Scaffolding Modelling for Real-Time Monitoring using a Strain Sensing Approach

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Abstract –

Scaffolding structures are important as a temporary structural element that are used to support workers, equipment, and materials during construction activities. Although 65% of construction workers work on scaffolding structures and often are exposed to safety hazards, the current method of monitoring scaffold structures still is premature. As an example of practices set by the U.S. Occupational Safety and Health Administration, a knowledgeable and experienced individual conducts a visual and labor-intensive inspection. However, one difficulty in conducting structural analysis of a scaffolding structure involves its boundary conditions and material design parameters, which vary depending upon loading conditions. This research explored a new method to accurately model the boundary conditions and design parameters of a scaffolding structure in real time by using wireless strain sensors. An Internet of Things (IoT) open-source Arduino module was used to develop wireless strain sensors to acquire strain data directly from a scaffolding structure. The strain data were transmitted to a finite element method (FEM) model, which was used to estimate the real-time structural behavior of a scaffold. A model-updating technique was used to improve the synchronizing accuracy between the FEM model (i.e., the cyber model) and the actual scaffold. The test results indicated that the proposed synchronizing method described the real-time structural behavior of the scaffold accurately, especially for modelling the boundary conditions and design parameters. The outcomes of this paper are expected to foster the use of wireless sensing technology for safety monitoring of temporary structures and to offer the potential of improving construction safety by preventing the collapse of temporary structures.

Keywords –

Temporary structures, monitoring, FEM, scaffold, wireless sensor

1 Introduction

In the construction industry, scaffolding structures have been the most widely used temporary structures; according the U.S. Occupation Safety and Health Administration (OSHA) as many as 2.3 million construction workers work on scaffolds [1]. Thus, proper inspection and the safety conditions of scaffolds are crucial to ensure the safety of construction workers. Currently, the entire structural condition of scaffolds is inspected visually by a knowledgeable and experienced individual [2]; this approach is labor intensive, subjective, and prone to error. However, due to the lack of systematic tools, it is difficult to continuously monitor and inspect multiple scaffolds in a dynamic construction site by using the traditional visual inspection technique.

The real-time monitoring of scaffolds is exacerbated even further by the external work environment, which often occurs under high-pressure conditions; difficulty in identifying defects in scaffolds when at full scale; and simple human errors [3]. As a result, the construction industry has suffered a high number of accidents – 50 deaths and 4,500 injuries (estimated every year) – and has incurred costs exceeding $90 million a year due to improperly managed scaffolds [4]. To improve the effectiveness of monitoring the scaffolds, thus ensuring safety of the scaffolds, there have been efforts to monitor temporary structures automatically with sensors, including load cells, switch sensors, an accelerometer, and a displacement sensor [5]. However, this approach focused only on measurements of the structural responses (e.g., strain, displacement, and load) at a local level without taking into consideration a global structural analysis. In this study, a structural FEM modeling technique was developed for scaffolding monitoring by proposing transforming the boundary conditions of and model updating for a scaffold.

2 Background

OSHA requirements and recommendations for designing, erecting, dismantling, and inspecting scaffolds [2] are the basis for conventional scaffolding inspection in the construction industry. OSHA regulations require inspection of each scaffold before each work shift and after any incident that might have affected its structural integrity as well as safety training programs to educate workers. Despite these efforts to identify and prevent potential safety hazards related to scaffolds, the actual application of this knowledge to a complex construction site still remains challenging.

Thus, researchers have sought more advanced methods to monitor temporary structures. Moon et al. [6] developed a sensing network to collect static structural responses – such as strain, displacements, and loading condtions – and compare them to allowable limits in order to determine structural safety conditions. By analyzing video streams to characterize deformations of targeted temporary structures, Jung [7] developed an image-processing method to automatically identify defects in scaffolding and shoring. Yuan et al. [5] introduced a cyber-physical system that synchronizes a virtual model and a real model of a scaffold with a sensor-based system to monitor its physical status.

However, such past research investigated only element-level behaviors of temporary structures and overlooked integral structural analysis; therefore, the potentially varying boundary conditions of a scaffold were not properly investigated. Since locally stable structures still can be globally unstable, resulting in structural problems, understanding global behaviors should be investigated to ensure the safety of scaffolds in a more comprehensive manner. Hence, there was a need to develop a more reliable scaffolding modelling technique that considers the global behaviors of scaffolding structures to ensure their structural stability as well as the safety of the construction workers and the general public.

3 Objective

The main objective of this study was to improve a structural modeling technique to precisely reflect the actual behaviors of scaffolding structures. In contrast to general structures, such as buildings and bridges, the boundary conditions of temporary structures can be unstable because they often stand on the site without having proper fixtures. To address instability issues in the boundary conditions of a scaffold, our research team developed a technique of a boundary transformation to describe structural behaviors more reliably. In addition, we developed a technique to update design parameter models using the finite element method (FEM). The proposed technique for parameter modelling uses wireless strain sensors to measure the strain data from each of the scaffolding components under given loading. By synchronizing real data with the corresponding data from the FEM model, we updated the model to reflect the actual conditions more accurately of a scaffold. Then, we applied various loading cases to the scaffold model in order to validate the proposed techniques with respect to the boundary conditions and design parameters of the scaffold.

4 Modeling Approach for Monitoring Temporary Structures

4.1 Overview

The overall approach of the proposed methodology was to synchronize the strain data that was collected from the columns of an actual scaffold with that of an FEM model, which represented the behavior of a scaffolding structure by transforming the boundary conditions. To improve accuracy of the FEM model even further, a model-updating procedure was conducted to optimize the material and geometry parameters of the scaffold.

Figure 1 shows an overview of the proposed methodology. The research team developed the wireless strain sensors with the combination of an Arduino Yun board, a strain-gage board, and commercial strain gages (350 Ω and gage factor 2.18). An interface shield provided electrical connections to integrate these three components.

The Arduino Yun board, which is an Internet of Things (IoT) open source hardware, converted an analog signal to a digital signal from the strain gages, and had Wi-Fi communication capability. The strain-gage board managed the measured voltage difference by amplification. The designed wireless strain sensor required 5 V for operation, and the wireless interrogation distance was 30 m of line-of-sight communication. Strain sensing ranged from –1,000 $\mu\varepsilon$ to 1,000 $\mu\varepsilon$, with a resolution of 2 $\mu\varepsilon$.

To measure the strain responses, wireless strain sensors were installed on the column components of the scaffold. The wireless sensors measured the strain data for each column of the scaffolding and transferred the strain data to the FEM model. In the FEM model, the boundary conditions were transformed based on loading conditions and amplitudes, as described in Section 4.3. The FEM model sought to optimize the material and geometric parameters of the scaffold, as described in Section 4.4, by processing the model updating until the strain responses from the FEM analysis were close to the measured values.

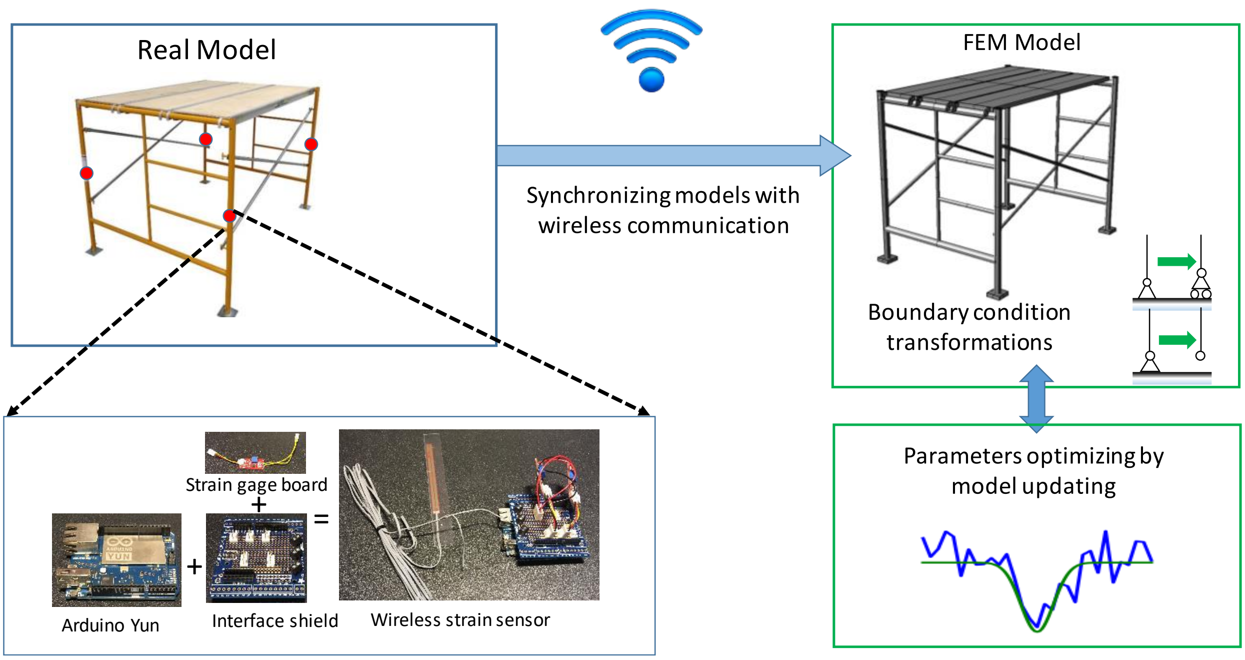
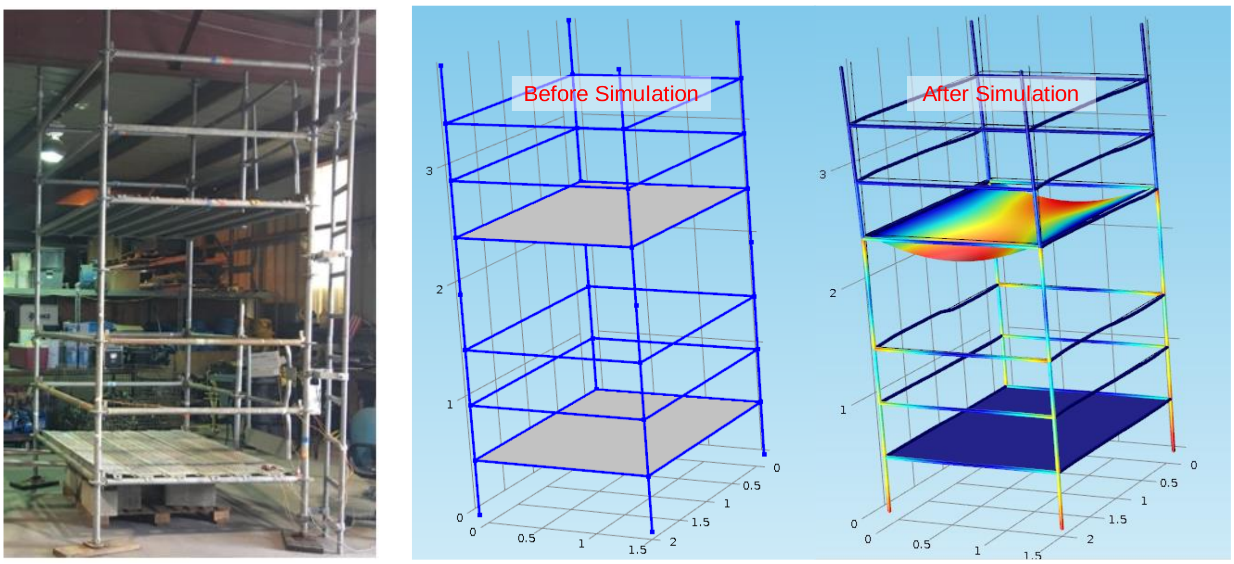


Figure 1 System overview

4.2 Scaffolding Models

For laboratory testing, as shown in Figure 2(a), the research team prepared a one-bay scaffold with two stories; this scaffold consisted of four columns and 24 side frames, with a circular pipe section that was 5-mm in diameter. The dimension of the scaffolding structure was 84 in × 62 in × 152 in (2,133 mm ×1,575 mm ×3,861 mm). Six steel scaffold planks having the dimensions of 84 in. × 10 in. ×0.12 in. (2,133 mm ×254 mm ×3 mm) were placed on each floor.



(a) Actual scaffolding model

(b) FEM model

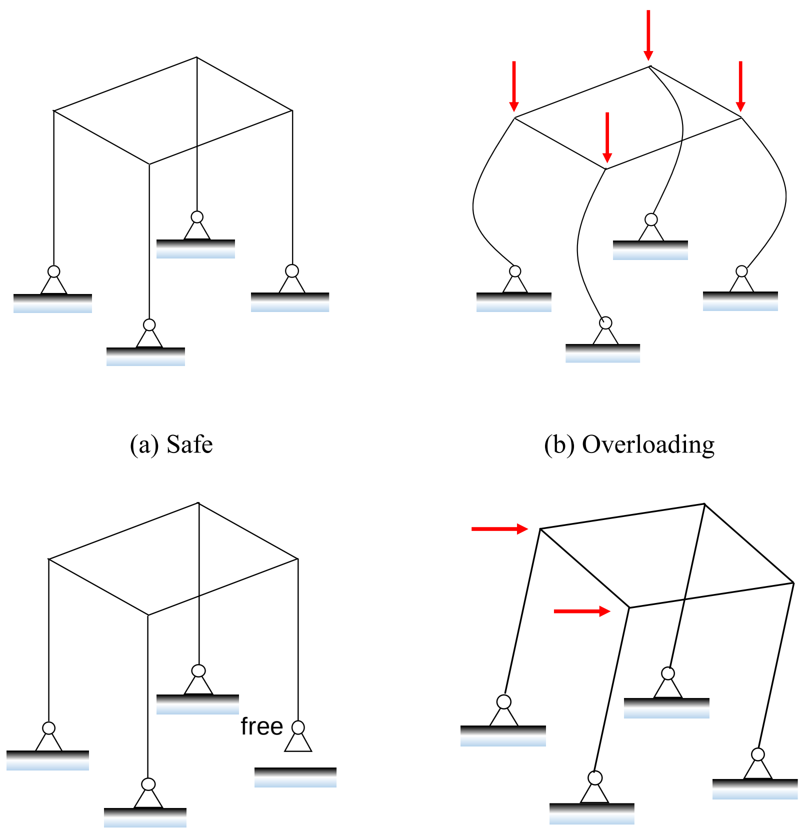
Figure 2 Scaffolding model

The columns of the scaffolding structure stood on wooden foundations; these were not the same type of boundary as conventional boundaries, such as hinges, and fixed boundaries. For convenience, it is a common practice not to attach the columns of a scaffold to the foundation; thus, the boundary conditions of a scaffold might be different from conventional ones. For modelling the scaffold, the research team employed a commercial FEM software package, COMSOL Multiphysics [8]. The frame of the scaffold was modeled by beam-column elements, and shell elements were used to model the scaffold planks.

Figure 2(b) shows the FEM model of the scaffolding structure before and after simulation. The deformed shape shown in Figure 2(b) is an example of a result of structural analysis. In the FEM simulation, each node was formulated with six degrees of freedom due to three-dimensional (3D) analysis.

4.3 Transformation of Boundary Conditions in an FEM Model

As described previously, the columns of the scaffold rested on wooden foundations. From a structural point of view, these boundaries were unstable, and were considered to be a free-boundary condition. While compensating for the boundary conditions of a scaffold, this study proposed a new method for modelling the boundary condition in order to analyze scaffold structures. The structural conditions of a scaffold were classified into four categories: safe, overloading, overturning, and unevenly settled conditions, as shown in Figure 3.



(a) Safe (b) Overloading

(c) Uneven settlement (d) Overturning

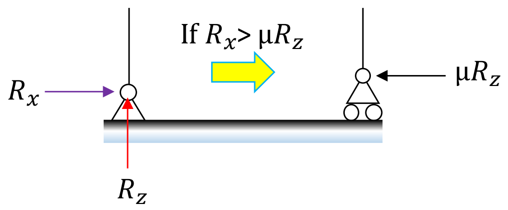
Figure 3 Structural conditions of a scaffold

The boundary conditions were transformed as follows:

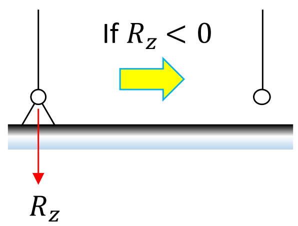
Case I: When lateral forces are greater than the maximum reaction forces of the wooden foundation, the column starts to slip. In other words, when lateral forces (R_x or R_y) are greater than the vertical reaction force (R_z) multiplied by a friction coefficient (μ), a hinge is transformed to a roller boundary with the lateral reaction force of μR_z, as shown in Figure 4(a).

Case II: A reaction force along the Z axis is less than zero, which means that the associated columns are unevenly settled or that a full structure is bounded to an overturning condition. Such columns disable to support any reactions. Therefore, the hinge boundary conditions of the columns are transformed to a free condition, as shown in Figure 4(b).

At this point, the FEM simulation performed another analysis on the structure with the transformed boundaries for both Case I and Case II, as shown in Figure 4.



(a) Case I



(b) Case II

Figure 4 Computational modeling for the boundary-conditions transformation

4.4 Model Updating

For structural analysis by means of FEM simulation, nominal parameter values, such as material properties and geometric dimensions were selected. However, these nominal values often are the main factors that lead to a discrepancy between numerical analysis and experimental measurements. To minimize this discrepancy, the research team employed a model-updating technique to extract the precise values of the parameters from experimental data. Upon updating the material parameters and geometric parameters in the model, the FEM model was able to reflect the physical reality of the scaffold more accurately as compared with the initial model, which relied on nominal parameter values. The optimization problem for model updating was formulated as:

$$\begin{aligned} &\underset{\mathbf{x}}{\text{minimize}} \left\|\text{Strain}_{\text{Exp}}(\boldsymbol{P}) - \text{Strain}_{\text{FEM}}(\boldsymbol{P},\mathbf{x})\right\| \\ &\qquad \text{subject to } \mathbf{x}_{\text{L}} \le \mathbf{x} \le \mathbf{x}_{\text{U}} \end{aligned} \tag{1}$$

where:

$\|\cdot\|$ is the Euclidean norm;

$\boldsymbol{P}$ is a loading vector;

$\mathbf{x}$ is the updating vector parameter, which consists of Young's Modulus E and the thickness of a structural pipe t ($\mathbf{x} = [E, t]$);

$\text{Strain}_{\text{Exp}}(\boldsymbol{P})$ is a vector function to generate the experimental strain values against loading $\boldsymbol{P}$;

$\text{Strain}_{\text{FEM}}(\boldsymbol{P},\mathbf{x})$ is a vector function to generate simulated strain values with loading $\boldsymbol{P}$;

The updating parameters $\mathbf{x}$, $\mathbf{x}_{\text{L}}$, and $\mathbf{x}_{\text{U}}$ are (element-wise) the lower and upper bounds of the updating vector parameter $\mathbf{x}$.

5 Experimental Validation

To demonstrate the proposed method, three types of structural conditions – overloading, uneven settlement, and overturning conditions – were generated in an extensive experimental validation. Strain gages were installed and connected to the wireless unit for real-time strain measurement from the four columns of the scaffold (C1, C2, C3, and C4), as shown in Figure 5. Then, the strain data were synchronized with the FEM model. For the test of the overloading condition (Case I), the maximum loading capacity of the scaffolding – which as 84 in (213 cm) in width and 62 in (157 cm) in depth – was calculated based on OSHA standards. This specified that the maximum weight exerted on a heavy-duty scaffolding was not to exceed 75 lbs/ft^2, as follows [9]:

$$\begin{aligned} 7\text{ ft } (84\text{ in}) \times 5.16\text{ ft } (62\text{in}) \times 75\frac{\text{lb}}{\text{ft}^2} &= 2{,}709\text{ lb} \\ &= 1{,}229\text{ kg\_force (kgf)} \end{aligned}$$

However, for safety reasons, we limited a loading size up to 400 kgf. We recruited six subjects, and measured their weights prior to the experiment. The subjects stepped on the scaffold one by one until the weight reached near 400 kgf.

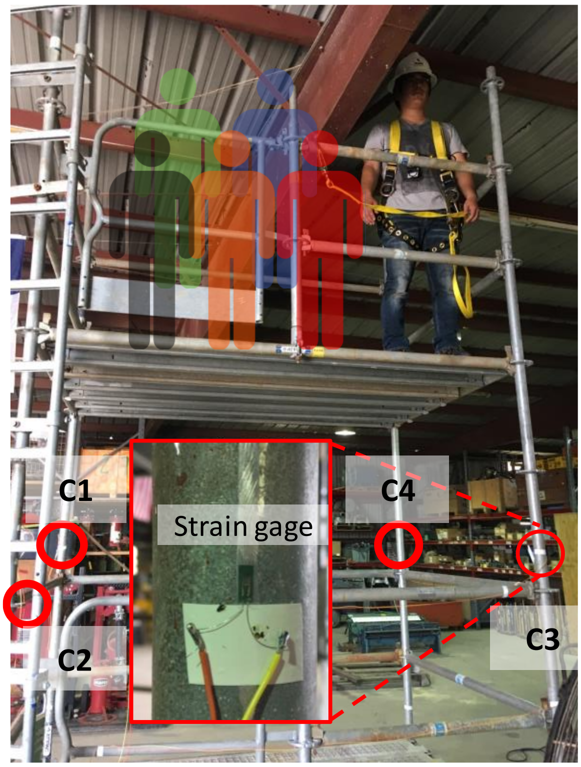


Figure 5 Experimental setup for overloading conditions

In the model updating procedure, initial parameters of vector $\mathbf{x}_0$ were chosen as:

$$\mathbf{x}_0 = [200\times10^9\,\text{Pa},\, 3\text{ mm}] \tag{2}$$

The lower and upper bounds were set with a 10% difference from $\mathbf{x}_0$:

$$\mathbf{x}_\text{L} = [200\times10^9\,\text{Pa},\, 3\text{ mm}] \times 0.9 \tag{3}$$

$$\mathbf{x}_\text{U} = [200\times10^9\,\text{Pa},\, 3\text{ mm}] \times 1.1 \tag{4}$$

During the experiment, the loading step was 100 kgf, which was uniformly distribuited to the second-floor scaffold planks. The loading amplitude increased up to 400 kgf. For benchmark comparisons, the FEM model simulated the structural analysis with the identical loading conditions to obtain analytical strain values. A MATLAB™ optimization toolbox, `MultiStart`, was adopted and integrated with the FEM model to conduct the model-updating procedure. Since this objective function was not convex, we set 1,000 trial starting points for a global search (global optimization). The updating variables ($\mathbf{x} = [E, t]$) for each of the parameters were randomly generated. Starting from each of 1,000 points, the `lsqnonlin` (nonlinear least-squares solver) with the 'trust-region-reflective' algorithm found a local optimum around the point. Among local optimums, the most optimized value was as shown:

$$\mathbf{x}^* = [198.12\times10^9\,\text{Pa},\quad 2.612\text{ mm}] \tag{5}$$

Figure 6 presents the results of model updating. The Y-axis indicates the average strain values from the four columns. This figure reveals an intriguing finding in that the model updated by the proposed method showed more accurate behaviors for the tested scaffold compared to the initial model with nominal parameters. This indicated that the proposed updating technique was superior over the model with the initial parameters.

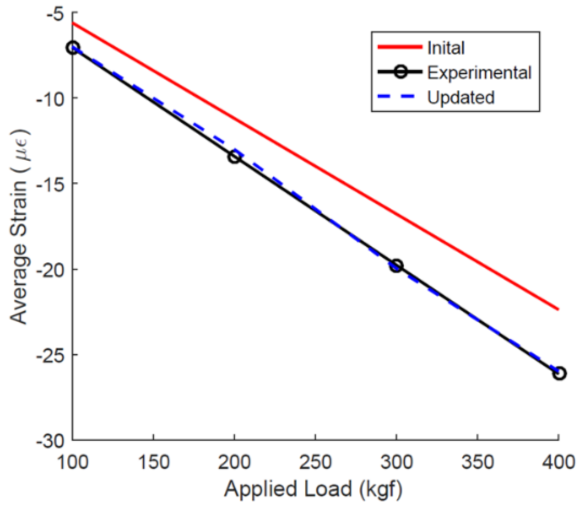


Figure 6 Comparison of strain data of various model updating

To generate unevenly settled (Load Case II) and overturning (Load Case III) conditions, we used a forklift to lift one or two columns, as shown in Figure 7. For safety reasons, the lifting height was limited to 2 in (approximately 5.1 cm). However, this small displacement was enough to emulate unevenly settled and overturning conditions.

Figure 7 Experimental setup for uneven settlement and overturning conditions

Table 1 Test Results shows the results of the experimental validation by comparing the strain data of the FEM simulation and those of the experiments conducted for all three cases to ascertain that the proposed method could perform reliably for various cases. For the overloading condition (Load Case I), the total loads approached near 400 kgf, and strain values were measured from the four columns of the scaffold. The average strain value from both the experiment and simulation indicated –75 με. For uneven settlement (Load Case II), C1 was lifted by the forklift, and its corresponding strain value was close to zero. Strain values from other three columns were from –7με to –8με. For the overturning condition (Load Case III), because C1 and C4 had zero strain, the other two columns needed to support the entire scaffold structure. Strain values from C2 and C3 were approximately –12 με. Thus, both experimental and simulation results were well matched in the three loading conditions.

Table 1 Test Results

Load Case		Strain (με)			
		C1	C2	C3	C4
I	Exp.*	-75.132	-75.142	-75.149	-75.123
	Sim.**	-75.069	-75.027	-75.954	-75.949
II	Exp.	0.013	-7.082	-8.041	-8.071
	Sim.	0.000	-7.004	-8.599	-7.004
III	Exp.	0.001	-12.25	-13.02	0.004
	Sim.	0.000	-12.02	-12.02	0.000

* Experiment, ** Simulation

6 Conclusion

A scaffold plays an essential role as a temporary structure during construction. However, the current approach to monitoring scaffolding structures has focused mainly on local behaviors of a scaffold in spite of the importance of their global behaviors to understand their safety status. This study proposed a modeling technique that could compensate the unstable boundary conditions of a scaffold structure by transforming its boundary conditions based on loading cases. In addition, the model-updating technique improved simulation accuracy to more closely reflect on behaviours of a real scaffold.

For the validation, four structural conditions (safe, overloading, uneven settlement, and overturning conditions) were generated and tested with physical experiments and computational analysis. The results indicated that the proposed method, using boundary transformation and model updating techniques, was reliable for determining real-time structural condition of scaffolds. This result implies that the global behaviours of a scaffold could be modelled and analysed more accurately in an FEM model. In addition, real-time monitoring of a scaffold with rigorous analysis is possible when such an FEM model is synchronized with real-time strain data from an actual scaffold on site. Thus, application of such a technique in the construction industry is expected to significantly improve the safety of the workers at a construction site.

Despite the advancement made in this research, it is limited in the following aspects: it needs model information of a scaffold for initial FEM model development and the following updates. Also, the developed system was a prototype system that was applied to a small scaffolding structure with only four strain sensors applied to each of the four columns. For our findings to be converted to more practical results, the proposed approach should be validated with large systems with more variability.

7 References

[1] Occupational Safety and Health Administration (OSHA). Safety and Health Topics - Scaffolding. Online: https://www.osha.gov/SLTC/scaffolding/construction.html, Accessed: 07/08/2017.

[2] Occupational Safety and Health Administration (OSHA). A Guide to Scaffolding Use in the Construction Industry. Online: https://www.osha.gov/Publications/osha3150.pdf, Accessed: 07/03/2017.

[3] Fabiano B., Currò F., Reverberi A. P., and Pastorino R. A statistical study on temporary work and occupational accidents: Specific risk factors and risk management strategies. *Safety Science*, 46(3):535–544, 2008.

[4] Occupational Safety and Health Administration (OSHA). Scaffolding eTools. Online: https://www.osha.gov/SLTC/etools/scaffolding/overview.html, Accessed: 07/08/2017.

[5] Yuan X., Anumba C. J., and Parfitt M. K. Cyber-physical systems for temporary structure monitoring. *Automation in Construction*, 66:1–14, 2016.

[6] Moon S., Choi B., and Yang B. USN-Based Data Acquisition for Increasing Safety in the Concrete Formwork Operation. *Journal of Computing in Civil Engineering*, 26(3):271–281, 2011.

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

[8] COMSOL Multiphysics. *COMSOL multiphysics reference guide*, COMSOL, Inc., Burlington, MA, USA, 2012.

[9] Occupational Safety and Health Administration (OSHA). Scaffold Specifications - 1926 Subpart L App A. Online: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10917, Accessed: 09/01/2017.