Documentation of Concrete Slabs Prior to Pours

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Concrete slabs in multi-level commercial building projects contain many components that become no longer visible once concrete has been poured. As building designs advance and continue to locate components in concrete, it is important to document what these slabs contain in order to verify accurate craftsmanship and allow for improved future construction workflows and building modernizations. This paper explores current industry needs for proficient documentation as well as practices to achieve this. A case study was conducted, testing four devices that analyzed feasibility factors for realistic implementation by a contractor such as cost, interoperability, and level of skill required for operation. Collectively, two options were determined for ideal ways to document concrete slabs, dependent on details of the construction project in review.

Keywords: BIM, as-built, laser scan, drone, 3D camera, concrete slab

Introduction

There are five main phases that an architect's services are categorized in: Schematic Design, Design Development, Construction Documents, Bidding, and Construction Administration. The initial phase, Schematic Design, includes building codes and zoning requirements that are custom to the area of the site in discussion (Fontan 2019). These two points of discussion initiate preliminary structural design of the building in regard to structural code requirements and building height. The Schematic Design phase occurs between the architect and the owner/client, meaning that general desires and uses of the building spaces are addressed as well.

Through conversations during Schematic Design, a building height is determined, and consequentially, the number of levels and height of each level are also substantially determined. While a building design is still quite primitive at this point in design, an understanding of the genetic makeup of each level's concrete slab can be predicted. "A **concrete slab** is a common structural element of modern buildings, consisting of a flat, horizontal surface made of cast concrete. Steel-reinforced slabs, typically between [4 inches – 20 inches] thick, are most often used to construct floors and ceilings" (Wikipedia 2019). Taller buildings result in an increase of floor space for items such as stairs and MEP shafts, thus the amount of useable space is reduced (Janis & Tao, 2004, p.8). Thus, knowing that multistory structures composed of concrete slabs are limited on MEP floor space, and ceiling heights are outlined, the design for what will be buried in each slab begins. Structural code requirements outlined in The American Concrete Institute's documentrequire steel reinforcing to be present in each slab of a multilevel building, the complexity of each slab makeup increases with multiple building components (MEP and reinforcing) embedded into the slabs. With concrete poured with materials from multiple subcontractors scopes', each level's slab becomes congested.

One component commonly found in multistory concrete building slabs is post-tensioned reinforcement, commonly referred to as PT cable. A PT cable consists of multiple steel tendons, encased in a plastic coating. The result is a flexible form of reinforcing that is tensioned post concrete pours to strengthen the concrete. The concrete holds the tension which creates a stable and strong slab (Palmer). PT cable has many advantages in commercial concrete buildings. See Figure 1 below, produced by VSL International, a construction company based in Switzerland, for several advantages of utilizing post tension reinforcing to suffice design objectives. The major advantages as outline in Figure 1 are thinner, stronger slabs that can span larger areas. However, there are disadvantages of PT cable. Two disadvantages of using post-tensioned reinforcing include misplacement and effects of cutting tensioned cables. If the PT cable is not in proper locations, then the risk of an increase of uplift force in slabs can occur. An uplift force can lift a slab from attached columns and beams, therefore reducing the strength of the structure. When an already tensioned cable is cut, a large release of tension occurs, resulting in a large boom sound and the potential to blow portions of the concrete out (Allred 2006). To reduce these scenarios that have dangerous effects, documentation of slabs is necessary.

Overall Objective	Benefits for the Project	How the objectives can be met
large column-free spaces, i.e. large spans	• flexibility of occupancy, • maximum rentable space	•**post-tensioning**
high repeatability from stage to stage and from floor to floor	• improvement of constructability and thus saving of time	•simple, standardised details for reinforcement •simple, standardised details for formwork •**post-tensioning** 2)
quickest-possible turn around of formwork	• saving of time • reduction of required number of formwork sets	• high early strength concrete • simple reinforcing and formwork in large pre-assembled units • simple details with high repeatability • pre-fabrication of critical path elements (columns, beams, slab soffits, walls) • **post-tensioning** 2)3)4)
no back-propping wherever possible	• direct saving of time, indirect saving of time by allowing building fit-out to start earlier (early access)	• use of self-supporting falsework that only needs to be supported near vertical elements • high early strength concrete • **post-tensioning** 5)
for some commercial and industrial developments: strict deflection limitations	• (requirement)	• pre-cambered formwork • sufficient stiffness of multi-span floors post-tensioning • high early strength concrete • **post-tensioning** 5)
for some commercial and industrial developments: strict limitation of crack widths	• (requirement)	• lay-out of columns and walls to avoid res traint of shrinkage and temperature shortening • temporary or permanent separation of floor from restraining vertical elements • careful concrete mix design • careful curing of concrete • well distributed non-prestressed steel • **post-tensioning** 6)
for some warehouse or industrial buildings : floor free of expansion joint	• improved riding surface, for fork lifts, easy-to-clean surfaces	• same as above
for parkings (typically): lowest-possible floor-to-floor height	• more rentable space for given total building height. • shorter ramps	• **post-tensioning** 1)

Why does post-tensioning help to meet the design objectives?

1) **post-tensioning** allows greater,span/depth ratio, thus more economical for large spans
2) if a significant part of the load is resisted by **post-tensioning** the non-prestressed reinforcement can be simplified and standardised to a large degree. Furthermore, material hand-ling is reduced since the total tonnage of steel (non-prestressed + prestressed) and concrete is less than for a R.C. floor
3) **post-tensioning** allows earlier stripping of formwork
4) assembling of precast elements by **post-tensioning** avoids complicated reinforcing bar connections with insitu closure pours, or welded steel connectors, and thus can significantly reduce erection time
5) usually the permanent floor load is largely balanced by draped **post-tensioning** tendons so that only the weight of the wet concrete of the floor above induces flexural stresses. These are often of the same order as the design live load stresses. Hence back-propping of one floor below is usually sufficient
6) **post-tensioning** usually balances most of the permanent loads thus significantly reducing deflections and tensile stresses
7) the P/A stress provided by **post-tensioning** may prevent tensile stresses causing the floor to crack.

Figure 1 – Advantages of Using PT Cable for Design Objectives

Aside from reinforcing, MEP system components are commonly buried or penetrate through slabs vertically. Rough-in piping is buried in slabs to reduce floor and ceiling exposure. Waste water pipes and electrical conduit are two examples of piping typically present inside slabs. Other MEP components set to be housed in concrete slabs include electrical boxes, plumbing sleeves, and Blue Bangers. Electrical boxes are connected to conduit piping running through slabs to provide various benefits such as exposed access to the conduit piping or in-floor electrical outlets. Plumbing sleeves are can-like cylinders that provide an opening in the concrete so a pipe can be installed vertically, connecting a level to the level below or above. Blue Bangers are attached to concrete formwork and provide a threaded connection for MEP tracks to attach to (The Home Depot 2019). Since all MEP systems can't be routed in concrete due to issues with accessibility and size, for example: an HVAC duct, Blue Bangers are utilized to provide structural attachments for the ceiling below to allow for overhead housing of MEP systems.

In addition to MEP components and reinforcement being placed in slabs, steel embeds are also located throughout each level of cast in place concrete slabs. Steel embeds, also known as concrete embeds, are connections cast into concrete, that allow for systems such as curtain walls to be attached to the structure (Klinger, Salzano, Manherz, & Suprenant, 2018, p.1). Similar to the concept behind Blue Bangers, embeds are an anchorage for attaching building components that are not housed in concrete but require structural connections.

All of the building components described above are poured in place, and are confined into spaces via formwork. Formwork establishes building outlines and include large openings, referred to as block-outs, that create openings for building systems such as elevator, stairway, and mechanical shafts. These technical designs are created and coordinated during the Construction Documents phase (Fontan 2019) and implemented when physical construction occurs. The design and coordination of what will be installed in each levels slab is a lengthy process, while the actual construction from install of formwork to pouring concrete could take one or two weeks. Since the construction workflow is much shorter than that of Construction Documents, there is more room for error in design versus install. This area of error can be reduced by utilizing effective documentation strategies that ultimately are cost and time efficient. Effective documentation not only helps the construction process reduce time and money, but also enables future tenant improvement construction that relies on accurate documentation.

Background

Documenting PT Cable

From previous internship work experience, I have been able to personally witness and demonstrate different ways of documenting concrete prior to pours. Working as a Carpenter's Apprentice for a Bay Area general contractor who self performs concrete is where my interest in documentation ignited. The construction project I worked on was a 12 story concrete building in the SOMA neighborhood of San Francisco, California. The building consists of a concrete structure that totaled 120,000 square feet and now serves as a hotel. At the beginning of my internship, Level 1, the ground level of the hotel was beginning to be formed for an eventual slab. As my internship came to a close, Level 4 had been poured, allowing me to witness varying forms of documentation. Also, this project was utilizing PT cable in the reinforcement of slabs and beams, which drove varying uses of documentation as the building progressed into the skyline.

In the construction process of multistory concrete structures, slabs and connected beams are constructed first, followed by the columns that will support the future slab above. Column formwork requires braces to be secured to the recently poured slab below, in order to provide plumb columns. These braces typically are secured to the slab by drilling a hole into the slab so that a nail and strip of tie wire can be hammered in, allowing the brace to be secured from moving. This process had associated risk as holes were to be drilled in slabs that did not foreshadow what was inside, referring to MEP systems and post-tensioned reinforcement. As mentioned, breaking a PT cable tendon has dangerous effects, thus care of documenting these cables was a priority to the general contractor.

On Level 1, the documentation of where installed PT cables were located was executed by attaching Marking Whiskers, also referred to as Surveyor Feathers Marking Whiskers are a bundle of plastic threads that can be fixed to a component in the concrete prior to pour. The result is an exposed indicator that sits taller than the poured concrete slab. For Level 1, Marking Whiskers were placed on opposing ends of PT cable runs (3-6 cables per run), specifically around future columns as these locations were areas of concern for drilling into the concrete. The result of this type of documentation when the next task was to pour the columns was that Marking Whiskers were not effective enough. Due to the limited location placement of markers, which were dependent on attachable locations such as nearby rebar, the result was that one could identify the general route of PT cables, but not accurately enough to pull dimensions. Furthermore, since PT cable is flexible, one can't assume Marking Whiskers indicate straight paths of travel for runs of multiple cable. This way of documentation was cheap and simple, but proved limited on future use of documentation.

On Level 2, an improved documentation process was necessary. It was determined that taking pictures of the makeup of the slabs would be sufficient. This process consisted of using an iPad to take several pictures at each side of a column. Documentation consisted of a picture of where in the drawings the images were being taken from, pictures of each side of a column, and pictures with a tape measurer measuring the distance a column formwork brace would extend away from the column and what was present at that distance. Images like these described, which were captured on an iPad, are beneficial for documenting building components visually, however they have limitations to use in the future due to lack of accuracy due to the amount of pictures needed and lack of capturing large areas of slabs.

On Level 3, and the rest of the building's upper levels, the workflow was altered to indicate where exactly the column braces would be secured into the slab, as opposed to documenting areas where the braces could not be drilled into the slab. This alternative approach was achieved by using a total station to shoot points where a brace would extend and needed to be drilled into the slab. The process consisted of aligning a total station to reference points, such as layout markers, and placing points on digital plans for the exact areas of brace placement. After a slab was poured, a total station would need to be used again to locate those points of brace placement and mark on the newly poured slab. Using a total station provided accuracy and reduced the risk of drilling and striking a component housed in the concrete slab. While the risk of concrete construction was reduced with this new approach, the process itself had a significant increase in time and skill required. The documentation required two rounds of using a total station and had to be operated by someone with proficient experience in surveying, which is contrary to the approaches implemented in Level 1 and Level 2, where costs, time, and experience required were minimal.

Documenting Steel Embeds & Block-outs

The following year, while working for a different general contractor in the Bay AreaI observed a simple, industry-common practice for documenting concrete slabs prior to pours. While this project, a two building multistory tech campus located in the Mission Bay neighborhood of San Francisco, was a steel structure, the concrete slabs of each level housed building components that would be buried in concrete. My personal documentation of the slabs consisted of confirming that embeds and block-outs were installed correctly by referring to plans in the field and measuring distances from known gridlines. This was a form of documentation because I was confirming that the as-built conditions are accurate to the drawings, therefore producing plans that show where embeds and block-outs are located in the field. An approach like this is simple, but can only be used to a certain extent as limitation on measurement feasibility and gridline accuracy are areas of concern when confirming location is accurate.

Presentation on Documentation

Autodesk University is an annual conference that occurs throughout the world. For the United States, Las Vegas is home to the international conference each year. I had the privilege to attend the 2018 conference on behalf of the Construction Management Department at Cal Poly San Luis Obispo. The event was filled with hundreds of educational seminars, workshops, and a tech expo. One presentation I attended at the conference, titled *3D Laser Scanning – Pioneering a New Approach to Maximize Contractor & Project Value*, was presented by VEC, a company that provides tech solutions to the AECO industry, and Webcor Builders, a commercial general contractor. The presentation consisted of a case study between the two companies. Webcor, as the general contractor of a ground-up hospital building, was contracted by the owner to provide accurate 3D models of PT cable installed for the use of future building modernizations. VEC specializes in laser scanning services, and thus was hired to provide the data to suffice the contractual obligation. VEC realized that providing this data has the potential to extend past the obligation of PT cable documenting, and provide accurate 3D as-built data that would incur savings for Webcor during construction and the owner during future tenant improvements. The immediate results included installing accurate formwork, embeds, block-outs, and reinforcement. Figure 2 represents the cost savings that were incurred during this case study, solely in regard to steel embed installments. VEC and Webcor's presentation outlined numerous short and long term benefits of selecting laser scanning as an option for documentation of concrete slabs (Saltzgiver, Castillo, & Shimamoto 2018).

Hypothetical Cost Savings

	Embeds			
	Missing	Incorrect Size	Deviation 2" to 6"	Deviation > 6"
Totals From Table Above	8	40	17	9
Approx. % That Required Corrective Action	75%	15%	25%	50%
Quantity That Required Corrective Action	6	6	4	5
Quantity - Minor Impact	3	4	2	3
Quantity - Moderate Impact	2	2	2	0
Quantity - Major Impact	1	0	0	2
Cost Savings - Minor - $5,000/EA	$ 15,000	$ 20,000	$ 10,000	$ 15,000
Cost Savings - Moderate - $7,500/EA	$ 15,000	$ 15,000	$ 15,000	
Cost Savings - Major - $10,000/EA	$ 10,000			$ 20,000
Subtotal Hypothetical Cost Savings:	$ 40,000	$ 35,000	$ 25,000	$ 35,000
Total Hypothetical Cost Savings:	$ 135,000			

Figure 2 – Embed Cost Savings of Case Study Presented at Autodesk University 2018

Methodology

The methodology for this topic includes several interviews with employees from varying AEC-related companies to understand current practices in regard to documenting concrete slabs. These interviews aided in understanding of current practices for physical documentation and understanding of resources provided to document. Several companies were interviewed in order to provide a diverse reality of what the AEC industry practices that allows for non-project or non-company specific conclusions. Additionally, a case study was conducted to test different devices available in the industry for their effectiveness in achieving well-put together documentation as-builts.

Matthew Susank, a Project Engineer for Webcor Builders, recently completed a new dormitory complex on Cal Poly's campus. Webcor Builder's is a general contractor that self-performs several scopes of construction work, including concrete. While conversing with Susank, I was able to learn some project-specific details that aided my research. He mentioned that the process for checking slabs prior to pours for this project consists of combining multiple trade scopes' slab components into a single drawing, called a Superplot. See Figure 3 for an example of a Superplot of the Cal Poly project. This single document allowed for quick documentation that all necessary trade components were installed in accordance to the design. Additionally, Matthew would capture images of the slabs prior to pours by using an iPad and PlanGrid. While understanding the level of Building Information Modeling

(BIM) used on the project, it was interesting to hear that PT cables were modeled, not to be used for documentation purposes, but rather to understand the congestion of all building components that were to be cast into each slab.

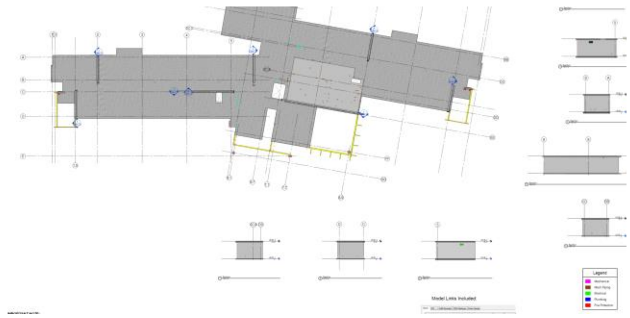

Figure 3 – Example of a Superplot

Daniella Castro is the cofounder of DNA Detailing, which specializes in detailing rebar. When asked if she has seen 3D models of PT cables, her response was that she has been "seeing more and more interest in seeing PT modeled," (Castro 2019) by request of clients. Castro further explained that in regard to building off of plans, "the PT detailer and installer can make decisions on the fly about how to place the anchors" (Castro 2019). Knowing that PT cables tend to vary from exact design locations, it is clear that there is a need for capturing as-built conditions.

Trey Garcia, a Project Engineer with Truebeck Construction, is currently involved with managing MEP scopes on a ground-up office building project located in the Bay Area. Trey discussed the level of development (LOD) that is required of MEP subcontractors for this specific project. Garcia noted that each subcontractor has to have a LOD for 3D models of either 200 or 500. An LOD of 500 means that there is a 3D as-built model for documentation. Laser scanners are able to aid in achieving this task, thus indicating laser scanners as a beneficial device for documentation of slabs prior to pours.

Johnathan Espinoza is a part-time employee of Conco, a concrete subcontractor, while studying Civil Engineering at Cal Poly. Espinoza was able to provide information on design items that Conco produces. Currently, Conco does not 3D model any reinforcing. Reinforcing designs are produced in AutoCAD instead, which is 2D.

While conducting the case study mentioned below, I interviewed Leeroy Duarte, an HDS Specialist with VEC. Leeroy was able to provide an impressive amount of knowledge on laser scanning and documentation. He stated that in terms of documenting slab conditions prior to pours, a contractor is concerned with if a building component deviates from design more than one inch.

These interviews allowed me to determine that in complex and higher budget projects, almost everything installed is 3D modelled. Reinforcing is not commonly 3D modeled, especially post-tensioned reinforcing.

Case Study

Approach

This case study tested four different document-capturing devices that are innovative and were predicted to be deemed useful for documenting slabs. The devices used were: a list the make of the drone drone, a 3D make of camera, and two laser scanners. See Figures 4 and 5 for how the devices varied in specs and price. Figure 5 includes scan times specific to this case study. The objective of this case study was to test the accuracy of each device and analyze the feasibility of each device to be used on a construction project of a multistory building. Each device was selected based off of availability and varying results each is able to produce. The laser scanners create point clouds, the Matterport camera creates a 3D model with imaging applied, and the drone produces high resolution images that capture large areas of space.

Type of Device	Maker	Model	Data Type	Time Per Scan (Seconds)	Total Scanning Time (Minutes)	Shooting Distance (Feet)	Tolerance (Inches)
Laser Scanner	Leica	P40	Point Cloud	210	50	50	1/8
Laser Scanner	Leica	RTC	Point Cloud	110	50	50	3/8
Drone	DJI	Inspire 2	Image	N/A	2	1640 (Height)	N/A
3D Camera	Matterport	Pro2	3D Image	18	25	15	1/8

Figure 4 – Specs for Devices Used in Case Study

Type of Device	Maker	Model	Purchase Price	Attachment	Attachment Price	Total Price
Laser Scanner	Leica	P40	$ 102,000	Lightweight Tripod	$ 150	
				Cyclone Register 360 Software	$ 4,810	$ 106,960
Laser Scanner	Leica	RTC	$ 78,000	Lightweight Tripod	$ 150	
				Cyclone Register 360 Software	$ 4,810	$ 82,960
Drone	DJI	Inspire 2	$ 3,000	Zenmuse X5S Camera	$ 1,900	
				Cendence Remote Controller	$ 1,400	$ 6,300
3D Camera	Matterport	Pro2	$ 3,400	Monthly Subscription	$ 270	
				Manfrotto 290 Xtra Aluminum 3-Section Tripod	$ 120	$ 3,790
						with $270 monthly fee

Figure 5 – Purchase Prices for Devices Used in Case Study

Mockup Design

The mockup for this case study was designed to replicate a concrete slab that would contain typical building components for a slab located in a multistory concrete building. I designed a 5'x5' mockup that housed rebar, PT cable, steel embeds, and MEP components (conduit, plumbing sleeves, and an electrical box. Industry practices, such as height of formwork and rebar spacing were followed. I modeled the mockup, using Revit and Tekla, and added survey points using Autodesk Point Layout. See Figure 6 for a 2D drawing of the model and Figure 7 for materials used. The mockup was constructed exactly to the model, to provide an accurate basis for future analysis.

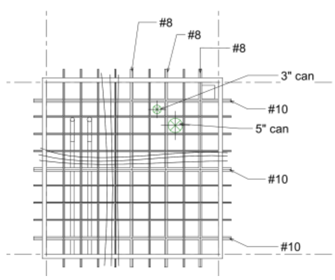

Figure 6 – Case Study Mockup Drawing

Number	Description	Dimensions	Quantity
1	2x6 Lumber	5'-0"	2
2	2x6 Lumber	5'-3"	2
3	#4 Rebar	5'-6"	12
4	#8 Rebar	5'-6"	3
5	#10 Rebar	5'-6"	3
6	1/2" PT Cable	5'-6"	3
7	1/2" Flex Tube	5'-6"	3
8	Plastic Concrete Pipe Sleeve	3"	1
9	Plastic Concrete Pipe Sleeve	5"	1
10	Conduit Box	4 1/2" x 4 1/2"	1
11	1" PVC Conduit	4'-6"	2
12	90° 1" PVC Elbow	-	2
13	Steel Embed Type 1	4" x 4" x 9"	2
14	Steel Embed Type 2	5" x 6" x 11"	1

Figure 7 – Case Study Materials Used

Execution

To conduct the case study, I partnered with VEC, who either owns or has access to the four devices. We tested each device with the mockup in a mall parking lot early in the morning. The case study had to be conducted in the early morning due to the Matterport's inability to document in direct sunlight. The parking lot was a flat surface and had sufficient space for using each device. Laser scanner target spheres were also set up around the mockup to tie multiple scans together. Markers were also placed on the ground around the mockup to aid in the analysis of device accuracy. The distance between two of the markers was measured and used for measurement calibration of drone pictures.

The process of using the 3D camera and the two laser scanners were similar. We tested the 3D camera first because of its inability to operate in direct sunlight. The Matterport was on a tripod and was controlled by an iPad that it was connected to. The process of documenting entailed setting up the camera in one area around the mockup, tapping a scan icon on the Matterport application on the iPad which enabled the capturing process, and then moving the Matterport to another area around the mockup. We determined that breaking the area up around the mockup into six regions would suffice to capture the mockup. Essentially, the Matterport was moved and capturing from six spots that circled the slab mockup. The laser scanners were operated in a similar process, except for they were not controlled by a tablet as they had built in screens to the scanners themselves.

The drone was flown from differing heights: 30 feet, 60 feet, and 100 feet. Varying drone heights were tested to investigate the accuracy of the drone as it was further away from the mockup.

Once all of the data was collected from the four devices, VEC invited me to their office to download and clean up the data. Since the laser scanners create point clouds, I saw the process of using a software program called Cyclone, to piece the six different region scans of the mockup into one 3D model. Using the layout markers and laser scanner spheres aided in a more efficient process of piecing together the point clouds. The data from the Matterport camera was synced to the in-house Matterport website, which allows for easy access and did not require any piecing of data together. The drone images were synced to an iPhone wirelessly.

Analysis

To measure the accuracy of the laser scans, I used two software programs, Autodesk Recap and Autodesk Navisworks Manage. Autodesk Recap was used to convert the point clouds from Cyclone to a file type that could be opened in Manage. Recap also aided in aligning the scans with the layout markers in the Revit/Tekla model. In Manage, the files were combined the Revit/Tekla model and the laser scan models, creating separate merged models for each laser scanner. By overlaying the two models in one file, one is able to easily recognize variations in design versus install. Manage has a measurement tool feature which I utilized to measure distances in the point cloud model and compare those distances with actual distances.

Since the Matterport-produced model was only available on the Matterport website, the website's measurement tool feature. This was not ideal because the measurement tool was not easy to operate and was not able to pinpoint exact points in the model.

The drone captured images of the mockup and surrounding area, including the layout markers. The images were opened in Bluebeam and calibrated based off the known distance between the layout markers. With the image scaled the same distances as conducted for the data from the other three devices were measured. Figure 8 displays the results of each set of measurements for each device.

Device	Measurement	Recorded (Decimal Feet)	Actual (Decimal Feet)	Difference (Inches)
Leica P40	1	4.039	4.083	17/32
	2	4.976	5	9/32
	3	0.737	0.75	5/32
Leica RTC	1	4.049	4.083	13/32
	2	4.959	5	1/2
	3	0.746	0.75	1/16
Drone (30')	1	4.026	4.083	11/16
	2	4.942	5	11/16
	3	0.744	0.75	1/16
Drone (60')	1	4.052	4.083	3/8
	2	5.005	5	1/16
	3	0.734	0.75	3/16
Drone (100')	1	4.098	4.083	3/16
	2	4.968	5	3/8
	3	0.755	0.75	1/16
Matterport	1	4	4.083	1
	2	5	5	0
	3	0.5	0.75	3

Figure 8 – Case Study Measurements

Results

From the case study conducted, the four devices proved to be sufficient for accurately documenting the slab mockup. The Matterport 3D camera, however, due to its inability to capture in direct sunlight, is not a viable option for documenting concrete slabs prior to pours. While reasonable in price and level of skill required to operate is minimal, the requirement of being able to capture data during sunrise only in an outdoor setting makes the Matterport an insufficient device for documenting slab components. The requirement to use the Matterport website for model viewing further adds to the decision not to use the device for documentation. Being able to have interoperable data is important for documentation for future building modernizations as technology is rapidly changing and there is no way to guarantee the data will be protected from potential issues with the Matterport company.

The laser scanners used in the case study are expensive and require advanced Virtual Design and Construction (VDC) skill to operate and mesh point clouds together to produce a full, useable 3D model. However, these devices are extremely accurate and provide a 3D model of the as-built conditions. Having a 3D as-built model is incredibly useful for a building. During the construction of the building, one can easily reference a 3D model and know what is concealed in each slab. If future building modernizations occur that require drilling into slabs, then 3D models will be incredibly beneficial to have. As augmented reality (AR) increases in popularity within the AEC industry, it is likely that 3D models produced from laser scanners could be synced with an AR device so that one could look at an existing slab and see the makeup of components buried in the slab.

The drone used in the case study was similar in price to the Matterport and produced relatively accurate results. I would recommend not flying a drone higher than 60 feet for documentation as images became pixelated in the case study and therefor unusable. This device is documenting 2D and required little skill to operate and analyze. Since the drone was at a high, aerial height, large areas of space could be documented in one picture, and the picture would have minimal camera angle.

Conclusion

Documenting as-built conditions of concrete slabs is necessary for future immediate and future construction. Capturing what is in a slab benefits the contractor as they are continuing to construct the building and benefits the owner as they have accurate data for how the materials in the slabs were installed. This knowledge allows future contractors improved understandings of as-built conditions and reduces concerns for whether or not installations reflect designs.

There are many ways and devices available to document concrete slabs prior to pours. These ways and products can be categorized into two categories: 2D and 3D. 2D documentation is mostly composed of picture-taking practices. This type of documentation is ideal for construction projects that are low budget and simple in design. Unfortunately with 2D documentation, depths are not able to be documented, which may be an area of concern for future use of captured data. A construction project with these characteristics is likely to have low LOD BIM models, meaning that the advantages of comparing an as-built 3D model to a design model is not apparent. Using a drone to fulfill this process is best practice due to its accuracy, affordability, and minimal level of skill required. 3D documentation is much more expensive than 2D and requires more skill in operation and processing. Construction projects that can afford this process and have high LOD design models should document using laser scanners. Comparing the Leica RTC and P40 used in the case study, the RTC is the better option because of its reduced scan times and more cost-efficient purchase price. Point clouds produced from an RTC are slightly less accurate and detailed than those from a P40. The ability to overlay design models with as-built models provides an easy verification for all components installed and in correct locations. This allows for design models to be adjusted to as-built conditions, as well, resulting in easily producible drawings of as-built conditions. In addition, 3D representation of items, such as post-tensioned reinforcement, is very beneficial at reducing risk of questioning where cables are located in concrete.

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