A framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning

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Abstract

This study presents a systematic and practical approach for dimensional and surface quality assessment of precast concrete elements using building information modeling (BIM) and 3D laser scanning technology. As precast concrete based rapid construction is becoming commonplace and standardized in the construction industry, checking the conformity of dimensional and surface qualities of precast concrete elements to the specified tolerances has become ever more important in order to prevent failure during construction. Moreover, as BIM gains popularity due to significant developments in information technology, an autonomous and intelligent quality assessment system that is interoperable with BIM is needed. The current methods for dimensional and surface quality assessment of precast concrete elements, however, rely largely on manual inspection and contact-type measurement devices, which are time consuming and costly. In addition, systematic data storage and delivery systems for dimensional and surface quality assessment are currently lacking. To overcome the limitations of the current methods for dimensional and surface quality assessment of precast concrete elements, this study aims to establish an end-to-end framework for dimensional and surface quality assessment of precast concrete elements based on BIM and 3D laser scanning. The proposed framework is composed of four parts: (1) the inspection checklists; (2) the inspection procedure; (3) the selection of an optimal scanner and scan parameters; and (4) the inspection data storage and delivery method. In order to investigate the feasibility of the proposed framework, case studies assessing the dimensional and surface qualities of actual precast concretes are conducted. The results of the case studies demonstrate that the proposed approach using BIM and 3D laser scanning has the potential to produce an automated and reliable dimensional and surface quality assessment for precast concrete elements.

Keywords:
3D laser scanning
Building information modeling (BIM)
Dimensional and surface quality assessment
Framework
Precast concrete elements

1. Introduction

Over the last few decades, precast concrete elements have become a popular construction component in the construction industry. Prefabrication is a manufacturing process where various materials are joined to form a component of the final installation in a specialized facility [13]. As part of industrialization, prefabrication has brought several benefits to the construction industry. Compared to site-cast (or in-situ) construction, precast concrete elements offer faster production, lower cost, and more efficient assembly of elements [44,40,49]. It was reported by [59,23] that when in-situ concrete casting panels were replaced with prefabricated elements, 70% of construction time and 43% of labor costs could be saved. Moreover, the use of the precast concrete elements leads to a cleaner and safer construction environment. The use of precast concrete elements, however, could suffer from unexpected construction delays and system failures if the dimensional and surface quality of precast concrete elements is not assessed properly. For instance, construction delays as well as additional costs for repair or replacement are unavoidable when there are serious dimensional mismatches or volumetric surface defects on precast concrete elements [57]. Research conducted by Construction Industry Institute (CII) [14] revealed that the average cost of rework caused by construction defects is 5% of total construction costs. Mills et al. [33] also indicated that defect costs accounted for 4% of the contract value of new residential construction. According to a study [32] that examined the causes of rework, systematic quality assessment and management for construction components during design and construction phases are important to reduce or eliminate the rework in projects. Hence, a systematic dimensional and surface quality assessment (QA) for precast concrete elements at an early stage of construction process is essential for the successful and timely completion of a construction project.

Current method of dimensional and surface QA for precast concrete elements is manually assessed by certified inspectors using contact-type measurement devices such as measuring tapes, calipers and straightedges [29]. Normally, inspectors follow guidelines such as the quality management system from the International Organization for Standardization (ISO) [22] or the tolerance manual for precast and...
prestressed concrete from the Precast Concrete Institute (PCI) [38]. One of the main inspection objectives is to scrutinize dimensional (dimension and position) errors and surface defects (crack and spallings) of precast concrete elements. However, the current manual inspection method has certain limitations. First, the results obtained by manual inspection are subjective and may not be reliable [39]. Second, the manual inspection process is time consuming and costly. Third, there is a lack of data storage and management system which is necessary for effective and efficient information sharing and management between participants of a construction project. Therefore, developing an automated and systematic system that can access and manage dimensional and surface qualities of precast concrete elements is an urgent need in the construction industry.

To overcome these limitations of the current system, this study presents a holistic framework for dimensional and surface QA of precast concrete elements based on BIM and 3D laser scanning technology. Here, the term ‘holistic’ used in this paper refers to the ‘end-to-end’ from actual dimensional and surface QA to storage and management of the inspection data. First, a framework is developed to answer four essential questions for practical precast concrete QA: (1) what the inspection checklists should be; (2) what quality inspection procedure should be employed; (3) which kind of laser scanner is appropriate and which scan parameters are optimal for the intended quality inspection; and (4) how the inspection data should be stored and delivered. Then, the applicability of the proposed framework is evaluated using case studies where dimensional errors and surface defects within actual precast concretes are detected and measured. The uniqueness of this paper includes (1) the first study that systematically illustrates how dimensional and surface QA for precast concrete elements can be implemented and how the inspection data can be stored and managed by combining BIM and laser scanning technology, and (2) the identification of the applicability of the proposed approach through actual precast concrete element tests.

The rest of this paper is organized as follows. In Section 2, a review of the related literature is presented, followed by a systematic framework development for the dimensional and surface QA of precast concrete elements in Section 3. Subsequently, case studies and their results for validating the feasibility of the proposed framework are presented in Section 4. Finally, this paper concludes with a summary and future work in Section 5.

2. Research background

2.1. Building information model and 3D laser scanning technology

Recently, information technology (IT) has gained much attention as a key driver of change in the Architecture, Engineering and Construction (AEC) industry. Developments in IT have provided numerous opportunities for the AEC industry, one of which is Building Information Modeling (BIM). BIM serves as a central data repository that can store and recall information about a facility and is currently regarded as an essential tool in managing the lifecycle of a construction project from the initial design to its maintenance [18]. Unlike a traditional CAD model that is mainly used for visualization, BIM represents a facility in a semantically rich manner. For example, while a CAD model would represent a wall as a set of independent planar surfaces, BIM would represent the wall as a single, volumetric object with multiple surfaces, while also showing the adjacent relationships with other components in the model [53]. Because of this unique characteristic of BIM, working environment of the AEC industry is shifting from 2D-based information platforms to object-based 3D information platforms. Moreover, the advent of BIM has allowed the participants of a project to more effectively share and update the information generated during construction processes in a timely manner, producing a synergy effect. Another leading piece of IT in the AEC industry is 3D laser scanning technology. 3D laser scanning is a relatively new technology, first developed for surveying engineering. A laser scanner emits a laser beam and measures the arrival time of the laser beam reflected from a target point. Based on the travel time and velocity of the laser beam, the distance from the scanner to the target point is computed. Compared to conventional contact-type sensors used in the AEC industry, a 3D laser scanner provides the following advantages: (1) It allows scanning of a large structure and measurement of a surface profile in a speedy manner; (2) It can yield ‘point cloud’ data of a scanned target surface with millimeter-level accuracy and spatial resolution; and (3) It can offer long-range measurement up to 6000 m [42]. With these features, laser scanning has been successfully employed for a wide variety of applications, including 3D modeling of structures [7, 48], deflection and deformation monitoring [37], construction progress monitoring [25] and topographical surveys [41].

2.2. Non-contact sensing based dimensional and surface quality assessment

2.2.1. Vision-based approaches

Over the past few decades, dimensional and surface QAs have been mainly studied in industrial engineering sectors for the purpose of faultless goods production [34]. In most cases, inspections are conducted by using image processing techniques utilizing one or more cameras, and the scene is appropriately illuminated and arranged in order to extract image features necessary for processing and classification. As for the dimensional QA, various real-time applications, including solder joint inspection of printed circuit boards and shape/size inspection of food products have been performed [17, 12]. As for the surface QA, detection of defects such as scratches, cracks and corrosions has been typical tasks in various industries [8, 11]. However, these studies are limited to relatively small objects and the inspection environment is well-controlled, which is not allowable for the inspection of precast concrete elements. In the AEC industry, many researchers have explored non-contact sensing techniques to monitor the dimensional and surface qualities of structures. Among the non-contact sensing technologies, the use of images obtained from 2D cameras is one of the most common approaches to detect the dimensional errors or surface defects of a structure because it is speedy and inexpensive. In terms of the dimensional QA, Ordonez et al. [36] proposed two different image-based approaches for detecting and measuring dimensions of flat building elements. Shin and Dunston [47] presented an augmented reality method for the steel column inspection (anchor bolt positions and plumbness). These approaches, however, require significant human interaction for the dimensional inspections. As for the surface QA, the majority of studies have focused on detection of cracks, air-pockets and spallings. Abdel-Qader et al. [1] suggested a concrete crack detection technique using the principal component analysis for the purpose of autonomous bridge inspections. Hutchinson and Chen [21] proposed a probabilistic method based on Bayesian decision theory for automatic crack detection of concrete surfaces. Zhu and Brilakis [62] suggested the use of three circular filters to detect air pockets on the surfaces of concrete. Koch and Brilakis [27] proposed a technique utilizing image segmentation and morphological thinning to detect the spalling defects on concrete surfaces. While these image-based methods generally offer good measurement accuracy, their performance is heavily affected by lighting conditions. In addition, although identification of size information such as length, width, area and volume is important for the dimensional and surface QA of concrete structures, this kind of qualitative information cannot be retrieved using image-based methods without multiple cameras (at least two) or prior knowledge such as the distance between a camera and a target structure or the size of a reference target.

2.2.2. Laser scanning-based approaches

Contrary to the digital imaging approach, laser scanning directly acquires 3D data with good accuracy (typically 2–6 mm at 50 m [35]) and high point density (up to 960,000 points/s [15]). Due to these merits, the feasibility of laser scanning technology for the dimensional and
surface QA of structures has been investigated by several researchers during the last decade. As for the dimensional QA, Bosche [10] proposed an automated technique of recognizing 3D CAD objects from laser-scanned data for dimensional compliance inspection of construction elements. Shih and Wang [46] reported a laser-scanning-based system for measuring the dimensional quality of finished walls. Akinci et al. [3] proposed a general framework for quality inspection of structures based on comparison of as-built models obtained from laser scanning with the corresponding design CAD models. Han et al. [19] suggested an automated technique of extracting tunnel cross sections using laser scanning data for dimensional quality control. Gordon and Lichti [16] and Park et al. [37] reported deformation measurement results obtained from laser scanners for dimensional quality control of structures. In terms of the surface QA, Teza et al. [55] proposed a damage detection technique based on the computation of the mean and Gaussian curvatures of a concrete surface. Tang et al. [52] investigated the detectability of surface flatness defects using several damage detection algorithms and laser scanners. Olsen et al. [35] proposed a volume loss quantification technique for a reinforced concrete structure. Lastly, Liu et al. [31] proposed a distance and gradient based volume loss estimation technique for an in-situ concrete bridge. Although laser scanning data has been widely utilized for the dimensional and surface QA in variety of civil applications, there have been no studies utilizing laser scanning for dimensional and surface QA of precast concrete elements. In this study, a laser scanning based accurate and reliable technique is proposed for dimensional and surface QA of precast concrete elements.

2.3. Data storage and delivery for quality assessment of precast concrete elements

Current data storage and delivery for QA of precast concrete elements is conducted based on the following procedure [61]: (1) certified inspection personnel monitors and records the inspection results of specified checklists in the inspection form; and (2) once the QA is completed, the inspector comes to the office and stores the inspection data of the inspection form into a database system via a computer. The current data storage and delivery system, however, has limitations. First, it is inefficient due to the duplicated process of recording the inspection data in both document forms and databases. Second, there is a possibility of data entry error and inspection form loss. Third, there are difficulties in interactively updating and sharing the inspection data with other project participants who work in different places. Therefore, an efficient and effective data storage and delivery system is necessary for dimensional and surface QA of precast concrete elements.

Recently several studies have explored the possibility of BIM-based system for efficient and effective data storage and management. The majority of those studies have focused on solving data exchange problems that frequently occurred in construction projects due to the diversity of construction participants. Jeong et al. [24] tested various BIM tools such as Revit Architecture from Autodesk Inc. [6] and Tekla Structures from Tekla Inc. [54] to identify the interoperability of BIM data such as geometric shapes and relationship information of precast concrete elements. It has been summarized in that study that the IFC (Industry Foundation Classes) is the only candidate for effective exchange of geometry and other information among various data formats, but current IFC based data exchanges remains lacking for reliable data exchanges between BIM tools. To this end, Venugopal et al. [58] proposed an IFC based framework for the purpose of facilitating data exchanges and avoiding ambiguities of IFC information for precast/pre-stressed concrete elements. The study recommended that definitions of entities, attributes and relationships of precast concrete models should be clearly defined for reliable data exchanges. Aram et al. [5] 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, and less attention has been paid on storing and delivering dimensional and surface QA data of precast concrete elements.

Regarding the representation of QA data obtained from non-contact sensors, Yin et al. [61] proposed a precast production management system based on Radio Frequency Identification (RFID) technique. Several quality inspection targets such as material property and production process were monitored in that system, but the dimensional and surface qualities have not been studied and there is no standard data format for the system. Anil et al. [4] investigated the data representation requirements of as-built BIM generated from laser scanned point cloud data. It has been found in that study that there is no formalized schema of representing the quality of as-built BIM such as model deviations and noises in the current version of IFC. Hence, a formalized and systematic data storage and delivery method for representing the dimensional and surface QA of precast concrete elements is necessary. In this study, an IFC-based data storage and delivery system is proposed for dimensional and surface QA of precast concrete elements.

3. Development of a dimensional and surface quality assessment framework for precast concrete elements

Fig. 1 shows an overview of the proposed BIM and laser scanning based precast concrete QA system. In Fig. 1(a), it is assumed that a precast concrete element is placed at a predetermined location and the laser scanner is positioned above the element and scans the whole surface of the element in a single scan. Fig. 1(b) shows two main modules of the proposed dimensional and surface QA system in relation to BIM, i.e., inspection and data management modules. For the inspection module, the following three issues should be clarified: (1) what the inspection checklists should be; (2) what QA procedure should be employed; and (3) which type of laser scanner is appropriate and which scan parameters are optimal for the intended QA checklists. For the data management module, one should determine how inspection information, including the inspection checklists, scan parameters and inspection results, is stored and delivered so that the system is interoperable with BIM. To answer the issues posed above, a systematic framework consisting of four parts is developed and described below.

3.1. Inspection checklists

Prior to performing precast concrete QA, it is essential to identify the inspection checklists — namely, what attributes of precast concrete elements need to be inspected with what degree of accuracy. In general, the construction specifications for a project play a major role in identifying the inspection checklists for precast concrete elements. These specifications detail the quality requirements for each precast component of the construction project, and these quality requirements can then be translated into inspection checklists. In this study, the inspection checklist is determined from the tolerance manual for precast and prestressed concrete specified in the Precast Concrete Institute [38] and the guide for precast concrete wall panels from American Concrete Institute [2]. Table 1 shows the determined inspection checklists, consisting of two categories — geometry and defects. For the geometry category, there are four dimensional features — dimension, position, straightness and squareness of precast concrete elements. Each dimensional feature has its own inspection checklists, called ‘attributes’. For example, length, width, thickness are the attributes for the feature ‘dimension’. The tolerance corresponding to each attribute varies with construction type, element type, length of the element and so on. In Table 1, tolerances for an exemplary precast slab of bridge deck are presented. Each dimensional attribute should be carefully inspected so that its value falls within the specified tolerance. Otherwise, the dimensional errors in each precast element can accumulate over the entire precast section. Within the defect category, there are four features — spalling, crack, warping and flatness. The ACI reports that these defects occur mainly due to improper concrete mixture proportions, careless curings.
as well as friction between the element and the mold form [2]. The attributes for the defect features include the number, size, depth, length, width, area, location and volume of defects.

### 3.2. BIM and laser scanning based quality inspection procedure

Once the inspection checklists and desired tolerances are determined, an inspection procedure needs to be established. Fig. 2 describes the proposed dimensional and surface QA procedure for precast concrete elements using BIM and laser scanning. The QA procedure is composed of 4 phases:

1. **Supply:** Suppliers manufacture the precast elements ordered for a given project and deliver the elements to an inspection site. It is important to note that the inspection site can be at a predetermined location in the manufacturing factory or at a certain location in the construction site. The suppliers also store the reference CAD model of each precast concrete element and their material and geometry properties, such as the concrete strength and dimensional tolerances of the precast elements in a BIM library.

2. **Preparation:** Prior to the implementation of the QA, preliminary action on both the precast concrete element and the laser scanner is performed. This action includes the confirmation of the information of the precast element, inspection set-up, treatment for the precast elements and the selection of the optimal scan parameters of the laser scanner. Here, the confirmation of detail information of the precast concrete elements, which is stored in the BIM library, is ideally carried out through portable electronic devices such as a smartphone or personal digital assistants (PDAs). Once the confirmation of the information of the precast element is completed, the precast element is sent to a designated location, and treatment processes such as the surface checking and cleansing of finished (hardened) precast concrete are undertaken before actual inspection. At the same time, the optimal scan parameters of the laser scanner are selected as described in Section 3.3.2.

3. **Scan and inspection:** Once the preparation for scanning is completed, data acquisition using the laser scanner is undertaken. In this step, the selection of the region of interest (ROI) is conducted with a coarse scan, followed by a dense scan for effective and accurate inspection. Once the raw scan data is acquired, data processing, which includes data cleansing and feature extraction, is conducted to automatically measure the intended inspection goals. Since the raw scan data has a high data capacity, data cleansing and feature extraction algorithms are needed for reducing number of data and computation cost. Subsequently, comparisons between the measured inspection results and the reference CAD model exported from the BIM library are conducted. In this phase, the inspection results are also delivered to and stored in the BIM library.

4. **Decision and delivery:** At this stage, the decision of whether the discrepancies between the actual element and the reference model are within the tolerances in the inspection checklists is made. If any specific discrepancy exceeds the corresponding tolerance, disposal or rework of the precast element follows. Otherwise, the precast element is approved for use and delivered to a construction site for assembly. Here, the classification and detail information of the accepted and rejected elements are also accessible through the BIM library so that field engineers in the construction site can access and check the condition of the delivered precast concrete element via portable electric devices.

### Table 1: Inspection checklists for precast concrete elements.

<table>
<thead>
<tr>
<th>Quality category</th>
<th>Feature</th>
<th>Attribute (tolerance*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Dimension Length (±6 mm); width (±6 mm); thickness (±6 mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Position Length (horizontal (±6 mm); vertical (±6 mm))</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Straightness Size (±10 mm); location</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Squareness Size (±3 mm); location</td>
<td></td>
</tr>
<tr>
<td>Defect</td>
<td>Spalling Number; location; area; volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crack Number; depth; length; width (0.3 mm); location</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warping Number; size (±6 mm); location</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flaxness Number; size (±6 mm); location</td>
<td></td>
</tr>
</tbody>
</table>

*The tolerances are exemplary values for bridge deck precast concrete elements.

### 3.3. Selection of optimal scanner and scan location

#### 3.3.1. Selection of optimal laser scanner

The inspection quality depends largely on the specifications of a laser scanner such as laser source type, laser wavelength and operation principles. In addition, different inspection checklists may have different scanning requirements. For instance, checking the alignment of an anchor bolt attached to a precast concrete element may require higher scanning resolution than simply identifying the existence of an anchor bolt. Therefore, the selection of the most appropriate laser scanner for a given project is critical for successful inspection. In this study, five
criteria for the selection of a laser scanner are established as shown in Fig. 3:

- **Inspection tolerance**: This refers to the limit of an acceptable discrepancy value (normally in mm) between the actual and the reference model for a specified inspection checklist. For example, the tolerance for length and width of a precast slab for bridge construction is ±6 mm according to the PCI [38]. Note that the tolerance which is project-dependent is the criterion to be first considered for the selection of an optimal laser scanner.

- **Accuracy**: This refers to how close a measured value is to the actual (true) value. In laser scanning, this is often referred to as the ‘error’ in the range measurement. The accuracy of a laser scanner depends on its working principle. Typically, phase-shift laser scanners offer a relatively higher accuracy (up to 2 mm at 20 m) [15] than time-of-flight (TOF) laser scanners (up to 4 mm at 100 m) [35]. Note that there is a certain condition for the optimal scanner selection that the accuracy of a laser scanner should be below the tolerance of inspection checklists.

- **Measurement range**: This refers to an allowable scanning distance for the laser scanner. The measurement range is mainly affected by the working principle and laser source of the laser scanner. In general, TOF laser scanners have a longer measurement range (up to 6000 m) [42] compared to phase-shift laser scanners (up to 120 m) [15].

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**Fig. 2.** Proposed BIM and laser scanning based precast concrete quality assessment procedure.

**Fig. 3.** Criteria for optimal selection of a laser scanner for precast concrete quality inspection.

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• Price: In this study, it is assumed that the quality inspection of precast concrete elements is conducted using a commercially available laser scanner. The price of laser scanners ranges from $40,000 to $200,000 USD.

• Scanning time: This refers to the time required for scanning the desired inspection area. The scanning time depends mainly on the selection of a laser scanner’s angular resolution, which dictates horizontal and vertical scanning rate of the laser scanner. The scanning time is also influenced by the size of the target precast concrete element.

Depending on the goal of each checklist, different weighting on each aforementioned criterion can be assigned. For instance, for a dimensional QA which requires a tolerance of ±6 mm, accuracy is the most important criterion for the laser scanner selection and thus, a higher weighting can be given.

3.3.2. Selection of optimal scan parameters

The scan parameters of a laser scanner should be optimized to obtain the best dimensional and surface quality inspection results. For the scanning of a precast concrete element, the scan distance and angular resolution are determined assuming that the laser scanner is positioned right above the center of the target precast concrete. These two parameters mainly govern the density of scan points. In general, the higher the density of the scan points is, the better the inspection results are. However, a high density of scan points requires more scanning time and computing cost, which may not be allowed in real applications. Hence, a trade-off between accuracy, cost and time is necessary considering the inspection requirement of a project.

Since the dimensional quantities such as length, width and position of a target precast element may require the extraction of features such as edges and corners from point cloud data, enough scan points should lie on both the edge and corner regions of the precast element. Furthermore, for the QA of defects such as spalling, warping and flatness, the scan region needs to be further divided into a number of subdivisions, and at least one scan point should fall inside each subdivision for localization and quantification of defects.

Here, a mathematical model is developed to theoretically determine the minimum size of the subdivision considering the scanning distance and the angular resolution as shown in Fig. 4. For simplicity, the inspected precast concrete element is assumed to have a rectangular shape and a flat surface although the concept here can be generalized to more complex geometries. In the developed mathematical model, the maximum incident angle (θ) and the maximum spatial resolution (d) of the laser scanner can be computed as:

\[ \theta = \tan^{-1}\left(\frac{\sqrt{L^2 + W^2}}{2 \cdot H}\right) \]  
\[ d = \frac{\sqrt{L^2 + W^2} - H \cdot \tan(\theta - \Delta\theta)}{2} \]

where \( H, L \) and \( W \) are the laser scanner height (normal distance from the scanner to the target precast element), the length and the width of the precast element, respectively. Here, \( L \) and \( W \) are assumed to be known from the blueprint of the precast concrete element. \( \Delta\theta \) denotes the angular resolution of the laser scanner. Note that a square shape is assumed for the subdivision, and the size is the length and/or width of the subdivision. As a result, the minimum size \( s \) of the subdivision which can cover the maximum spatial resolution \( d \) can be formulated as:

\[ s = \frac{d \cdot L}{\sqrt{L^2 + W^2}} = \frac{L \cdot H}{\sqrt{L^2 + W^2}} \cdot \tan(\theta - \Delta\theta). \]  

Note that Eq. (3) only specifies the minimum requirement, which may not be large enough for robust localization and quantification of defects. Therefore, a generous selection of scan parameters \( (H \) and \( \Delta\theta) \) for determining the size of subdivision is recommended so that several scan points are included in each subdivision. Note that finding specific solutions for an optimal subdivision size and the number of scan points in a subdivision, which cannot be solved through only theoretical analysis and depend on many other factors such as surface roughness and reflectivity, is out of scope of this study.

In addition, the effects of the scanning parameters should be investigated for the selection of optimal scan parameters, as several studies show that a wrong selection of scanning parameters can have a negative impact on the results of quality inspections [49,30,28]. Among the scanning parameters, the incident angle, defined as the angle between the laser scanner and the scan point, is the key parameter affecting the measurement results. Lafer et al. recommends that scans with an incident angle of over 45° be avoided [28]. Here, the scanning distance \( (H) \) is
controlled so that the maximum incident angle (θ) is less than 45°, i.e., \( H > \sqrt{\frac{2 \cdot \text{W}}{\text{p}}} \).

3.4. Data storage and delivery method

To address the data interoperability problem mainly caused by differences in data format, IFC developed by BuildingSMART [56] (formerly called the International Alliance for Interoperability (IAI)) is used as a delivery file format in this study. IFC is chosen here because (1) it is currently an open and neutral data format that is compatible with various BIM applications; (2) it is the only public standard for building model data exchanges that includes object structure (topology), geometry and material and performance attributes; and (3) it has been found that the IFC format is a promising candidate for effective exchange of geometry and other information of precast concrete [24].

Fig. 5 illustrates the IFC based data storage and delivery scheme for dimensional and surface QA of precast concrete elements. All the data, from supply to delivery of the precast products, is created in the IFC format, then stored in and delivered to the BIM library through the cloud.

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**Fig. 5.** Schematic diagram of data storage and delivery for dimensional and surface quality assessment of precast concrete elements.

**Fig. 6.** IFC based entity relationship model for the precast concrete element quality inspection.

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Table 2
Specifications of commercial 3D laser scanners.

<table>
<thead>
<tr>
<th>Scanner number</th>
<th>Maximum range (m)</th>
<th>Measurement rate (pts/s)</th>
<th>Accuracy (mm)</th>
<th>Price (order)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400</td>
<td>125,000</td>
<td>5 mm @ 100 m</td>
<td>1 (expensive)</td>
</tr>
<tr>
<td>2</td>
<td>350</td>
<td>5000</td>
<td>7 mm @ 100 m</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>25,000</td>
<td>7 mm @ 100 m</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>50,000</td>
<td>4 mm @ 50 m</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
<td>960,000</td>
<td>2 mm @ 20 m</td>
<td>5 (cheap)</td>
</tr>
</tbody>
</table>

server. The cloud server serves the role of bridging all participants of a project, allowing them to reach the information whenever and wherever it is needed, and updating the information with a secure insurance. Inspectors who are in charge of inspecting the quality of precast elements, for instance, can call up the material and geometry information stored in the BIM library via the cloud server. In addition, the inspectors can upload the scanning parameters they used and the inspection results in the format of IFC into the BIM library. Similarly, on-site engineers in the construction site can use tablets to access the inspection information for precise assembly of precast concrete elements.

Fig. 6 shows the IFC-based entity relationship model (ER model), which illustrates the association between different entities included in IfcPrecastElement, of a precast concrete element for quality inspection. The presented entities are created by the authors based on the general scheme and properties of the latest IFC version (IFC4) due to the absence of entities related to QA of precast concrete elements. The ER model consists of several entities and their attributes. The entity IfcQualityInspection, which is a sub-entity of IfcPrecastElement, consists of two sub-entities, IfcInspectionInfo and IfcInspectionResult. IfcInspectionInfo provides specific details regarding inspection preparation, such as laser scanning (IfcScanInfo), the design geometry of the inspected element (IfcDesignGeometry), and inspection checklist (IfcInspectionCriteria). The entity IfcScanInfo includes detailed information regarding scanning time (IfcScanTime), the laser scanner (IfcScanSensor) and the scanning parameters (IfcScanParameter). The other high-level entity in the quality inspection process is IfcInspectionResult, and it contains the inspection results of the geometry (IfcInspectionDimensional) and defect (IfcInspectionDefect) quality for the precast element. The inspection result entities (IfcInspectionDimensional and IfcInspectionDefect) both provide quantitative values of the corresponding attributes defined in the inspection checklists of Table 1. For instance, the entity IfcInspectionSpalling has four quantitative attributes, which indicate how many (number) and how large (area and volume) the spalling defects are, as well as where (location) they are. Due to the limited space, not all attributes of the QA entity are included in Fig. 6.

4. Case studies

To examine the applicability of the proposed framework to dimensional and surface QA of precast concrete elements, two case studies composed of dimension estimation and surface defect characterization were conducted on actual precast concrete panels.

4.1. Selection of inspection checklists and laser scanner

The inspection checklists were determined prior to the experiments. For dimensional estimation, three dimensional properties were estimated: (1) the dimensions (length and width) of the precast concrete element, (2) the dimension and positions of the shear pockets, which are rectangular holes within the precast concrete element, and (3) the squareness of the precast concrete element. The squareness error is defined as the difference of length between the longer sides of a precast component [38]. The surface defect characterization mainly targeted spalling defects, and four specific checklists, the number, location, area and volume of defects, were established as shown Table 1.

Once the inspection checklists were selected, an optimal laser scanner was then selected. Table 2 shows the specification of five commercially available laser scanners. As mentioned in Section 3.3.1, the primary criterion considered for laser scanner selection in this study was the accuracy of a laser scanner since the target tolerance for the dimensional QA was set to be 6 mm. The measurement rate (speed) and the price were also important considerations. In terms of the

![Figure 7](image1.png)

**Fig. 7.** Test specimens for the dimensional estimation and surface defect characterization: (a) A photo and dimensions of the precast panel I used for dimensional estimation test; (b) A photo and defect dimensions of the precast panel II used for surface defect characterization test.

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measurement range, all the candidate scanners satisfied the minimum requirement (20 m) of the measurement range. From these considerations, scanner no. 5 which offers the best accuracy, measurement rate and price was selected as the optimal laser scanner in this study.

4.2. Test specimens

Fig. 7 shows two test specimens used for the case study. Two precast panels (precast panels I and II) were designed and fabricated for dimensional estimation and surface defect characterization, respectively. The precast panels were fixed on a concrete wall and scanned by the laser scanner positioned at 10 m away from the panels, and scans with two different angular resolutions (0.009° and 0.018°) were conducted for both case studies. Here, the scanning distance and the angular resolutions, which dictates the density of scan points, were selected by considering scanning time (around 3–5 min), point-to-point scan spacing (around 2–3 mm), the minimum size (s) of subdivision for precast panel II (1.26 mm for 0.009° angular resolution and 2.52 mm for 0.018° angular resolution) and maximum incident angle (5.71° for precast panel I and 3.43° for precast panel II). Precast panel I, used for dimensional estimation, has dimensions of 2000 mm (actually it has 1980 mm on one side) × 1000 mm × 150 mm and includes six rectangular shear pockets as shown in Fig. 7(a). Three dimensional errors were intentionally introduced to Panel I — a 20 mm loss of the upper horizontal dimension (1980 mm), a shift of No. 2 shear pocket to both right and downward by 25 mm and a shift of No. 6 shear pocket to both left and downward by 25 mm. Precast panel II, used for surface defect characterization, has dimensions of 1200 mm × 900 mm × 150 mm, and nine artificial spalling defects with different sizes and depths were induced on the surface of panel II as shown in Fig. 7(b). The defects were either flat top (numbered from 1 to 5) or concave-shape (numbered from 6 to 9). Based on the computed minimum size of subdivision from Eq. (3), the subdivision size of precast panel II for defect localization and quantification was selected as 5 mm for both 0.009° and 0.018° angular resolution cases.

4.3. Data analysis

4.3.1. Data analysis for dimensional estimation

Once a set of point cloud data was acquired from laser scanning, several steps of data analysis were performed.

Step 1 — coordinate transformation: the 3D coordinates of the scan data with respect to the laser scanner were transformed into a new coordinate system with respect to precast panel I. In this step, a 2D range image which each pixel holds the distance value between the scan point and the laser scanner was generated from the scan data.

Step 2 — filtering: unwanted background scan points positioned behind the precast panel surface were filtered out. Due to the coordinate transformation process, elimination of unwanted background scan points was implemented by setting a margin to each axis.

Step 3 — edge and corner extraction: an autonomous edge point extraction algorithm called ‘Vector-sum algorithm’ [26] was implemented to extract only edge points along the horizontal and vertical edge lines of precast panel I. Once the edge points were extracted, the corners of the panel were identified by line fitting the edge points and finding the intersections between the fitted edge lines.

Step 4 — dimension estimation: the dimensions of precast panel I were initially estimated based on the extracted corner points. However, because of the mixed-pixel phenomenon of the laser scanner [20], a phenomenon called edge loss occurs and the actual dimensions will be always underestimated. This underestimation caused by the edge loss was compensated based on an edge loss model [50]. A more detailed explanation of the dimensional estimation steps is provided in [26].

4.3.2. Data analysis for surface defect characterization

The first two steps for surface defect characterization are identical to the ones presented in Section 4.3.1. Defect identification, localization and quantification were then performed using two defect sensitive features as shown in Fig. 8: (1) angle deviation between the surface normal of a locally fitted plane and the reference direction, and (2) distance deviation between each scan point and a globally fitted plane.

Step 3 — angle deviation: first, the eight nearest neighbors for a given scan point (p_i) were identified based on the Euclidean distance, and the covariance matrix of the eight neighboring points was computed. Second, a principal component analysis (PCA) [45] was performed on the covariance matrix to estimate the normal vector of a local plane fitted by the eight neighboring points. Here, the eigenvector corresponding to the smallest eigenvalue approximates the normal vector of the local plane. Finally, the angle deviation, defined as the angle difference between the estimated normal vector and the reference direction, was calculated, and the defect index (D_l(p_i)) for the angle deviation was computed at the specific scan point. Here, the + z direction perpendicular to the x–y plane is set to the reference direction. Fig. 8(a) illustrates that the angle deviation increases as the scan point within the defect area moves closer to the defect edges. Therefore, D_l is sensitive to the defect boundaries.

Step 4 — distance deviation: as the second defect sensitive feature, the distance deviation from a globally fitted plane was calculated.

Fig. 8. Definitions of surface defect sensitive features: (a) Definition of the angle deviation from the reference direction in x–z plane view; (b) Definition of the distance deviation from the globally fitted plane in the x–z plane view.

Fig. 9. Results of edge and corner point extraction as part of dimensional estimation (obtained by scanning precast panel I with angular resolution of 0.009°).
Fig. 8(b) illustrates the definition of the distance deviation. The globally fitted plane was obtained by least-square fitting a linear plane into all scan points within the surface of precast panel II. The distance deviation of a scan point \((p_i)\), defined as the shortest distance of the scan point from the fitted plane, and the defect index \(D_{II}(p_i)\) of the scan point for the distance deviation was then computed. Here, the deviation index typically has a larger value near the center of the defect area than near the edges. Therefore, DI1 and DI2 are complementary for defect localization.

Step 5 — unified defect index and threshold: once the two defect indices for all the scan points were obtained, the defect indices for each subdivision were computed by averaging the defect index values of the scan points falling inside each subdivision. Hence, each subdivision holds two defect index values (DI1\((S_i)\) and DI2\((S_i)\)), where \(S_i\) stands for the \(i\)-th subdivision. Then, DI1 and DI2, which are complementary to each other, were combined such that the combined damage index is sensitive to both the edge and inner defect areas. The unified defect index for each subdivision is defined as follows:

\[
D(S_i) = \alpha \cdot DI_1(S_i) + (1-\alpha) \cdot DI_2(S_i) \quad 0<\alpha<1
\]  

(4)

where \(\alpha\) and \((1-\alpha)\) are weighting factors for DI1 and DI2 respectively. \(\alpha\) can be determined by the users, considering factors such as target defect shape and the expected laser scanner sensing range. In this study, an equal value of 0.5 was assigned to \(\alpha\) and \((1-\alpha)\). In a similar manner, a threshold \((TR)\) for defect diagnosis was computed from the intact subdivisions. There are three steps to determine a threshold value from the intact subdivisions. First, a Weibull distribution is fitted to all subdivision DI values. Here, the Weibull distribution is selected because the Weibull distribution is one of the extreme value distributions, and it provides good performance in modeling the upper tail of the DI values. The appropriateness of using the Weibull distribution for the given DI values is validated through the goodness-of-fit test [43]. Second, the selection of candidate intact subdivisions is undertaken. Since actual intact subdivisions are initially unknown, the subdivisions, whose DI values are below the threshold value corresponding to 95% confidence level of the fitted Weibull distribution, are selected as the candidate intact subdivisions. Once the candidate intact subdivisions are obtained, TR1, which corresponds to 95% confidence level of the Weibull distribution of DI1, obtained from the candidate intact subdivisions of precast panel II is established. TR2 is obtained in a similar manner from the Weibull distribution of DI2. Finally, the unified threshold \((TR)\) was obtained as follows:

\[
TR = \alpha \cdot TR_1 + (1-\alpha) \cdot TR_2. \quad 0<\alpha<1.
\]

(5)

Step 6 — defect diagnosis: finally, a defect diagnosis was undertaken based on the following statement:

“If DI\((S_i)\) exceeds TR, the subdivision \((S_i)\) is diagnosed as defected. Otherwise the subdivision is classified as healthy.”

In addition, the volume loss caused by defected was estimated by multiplying the area of each subdivision with the defect depth (the distance deviation from the global plane).

Table 3
Dimensional estimation results from precast panel I (unit – mm).

<table>
<thead>
<tr>
<th>Angular resolution (°)</th>
<th>Panel</th>
<th>Upper length</th>
<th>Bottom length</th>
<th>Width</th>
<th>Hori.</th>
<th>Vert.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S.P. 1</td>
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<td></td>
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<tr>
<td></td>
<td>S.P. 2</td>
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<td></td>
<td>S.P. 3</td>
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<td></td>
<td>S.P. 4</td>
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<td>S.P. 5</td>
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<td></td>
<td>S.P. 6</td>
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<tr>
<td>Dimension estimation (error)</td>
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<td></td>
</tr>
<tr>
<td>0.009</td>
<td>1978.9 (21.1)</td>
<td>2002.4 (2.4)</td>
<td>1995.9 (4.1)</td>
<td>149.6 (0.4)</td>
<td>149.6 (0.4)</td>
<td>150.8 (0.8)</td>
</tr>
<tr>
<td>0.018</td>
<td>1979.5 (20.5)</td>
<td>2004.0 (4.0)</td>
<td>998.6 (1.4)</td>
<td>246.6 (3.1)</td>
<td>153.1 (1.9)</td>
<td>251.9 (1.9)</td>
</tr>
<tr>
<td>Position estimation (error)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>0.009</td>
<td>–</td>
<td>132.7 (2.8)</td>
<td>277.6 (2.6)</td>
<td>1026.1 (26.1)</td>
<td>299.2 (24.2)</td>
<td>1675.1 (1.9)</td>
</tr>
<tr>
<td>0.018</td>
<td>–</td>
<td>328.6 (3.6)</td>
<td>278.9 (3.9)</td>
<td>1026.9 (26.9)</td>
<td>300.5 (25.5)</td>
<td>1675.9 (1.9)</td>
</tr>
<tr>
<td>Squareness estimation (error)</td>
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<tr>
<td>0.009</td>
<td>23.5 (3.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.018</td>
<td>23.5 (3.5)</td>
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</table>


Table 4
Manual inspection error of precast panel I (unit – mm).

<table>
<thead>
<tr>
<th>Panel</th>
<th>Upper length</th>
<th>Bottom length</th>
<th>Width</th>
<th>Hori.</th>
<th>Vert.</th>
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<tr>
<td></td>
<td>S.P. 1</td>
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<td>S.P. 2</td>
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<td></td>
<td>S.P. 3</td>
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<td>S.P. 4</td>
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<td></td>
<td>S.P. 5</td>
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<td></td>
<td>S.P. 6</td>
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</tr>
<tr>
<td>Dimension estimation (error)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980.0 (20.0)</td>
<td>2000 (0.0)</td>
<td>999.5 (0.5)</td>
<td>150.0 (1.5)</td>
<td>150.0 (0.0)</td>
<td>150.0 (0.5)</td>
</tr>
<tr>
<td>Position estimation (error)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>–</td>
<td>322.0 (3.0)</td>
<td>274.0 (1.0)</td>
<td>1022.0 (22.0)</td>
<td>301.0 (26.0)</td>
<td>1678.0 (3.0)</td>
</tr>
<tr>
<td>Squareness estimation (error)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>20.0 (0.0)</td>
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</tbody>
</table>

4.4. Test results and data storage and delivery

4.4.1. Test results for dimensional estimation

Fig. 9 shows the edge and corner points obtained from scanning precast panel I with an angular resolution of 0.009°. The edge and corner points of the panel and six shear pockets were successfully identified. Table 3 summarizes the dimensional estimation results. Each entity in Table 3 is the estimated dimensional (dimension, position and squareness) value, and estimation error compared to the design value is presented in parenthesis next to each entity. The estimated upper lengths of the panel were 1978.9 mm and 20.5 mm shorter than the design length value (2000 mm), and agree well with the intended length loss (20 mm) with 1.4 and 0.1 mm differences compared to the estimation result of the proposed technique. In terms of the squareness estimation, the estimated errors were 2.1 mm and 2.4 mm, respectively. The average position errors of all the entities with 0.009° and 0.018° angular resolutions were 2.7 and 3.0 mm respectively. The average position errors of all the entities with 0.009° and 0.018° angular resolutions were 2.1 mm and 2.4 mm, respectively. In terms of the squareness estimation, the estimated errors were 23.5 mm and 23.5 mm with 0.009° and 0.018° angular resolutions, and close to the exact squareness error value of 20 mm.

In order to compare the estimated results with the conventional method, manual inspections were conducted on the precast panel I. Table 4 shows the manual inspection error results comparing to the design dimensions of the precast panel. The average errors of the manual inspection for the dimension and position estimations were 0.4 and 2.2 mm, respectively, which have 1.4 and 0.1 mm differences compared to the estimation result of the proposed technique. In terms of the inspection time, the proposed method provided a quick (total 5 min) inspection than that of the manual inspection (total 20 min). This result demonstrates that the proposed dimensional QA technique can measure the length, position and squareness of precast concrete elements in an accurate and timely manner.

4.4.2. Test results for surface defect characterization

Fig. 10 shows the localization results of spalling defects on precast panel II obtained with 0.009° angular resolution. The defect localization results show that all defects were successfully identified except defects 3 and 4, which had small thickness deviations (3 and 2 mm). The manual inspection of the concrete panel revealed that the upper-left corner of the panel had a noticeable non-flat surface, and this non-uniform surface condition attributed to difficulties in detecting shallow spalling defects (defects 3 and 4). Table 5 summarizes the defect estimation results for precast panel II. Note that Table 5 presents the detected area and volume loss values of the seven successfully localized defects. For defect area estimation, the average accuracies of 85.8 and 89.8% for each angular resolution were obtained compared to the actual defect area. Here, the accuracy is defined as (actual area − estimated area) divided by actual area. As for the volume loss estimation of the detected defects, the average accuracies of 84.8 and 87.2% for each angular resolution were obtained. The results demonstrate that the proposed laser scanning method can successfully locate and quantify surface defects except small defects where the thickness change is comparable to the measurement noise level of the laser scanner.

4.4.3. Inspection data storage and delivery

Figs. 11 and 12 describe the IFC-based inspection data storage and delivery for dimensional estimation and surface defect characterization, respectively. The inspection results of Tables 3 and 5 were stored in the attributes of each IFC entity. As for the dimensional estimation, all estimated dimensional values in Table 3 were stored in the corresponding attributes of the dimensional entities IfcDimension, IfcPosition and

Table 5
Surface defect characterization results from precast panel II.

<table>
<thead>
<tr>
<th>Angular resolution (°)</th>
<th>Defect 1</th>
<th>Defect 2</th>
<th>Defect 5</th>
<th>Defect 6</th>
<th>Defect 7</th>
<th>Defect 8</th>
<th>Defect 9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Est.</td>
<td>Actual</td>
<td>Est.</td>
<td>Actual</td>
<td>Est.</td>
<td>Actual</td>
</tr>
<tr>
<td>Defect area (10⁻⁴ × m²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.009</td>
<td>324.0</td>
<td>346.0</td>
<td>144.0</td>
<td>164.0</td>
<td>254.0</td>
<td>281.0</td>
<td>177.0</td>
</tr>
<tr>
<td>0.018</td>
<td>349.0</td>
<td>340.0</td>
<td>108.0</td>
<td>168.0</td>
<td>287.0</td>
<td>287.0</td>
<td>181.0</td>
</tr>
<tr>
<td>Defect volume loss (10⁻⁶ × m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.009</td>
<td>486.0</td>
<td>428.3</td>
<td>72.0</td>
<td>80.2</td>
<td>254.5</td>
<td>276.4</td>
<td>353.4</td>
</tr>
<tr>
<td>0.018</td>
<td>445.2</td>
<td>445.2</td>
<td>85.5</td>
<td>85.5</td>
<td>288.8</td>
<td>305.3</td>
<td>167.8</td>
</tr>
</tbody>
</table>

Est. stands for ‘estimated’.

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IfcSqureness as shown in Fig. 11(c). For example, the estimated length and width of seven objects (panel I and six shear pockets) of precast panel I were stored in the attributes (length (#134) and width (#146)) of the IFC entity IfcDimension. Here, the ‘#’ refers to the line number of the IFC file. In addition, the dimensional abnormalities, which exceed the corresponding dimensional tolerances, were visualized with the error values as shown in Fig. 11(b). Similarly, the detected spalling defect information of precast panel II were stored in the attributes (number, area, volume and location) of the IFC entity IfcSpalling as shown in Fig. 12(c). For instance, the lines #276, #277, #10 and #6 in the IFC file of precast panel II indicate that seven spalling defects were detected and the corresponding defect area, volume loss and defect location were quantified.

5. Conclusion and future work

This paper describes a holistic approach for dimensional and surface quality assessment of precast concrete elements based on BIM and 3D laser scanning technology. To make the proposed approach practical and systematic, a detailed framework consisting of four cores – (1) the inspection checklists, (2) the inspection procedure, (3) the selection of an optimal scanner and scan parameters, and (4) the inspection data storage and the delivery method – was developed for the quality assessment of precast concrete elements. The applicability of the proposed framework was examined by assessing the dimensional and defect qualities of actual precast concrete panels using a 3D laser scanner. Furthermore, IFC-based inspection data storage and delivery method was...
validated using the estimated dimensional and surface quality assessment results. The experimental results demonstrate that the proposed BIM and laser-scanning-based quality assessment system has potential in autonomous and reliable quality assessment of precast concrete elements. More specifically, the proposed method successfully estimated dimensions of a precast panel with average error of 2.5 mm and detected spalling defects on the surface of another panel with average localization and volume estimation accuracy of 86.9% when the thickness change of the spalling defect was over 3 mm.

However, the proposed system has some limitations, which are topics for future research. First, the applicability of the proposed dimensional and surface quality assessment system is currently limited only to precast concrete elements with a rectangular shape and a uniform thickness, and further investigation is warranted to extend the applicability of the proposed system to other types of precast concrete elements that have more complex geometries. Second, quantitative analysis of selecting the optimal laser scanner and its scan parameters is out of scope of this paper. Since data collection parameters and scanner selection may influence the accuracy of the proposed system, further investigation is warranted.

Acknowledgment

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