Analysis of a Concrete Bridge using BIM and 3-D Reconstruction Technique

Final Year Project UG 2017

By

Mudassir Ahmad

Hamza Tariq

Ghufran Ahmad

Muhammad Waleed Afzal Khan

Supervisor

Dr. Muhammad Usman Hanif

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences and Technology, Islamabad

Pakistan

2021

This is to clarify that the Final Year Project titled

Analysis of a Concrete Bridge using BIM and 3-D Reconstruction Technique

Submitted By

Mudassir Ahmad	00000 214655
Hamza Tariq	00000 209861
Ghufran Ahmad	00000 221360
Muhammad Waleed Afzal Khan	00000 217717

---

has been accepted towards the requirements for

the undergraduate degree

in

CIVIL ENGINEERING

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences and Technology, Islamabad

Pakistan

2021

Acknowledgements

In the name of Allah, the Most Beneficent, the Most Merciful. Peace and blessings be upon our master Muhammad, the servant of Allah and the last of His Final Messenger. First and foremost, all praise and thanks is due to Allah who brought us this far on the path of knowledge and enabled us to conduct this research under competent and accomplished guides and without whose blessing we would not have been able to accomplish such an enormous task. We hope that this work contributes to the development of mankind.

Our parents and mentors have made efforts and sacrifices over the course of our lives to lead us where we stand today for which they have our eternal gratitude.

We respect and highly appreciate the guidance and aid provided by our supervisor Dr. Muhammad Usman Hanif, Assistant Professor at NUST Institute of Civil Engineering (NICE) at every step of the way. His valuable advice and calm commitment to this research were a source of motivation for us. Throughout the research project his constant support and taking time out of his busy schedule for mentorship kept us proceeding forward. His professional grooming of the group in thesis writing, presentation and mentorship is a valuable precedent for us that will help us in our practical life.

Special thanks to Lecturer Muhammad Fawad who is currently perusing his PhD in Silesian University of Technology, for supervising us during the initial phase of our project and helping us the finalize the topic of the project. We would express our gratitude towards Dr. Salman Atif, Assistant Professor in IGIS, NUST for providing and operating the drone.

Special thanks to 3DFlow, Agisoft, 3DS, CSi and Autodesk for providing us the student licenses of 3DF Zephyr, Agisoft Metashape, ABAQUS, SAP2000 and Revit respectively.

Finally, we would extend our appreciation towards our friends and colleagues who kept encouraging us and provided necessary assistance in completion of this research project.

Dedication To

Our Supervisor *Dr. Muhammad Usman Hanif*

&

Our families

Abstract

Visual inspections are the initiating procedures for any structural health assessment method. In civil engineering structures, visual inspections have become more challenging because of the massiveness of the structures. In case of bridges, which are constantly exposed to dynamic loads (such as wind and traffic loads), the health inspection procedures involve heavy machinery, thus, disrupting the traffic flow. This research was aimed at addressing the said challenge by using Building Information modeling and 3D reconstruction technique, which not only provides data for visual inspection, but is also capable of producing a 3D finite element model for static or dynamic analysis. Utilizing these capabilities of BIM and 3D reconstruction techniques, it was found that 3d reconstruction has great potential in its applications in civil engineering.

Keywords: *3D Reconstruction, Photogrammetry, FE Modal Analysis,*
Bridge Inspection

Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

Abbreviations

BIM	Building Information Modeling
NHA	National Highways Authority
AASHTO	American Association of State Highway and Transportation Officials
GPR	Ground Penetrating Radar
IR	Infrared
TLS	Terrestrial Laser Scanners
AEC-FM	Engineering, Construction, and Facilities Management
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
DEM	Discrete Element Methods
FEM	Finite Element Model
NDT	Non-Destructive Testing
png	Portable Graphics Format
jpg	Joint Photographic Expert Group
MBE	Manual for Bridge Evaluation

FHWA	Federal Highway Administration
BMS	Bridge Management System
RAMD	Road Asset Management Director
IS	Infrared Scanning
RGBD	Red-Green-Blue-Depth
CRP	Close-Range Photogrammetry

Chapter 1

Introduction

1.1 General

Civil engineers using their knowledge and expertise to find very creative solutions to the world's most critical problems. These global problems and challenges include water shortages, climate change, natural and human-induced disasters, growing urbanization, and energy shortages. Civil engineers design, construct, supervise, operate, and maintain large construction projects and systems, including buildings, roads, tunnels, airports, dams, bridges, and systems for water and sewage treatment [1].

Transportation systems are a part of the basic need for business and society to operate because it provide connections between two destinations, using sea, land, or air, creating a link for social and economic activities. Bridges are widely used to cross rivers, valleys, and roads easing passage to other parts of the land from ancient times to modernity.

Photogrammetry, an optical method, is used to visualize and analyze terrains, buildings, and infrastructure in both two and three dimensions. Spatial analysis is an important application of photogrammetry and the creation of 3D models from 2D photographs is a part of the modern digital age. Virtual realities, cultural heritage documentation, geospatial applications are now possible due to the availability of high computing power and automation in 3D reconstruction. While in its early days photogrammetry was used mostly as a tool for cartography, it is recently being used in civil and architectural engineering for 3D modeling of structures especially heritage structures. The use of photogrammetry has motivated the civil engineering researchers to develop its potential use in automated FE modeling and structural analysis.

1.2 Cultural Heritage Structures

In developed countries, much importance and priority are given to the preservation of heritage structures because it preserves their history, promotes tourism which boosts their economy. However, in developing countries likes Pakistan, the idea of heritage conservation is not given much importance due to very limited resources. Now the government of Pakistan is trying to promote tourism and there is a dire need to preserve our history. We need to consider our buildings and sites as assets and resources as they are a reflection of the history of our values and cultural association that provides a person with a sense of identity, roots, and destiny [2].

The problem of inspecting heritage sites is that no documentation or plans are available for the previous state of the structure. These sites usually cover a large area and the manual inspection consumes a lot of time, effort, and manpower. To address these constraints, efforts are being made to utilize the technology for visual inspection, such as 3D laser scanning and photogrammetry which also fulfill the purpose of documentation like preparation of architectural plans.

1.3 Inspection of Bridges

Inspection of bridges is an integral part of the maintenance cycle of bridges. The current practice is the in-person visual inspection of bridges (carried out by an inspector). Some portions of the bridge are accessible by foot and some require the mobilization of heavy machinery such as a platform connected to a crane by standing on which, the inspector examines the bridge.

The problem with this method is that it is tedious, involves safety risk and may disrupt the serviceability of the bridge while the equipment is in place. Moreover, every inspector reports conditions or damages subjectively and it is very time-consuming. Hence there is a need for an alternate method that utilizes the latest technology which addresses the drawbacks of the conventional methods. One possible alternative is the use of optical methods, particularly the photogrammetric method. This method allows us to capture data remotely using drones in the form of images and process them into a 3D form for visualization. The use of this method is relatively a new concept in civil engineering.

1.4 Problem Statement

Surface defects such as cracking, spalling, efflorescence are analyzed by visual inspection. In high-rise bridges or in the bottom of overwater bridges, heavy equipment such as elevating platforms must be mobilized, which subjects the inspectors to safety risks. Despite all this time-consuming and laborious effort during the bridge inspection, the whole bridge evaluation is not objective i.e., every inspector reports the damage subjectively according to their experience.

Due to all these problems, there is a need to explore an innovative method in the visual analysis process of bridges that makes the use of high computing power, modern software, and cameras. Also, the use of finite element model for modal analysis and determining modal frequencies, which has great potential in efficient model-updating and system identification of structural systems for SHM.

1.5 Objectives

1. To obtain photographic data from a bridge structure for the generation of 3d model.
2. To obtain and evaluate the 3D textured mesh model of the bridge.
3. To obtain the automatic and manually generated structural model.
4. To analyze and compare the auto-generated model with the separately developed Finite element model of the bridge.

1.6 Thesis Structure

Followed by the introduction, a detailed literature review has been provided in chapter 2 pertaining to 3D construction, bridge inspection, and cultural heritage sites. Chapter 3 explains the in-depth methodology adopted for this research study comprising of data acquisition and data processing. The field measurements, their analysis and critical discussion are presented in chapter 4. Chapter 5 discusses the limitations of our research and chapter 6 discusses the recommendations for the future study. The conclusions drawn from this research work are composed in chapter 5 of this thesis.

Chapter 2

Literature Review

2.1 Introduction

Bridge inspections are conducted to figure out the physical and functional condition of the bridge, to start the maintenance actions, to provide a continuous record of bridge condition and rate of deterioration, and to set priorities for repair and rehabilitation programs. Bridge inspections are done once a year or no longer than the two years interval for certain bridges to maintain the serviceability of the bridge [3].

2.2 Current Bridge Inspection practices

2.2.1 AASHTO Method and US Federal Highway Administration

The AASHTO Manual for Bridge Evaluation (MBE) identifies seven types of inspections: initial (inventory), routine (periodic), damage, in-depth, fracture critical, underwater, and special (interim) [4]. The inspection rate, as well as the details vary according to the types of inspections together with the bridge conditions. The periodic routine, the most commonly used inspection, is typically based on visual observation and basic measurements to help identify any bridge defects or changes from prior records. For defects that are not easily noticeable using regular inspection methods, unplanned and proactive inspections, such as in-depth inspections, are used [5].

The Federal Highway Administration (FHWA) requires that all states conduct routine inspections of each bridge after every two years [4] and recommends annual inspections for the bridges classified as structurally deficient [6]. The procedures involved in a routine inspection differ significantly based on the type of bridge, mainly because different defects tend to be associated with different materials. For instance, the primary focus of routine inspections of concrete bridges are the concrete cracks. Current routine inspections typically involve the use of visual and paper-based practices. Initially, the type, location, and severity of defects on each bridge element is correctly identified by a qualified inspector within their grasp following a planned sequence based on the element numbering system. Secondly, the damage is recorded manually by using checklists, taking notes, sketching, and taking photos while on site. Ultimately, the inspector assesses all the elements, and the data is then documented by using standard inspection reports, which are uploaded to the Bridge Management System (BMS). The BMS enables bridge engineers to access and compare their reports with previous inspection results and identify any repair/rehabilitation/maintenance needs [5].

2.2.2 National Highway Authority (NHA) Method

NHA method is almost similar to the AASHTO method except that NHA has developed its own 'Bridge Inspection Report' forms. The maintenance staff visits each individual bridge fills these forms during the inspection and dispatches them to Road Asset Management Director (RAMD) and their respective regional offices. This qualitative method is subjective so the results may differ depending upon the experience of the maintenance staff. The maintenance staff visually inspects the superstructure of the bridge (beams, girders, trusses, etc.), bridge surface (bitumen, cracking, spalling), the river (blockage of water passage, trees, and bushes growing under the bridge), Parapets, Railings, Guards, Masonry Arches, abutments, retaining walls, etc.

2.3 Problems in Current Bridge Inspection Practices

TThe current visual methods of bridge inspection have numerous limitations which are causing various problems for engineers, routers, and bridge management bodies. The Pakistan Engineering Council's (PEC) Code of Conduct makes it the responsibility of all the employees and organizations to ensure the safety of the public, health, and welfare of the public but under the current bridge inspection practices, the safety of inspectors and public are not fully assured. The inspectors use raised platforms to reach the inaccessible part of bridges to observe possible defects, but it places the safety of the inspector under uncertainty in case of any mishap. The placement of the equipment such as elevating platforms and scaffolding increases the cost, time, and effort for inspecting a bridge. It also disrupts the flow of traffic which causes a lot of inconvenience of commutes [7]. and as well as loss to the overall economy since the major bridges might be blocked for several business hours. Every inspector is handed a form to be filled during the visual bridge inspection and all possible defects are given a rating, for instance, from 1 to 10 (or depending upon the scale which the organization uses). The evaluation process is not objective, it is heavily dependent on the inspector's judgement so the results may vary from inspector to inspector depending upon his temper, experience, and environment [8]. All these shortcomings make the whole evaluation process laborious and time-consuming for large and complex bridges.

Furthermore, there is a lot of information generated during all this visual bridge inspection process as in National Highway Authority's (NHA) method in which inspectors must fill 'Bridge Inspection Report' forms, and for an exceedingly large number of bridges, managing the repository of these forms requires a lot of staff which further increases the costs and effort. Even during this period of technology and software, many Bridge Management System uses paper-based practices for the whole visual bridge inspection process. The issue of coordinating the inspection process further exacerbates the problem. For instance, a lot of staff members are required just to manage the inspectors among various sections of a bridge, and coordinating the bridge inspection during all the phases of the visual bridge inspection process is another challenge [9]. The current BMSs focus mostly on the database (such as ratings) but the direct visualization of data in the form of graphs and charts are mostly absent since the visual inspection process is mostly qualitative [10]. The numerous sources from which the data is taken poses another challenge for analyzing and comparing the data [11]. Finally, two or more types of defects can be grouped together in reporting the defects, for instance, longitudinal and transverse cracks can be placed in one category due to the error of the inspector [5, 10].

The above discussion illustrates that there is a need to address the flaws in the current visual bridge inspection system by augmenting it with powerful computing technology and the latest software, which will make the bridge inspection process objective, quantitative and efficient, saves time, and is less costly [5].

2.4 Types of defects in bridges

2.4.1 Sub- Surface Defects

Subsurface defects, such as corrosion of the reinforcements and concrete delamination, are not directly visible but these defects have a strong impact of reducing elements' structural capacity and are very harmful to the entire structure. It is a very critical task to detect these subsurface defects and measure their severity and intensity for in-depth bridge inspections. Sub-surface defects can be detected using Ground Penetrating Radar (GPR), Infrared (IR) Thermography, etc. [5].

2.4.2 Surface Defects

Surface defects are deficiencies on the surface of concrete members such as cracks, spalling, and efflorescence. Terrestrial laser scanners (TLS) can capture these surface defects and are known for their ability to rapidly obtain accurate surface information of structures and present this information in the form of three-dimensional (3D) high-density point clouds. TLS has also been used for the purpose of bridge inspection. Thruong Hong et al. suggested a framework that applied TLS technology to inspect bridges to determine the damage and deformation and to reconstruct 3D models. They have demonstrated that TLS can provide adequate and useful information regarding the structural condition assessment. Although TLS has the advantage to produce a very high-resolution and accurate model output but the downside is its large file sizes and long processing times. These are primary barriers to its wider adoption in the architectural, engineering and construction, and facilities management (AEC-FM) industry [12].

Another remote sensing technology for detecting surface deterioration is unmanned aerial systems (UAS). The deployment of UAS to collect aerial images has recently received considerable attention in the AEC-FM industry due to its mobility, ease of use, low cost, and safety [13]. The ability of UAS to be operated remotely and flown very close to a structure has led to its repeated use during high-risk situations to separate the inspectors from potential workplace hazards. In addition, the impact on traffic is very small when using UASs for bridge inspection because it eliminates the need to use large equipment, the inspection process is accelerated, and cracks are detected through a non-destructive technique [14]. The collection of images by UAS are high resolution and comparable to traditional bridge inspection results. Especially relating to the identification of defects they maybe potential in bridge connections, concrete spalling, and cracks [15]. Khaloo et al. used computer vision techniques and UAS imaging to develop a high-resolution 3D model of a bridge in Alaska. They have come to the conclusion that unmanned ariel systems are very useful tools for assisting structural inspections [16]. Although previous studies suggested that the detailed images generated by UAS can be used for condition assessment of civil structures, the overall quality of images are vulnerable to environmental factors such as lighting conditions and wind speed and direction [5, 7].

2.5 Bridge Management System

The current BMS typically focuses on the database but does not provide direct representation or visualization of the data [10]. US has documented the inventory of bridges: how many bridges are there, how many are structurally deficient, how many are damaged but serviceable etc. [17]. In Pakistan, no such system is developed where visual data of bridges is stored so that new visual inspection can be compared to the previous state of the bridge. Currently, the inspection work is still saved on Bridge Inspection Forms.

Cloud computing technology is still not utilized so that the visual data of the bridges can be accessed anywhere. UAS can store the visual data of bridges which can also be accessed through the internet. Moreover, using these images 3D Geometry Model of the structure can be ascertained using software such as 3DF Zephyr [18], Agisoft Metashape [19], etc.

2.6 3D Reconstruction

Three-dimensional (3D) reconstruction is a method of obtaining 3D points from corresponding two-dimensional (2D) images as viewed by multiple cameras with overlapping fields of view. 3D reconstruction is an important topic in the field of computer vision that has recently seen increased demand for many practical applications including virtual reality and medical imaging [20]. However, little research has been conducted on the application of this technology for civil engineering purposes [21]. 3D reconstruction can be done either by active methods or passive methods. Active and passive methods of 3D reconstruction are explained in the subsequent text.

2.6.1 Active Methods of 3D reconstruction

In Active Methods, such as, Terrestrial Laser Scanning, Infrared Scanning (IS) and Red-Green-Blue-Depth (RGBS) cameras, the data for reconstructing a 3D model is obtained by first emitting the radiations from the an sensor such as laser and then recording the reflected radiations [22]. Chen et al, modelled a bridge and estimated its damage by generating a 3D model using TLS [23]. 3D model of bridge generated using Terrestrial laser scanners have been used to find the geometric properties of the bridge from which bridge clearance was measured. The bridge displacement alone the weak spots have been measured for different loadings to access the overall health of the structure [24–26]. Conde et al. obtained a 3D finite element model of masonary bridge using Laser Scanning [27]

2.6.2 Passive Methods of 3D reconstruction

In the Passive Methods, such as in Close-Range Photogrammetry (CRP), instead of emitting the radiations from the sensor, ambient light is recorded using camera or a drone, which catches the detailed information of the bridge in the form of images, which are than processed in the software to first generate a point cloud model which is than converted to mesh model and a solid body [28].

2.7 Photogrammetry

Photogrammetry is a passive method of 3D Reconstruction. The technique of photogrammetry is used to determine the three-dimensional geometry such as its size, shape, location with respect to the surrounding, physical objects by assessing and examining their two-dimensional photographs. Generally, photogrammetry is split into two categories: aerial and terrestrial photogrammetry. In aerial photogrammetry, images are captured using aircraft or a UAV to obtain overhead shots, that provide topographic maps and land use details. In terrestrial photogrammetry (also called non-topographic photogrammetry), images are captured on the surface of the earth and provide detailed dimensional information about an object. When the size of the structure and the distance of the camera to the structure are both less than 100 m (330 ft), terrestrial photogrammetry is further defined as close-range photogrammetry, an approach where images are acquired around an object with highly convergent camera orientations, generally pointing towards the center of the object [29].

Technological advancement in computing power such as semiconductor chips has made it possible to the processing of data taken from images fast and resources and the digital camera industry has made the photogrammetry solution a very fast, low-cost, contactless, and non-destructive technique. It can represent an excellent alternative to obtain 3D information for monitoring and conservation of cultural heritage assets, especially where it is not possible to use 3D laser scanners and in situations where areas to be inspected are not easily accessible [30]. Resolution generally depends on the number of images, their quality, and the level of overlap between them, as well as hardware and software capabilities. Photogrammetry allows the reconstruction of a 3D model of the real bridge (containing all macro defects) from its 2D aerial or terrestrial photographic images by creating its 'point cloud', from which accurate 3D measurements of large architectural elements can be derived.

2.8 Cultural Heritage Sites

Cultural Heritage Sites are important infrastructure that represent the culture, values, and history of the people of a particular region. The preservation of cultural heritage sites is a natural and internationally recognized phenomenon. The deterioration and destruction of these sites are prevented by local, national, or international authorities. Physical and structural evaluation of these structures and sites is an important step in their preservation.

2.8.1 DIGITAL PRESERVATION OF CULTURAL HERITAGE SITES

A method of preserving the details of these sites is the digital 3D reconstruction of such ancient infrastructure using TLS or UAV for acquisition of visual data. The 3D reconstructed models of these sites act as source of determining the physical state of these sites at multiple instances in time to determine their deterioration patterns.

2.8.2 HERITAGE SITES FOR SUSTAINABLE DEVELOPMENT

Sustainable development is the development that fulfills the needs of the existing generation without putting in harm's way the ability of coming generations to meet their own needs. The preservation of heritage sites is not limited to environmental impacts but also broadly impacts social, cultural, and economic stability and contributes to the well-being and better life quality of communities. It also nullifies the effects of cultural globalization. Preservation of cultural heritage is generally considered a wall in the path of economic development but on the contrary, it can create income and jobs, job training and maintenance related craftsmanship skills, the revival of city centers, heritage tourism, increase in property values, enhancement of small business, etc. The use of abandoned or inefficiently used historic buildings after their rehabilitation is integral for reviving communities and improving quality of life. Hence it is important to recognize the economic and developmental worth of heritage sites [31].

2.8.3 PRESERVATION OF HERITAGE STRUCTURES

It is important to determine the general integrity of structures such as buildings and bridges to take steps towards its preservation. Deterioration patterns are determined by studying the historical data of the structure and its response under different natural load phenomenon life earthquakes and soil settling etc. or manmade phenomena like wars etc. The response is important to get a better overall understanding of the structure. Structural integrity is determined by acquiring the geometry of the structure and conducting NDT to determine the material properties of the structure and the current conditions of the structure. The structure is then analyzed under different types of predicted loads using different analysis methods like FEM macro- or micro-modeling and discrete element methods (DEM) and necessary steps towards the preservation of the structure like rehabilitation and reinforcement. Structural analysis is an important factor in the endeavors (including diagnosis, reliability assessment, and design of intervention) that contribute towards efficient and respectful conservation of monuments and historical buildings. The accuracy of the structural analysis is crucial to avoid erroneous decisions that may result in over-strengthening of structure, resulting in avoidable loss of original material and cultural value. It is also important to ensure sufficient intervention as to not expose people or the structure itself to negatable risks, constitutes a source for knowledge.

Chapter 3

Methodology

The procedure incorporating the generation of textured model for bridge inspection and FE model for modal analysis is presented by a flowchart in Figure 3.1.

Figure 3.1

3.1 Site Selection

The pedestrian bridge over the NUST lake was chosen as an ideal test subject for our research because of its accessibility and existing experimental research results. A preliminary reconnaissance survey was carried out on the bridge site to identify possible hurdles such as bushes, trees and pedestrian rush-hour, which would be categorized as hurdles in the data acquisition process. After the survey, it was concluded that the bushes were needed to be cleared by hand. Then the data acquisition plan was devised. The plan included acquiring the data using a drone supplemented with a camera at places inaccessible by drone.

Figure 3.2: Bridge Site

3.2 Data Acquisition

A 4k video capable camera was employed for capturing the bridge from every possible angle in the form of video. The actual dimensions (Fig. 3.3), material properties (Table: 3.1), and experimental modal frequencies of the bridge were extracted from an existing research material on the bridge [32].

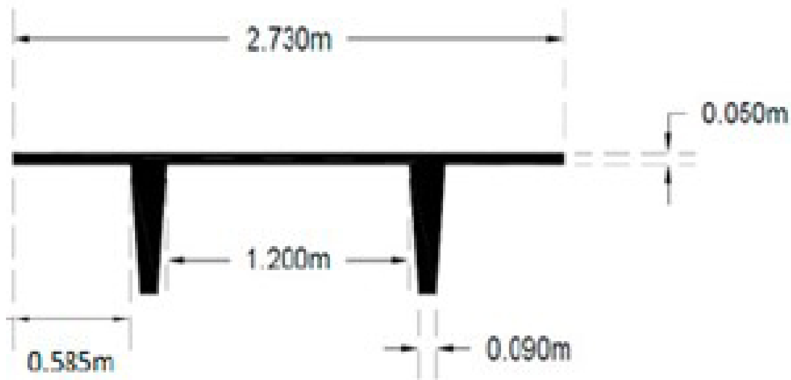


Figure 3.3: Reference Cross Section of the Bridge

Concrete Properties	
Density	2500 kg/m^3
Poisson Ratio	0.15
Modulus of Elasticity	30 GPa
Shear Modulus	13.4 GPa

Table 3.1: Reference Material Properties

3.3 Image Extraction

Multiple videos were combined into one video to aid the image extraction process. It is a tedious process to extract images from videos if there are a lot of videos. For each extraction process, the input video and output folder have to be located and set because the program does not automatically refer to the previously accessed folder. Hence, the following steps were taken for image extraction.

- The videos were combined using Any Video Converter, which is a freeware software.

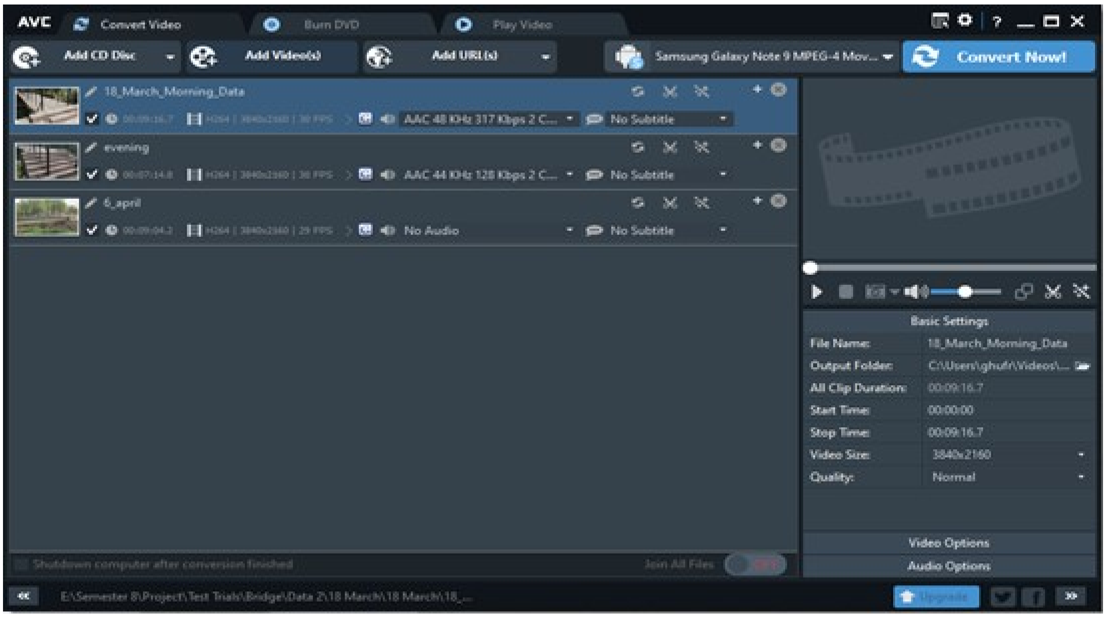


Figure 3.4: Combination of video files using Any Video Converter

- The images were extracted using an 'image extraction from videos' feature in 3DF Zephyr. The format of the images can be set to PNG or JPG. The PNG format produces better quality images with more details compared to JPG but with greater file size.

- The format was set to PNG to account for better details in the reconstructed 3D model of the bridge. Images can be extracted either using the frame rate of the video or using a custom sample rate that is less than the frame rate of the video. The program also provides filtering of blurry images that may be present in the resulting image data set. The filtering can be completely disabled or set to “fast” for rough filtering or to “normal” for accurate removal of blurry images. The fast option consumes less time and the normal option greatly increases the time for the image extraction process.
- To limit the size of the resulting image dataset, this option was set to normal.

The “Similarity auto-discard threshold” is an option that allows us to set the overlap that should exist in adjacent images which is why it is important to acquire the data in an orderly manner. A 5% threshold means images will have 95% overlap and a 40% threshold means images will have 60% overlap. A larger overlap (less threshold) results in a larger data set that produces an accurate model. A large dataset can not be processed unless the hardware is suitable for intensive computing. Unless the threshold is set to 0%, this feature overrides the frame-rate features for frames to be extracted and all frames are assessed to fulfill the overlap criteria.

- For the initial trial, the threshold was set to 80%. For the final trials, that yielded the desired model, the threshold used was 20% i.e. 60% overlapping images were used.

3.4 Point Cloud

The images that were extracted from 3DF zephyr as explained above were then processed in the Agisoft Metashape.

3.4.1 Sparse Point Cloud

Following steps were taken to generate the sparse point in Agisoft Metashape.

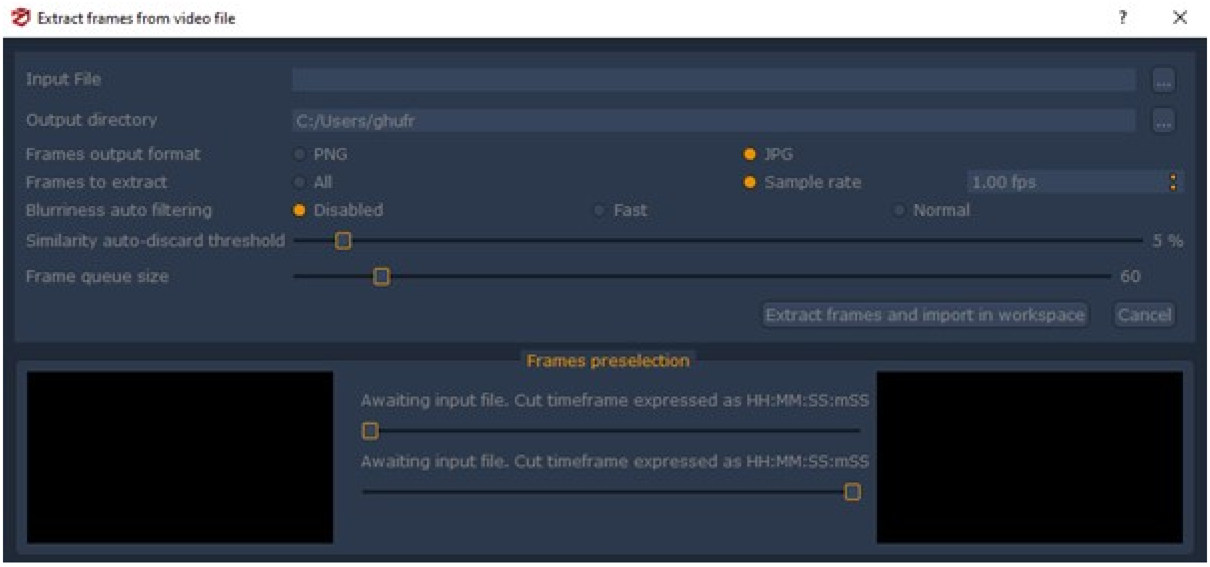


Figure 3.5: Extraction of frames from video file

- Photos were loaded by going to the 'Workspace' tab and clicking on 'add photos'.
- Photos were aligned by again clicking on 'workspace' and selecting the option 'align photos'. the highest accuracy mode was selected as shown in the figure 3.6;

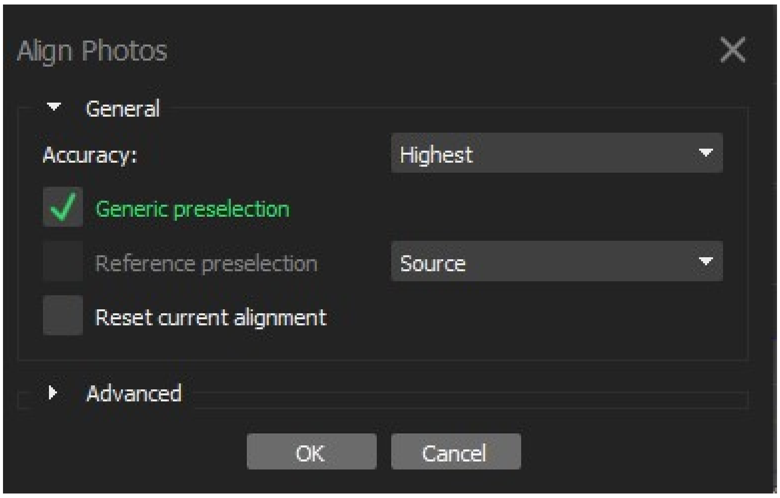


Figure 3.6: Alignment of images

- At the time of image capture, the position of camera is defined by the parameters of interior and exterior orientation. Interior orientation parameters include camera focal length, coordinates of the image principal point, and lens distortion coefficients. Exterior orientation parameters define the position and orientation of the camera. These parameters during the image alignment are estimated. The

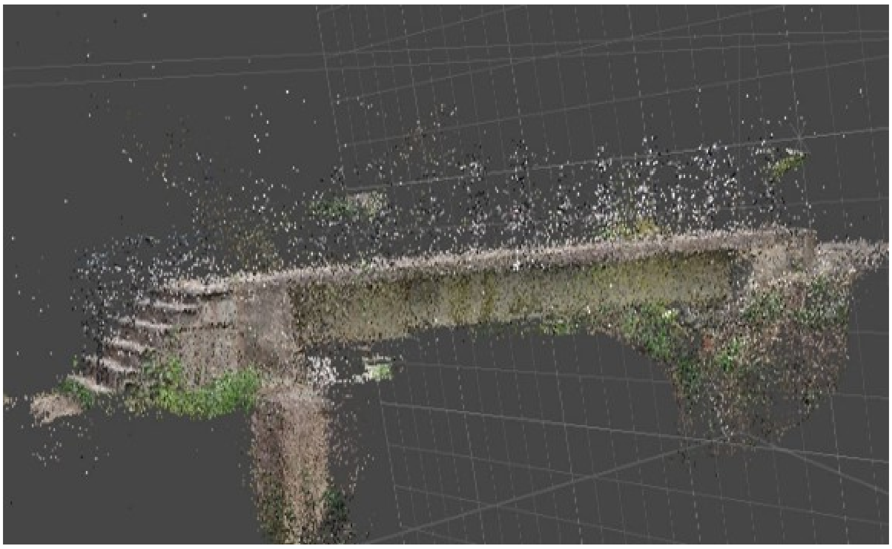


Figure 3.7: Sparse Point Cloud Model

result of this processing step consists of estimated exterior (translation and rotation) and interior camera orientation parameters together with a sparse point cloud containing triangulated positions of matched image points. The sparse point that we obtained can be seen in the figure 3.7.

The unwanted points were removed using the 'free selection tool', the total points generated were 215,713 and the total processing time taken on Agisoft's cloud server was about 34 minutes 6 seconds.

3.4.2 Dense Point Cloud

Depth maps are used to generate the dense point cloud and it is calculated using dense stereo matching. Depth maps are calculated for the overlapping image pairs considering their relative exterior and interior orientation parameters estimated with bundle adjustment. Multiple depth maps are generated in pair for each camera and merged together into a combined depth map, the wrong depth measurements are filtered using abundant information in the overlapping regions.

- For generating dense cloud, the "build dense cloud" command was selected from the workspace menu and the high-quality option was selected a shown in figure 3.8.
- The acquired dense cloud is shown in figure 3.9.

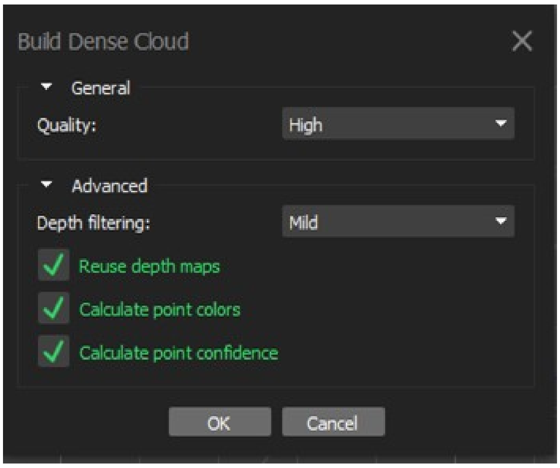


Figure 3.8: Building Dense Point Cloud

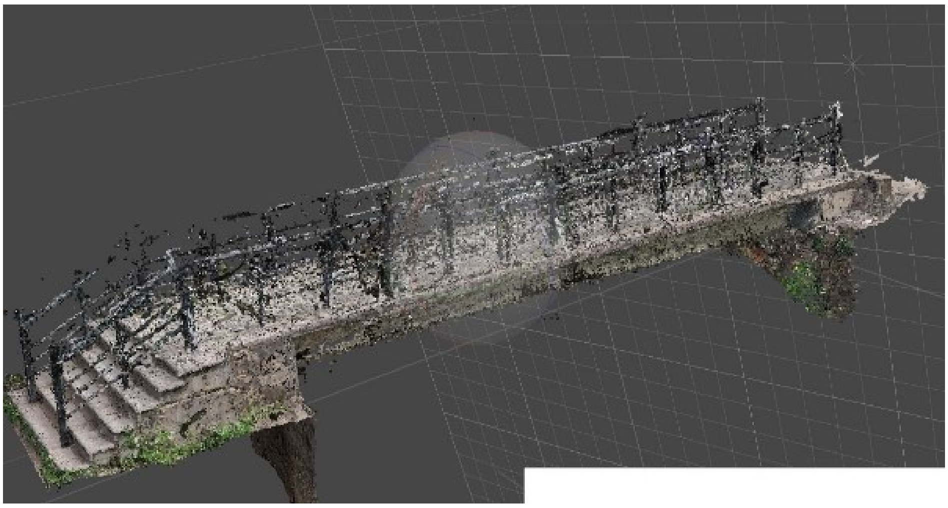


Figure 3.9: Dense Point Cloud Model

The dense cloud model had 22,079,612 points and the processing was done on Agisoft's cloud server which took 1 hour 1 minute and 8 seconds.

3.5 Mesh Generation

In this step, a Mesh model was formed by using the dense point cloud by selecting the "Build mesh" command from the workflow menu. High face counts option was selected. In addition, the following parameters shown in figure 3.10 were used.

The processing time was 27 min 51 sec on their cloud. The mesh generated can be seen in the figure 3.11.

Figure 3.10: Reconstruction Parameters

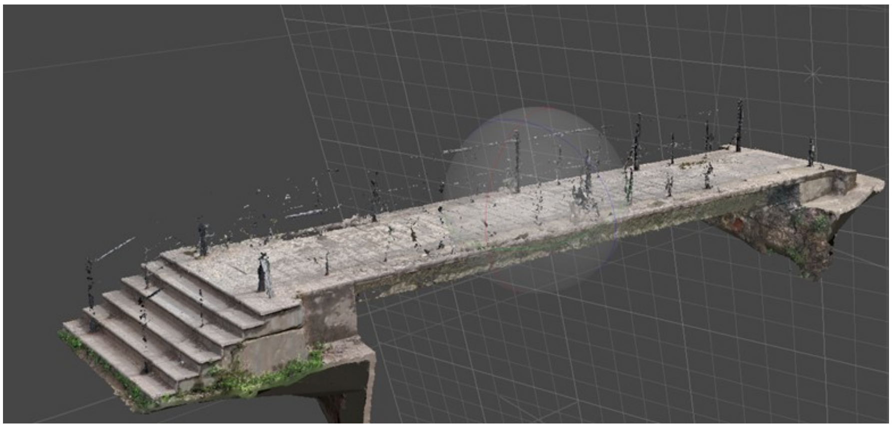


Figure 3.11: Mesh Model

3.5.1 Mesh to Automatic Model

The next step was to convert the 3D mesh into a solid body (automatic model) so that it would be recognized as an object in ABAQUS and analysis could be performed. But before converting into a solid body the number of faces of the mesh was first reduced as it contained a lot of faces which made the file very heavy for processing. A high face count is good for 3D visualization; however, it makes a negligible difference for analysis.

- So, to reduce the face count, firstly, the stairs and railings were cropped as they were not the structural part. Then the mesh was exported as .stl format to MeshLab (an open-source system for processing and editing 3D triangular meshes.) In MeshLab, "simplification: quadratic edge collapse decimation was selected" under the filters tab as shown in the figure 3.12 and the number of faces were reduced to 20,276. The reduced polygons can be seen in the figure 3.12
- In the next step, the reduced polygon model was exported as .stl format to rhino7 (A cad software). In rhino 7 by a command "MeshtoNurb" the solid body was generated.

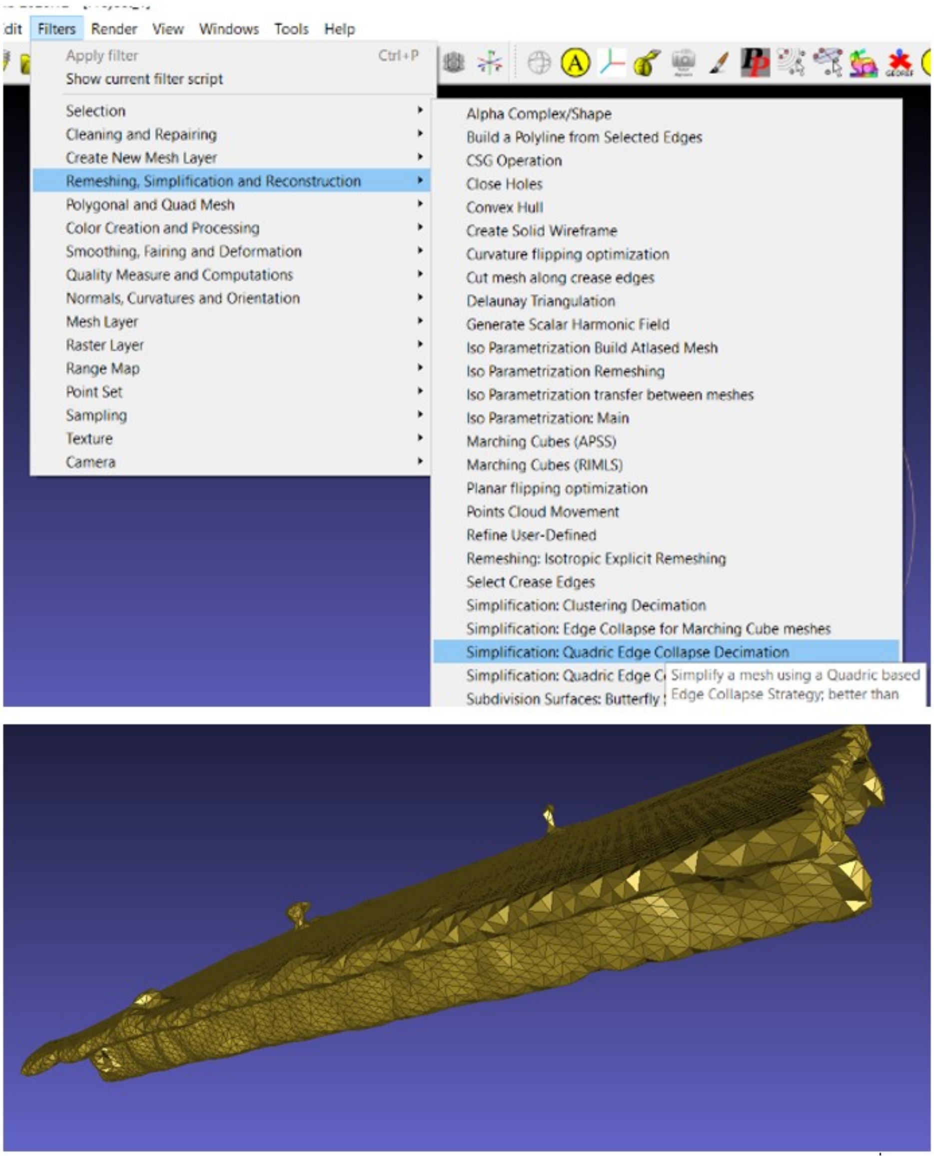


Figure 3.12: Reduction of Polygons

- The obtained solid body shown below was then exported to ABAQUS as a .step format for analysis (figure 3.13).

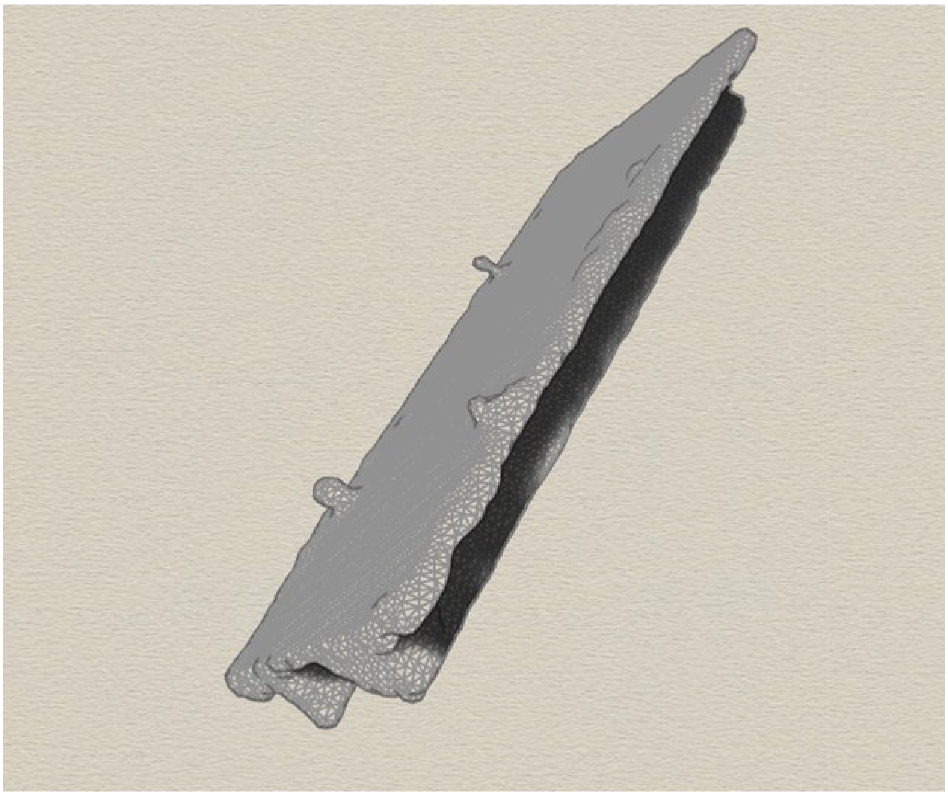


Figure 3.13: Automated 3D Model

3.5.2 Manual Model in Revit

- The bridge model was scaled after dense point cloud generation using the slab depth of 4 in of the bridge as reference dimension after setting the dimension units to feet.

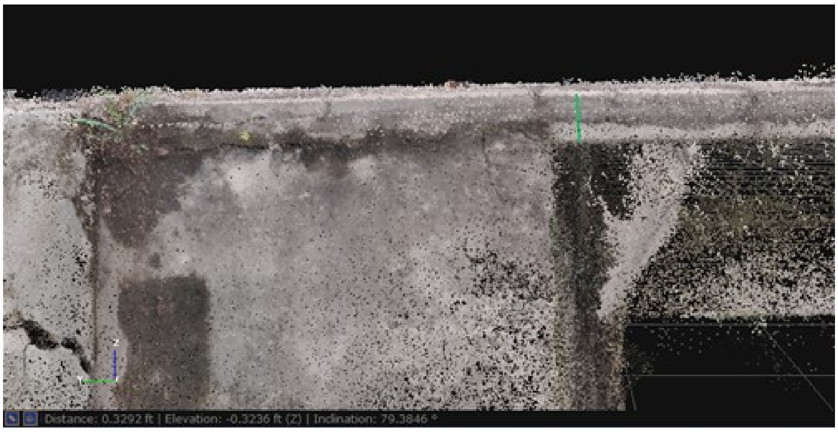


Figure 3.14: Scaling of model by taking depth of slab as reference

- The bridge model opened in 3DF Zephyr was exported to REVIT as .rcs format using the GEOBIM extension available in 3DF Zephyr after the decimation of the point cloud.

- The next step was to trace the 3D model of the bridge by manually tracing the point cloud. For that three “levels” and a new reference plan in “elevation view” were created at both ends of the bridge by clicking on ‘Ref Plane’ in the ‘work plane’ menu under the ‘Architecture’ tab.

- After that “In Place Bridge Mass” option was selected from the “Massing Siting” tab. The edges of the cross-section of the bridge were traced on the point cloud model using model lines on one end of the “elevation plan”.

- The “Model Lines” that were traced were copied on the other end of the cross-sectional plan.

- After that, the model lines were selected on the elevation plans and, the “Solid Form” option was selected from the “Create Form” option in the “In-Place Bridge Mass” window.

- Then finally “Bridge Mass” was created as shown in the figure 3.15.

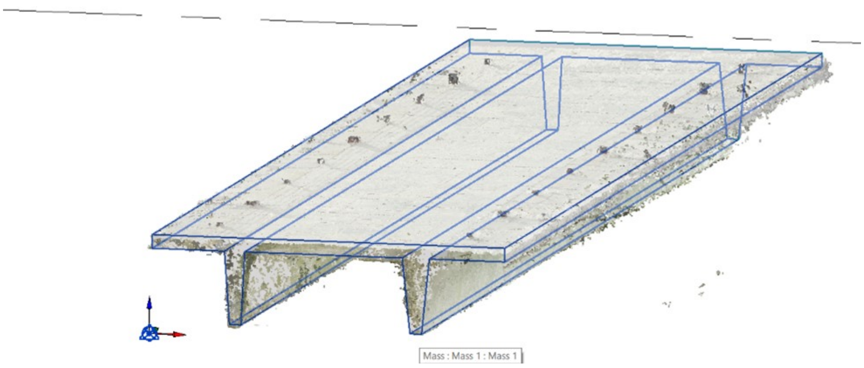
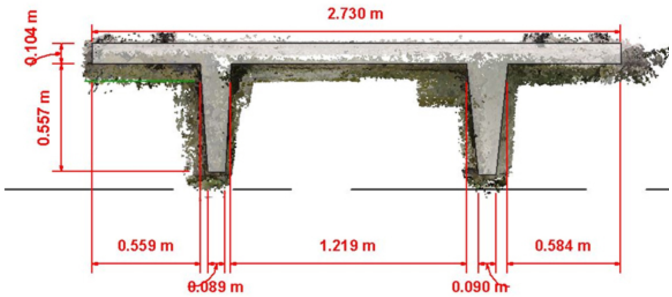
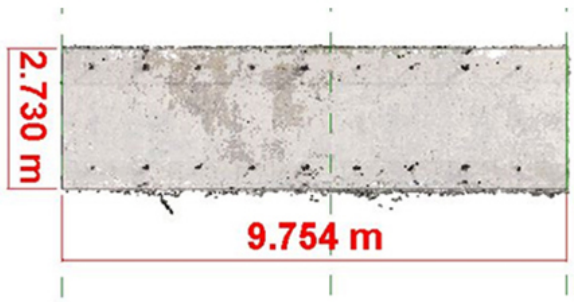


Figure 3.15: Manual Model in Revit

- The dimensions were also measured as shown in the figure 3.16.



(a) Cross-Sectional view



(b) Plan View

Figure 3.16: Dimensions of Manually Created Model

3.6 Modal Analysis

To perform flexural modal analysis on the bridge, the bridge model was converted into a beam element in ABAQUS to acquire the flexural mode shapes of the bridge. Since the desired cross-section is not supported in ABAQUS software i.e., double T with tapered webs, a generalized beam section was used in ABAQUS by incorporating the calculations of moment of inertias and torsional coefficient with the help of SAP2000's section designer.

3.6.1 Section Designer

- The section designer was opened in SAP2000 by going to 'Define' then 'Frame Sections' and on this window clicking 'Add new property' and selecting "other" from the 'Frame section property type' to open "Section Designer".
- In section designer, the cross-sections of both manual and automated models were created. The dimensions of the manual model were acquired from Autodesk Revit. For the automated model, the model was first imported to AutoCAD to extract the dimension and then the model was created in SAP2000's section designer.

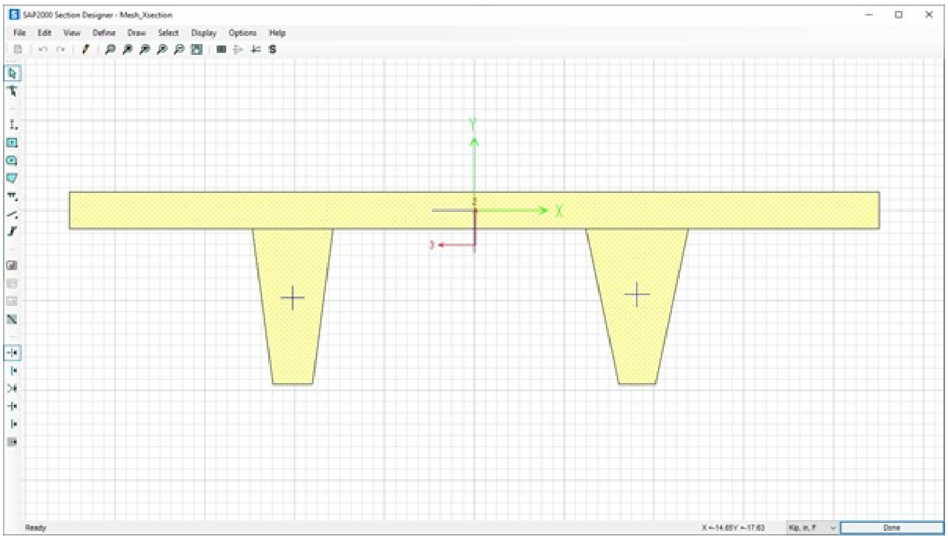


Figure 3.17: Cross section of Manual Model in SAP2000

- After when the cross-sections were created in Section Designer their section properties were opened from the 'Display' menu and then selecting show 'Show Section Properties' (figure 3.19).

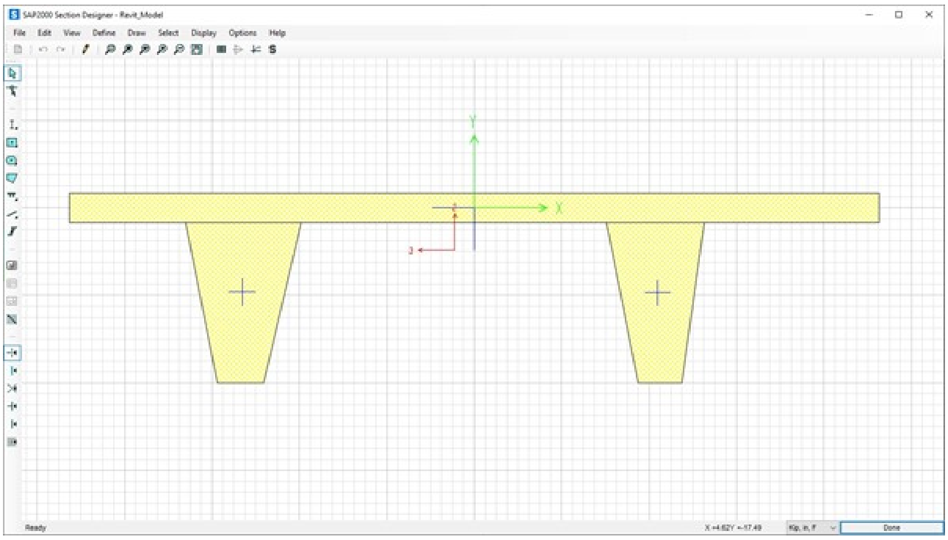
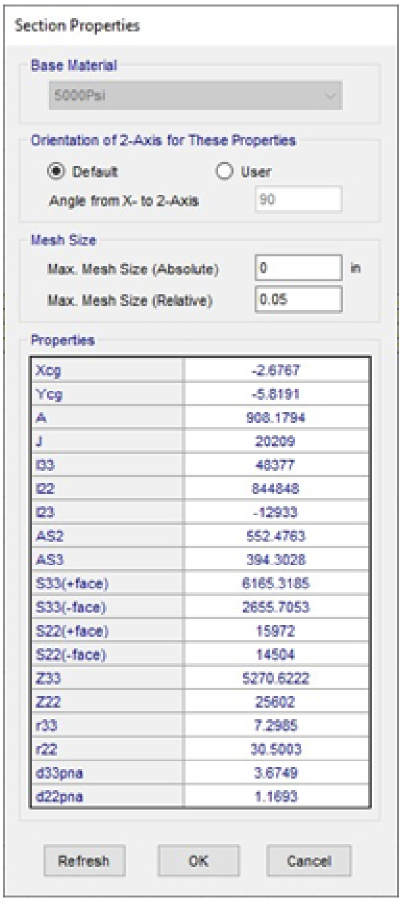


Figure 3.18: Cross Section of Automated Model in SAP2000



Section Properties

Base Material: 5000Psi

Orientation of 2-Axis for These Properties: (•) Default ( ) User — Angle from X- to 2-Axis: 90

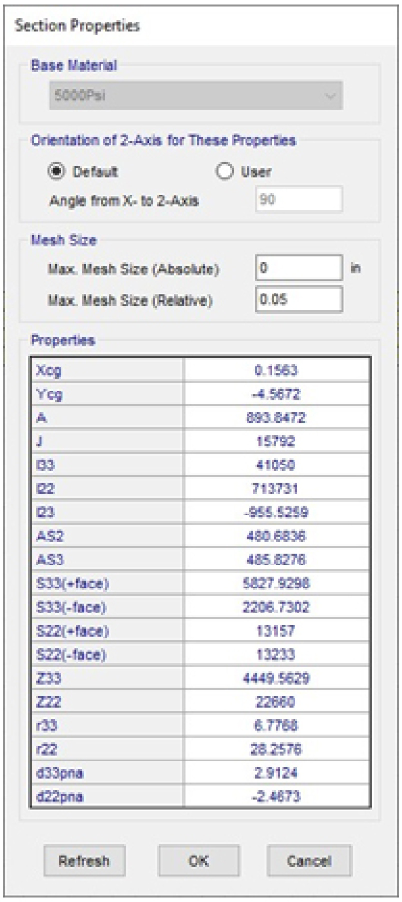
Mesh Size — Max. Mesh Size (Absolute): 0 in; Max. Mesh Size (Relative): 0.05

Properties

Xcg	-2.6767
Ycg	-5.8191
A	908.1794
J	20209
I33	48377
I22	844848
I23	-12933
AS2	552.4763
AS3	394.3028
S33(+face)	6165.3185
S33(-face)	2655.7053
S22(+face)	15972
S22(-face)	14504
Z33	5270.6222
Z22	25602
r33	7.2985
r22	30.5003
d33pna	3.6749
d22pna	1.1693

Refresh OK Cancel

Automated Model Properties



Section Properties

Base Material: 5000Psi

Orientation of 2-Axis for These Properties: (•) Default ( ) User — Angle from X- to 2-Axis: 90

Mesh Size — Max. Mesh Size (Absolute): 0 in; Max. Mesh Size (Relative): 0.05

Properties

Xcg	0.1563
Ycg	-4.5672
A	893.8472
J	15792
I33	41050
I22	713731
I23	-955.5259
AS2	480.6836
AS3	485.8276
S33(+face)	5827.9298
S33(-face)	2206.7302
S22(+face)	13157
S22(-face)	13233
Z33	4449.5629
Z22	22660
r33	6.7768
r22	28.2576
d33pna	2.9124
d22pna	-2.4673

Refresh OK Cancel

Manual Model Properties

Figure 3.19: Properties of 3D Models

3.6.2 ABAQUS

- In ABAQUS a 2D Planar wire was created in the 'Parts' Module. The wire length for the automated model was *10.1 meters* and *9.75 meters* for the manual model.
- Both the models were assigned pin-pin supports.
- In the 'Profile' module the models were assigned "Generalized" shape properties whose values were calculated using Section Designer.

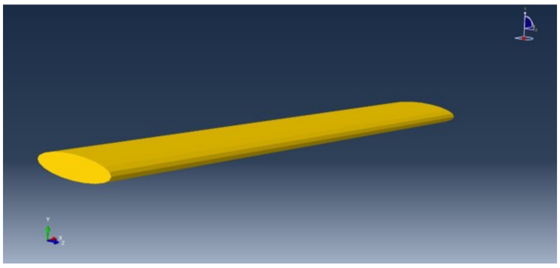
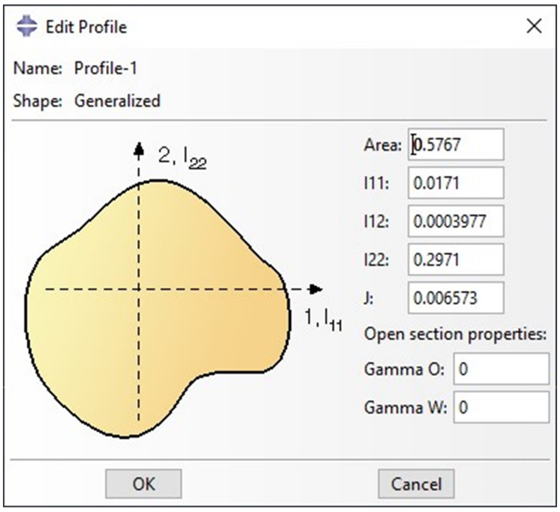


Figure 3.20: Generalized Profile Section



Generalized Profile of Manual Model

Figure 3.21: Generalized Profile Properties in ABAQUS

- In the 'Section' module the material properties as mentioned in table 3.2 were assigned. The concrete properties were referenced from a similar research [32].
- In the 'Step' module a "Frequency" step was created by selecting "Linear Perturbation" as the procedure type and *3 eigenvalues* were requested.
- In the 'Load' Module, pin-ended supports were assigned at the ends of the section.

Concrete Properties	
Density	2500 kg/m^3
Poisson Ratio	0.15
Modulus of Elasticity	30 GPa
Shear Modulus	13.4 GPa

Table 3.2: Assigned Concrete Properties

- The last step was to create a job in the 'Job' module to run the analysis and visualize the results.

Chapter 4

Results and Discussion

4.1 Visual Analysis

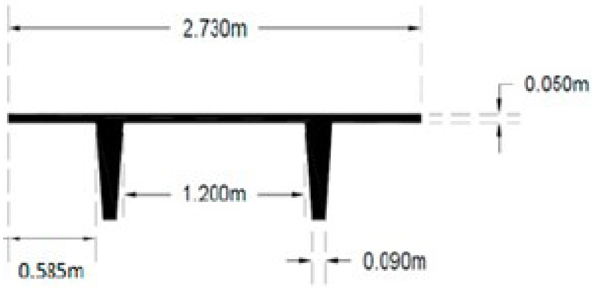
The 3D model of the bridge as previously shown in the figure 3.11 was obtained after 3D reconstruction of the bridge. The bridge was visually inspected within the program for any possible defects such as macro cracks and concrete deterioration etc.

Since the bridge did not have any defects, the joint as shown in the figure 4.1 was taken as an example to locate its position in the model. The joint was identified using a polygon that was drawn on the image from the dataset which was reflected on the 3d model. Furthermore, the joint was directly marked on the 3d model using a polygon.

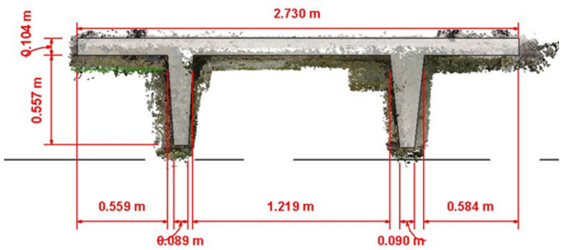
Figure 4.1: Selection of marking using a polygon

4.2 Feature Extraction

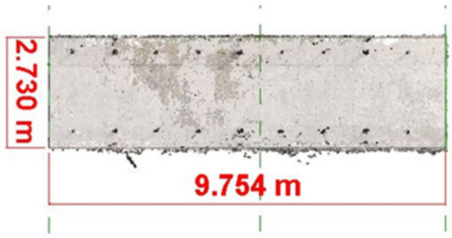
The dimensions of the bridge were extracted by using a plane to cut through the clear span of the bridge as explained in section 3.5.2. The bridge model is compared with a similar research paper [32].



(a) Actual dimensions of the bridge



(i) Cross-sectional view



(ii) Plan view

(b) Dimensions of the 3D reconstructed model

Figure 4.2: Comparison 3d reconstructed model with actual bridge

The dimensions from the 3d model were comparative to the actual dimensions of the bridge. The major variation was in the depth of the slab which was due to the inclusion of a 2-inch layer of flooring of the bridge. All dimensions were within the 5% acceptable experimental limit of results. The table 4.1 shows the variation in the dimensions obtained.

	Reference Bridge	3D Reconstructed Model	Percentage Variation
Depth of slab	0.05	0.104	100%
Width of slab	2.730	2.730	0%
Distance between T's min	1.200	1.219	1.5%
Min width of left web	0.090	0.089	1.1%
Min width of right web	0.090	0.090	0%
Left Overhang	0.585	0.559	4.4%
Right Overhang	0.585	0.584	0.2%
Length of bridge	9.8	9.75	0.5%

All units are in m

Table 4.1: Comparison of Dimensions

4.3 Modal Analysis

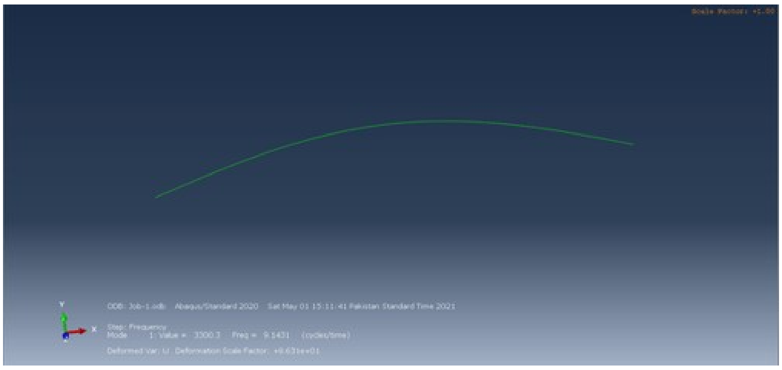
The results of flexural modal analysis were compared with a similar research [32] that is shown in the table 4.2 and the mode shapes are shown in figure 4.3.

	Reference Research Paper [32]	Manual Model (% Error)	Automated Model (% Error)
Mode 1	10.94	10.533 (3.7%)	9.143 (16%)
Mode 2	38.34	41.44 (-8%)	36.084 (5.8%)
Mode 3	75.31	90.846 (-20%)	79.474 (-5.5%)

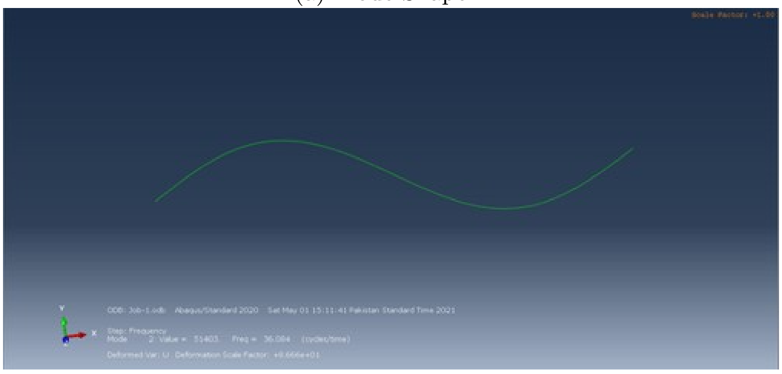
All units are in Hz

Table 4.2: Comparison of Modal Analysis

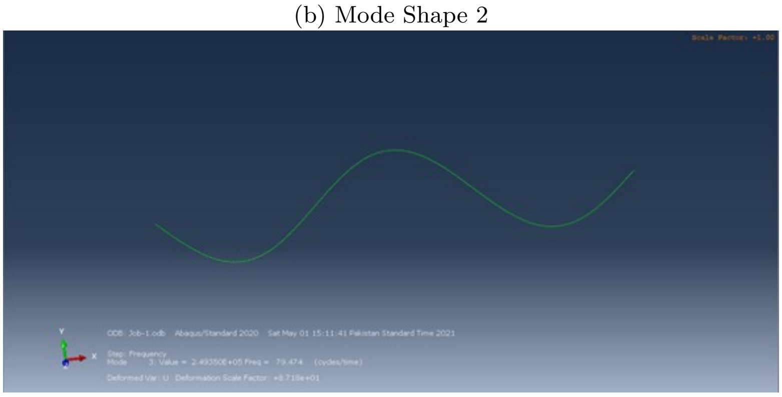
The variation in the model is due to the reason that the bridge is a reinforced structure non-homogeneous structure. The material properties in the FEM model were assumed to be homogeneous and reinforcement was not accounted for. Secondly, the variation in the dimensions in the reconstructed model may have added to the error in the experimental results.



(a) Mode Shape 1



(b) Mode Shape 2



(c) Mode Shape 3

Figure 4.3: Mode Shapes in ABAQUS

Chapter 5

Conclusions & Recommendations

5.1 Conclusion

Bridge inspection is a crucial activity in the life cycle of a bridge to ensure its quality and Serviceability. Currently, the bridge inspection practices are inefficient, time-consuming, costly, unsafe, subjective, and do not make use of advanced technology. Errors are likely to occur depending on how the inspection is conducted and the inspector's experience and personal judgement. The photogrammetric method of the 3D reconstruction is a viable alternative to the on-site inspection of the bridge during its maintenance cycle. The data of every routine inspection of the bridge can be stored which can be used for comparison purposes in the next maintenance cycles of bridges. In this way, the damages that are occurring in the bridge can be extrapolated and proactive measures can be done to prevent these damages. It was observed that visual analysis can be done for the components of the bridge. In this 3D model of the bridge defects like cracking, spalling, efflorescence, and concrete deterioration can be easily noted. Furthermore, structural analysis of the 3d reconstructed model can also be done.

Following conclusions can be drawn from this research work:

1. The textured mesh model from the photogrammetric 3D reconstruction technique is a viable option for accurate inspection and inventorying of the physical state of the bridge.
2. The structural models using the point cloud and mesh models showed comparable analysis results which indicates the practicality of 3D reconstruction to obtain the

geometry of the bridge for structural analysis.

5.2 Limitations

1. Data acquisition is very difficult on rainy or windy days. As the camera has sensitive electronic components that can get damaged from the rainwater and in case of high wind speed the drone is difficult to control.

2. The camera only captures the data of the outside shell of the structure and not the inside, thus, the cross-section is not obtained in this process. Therefore, this technique is limited to structures having solid geometry and cannot be used for hollow structures.

3. Material properties are not obtained in the data acquisition process for the structural analysis process.

4. The process of reconstructing a 3D model is very hardware intensive as it requires very high processing power and brand-specific GPUs. As the data set is increased the amount of RAM required is also increased. Local Processing may consume a lot of time in case the recommended hardware requirements are not met.

5.3 Recommendations

1. Data acquisition should be done on a clear or cloudy day so that sufficient light is present to capture the data. Also, rainy and windy days should be avoided as it makes the data acquisition process difficult.

2. For the structural analysis process, material properties are required so that software can run the analysis. 3D reconstruction technique is recommended for structures having uniform materials, like masonry or steel structures. Their properties can be determined by finding strength, elastic modulus, etc. from nondestructive testing techniques. And in the case of reinforced structure, x-ray scanning can be done to find out the layout of the reinforcements

3. To process the data quickly cloud processing can be used where the data is processed in the dedicated servers. It requires a monthly subscription, and the results

can be achieved in a matter of minutes as compared to several hours if processed locally.

References

[1] Arturo Gonzalez, Michael Schorr, Benjamin Valdez, and Alejandro Mungaray. Bridges: Structures and materials, ancient and modern. In *Infrastructure Management and Construction*. Intechopen, 2020.

[2] Fauzia Qureshi. *Conserving Pakistan's Built Heritage*. The World Conservation Union, 1994.

[3] NATIONAL HIGHWAY AUTHORITY. *NHA Code 1999 as revised in 2005*. NHA, 2005.

[4] Transportation Officials. Subcommittee on Bridges. *The manual for bridge evaluation*. AASHTO, 2011.

[5] Yiye Xu and Yelda Turkan. Bridge inspection using bridge information modeling (brim) and unmanned aerial system (uas). In *Advances in informatics and computing in civil and construction engineering*. Springer, 2019.

[6] Infrastructure report card: Purpose and results. 2017.

[7] Norman Hallermann and Guido Morgenthal. Visual inspection strategies for large bridges using unmanned aerial vehicles (uav). In *Proc. of 7th IABMAS, International Conference on Bridge Maintenance, Safety and Management*, pages 661–667, 2014.

[8] Guoping Bu, Jaeho Lee, Hong Guan, Michael Blumenstein, and Yew-Chaye Loo. Development of an integrated method for probabilistic bridge-deterioration modeling. *Journal of Performance of Constructed Facilities*, 28(2):330–340, 2014.

[9] Arun M Shirole, Timothy J Riordan, Stuart S Chen, Qiang Gao, Hanjin Hu, and

Jay A Puckett. Brim for project delivery and the life-cycle: state of the art. *Bridge Structures*, 5(4):173–187, 2009.

[10] Brodie Chan, Hong Guan, Lei Hou, Jun Jo, Michael Blumenstein, and Jun Wang. Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments. *Journal of civil structural health monitoring*, 6(4):703–714, 2016.

[11] S DiBernardo. Integrated modeling systems for bridge asset management—case study. In *Structures Congress 2012*, pages 483–493, 2012.

[12] Linh Truong-Hong, Holger Falter, Donal Lennon, and Debra F Laefer. Framework for bridge inspection with laser scanning. In *EASEC-14 Structural Engineering and Construction, Ho Chi Minh City, Vietnam, 6-8 January 2016*, 2016.

[13] Peter Liu, Albert Y Chen, Yin-Nan Huang, Jen-Yu Han, Jihn-Sung Lai, Shih-Chung Kang, Tzong-Hann Wu, Ming-Chang Wen, Meng-Han Tsai, et al. A review of rotorcraft unmanned aerial vehicle (uav) developments and applications in civil engineering. *Smart Struct. Syst*, 13(6):1065–1094, 2014.

[14] Najib Metni and Tarek Hamel. A uav for bridge inspection: Visual servoing control law with orientation limits. *Automation in construction*, 17(1):3–10, 2007.

[15] Daniel T Gillins, Christopher Parrish, Matthew N Gillins, and Chase Simpson. Eyes in the sky: bridge inspections with unmanned aerial vehicles. 2018.

[16] Ali Khaloo, David Lattanzi, Keith Cunningham, Rodney Dell'Andrea, and Mark Riley. Unmanned aerial vehicle inspection of the placer river trail bridge through image-based 3d modelling. *Structure and Infrastructure Engineering*, 14(1), 2018.

[17] Status of the nation's highways, bridges, and transit: Conditions and performance.

[18] 3d flow 3df zephyr user manual - version 4.5.

[19] Agisoft metashape user manual - professional edition, version 1.5.

[20] SUNANDO Sengupta. *Issues in 3D reconstruction from multiple views.* PhD thesis, Citeseer, 2009.

[21] Joshua Caron. 3d reconstruction for post-disaster analysis of civil infrastructure. 2012.

[22] Cosmin Popescu, Björn Täljsten, Thomas Blanksvärd, and Lennart Elfgren. 3d reconstruction of existing concrete bridges using optical methods. *Structure and Infrastructure Engineering*, 15(7), 2019.

[23] Shen-En Chen, Wanqiu Liu, Haitao Bian, and Ben Smith. 3d lidar scans for bridge damage evaluations. In *Forensic Engineering 2012: Gateway to a Safer Tomorrow*, pages 487–495. 2013.

[24] Wanqiu Liu, Shen-en Chen, and Edd Hasuer. Bridge clearance evaluation based on terrestrial lidar scan. *Journal of Performance of Constructed Facilities*, 26(4): 469–477, 2012.

[25] Wanqiu Liu, Shen-en Chen, David Boyajian, and Edd Hauser. Application of 3d lidar scan of a bridge under static load testing. *Materials evaluation*, 68(12):1359–1367, 2010.

[26] Michael Hess, Vid Petrovic, Mike Yeager, and Falko Kuester. Terrestrial laser scanning for the comprehensive structural health assessment of the baptistery di san giovanni in florence, italy: an integrative methodology for repeatable data acquisition, visualization and analysis. *Structure and Infrastructure Engineering*, 14(2):247–263, 2018.

[27] Belén Riveiro and Mercedes Solla. *Non-destructive techniques for the evaluation of structures and infrastructure*, volume 11. CRC Press, 2016.

[28] Borja Conde, Luís F Ramos, Daniel V Oliveira, Belén Riveiro, and Mercedes Solla. Structural assessment of masonry arch bridges by combination of non-destructive testing techniques and three-dimensional numerical modelling: Application to vilanova bridge. *Engineering Structures*, 148:621–638, 2017.

[29] S. Robson M.A.R. Cooper. Close range photogrammetry and machine vision. *Engineering Structures*, pages 9–50, 2000.

[30] Pedro Arias, J Herraez, H Lorenzo, and C Ordonez. Control of structural problems in cultural heritage monuments using close-range photogrammetry and computer methods. *Computers & structures*, 83(21-22):1754–1766, 2005.

[31] Indrė Gražulevičiūtė. Cultural heritage in the context of sustainable development. *Environmental Research, Engineering & Management*, 37(3), 2006.

[32] Azam Ali, Talha Yousaf Sandhu, and Muhammad Usman. Ambient vibration testing of a pedestrian bridge using low-cost accelerometers for shm applications. *Smart Cities*, 2(1), 2019.