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Automated dimensional quality assurance of full-scale precast concrete elements using laser scanning and BIM

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ABSTRACT

This study presents a quality inspection technique for full-scale precast concrete elements using laser scanning and building information modeling (BIM). In today's construction industry, there is an increasing demand for modularization of prefabricated components and control of their dimensional quality during the fabrication and assembly stages. To meet these needs, this study develops a non-contact dimensional quality assurance (DQA) technique that automatically and precisely assesses the key quality criteria of full-scale precast concrete elements. First, a new coordinate transformation algorithm is developed taking into account the scales and complexities of real precast slabs so that the DQA technique can be fully automated. Second, a geometry matching method based on the Principal Component Analysis (PCA), which relates the as-built model constructed from the point cloud data to the corresponding as-designed BIM model, is utilized for precise dimension estimations of the actual precast slab. Third, an edge and corner extraction algorithm is advanced to tackle issues encountered in unexpected conditions, i.e. large incident angles and external steel bars being located near the edge of precast concrete elements. Lastly, a BIM-assisted storage and delivery approach for the obtained DQA data is proposed so that all relevant project stakeholders can share and update DQA data through the manufacture and assembly stages of the project. The applicability of the proposed DQA technique is validated through field tests on two full-scale precast slabs, and the associated implementation issues are discussed. Field test results reveal that the proposed DQA technique can achieve a measurement accuracy of around 3.0 mm for dimension and position estimations.

1. Introduction

1.1. Precast concrete element based construction

The construction industry is typically characterized by high labor intensity, low productivity, and high safety risk [27]. According to a UNEP report [43], these problematic conditions primarily result from the slow integration of technological advances and industrialization principles such as computer-aided construction, automation, standardization and modularization. Construction based on precast concrete elements is a recent revolution in the construction industry, in which the principles of industrialization are adopted in the construction process. Precast concrete elements can offer faster production and lower cost compared to cast-in-place construction [37,44,23]. Moreover, the use of the precast concrete elements leads to a cleaner and safer construction environment. Precast concrete elements are therefore becoming popular components for construction projects such as low and mid-rise apartments, office buildings and bridges. As precast concrete elements gain prominence, there is increasing demand to control their dimensional quality during the fabrication and assembly stages.

1.2. Current dimensional quality assurance for precast concrete elements

The use of precast concrete elements, however, can suffer from system failures due to dimensional mismatches of precast products with other precast components, or the rest of the structure, during assembly. The Construction Industry Institute (CII) [9] revealed that the average cost of rework caused by construction defects was 5% of the total construction costs and, Mills et al. [30] also reported that defect costs accounted for 4% of the contract value in new residential construction. For these reasons, dimensional quality assurance (DQA) of precast concrete elements is strictly enforced before shipping to construction sites. The main objective of the dimensional inspection for precast concrete elements is to scrutinize for dimensional abnormalities such as dimension and position defects. For visual inspection, certified inspectors take responsibility for the dimensional assurance, and there are formal guidelines that the inspectors follow, such as the quality management

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system from the International Organization for Standardization (ISO) [22] and the tolerance manual for precast and pre-stressed concrete from the Precast Concrete Institute (PCI) [36]. Normally, inspectors check the dimensional checklists by using contact-type measurement devices such as rulers and measurement tapes. However, such manual inspections are time consuming and labor intensive, and there is a lack of systematic storage and management of the information obtained.

Some researchers have explored non-contact sensing techniques to monitor the dimensional properties of civil structures. The use of 2D cameras is one of the most common and popular approaches for the detection of dimensional abnormalities, since it is speedy and inexpensive. Ordonez et al. [34] proposed two different image-based methods for dimensional error checking of building elements; Shin and Dunston [39] presented an augmented reality technique for measuring the position of anchor bolts and plumbness in steel column inspection; and Fathi and Brilakis [12] presented an as-built data collection method for digital fabrication of metal roof panels using a series of vision data. The above dimensional inspection approaches, however, report that significant human interactions and often external lighting sources are required during data acquisition and data analysis [6]. In addition, the performance of these vision based approaches can deteriorate due to the quality of the photos [11] and poor lighting conditions. For example, shadows lying on the surface of a precast concrete element can cause difficulties in extracting certain features from images.

Laser scanners have been one of the most popular recent measurement tools in the construction industry, and many applications using laser scanners have been proposed [13,35,40]. Laser scanning directly acquires 3D data with good accuracy (typically 2–6 mm at 50 m [33]) and high measurement rate (up to 960,000 points/s [14]). According to studies [10,11,17] which conducted comparisons between laser scanning methods and vision based approaches, the laser scanning approaches offer better accuracy than vision based methods. Due to these technical merits, the possibility of dimensional measurements using laser scanning has been investigated by a number of researchers. Bosche [6] proposed a technique for recognizing 3D CAD objects from laser-scanned data for dimensional compliance control of steel elements. Bosche et al. [8] also reported a surface flatness control technique for concrete floors using laser scanning and Building Information Modeling (BIM). Nahangi et al. [31,32] proposed dimensional and defect control techniques with the aim of monitoring and checking pipes. Bosche et al. [7] reported a discrepancy assessment technique for cylindrical pipes using laser scanning data. Shih and Wang [38] reported a laser scanning system for measuring the dimensional features of finished walls. Han et al. [20] presented an automated dimensional quality control technique for extracting tunnel cross sections using laser scanning data. Gordon et al. [18] measured deformation using laser scanners to control the dimensional quality of structures. Kim et al. [29] proposed a surface defect control technique for concrete elements using laser scanning data. Although laser scanning has been adopted in various civil applications, the studies mentioned do not offer fully automated techniques for dimension estimations. More importantly, less attention has been paid to the DQA of precast concrete elements despite of the urgency of demand.

Our research group previously proposed an automated technique that can assess the dimensional qualities of precast concrete elements by using a 3D laser scanner [28]. This technique, however, has some limitations. First, the effectiveness of the technique is validated only with small-size specimens with simple (rectangular) geometry, and the feasibility of applying it to in-situ full-scale precast concrete elements with complex geometry is not tested. Second, the technique operates in a semi-automated way such that manual corner selection is necessary for a data processing step. Third, its dimensional estimation results are significantly affected by the incident angle between the laser beam and the surface of the target object, which makes the method unreliable and hard to apply to full-scale precast concrete elements. Hence, the need for a fully-automated DQA technique that can be applied to full-scale precast concrete elements still remains.

1.3. Current storage and management system for dimensional assurance data

In practice, typical storage and management of DQA data obtained by inspectors complies with the following two steps [46]. First, authorized inspectors measure specified DQA checklists and record the information in paper-based inspection forms. The inspectors return to the office, then type and store the inspection data into a database via a computer. However, the conventional practice is inefficient and ineffective because repeated data storage for the same inspection data is conducted in both paper and database formats. BIM is currently revolutionizing the Architecture, Engineering and Construction (AEC) industry. It is now regarded as an essential tool in managing the lifecycle of a construction project from initial design to maintenance [19], and it serves as a central data repository that can store and retrieve information on a facility. For these reasons, BIM is expected to effectively share and update the information generated during construction processes in a timely manner. Current BIM tools for precast concrete elements, such as Tekla Structures [42] and Allplan Precast [1] BIM software provide useful functions with respect to data storage and management. However, those functions are mainly used for the design and fabrication processes so that sharing and updating of DQA data for precise assembly of precast concrete elements are not provided in those BIM tools.

Some recent studies have explored the possibility of a BIM-based system for efficient and effective data storage and management of precast concrete elements. The majority of these studies have focused on solving data exchange problems that frequently occur in construction projects due to the diversity of construction participants. Jeong et al. [25] tested various BIM tools to identify the interoperability of BIM data of precast concrete elements such as geometric shapes and relationship information. The study concluded that the IFC (Industry Foundation Classes) is a promising candidate for effective exchange of geometric and other information, and identified that current IFC-based data exchanges remain lacking of reliable data exchanges of precast concrete elements between BIM tools. Venugopal et al. [45] proposed an IFC based framework for facilitating data exchanges and avoiding ambiguities of IFC information for precast/pre-stressed concrete elements. Also, Belsky et al. [5] proposed a method for supplementing an IFC exchange file with semantically useful concepts in precast concrete elements of building models. Lastly, Aram et al. [2] proposed a process model for identifying the necessary capabilities of BIM tools for supporting and improving the entire data exchanges of concrete reinforcement supply chain.

However, those aforementioned studies mainly focus on data interoperability of design models of precast concrete elements, few studies have been conducted on storing and delivering DQA data of precast concrete elements. In addition, there is no formalized schema of representing the DQA data of precast concrete elements in the current version of IFC. The lack a practical and systematic solution for data storage and delivery of DQA of precast concrete elements is addressed in this paper.

1.4. Objective and uniqueness of this study

The main objective of this study is to develop a non-contact DQA technique that automatically and precisely assesses the key quality checklists of full-scale precast concrete elements with complex geometry. A new coordinate transformation algorithm is developed taking into account the scales and complexities of real precast slabs, enabling the DQA technique to be fully automated. In addition, a BIM-assisted storage and delivery approach for the obtained DQA data is proposed so that all relevant project stakeholders can share and update DQA data through the manufacture and assembly stages of the project. The