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# Automated quality assessment of precast concrete elements with geometry irregularities using terrestrial laser scanning

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ABSTRACT

Precast concrete elements are popularly used and it is important to ensure that the dimensions of individual elements conforms to design codes. However, the current quality assessment of precast concrete elements is inaccurate and time-consuming. To address the problems, this study presents an automated quality assessment technique which estimates the dimensions of precast concrete elements with geometry irregularities using terrestrial laser scanners (TLS). While the scan data obtained from TLS represent the as-built condition of an element, a Building Information Modeling (BIM) model stores the as-design condition of the element. Taking the BIM model as a reference, the scan data are processed to estimate the as-built dimensions of the element. Experiments on a specimen demonstrated that the proposed technique can estimate the dimensions of elements effectively and accurately. Furthermore, a mirror-aided scanning approach, which aims to achieve reduced incident angles in real scanning environments, is proposed and validated by experiments.


## 1. Introduction

Precast concrete elements have been widely used in buildings and civil infrastructures. Compared to cast-in-place concrete, precast concrete brings higher quality control, reduced construction time, and environmental benefits [1,2]. Despite these advantages, structural failure of precast concrete systems can occur if the dimensional quality of individual components does not conform to design codes, as reported in [3]. Thus, it is of great significance to perform quality assessment on precast concrete elements before they are shipped to construction sites. Currently, the quality assessment of precast concrete elements primarily relies on manual inspection using traditional tools such as measuring tapes and following specified design codes. However, manual inspection suffers from two problems. Firstly, the result of manual inspection is inaccurate and unreliable [4]. Secondly, manual inspection is time-consuming and costly, especially for large-size and complex structures. Hence, it is necessary to provide solutions which are able to perform quality assessment for precast concrete elements in an accurate and efficient manner.

In recent years, terrestrial laser scanners (TLS) have gained popularity since they are able to acquire range measurement data at a high speed and high accuracy [5]. Due to these advantages, TLS has been used for the quality assessment of civil structures, including structure deformation measurement [6,7], and the identification and quantification of surface damages [8,9]. Some studies have applied TLS to estimate the dimensions of civil structures. Bosché [10] reported an approach for calculating the as-built poses and dimensions of CAD model objects from the scan data of an industrial building's steel structure. The authors published previously a few works on quality assessment of precast concrete elements using laser scan data [11,12]. Research reported in [11] developed a dimensional quality assessment technique for precast concrete elements with rectangular-shape surfaces, and the developed technique was validated on lab-scale test specimens. Additional on-going research will enhance the developed technique and implement it on full-scale precast concrete panels. Research reported in [12] developed a framework for surface quality assessment of precast concrete elements by combining 3D laser scanning with building information modeling (BIM). However, the applicability of the existing research on dimension estimation as described in [11,12] is limited only to elements with simple geometries, such as straight columns or rectangular panels. No study has been conducted to estimate the dimensions of elements with geometry irregularities. In addition, photogrammetry has also been used in quality assessment, either stand-alone or combined with laser scanning. Scaioni et al. [13] proposed techniques to measure deformations of the transversal cross-section and the longitudinal profiles of tunnels using photogrammetry. Safa et al. [14] developed an automated measurement system to detect defects in piping fabrications using both laser scanning and photogrammetry. Riveiro et al. [15] also applied these two technologies to measure the minimum vertical underclearance and beam geometry during bridge inspections. Although photogrammetry is more economical and accessible compared

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to laser scanning, it suffers from a lower accuracy. Since the application discussed in this study requires high accuracy, laser scanning is adopted.

This study proposes an automated quality assessment technique for estimating the dimensions of precast concrete elements with geometry irregularities, particularly focusing on the transverse sides of precast concrete bridge deck panels, using TLS. The uniqueness of this study includes, (1) the developed quality assessment technique can automatically estimate the dimensions of irregular geometry elements, (2) a new edge line estimation algorithm is developed which can estimate edge lines with arbitrary orientations, and (3) a mirror-aided scanning approach is proposed and validated to achieve reduced incident angles in real scanning environments. This paper is organized as follows. Section 2 introduces the research background on precast concrete bridge deck panels and TLS. Then, the proposed quality assessment technique is described in Section 3. Section 4 validates the effectiveness and accuracy of the proposed technique using scan data of a laboratory specimen. Furthermore, a mirror-aided scanning approach is proposed and validated in Section 5. Lastly, Section 6 concludes the whole study and suggests future work.

## 2. Research background

### 2.1. Precast concrete bridge deck panels

A complete precast bridge deck consists of a series of bridge deck panels. To connect adjacent panels and ensure the integrated performance of complete decks, two structural features, shear keys and ducts, are usually provided on the transverse sides of the bridge deck panels. Fig. 1 shows a transverse side of a precast concrete bridge deck panel, with a polygonal outer boundary, as well as shear keys and ducts on the panel. Shear keys are distributed along the transverse side and serve as transverse panel-to-panel joints. They are designed to eliminate relative vertical movement between adjacent panels and to transfer the traffic load from one panel to the next [16]. Shear keys are mainly in two categories, non-grouted match-case shear keys using epoxy adhesive and grouted female-to-female shear keys, and the one shown in Fig. 1 is the latter. Similarly, ducts are also distributed along the transverse sides. They are used to place post-tensioned longitudinal reinforcements, which put the transverse panel-to-panel joints under compression [1]. Ducts are usually rounded or flat in shape, and the one shown in Fig. 1 is a flat duct. It was reported that one main problem of bridge deck systems is the deterioration associated with transverse joints [16]. Therefore, the dimensions of the transverse sides of a panel should conform to specified design codes in order to guarantee the performance of transverse joints.

PCI [1,17] specifies the necessary dimensions for quality assessment of the transverse sides of panels and their tolerances, as shown in Table 1. Fig. 2 illustrates these dimensions using an example of a panel, on which two identical shear keys and a flat duct are provided.

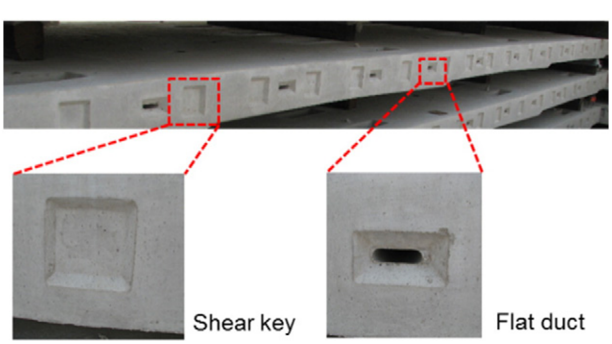


**Fig. 1.** A transverse side of a precast concrete bridge deck panel with shear keys and flat ducts.

**Table 1**
Necessary dimensions for quality assessment of the transverse sides of panels and their tolerances.

| Dimensions | Notations | Tolerances |
|---|---|---|
| Panel depth | $d$ | $-3$ mm, $+6$ mm |
| Dimensions of shear keys | $a_1$ (outer horizontal)<br>$a_2$ (outer vertical)<br>$a_3$ (inner horizontal)<br>$a_4$ (inner vertical) | $\pm 6$ mm |
| Locations of shear keys | $b_1$ (horizontal)<br>$b_2$ (vertical) | $b_1$: $\pm 6$ mm<br>$b_2$: $\pm 3$ mm |
| Locations of flat ducts | $c_1$ (horizontal)<br>$c_2$ (vertical) | $c_1$: $\pm 6$ mm<br>$c_2$: $\pm 3$ mm |

Note that the dimensions of a shear key include outer horizontal, outer vertical, inner horizontal, and inner vertical dimensions, denoted as $a_1$, $a_2$, $a_3$, and $a_4$, respectively. Locations of a shear key include both horizontal and vertical locations, denoted as $b_1$ and $b_2$, respectively. The horizontal location is defined as the horizontal distance from the center of the shear key to the left edge of the panel, while the vertical location is defined as the vertical distance from the center of the shear key to the top edge of the panel. Additionally, the locations of a flat duct, denoted as $c_1$ and $c_2$, are defined similar to the locations of a shear key.

### 2.2. Terrestrial laser scanners

TLS measures the distance to a target by emitting laser beams and detecting the reflected signals from the target. When TLS is in operation, the scanner head keeps rotating vertically and horizontally so that TLS can measure the distances of different measurement points. The scan data obtained from each measurement point contain a set of three-dimensional X, Y, and Z coordinates, a row index (corresponding to the scanner head's vertical rotation), and a column index (corresponding to the scanner head's horizontal rotation).

TLS mainly adopts two different techniques for distance measurement, time-of-flight, and phase-shift. TLS using the time-of-flight technique emits a laser pulse and measures the travelling time of the reflected pulse. Since the velocity of the laser is known, the distance measurement can be inferred from the travelling time. TLS using the phase-shift technique emits an amplitude modulated continuous wave and measures the phase shift between the emitted and reflected signals. The distance measurement can be obtained based on the phase shift and the wavelength of the modulated continuous wave. Between these two techniques, the time-of-flight technique has a longer measurement distance while the phase-shift technique has higher measurement speed and higher accuracy [18].

Due to the substantial advantages over conventional range sensors, TLS has been widely used in different applications include as-built model reconstruction [19–22], heritage conservation [23,24], earthwork volume measurement [25,26], construction progress tracking [27,28], structural health monitoring [29,30], etc. While the scan data obtained from TLS represent the as-built conditions of objects, the corresponding as-design objects are usually stored in BIM models, which represent a digital representation of physical and functional characteristics of a facility. Some studies have compared the scan data with BIM models for quality inspection of as-built conditions [12,31,32].

## 3. Development of TLS-based automated quality assessment technique

The proposed TLS-based quality assessment technique focuses on the transverse sides of bridge deck panels, which have a polygonal outer boundary, while a few shear keys and flat ducts are distributed on it, as shown in Fig. 3. The scan data are acquired by a TLS, as shown in Fig. 4(a), and represent the as-built geometry of the panel. Note that two different approaches for scan data acquisition are used in this

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