Quality Control for Concrete Steel Embed Plates using LiDAR and Point Cloud Mapping

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Abstract –

Steel embed plates are a vital component in connecting steel to concrete members. They are most often used in the construction of tilt-wall concrete buildings, but can be used anytime there is a need to attach steel to a concrete panel or slab. Proper anchorage and connection to concrete should follow the ACI standards. Inspections need to verify the correct location (x, y, z) of steel embeds until concrete placements are finished. Typically, embeds should not affect the positioning of reinforcement, unless specifically allowed in the specifications. Currently, the process of ensuring the position of embeds is completed manually, which is costly, time consuming, and involves errors in complex construction. This paper proposes an approach to ensure embeds are positioned as per the design and within the tolerance limits stated in ACI 117. The proposed approach maps the BIM model geometry into a 3D point cloud of the as-built construction. The mapping process uses different computing platforms that eventually result in a position deviation report in the x, y, and z directions. An experiment was developed and conducted in the laboratory to show the applicability of the method. The results showed high accuracy in capturing the steel plates' deviations from the original position and generated a meaningful report for improving quality control and quick rework.

Keywords –

Concrete Embeds; Building Information Modeling; Quality; 3D Point Cloud; LIDAR

1 Introduction

1.1 Overview

Steel embeds are an element of precast concrete construction that take the form of pipes, ducts, sleeves, and conduits [1, 2]. Embeds, also known as headed studs, serve as connectors of concrete and steel as modelled in Figure 1. These elements in embedded steel plates connect to structural steel framing, MEP components, and other elements of construction [3]. Embeds are utilized for purposes of ventilation, passing cables, and wherever proper connection to concrete is necessary [3]. Proper implementation results in cleaner and safer construction practices, whereas oversight in the manufacturing process can lead to system failures and construction delays [2, 3].

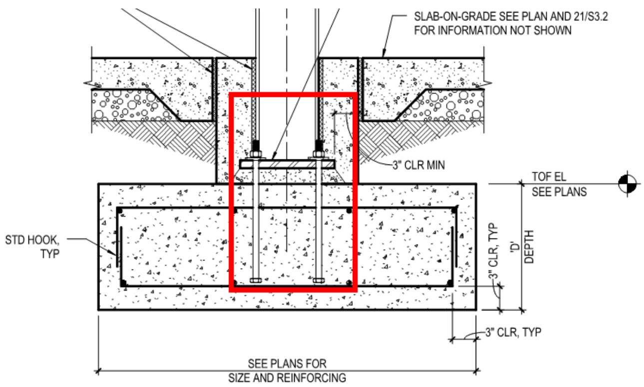


Figure 1. Model of beams connecting to girder at steel embeds.

Per ACI 318, embedment can be manufactured using any material that is not harmful to concrete, and that which is approved by a licensed design professional. Embeds made using aluminium must be coated to prevent corrosive reactions between aluminium and steel. Thus, they are typically manufactured using different materials as designed [1].

1.2 Design

The placement of steel embed plates should follow ACI 318 standards and cannot be implemented where concrete strength is decreased significantly. Proper positioning directly impacts RC strength, such as in the reinforced concrete beam in a CMU wall shown in Figure 2, and thus guidelines set by ACI 318 and ACI 117 must be followed. Embed placement is permitted where (1) strength of concrete is not significantly decreased, (2) total embedment within a column does not surpass 4% of the area of the cross-section, (3) outside dimensions do not exceed 1/3 of the structure where embedded for pipes and conduits, (4) designed to resist effects of associated materials, temperature, and pressure, (5) not spaced less than three diameters on center, and (6) other limitations in Code 3.6 are maintained [5].

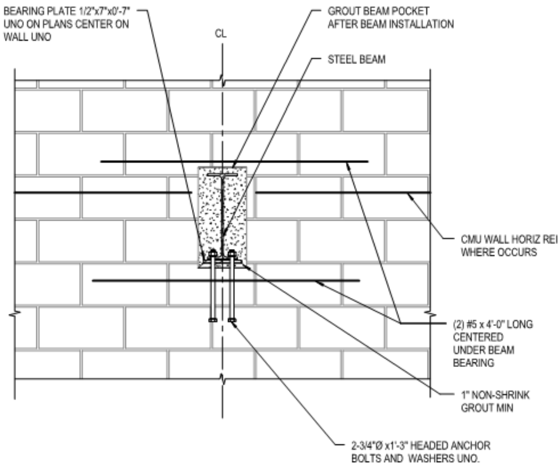


Figure 2. Bearing steel embeds on Concrete Masonry Wall.

Per ACI 117-23, embedment should meet outlined tolerances such that (1) horizontal and vertical deviation from the centreline of the assembly is ±1 in (25 mm), (2) the surface of an assembly from the specified plane for an assembly 12 in. (305 mm) or smaller is ±1/2 in per 12 in (40 mm per m), otherwise, it is ±1/2 in., and (3) anchor bolts and other elements follow through standards outlined [6].

1.3 Coordination and Construction

A careful review of formwork, embed, reinforcing bar, and structural steel drawings should be conducted to regulate work packages from multiple subcontractors [3]. Coordination should run through embed changes guidelines, shipping, on-site operations management, and construction procedures, as well as cover possible conflicts that may arise in any of these fields. Planning should be conducted to reduce potential damage to formwork panels and other structures in the installation of embeds [3]. Clear communication and coordination between parties responsible for design and construction should be the main goal.

Embeds should be placed as per the design. Proper layout reduces discrepancies in as-designed and as-built work. Quality in the field can be preserved by (1) providing sufficient control lines in order to provide accuracy and consistency in layout, (2) checking control lines back to primary control on ground, (3) revising dimensions prior to layout, (4) locating centerline, edges and sizes of embeds, and noting where placement is critical, to name a few [3]. Procedures for layout are outlined by the contractor, but coordination prior to construction is essential to reduce the need for rework in the long run. Installation of concrete should be conducted after all embeds are set, and supervision should be maintained to prevent movement or displacement of embeds as much as possible. Placement of steel embeds in concrete walls or foundations present a great challenge to contractors. The misalignment of these small supports, in addition to non-compliance with code requirements, can result in costly rework and design changes. Hence, it is imperative for contractors to have a tool that allows for a comparison between as-designed and as-built embed locations to capture misplacement or out-of-tolerance variation.

In the past years, smart sensing technologies have gained great interest in the construction sector. Laser scanning and photogrammetry are being used in many aspects of construction. One of them is capturing reinforcement layout and quality of the formwork geometry [4, 7-9]. However, none of these studies address the proper position of concrete embeds prior to concrete casting. Consequently, the objective of this study is to develop an approach to identify the tolerance of the concrete embeds in the three directions (x, y, z).

2 Background

Traditional methods of ensuring embeds are properly placed involve manual inspection performed by quality personnel which is time consuming and costly [10]. Three-dimensional models that capture precise details can be used for planning and coordination of systems like earth retention, safety perimeters, shoring and formwork, post-tensioning, mild reinforcing, embeds, and equipment such as screen walls, tower cranes, and material hoists. Team members at the jobsite can capture value from Building Information Modelling (BIM) by using apps on tablets and smartphones, and workers can transfer coordinates and linework from 3-D models to total stations for concrete layout. The visual nature and the enormous information provided by BIM models help crews understand exactly what they are building and when, while in the field [11]. The approach of directly identifying an object with a laser scanner and comparing it to a uniquely placed object within a BIM model is known as the "Scan-vs-BIM" approach [12]. This allows for a quick and efficient comparison of the as-built state to the design model to determine if there are any unacceptable discrepancies. This is a common approach used in the relevant research discussed.

2.1 Dimension and position estimation for cast-in-place concrete and other applications

Various studies have been conducted using BIM technologies for quality assurance of concrete structures. Kim et al. describe a holistic approach for dimensional and surface quality assessment of precast concrete elements based on BIM and 3D laser scanning technology. They created a framework consisting of four cores: inspection checklists, inspection procedure, selecting an optimal scanner and scan parameters, and the inspection storage and delivery method. Their BIM and laser scanner quality assessment system were successful in estimating precast panel dimensions with an average error of 2.5 mm and detecting spalling defects with an accuracy of 86.9%. However, their results are limited to precast elements that are rectangular and uniform in thickness and their system did not fully automate the process of comparing the as-built data to the design model [2]. Wang et al. completed a similar study and estimated the dimensions of precast concrete elements with a direct scanning error of 1.7 mm [8]. Kim et al. achieved full automation by developing a non-contact Dimensional Quality Assurance (DQA) technique that automatically and precisely assesses the key quality criteria of full-scale precast concrete elements. They achieved this by developing a new coordinate transformation algorithm to account for the scales and complexities of precast slabs to fully automate the DQA. Precise dimension estimations of the actual precast slab were determined using 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. Lastly, a BIM-assisted storage and delivery approach for the obtained DQA data was proposed so that all relevant project stakeholders can share and update DQA data through the manufacture and assembly stages of the project [4]. Tan et al. used LiDAR and BIM to inspect the geometric quality of individual structural, mechanical, and MEP elements of prefabricated housing units. Their results showed the technique provides inspection results with 0.7 mm and 0.9 mm accuracy for structural and MEP elements [13].

2.2 Related studies on Concrete Embeds inspection

While there are not many studies specifically tailored towards concrete embeds, there has been work done on a similar topic: automated dimensional quality assessment for formwork and rebar of reinforced components. DQA of formwork and rebar is relevant to concrete embeds inspection because embed plate sizes or locations may force altering of formwork tie locations and all embeds should be set before concrete placement — just like the formwork and rebar [3]. Figure 3 demonstrates the interconnectedness of formwork, rebar, and steel embeds as they are all present in the stage of construction that precedes concrete pouring. Because of this, any demonstrated successes in using laser scanners to inspect formwork and rebar can be assumed to have the capacity to inspect steel embeds as well.

Figure 3. Formwork, rebar, and embeds positioned prior to concrete pour.

Kim et al. conducted a study focusing on DQA of formwork and rebar during the fabrication stage. The authors describe a TLS-based automated DQA technique that measures the dimensions of formwork and rebar of RC elements to assess dimensional conformity with design specifications. The proposed method resulted in small average discrepancies in the items measured: rebar spacing (2.15 mm), formwork dimension (2.52 mm), concrete cover (2.18mm), and side cover (3.12 mm). The experimental results demonstrate that the proposed technique yields accurate solutions for the formwork and rebar DQA during fabrication before concrete is poured [10]. Wang et al. developed a system to automatically estimates positions of precast concrete rebar using colored laser scan data. Their technique was successful with the vast majority of differences between the rebar positions estimated by the developed technique and those measured by the manual inspection under 1.5 mm (137 out of 142) and an average difference of 0.9 mm [7]. Gikas combined high accuracy total station and laser scanning surveys to check 3D geometric documentation of the formwork for a highway tunnel in full expansion and compared against the design drawings. The laser scanner method arc radius of both sides of the formwork deviate from their nominal values by less than 2.0 cm [14]. Turkan et al. used two methods based on extensions of the discussed "Scan vs. BIM" object recognition framework to detect and track temporary structures (formwork, scaffolding, and shoring) and secondary components (rebar). Their experimental results showed it is feasible to recognize secondary and temporary objects in TLS point clouds with good accuracy using their two novel techniques [12].

While the various studies investigated in this literature review are not specifically targeted towards steel embeds in concrete, their demonstrated successes in the areas of rebar and formwork indicate that the technology for high-quality dimensional quality assurance using laser scanners currently exists.

3 Methodology

The proposed components of the approach used to identify the concrete embedded steel plates is shown in Fig. 4. In the following subsections, details are provided on each stage.

3.1 Data Collection

The data of the concrete embed is acquired using FARO Focus 350 [15]. Proper planning of the scan position, resolution, and quality should be completed before conducting the actual scan. A resolution of 1/4 or 1/5 and quality of 4x are reasonable for outdoors in sunny condition scans. The engineer should ensure enough data is collected to ensure enough scans are completed to achieve proper registration with high accuracy.

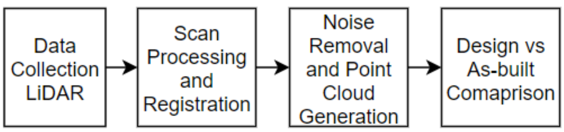


Figure 4. Workflow of identifying concrete embedded steel plates

3.2 Scan Processing and Registration

FARO SCENE software is used to process, register, and generate the point cloud data [16]. Processing the scans is a stage where the captured data is handled to improve the scan quality; this ensures the best results in 3D data. This step is followed by scan registration, which involves aligning multiple scans in a parent coordinate system using reference positions common between scans. These references can be natural or artificial that help in completing the registration.

3.3 Noise Removal and Point Cloud

During the data collection, the required scan parameters are identified. These parameters determine if the scan is acceptable or not. Based on these parameters the scan limit can be defined. Scan points outside of the acceptable parameters are considered "noise." Different filters such as Outlier, Dark Scan Points, and Smooth are available in SCENE software and can be applied to minimize the noise in the data. Once the scan nose is removed from the registered scans, the final step involves generating and exporting the point cloud model that will be used in the analysis and the as-built comparison.

3.4 Design Vs As-Built Comparison

The comparison of the BIM model to the as-built model to determine the deviation can be done in different ways. This step can be completed by comparing the BIM model to an as-built point cloud or comparing old as-built to new as-built. The latter is most widely used in quality control. The analysis of different as-builts is completed using CloudCompare vs2.11.0 [17].

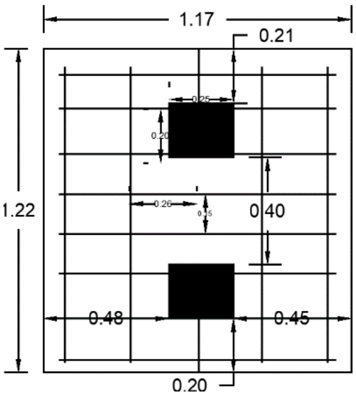
4 Experiment and Results Analysis

The proposed approach involved testing in the lab by building a formwork of a square concrete footing with rebar and steel embed plates. Then, the footing was scanned to generate the as-built point cloud. In the next stage, the steel plate position was modified, and another round of scanning was completed to generate a second as-built point cloud model. In the following sections, more details are provided about the experiment and testing procedures.

4.1 Experiment

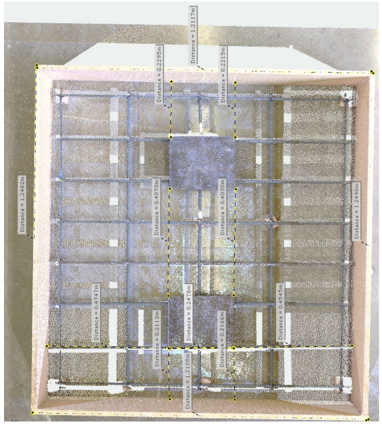
The designed BIM model of a concrete footing is shown in Fig. 5a. This plan view shows the dimensions of the footing and distances in relation to the steel plates. The footing itself was designed to be 1.17 m wide by 1.22 m long. The distances from the edge of the steel plates to the short inner edge of the footing are 0.21 m and 0.20 m. The distance between the steel plates is 0.40 m. The distances from the outer edges of the steel plates to the longer inner sides of the footing are 0.48 m and 0.45 m. The footing formwork has a depth of 2 ft and #4 rebar used in both directions. Fig 5b shows an image of the constructed formwork of the footing, steel plates and rebar. Fig 5c shows the point cloud of the scanned footing. This 3D point cloud informs on the dimensions of the actual structure, and the deviations from the intended design. By comparing the constructed footing measurements with measurements obtained from the point cloud model, the results show that a deviation of

0.7 mm is captured for one side and a 0.3 mm deviation between Fig 5a and 5e. The scanner registration accuracy is 0.7 mm as shown in Fig 5d. In conclusion, the scanner achieved high accuracy and can be used to verify the measurement and conduct quality control in construction.

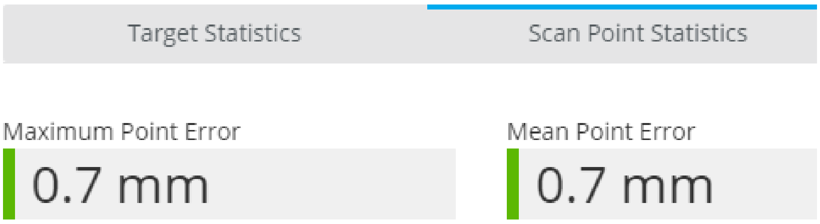


a) BIM model

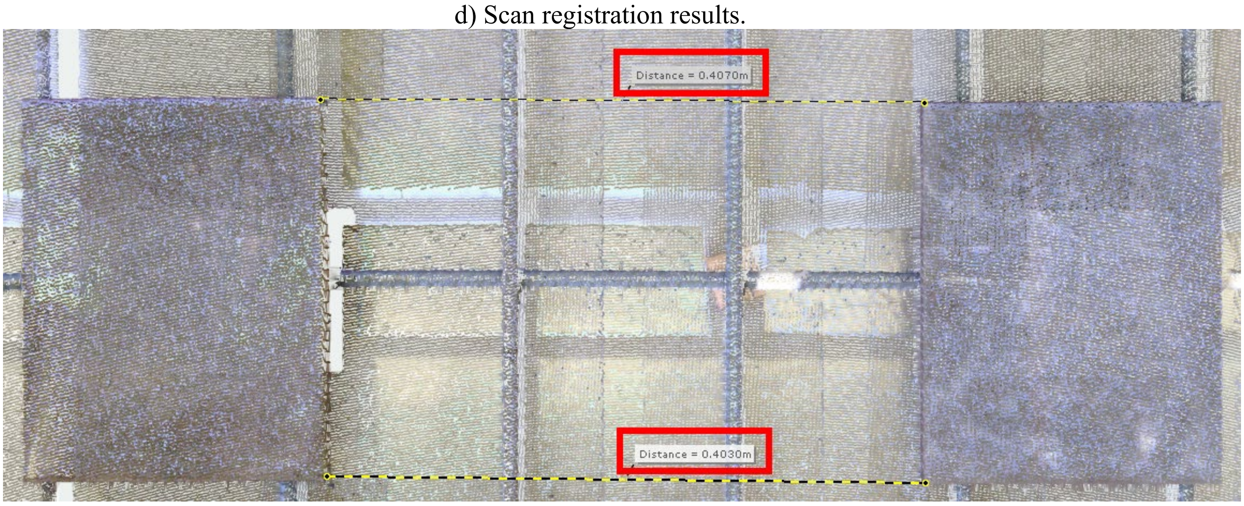
b) Constructed footing



c) 3D Poind Cloud of the footing (as-built 1)



d) Scan registration results.



e) Steel Embed Plates Spacing and Position

Figure 5. Experiment Design and Components

4.2 Results and Analysis

The proposed approach can be verified in two different ways. Method 1: compare the BIM model (Fig 5a) with the as-built point cloud model of the footing (Fig 5c) or, Method 2: compare as-built point cloud model (Fig 5b) to a modified as-built model (Fig 6). In this experiment, we used Method 2. After constructing the footing as per the BIM model, the footing was scanned to create an as-built model (as-built 1). In the next stage, we modified the steel plates' location, as shown in Fig. 6, and then rescanned to generate another point cloud model (as-built 2). The embed placements were changed from the layout in Figure 5c to the layout in Figure 6. Each layout was scanned using the FARO 350 laser scanner, and the new layout was compared to the original. Figure 7 shows the two layouts with embeds 1 and 3 denoting the original placements and embeds 2 and 4 being the final positions.

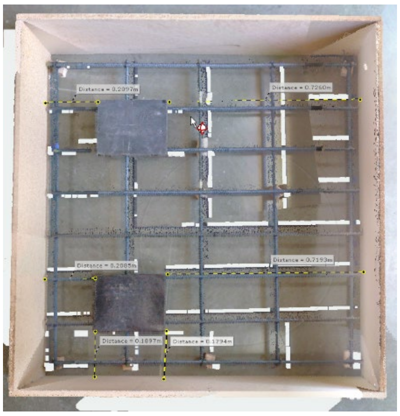


Figure 6. New layout with steel embed plates shifted to the left (as-built 2).

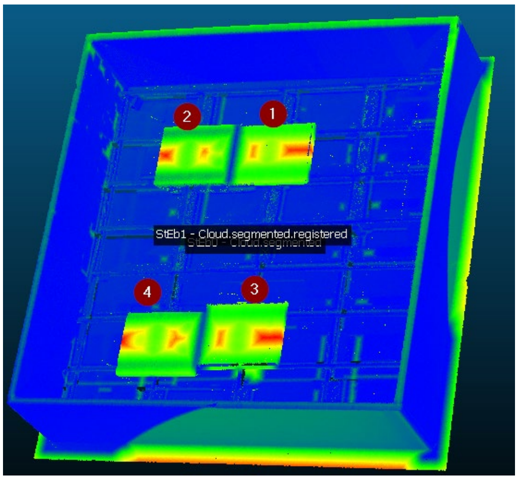


Figure 7. Original embed locations (1 and 3) and moved locations (2 and 4).

Figure 8 shows the heat map that was generated in the model analysis comparing the moved embeds (embeds 2 and 4) to the original layout (embeds 1 and 3). The heat map essentially detects and informs engineers if the embeds are in the correct position by overlaying the as-designed model with the as-built model. For this experiment, the heat map highlights areas in blue to denote negligible change (less than 0.5 mm) between the two scans, which is correct because no adjustments were made there. However, the location where the embeds were moved to is in stark contrast with the surrounding rebar with deviations ranging from 3 cm to 8 cm. This is because the model expected this location to have rebar, but instead it has embeds. Note that the largest deltas, marked with red and orange, occur at the areas that should have open space but now have embed plates. The regions where the embed is on top of rebar still have a difference but the heat map shows a smaller delta because the difference in elevations between the rebar and embed plate is smaller than the elevation changes between the bottom of the formwork and the embed plates.

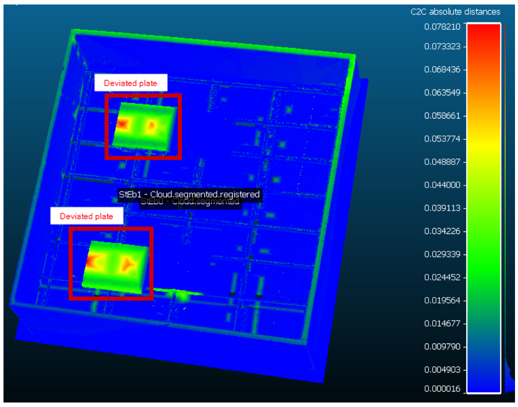


Figure 8. Heat map identifying out of compliance regions.

In addition to identifying which areas are out of compliance, it is also helpful to know how far the items have moved to assist in adjusting the layout to its correct position. Comparing the original and moved layouts provides distance values for how far out of tolerance each embed is. The delta of the left corner of each embed is measured by the software as shown in Figure 9. The shift of the top embeds from location 1 to 2 was 0.262 m horizontally. The shift of the bottom embeds from location 3 to 4 was 0.269 m in magnitude with components in the x, y, and z directions identified. Note that the model can capture differences in a three-dimensional coordinate system which provides precise direction on how far out of tolerance the items are.

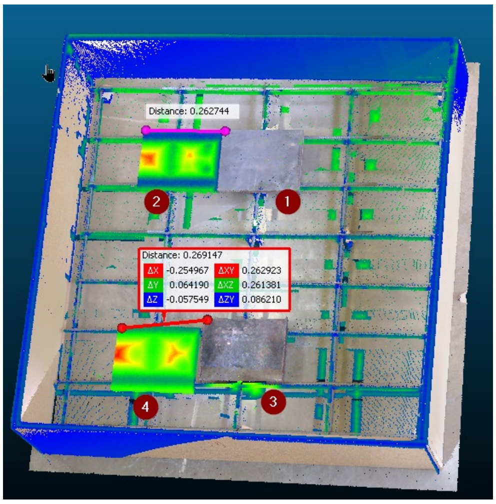


Figure 9. Determination of how far the embeds moved.

This experimental study showed a successful application of LiDAR technology to inspect the as-built conditions of formwork with steel embed plates. The scan created an accurate point cloud model of the formwork and extracted dimensions. CloudCompare vs2.11.0 compared the two scans and generated a heat map that showed the differences between the two. This application can significantly improve rebar and embed inspections, especially for large sites, by linking all the deviations to surveying data to quickly identify what items are out of compliance and where they are.

5 Conclusion

Rework and quality control of steel embed plates installation in construction are difficult tasks for construction professionals. Even small deviations in embeds position can be costly to correct, especially after the concrete hardens. This paper proposed a method to enhance the quality control of steel embed plates installed in concrete and verifies the geometry of the formwork. The method uses a high-quality LiDAR system (laser scanner) and multiple analysis platforms. A 3D point cloud model that is generated from the laser scanner allows for better analysis and reduction of costly rework compared to traditional methods.

The developed method was implemented using a FARO Focus 350 laser scanner. A custom-built 1.17m x 1.22m formwork was built with rebar and steel embed plates placed as per the BIM design that was created. The constructed formwork was scanned to generate an as-built model of the formwork (as-built 1). Then, the position of the steel embed plates was modified and another round of scanning and registration was completed to generate as-built 2. Cloud to Cloud comparison was conducted to capture the deviation the two as-built models in three directions (x, y, z). The experiment showed high accuracy in the results (0.3 mm). This methodology will be especially helpful for capturing the deviation of complex steel embed plates layout so construction practitioners can quickly inspect concrete formwork and embeds. Using LiDAR for concrete embeds inspection will result in increased time and labor savings and can be extremely helpful to construction practitioners.

Future research will focus on developing a tool that automatically captures the deviations once the design and point cloud model are loaded. Currently, the process follow many steps to generate the deviation report. Thus, eliminating steps that require user input will speed up the process and make the framework more user-friendly.

Data Availability

All data generated from this study is available upon request from the first author.

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