the IoTCMS were to be taken on an actual construction work site (a demolition work site).

Soon after the commencement of the research project, the project team conducted a series of activities including (i) consultations with key stakeholders in the relevant construction trades, such as demolition specialist contractors and formwork sub-contractors; and (ii) invitations to key stakeholders to visit the Internet of Things Laboratory of Chu Hai College of Higher Education ("CHCHE") to show the research project plan. During the show and discussions, the formwork sub-contractors were very interested in the proposed site tests. However, they opined that the system with the existing sensor devices could not serve their need, but would be of great help to their trade if the sensor devices could be modified to monitor the popular type of falsework systems which are used to support the formwork for concrete pouring of RC building structures.

In response to the opinions from the formwork sub-contractors, the research team contacted engineers of the sensor device manufacturer and discussed with them these suggestions. The manufacturer subsequently proposed an alternative design for the sensor device. The revised sensor device was detachable and could be attached to both the telescopic type of props used in demolition work and also the portal frame type of falsework scaffolding modules used in new construction work.

The revised sensor device design concept was presented to the CIC Management Team during a visit by the team to the IoT Laboratory of CHCHE on 8 May 2019. The management team was interested in the new sensor device proposal and encouraged the research team to request that the manufacturer produce a prototype which could demonstrate field applicability in the soonest possible time.

A short video together with a photo of the prototype model (Figure 4) were presented to the CIC Sub-committee on Safety Technical Issues on 17 June 2019. Members of the Sub-committee were very interested and keen to follow the development of the project.

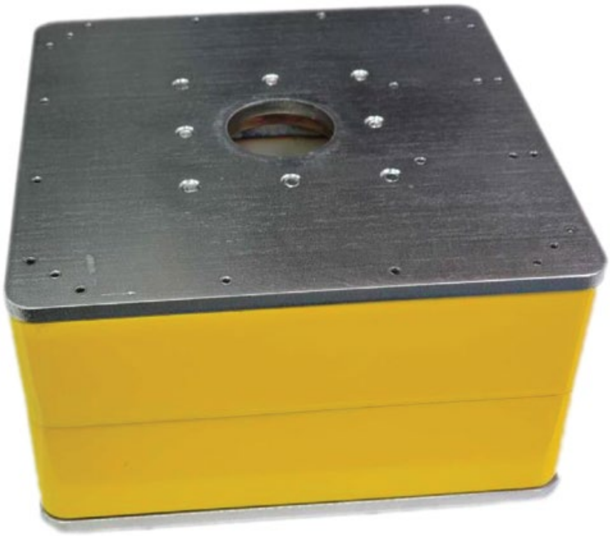

Figure 4 – Prototype Model of the Revised Sensor Device

Figure 5 is a simulated image showing where the new sensor devices are placed in a typical falsework assembly unit.

After the presentation, and noting the very positive views of the members of the sub-committee, the research team set and finalised the research strategy and methodology of this project.

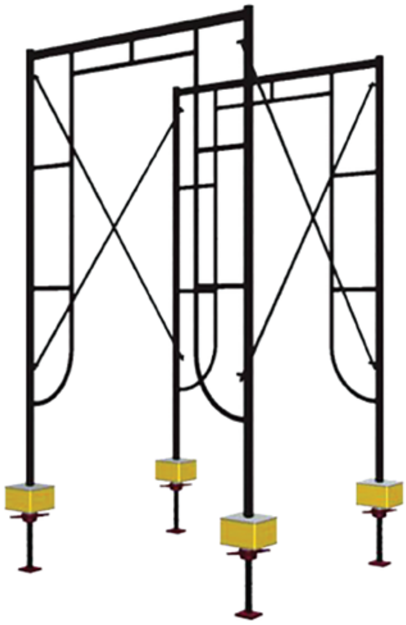

Figure 5 – Sensor Devices Installed to Scaffolding Portal Frames

In addition to the planned research work in the original proposal, the research team's revised plan also included managing the manufacturer to ensure that the proposed revised sensor device will have no negative effect on the original objectives and deliverables of this research project. Hence, the revised research plan consisted of three main parts, namely:

Part A – Development of the new sensor device;

Part B – Review and studies on failure problems of falsework systems prior to construction site tests; and

Part C – Construction site tests.

The following milestones outline the various stages in fulfilling the research objectives:

Milestone 1: Preparations for real-time monitoring of falsework in a construction site.

The initial milestone consisted of multiple parts. Firstly, proper equipment and instruments had to be procured and tested for use. The equipment was then calibrated to ensure that it provided correct and accurate readings. Calibration of the sensor-mounted props used in this proposed research project was carried out in the IoT Laboratory of Chu Hai College of Higher Education with existing specially designed apparatus.

Milestone 2: Simulation analysis of the typical scaffolding falsework system.

Similar to the review and studies on the demolition work falsework system, analytical study on the falsework system for new construction was also carried out to verify the significance of real-time monitoring. This information is critical in reconciling measured and theoretical results. The analysis would also shape the installation plan for the force-sensing and inclination monitoring devices. Cellular signal reception throughout the selected site was also analysed so as to ensure reliable data transmission for the IoTCM system.

Milestone 3: Installation of the sensors at a construction site and analysis of the results.

The installation of the force and inclination sensors was synchronised with the construction of the supporting falsework structure. During this period, the PI worked closely with the contractor/sub-contractor and the Hong Kong Housing Authority to implement real-time IoT monitoring on the selected site.

Milestone 4: Consolidation of test results and design of a practical methodology for applying IoT monitoring.

After the monitoring period ended, test results throughout the period were consolidated and the PI worked with the research team to come up with a practical methodology for applying IoT monitoring in typical falsework systems. The objective is to provide rule of thumb for optimal sensor placements and, wherever applicable, guidelines for sensor density and the number of floors that require monitoring, such that comprehensive information of site conditions can be obtained at a minimum cost.

3 RESEARCH FINDINGS AND DISCUSSION

The research work carried out in this project has successfully led to the completion of an IoT-based monitoring system which is applicable to both new construction and demolitions work after the modification of the sensor device. The site tests carried out in this project have demonstrated that the system used in the test, from sensor devices, signal capturing, and signal transmission, to data storage and analyses, and finally reaching the user via user interfaces, all performed smoothly and complied with all the designed anticipations. The system is now ready for use by the industry to improve the safety of construction scaffolding carrying heavy loads.

The results revealed that the loading distribution among the vertical supporting members in a falsework system can have large variations. The traditional assumption of uniformly distributed load among the four vertical legs in a portal frame-type scaffolding module could lead to a highly hazardous situation when the load in the heaviest loaded member exceeds the safety limit provided. Should there be additional defects, such as deformation of a load-bearing member (bent or dented), due to repeated reuse of components of a temporary system, buckling would occur all of a sudden. Real-time monitoring with a properly prepared warning signal issued at different alert levels will safeguard against such sudden failures.

The monitoring system can provide the additional advantage of allowing adjustments to loading among the vertical load-bearing members at two different stages. The first stage can be carried out after the erection of the scaffolding system and the completion of the formwork assembly. At this stage, the loading in the vertical load-bearing members is still relatively light. Adjustment at the screw jack base could be carried out easily with the help of the real-time readings obtained from the IoTCMS and displayed on a mobile phone. The second stage of adjustment can be carried out after the fixing of rebars and before concreting.

4 RECOMMENDATIONS

The investigators of this research strongly recommend that revised practices for demolition work and heavy load-carrying scaffolding in new construction work should have the vertical load-bearing members monitored in real-time for internal force and inclination – in particular, members at strategic locations where failure of falsework would be likely. Should the cost of monitoring be reduced with massive adoption of this procedure, full monitoring of falsework would be beneficial for the construction industry in respect of both safety and reduction in liquidated damage costs caused by site accidents.

For further development of the IoTCMS, it is proposed to integrate the IoTCMS with a BIM system such that, during construction, the construction process information can be captured and monitored spatially in real-time. The ability to provide spatial information in addition to load and inclination information would give stakeholders a comprehensive view of the site.

As for optimisation in the number of sensor devices to be used, it is generally recommended to carry out real-time monitoring for scaffolding of formwork systems designed to support pouring of concrete to structural members of more than 1200 mm deep, including transfer beams, transfer plates and deep beams. Sensor devices are to be installed to scaffolding modules which are placed at the following locations.

1. The scaffolding module adjacent and closest to a column;
2. The scaffolding module at mid-span between two columns along a grid line; and
3. The scaffolding module at the centre of a rectangular panel.

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