Real-time Cyber-Physical Systems (CPS)-based Monitoring of Temporary Structures: a Scaffolding System Example

Xiao Yuan, xxy116@psu.edu
The Pennsylvania State University, United States

Chimay J. Anumba, anumba@engr.psu.edu
The Pennsylvania State University, United States

M. Kevin Parfitt, mkp@psu.edu
The Pennsylvania State University, United States

Abstract
Developments in information technologies, notably Cyber-Physical Systems (CPS), have shown the potential to improve the construction industry from various perspectives. Examples include the use of CPS for structural health monitoring of critical infrastructure. However, in contrast to the increasing effort on safety management of permanent structures, there has been little focus on temporary structures monitoring, the failure of which results in more than 100 deaths, 4500 injuries, and costs $90 million annually. This study proposes the use of CPS for the monitoring of temporary structures, and developed a CPS-based temporary structures monitoring system (TSM) to facilitate real-time monitoring of, and remote access to, temporary structures (by integrating the physical structure with their digital representations in virtual models). Based on the result of the experiment, it is concluded that CPS provides an effective way for the enhanced monitoring and control of temporary structures. Further work will focus on extending the concept to more complex experimental tests and field tests of the prototype system.

Keywords: Cyber Physical Systems (CPS), Temporary Structure, Real Time Monitoring

1. Introduction
An average of two workers suffer fatal injuries every day on construction job sites. In general, more than 100 deaths, 4500 injuries and $90 million in costs results from the failures of temporary structures (such as earthwork, sheeting & shoring, temporary bracing, soil backfill for underground walls, formwork systems, scaffolding, and underpinning of foundations (OSHA 2014)) in construction. In general, the term 'temporary structures' refers to systems and assemblies used for temporary support or bracing of permanent work during construction, and structures built for temporary use. The former are defined as the elements of civil engineering work, which support or enable the permanent works (Grant and Pallett, 2012). The second category includes temporary or emergency shelters, public art projects, lateral earth retaining structures in construction zones, construction access barriers, temporary grandstands and bleachers, and indoor and outdoor theatrical stages (Parfitt 2009). While three quarters of construction workers work on or near temporary structures (OSHA 2014), current safety management of temporary structures mainly relies upon the experience of construction workers and professionals (Feld & Carper, 1997). Relatively little focus has been placed on the structural health monitoring of temporary structures, compared to the large amounts of effort devoted to safety design and construction of permanent structures. The serious safety problem related to temporary structures highlights the urgent need for improved methods for temporary structure monitoring (Parfitt 2009).

Developments in information technologies, notably Cyber-Physical Systems (CPS), have shown the potential to improve temporary structures monitoring. CPS entails the effective bidirectional integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes with feedback loops, where physical processes affect computations and vice versa (Derler et al., 2012). By definition, a CPS involves a high degree of integration between computing (virtual) and physical systems (Wu and Li, 2011), which is supported by the networked implementation of CPS (Anumba et al., 2010). Distributed applications are also common which involve distributed management and/or distributed operations such as a power grid. Other features of CPS include the ability to provide timely service in the face of real-time constraints (Wan and Alagar, 2012), to adapt to changing situations through dynamic reorganizing/reconfiguration (Shi et al. 2011), to automatically control a physical system according to continuous tracking (Wan et al., 2011), and to integrate several different communication systems and devices (Wan et al., 2011).

In view of the potential benefits of CPS to the construction industry, this study presents an advanced method of temporary structures monitoring based on CPS, called Temporary Structures Monitor (TSM). In doing this, this study reviewed CPS applicability to temporary structures and designed the system architecture of TSM. A framework of the TSM operation is demonstrated through seven main steps. Finally, an experiment on a scaffolding system was designed and conducted with a focus on the problem of base settlement. The experimental results demonstrated that the CPS-based TSM provides an advanced approach to real time temporary structures monitoring.

2. Related Work on Temporary Structures Monitoring

Before discussing how the TSM system was developed, it is important first to discuss CPS applicability and necessity to temporary structures monitoring by reviewing the conventional approaches to temporary structures monitoring. This section summarizes the significant efforts that have been made by government, industry, and academic researchers.

2.1 Traditional Approaches to Temporary Structure Monitoring

Several attempts have been made to address the safety problems of temporary structures. These include OSHA standards, safety training programs, and industry best practices. OSHA standards cover the design, installation, maintenance, and dismantling of temporary structures. A variety of personal protection equipment (PPE), such as lifelines and hardhats, are mandatory to minimize the exposure of construction workers to various types of hazards. In order to increase the safety awareness of construction workers, a number of safety training programs are also required by OSHA regulations. In addition, various industry safety practices related to temporary structures are provided by industry organizations (such as Mason Contractors Association of American) as reference or guidance to industry practitioners.

Significant decrease in construction fatalities has been achieved with the traditional approaches, yet recent high records of fatalities related to temporary structures failures calls for more efforts in this area. In addition, there are still some temporary structures, such as indoor and outdoor theatrical stages, which are not covered by any safety regulations (McKiniley 2011). Furthermore, the temporary structures failures could not be fully prevented by manual inspection as the workers tend to work under great pressure and unconsciously make mistakes (Fabiano, et al. 2008).

2.2 Conventional IT-based Methods of Temporary Structures Monitoring

Aside from traditional practices, a large amount of research has been conducted to improve temporary structures monitoring with the aid of IT-based methods, such as BIM and automated DAQ (Data Acquisition). As early as 2008, Li et al. (2008) proposed to integrate the design and construction of temporary structures through virtual prototyping. For fast modeling of temporary structures, Chi et al. (2012) proposed to develop BIM objects of temporary structures embedded with safety information. Similarly, a safety rule-based BIM for temporary structures was developed, with a focus on automatically eliminating potential fall hazards during the design stage (Zhang et al., 2015); A DAQ system refers to computer based systems with digital input and output (UEI, 2006). With developing technologies, DAQ systems have been increasingly utilized for temporary structures management (Moon et al. 2012). These efforts include the use of RFID (Yabuki and Oyama, 2007), sensing technology (Moon et al., 2012), and videos (Jung, 2014).

The above research projects have explored the benefits of IT-based methods to prevent potential failures of temporary structures. However, most of the research focused on the safety design or plan of temporary structures with limited consideration of the dynamic environment on the construction jobsite. In addition, the proposed methods of real time inspection of temporary structures are limited to passive inspection with little interaction between temporary structures and construction workers. However, while the application of IT-based methods in temporary structures monitoring is still at the initial stage, their benefits and limitations highlight the opportunities for the deployment of CPS in this domain.

2.3 CPS Applicability to Temporary Structures

As indicated by its key features, CPS offers a potential solution to address emerging problems, and has been implemented in several industry sectors, including the manufacturing industry (Kaihara and Yao, 2012), the power grid (Krogh et al., 2008), the transportation industry (Gong and Li, 2013), and the healthcare industry (Shi et al., 2011). These initial applications of CPS in the industry sectors mentioned above have given rise to the recognition of the importance of CPS to the construction industry. As a result, CPS applicability and potential benefits have been explored in various areas of the construction industry, including the project delivery process (Anumba et al., 2010), light fixture control and monitoring (Akanmu et al., 2012), Structural Health Monitoring (Hackmann et al., 2010), and temporary structures monitoring (Yuan et al., 2014). Based on these investigations, CPS is considered to be applicable to the monitoring of temporary structures.

3. Overview of CPS-based TSM

With the objective of real time and remote inspection of temporary structures, a Temporary Structure Monitor (TSM) has been developed based on CPS. The development of TSM involves the selection of hardware (such as DAQ instruments, physical temporary structures) and software environment (such as virtual modeling system, DAQ system for data calibration and transmission, database for data storage, and the communication network). By reviewing various platforms and the objectives of the TSM, the Autodesk Navisworks system was selected as the virtual platform for the study due to its benefits as an open .NET application programming interface; sensors and Lab-view are used as the DAQ system; an Amazon on-cloud communication service was adopted for the communication network and database. For better understanding of the TSM, a comprehensive demonstration is presented below with details of the system architecture and operation.

3.1 TSM System Architecture

The CPS-based TSM system consists of the physical structures, their virtual models, a communication network, a database, and portable devices. A system architecture of the CPS-based TSM is shown in Figure 1, demonstrating how the close interaction between a temporary structure and its virtual model is realized through a CPS Bridge, which consists of a "Physical-to-Cyber Bridge" and a "Cyber-to-Physical Bridge". The Physical-to-Cyber Bridge is the sensing process that keeps the virtual model "alive" with updated structural information of the corresponding physical structure while the Cyber-to-Physical Bridge is the process of adjusting or monitoring the physical structure through its virtual model, which can be realized through the use of actuators (such as the air dampers used in ventilation systems) or by alerting the supervisors to make adjustments to the physical structure.

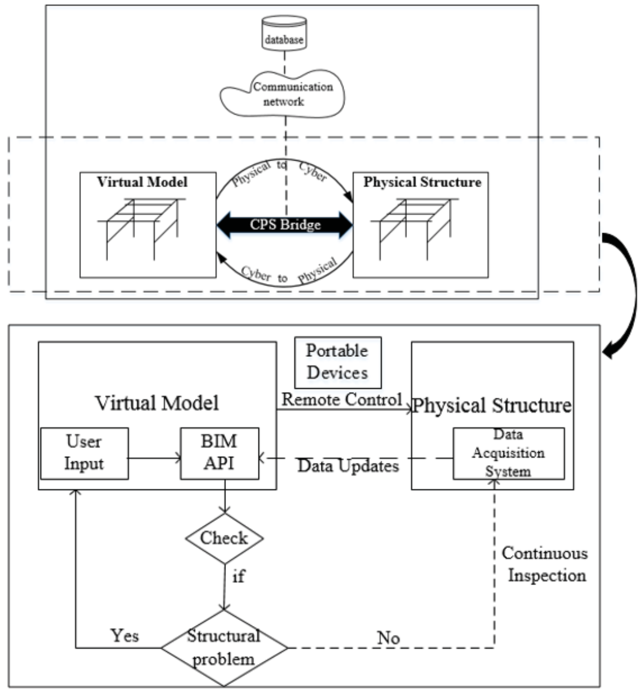


Figure 1 System Architecture of CPS-based TSM

3.2 Framework for TSM Operation: an Example of Scaffolding Systems

As discussed in the previous sections, there are various types of temporary structures that may benefit from the CPS application. For system prototyping and validation, a frame scaffolding system has been selected for three reasons:

1. Scaffolding systems, ranking third among the top 10 OSHA violations in 2013, account for a large number of fatalities and injuries in the construction industry (U.S. Department of Labor, 2014). The root cause analysis reveals that the "failure to identify, assess or control risk" ranks as the top frequent deficiency of scaffolding incidents (Whitaker, et al 2003);
2. The principles of TSM for scaffolding system monitoring are similar to those of other types of temporary structures, which indicates that the TSM for scaffolding systems can be easily modified and is expandable to other types of temporary structures;
3. Frame scaffolds are amongst the most commonly used temporary structures (Halperin & Maccan 2004).

A TSM for scaffolding monitoring is developed following seven key steps as follows:

3.2.1 Identify the Key Structural Information for Structural Monitoring of Scaffolding Systems

Based on the failure mode analysis of scaffolding systems (Yuan, 2013), four typical types of structural information are required for structural monitoring, including loading information on the scaffolding system, displacement of scaffolding planks or plank supports, connection between the ground and the bases of the scaffolding system, and 3 directional inclination of the scaffolding posts. All of this information should be closely monitored for structural integrity analysis.

3.2.2 Identify Warning Threshold through User Input, OSHA Standards, and Industrial Best Practice

The warning threshold is the value that is predefined in TSM as the reference point for potential structural failures. If the actual structural behavior information exceeds the warning threshold (with other exceptional situations excluded), there is a potential for structural failure or excessive movement. According to the OSHA standards and industrial best practice, the load placed on the scaffolding system should be no more than its rated working capacity; the maximum allowed displacement of scaffolding planks is 1/60 of the span; furthermore, disconnection between the bases of the scaffolding system and the ground or support surface is not allowed. While there is no specific requirement of maximum allowable inclination of the scaffolding system, it can be set by the safety experts or users based on heuristics. In reality, the user can also define higher warning thresholds for more stringent safety requirements.

3.2.3 Tie Physical Scaffold to its Corresponding Virtual Model

A virtual model of the frame scaffold was developed in Autodesk Revit and imported into Autodesk Navisworks as the virtual platform of the TSM. For recognition of each physical component by TSM in the virtual model, the physical components and their corresponding virtual representations were linked through their unique ID in the virtual model.

3.2.4 Transfer Structural Information of Physical Scaffolding Systems to Their Virtual Model

A DAQ system and on cloud database are used for information collection and transmission. To be specific, several sensors, as shown in Figure 2, are mounted on the scaffolding system for structural information detection. This information is retrieved by NIMAX (National Instrument Measurement & Automation Explorer, which provides access to the information from the sensors), calibrated through LabView (which provides the platform of data calibration), and then exported into the on cloud database. Every few seconds, the virtual model queries the on cloud database for updated structural information.

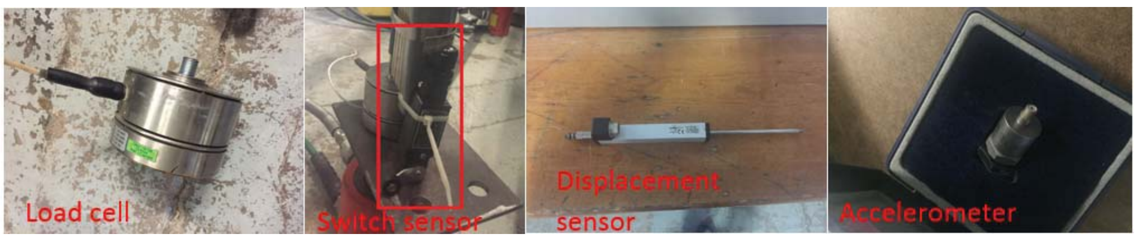


Figure 2 Sensors for Structural Information Monitoring

3.2.5 Potential Structural Hazards Prediction in the Virtual Model

Based on the value of warning threshold predefined and the real time structural information, the potential structural hazards can be predicted. For example, if the actual displacement of a scaffolding plank exceeds its corresponding warning threshold, it is an indication of a structural or serviceability deficiency of the scaffolding plank.

3.2.6 Physical Structural Deficiency Updated and Visualized in Virtual Model

Once a potential hazard or performance is identified, the components in question will be visualized (marked in an easily identifiable color) in the virtual model, with the aim of providing direct and detailed information to assist safety inspectors and project managers in the safety inspection of the scaffolding system. Meanwhile, the virtual model will inform the project manager of how the warning and instruction has been sent to the site supervisors regarding this potential hazard.

3.2.7 Virtual Model Enables Control of Physical Structures through the Guided Performance of Supervisor

For safety concerns, immediate warnings are expected to be delivered to construction site supervisors/foremen. Although a degree of automatic structural control can be achieved by using actuators (which have been used in the control of civil infrastructures by CPS), they may induce movements that affect the stability of workers working on the scaffolding system, which may impair the stability of the system itself. Therefore, to ensure the safety of construction workers, the structural control of TSM is designed to be completed through interaction with the directed intervention of construction supervisors following notification by the CPS system. In doing this, a mobile APP, named TSM, has been developed and installed on the smart phone of construction supervisors. Once a potential hazard is identified, the TSM mobile App is activated and it alerts the relevant supervisors through vibration and a warning alarm. Along with it, an overview of the structural performance of the scaffolding system is displayed as an instruction to supervisors, so that appropriate corrective actions can be taken to correct the structural deficiencies.

4. Experiment on Base Settlement of a Scaffolding System

As identified by Whitaker et al (2003), base settlement ranks as one of the key causes of scaffolding accidents. For system validation of the TSM, an experiment on the base settlement of the frame scaffold was set up and conducted.

4.1 Laboratory Design for Experiment of Base Settlement

A simple frame scaffold (5 ft. x 5 ft. x 7 ft.), along with six OSHA certified scaffolding planks (2 inches x 10 inches x 10 ft.) as shown in Figure 3, was set up in the laboratory as the physical scaffolding system. The bases of scaffolding posts were placed at the top of hydraulic cylinders. For loading purposes, a load cell was inserted between each hydraulic cylinder and post. The load cell produced a positive signal when the post is pulled up from the load cell, and a negative signal when there is pressure from the post onto the load cell. To simulate the use of jack posts, a steel adapter of similar shape and same diameter as the jack posts was mounted on top of the load cell and inserted into the post, as shown in Figure 3. Switch sensors are attached at the base of the scaffolding system, with their connectors touching the steel plates, which are used to simulate the ground surface. Once there is movement that results in a disconnection between the connectors and the steel plates, a signal will be initiated by the switch sensors. The base settlement of the frame scaffold is simulated by initially raising all the posts three inches – this is achieved by raising the hydraulic cylinders under them - and gradually lowering the base of post 3, which simulates the base settlement of post 3.

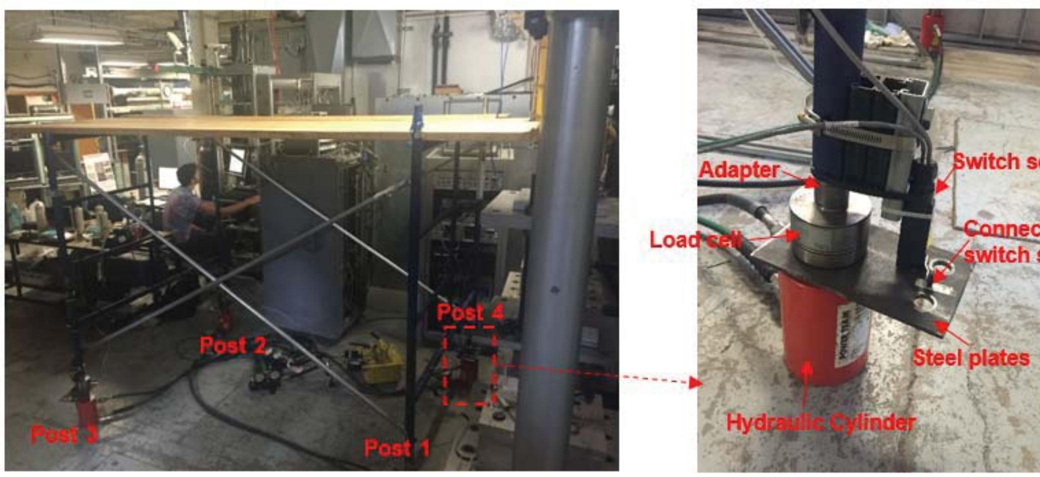


Figure 3 Experimental Set-up

4.2 Experimental Results

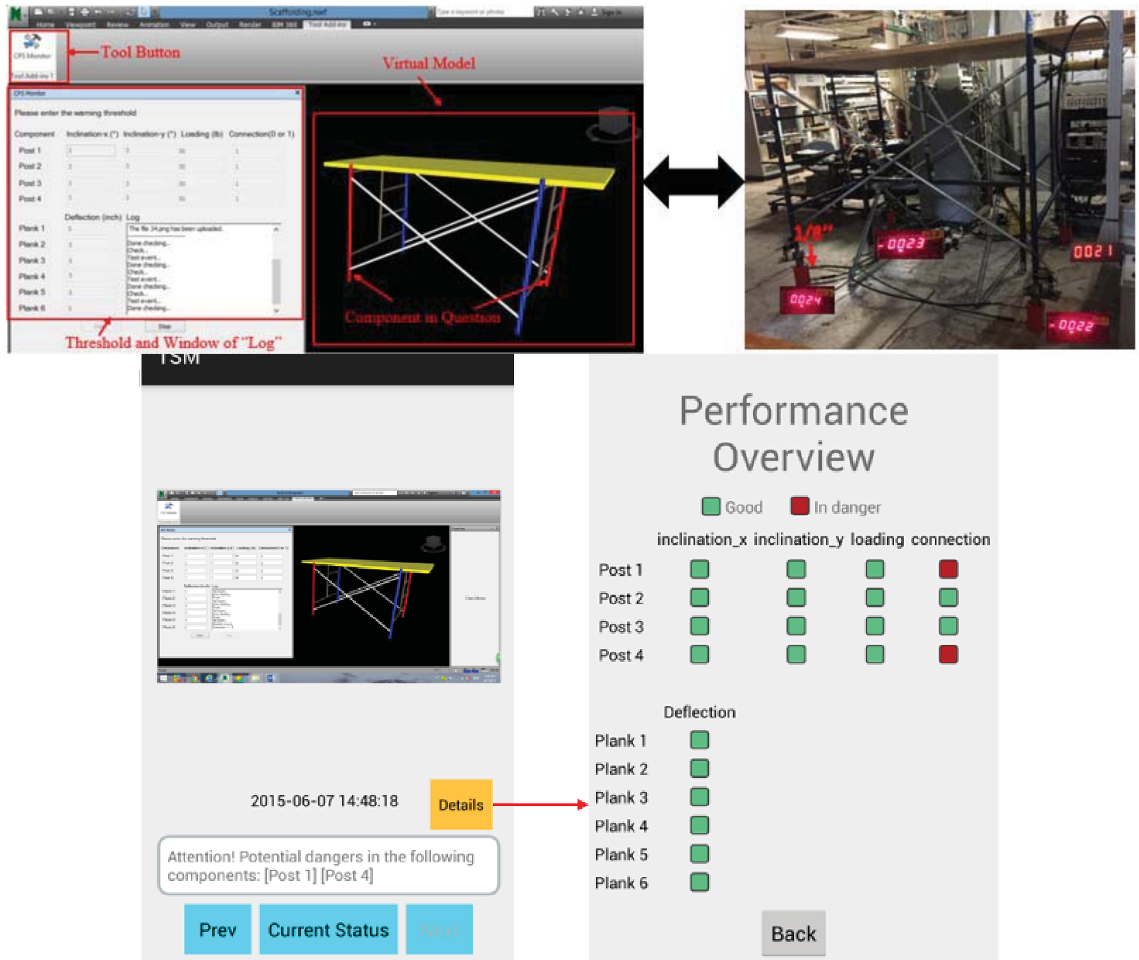
In order to detect the potential base settlement, it is important to identify which information should be checked during the whole process. Although the base settlement of post 3 is simulated, the main objective of the TSM is to identify the components that have a potential problem regardless of the causation. This is because the direct monitoring of the temporary structure's integrity would be more effective than the control of numerous unexpected causes. Two significant stages, initial stage and second stage, were observed during the simulation of the base settlement of post 3.

4.2.1 Initial Stage

The initial stage indicates the situation when there is a trend of base settlement before actual settlement occurs. This is simulated by lowering the base of post 3 by up to 1/8''. It is noticed that the load placed at the base of post 3 and post 4 becomes positive, indicating that the post is moving up against its base plates (as shown in Figure 4). In one second, post 3 and post 4 were highlighted immediately as the deficient component in the virtual model, as shown in Figure 4. Besides, the window of "log", shown in Figure 4, also indicates that the warning and instructions have been successfully sent to the construction supervisors through the mobile App "TSM". In particular, a picture which highlights the component in question is displayed, along with messages in the box below, as shown in Figure 5. For more detailed information, supervisors can click the "details" button, which then displays a check list that specifies how each component performs. In this way, supervisors understand immediately that there is a potential disconnection between post 3 and post 4 and their supporting ground. By checking these posts in the real world, supervisors can take corrective actions or report to project manager for further investigation.

4.2.2 Second Stage

In case that the initial stage is not well prevented by supervisors, the second stage indicates the situation when the base settlement of post 3 actually happens. This is simulated by lowering the base



of post 3 up to 2''. At this point, there is a disconnection signal from the switch sensor placed at the base of post 3, along with increasing negative loading information at the base of post 3 and post 4. This happens due to the severe inclination of the whole structure. The actual danger of post 3 and

Figure 5 User Interface of TSM Mobile App

potential problem of post 4 are updated immediately at the virtual model, with the component with actual problem (post 3) in purple color and one with potential hazard (post 4) in red color, as shown in Figure 6. Meanwhile, warnings and instructions were also sent to the supervisors.

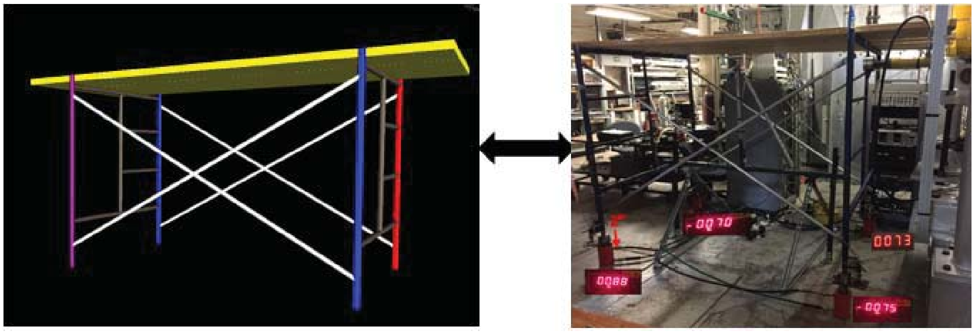


Figure 6 Test of Base Settlement - Second Stage

4.3 Discussion

As shown by the scaffolding experiment described here, CPS-based TSM offers a method for improving the monitoring of temporary structures through real time coordination between virtual and physical systems. With the CPS-based TSM, a number of benefits can be achieved as follows:

- Real time inspection: in lieu of inspecting specific influential factors, TSM can monitor the performance of temporary structural components in real time, and provide warnings that can help to ensure structural stability.
- Tight coordination between physical component and virtual model: TSM enables bi-directional communication between physical components and their virtual representations. Through the "Physical-to-Cyber Bridge", the displacement of physical components are tracked and transmitted to the virtual model, where the difference between designed and actual structure is highlighted. Through the "Cyber-to-Physical Bridge", once potential hazards are detected, safety alerts or instructions can be sent from the virtual model to the site supervisors.
- Remote and multi-party access: due to the bi-directional information loop between the physical and virtual system, structural performance can be remotely monitored through virtual models. TSM enables multiple parties to obtain access to the virtual model remotely. This benefits project managers, structural designers, and other involved parties for routine monitoring, potential structural problem analysis, and enhanced collaboration.
- Early warning with customized safety level: TSM has the potential to shorten the time interval between the onset of an initial hazard and potential collapse. Instead of having alarms when there are already structural failures, an early warning will be sent once there is a trend towards potential structural failure or performance issues. The safety factor can be used as recommended by the manufacturers of the temporary structure, or customized if the user wishes to have a higher level of safety.

5. Conclusions and Future Work

This paper has explored CPS applicability to temporary structures. A CPS-based Temporary Structure Monitor (TSM) was designed and developed for advanced control of temporary structures for structural integrity; this was further validated through experimental tests. It can be concluded that:

- *CPS serves as a potential solution to temporary structures monitoring*: there is an urgent need for an enhanced approach to preventing the failure of temporary structures. Meanwhile, the initial applications of CPS and in the construction industry indicate the applicability of CPS to temporary structure monitoring.
- *A CPS-based temporary structure monitoring can be realized through the CPS Bridge*: the physical structure and its virtual representation are integrated through a CPS Bridge, which enables both the "communication" from the physical structure to the virtual model (sensing process) and the "response" from the virtual model to the physical structure (control process).
- *A scaffolding system can be considered as a representative temporary structure for advanced monitoring*: based on literature review, safety problems relative to scaffolding systems have been

serious over decades. In this regard, the TSM developed for a scaffolding system can be easily modified for monitoring other types of temporary structures.

- *CPS-based TSM works effectively in the real time monitoring of temporary structures*: based on the experimental results, the developed TSM identified the potential problem in a few seconds, with both notification and control being activated. In other words, a potential hazard can be diagnosed and corrected continuously and immediately.
- *Other benefits, in addition to real time monitoring, can be achieved by TSM*: according to the key features of CPS, the CPS-based TSM also provides for remote access to the updated structural performance of temporary structures and can be shared by multiple parties. Other benefits also include the visualization of the structural deficiency, and analysis of historical performance of temporary structures.

The study reported in this paper has a number of limitations. For example, the sensors used in the experiment were wired. With the increasing number of sensors, the cable management would be time-consuming and may affect the experimental results. Besides, in order to mount the load cell at the base of posts for loading information, the jack posts were replaced by adapters which work similar to the jack posts. This difference may impact the experimental result. However, because various types of sensors were used in this study, the use of load cells may be proved unnecessary due to the duplication of sensors.

With regard to the limitations discussed above, this study will try to use wireless sensors and other types of DAQ, such as laser scanners, for a totally wireless TSM. Meanwhile, future work will also extend the experiment to more complex situations with other failure types, such as overloading and lack of diagonal braces. In addition to the laboratory experiment, field testing of the TSM prototype system will be also conducted.

Acknowledgements

This project is supported by the Pennsylvania State University and China Scholarship Council.

References

Akanmu, A., Anumba, C., & Messner, J. (2013). "Scenarios for cyber-physical systems integration in construction." *Information Technology in Construction (ITCon),* Vol. 18, 240-260.

Anumba, C., Akanmu, A., Messner, J. (2010). "Towards a cyber-physical systems approach to construction." *Proc., 2010 Construction Research Congress*, Banff, Alberta, May 8-10. 528–538.

Ayub M. (2010). "Structural Collapses During Construction: Lessons Learned 1990-2008." *Structure Magazine*, 12-20.

Chi, S., Hampson, K. D., Biggs, H. C. (2012). "Using BIM for smarter and safer scaffolding and formwork construction: a preliminary methodology." *Proc., Modelling and Building Health and Safety*, Singapore. (In press)

Derler, P., Lee, E.A., Vincentelli, A.S. (2012). "Modeling Cyber–Physical Systems." *Proc., IEEE 100*, 13–28.

Feld, J., and Carper, K. (1997). *Construction failure*, 2nd Ed., Wiley, New York.

Fabiano, B., Fabio, C., Reverberi, A.P., Pastorino, R. (2008). "A statistical study on temporary work and occupational accidents." *Specific risk factors and risk management strategies.*

Fattal, S. G., Mullen, C. L., Hunt, B. J., & Lew, H. S. (1980). "Analysis of scaffolding accident records and related employee casualties." *Washington, DC: National Bureau of Standards*, National Engineering Laboratory.

Gong, Y., and Li, S. (2013). "Fusion framework of urban traffic control and route guidance based on Cyber-physical System theory." *Journal of Highway and Transportation Research and Development.* (Engl. Ed.), 7 (1), 82–89.

Grant, M., and Pallett, P.F. (2012). *Temporary Works: Principles of Design and Construction.* ICE Publishing. London.

Hackmann, G., Guo, W., Yan, G., Sun, Z., Lu, C., & Dyke, S. (2014). "Cyber-physical codesign of distributed structural health monitoring with wireless sensor networks." *Parallel and Distributed Systems, IEEE Transactions*, 25(1), 63-72.

Hsiao H. and Stanevich R. L. (1996). "Biomechanical Evaluation of Scaffolding Tasks." *International Journal of Industrial Ergonomics,* 18: 407-415.

Jung, Y. (2014). "An Approach to Automated Detection of Failure in Temporary Structures using Image Processing." *Journal of Engineering and Architecture*, 2(1), 49-61.

Kaihara, T., & Yao, Y. (2012). "A new approach on CPS-based scheduling and WIP control in process industries." *Simulation Conference (WSC), Proceedings of the 2012 Winter.*1-11.

Krogh, B.H., Lee, E., Lee, I., Mok, A., Rajkumar, R., Sha, L.R., Vincentelli, A.S., Shin, K., Stankovic, J., Sztipanovits, J. (2008). "Cyber-Physical Systems: executive summary." *CPS Steer Group*, Wash. DC.

Li, H., Huang, T., Kong, C. W., Guo, H. L., Baldwin, A., Chan, N., & Wong, J. (2008). "Integrating design and construction through virtual prototyping." *Automation in Construction*, 17(8), 915-922.

Moon, S., Choi, B., Yang, B. (2012). "USN-Based Data Acquisition for Increasing Safety in the Concrete Formwork Operation." *J. Comput. Civ. Eng.* 26, 271-281.

Mckiniley J. C. (2011). "After Accidents, a Call for Regulation." <http://www.nytimes.com/2011/08/24/arts/music/after-accidents-a-call-for-regulation.html?_r=0> (August, 23, 2011)

OSHA (2014). "OSHA Scaffold Certificate Course." <http://www.usfosha.com/scaffolds-certificate.aspx> (2014).

Parfitt, M.K. (2009). "Cranes, structures under construction, and temporary facilities: are we doing enough to ensure they are safe?" *J. Arch. Eng.* 15, 1–2.

Ratay, R.T. (1996). *Handbook of Temporary Structures in Construction*, 2nd ed., McGraw-Hill. New York.

Shi, J., Wan, J., Yan, H., Suo, H. (2011). "A survey of cyber-physical systems, in: Wireless Communications and Signal Processing (WCSP)." *Proc., 2011 International Conference.* 1–6.

Stewart P. (2010). "Four Times Square - Scaffold Collapse (July 21, 1998)." <http://failures.wikispaces.com/4+Times+Square+Scaffold+Collapse > (Oct. 1, 2013).

UEI (United Electronic Industries) (2006). "Data Acquisition Systems Then and Now." < http://www.ueidaq.com/media/static/other/so/data-acquisition.pdf > (Oct. 20, 2014).

U.S. Department of Labor (2014). "Top 10 Most Frequently Cited Standards." < https://www.osha.gov/Top_Ten_Standards.html > (Jan. 01, 2015).

Wan, K., and Alagar, V. (2012). "Resource modeling for Cyber Physical Systems, in: Systems and Informatics (ICSAI)." *Proc., 2012 International Conference.* 2541–2546.

Wan, J., Suo, H., Yan, H., & Liu, J. (2011). "A general test platform for cyber-physical systems: unmanned vehicle with wireless sensor network navigation." *Procedia Engineering*, 24, 123-127.

Whitaker, S. M., Graves, R. J., James, M., & McCann, P. (2003). "Safety with access scaffolds: Development of a prototype decision aid based on accident analysis." *Journal of safety research*, 34(3), 249-261.

Weesner, L. B., & Jones, H. L. (2001). "Experimental and analytical capacity of frame scaffolding." *Engineering Structures*, 23(6), 592-599.

Yabuki, N., & Oyama, T. (2007). "Application of radio frequency identification technology for management of light weight temporary facility members." *In ASCE Workshop on Computing in Civil Engineering*, Pittsburgh, 697-704.

Yuan, X., Parfitt, K. M, Anumba, C. J. (2014). "The Use of Cyber-Physical Systems in Temporary Structures–An Exploratory Study." *In Computing in Civil and Building Engineering. ASCE*, Florida, 1707-1714.

Yuan, X. (2013). "Overview of Temporary Structural Failures in Construction." <http://failures.wikispaces.com/Overview+of+Temporary+Structures+Failures+in+Construction> (April. 12, 2015).

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015). "BIM-based fall hazard identification and prevention in construction safety planning." *Safety science*, 72, 31-45.