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

Min-Koo Kim a, Qian Wang b,c, Joon-Woo Park b, Jack C.P. Cheng c, Hoon Sohn b,⁎, Chih-Chen Chang c

a Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, United Kingdom
b Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daeak-ro 291, Yuseong-gu, Daejeon, Republic of Korea
c Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

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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.

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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...
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 deformations 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
uniqueness of this study includes (1) the development and validation of a DQA technique for full-scale precast concrete elements based on a new coordinate transformation algorithm that makes the technique fully-automated; and (2) the development of a BIM based data storage and delivery concept that enables the project stakeholders to share and update DQA data effectively.

The rest of this paper is organized as follows. Section 2 presents an overview of the proposed DQA technique for full-scale precast concrete elements and details its procedures. Section 3 presents the experimental setup for field tests on full-scale precast concrete elements. Subsequently, accuracy analysis and DQA results of the field tests are presented in Section 4, and a BIM based data storage and delivery approach is described in Section 5. Finally, the paper concludes with a brief summary and discussion in Section 6.

2. Development of dimensional quality assurance technique

2.1. Overview of the DQA technique

The DQA technique proposed is composed of six data processing steps as shown in Fig. 1: (1) It starts with acquisition of the point cloud data for a precast concrete element using the laser scanner. The laser scanner is assumed to be located right above the center of the precast concrete element so that the entire surface of the precast concrete element can be scanned in a single scan; (2) Once a set of point cloud data is acquired, coordinate transformation is undertaken. The initial coordinate system with respect to the laser scanner is transformed into a new coordinate system with respect to the precast concrete element so that next data processing steps can be automated and easily implemented; (3) In the next step, the extraction of key dimensional features, i.e. edges and corners, is performed. An edge extraction algorithm, called the ‘vector-sum’ algorithm [28], is applied to the coordinate-transformed point cloud data to extract only the edge points of a precast concrete element. The corners of the precast concrete element are then extracted by fitting the edge points to straight lines and finding the intersection points of these fitted lines; (4) The dimensional properties of the precast concrete element are computed from the extracted corners. However, the initial estimates of dimensions are always less than the true dimensional values due to a phenomenon called the mixed-pixel phenomenon [21]. This phenomenon occurs when the laser beam is split into two and reaches two distinctive surfaces which have different distances from the laser scanner. To compensate for this dimension loss due to the mixed-pixel phenomenon, an edge loss model [41] is employed and correction values are added to the initially computed dimensions; (5) Dimensional error calculation is followed by comparing the finally estimated dimensions of the precast element with the corresponding design dimensions; and (6) Finally, a decision on the appropriateness of the tested precast concrete is made based on a comparison of the computed dimensional errors with the specified tolerance values.

2.2. A new coordinate transformation algorithm

In this subsection, a new coordinate transformation algorithm developed for the field tests is described. Fig. 2 shows the range image of a full-scale precast slab (slab type I, see Fig. 11(a)). In the previous coordinate transformation algorithm [28], a 2D range image generated from point cloud data is used and the identification of three points ‘near’ the corners of the precast slab is required to cope with the ‘mixed pixel’ phenomenon, which occurs at the edges of a scanned object. Note that these three near corner points should be selected so that the two axes formed by the three points are orthogonal for coordinate transformation. In practice, it is, however, difficult to identify the three points forming an exact right angle because the range image generated from a full-scale precast slab is distorted and curved as shown in Fig. 2. Furthermore, the external steel bars (see Fig. 8(a)) installed for lifting are positioned near the corners of the precast slab and adversely affect the extraction of these near corner points. To address these issues, a new coordinate transformation algorithm is developed by directly using 3D point cloud data rather than 2D range images. The new coordinate transformation algorithm consists of the following four steps. Note that the slab type I (see Fig. 11(a)) is used as an example throughout.

2.2.1. Step 1 - Removal of background scan points

Because the laser scanner is positioned right above the center of the precast slab in the Z coordinate direction, the Z values of the unwanted background scan points outside the target precast concrete surface

![Fig. 1. Procedure of the proposed DQA technique.](image1)

![Fig. 2. The range image of the full-scale precast slab type I.](image2)
should be less than the values of the scan points on the target precast concrete surface as shown in Fig. 3(a). Based on this observation, a threshold value is established as follows. First, the maximum Z value among all scan points, $Z_{\text{max}}$, is selected. Then, $Z_{\text{mid}}$, which is the Z value of the scan point whose X and Y coordinates are the median values of all scan points, is selected by interpolating the Z values of the eight neighboring scan points. Here, the distance difference between $Z_{\text{max}}$ and $Z_{\text{mid}}$ is denoted as $d$. Since the scanned surface is assumed to be flat, it is expected that the majority of scan points residing on the slab surface will have Z values between $Z_{\text{max}}$ and $Z_{\text{min}}$ which is defined as $Z_{\text{mid}} - d$ (see Fig. 3(a)). Assuming that the scan points of the top surface are all within the target surface and separated from the background point cloud, the threshold, $Z_{\text{mid}} - 2d$, is selected empirically as 'the mean of Z values minus two times the distance between the mean Z value and the maximum Z value of the precast slab'. Hence, all the scan points whose Z values are smaller than the threshold value are removed as shown in Fig. 3(b).

2.2.2. Step 2 – Four corner point extraction from a range image

Once the background scan points are eliminated from the point cloud data, a range image is generated from the remaining scan points corresponding to the top surface, and the four corner points of the precast slab are extracted. Fig. 4 shows the four sub-steps in this step 2 process as follows: (1) Generation of a range image - a range image is generated by dividing the X and Y axes of the remaining scan points (see Fig. 3(b)) with a user-defined spacing. Note that the remaining scan points are projected to the 2D plane fitted using the scan points, resulting in no image distortions. A group of X, Y and Z values are then allocated to each grid. X and Y coordinates of the center of each grid become X and Y values for each grid, while the Z value corresponding to the center of each grid is determined by interpolating the Z values of the eight neighboring scan points which can be extracted based on Euclidian distance. Note that range image resolution is dictated by how densely the remaining scan points are divided with the selected spacing of a grid. If a grid of the range image is within the slab’s boundary, a valid Z value is returned, but if the grid is outside the slab’s boundary, no Z value is assigned to the pixel. For each grid with a valid Z value, the range value is computed as \[ \sqrt{X^2 + Y^2 + Z^2} \] and then normalized by the maximum range value within the slab’s boundary, resulting in the normalized value between 0 and 1. The precast slab closer to the laser scanner is shown in a darker grey as shown in Fig. 4(a); (2) Edge pixel detection - the edge pixels of the precast slab are then extracted. An edge detector is developed so that only the outside boundary edges of the precast slab are extracted in a binary image, as shown in Fig. 4(b). The proposed edge detector searches for the first and last pixels in each row and column pixel, which have a range value between 0 and 1, and they are determined as edge pixels; (3) Line extraction - four lines which represent the four sides of the slab are extracted using the
Hough transform [4] as shown in Fig. 4(c); and (4) Corner detection – intersections between these four lines are defined as four corner points A, B, C and D as shown in Fig. 4(d).

2.2.3. Step 3 – Matching between as-designed and as-built precast slab patterns

The four corner points A, B, C and D of the as-built precast slab are translated and rotated so that it can be best matched with its corresponding as-designed precast slab. In this study, the left-bottom corner \((A_0)\) and the left-side \((A_0D_0)\) of the as-designed precast slab are set to be the origin and the Y axis, respectively, as shown in Fig. 5(a). Note that the corners of the as-designed slab are denoted as \(A_0, B_0, C_0\) and \(D_0\), and precast slab type I, which is a trapezoid slab, is used to exemplify the detail of Steps 3 and 4. Also, the four sides of the as-built and as-designed slabs are shown in Fig. 5 using dotted red and solid blue lines, respectively. Principal Component Analysis (PCA) [24] is used for the matching process in this study. The PCA is undertaken in the following two sub-steps: (1) Translation - the center of the as-built slab is moved to the center of the as-designed slab so that the center coordinates of the two slabs coincide shown in Fig. 5(b). Note that the corners of the as-built slab after translation are denoted as \(A_1, B_1, C_1\) and \(D_1\); and (2) Rotation – the principal axes of the as-built and the as-designed corner points are computed and then aligned. The principal axes can be extracted from the covariance matrices of each of the as-built and the as-designed corner points. Note that the covariance matrices are \(2 \times 2\) matrices and the eigenvectors of both covariance matrices represent the principal directions of the corner points as shown in Fig. 5(c). Once the eigenvectors for the as-built and as-designed corner points are determined, the angle \((\theta)\) between the eigenvectors with largest eigenvalues is computed. Finally, alignment is achieved by rotating each as-built corner point about its center by the angle \(\theta\) as shown in Fig. 5(d). Note that \(A_2, B_2, C_2\) and \(D_2\) denote the as-built corners after the rotation.

2.2.4. Step 4 – Coordinate transformation

After the geometry matching process, the coordinates of the as-built scan points are transformed into the new coordinate system. Note that since the top surface of the precast slabs is planar, the depth-elevation of the transformed point cloud is not considered in this study by projecting the scan points onto the fitted 2D plane estimated by the least-squares fitting method. Sequentially, a line is fitted only to the scan points within the box boundary automatically established from the as-designed slab. For instance, for the line fitting of the left-vertical edge of the slab, the x coordinates of the boundary are set to be \([0 (x coordinate of the left-bottom/left-upper corner of as-designed slab) - margin, 0 + margin]\), and \([0 (y coordinate of the left-bottom corner of as-designed slab) + margin, y coordinate of the left-upper corner of as-designed slab – margin]\) for the y coordinate of the boundary as shown in Fig. 6. In order to determine a threshold for the margin value, the effect of box boundary size on dimensional accuracy was investigated. As a result, a heuristic threshold for the margin value was determined to be three times of the spatial resolution of the last beam \((3 \times \Delta)\).

2.3. Improved edge and corner extraction

For the edge and corner extraction, there were additional technical challenges that needed to be addressed. First, as the size of the precast slab increases, the incident angle between the laser scanner and the edge of the precast slab increases, resulting in a deterioration of the edge detection performance of the DQA technique. For instance, as seen in Fig. 7, the incidence angle of the laser beam to vertical (side) edges of the precast slab type I is measured to be around 25°, while the incidence angle of the shear pockets in the 2nd- and 3rd-columns near the slab center is about 10°. On top of that, scan points corresponding to the external steel bars shown in Fig. 8(a) remained after the edge point extraction, which prevented accurate extraction of vertical edge lines as shown in Fig. 8(b).

![Fig. 5. Matching between as-designed and as-built precast slab patterns: (a) Coordinate system of as-designed slab; (b) Translation - the center of the as-built slab is moved to the center of the as-designed slab; (c) The principal axes are computed for the as-built and as-designed slabs; and (d) Rotation – the as-built precast slab is rotated by the angle between the principal axes with largest eigenvalues (the as-built and the as-designed sides of the slab are shown in dotted red and solid blue lines).](image)

![Fig. 6. Box boundary generation: Only scan points within the box boundary established from the as-designed slab are used for fitting the corresponding edge line.](image)
In order to handle the aforementioned problems, the RANSAC (Random Sample Consensus) algorithm [16] is applied to the edge points obtained after the first edge extraction. Here, the RANSAC algorithm is employed because it can estimate the parameters of edge lines with a high level of accuracy, even when a significant number of outliers are present near the true edge points. Fig. 9 shows that the two fitted lines for the left and upper edges are a little biased due to the remaining non-edge scan points in Fig. 9(a), but better line fittings are obtained using the RANSAC algorithm in Fig. 9(b), improving the coordinate estimation of the top-left corner. Compared to the previous edge extraction method [28], an accuracy enhancement of 1.8 mm and 0.4 mm for the dimension and position estimations is achieved using the RANSAC algorithm with the angular resolution of 0.036 for the precast slab type I (see Fig. 11(a)).

3. Field test configuration

Figs. 10 and 11 show the experimental configuration for the field test and the details of the full-scale precast slabs, respectively. The field tests were conducted in a precast concrete manufacturing company located in Gim-Je in the Republic of Korea. A set of point cloud data from the tested full-scale precast slabs was acquired using a phase-shift laser scanner, FARO Focus-3D [14]. Note that the phase-shift laser scanner was selected since it is cheaper and offers a better distance estimation accuracy (2 mm within 20 m distance [14]) than a time-of-flight laser scanner. The laser scanner was positioned 9 m away from the center of the target precast slab, and fixed to the top of a crane as shown in Fig. 10(a). Note that the distance of the laser scanner from the slab was dictated by the crane height, and the position of the laser scanner was selected to minimize the incident angle effect described in the first paragraph of Section 2.3. Table 1 illustrates the scan parameters used in the test and the specific dimensions of the two precast slabs. For the scanning, three different angular resolutions (0.018, 0.036 and 0.072°) available in the laser scanner were investigated. The main target of scanning in this study was the top surfaces of the slabs. Two DQA checklists, (1) the dimensions of the precast slabs and the shear pockets on the slabs and (2) the position of the shear pockets, were determined according to the PCI [36]. Note that the shear pockets serve as the joint connector between precast slabs and bridge girders.

In the field test, two types of precast slab were tested, i.e. precast slab type I and type II. For precast slab type I, the design dimensions are 10,610 mm × 1980 (1956) mm × 240 mm, and it has 16 shear pockets with identical dimensions of 220 mm × 200 mm on the top surface as shown in Fig. 11. Note that the left and right widths of the slab type I, 1980 mm on the left and 1956 mm on the right, are slightly different. For precast slab type II, the dimensions are 12,600 mm × 2480 mm × 240 mm, and it has 25 shear pockets with identical dimensions of 440 mm × 140 mm. Note that the corners of the slab type II have two different angles (89.4° and 90.6°) such that the slab is of parallelogram shape. Thus, both the slabs type I and II are non-rectangular slabs with complex geometry. The manufacturing tolerances allowable for the slabs are specified in the blueprints as follows: for the outside boundary dimensions of the two precast slabs, tolerances for the length and the width are specified as ±10 mm and ±5 mm, respectively; for the dimensions (length and width) and the position of the shear pockets, the tolerances are specified as ±5 mm. Note that position of a shear pocket is defined as the distance from the center of the shear pocket to the closest horizontal and vertical edges of the precast slab.

4. Field test results

This section analyses the results of the field test. First, a comparison between the as-built data and the manual inspection is conducted to investigate how accurately the proposed DQA technique assesses the dimensions and positions of the precast slabs. Second, quality assurance on whether precast slab types I and II are precisely manufactured according to the blueprint is then performed by comparing the dimension and positions of the as-built data with the blueprint.
4.1. Dimensional estimation accuracy for precast slab types I and II

Fig. 12 shows the corner extraction result of precast slab type I with angular resolution of 0.036°. Once the point cloud data is acquired from precast slab type I using the laser scanner, coordinate transformation is performed as explained in Section 2.2. Subsequently, the edge points are obtained using the improved edge extraction algorithm regardless of the incident angle effect on edge extractions. The corners are finally identified by finding the intersections between the fitted edge lines, and the dimensions and positions of the precast slab and shear pockets are computed based on the extracted corners and the dimensional compensation model. Fig. 13 shows the dimension and position estimation results compared with the manual inspection when the angular resolution of the laser scanner is set to be 0.036°. Note that an independent manual inspection was conducted to set the reference (ground truth) dimensions of the precast slabs. Table 2 summarizes the dimension and position estimation errors with the angular resolutions of 0.072, 0.036 and 0.018°. As for dimension estimation, a total of 68 dimensions, i.e. 4 for the slab and 64 for the sixteen shear pockets, were estimated from each scan. The average dimension errors among all these 68 dimensions were estimated to be 3.5, 2.8 and 3.3 mm for the angular resolutions of 0.072, 0.036 and 0.018°, respectively. As for position estimation, a total of 32 positions were obtained from each scan, and the average position errors of 32 positions were 4.0, 2.8 and 2.4 mm for angular resolutions of 0.072, 0.036 and 0.018°, respectively. The results show that the dimension estimation accuracy tends to decrease as the angular resolution increases since the number of point cloud data used for the estimation is less for larger angular resolutions.

Table 3 summarizes the dimension and position estimation errors of precast slab type II compared with the manual inspection with the angular resolutions of 0.072, 0.036 and 0.018°. A total of 104 dimensions, i.e. 4 for the slab and 100 for the 25 shear pockets, were estimated from each scan. The average dimension errors among all these 104 dimensions were estimated to be 5.4, 3.7 and 3.4 mm for angular resolutions of 0.072, 0.036 and 0.018°, respectively. A total of 50 positions were obtained from each scan, and the average position errors of 50 positions were 5.1, 3.5 and 3.8 mm for angular resolutions of 0.072, 0.036 and 0.018°, respectively. From the dimensional estimation error results for both precast slab types I and II, the average accuracy of the proposed DQA technique for the full-scale precast slabs is around 3 mm. Since the tolerance requirements for the dimensions of precast slabs and shear pockets are ±10 mm and ±5 mm, the obtained accuracy is acceptable for DQA of full-scale precast slabs.

4.2. Dimensional quality assurance for precast slab types I and II

Next, to investigate whether precast slab types I and II are precisely manufactured according to the blueprint, quality assurance was performed by comparing the dimensions and positions obtained from the scanned slabs with those of the blueprint. Fig. 14 shows the discrepancies of the dimensions between the scanned slab and the blueprint when the angular resolution is 0.036°. The position errors of shear pockets were significantly larger than their dimension errors. For instance, the position error of #5 shear pocket in the horizontal direction exceeded 40 mm and the vertical position errors of #4, #8 and #15 were over 15 mm. Table 4 summarizes the dimension and position estimation errors of precast slab type I under varying angular resolutions. Average dimension errors of 4.7, 4.1 and 4.6 mm were obtained for angular resolutions of 0.072, 0.036 and 0.018° respectively, which are within the specified tolerance of 5 mm. Turning to position estimation, average position errors of 9.1, 7.8 and 7.0 mm were obtained for angular resolutions of 0.072, 0.036 and 0.018°, respectively. Since all average position estimation errors exceeded the allowable tolerance, it can be speculated that the shear pockets within precast slab type I are manufactured with large position errors. In addition, there is an unexpected result that the minimum average dimension error for precast
type I occurs at the angular resolution of 0.036°. This result can be attributed to the fact that when the shear pocket is scanned with a high angular resolution (0.018°) and a large incident angle, the side walls of the shear pocket are also scanned, resulting in an adverse effect on the dimension estimation accuracy. In addition, there is a major finding from the test results. For accurate estimation of the dimension and positions of shear pockets, at least 10 from the test results. For accurate estimation of the dimension and positions of shear pockets, at least 10–15 points for each edge (boundary) line are required, and the number of scan points per edge line is determined by the combination of scan distance, angular resolution and incident angle.

Table 5 shows the dimension and position estimation errors of precast slab type II compared with the blueprint under varying angular resolutions. Similarly to precast slab type I, the position errors of the shear pockets of precast slab type II were larger than their dimension errors. Average position errors of 8.2, 7.4 and 9.4 mm were obtained for angular resolutions of 0.072, 0.036 and 0.018°, respectively. With these results, it can be speculated that some shear pockets within precast slab type II have large manufacturing position errors which exceed the allowable tolerance.

Fig. 15 shows the visualization of the DQA results for both precast slab types I and II. Note that the as-designed boundary is drawn in blue and the as-built boundary is drawn in red. The dimensional discrepancy is shown with different colors, and the color filled between the as-designed and as-built boundaries indicates how large the discrepancy is. For example, the color filled in the position error of #5 shear pocket for precast slab type I is shown in dark red, which means the discrepancy is over 40 mm according to the color index bar.

5. Data storage and management of the DQA results

In this section, a BIM based data storage and management method of the obtained DQA results is proposed. In this study, IFC (Industry Foundation Classes) files were chosen as the means of data storage and exchange because (1) they are currently an open and neutral data format that is compatible with various BIM applications; (2) they are the most comprehensive public standard for building model data exchanges that includes object structure (topology), geometry and material and performance attributes; and (3) they have been demonstrated to be a promising candidate for effective exchange of geometry and other information concerning precast concrete elements [25].

5.1. Geometric information extraction from the IFC file and matching with DQA data

Assuming that a BIM model of the precast concrete element is available from precast suppliers, storage and update of DQA data into the IFC file can be performed in the following two steps. First, extraction of key geometric information of the precast concrete element is conducted using the IFC file of the as-designed BIM model described in Fig. 16 and in the paragraph below. Note that the precast slab I BIM model used in this study was generated from Autodesk Revit [3] and its IFC file was exported from the BIM software. A matching process between the DQA data obtained from the laser scanning inspection with the corresponding as-designed data is performed so that the discrepancies between the two data sets are automatically calculated and updated into the IFC file.

In the IFC file of the precast concrete element, there are several IFC entities representing the geometric information and the entities have a hierarchical structure. For instance, the entity representing the entire precast slab is IfcExtrudedAreaSolid (#298), meaning the 3D object generated by extruding a cross section with a sweeping direction. Here, the cross section refers to the horizontal cross section of the precast slab, and the sweeping direction is the height direction perpendicular to the cross section. As a subordinate entity, the cross section is expressed with IfcArbitraryProfileDefWithVoids (#293), which means the two-dimensional profiles containing holes (shear pockets). The IFC entity regarding the cross section information consists of two types of

![Table 1 Specifications of the scan parameters and the precast slabs.](image URL)
boundaries: (1) an outer boundary which represents the outer edge of the precast slab; and (2) an inner boundary representing the holes (shear pockets) within the slab. The outer boundary is expressed with IfcPolyline (#131), and it contains the coordinate information of the four corner points expressed with IfcCartesianPoint (#123, #125, #127, and #129), and these four points are the corner points of the precast slab to be used for the data matching. In a similar manner, the inner boundary is also expressed with IfcPolyline (#141, #151...#291) and the corner points of each shear pocket are extracted for the data matching. To automatically extract the coordinate information of the corner points stored in the lower-level IFC entities, an IFC parser was developed based on JSDAI[26]. Note that JSDAI is an Application Programming Interface (API) for reading, writing and runtime manipulation of the object oriented data defined by an EXPRESS based data model such as an IFC file. Once the extraction of the desired geometric information using the IFC parser is completed, matching between the as-built and as-designed data is finally conducted. As a result of the matching, the dimensional discrepancy is computed, followed by a decision on whether the inspected precast concrete elements are acceptable or not based on the comparison of the discrepancy values with the corresponding tolerance values.

5.2. Extension of IFC schema for storing dimensional quality information

In order to store and share the updated the computed DQA information, an IFC extension containing a new property set and six properties was performed in this study due to the absence of data schema regarding DQA of precast concrete elements in the latest version of the IFC schema (IFC 4). Table 6 shows the property set and the properties for the IFC extension. The proposed property set is named ‘QualityAssessment’ and the six properties are (1) inspection checklists, (2) tolerances in dimensions, (3) tolerances in positions, (4) measured discrepancies in dimensions, (5) measured discrepancies in positions, and (6) decision making result. Note that the checklists and the corresponding tolerances are generally specified prior to the launch of a construction project. In this study, the checklists of the tested full-scale precast slabs are the dimensions and positions of the slabs and the shear pockets, as mentioned earlier in Section 3. The dimensional discrepancy indicates the outputs of the data matching process. The last property ‘IsAccepted’ represents the decision result, and ‘True’ means acceptable and ‘False’ means that a repair or a disposal is required.

Fig. 13 shows the IFC extension results that the new property set and its properties are shown in a commercial IFC viewer, FZKViewer[15].
Field tests on two types of full-scale precast slabs have been conducted to identify the effectiveness of the proposed DQA technique and the DQA data management method. Results reveal that the proposed DQA technique can achieve a measurement accuracy of around 3.0 mm for dimension and position estimations, indicating that it can provide reliable and accurate dimensional estimations for full-scale precast concrete elements. In addition, there are two major findings from the test results. First, for accurate estimation of the dimension and position of shear pockets, at least 10 points for each edge (boundary) 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. 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 throughout the manufacture and assembly stages of the project.

Fig. 14. Dimension estimation results of precast slab type I compared with the blueprint: (a) Dimensions; (b) Positions (with the angular resolution of 0.036°).
Fig. 15. Visualization of the DQA results by comparing the as-designed and as-built geometries for precast slab types I and II.

Fig. 16. Geometric information extraction from the IFC file of the as-designed precast BIM model and data matching with DQA results.
line are required, and the number of scan points per edge line is determined by the combination of scan distance, angular resolution and incident angle. Second, when a shear pocket is scanned with a large incident angle and a high angular resolution, the side wall of the shear pocket is also scanned and the dimension estimation accuracy can deteriorate. To prevent this phenomenon, (1) the incident angle of the laser beam with respect to the shear pocket should be minimized and (2) excessively high angular resolution should be avoided.

The proposed DQA technique is, however, currently limited to the scanning of the top surface of precast concrete elements. Further advancement covering the side surfaces of precast concrete elements is warranted to extend the applicability of the DQA technique to full 3D models of precast concrete elements.

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References


Table 6
The proposed IFC extension: A property set “QualityAssessment” and it’s six properties.

<table>
<thead>
<tr>
<th>Property Name</th>
<th>Data Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Checklists</td>
<td>String</td>
<td>Lists of inspection checklists</td>
</tr>
<tr>
<td>Tolerance_Dimension</td>
<td>Double</td>
<td>Allowable tolerances of dimensions of checklists</td>
</tr>
<tr>
<td>Discrepancy_Dimension</td>
<td>Double</td>
<td>Errors between the BIM model and the estimated dimension</td>
</tr>
<tr>
<td>Discrepancy_Position</td>
<td>Double</td>
<td>Errors between the BIM model and the estimated position</td>
</tr>
<tr>
<td>IsAccepted</td>
<td>Boolean</td>
<td>Decision on whether the precast product is accepted or not. True means acceptable and False means repair or disposal is needed</td>
</tr>
</tbody>
</table>

Fig. 17. IFC extension result of the DQA information shown in an IFC viewer.