buildings

MDPI

Article

A Case Study of Integrating Terrestrial Laser Scanning (TLS) and Building Information Modeling (BIM) in Heritage Bridge Documentation: The Edmund Pettus Bridge

Danielle S. Willkens [1,*], Junshan Liu [2,*] and Shadi Alathamneh [2]

[1] School of Architecture, Georgia Institute of Technology, Atlanta, GA 30332, USA
[2] McWhorter School of Building Science, Auburn University, Auburn, AL 36849, USA; shadi@auburn.edu
* Correspondence: danielle.willkens@design.gatech.edu (D.S.W.); liujuns@auburn.edu (J.L.); Tel.: +1-334-844-5387 (J.L.)

Abstract: The Edmund Pettus Bridge, Selma, Alabama, a symbol of the American Civil Rights Movement and an exemplar of early 20th-century engineering, stands as a testament to the progress and challenges of its era. The bridge, recognized for its pivotal role in the 1965 "Bloody Sunday" conflict and the following Selma to Montgomery marches for voting rights, also represents significant engineering achievements with its distinctive design and construction methodology. In this study, the research team presents a comprehensive framework for documenting heritage bridges by utilizing Terrestrial Laser Scanning (TLS) technology, supplemented by other Reality Capture (RC) techniques, including Structure from Motion (SfM), 360-degree photography, and Unmanned Aerial Vehicle (UAV), and integrating the data within a Building Information Modeling (BIM) environment. The focus on the Edmund Pettus Bridge case study demonstrates how this novel approach can capture the intricate details of its structural and architectural features while preserving its historical narratives. The documentation outcomes, including a detailed BIM model and a set of Historic American Engineering Record (HAER) drawings, highlight the effectiveness of combining TLS and BIM in conserving unconventional heritage structures like bridges. This paper also discusses the technological challenges encountered, such as dealing with heavy traffic and environmental constraints during data acquisition and developing the BIM model and drawings. It outlines the strategies implemented to address these issues. This research contributes to preserving a severely under-represented American National Historic Landmark (NHL). It sets a precedent for documenting other non-building heritage structures, balancing technological advancements with historical integrity.

Keywords: BIM; cultural heritage; Edmund Pettus bridge; heritage infrastructure; scan-to-BIM; TLS

check for updates

Citation: Willkens, D.S.; Liu, J.; Alathamneh, S. A Case Study of Integrating Terrestrial Laser Scanning (TLS) and Building Information Modeling (BIM) in Heritage Bridge Documentation: The Edmund Pettus Bridge. *Buildings* **2024**, *14*, 1940. https://doi.org/10.3390/buildings14071940

Academic Editors: Pramen P. Shrestha, Silvana Bruno, Irem Dikmen, Juan Enrique Nieto-Julián and Juan J. Moyano

Received: 29 March 2024
Revised: 20 June 2024
Accepted: 22 June 2024
Published: 26 June 2024

1. Introduction

Heritage engineering structures, like bridges, stand as a testament to historical and cultural narratives and the advancements in engineering and architecture over the ages. Often representing significant historical events and technological milestones, these structures impose documentation and preservation for future generations to study, interpret, understand, and appreciate. The conservation of heritage bridges is critically dependent on accurately documenting their current state [1]. However, the documentation of heritage bridges presents unique challenges. Traditional methods mainly relied on manual measurements, hand-drawn sketches, and photography, which, while valuable, often fall short of capturing the intricate details in the required precision [2,3] and the full scope of these structures. These techniques are invasive, posing risks to the physical condition of the often delicate historical sites [2,4,5]. The complexity of the design of the bridges, combined with their historical significance, requires a documentation approach that is comprehensive and respectful of the structure's integrity [6].

The documentation of heritage bridges has seen a significant shift in the past few decades towards adopting modern Reality Capture (RC) technologies, supplementing traditional labor-intensive methods with more sophisticated, accurate, and non-intrusive techniques. This transition is primarily driven by advancements in digital imaging, laser scanning, computer-aided drafting (CAD), and three-dimensional modeling technologies [2,7,8], which offer unparalleled precision and efficiency in capturing the details of heritage infrastructures. One of the most prominent technologies reforming heritage documentation is Terrestrial Laser Scanning (TLS). TLS provides high-resolution, three-dimensional point clouds that accurately represent the spatial dimensions of built heritage [9,10]. This technology enables the detailed examination of structural conditions without physical contact, thus preserving the historic site. Furthermore, the data captured through TLS can be easily archived and shared, supporting collaborative research and preservation efforts across different disciplines and by different stakeholders [11]. Building Information Modeling (BIM) has also emerged as a powerful tool in the documentation and management of heritage sites [12,13]. According to Borkowski [14], BIM can be understood broadly as a collaborative process involving people, information systems, databases, and software. In a narrower sense, BIM is a semantic database that tracks and manages information about a built object throughout its lifecycle. One of the recent advancements in utilizing BIM in heritage preservation practice was the introduction of Historic (or Heritage) Building Information Modeling (HBIM) by Murphy [15]. BIM and HBIM go beyond precise and comprehensive geometric representation. They also incorporate detailed metadata about materials, structural conditions, and historical significance into a comprehensive digital model. This integration of information facilitates a holistic approach to heritage conservation, allowing for better planning and execution of restoration projects while ensuring that all interventions are accurately recorded for future reference [16]. Additionally, the use of unmanned aerial vehicles (UAVs), also known as drones, equipped with cameras and Structure from Motion (SfM) or photogrammetry technology, has become increasingly common. These drones can access difficult-to-reach areas of bridges and effectively cover a large structure in a short period of time, providing unique vantage points and detailed imagery that can be used to create precise 3D models of the structures [17–19]. This capability is also useful for monitoring the condition of bridges over time, identifying potential issues before they become critical.

The inclusion of these modern technologies represents a new era in the documentation of heritage bridges. They offer greater accuracy and detail in the recording process and provide a dynamic platform for the analysis, conservation, and sharing of heritage data. As these technologies continue to evolve and become more affordable, it is expected that their application in heritage preservation will become more accessible, ensuring that invaluable cultural landmarks are documented and preserved for future generations with unprecedented fidelity and care. The aim of this study is to illustrate a novel framework of integrating TLS and BIM, along with several other RC technologies, to create detailed, accurate, and non-intrusive digital records of heritage bridges, using the Edmund Pettus Bridge (EPB) as a focal case study. The EPB, located in the city of Selma, Alabama, USA, as a symbol of the American Civil Rights Movement and a marvel of engineering in its days, offers a rich context for exploring the capabilities of modern documentation technologies.

This research presents a comprehensive account of developing an accurate BIM representation of the EPB, primarily utilizing TLS technology. While BIM involves a wide array of functionalities beyond creating a 3D model—including integrating historical records, maintenance plans, damage assessments, and component-specific information—this study focuses on laying the foundational geometric model that accurately reflects the bridge's current state. It is important to clarify that although the research emphasizes the development and documentation of this structural representation, the potential of BIM as a platform for the holistic preservation and maintenance of heritage structures is fully recognized. Therefore, this article's scope is centered on establishing a detailed and accurate baseline BIM model, intended as a robust platform for future extensions. Such extensions could include incorporating detailed condition assessments, maintenance strategies, and the integration of historical data, which are critical to the comprehensive management and preservation of heritage sites.

The structure of this article begins with an introduction that sets the stage by presenting the need for accurate and non-intrusive heritage bridge documentation methods. Next, it delves into a literature review that surveys existing documentation practices and the emergence of modern techniques like TLS and BIM. The Materials and Methods section outlines the specific approaches taken in this case study, detailing the data acquisition process and the development of a BIM model and Historic American Engineering Records (HAER) drawings. Following this, the Results and Discussion section presents the findings from the TLS survey and BIM model development, addressing the challenges encountered during the process, the solutions employed by the research team to overcome these challenges, and the impact of the documentation on preserving the EPB. The article concludes with a summary of key findings, reflecting on the implications of this research for the field of heritage documentation and offering recommendations for future studies of these technologies in similar conservation efforts.

This paper uses many abbreviations to refer to various terms and concepts. To avoid confusion and ensure clarity, the authors provide a list of these abbreviations and their corresponding meanings:

- AI: Artificial Intelligence
- AR: Augmented Reality
- BIM: Building Information Modeling
- EPB: Edmund Pettus Bridge
- GPS: Global Positioning System
- HABS: Historic American Buildings Survey
- HAER: Historic American Engineering Record
- HBIM: Heritage (or Historic) Building Information Modeling
- HDP: Historic Documentation Programs
- HSR: Historic Structure Report
- LiDAR: Light Detection and Ranging
- MLS: Mobile Laser Scanning
- MTLS: Mobile Terrestrial Laser Scanning
- NPS: National Park Service
- RC: Reality Capture
- SfM: Structure from Motion
- STLS: Static Terrestrial Laser Scanning
- TLS: Terrestrial Laser Scanning
- UAV: Unmanned Aerial Vehicle
- VR: Virtual Reality

2. Literature Review

2.1. Traditional Heritage Documentation Methods

The Historic American Engineering Record (HAER) program, established in 1975 by the Historic Documentation Programs (HDP) of the U.S. Department of Interior's National Park Service (NPS) [20], has started a deliberate campaign to chronicle historic bridges across the United States. Since its founding, over 250,000 bridges have been marked for replacement due to structural deficiencies or obsolescence in functionality. Although it is impractical to preserve every historic bridge, the HAER documentation initiative ensures that selected bridges are conserved on paper. It is the hope that, through this process, a number of these exceptional bridges will be retained for future generations to appreciate [21]. Most of the bridges in the HAER collections were documented using traditional methods. These methods have relied on a combination of manual measurements, hand-drawn sketches, photography, and measured drawings [8,21,22]. These techniques, while valuable for their historical use and simplicity, come with several limitations in the context of modern heritage conservation needs. The following sections will discuss these traditional methods and their limitations.

2.1.1. Manual Measurements and Hand-Drawn Sketches

Manual measurement involves the use of tools like tape measures, levels, and plumb lines to obtain physical dimensions of structures. These measurements are often complemented by hand-drawn sketches that attempt to capture the architectural details and structural elements of the bridge. Some researchers argue that these methods provide opportunities for the recorders to have close interaction with the structures of interest [23–25] and are effective for small-scale projects [21]. However, they are also subject to human errors and may not capture the precise dimensions needed for detailed analysis and restoration work [25]. The complexity of heritage bridges, with their intricate designs and hard-to-reach areas, compounds these accuracy issues. The manual process is slow and requires a significant amount of manpower, making it impractical for large or complex structures [26–28]. Furthermore, physical contact with the structure is often necessary with these methods, which can be harmful to fragile or deteriorating heritage structures [29].

2.1.2. Photography

Photography has been a main technique in documenting heritage structures, offering visual records that provide insights into the condition and appearance of the bridge at a given time [30]. While photographs offer valuable visual information, they cannot capture the three-dimensional aspects of structures effectively. This can lead to gaps in understanding the spatial relationships and dimensions of structural components [31]. Additionally, the information captured can vary significantly depending on the photographer's skill, the equipment utilized, and environmental conditions [32].

2.1.3. Measured Drawings

Measured drawings are detailed drawings created from manual measurements, intended to represent the structure accurately on paper or in digital form. Producing these drawings is labor-intensive and requires a high level of expertise to ensure accuracy. Scaling down complex structures like a bridge accurately to a drawing presents challenges, potentially leading to oversimplification or loss of detail. Like photographs, measured drawings are limited to providing a static view of the structure, lacking the ability to easily update or manipulate the data for further analysis [33,34].

2.2. Modern Documentation Techniques

Over the years, documenting built heritage has demonstrated a dynamic evolution in integrating modern digital technologies with traditional analog techniques. The incorporation of modern digital survey technologies like laser scanning, close-range and aerial photogrammetry, and advanced topographic surveying has significantly enhanced documentation processes [26]. These advancements offer improved efficiency, heightened accuracy, broader data compatibility, and enriched information interpretation.

HDP's roadmap of adopting modern techniques, as illustrated in Figure 1, is an excellent example of how digital technologies have advanced in the field of heritage documentation. Starting in the 1950s, HDP integrated photogrammetry into its documentation [35] to record historical structures with enhanced detail. By the 1970s, aerial photogrammetry expanded its scope to larger sites, including Native American villages in Arizona and New Mexico [27]. The 1980s saw the adoption of CAD for precise drawings, which significantly improved documentation accuracy [36]. The 1990s introduced laser technologies for enhancing measurement precision [30], and the 2000s marked a major shift with laser scanning technologies for 3D documentation, exemplified by the Statue of Liberty project [26].

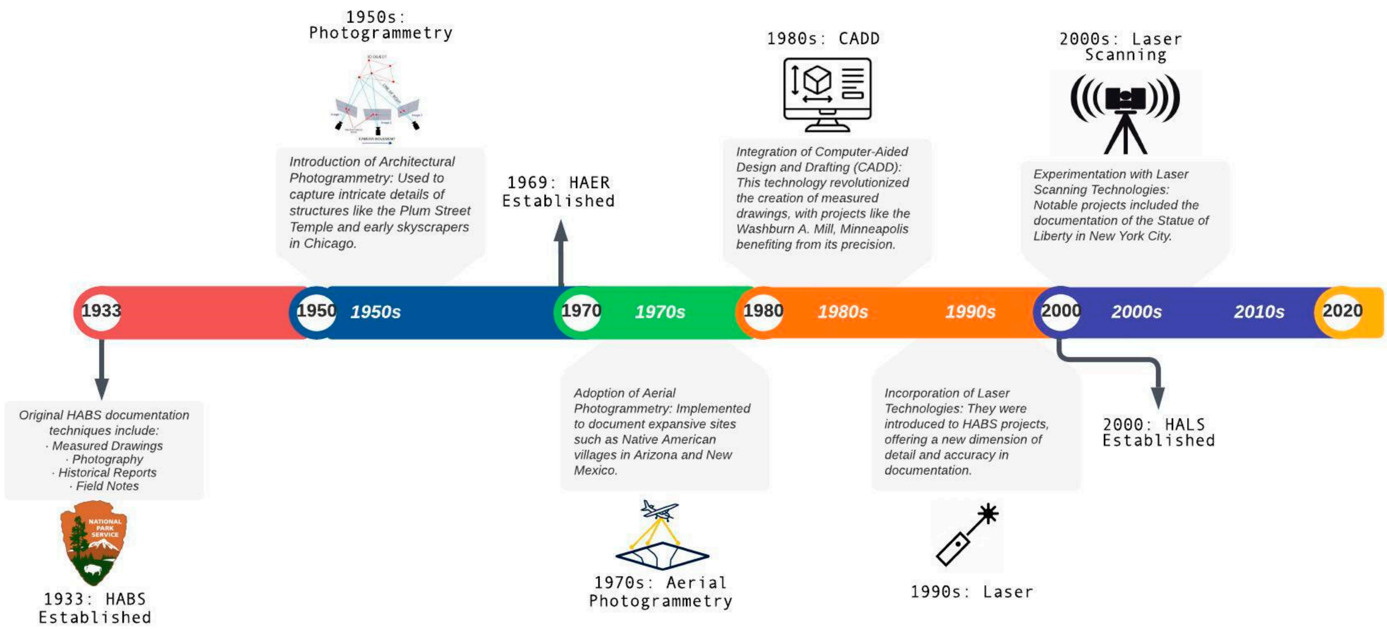


Figure 1. Roadmap of the technological evolution of HDP's documentation [23].

2.3. Terrestrial Laser Scanning (TLS)

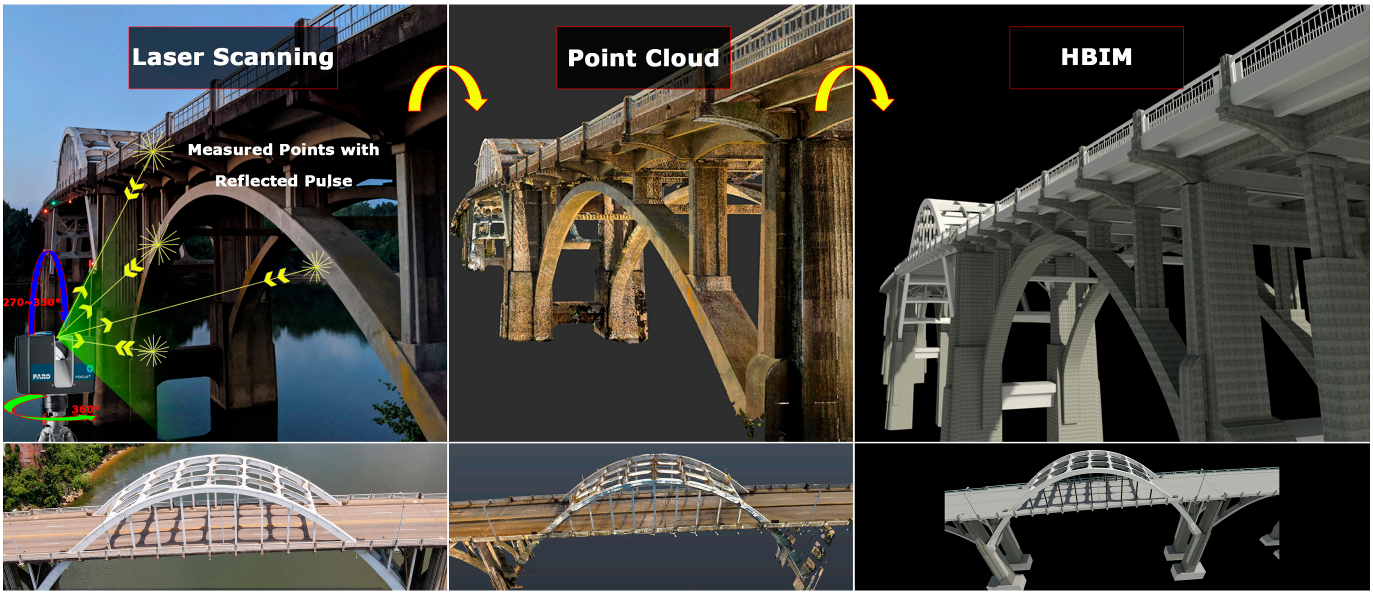
2.3.1. Introduction to TLS

TLS is a form of ground-based LiDAR (light detection and ranging) technology [37] that employs laser sensors to gather detailed point clouds representing physical objects [38]. There are two primary forms of TLS: static TLS (STLS) and mobile TLS (MTLS). STLS involves using a tripod-mounted laser scanner positioned at a fixed point. This method scans the environment from various positions to gather high-resolution 3D data. STLS is frequently employed in fields such as construction, architecture, and engineering for precise measurements of built structures and site conditions [39,40]. MTLS, in contrast, involves mounting a laser scanner on mobile platforms, such as vehicles, backpacks, or even handheld devices. As the platform moves through an area, the scanner captures 3D environmental data, facilitating rapid and efficient data collection. MTLS finds relatively widespread use in surveying, mapping, autonomous driving, and infrastructure management [41–43].

Both technologies have distinct advantages and drawbacks. STLS is known for its high resolution and accuracy, making it particularly suitable for capturing detailed data in smaller areas [44,45]. Meanwhile, MTLS can cover larger areas quickly, which is ideal for extensive site scanning. It can also reach areas that are difficult to access, like very tight spaces [46,47]. However, the data captured by MTLS often are less detailed than those from STLS due to the movement involved during scanning, and factors like the platform's speed and trajectory can impact MTLS data accuracy as well [41,42].

Figure 2 illustrates the principle of STLS technology. As noted by Yang et al. [48], STLS has become a vital tool for capturing point clouds of heritage structures. While MTLS has been less explored in heritage documentation [49,50], most research employing TLS for data acquisition has focused on STLS exclusively. Therefore, this study concentrated solely on STLS, with all references to TLS in this context pertaining to the static form of the technology.

TLS surveys involve capturing multiple scans from various angles to comprehensively document a heritage structure. These scans are then processed through alignment and registration within specialized software to compile a complete point cloud model. Initially, scan alignment identifies common reference points or features within the overlapping scans, which can be either naturally occurring elements or intentionally placed markers. Software algorithms proceed to calculate the necessary adjustments, including shifts and rotations, to align these reference points precisely, thereby reducing spatial inconsistencies among the scans. Following alignment, the registration phase integrates these adjusted scans into a singular, coherent point cloud. This step fine-tunes the alignments to ensure smooth transitions between scans, removes overlapping data redundancy, and verifies that the resulting unified point cloud faithfully captures the structure's geometric and spatial attributes.



(**a**) (**b**) (**c**)

Figure 2. TLS technology and its application in heritage documentation. (**a**) Principle of TLS. (**b**) A resultant point cloud of TLS survey. (**c**) A Heritage BIM (HBIM) model developed using the TLS point cloud data.

2.3.2. TLS in Heritage Documentation

Transitioning from modern construction, TLS has found a unique and invaluable place in heritage documentation. In this domain, the technology is used to capture the existing condition of heritage structures. Subsequently, the captured data are utilized to conduct a structural assessment or develop materials to help manage and interpret the heritage asset. Specifically, TLS is instrumental in various aspects of heritage bridge documentation. It includes the development of BIM or HBIM [6,13,22,51–53], structural analysis [6,22,54,55], and damage detection [56–58]. Additionally, TLS data can be integrated with virtual reality (VR) and augmented reality (AR) technologies to create immersive virtual museums and tours [52] for enhancing public education and research.

TLS is particularly valuable in documenting built heritage that is in poor condition. An example is the Kunerad Mansion in Slovakia [59], where TLS effectively captured data in challenging environments characterized by inadequate lighting and structural instability. The non-destructive nature of the TLS method facilitated thorough and precise documentation, forming a critical foundation for the restoration and conservation work that followed [60,61].

2.3.3. TLS Advantages and Limitations

Recent research studies have highlighted the emergence of TLS as a critical tool for collecting existing condition data of heritage assets [62]. The leading benefits of TLS, as compared to traditional documentation methods, include its exceptional precision [63,64], its ability to rapidly gather extensive data relative to the time invested [65], and its comprehensive, non-intrusive approach to capturing objects without the requirement for physical contact or repeat field visits [54,66], thus preventing the need for subsequent site surveys [59]. Al-Bayari and Shatnawi's study [67] noted that utilizing TLS in heritage documentation reduced field survey time by 25–30%.

While TLS offers significant advantages in heritage documentation, it also presents specific challenges and limitations. Primarily, the cost factor is considerable; acquiring a new laser scanner can require an investment of tens of thousands of dollars [59]. TLS demands the use of specialized software, robust hardware, and skilled professionals for effective data processing and management [63,68]. Another challenge is the time-intensive nature of TLS surveys [69] for very large or complex heritage sites. TLS fieldwork is sensitive to environmental factors such as lighting, dust, fog, and rain, which can affect data quality [59]. Furthermore, TLS faces challenges in capturing certain surfaces or materials. Shiny, reflective, black, extremely hot, very bright, and transparent surfaces often pose difficulties in accurate scanning. Objects that are not within the line of sight or are obscured remain beyond TLS's capturing capability [70]. Accurately capturing color and texture also presents a challenge for many LiDAR scanners used in heritage studies [71].

2.4. Intergration of TLS and BIM

TLS data can generate several outputs that are instrumental in heritage documentation. A primary product is the creation of BIM models [15], which are developed from scan data. These models offer a detailed and accurate digital representation of heritage sites, proving invaluable for tasks such as preservation planning, damage assessment, and restoration initiatives. Additionally, the point cloud data generated by TLS can be used to produce 2D drawings, such as HAER or HABS. These drawings serve as a traditional form of documentation, capturing the structural and architectural details of heritage assets [72,73]. Another significant output of TLS is the development of 3D interactive environments that merge VR or AR with the scan data and BIM models. These immersive environments provide a dynamic and engaging way for the public to explore and learn about heritage sites, making them an effective medium for interpretation and educational purposes [15,74,75]. These various outputs of TLS data collectively enhance people's ability to understand, preserve, and share the rich heritage captured in historical structures.

Much published research utilizes the scan-to-BIM approach to develop BIM models for heritage bridges from the captured TLS point clouds as a primary data source [5,8,76]. This method starts with scanning the bridge structure to create a detailed point cloud, which is then used as a reference to build an accurate 3D model in a BIM software platform, such as Autodesk Revit, Trimble Tekla, or Bentley OpenBridge Modeler [77–79]. This approach is particularly effective for capturing the as-built conditions of existing structures, providing a precise digital representation based on real-world data [5,22]. The scan-to-BIM approach is feasible for documenting heritage bridges due to the following:

- Accuracy and Detail: Given the bridge's historical significance and complex structure, the scan-to-BIM approach is ideal for capturing its intricate details with high accuracy.
- Preservation and Documentation: This method is non-intrusive and perfect for historic preservation efforts, allowing for detailed documentation without physically impacting the structure.
- Efficiency and Integration: It provides an efficient workflow for integrating the scanned data into the 3D modeling platform, streamlining the process of converting point clouds into a usable BIM model.
- Facilitation of 2D CAD Drawings: An additional value of the scan-to-BIM approach is its utility in creating accurate 2D as-built CAD drawings. Usually the detailed 3D BIM model can be utilized to generate precise 2D drawings, which are essential for heritage documentation.

The integration of TLS and BIM technologies represents a pivotal advancement in structural analysis and preservation. This combination allows for the precise capture and detailed modeling of heritage structures [80], enabling the assessment and monitoring of structural integrity over time [81,82]. For instance, BIM's parametric models facilitate ongoing monitoring cycles, crucial for tracking displacements and deformations in structures like wooden trusses [70], thus offering a dynamic approach to conservation efforts. Moreover, the versatility of BIM extends to documenting, managing, and analyzing structural health information, including damage and decay, thereby providing a comprehensive understanding of a structure's condition [83]. The ability to model and quantify structural deformations and damages within the BIM framework enhances the decision-making process in restoration and maintenance plans [81,84]. Furthermore, the integration of TLS with BIM enriches the structural safety assessment, enabling the identification of pathological symptoms and the analysis of complex geometries through non-destructive techniques [81].

2.5. Other RC Technologies Complementing TLS

While TLS plays an important role in modern heritage documentation, the complex geometry of built heritage, especially bridges, and specific limitations inherent to laser scanning technology mean that TLS alone may not suffice for comprehensive data acquisition. To address this, additional technological tools and techniques are often employed to supplement the TLS data or to enhance its accuracy and quality [68,85,86]. These supplementary technologies can be categorized as follows:

- Structure from Motion (SfM) or Photogrammetry: This technique can be implemented terrestrially or via UAVs. It offers alternative means of capturing detailed imagery and constructing 3D models of built heritage [54,87–90].
- Mobile/Handheld LiDAR or Photogrammetry Scanners: These portable devices provide flexibility and ease of use in diverse environments. They enable the capture of detailed spatial data in areas where TLS might be less effective [91,92].
- 360-Degree Photography: This technology captures a full spherical view of a surrounding area to provide an immersive experience by allowing viewers to look around in all directions from a single point. In heritage documentation, this technology offers applications such as immersive virtual tours to record detailed texture and colors of the built heritage and to enhance accessibility [93–95].
- Error Control and Data Verification Devices: To ensure the accuracy and reliability of the captured data, devices such as total stations and global positioning systems (GPSs) are utilized. These instruments are beneficial in controlling errors and verifying the quality of data obtained from TLS surveys [84,89,96].

Integrating these RC technologies with TLS to document heritage structures also introduces challenges, notably in merging diverse datasets (or data fusion). Aligning data across different formats and resolutions demands advanced software and technical expertise [63,97]. Ensuring uniform accuracy and addressing discrepancies in data quality, especially in less accessible areas, adds complexity [98]. Additionally, the integration process is resource-intensive, requiring substantial computational power and storage to manage the vast amounts of data generated [86]. Despite these obstacles, leveraging a combination of these technologies offers a path towards more detailed and comprehensive documentation of heritage sites.

Documenting built heritage may require georeferencing TLS point clouds, which involves assigning real-world coordinates to each point captured during scanning, ensuring that the data accurately represents its physical location and orientation. This process is valuable in heritage documentation, as it allows for the precise mapping and modeling of historic sites and structures [99–101]. By integrating these georeferenced point clouds into GIS or BIM systems, conservationists and architects can perform detailed analyses, assess structural conditions, plan restorations, and virtually explore and share the heritage site's spatial data, enhancing both preservation efforts and public engagement. As explained by Shabani and Kioumarsi [102], two total stations were used to define targets for establishing a local coordinate system to document a historical masonry bridge and eventually helped georeference the point clouds to avoid possible errors captured from different instruments.

2.6. Need for the Current Study

Despite the abundance of studies on employing TLS and BIM in heritage documentation, most have focused on buildings, presenting a gap in research and application concerning non-building structures such as bridges. By demonstrating the effective use of these technologies on a historically and structurally complex bridge, this study tries to fill a critical gap in the existing literature. It expands the applicability of digital documentation methods within heritage conservation. It provides a robust and adaptable model for documenting a variety of heritage infrastructures that pose unique challenges for preservation.

3. Materials and Methods

3.1. Project Information

The Edmund Pettus Bridge (EPB), a significant landmark in American history and an example of early 20th-century engineering, spans the Alabama River in Selma, Alabama (Figure 3). Constructed from 1938 to 1940, the bridge was named after Edmund Pettus (1821–1907), a Confederate general who later became a US Senator and a figure deeply embedded in the racial hierarchy of the Antebellum period. It is a complex symbol of historical oppression and the fight for African American civil rights [58]. Designed by a Selma-born engineer, Henson Stephenson (1897–1978), the bridge's architectural style is characteristic of its era, featuring a steel through-arch with concrete open-spandrel arches. It stretches 1248 feet and 6 inches long (380.5 m), navigating significant topographical changes along its path. The bridge's unique structural design, including its asymmetrical arches and decorative elements, showcases the engineering achievements of the time. However, the only substantial change since its construction was replacing its original green paint with a cool gray in the early 1980s [58]. Beyond its architectural significance, the Edmund Pettus Bridge is marked by its role in the American Civil Rights Movement. It was the site of "Bloody Sunday" on 7 March 1965, a pivotal event where peaceful civil rights demonstrators were violently confronted by law enforcement. This event was a critical moment in the Selma Voting Rights Movement, leading to the passage of the Civil Rights Act in 1965. The bridge's dual symbolism is further highlighted by its inclusion in the Selma to Montgomery National Historic Trail, a testimony to its role in the Civil Rights struggle. The bridge was declared a National Historic Landmark (NHL) on 27 February 2013.

Despite its historical and architectural significance, the EPB faces challenges concerning its condition and the need for attention. As it continues to serve as a vital connection along Highway US-80, the preservation and maintenance of the bridge are of paramount importance. As shown in Figure 4, the bridge's structure, while largely intact, reflects the wear of decades and the need for thorough assessment and careful conservation.

The documentation for the EPB, as a part of an effort for developing a Historic Structure Report (HSR) of this historically significant structure, aimed to thoroughly record and archive the bridge's existing condition to preserve its historical and architectural legacy for future generations. The two primary documentation outcomes included a BIM model and a set of HAER drawings. The BIM model served multiple purposes: it aided in the preservation efforts by providing a precise representation of the bridge's current state, and it also formed the basis for the development of the HAER drawings. The HAER drawing set, the second crucial outcome of the project, provided a detailed architectural and engineering record of the bridge.

3.2. TLS Survey

As illustrated in Figure 5, the process of digital documentation of the EPB involved four main stages: site assessment and project planning, on-site data acquisition, data post-processing and management, and data utilization for developing the BIM model and HAER drawings.

Figure 3. An aerial photograph of the Edmund Pettus Bridge.

(**a**) (**b**) (**c**) (**d**)

Figure 4. Places of the bridge needing maintenance and repairs. (**a**) Corrosion and paint maintenance needed along Span-2. (**b**) Damaged railing plate and baluster on Span-8. (**c**) Chipped and damaged cast-in-place concrete stanchion and broken baluster on Span-7. (**d**) Damaged expansion joint and missing cover plate near the north approach ramp.

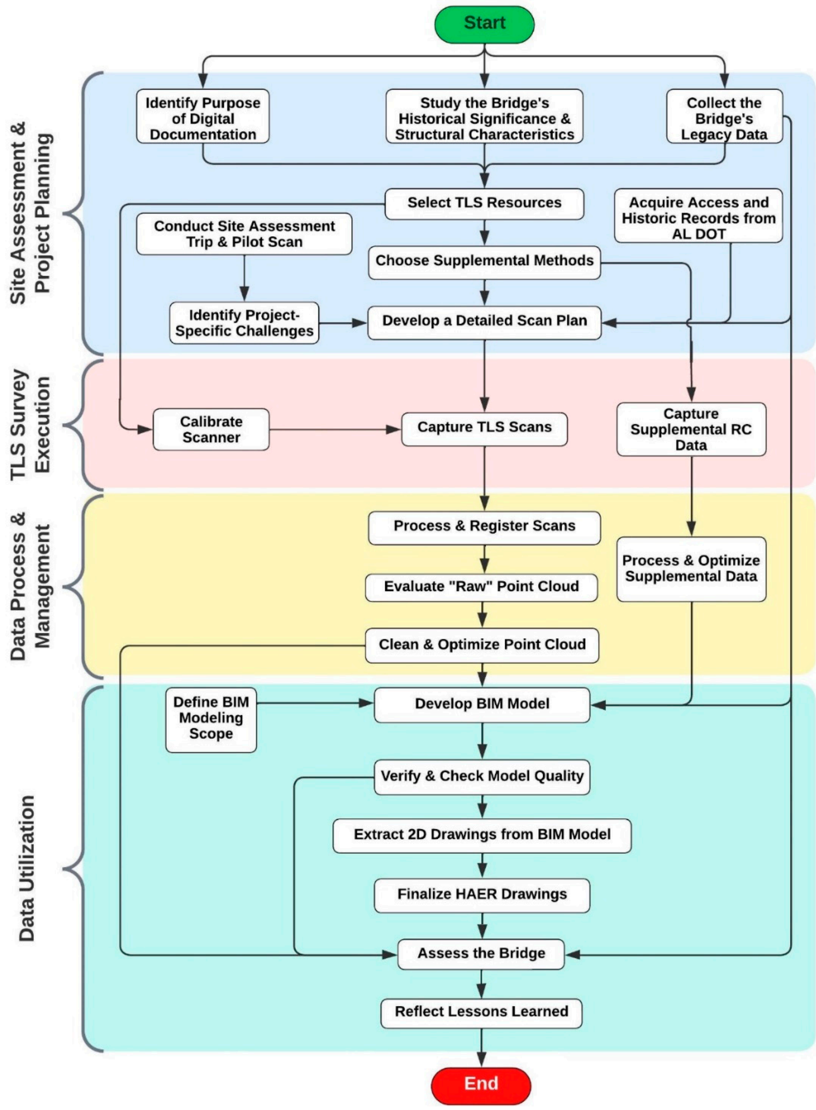


Figure 5. The process of documenting the Edmund Pettus Bridge.

3.2.1. Selection of Techniques and Resources

Selecting TLS as the primary data acquisition method for the EPB documentation was influenced by its precision, efficiency, and non-intrusiveness. TLS's ability to capture detailed and comprehensive three-dimensional data without making contact with the structure makes it ideal for preserving historic integrity. Additionally, its speed in surveying complex structures, adaptability to various conditions, and compatibility with integration technologies like BIM and CAD render it highly suitable for efficiently documenting and assessing this historically and architecturally significant bridge with accuracy and care.

A FARO Focus3D X-330 HDR (FARO X330) scanner was employed to conduct the TLS survey. At the time of the documentation project, the FARO X330 scanner was extensively used in documenting the built environment due to its high precision, outstanding efficiency, and superior mobility. Its cost-effectiveness further contributed to its widespread popularity in commercial laser scanning applications. Table 1 provides an overview of the key specifications and functionalities of the scanner. These features highlight its appropriateness for the documentation needs of the bridge.

Several software programs were also utilized for data acquisition, processing, and modeling. Each piece of software was chosen for its specific capabilities and compatibility with the project's goals. Table 2 summarizes the roles and rationales for each software program in the project workflow, from processing the TLS scans to developing the final

BIM model and 2D HAER drawings. The following sessions will explain details of the workflow and how the software programs were used in the case study.

Table 1. Key specifications of a FARO X-330 scanner.

Specification	Detail
Range	Up to 330 m (1082 feet)
Field of View	360° horizontal, 305° vertical
Accuracy	Up to ±2 mm (±0.08 inches) at 25 m (82 feet)
Laser Class	Class 1
Scan Speed	Up to 976,000 points/second
HDR Imaging	Yes, integrated
Weight	Approximately 5.2 kg (11.5 lbs)
Multi-Sensor	GPS, Compass, Altimeter, Dual-Axis Compensator
Battery Life	4.5 h of continuous scanning
Data Storage	SD Card or via Wi-Fi

Table 2. Software programs used for the Edmund Pettus Bridge project.

Software	Use in Project	Justification
FARO SCENE	Processing and registering TLS scan data.	Compatible with FARO scanners; efficient in processing and registering a large amount of TLS scans.
Autodesk ReCap Pro	Cleaning and preparing point cloud for BIM and CAD use.	Advanced editing tools; integrates well with Autodesk products.
Autodesk Revit	Developing the BIM model of the bridge.	Industry standard for BIM; supports point cloud data.
Autodesk AutoCAD	Creating CAD drawings of the bridge.	Precision drafting; widely accepted in professional fields.

To complement TLS, several other RC technologies were employed for a more comprehensive data acquisition. SfM captured complex details and surface textures to enhance the geometric data from TLS, especially in hard-to-reach areas. Matterport 360-degree photography technology offered interactive panoramic views, aiding in the visualization of surface details for BIM model development [103,104]. UAVs equipped with high-resolution cameras provided aerial perspectives and access to challenging sections, such as the bridge's arch, and spans over the river. Additionally, UAV-based infrared photography was instrumental in identifying hidden structural vulnerabilities, like moisture intrusion, which was crucial for assessing the bridge's condition.

3.2.2. TLS Survey Planning

An initial assessment for the TLS survey of the EPB was conducted first, involving several critical steps:

- Preliminary Site Visit and Pilot Scans: This site visit focused on the north approach ramp and Span-1 on the city of Selma side of the bridge. Pilot scans using the FARO X330 laser scanner were also performed (Figure 6) to evaluate the equipment's effectiveness in the bridge's environment and validate scanning strategies.
- Photographic Surveys and Coordination with ALDOT: Photographic surveys were conducted to document existing conditions and assist in planning the scanning process. A meeting with the Alabama Department of Transportation (ALDOT) was held to discuss the project scope and the operational, safety, and logistical aspects, and gain access to the bridge's historical and maintenance records.

Figure 6. Pilot scans of Edmund Pettus Bridge.

The project team discovered several challenges and notable features of the site through the assessment visit and pilot scans. They included the following:

- Traffic Conditions: The bridge experienced traffic at high speeds, often exceeding the official limit of 20 MPH (32 km/h). Observations indicated that traffic speed could reach up to 45 MPH (72 km/h), causing significant vibration that potentially affected scanning accuracy.
- Optimal Timing for Field Survey: The least traffic, identified as early Sunday mornings, was considered the most feasible time for extensive field surveys to minimize safety risks and data acquisition interference.
- Environmental Factors: The dense vegetation south of the Alabama River (Figure 7), high humidity levels, potential for high winds, and significant temperature-induced expansion of the bridge were noted. These factors required considerations for equipment stability and data accuracy, especially since the survey was anticipated to span several months.
- Access Limitations: Restricted access was noted in areas under the bridge, particularly over spans 1, 2, and 3 above the Alabama River (as shown in Figure 8) and on the bridge's medians. These limitations required strategic planning for scanner placement and data capture with alternative methods.

Figure 7. Dense vegetation around the bridge.

3.2.3. TLS Survey Execution

The TLS survey started in November 2019, with completion initially targeted for Spring 2020. However, due to the COVID-19 pandemic outbreak, the project experienced a temporary halt, resuming in summer 2020 and concluding in July 2020. A total of 72 scans were captured. The bridge was divided into four sections for systematic scanning, as shown in Figure 9:

- Section-A (bottom and deck, Selma City side, north of the Alabama River)
- Section-B (bottom, Dallas County side, south of the Alabama River)
- Section-C (deck, Dallas County side, south of the Alabama River)
- Section-D (deck, Selma City side, and the arch of Span-2, north of the Alabama River)

The project team chose strategic points to set up the scanner for optimal coverage, particularly paying attention to elevated areas, complex elements, and the scanner's range limits. Scanner locations identified on the bridge deck are illustrated in Figure 10.

A targetless approach was used to capture all the scans due to the time and resource constraints of the project. Scanning of the deck (e.g., sections C and D) was carried out early on Sunday mornings to avoid heavy traffic. Scanning of the bridge bottom (e.g., sections A and B) was performed throughout the day.

For a comprehensive TLS survey of this large and complex structure, choosing an optimal scanner setting was crucial to balance detail, coverage, and efficiency. The project team used the same settings for all 72 project scans, as shown in Table 3.

Table 3. Scanner settings for Edmund Pettus Bridge project.

Scanner Setting	Chosen Value
Range	Max (330 m/1082 feet)
Resolution	1/2
Quality	2×
Scan Size	20,480 × 8533 Pt
Point Distance	0.110 in/30 ft
Scan with Color (Imaging)	On
GPS	On
Inclinometer	On
Scan File Size	approx. 670 MB
Scan Speed	approx. 12:00 min/scan
Firmware Version	Rev. 5.5.9.1059

3.3. TLS Scan Data Processing and Management

All 72 scans were initially processed through FARO SCENE software. This step included colorizing and converting the raw data into usable point clouds, ready for further processing and analysis. Next, the "Moving Objects Filter" feature within FARO SCENE was utilized to eliminate noise, such as points of passing vehicles and pedestrians, from the data. This feature helped improve the cleanliness and clarity of the point cloud, especially given the bridge's high-traffic environment.

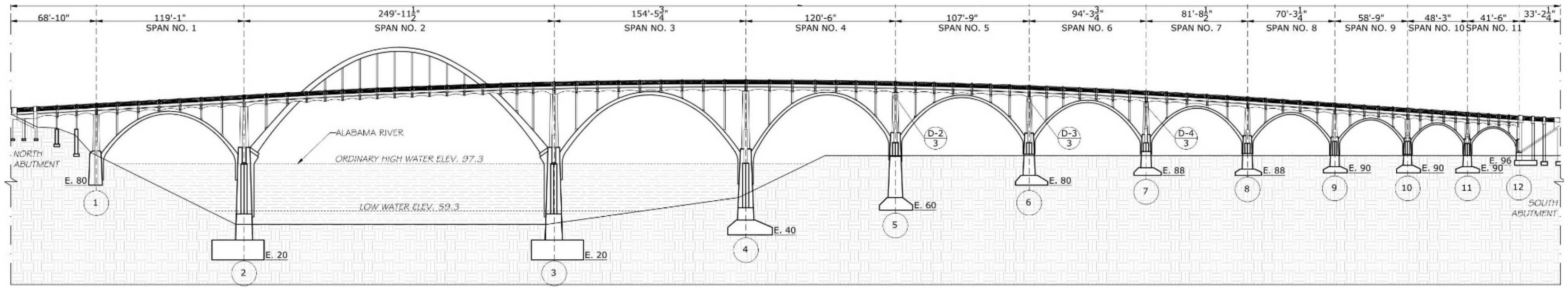


Figure 8. West elevation of Edmund Pettus Bridge.

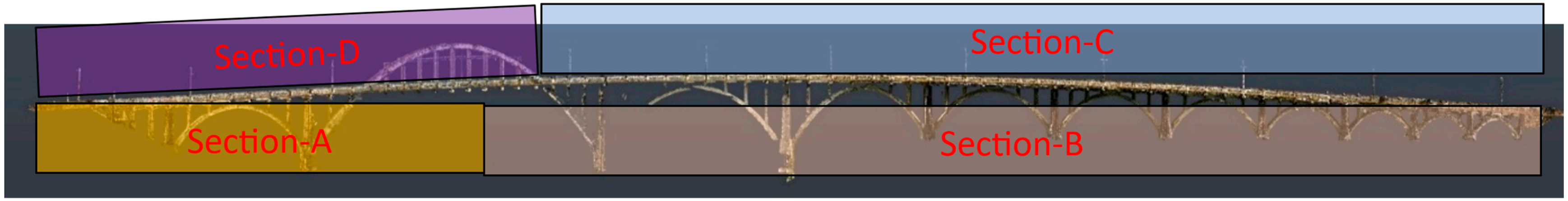


Figure 9. TLS survey phasing plan for Edmund Pettus Bridge.

Figure 10. Planned scanner locations on the bridge's deck.

Next, the scans were combined into one comprehensive point cloud in a few steps. First, the 72 scans were grouped into four clusters based on the bridge's different sections, making it easier to work on. Then, an automatic registration feature in FARO SCENE aligned the scans within each cluster and merged them into one whole. After this automatic step, manual tweaks were made to improve the alignment, especially where the bridge's design was more complex or scans were far apart. This process resulted in a single point cloud that detailed the entire bridge, as shown in Figure 11. The final FARO SCENE project file was notably large, exceeding 117 GB.

Figure 11. Registered point cloud of the whole bridge.

The FARO SCENE scan registration report provided detailed error statistics and overlap information for each scan and cluster as a main matrix to evaluate the quality and accuracy of the TLS survey. The report showed that the average deviation between overlapping scan points, known as the point error, was generally low, with an average error of 3.7 mm, indicating precise data collection [105,106]. The maximum error found was 31.6 mm, which is acceptable for large outdoor scans and could result from hard-to-reach areas or environmental factors like vibration or temperature changes. The report also noted that the least overlap between scans was 5.9%, suggesting that, despite some areas having less coverage, the scan integration was successful. Overall, the quality and accuracy of the TLS survey were acceptable for the project, especially considering the scale and complexity of the bridge.

After initial processing with FARO SCENE, the point cloud data were refined and prepared for 3D modeling through several steps. First, the data were exported to Autodesk ReCap Pro (ReCap Pro) and saved in the RCP format, making them ready for use in applications like Autodesk Revit and Autodesk AutoCAD. Quality control checks to ensure the data's accuracy and quality were then conducted in ReCap Pro through visual inspections and measuring known distances on the bridge. To make the point cloud more manageable for modeling, the data were optimized by reducing their density, significantly shrinking the file size from 117 GB to 3.4 GB. This optimization facilitated more efficient handling and use of the data in 3D modeling software.

3.4. BIM Model Development

The project team chose to employ the scan-to-BIM approach to develop a comprehensive model for the EPB in Autodesk Revit. This approach was particularly effective for capturing the as-built conditions of existing structures, providing a precise digital representation based on real-world data. The primary foundation for developing the BIM model was the Autodesk ReCap RCP point cloud dataset, which was linked to the Revit model. This point cloud provided detailed and accurate information about the bridge's measurements and physical state. Where the point cloud data were insufficient, supplementary sources were referenced for a more comprehensive representation. These sources included the original 1938 design drawings, terrestrial and aerial photographs, an immersive virtual tour recorded using a Matterport 3D camera, and other historical records. This methodology ensured that the model was accurate to the current state of the bridge and respectful of its historical design.

3.4.1. Defining Scope of BIM Modeling

One of the most important steps in this project phase was identifying the scope of bridge elements to include in the BIM model. The team selected the primary structural framework, including essential components like beams, trusses, girders, piers, footings, piles, and supports, along with the decking and surface layer of the bridge. Attention was also given to specific architectural details that define the bridge's unique design, including decorative elements and the specifics of railings and barriers, such as their design, materials, and positioning, in addition to the expansion joints. However, to maintain a focus on the historical accuracy and integrity of the bridge's original design, certain elements were excluded from the model. These excluded elements involved lighting fixtures, roadway markings, signage, drainage systems, and utilities, as they either were not part of the original construction or did not accurately reflect the bridge's historical state. Furthermore, the environmental surroundings, including the river, and other less significant architectural details, like the steel plates of the railings, were also omitted to concentrate the modeling efforts on the bridge's structural and architectural essence.

3.4.2. Creating the BIM Model

Customized modeling was essential for this project due to the bridge's historic nature. The "Model In-Place" feature in Revit was extensively used for this purpose. This tool allowed for the creation of unique, non-standard elements that closely matched the bridge's evolved structure over the years, ensuring the model's historical authenticity. The following are the steps utilized for developing a comprehensive BIM model to reflect the existing conditions of the bridge.

- Preparing the Base Model
    - Importing Point Cloud Data.
    - Orientating Point Cloud Data.
- Structural Framework Modeling
    - Tracing over the Point Cloud: Using the "Model In-Place" component feature in Revit, start tracing and modeling the primary structural components (e.g., beams, girders, piers, and supports) over the point cloud.
    - Using the 1938 Drawings to Model Hidden Elements or Not Captured by Field Survey: Refer to the historical drawings to model other structural elements that were not captured by the fieldwork. These elements include framing members, beams, girders, footings, piles, and piers. Figure 12 shows the bridge's complete BIM model and some isolated elements in Revit.
    - Referencing Historical Drawings: Cross-reference with the 1938 drawings to ensure historical accuracy in the structural elements.
- Architectural Details and Decking
    - Architectural Details: Identify and model unique architectural features, such as decorative elements, using the point cloud and imagery as references.
    - Decking and Surfaces: Model the bridge's decking, ensuring replication of the surface details accurately as per the point cloud.

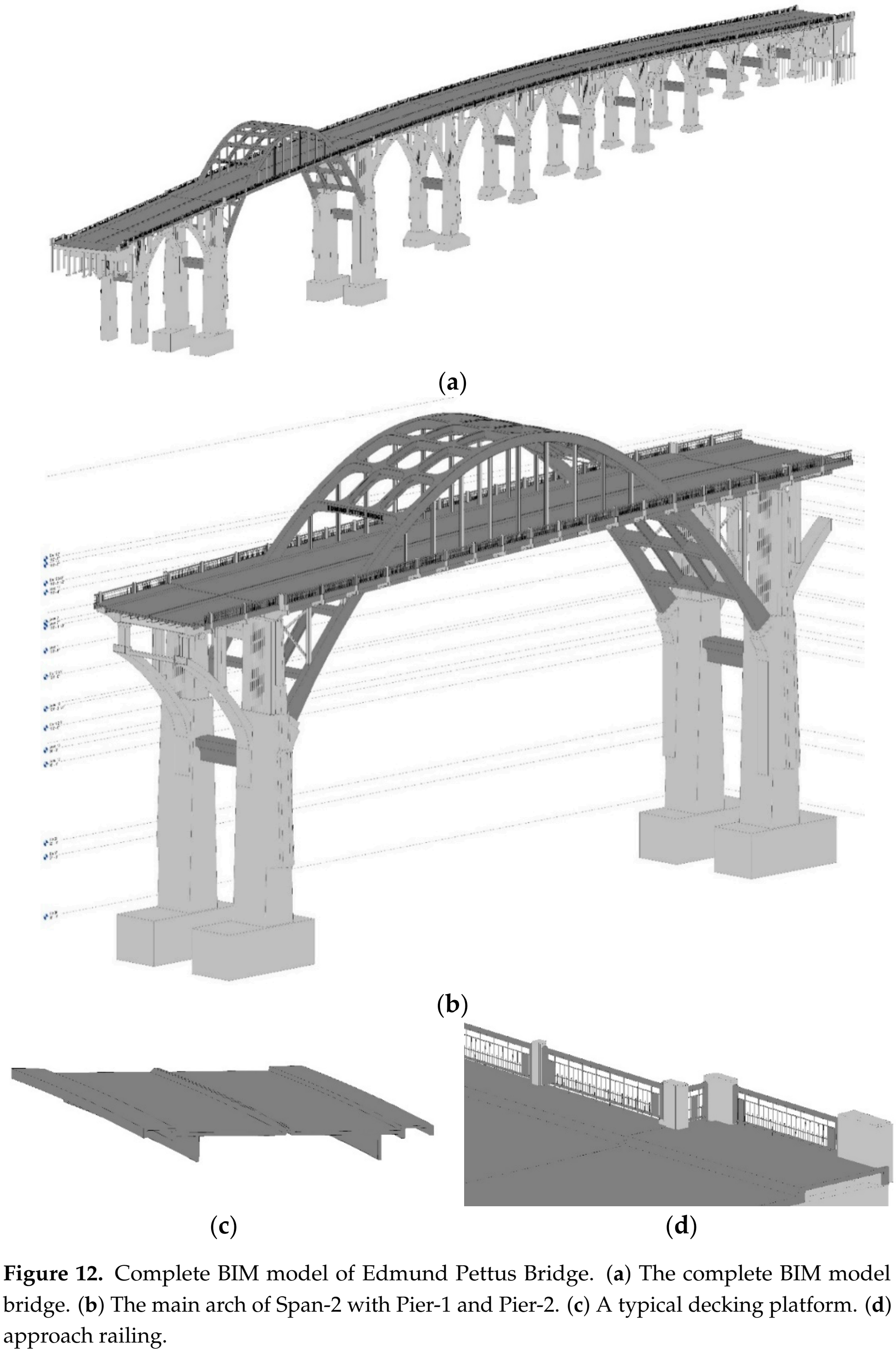
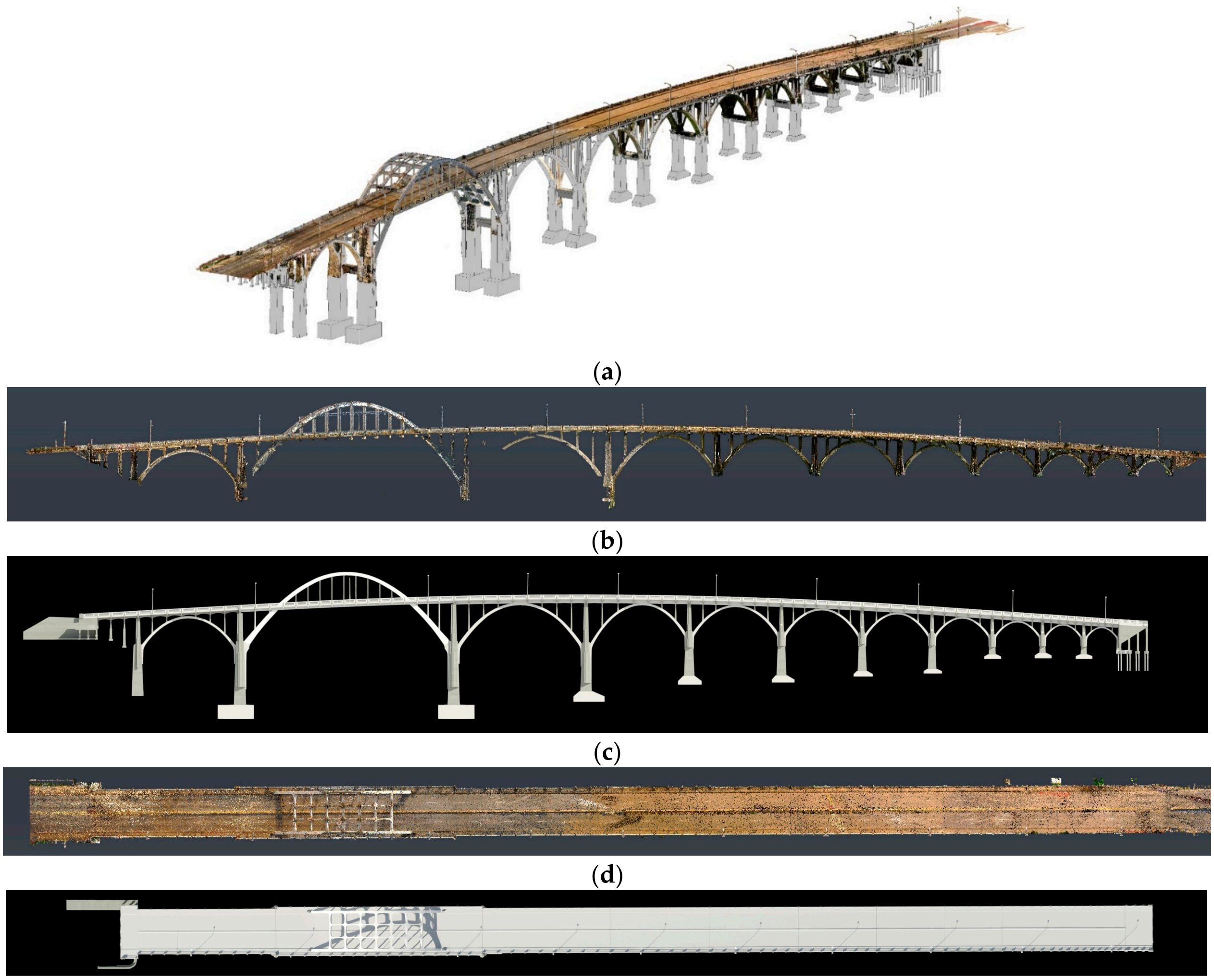


Figure 12. Complete BIM model of Edmund Pettus Bridge. (**a**) The complete BIM model of the bridge. (**b**) The main arch of Span-2 with Pier-1 and Pier-2. (**c**) A typical decking platform. (**d**) North approach railing.

- Additional Elements
    - Modeling Railings and Barriers: Model these safety and structural features using the point cloud data and the historical drawings, focusing on their design and positioning.
    - Expansion Joints: Include these critical elements, accurately located based on the point cloud.
- Data Verification and Adjustment

- ○ Regularly cross-verify the developing model with the point cloud and historical drawings for accuracy. Figure 13 illustrates a set of views overlaying both the BIM model (in light gray) and the point cloud (in color) to help visualize how the Revit model elements align with the point cloud. These views include a perspective of the entire bridge (Figure 13a), the west elevation (Figure 13b,c), the top view (Figure 13d,e), the main arch and piers of Span-2 (Figure 13f), Span-1 and Span-2 (Figure 13g), the main arch of Span-2 (Figure 13h) and its section view (Figure 13i), and the typical railing system (Figure 13j).
- ○ Make necessary adjustments to align with the as-built conditions and historical accuracy.

- Finalizing the Model
  - ○ Once all elements have been modeled, review the entire model for any discrepancies or missing details.
  - ○ Make final adjustments to ensure the model was a precise representation of both the current state and historical design of the bridge.



(**a**)

(**b**)

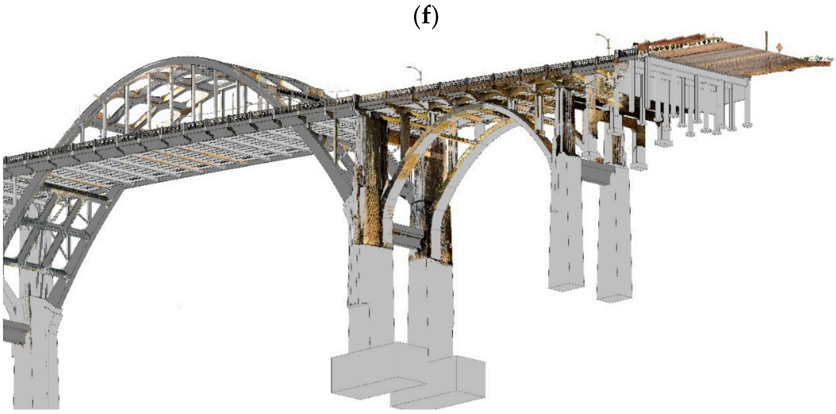
(**c**)

(**d**)

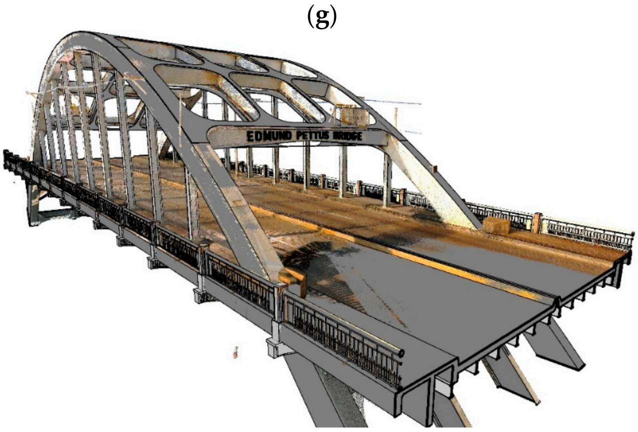
(**e**)

Figure 13. *Cont.*

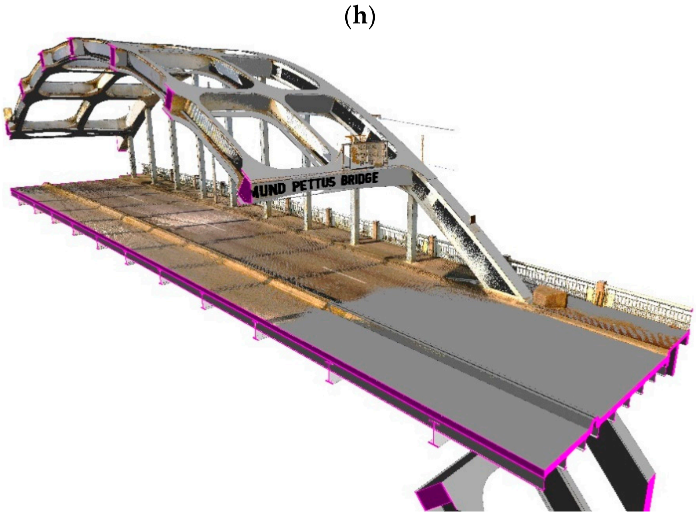
(**f**)



(**g**)

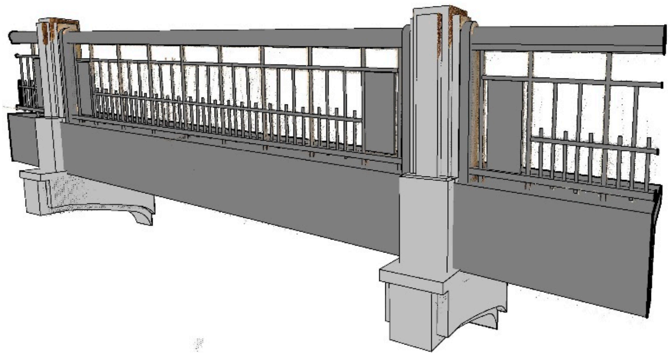


(**h**)



(**i**)

Figure 13. *Cont.*



(**j**)

Figure 13. Overlay of the complete BIM model on TLS point cloud for the Edmund Pettus Bridge, highlighting the integration of TLS data as a foundational layer. (**a**) An overlay view of the entire model (in gray) and the TLS point cloud (in color). (**b**) West elevation of the TLS point cloud. (**c**) West elevation of the model. (**d**) Top view of the TLS point cloud. (**e**) Top view of the model. (**f**) A view of the main arch and piers of Span-2, overlaying the model (in gray) and the TLS point cloud (in color). (**g**) A view of Span-1 and Span-2, overlaying the model (in gray) and the TLS point cloud (in color). (**h**) A view of the main arch of Span-2, overlaying the model (in gray) and the TLS point cloud (in color). (**i**) A section view of the main arch of Span-2, overlaying the model (in gray) and the TLS point cloud (in color). (**j**) Typical railing view, overlaying the model (in gray) and the TLS point cloud (in color).

A significant portion of the bridge's structural elements was precisely modeled using TLS point cloud data, such as decking, arches, above-ground sections of concrete piers, select concrete ribs, railings, and visible steel girders and beams. However, certain elements were either partially captured by the TLS or were entirely beyond its capture capabilities due to their obscured or submerged nature. These elements were modeled with the aid of the 1938 drawing set, photographs, and a virtual tour. This supplementary approach was essential for detailing hidden steel members, sections of concrete piers that are submerged or underground, concrete footings, and concrete piles. To visually delineate the sourcing of data for the BIM model, Figure 14 color-codes the sections of the BIM model based on the data source: green for areas modeled directly using TLS data, orange for those modeled with the assistance of other RC data sources and the 1938 drawings, and red for sections that relied solely on historical drawings. It is worth noting that how much of a heritage structure's element can be precisely modeled using TLS data exclusively is a qualitative analysis. It may depend on many factors, such as its unique architectural and structural features and the resolution of the TLS point clouds. Each project has its own set of variables that influence such estimations, making it challenging to develop a standardized method applicable to different scenarios.

3.5. HAER Drawing Creation

A HAER set, consisting of four drawings, was developed using the BIM model to illustrate the current condition of the EPB and highlight its architectural and structural significance. The set also revealed several discrepancies between the bridge's original design and its existing condition that were discovered through the documentation.

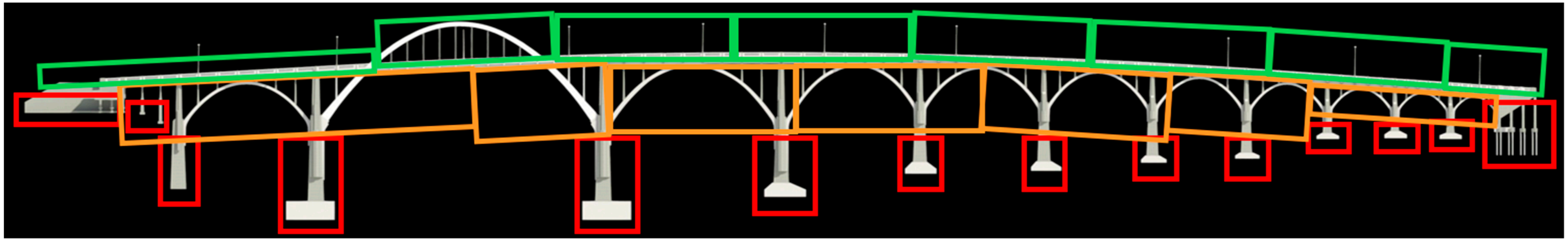


Figure 14. A color-coded view for data integration of the complete BIM model of the Edmund Pettus Bridge. Note: Green for areas modeled directly using TLS data; orange for those modeled with the assistance of other RC data sources and the 1938 drawings; and red for sections that relied solely on historical drawings.

The main approach utilized to create the HAER set was extracting 2D drawings (in the Autodesk AutoCAD's DWG format) from the BIM model, which is revealed in Figure 15. The main purpose of this extraction was to ensure that the 2D drawings met the HAER drawing guidelines by including the proper formatting, line weight, and drawing layers following the United States National CAD Standard®—V5 [107]. To confirm the coverage and precision of the drawings, information employed to guide the process included the TLS point cloud, the Revit model, terrestrial and aerial photos, the Matterport virtual space, and the bridge's original 1938 design drawings set.

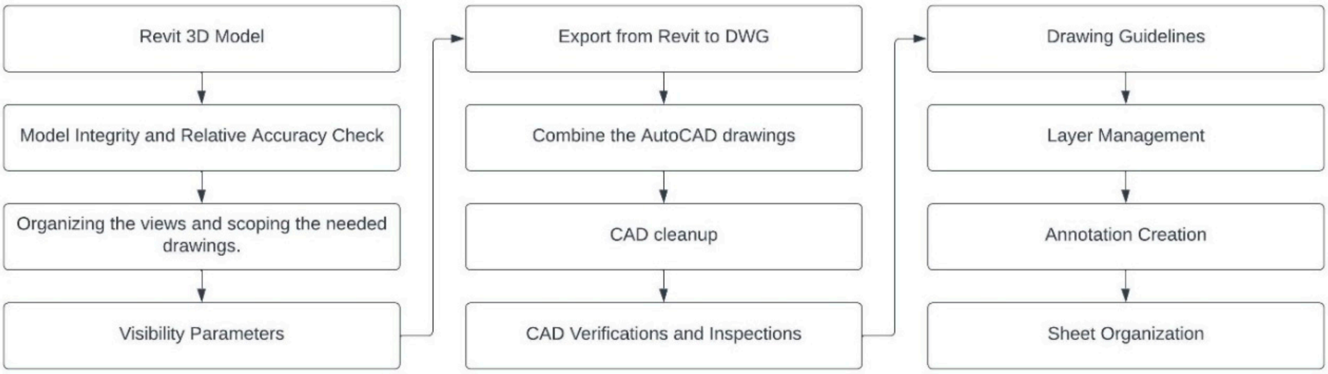


Figure 15. A process of developing the HAER drawings set.

The initial step of creating the set involved a thorough examination of the Revit model to ensure that it was free from extraneous elements and to identify any missing or obscured components. The Matterport virtual space and aerial images significantly aided this process by providing a comprehensive view of the existing conditions of the bridge. Subsequently, the focus shifted to organizing views in Revit to reflect the desired outcomes for the HAER drawings. This included creating various views like elevations, plans, sections, and isometric 3D views, based on a study of existing HAER documentation sets and inspired by the bridge's original 1938 design drawings. The visibility of each view in Revit was adjusted to include only the essential components, a process that was instrumental in ensuring the clarity and accuracy of the final drawings.

These prepared views were then exported from Revit to AutoCAD in DWG format, in alignment with HAER standards. The Revit export typically produced complex components as blocks or polylines. To refine this, an extensive cleanup process was performed, including the use of commands like EXPLODE and OVERKILL in AutoCAD to simplify these components and eliminate any overlapping or redundant lines. The subsequent phase of the process involved thorough manual verification to ensure that all drawing elements were correctly represented and aligned. The drawings were also visually inspected to remove unnecessary lines and achieve the level of detail and accuracy necessary for HAER documentation.

The final stages of the process centered around layer management, annotation creation, and standardization of the drawings. Adherence to HDP's HAER Measured Drawing Guidelines was paramount, dictating the drawing format, layer naming convention, and annotation styles. This also included decisions on drawing size, scale, and line weight to comply with HAER documentation requirements. Figure 16 shows a complete EPB HAER drawing, presenting an isometric view of Span-2, railing details, and discrepancies between the bridge's design and existing conditions.

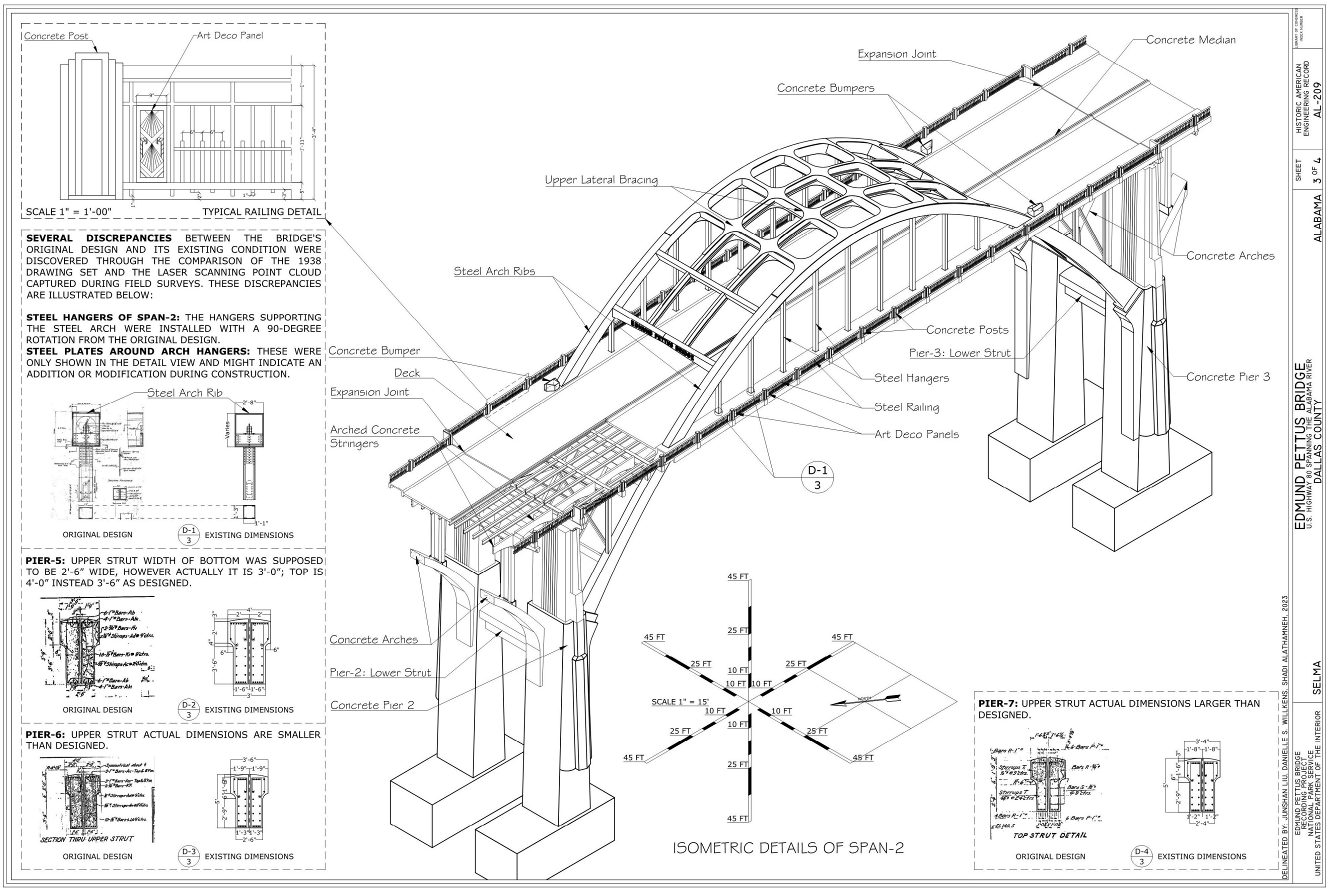


Figure 16. An HAER drawings of the EPB developed from the BIM model.

4. Results and Discussion

4.1. Technical Challenges and Solutions

During the documentation of the EPB, the project team faced various technical challenges across different stages, from the TLS survey to the processing of scan data and the development of the BIM model and HAER drawings. These hurdles required innovative solutions to ensure the project's success.

In the TLS survey phase, traffic and safety concerns were of the utmost importance due to fast-moving vehicles on the bridge, which could cause significant vibrations affecting scan quality. To mitigate this, the team coordinated with the ALDOT to detour traffic and opted to conduct scans during early morning hours on Sundays with minimal traffic, ensuring both safety and reduced vibration impact. The team also faced environmental challenges like dense vegetation and variable weather, which were addressed by adapting scanning techniques and choosing optimal weather conditions for scanning. Moreover, accessing certain bridge sections, especially those over the Alabama River, required creative approaches, leading to the use of aerial drone imaging to capture data from otherwise inaccessible areas.

Processing the TLS data introduced additional complexities. Aligning the numerous scans to create a cohesive point cloud was challenging due to the bridge's large size and intricate geometries. The team employed both automatic and manual registration techniques within FARO SCENE software to achieve acceptable results. Noise from moving objects (e.g., passing vehicles and pedestrians) and other undesired elements in the scans required the application of advanced filtering techniques and manual cleaning to ensure data clarity. The project also had to manage a substantial volume of scan data, which was streamlined through efficient data management protocols and the use of powerful computing resources.

The development of the BIM model presented its own set of challenges, particularly in modeling the bridge's unique architectural details. This was accomplished using Revit's "Model In-Place" feature for custom modeling, supplemented by the 1938 historical drawings for accuracy. Integrating different data sources, including point cloud data, historical drawings, 3D virtual tours, and photographs, required a layered modeling approach, starting with the point cloud data as a foundation. Ensuring the model accurately reflected both the bridge's historical design and its current condition involved thorough cross-referencing and validation among the available data sources.

Creating HAER drawings brought forth challenges in adhering to specific HAER guidelines, which demanded compliance with standards for line weights, scales, and annotations within the AutoCAD environment. Extracting precise 2D drawings from the 3D BIM model required detailed view creation and visibility adjustments in Revit. Additionally, organizing drawing elements into appropriate layers for standardization was achieved by applying the AIA CAD Layer Guidelines.

4.2. Outcomes and Impacts of the BIM Model

Developing a BIM model for the EPB project was aimed at enhancing heritage conservation efforts by providing a robust platform that detailed the bridge's current condition and served as a foundation for the maintenance and future changes into comprehensive BIM applications. These applications could include detailed condition assessments, heritage asset management, maintenance strategies, and future extensions.

- Detailed Condition Assessments: The model has been instrumental in providing comprehensive and precise condition assessments of the bridge. By integrating precise high-resolution data from TLS, the model allows for accurate identification of deterioration and variances in structural components, facilitating targeted maintenance and conservation strategies.
- Heritage Asset Management: The model enhances the management of heritage assets by enabling the integration of historical data and ongoing condition monitoring into a single model. This holistic approach improves decision-making processes and supports the preservation of the bridge's cultural and historical significance.
- Maintenance Strategies: The intelligent BIM model supports the development of effective maintenance strategies by enabling the simulation of maintenance scenarios and their impacts on the bridge's integrity. This predictive capability ensures optimal scheduling and implementation of preservation efforts, minimizing disruptions.
- Future Extensions: The foundational BIM model is designed to accommodate future technological integrations, such as augmented reality for virtual tours and advanced analytics for predictive maintenance. These extensions will further enhance the bridge's documentation and preservation, ensuring its legacy for future generations.

4.3. Impact on Documentation Objectives

The documentation of the EPB, facilitated through the innovative use of TLS and BIM technologies, successfully captured and preserved the current state of this historically and culturally significant structure. This detailed process has notably enhanced the assessment of the bridge and provided a comprehensive insight into its structural integrity and heritage preservation needs.

A key achievement of this digital documentation was the identification of structural discrepancies between the bridge's original design and its present condition. Notably, changes in the construction, such as the unexpected 90-degree distortion in the hangers of the main steel arch (see Figure 17a) and variations in the dimensions of the concrete struts (see Figure 17b), were discovered. These findings are invaluable, casting light on the bridge's construction history and informing future restoration efforts to ensure that any interventions are precisely aligned with the bridge's actual state.

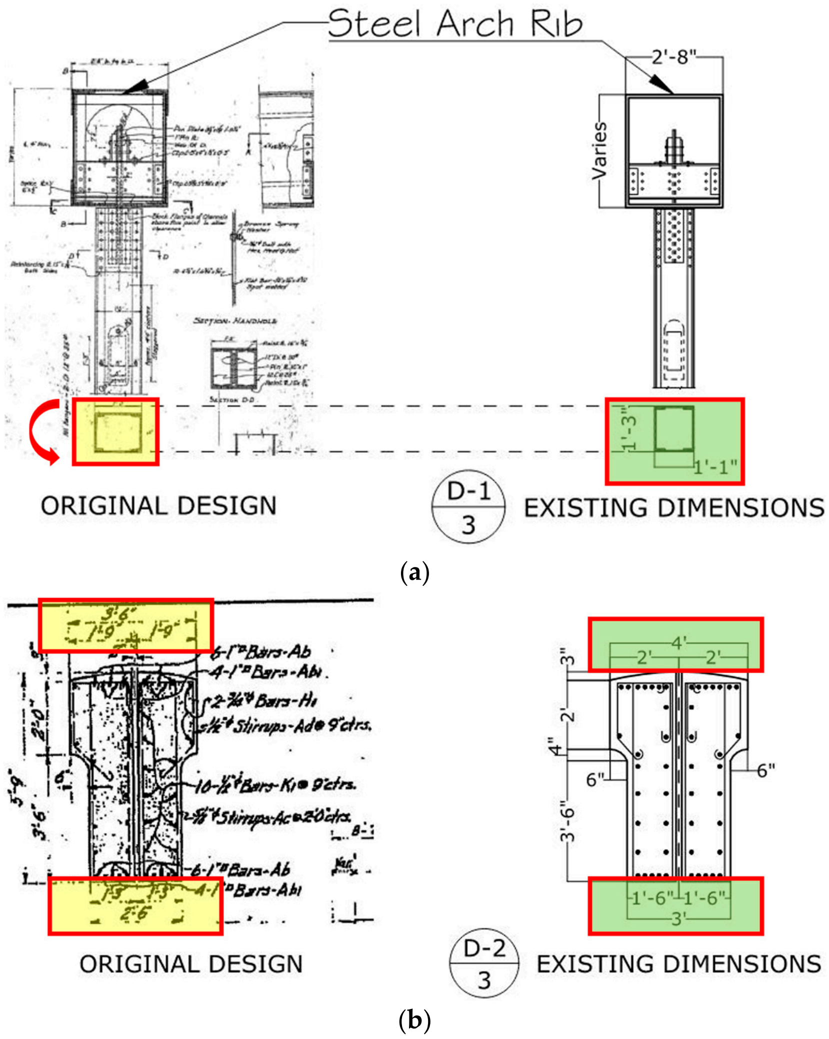


Figure 17. Discrepancies discovered from the documentation. (**a**) The actual installation of the hangers supporting the main steel arch of Span-2 were actually installed (highlighted in green) with a 90-degree rotation from the original design (highlighted in yellow). (**b**) The designed width (shown on the left highlighted in yellow) of the upper concrete strut of Pier-5 is smaller than the actual dimension (shown on the right highlighted in green).

Moreover, the TLS survey generated a detailed 3D point cloud, offering an unprecedented comprehensive view of the bridge's structural health. These data facilitated a thorough analysis of critical components, such as steel arches, concrete piers, and decking, highlighting potential concerns that might elude traditional inspection techniques. This information is crucial for preventively addressing structural vulnerabilities.

Additionally, this project has laid the groundwork for continuous monitoring by establishing a baseline record of the bridge's structural condition. These foundational data are essential for tracking changes over time, identifying emerging structural issues, and devising a proactive maintenance strategy to safeguard the bridge's integrity and longevity. Utilizing software tools like CloudCompare enables researchers to compare point clouds from different survey periods, pinpointing discrepancies and mapping changes. This ongoing monitoring emphasizes the project's long-term contribution to the bridge's preservation, ensuring that this landmark remains a testament to history for future generations.

4.4. Impact on HSR Development

The integration of digital documentation data into the Historic Structure Report (HSR) for the bridge significantly transformed the report, making it a more accurate, informative, and engaging document. Cited by Willkens & Liu [58], this advanced documentation method has captured the bridge's current state with unprecedented detail and precision and also played a pivotal role in shaping the conservation strategies moving forward. The TLS data, in particular, provided a digital snapshot of the bridge with exceptional clarity, directly contributing to the accuracy and depth of the HSR. This level of detail was instrumental in developing the report's key components, such as the BIM and the HAER drawings. The comprehensive nature of the data ensures that the HSR is a reliable resource for understanding the bridge's present condition and serves as a foundation for all future preservation efforts. Furthermore, the rich detail offered by this documentation process has directly impacted the conservation strategies detailed within the HSR. With a precise understanding of the bridge's structural elements, conservationists are better equipped to identify which areas need urgent attention and devise restoration methods that honor and preserve its historical essence.

Beyond its contributions to conservation, the digital documentation data has become a powerful tool for public engagement and education. By making detailed information about the bridge's structure and its storied history accessible through various platforms, such as websites or immersive virtual spaces, the HSR encourages a deeper public connection. This aspect of the HSR is especially beneficial in educational contexts or public exhibitions, where fostering an appreciation for historical landmarks is crucial.

5. Conclusions and Recommendations for Future Research

5.1. Key Findings

The case study of using TLS and BIM for the digital documentation of the Edmund Pettus Bridge marked a notable advancement in the preservation and understanding of heritage infrastructure. This research has tackled this under-addressed domain and demonstrated the capabilities and effectiveness of the technologies in capturing detailed and accurate representations of historic structures beyond traditional buildings.

In this study, the goal was to thoroughly record, archive, and access the bridge's current status. The TLS technology played a primary role by providing a comprehensive 3D point cloud that captured the existing condition of the structure. Then, BIM utilized the TLS dataset as the basis to create a 3D model and 2D HAER drawings for further analysis, documentation, and presentation of the bridge. The model and drawings offered a level of detail and accuracy previously unattainable for the bridge. The documentation process also revealed several discrepancies between the bridge's original design and its existing condition.

Throughout the case study, the advantages of TLS became evident, particularly its accuracy, non-intrusive nature, efficiency in data collection, and versatility in various environmental settings. These strengths were key in accurately documenting the historic bridge. However, the technology also encountered limitations, including challenges related to accessibility, environmental impacts on scan accuracy, and the complexities involved in managing vast datasets. These limitations highlighted the need for careful planning and execution to utilize TLS in heritage documentation.

This study broadens the scope of digital documentation methods in heritage conservation by demonstrating the effective integration of TLS and BIM on a historically and structurally complex bridge. It provides a comprehensive model that can be adapted for a wide range of heritage infrastructures and other engineering landmarks that are often challenging to document with high fidelity. The broader impact of this research also extends beyond the technical accomplishments. The comprehensive data collection and analysis have contributed to the structural assessment of the bridge. By establishing a detailed baseline record of the bridge's condition, the project has set the stage for ongoing monitoring and future maintenance. Additionally, the digital representation of the bridge, especially the Matterport virtual space, has become a valuable tool for improving public engagement.

5.2. Recommended Areas for Further Study

Future research in heritage documentation is poised to significantly benefit from the integration and advancement of digital technologies, particularly focusing on areas such as UAV-based LiDAR, SfM or photogrammetry, automated damage detection, long-term monitoring and predictive modeling, optimization of data processing workflows, and the application of machine learning and artificial intelligence (AI) in data analysis.

The potential of UAV-based LiDAR and SfM technologies extends beyond traditional laser scanning, offering new avenues for capturing high-resolution data of hard-to-reach areas with enhanced efficiency and reduced risk. Coupled with the development of automated algorithms for damage detection, these technologies can facilitate more proactive and preventative maintenance strategies for large heritage structures, such as bridges. Moreover, leveraging TLS for long-term structural monitoring and employing predictive modeling could revolutionize how heritage sites are preserved, allowing for anticipating structural issues before they become critical. Additionally, optimizing data processing workflows to handle the vast amounts of data generated by these technologies will be crucial for ensuring the accessibility and usability of digital documentation efforts. Finally, machine learning and AI applications promise to unlock new insights from complex datasets, potentially revealing untapped historical knowledge and informing more effective conservation strategies.

Future studies could also build upon the foundational BIM model of the Edmund Pettus Bridge, incorporating condition assessments and maintenance strategies directly into the model. This expansion will enable a more dynamic use of BIM for preservation efforts, making it a proactive tool for heritage management. Research should focus on the seamless integration of TLS data with additional sources and the inclusion of engineering data to enhance model accuracy. Moreover, the development of visual tools to indicate model reliability across different sections could significantly aid in prioritizing conservation efforts. These steps will deepen the stakeholders' understanding of heritage conservation practices and enhance the practical utility of BIM models in managing and preserving historic structures.

Author Contributions: Conceptualization, D.S.W. and J.L.; methodology, D.S.W. and J.L.; validation, D.S.W. and J.L.; formal analysis, D.S.W. and J.L.; investigation, D.S.W. and J.L.; data curation, D.S.W. and J.L.; writing—original draft preparation, D.S.W. and J.L.; writing—review and editing, D.S.W., J.L. and S.A.; visualization, D.S.W., J.L. and S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the U.S. Department of the Interior's National Park Service, AACR Grant P19AP00498.

Data Availability Statement: The data that support the findings of this study are available upon request from the corresponding authors. Due to the sensitive nature of the data and their file size, access to the data will be granted on a case-by-case basis and may require a data use agreement to be signed.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Knight, L. *A Guide to the Research and Documentation of Historic Bridges in Texas*; Texas Department of Transportation, Environmental Affairs Division: Kyle, TX, USA, 2004.
2. Trizio, I.; Marra, A.; Savini, F.; Fabbrocino, G. Survey methodologies and 3d modelling for conservation of historical masonry bridges. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, *8*, 163–170. [CrossRef]
3. Chen, Y.; Wu, Y.; Sun, X.; Ali, N.; Zhou, Q. Digital Documentation and Conservation of Architectural Heritage Information: An Application in Modern Chinese Architecture. *Sustainability* **2023**, *15*, 7276. [CrossRef]
4. Riveiro, B.; Arias, P.; Armesto, J.; Ordóñez, C. A Methodology for the Inventory of Historical Infrastructures: Documentation, Current State, and Influencing Factors. *Int. J. Archit. Herit.* **2011**, *5*, 629–646. [CrossRef]
5. Palieraki, V.; Oikonomopoulou, E.; Nikolopoulou, V.; Vintzileou, E.; Giannelos, C. The Historical Bridge of Konitsa-Epirus, Greece: Documentation of the Structural System. *Int. J. Archit. Herit.* **2023**, *17*, 1446–1463. [CrossRef]

6. Bruno, N.; Coïsson, E.; Diotri, F.; Ferrari, L.; Mikolajewska, S.; Morra di Cella, U.; Roncella, R.; Zerbi, A. History, Geometry, Structure: Interdisciplinary Analysis of a Historical Bridge. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 317–323. [CrossRef]
7. Savini, F.; Rainieri, C.; Fabbrocino, G.; Trizio, I. Applications of Stratigraphic Analysis to Enhance the Inspection and Structural Characterization of Historic Bridges. *Infrastructures* **2021**, *6*, 7. [CrossRef]
8. Conti, A.; Fiorini, L.; Massaro, R.; Santoni, C.; Tucci, G. HBIM for the Preservation of a Historic Infrastructure: The Carlo III Bridge of the Carolino Aqueduct. *Appl. Geomat.* **2022**, *14*, 41–51. [CrossRef]
9. Liu, J.; Azhar, S.; Willkens, D.; Li, B. Static Terrestrial Laser Scanning (TLS) for Heritage Building Information Modeling (HBIM): A Systematic Review. *Virtual Worlds* **2023**, *2*, 90–114. [CrossRef]
10. Markiewicz, J.; Robak, A. The Generation of High-Resolution Orthoimages Based on TLS Data and Close-Range Images—The Case Study. *J. Mod. Technol. Cult. Herit. Preserv.* **2022**, *1*, 1–13. [CrossRef]
11. Bagchi, S. The Digital Reflection: Implications of Three-Dimensional Laser Scanning Technology on Historic Architecture Documentation. Ph.D. Thesis, Texas Tech University, Lubbock, TX, USA, 2001.
12. Aburamadan, R.; Trillo, C.; Cotella, V.; Di Perna, E.; Ncube, C.; Moustaka, A.; Udeaja, C.; Awuah, K. Developing a Heritage BIM Shared Library for Two Case Studies in Jordan's Heritage: The House of Art in Amman and the Qaqish House in the World Heritage City of As-Salt. *Herit. Sci.* **2022**, *10*, 196. [CrossRef]
13. Antonopoulou, S.; Bryan, P. *BIM for Heritage: Developing a Historic Building Information Model*; Liverpool University Press: Livepool, UK, 2017; ISBN 978-1-84802-487-8.
14. Borkowski, A.S. A Literature Review of BIM Definitions: Narrow and Broad Views. *Technologies* **2023**, *11*, 176. [CrossRef]
15. Murphy, M.; McGovern, E.; Pavia, S. Historic Building Information Modelling (HBIM). *Struct. Surv.* **2009**, *27*, 311–327. [CrossRef]
16. Liu, J.; Foreman, G.; Sattineni, A.; Li, B. Integrating Stakeholders' Priorities into Level of Development Supplemental Guidelines for HBIM Implementation. *Buildings* **2023**, *13*, 530. [CrossRef]
17. Carvajal-Ramirez, F.; Martinez-Carridondo, P.; Yero-Paneque, L.; Aguera-Vega, F. UAV Photogrammetry and HBIM for the Virtual Reconstruction of Heritage. In Proceedings of the 27th CIPA International Symposium—Documenting the Past for a Better Future, Avila, Spain, 1–5 September 2019. *Int. Soc. Photogramm. Remote Sens.* **2019**, *42*, 271–278.
18. Sanseverino, A.; Messina, B.; Limongiello, M.; Guida, C. An HBIM Methodology for the Accurate and Georeferenced Reconstruction of Urban Contexts Surveyed by UAV: The Case of the Castle of Charles V. *Remote Sens.* **2022**, *14*, 3688. [CrossRef]
19. Bagnolo, V.; Argiolas, R.; Cuccu, A. HBIM for Archaeological Sites: From SfM Based Survey to Algorithmic Modeling. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 57–63. [CrossRef]
20. Komas, T.W. Historic Building Documentation in the United States, 1933–2000. The Historic American Buildings Survey: A Case Study. Ph.D. Thesis, Texas A&M University, College Station, TX, USA, 2005.
21. DeLony, E. Documenting Historic Bridges. In *International Engineering History and Heritage: Improving Bridges to ASCE's 150th Anniversary*; American Society of Civil Engineers: Reston, VA, USA, 2012; pp. 239–251. [CrossRef]
22. Yan, Y.; Hajjar, J.F. Automated Extraction of Structural Elements in Steel Girder Bridges from Laser Point Clouds. *Autom. Constr.* **2021**, *125*, 103582. [CrossRef]
23. Liu, J.; Willkens, D.; Gentry, R. A Conceptual Framework for Integrating Terrestrial Laser Scanning (TLS) into the Historic American Buildings Survey (HABS). *Architecture* **2023**, *3*, 505–527. [CrossRef]
24. Heritage Documentation Programs, U.S. National Park Service Heritage Documentation Programs Field Record Requirements for Laser Scanning and Photogrammetry. Available online: https://www.nps.gov/subjects/heritagedocumentation/laser-scan-guidance.htm (accessed on 7 January 2022).
25. Lavoie, C.C. HABS Documentation in the Digital Age: Combining Traditional and New 3D Methods of Recording. *Change Over Time* **2011**, *1*, 184–197. [CrossRef]
26. Akboy, S. The HABS Culture of Documentation with an Analysis of Drawing and Technology. Ph.D. Thesis, Texas A&M University, College Station, TX, USA, 2012.
27. Burns, J.A. *Recording Historic Structures*; John Wiley & Sons: Hoboken, NJ, USA, 2003.
28. Wright, H.E. "HABS: The First Fifty Years (1933–1983)"—An Exhibition at the Library of Congress, Washington, DC. *Technol. Cult.* **1985**, *26*, 253–256. [CrossRef]
29. Liu, J.; Bird, G.; Willkens, D.S.; Burt, R.A.; McGonagill, H. Preserving the history of African American education: Digital documentation of Rosenwald schools—A case study on the Tankersley school in Hope Hull, Alabama, USA. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 951–958. [CrossRef]
30. Lopez, R.; Mader, C.; Sarafraz, A.; Yin, L. HABS-Historic American Buildings Survey and the Integration of New Technology. *Arquit. Urban.* **2017**, *38*, 91–103.
31. Baneh, K.; Baneh, B.; Osman, A.; Mostafapour, O.; Bradosty, Z. Regeneration and Documentation of Historic Geometric Islamic Patterns via HBIM: A Case Study of Choli Minaret, Kurdistan Region. *Int. J. Build. Pathol. Adapt.* **2021**, *41*, 347–363. [CrossRef]
32. Donato, E.; Giuffrida, D. Combined Methodologies for the Survey and Documentation of Historical Buildings: The Castle of Scalea (CS, Italy). *Heritage* **2019**, *2*, 2384–2397. [CrossRef]
33. Gogo, M.E. Digital Documentation For Historic Resources, A Thesis Submitted to the Graduate Faculty of the University of Georgia. Master's Thesis, University of Georgia, Athens, GA, USA, 2011.

34. Mantia, M.L. Towards the Creation of a US National Heritage: Documentation and Survey for the Understanding and Safeguard of the Architecture of Frank Lloyd Wright. *Disegnarecon* **2015**, *8*, 1–24.
35. Borchers, P.E. Photogrammetry of the Indian Pueblos of New Mexico and Arizona. *Photogrammetria* **1975**, *30*, 189–196. [CrossRef]
36. Massey, J.C.; Schwartz, N.B.; Maxwell, S. *Historic American Buildings Survey/Historic American Engineering Record: An Annotated Bibliography*; Historic American Buildings Survey / Historic American Engineering Board: Washington, DC, USA, 1992.
37. UNAVCO. Available online: https://www.unavco.org/help/glossary/glossary.html#lidar (accessed on 7 January 2022).
38. Colombo, L.; Marana, B. Terrestrial Laser Scanning. Available online: https://www.gim-international.com/content/article/terrestrial-laser-scanning-2 (accessed on 7 January 2022).
39. Bauwens, S.; Bartholomeus, H.; Calders, K.; Lejeune, P. Forest Inventory with Terrestrial LiDAR: A Comparison of Static and Hand-Held Mobile Laser Scanning. *Forests* **2016**, *7*, 127. [CrossRef]
40. Gollob, C.; Ritter, T.; Nothdurft, A. Comparison of 3D Point Clouds Obtained by Terrestrial Laser Scanning and Personal Laser Scanning on Forest Inventory Sample Plots. *Data* **2020**, *5*, 103. [CrossRef]
41. Che, E.; Jung, J.; Olsen, M.J. Object Recognition, Segmentation, and Classification of Mobile Laser Scanning Point Clouds: A State of the Art Review. *Sensors* **2019**, *19*, 810. [CrossRef] [PubMed]
42. Kukko, A.; Kaartinen, H.; Hyyppä, J.; Chen, Y. Multiplatform Mobile Laser Scanning: Usability and Performance. *Sensors* **2012**, *12*, 11712–11733. [CrossRef]
43. Potó, V.; Somogyi, J.Á.; Lovas, T.; Barsi, Á. Laser Scanned Point Clouds to Support Autonomous Vehicles. *Transp. Res. Procedia* **2017**, *27*, 531–537. [CrossRef]
44. Del Duca, G.; Machado, C. Assessing the Quality of the Leica BLK2GO Mobile Laser Scanner versus the Focus 3D S120 Static Terrestrial Laser Scanner for a Preliminary Study of Garden Digital Surveying. *Heritage* **2023**, *6*, 1007–1027. [CrossRef]
45. Williams, R.D.; Lamy, M.-L.; Maniatis, G.; Stott, E. Three-Dimensional Reconstruction of Fluvial Surface Sedimentology and Topography Using Personal Mobile Laser Scanning. *Earth Surf. Process. Landf.* **2020**, *45*, 251–261. [CrossRef]
46. Barnhart, T.B.; Crosby, B.T. Comparing Two Methods of Surface Change Detection on an Evolving Thermokarst Using High-Temporal-Frequency Terrestrial Laser Scanning, Selawik River, Alaska. *Remote Sens.* **2013**, *5*, 2813–2837. [CrossRef]
47. Hohenthal, J.; Alho, P.; Hyyppä, J.; Hyyppä, H. Laser Scanning Applications in Fluvial Studies. *Prog. Phys. Geogr. Earth Environ.* **2011**, *35*, 782–809. [CrossRef]
48. Yang, X.; Grussenmeyer, P.; Koehl, M.; Macher, H.; Murtiyoso, A.; Landes, T. Review of Built Heritage Modelling: Integration of HBIM and Other Information Techniques. *J. Cult. Herit.* **2020**, *46*, 350–360. [CrossRef]
49. Di Stefano, F.; Chiappini, S.; Gorreja, A.; Balestra, M.; Pierdicca, R. Mobile 3D Scan LiDAR: A Literature Review. *Geomat. Nat. Hazards Risk* **2021**, *12*, 2387–2429. [CrossRef]
50. Moyano, J.; Justo-Estebaranz, A.; Nieto-Julian, J.; Barrera, A.; Fernandez-Alconchel, M. Evaluation of Records Using Terrestrial Laser Scanner in Architectural Heritage for Information Modeling in HBIM Construction: The Case Study of the La Anunciaci Acute Accent on Church (Seville). *J. Build. Eng.* **2022**, *62*, 105190. [CrossRef]
51. Adami, A.; Bruno, N.; Rosignoli, O.; Scala, B. HBIM for Planned Conservation: A New Approach to Information Management. In Proceedings of the CHNT23, Vienna, Austria, 12–15 November 2018; p. 41.
52. Banfi, F. HBIM, 3D Drawing and Virtual Reality for Archaeological Sites and Ancient Ruins. *Virtual Archaeol. Rev.* **2020**, *11*, 16–33. [CrossRef]
53. Barontini, A.; Alarcon, C.; Sousa, H.S.; Oliveira, D.V.; Masciotta, M.G.; Azenha, M. Development and Demonstration of an HBIM Framework for the Preventive Conservation of Cultural Heritage. *Int. J. Archit. Herit.* **2021**, *16*, 1451–1473. [CrossRef]
54. Abbate, E.; Invernizzi, S.; Spano, A. HBIM Parametric Modelling from Clouds to Perform Structural Analyses Based on Finite Elements: A Case Study on a Parabolic Concrete Vault. *Appl. Geomat.* **2022**, *14*, 79–96. [CrossRef]
55. Anton, D.; Pineda, P.; Medjdoub, B.; Iranzo, A. As-Built 3D Heritage City Modelling to Support Numerical Structural Analysis: Application to the Assessment of an Archaeological Remain. *Remote Sens.* **2019**, *11*, 1276. [CrossRef]
56. Olsen, M.J.; Kuester, F.; Chang, B.J.; Hutchinson, T.C. Terrestrial Laser Scanning-Based Structural Damage Assessment. *J. Comput. Civ. Eng.* **2010**, *24*, 264–272. [CrossRef]
57. Pathak, R.; Saini, A.; Wadhwa, A.; Sharma, H.; Sangwan, D. An Object Detection Approach for Detecting Damages in Heritage Sites Using 3-D Point Clouds and 2-D Visual Data. *J. Cult. Herit.* **2021**, *48*, 74–82. [CrossRef]
58. Willkens, D.S.; Liu, J. *Historic Structure Report, Edmund Pettus Bridge*; Department of the Interior, National Park Service, Southeastern Regional Office: Selma, AL, USA, 2024.
59. Palčák, M.; Kudela, P.; Fandáková, M.; Kordek, J. Utilization of 3D Digital Technologies in the Documentation of Cultural Heritage: A Case Study of the Kunerad Mansion (Slovakia). *Appl. Sci.* **2022**, *12*, 4376. [CrossRef]
60. Muradov, M.; Kot, P.; Markiewicz, J.; Łapiński, S.; Tobiasz, A.; Onisk, K.; Shaw, A.; Hashim, K.; Zawieska, D.; Mohi-Ud-Din, G. Non-Destructive System for in-Wall Moisture Assessment of Cultural Heritage Buildings. *Measurement* **2022**, *203*, 111930. [CrossRef]
61. Tejedor, B.; Lucchi, E.; Bienvenido-Huertas, D.; Nardi, I. Non-Destructive Techniques (NDT) for the Diagnosis of Heritage Buildings: Traditional Procedures and Futures Perspectives. *Energy Build.* **2022**, *263*, 112029. [CrossRef]
62. Moyano, J.; Nieto-Julián, J.E.; Lenin, L.M.; Bruno, S. Operability of Point Cloud Data in an Architectural Heritage Information Model. *Int. J. Archit. Herit.* **2022**, *16*, 1588–1607. [CrossRef]

63. Martín-Lerones, P.; Olmedo, D.; López-Vidal, A.; Gómez-García-bermejo, J.; Zalama, E. BIM Supported Surveying and Imaging Combination for Heritage Conservation. *Remote Sens.* **2021**, *13*, 1584. [CrossRef]
64. Moyano, J.; Gil-Arizón, I.; Nieto-Julián, J.E.; Marín-García, D. Analysis and Management of Structural Deformations through Parametric Models and HBIM Workflow in Architectural Heritage. *J. Build. Eng.* **2022**, *45*, 103274. [CrossRef]
65. Rocha, G.; Mateus, L. A Survey of Scan-to-BIM Practices in the AEC Industry—A Quantitative Analysis. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 564. [CrossRef]
66. Franco, P.A.C.; de la Plata, A.R.; Franco, J.C. From the Point Cloud to BIM Methodology for the Ideal Reconstruction of a Lost Bastion of the Caceres Wall. *Appl. Sci.* **2020**, *10*, 6609. [CrossRef]
67. Al-Bayari, O.; Shatnawi, N. Geomatics Techniques and Building Information Model for Historical Buildings Conservation and Restoration. *Egypt. J. Remote Sens. Space Sci.* **2022**, *25*, 563–568. [CrossRef]
68. Alshawabkeh, Y.; Baik, A.; Fallatah, A. As-Textured As-Built BIM Using Sensor Fusion, Zee Ain Historical Village as a Case Study. *Remote Sens.* **2021**, *13*, 5135. [CrossRef]
69. Mammoli, R.; Mariotti, C.; Quattrini, R. Modeling the Fourth Dimension of Architectural Heritage: Enabling Processes for a Sustainable Conservation. *Sustainability* **2021**, *13*, 5173. [CrossRef]
70. Massafra, A.; Prati, D.; Predari, G.; Gulli, R. Wooden Truss Analysis, Preservation Strategies, and Digital Documentation through Parametric 3D Modeling and HBIM Workflow. *Sustainability* **2020**, *12*, 4975. [CrossRef]
71. Alshawabkeh, Y.; Baik, A.; Miky, Y. Integration of Laser Scanner and Photogrammetry for Heritage BIM Enhancement. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 316. [CrossRef]
72. Liu, J.; Willkens, D. *Reexamining the Old Depot Museum in Selma, Alabama, USA*; WIT Press: Santiago de Compostela, Spain, 2021; Volume 205, pp. 171–186.
73. Santos, C.G.R.; Araújo, T.D.O.; Chagas, P.R., Jr.; Neto, N.C.S.; Meiguins, B.S. Recognizing and Exploring Azulejos on Historic Buildings' Facades by Combining Computer Vision and Geolocation in Mobile Augmented Reality Applications. *J. Mob. Multimed.* **2017**, *13*, 57–74.
74. Banfi, F.; Previtali, M.; Stanga, C.; Brumana, R. A Layered-Web Interface Based on HBIM and 360° Panoramas for Historical, Material and Geometric Analysis. *ISPRS—Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 73–80. [CrossRef]
75. Banfi, F. The Evolution of Interactivity, Immersion and Interoperability in HBIM: Digital Model Uses, VR and AR for Built Cultural Heritage. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 685. [CrossRef]
76. Rashidi, M.; Mohammadi, M.; Sadeghlou Kivi, S.; Abdolvand, M.M.; Truong-Hong, L.; Samali, B. A Decade of Modern Bridge Monitoring Using Terrestrial Laser Scanning: Review and Future Directions. *Remote Sens.* **2020**, *12*, 3796. [CrossRef]
77. McGuire, B.; Atadero, R.; Clevenger, C.; Ozbek, M. Bridge Information Modeling for Inspection and Evaluation. *J. Bridge Eng.* **2016**, *21*, 04015076. [CrossRef]
78. Jeong, S.; Hou, R.; Lynch, J.P.; Sohn, H.; Law, K.H. An Information Modeling Framework for Bridge Monitoring. *Adv. Eng. Softw.* **2017**, *114*, 11–31. [CrossRef]
79. Anwar, N. The Impact and Future Role of Computations and Software in Bridge Modeling, Analysis and Design. In Proceedings of the China Bridge Congress Chongqing, Chongqing, China, 29 March 2007; Volume 29.
80. Shabani, A.; Feyzabadi, M.; Kioumarsi, M. Model Updating of a Masonry Tower Based on Operational Modal Analysis: The Role of Soil-Structure Interaction. *Case Stud. Constr. Mater.* **2022**, *16*, e00957. [CrossRef]
81. Mol, A.; Cabaleiro, M.; Sousa, H.; Branco, J. HBIM for Storing Life-Cycle Data Regarding Decay and Damage in Existing Timber Structures. *Autom. Constr.* **2020**, *117*, 103262. [CrossRef]
82. Ursini, A.; Grazzini, A.; Matrone, F.; Zerbinatti, M. From Scan-to-BIM to a Structural Finite Elements Model of Built Heritage for Dynamic Simulation. *Autom. Constr.* **2022**, *142*, 104518. [CrossRef]
83. Santos, D.; Sousa, H.S.; Cabaleiro, M.; Branco, J.M. HBIM Application in Historic Timber Structures: A Systematic Review. *Int. J. Archit. Herit.* **2022**, *17*, 1331–1347. [CrossRef]
84. Grillanda, N.; Cantini, L.; Barazzetti, L.; Milani, G.; Della Torre, S. Advanced Modeling of a Historical Masonry Umbrella Vault: Settlement Analysis and Crack Tracking via Adaptive NURBS Kinematic Analysis. *J. Eng. Mech.* **2021**, *147*, 04021095. [CrossRef]
85. Fryskowska, A.; Stachelek, J. A No-Reference Method of Geometric Content Quality Analysis of 3D Models Generated from Laser Scanning Point Clouds for hBIM. *J. Cult. Herit.* **2018**, *34*, 95–108. [CrossRef]
86. Rocha, G.; Mateus, L.; Fernandez, J.; Ferreira, V. A Scan-to-BIM Methodology Applied to Heritage Buildings. *Heritage* **2020**, *3*, 47–65. [CrossRef]
87. Barrile, V.; Bernardo, E.; Bilotta, G. An Experimental HBIM Processing: Innovative Tool for 3D Model Reconstruction of Morpho-Typological Phases for the Cultural Heritage. *Remote Sens.* **2022**, *14*, 1288. [CrossRef]
88. Chen, L. *Integration of Terrestrial Laser Scanning and Close-Range Photogrammetry for Documenting Built Heritage*; University of Florida: Gainesville, FL, USA, 2020.
89. de la Plata, A.; Franco, P.; Franco, J.; Bravo, V. Protocol Development for Point Clouds, Triangulated Meshes and Parametric Model Acquisition and Integration in an HBIM Workflow for Change Control and Management in a UNESCO's World Heritage Site. *Sensors* **2021**, *21*, 1083. [CrossRef]
90. Reinoso-Gordo, J.F.; Rodríguez-Moreno, C.; Gómez-Blanco, A.J.; León-Robles, C. Cultural Heritage Conservation and Sustainability Based on Surveying and Modeling: The Case of the 14th Century Building Corral Del Carbón (Granada, Spain). *Sustainability* **2018**, *10*, 1370. [CrossRef]

91. Banfi, F.; Brumana, R.; Landi, A.G.; Previtali, M.; Roncoroni, F.; Stanga, C. Building Archaeology Informative Modelling Turned into 3D Volume Stratigraphy and Extended Reality Time-Lapse Communication. *Virtual Archaeol. Rev.* **2022**, *13*, 1–21. [CrossRef]
92. Nieto-Julián, J.E.; Antón, D.; Moyano, J.J. Implementation and Management of Structural Deformations into Historic Building Information Models. *Int. J. Archit. Herit.* **2020**, *14*, 1384–1397. [CrossRef]
93. Banfi, F.; Brumana, R.; Stanga, C. Extended Reality and Informative Models for the Architectural Heritage: From Scan-to-BIM Process to Virtual and Augmented Reality. *Virtual Archaeol. Rev.* **2019**, *10*, 14–30. [CrossRef]
94. García-Valldecabres, J.L.; Liu, J.; Willkens, D.S.; Escudero, P.A.; López-González, C.; Cortés Meseguer, L.; Orozco Carpio, P.R. Development of a virtual itinerary with HBIM and GIS. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 645–652. [CrossRef]
95. Liu, J.; Willkens, D.; López, C.; Cortés-Meseguer, L.; García-Valldecabres, J.L.; Escudero, P.A.; Alathamneh, S. Comparative analysis of point clouds acquired from a TLS survey and a 3D virtual tour for HBIM development. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 959–968. [CrossRef]
96. Brumana, R.; Della Torre, S.; Previtali, M.; Barazzetti, L.; Cantini, L.; Oreni, D.; Banfi, F. Generative HBIM Modelling to Embody Complexity (LOD, LOG, LOA, LOI): Surveying, Preservation, Site Intervention—The Basilica Di Collemaggio (L'Aquila). *Appl. Geo.* **2018**, *10*, 545–567. [CrossRef]
97. Rolin, R.; Antaluca, E.; Batoz, J.-L.; Lamarque, F.; Lejeune, M. From Point Cloud Data to Structural Analysis through a Geometrical hBIM-Oriented Model. *J. Comput. Cult. Herit.* **2019**, *12*, 1–26. [CrossRef]
98. Moyano, J.; León, J.; Nieto-Julián, J.E.; Bruno, S. Semantic Interpretation of Architectural and Archaeological Geometries: Point Cloud Segmentation for HBIM Parameterisation. *Autom. Constr.* **2021**, *130*, 103856. [CrossRef]
99. Murtiyoso, A.; Grussenmeyer, P. Comparison and Assessment of 3D Registration and Georeferencing Approaches of Point Clouds in the Case of Exterior and Interior Heritage Building Recording. In Proceedings of the ISPRS TC II Mid-Term Symposium towards Photogrammetry 2020, Riva del Garda, Italy, 3–7 June 2018; Volume 42, pp. 745–751.
100. Grussenmeyer, P.; Alby, E.; Landes, T.; Koehl, M.; Guillemin, S.; Hullo, J.-F.; Assali, P.; Smigiel, E. Recording Approach of Heritage Sites Based on Merging Point Clouds from High Resolution Photogrammetry and Terrestrial Laser Scanning. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2012**, *XXXIX-B5*, 553–558. [CrossRef]
101. Alba, M.; Scaioni, M. Comparison of Techniques for Terrestrial Laser Scanning Data Georeferencing Applied to 3-D Modelling of Cultural Heritage. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2007**, *36*, 8.
102. Shabani, A.; Kioumarsi, M. Seismic Assessment and Strengthening of a Historical Masonry Bridge Considering Soil-Structure Interaction. *Eng. Struct.* **2023**, *293*, 116589. [CrossRef]
103. Hill-Stosky, A.; Brothers, T. Reality Capture and the Potential for the Digital Twin: An Examination of the Matterport Pro2, the Samsung Galaxy Note 20 Ultra, and the Trimble XR-10 with Microsoft Hololens2. *Transform. Constr. Real. Capture Technol.* **2022**. [CrossRef]
104. Shults, R.; Levin, E.; Habibi, R.; Shenoy, S.; Honcheruk, O.; Hart, T.; An, Z. Capability of matterport 3D camera for industrial archaeology sites inventory. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 1059–1064. [CrossRef]
105. Mani, G.-F.; Jeffrey, B.; Jochen, T.; Silvio, S.; Feniosky, P.-M. Evaluation of Image-Based Modeling and Laser Scanning Accuracy for Emerging Automated Performance Monitoring Techniques. *Autom. Constr.* **2011**, *20*, 1143–1155. [CrossRef]
106. Oytun, M.; Atasoy, G. Effect of Terrestrial Laser Scanning (TLS) Parameters on the Accuracy of Crack Measurement in Building Materials. *Autom. Constr.* **2022**, *144*, 104590. [CrossRef]
107. *United States National CAD Standard—V5 (NCS V5)*; National Institute of Building Sciences: Washington, DC, USA, 2011.