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BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates

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Contents

List of Abbreviations

AEC	Architecture, Engineering, and Construction
ACC	MEMS Accelerometers
AI	Artificial Intelligence
ANN	Artificial Neural Network
API	Application Programming Interface
AR	Augmented Reality
BCF	BIM Collaboration Format
BIM	Building Information Management
BEP	Building Execution Plans
BMS	Bridge Management System
bSDD	buildingSMART Data Dictionary
CAD	Computer-Aided Design
CBMS	Comprehensive Bridge Management System
CDE	Common Data Environment
COBie	Construction Operations Building Information Exchange
CoMAC	Coordinate Modal Assurance Criteria
CM	Crack Meter
DAF	Dynamic Amplification Factor
DAQ	Data Acquisition system
DIC	Digital Image Correlation
DFOS	Distributed Fiber Optic Sensing
DT	Digital Twin
DTM	Digital Twin Model
DL	Deep Learning
EC	Eurocode
EIR	Employer Information Requirements
FBG	Fiber Bragg Grating
FEM	Finite Element Modeling
FIM	Fisher Information Matrix
FRF	Frequency Response Functions
HDR	High-Dynamic Range
HL	HoloLens
HMI	Human-Machine Interface
IBDTP	Immersive Bridge Digital Twin Platform
IDM	Information Delivery Manual
IDS	Information Delivery Specification
IFC	Industry Foundation Classes
INC	Inclinometers
IoT	Internet of Things
IR	Infrared
LCA	Life Cycle Assessment
LD	Load Displacement
LDS	Laser Displacement Sensor
LLS	Liquid Leveling Sensors
LOD	Level of Development / Level of Detail

LVDT	Linear Variable Differential Transformer
MEMS	Micro-electrochemical systems
MET	Meteo station
ML	Machine Learning
MR	Mixed Reality
MRKT	Mixed Reality Tool Kit
MVD	Model View Definition
NDT	Non-Destructive Testing
OMA	Operational Modal Analysis
OQ	Oculus Quest
RC	Reinforced Concrete
RTM	Reality Twin Model
SHM	Structural Health Monitoring
SV	Site Vision
TC	Trimble Connect
TLS	Terrestrial Laser Scanning
TM	Tilt Meter
UAV	Unmanned Aerial Vehicle
UI	User Interface
UWP	Universal Window Platform
VS	Visual Studio
VCCL	Visual Code Checking Language
VP	Visual Programming
VPL	Visual Programming language
VR	Virtual Reality
vQL4BIM	visual Query Language for 4D Building Models
WIM	Weigh in Motion
WSG	Wire Strain Gauge

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1 Introduction

1.1 Background of the thesis and research motivation

In an era where man has touched down the skies, the Civil Engineering domain is targeting infrastructure resilience as paramount. The maintenance and monitoring of critical infrastructure such as bridges is becoming a major focus of engineering innovation and intervention. Ensuring the structural integrity and operational safety of bridges is critical as it helps to maintain social functionality and safety, rather than only being a convenience for society. Here technology plays its role by offering sustainable solutions for the maintenance and monitoring of infrastructure. The use of immersive and three-dimensional reconstruction methods in integration with Building Information Management (BIM) opened novel avenues for improving the effectiveness of bridge health monitoring systems.

Bridges as a critical component of modern infrastructure, facilitating the mobility of goods and people across geographical regions. Despite the technological revolution in the engineering domain, bridges remain prone to deterioration over time, caused by factors such as environmental conditions, vehicular loads, and material fatigue. Which causes bridge failures that go beyond simple inconvenience; frequently resulting in disastrous outcomes that include everything from economic disruptions to the loss of life. Even with the increased bridge resilience, the frequency of incidents highlights the need for proactive monitoring and maintenance techniques. This is where a Structural Health Monitoring (SHM) system offers its services and provides robust solutions to mitigate such problems. Such systems help to understand that disasters—which are often attributed to structural damages—are today's issues rather than historical events putting a greater emphasis on employing technological developments to avoid tragedies in the bridge future. As an aspiring researcher, the prospect of contributing to the development of solutions that reduce the risks associated with bridge collapse serves as a motivation for my engagement in this domain where this dissertation serves as a paramount in integrating the BIM, 3D reconstruction, and immersive technologies to ensure the safety of bridges. The transformative potential of these technologies over the traditional methods of structural assessment and maintenance inspired and motivated me to go deeper into this multidisciplinary domain.

Taking advantage of these promising technologies, my PhD research presents a comprehensive framework exploring the potential of BIM, immersive technologies, and 3D reconstruction methodologies to strengthen the analytical and asset model updates integrated to bridge health monitoring. By developing a comprehensive framework specifically designed to meet the demands of bridge infrastructure, this dissertation contributes towards fostering a safer, and more resilient built environment.

1.2 Thesis outlines and research objectives

The major aim of my research is to provide a foundation for the development of an Immersive automated bridge Structural Health Monitoring (SHM) system by utilizing the applications of BIM methodology, 3D-reconstruction techniques, Internet of Things (IoT) approach, Virtual/Mixed Realities (VR/MR) technologies, and the concept of Digital Twins. The proposed framework addresses the automation of bridge health monitoring systems, the specificity of bridges, and their practical adaptation in the civil engineering industry. Novel use cases of the methodologies specified as components of the proposed immersive SHM framework support the practical adoptability of the suggested solutions.

To reach the above-mentioned aim of this dissertation, four major objectives have been defined.

1. Development of bridge asset management framework using analytical and BIM modeling tools.
2. Proposal of advanced SHM system and their validation.
3. Integration of SHM, BIM, and IoT technology for smart infrastructural health monitoring.
4. Development of Immersive Bridge Digital Twin Platform (IBDTP) using Mixed Reality technology.

To achieve the above-mentioned objectives successfully, this research provides a comprehensive review of the literature on SHM of bridges, focusing on the evolution of Bridge Management Systems (BMS) and their advancements. It further explores the use of BIM methodology for SHM, highlighting its applications in data collection, management, and predictive decision-making. It also discusses the use of Virtual and Mixed Reality (VR/MR) for visualization of future bridge design concepts. The study also explores the integration of VR/MR tools with BIM, leading to the development of an online web platform for bridge SHM, utilizing wireless sensors for monitoring and maintenance.

1.3 Layout of the dissertation

The main body of the dissertation includes four chapters with two additional chapters of introduction and conclusions. The details of each subsequent chapter are listed below:

Chapter 2: explores the issues of bridge management (BMS) and its applications in the SHM of bridges. It discusses conventional methods like visual inspections, which are labor-intensive and financially burdensome. The chapter also discusses the role of IoT technology in SHM, focusing on smart wireless sensors and their development components. It also highlights the benefits of SHM integration with BMS, which can be supplemented by IoT tools, to address the shortcomings of traditional inspection methods.

Chapter 3: explores the use of BIM and digital technologies in bridge engineering, including emerging technologies like visual programming, Artificial Intelligence (AI), 3D reconstruction methods, and Virtual/Augmented/Mixed Reality (VR/AR/MR) for bridge health assessment and monitoring. It also introduces the concept of a bridge Digital Twin, highlighting its benefits and applications in sustainable development. Finally, it discusses the practical implementation of VR/MR technologies using wearable devices (HMI, Human-Machine Interface), demonstrating the feasibility of VR/AR/MR in bridge design and maintenance.

Chapter 4: explores bridge modeling techniques, focusing on analytical modeling and BIM. It uses Finite Element Method (FEM) analysis for bridge damage assessment, proposing a robust SHM system. Two case studies demonstrate the practical application of analytical modeling and bridge load testing methods. This chapter also explores the integration of advanced technologies like BIM, IoT, and MR in the SHM domain. It highlights the use of IoT for real-time bridge health monitoring, the development of cost-effective wireless sensors, and the integration of IoT systems with MR through 3D game engines.

Chapter 5: discusses the case study of an arch bridge where 3D reconstruction techniques, focusing on developing 3D models, are used. Finite Element Analysis (FEA) is used to simulate the bridge damage state and to propose a bridge SHM system, which is installed to monitor bridge heath parameters. Further, this chapter discusses the development of a novel approach for infrastructure asset management, focusing on the development of an Immersive Bridget Digital Twin Platform (IBDTP). The platform automates the bridge SHM system and uses MR devices for immersive decision-making. The practical applications of the IBDTP are explored, potentially scaling for different bridge types and critical infrastructure.

1.4 Scope of the research

As the major objectives of this research are already defined in section 1.2, the scope of this research revolves around the spectrum of these objectives. To clearly define the scope of this PhD research, major points are highlighted below:

- An extensive review of existing literature on the evolution of bridge management (BMS), SHM for bridges, and the adoption of advanced technologies in bridge monitoring and management.
- Study of the traditional bridge inspection methods to highlight their limitations and further advancements in the dedicated SHM system.
- Use of BIM in bridge asset management, with a focus on using BIM tools for the development of automated SHM systems, and the BIM-based Finite Element (FE) modeling of bridges.
- Exploration of the basic applications of VR/MR tools for visualizing bridge concepts during design phases, and the assessment of bridge design concepts through immersive technologies.
- Investigation of the integration of IoT technology with SHM systems for real-time monitoring and periodic maintenance of bridges, by developing low-cost wireless sensors.
- Developing an online web platform for bridge SHM that incorporates IoT sensors and integrates MR using the BrIM models, giving birth to the Immersive Bridge Digital Twin Platform (IBDTP),
- Implementation of the IBDTP prototype in the field by conducting field testing and evaluation to assess its effectiveness in real-world bridge monitoring scenarios.
- Evaluation of the efficiency, accuracy, and scalability of the IBDTP as compared to traditional SHM approaches, emphasizing its potential for the automation of the SHM system and enhancing decision-making capabilities.

While the outlined areas represent the primary focus of this PhD research, it is essential to note that the scope extends beyond the defined parameters of this research. The outcomes of this study have the potential for broader applications, particularly in automation processes and the implementation of Digital Twins within the construction sector. Although the primary emphasis lies in the domain of bridges, it's important to acknowledge that the principles of this research are transferable to other structural domains, including buildings and various infrastructure projects.

2 Horizon of bridge asset management and structure health monitoring

2.1 Introduction

Monitoring and structural health assessment are the primary requirements for the performance evaluation of damaged bridges. This chapter discusses the Bridge Management System (BMS) in detail and highlights the applications of BMS for Structural Health Monitoring (SHM) of bridges. Therefore, it is important to discuss first the BMS in detail and how it can help infrastructure asset management. Further, this chapter discusses the bridge health monitoring methodologies, for which the assessment of bridge condition comes as a basic tool. These conventional assessment methods rely on visual inspections conducted in the field by bridge inspectors, with each developed country adhering to its own set of regulations and standards. However, this approach has its limitations, being labor-intensive and financially burdensome. These limitations are further discussed in detail in this chapter. Following the details of bridge inspection methods, Structural Health Monitoring (SHM), its global scope, used methodologies, and recent trends in SHM techniques are discussed in detail. After that, the role of Internet of Things (IoT) technology is discussed as a part of the SHM system. This way this chapter discusses the BMS as part of the SHM system, supplemented with IoT tools for bridge monitoring, while addressing the shortcomings of traditional inspection methods.

2.2 Bridge management systems as a part of Infrastructure Asset Management

A bridge management system (BMS) is a way of managing bridges throughout their design, construction, operation, and maintenance phases [1]. Due to tight budgets, infrastructure authorities around the globe are facing challenges associated with bridge management and increasing maintenance requirements of infrastructures. BMS helps authorities meet their safety and maintenance requirements, such as building inventories and inspection databases and planning for repair, maintenance, and rehabilitation interventions systematically. This way a BMS optimizes the allocation of financial resources, and increases the safety of assets and their users [2][3].

2.2.1 Components of bridge management system

Bridge management systems (BMSs) have been created to facilitate decision-makers in maximizing the safety, serviceability, and functionality of infrastructure within allocated budgets. There are four basic components of a BMS, developing the lifecycle of a bridge. These basic components include asset inventory, inspection/monitoring, performance evaluation, and decision-making. All these components (illustrated in Fig. 2-1) revolve around the asset’s lifecycle and help in the management of bridge performance throughout its life.

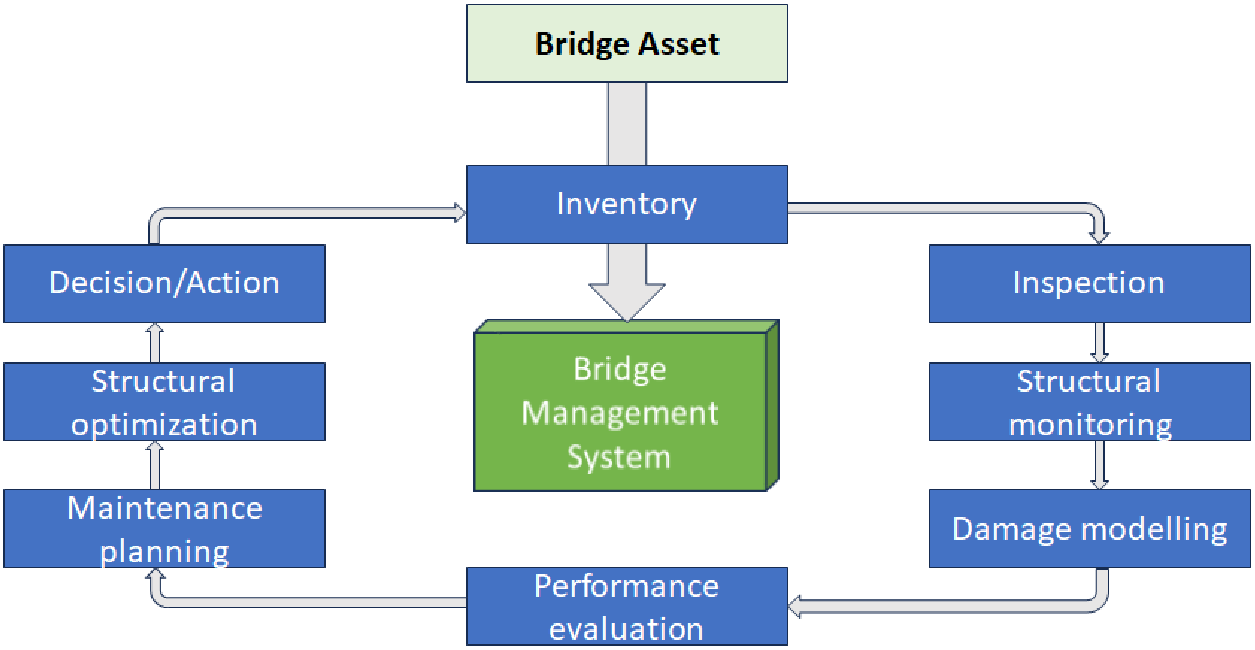


Fig. 2-1. Lifecycle of Bridge Management System

The architecture of a typical BMS consists of the following modules:

1. A knowledge base module: deals with the system database. The collection and input of data as well as the establishment of the database is a crucial aspect of bridge management and maintenance. The quality of data acquisition has a direct impact on the overall system performance. Therefore, database establishment must be paid much attention to. The BMS database consists of three parts; i) Basic information and data on the bridge geometry and structure ii) Business data for maintenance and management, including frequent inspections, regular inspections, maintenance record data, and assessment data, and iii) The GIS (Geographical Information System) data of the bridge, which is used to display the bridge's geographic information and data.
2. Bridge database management subsystem design module: this is the main module of a maintenance management system that consists of five sub-modules: bridge card information, manual inspection test records, condition monitoring records, bridge maintenance records, and engineering drawings management. These modules have programming functions for data maintenance, query, statistical analysis, and processing.
3. System management design modules: it has a deterioration prediction component, a lifecycle cost component, and a maintenance optimization component. It includes user management, privilege management, opening type management, data backup, data recovery, and other sub-modules. It provides security policies to secure the conservation of data from the BMS.

The BMS database stores inventory and appraisal data. The condition assessment module evaluates the existing health condition of the bridge(s). The condition assessment module evaluates the existing health condition of the bridge(s). The deterioration prediction module estimates the future condition of bridge components [4]. The life-cycle cost module calculates agency and user costs for various maintenance alternatives [5]. The optimization module determines the most cost-effective maintenance strategies [6]. The BMS differs in special requirements of departments, which have unique requirements. It comprises integral operational modules, including but not limited to bridge database management, systems management, integrated assessment subsystem management, forecasting, and auxiliary decision-making subsystem [7]. Although the modules are mutually independent, all capable of serving the purpose of enabling connection between systems by using the same key code (such as the bridge number) to series-connect or switch from each other [3].

2.2.2 Global appraisal of BMSs

Numerous countries have dedicated substantial resources and efforts towards the development of efficient BMSs, such as Finland [8], Denmark [9], Germany [10], China [11], and Japan [12]. In China, the comprehensive BMS plays a crucial role by overseeing fundamental data pertaining to highway bridges, overseeing regular inspections, and offering technical support for maintenance activities [2][11]. Despite the evident progress, the application of this BMS faces several challenges. One notable issue is the fragmented and isolated nature of the information stored within the system. Additionally, there exists a difficulty in achieving visualization as maintenance information is often separated from the bridge model, posing challenges for users. Furthermore, the current structure hinders effective collaboration between bridge engineers and managers, highlighting a need for enhanced integration and user-friendly interfaces in BMS applications where this dissertation filled this gap.

2.3 Assessment of bridge structure condition

2.3.1 Traditional bridge assessment methods

Traditional bridge health assessment refers to the manual assessment of a bridge's condition and performance, typically carried out by engineers and inspectors who physically examine the bridge and take measurements and observations [13]. This type of inspection is a critical component of bridge management systems and can provide valuable information about the current condition of the structure, its components, and the effects of the environment and use over time [1][14].

Traditional health assessment is considered a basic source of knowledge for bridge inspection because it provides a comprehensive understanding of the current condition of the structure and its components [15]. By physically examining the bridge, engineers, and inspectors can gather valuable information about the effects of the environment, use, and time on the structure, and identify potential problems and hazards [16]. This information is critical for making informed decisions about the maintenance, repair, and rehabilitation of the bridge [17].

Besides the repair and maintenance purposes, these system helps to develop long-term plans for the management of the bridge[18]. The inspections typically cover a range of aspects of the bridge's condition, such as:

1. Structural elements: Inspectors check for signs of distress, such as cracks, corrosion, and damage to the concrete and steel elements.
2. Superstructure: Inspectors examine the deck, beams, girders, and other structural elements that make up the superstructure to determine their condition and assess the need for repair or replacement.
3. Substructure: The foundation and supporting elements of the bridge, including the piers and abutments, are examined for signs of settling, cracking, and other forms of distress.
4. Bearings and expansion joints: Inspectors check the condition of the bearings and expansion joints that allow the bridge to move and absorb stresses due to temperature changes and other environmental factors.
5. Drainage: The drainage system, including the gutters and downspouts, is inspected to ensure that water is not causing damage to the bridge.

In addition to identifying issues and guiding maintenance and repair work, traditional health monitoring inspections can also provide valuable historical data on the bridge's performance and condition over time [19]. This information can be used to develop a long-term management plan for the bridge, taking into account its expected future performance and the need for maintenance, repair, and rehabilitation work [20][21][22].

2.3.2 Traditional assessment methods used globally

Traditional bridge inspection methods have proved their worth on some very well-renowned bridges across the world. In the USA, the Golden Gate Bridge in San Francisco [23], the Brooklyn Bridge in New York City [24], and the Mackinac Bridge in Michigan [25] are employed with the traditional bridge inspection methods. In Canada, the Lions Gate Bridge in Vancouver, British Columbia, the CN Tower in Toronto, Ontario, and the Confederation Bridge in Prince Edward Island are inspected using traditional methods [26]. In the UK the very famous Tower Bridge in London is still being inspected using traditional methods. Many European countries are also still using the traditional methods to inspect their very busy bridges, such as the Humber Bridge, the Rheinbrücke Maxau in Karlsruhe, the Berliner Stadtbrucke in Berlin, the Kölner Rheinbrücke in Cologne, in Germany, the Ponte Vecchio in Florence, the Ponte Sisto in Rome, the Ponte dell'Accademia in Venice, Italy, the Oresund Bridge connecting Denmark and Sweden, the Storebælt Bridge in Denmark, and the Øresundsbron in Sweden [27].

China and Japan are leading the world when it comes to bridge inspections using traditional methods. Their major bridges using this system include the Yangtze River Bridges [28], the Qiantang River Bridge in Hangzhou, the Hong Kong-Zhuhai-Macau Bridge, in China [29], the Akashi Kaikyō Bridge [30] and the Tōgane Bridge in Japan. In New Zealand and Australia several bridges like the Sydney Harbour Bridge, the Auckland Harbour Bridge, and the West Gate Bridge [31].

The sub-continent has also equipped the inspection of many of its bridges using traditional bridge inspection techniques. These bridges include the Howrah Bridge in Kolkata, the Bandra-Worli Sea Link in Mumbai, India, the Srinagar-Jammu National Highway bridge in Kashmir, the Attabad Lake Bridge, the Muzaffarabad Bridge, and the Mughal Road Bridge in Pakistan [32].

Poland has also been using the traditional bridge inspection methods for a long and has been employing such techniques on their bridges like the Tadeusz Mazowiecki Bridge in Rzeszów, The Łazienkowski Bridge in Warsaw and the Grunwaldzki Bridge in Wrocław, Poland [33].

These bridges are regularly inspected using traditional health monitoring methods. Inspectors perform detailed visual inspections, as well as manual measurements and observations, to assess the condition of the bridge's various components, including its suspension cables, steel girders, and roadway deck.

2.3.3 Limitations of traditional assessment methods

While traditional health monitoring inspections provide valuable information about the condition of a bridge, they also have some drawbacks that can limit their effectiveness:

1. These inspections are time-consuming and labor-intensive, especially for large or complex bridges, as they involve physically examining the entire structure.
2. Their accuracy can be impacted by inspector subjectivity and manual measurement limitations, leading to inconsistencies and errors in bridge condition assessment.
3. These inspections can pose safety risks for inspectors, as they may work in hazardous or hard-to-reach areas of a bridge in disrepair or deterioration.
4. These inspections may not cover all bridge conditions, leading to incomplete or inaccurate assessments in difficult-to-access or hidden areas.
5. Traditional health monitoring inspections can also be expensive, as they require a significant amount of personnel and equipment and may require the use of specialized tools and equipment.

To address these limitations, many BMSs now incorporate additional inspection methods and technologies, such as non-destructive testing and remote sensing, to supplement traditional health monitoring inspections and provide a more comprehensive understanding of the bridge's condition.

2.4 Structural Health Monitoring of bridges

The Structural Health Monitoring (SHM) framework is utilized to observe and evaluate the existing condition of civil infrastructure, which has broadly evolved to monitor the safety, serviceability, and sustainability of existing structures like bridges [34]. The SHM systems help to identify deterioration and damage caused by the aging and downgrading of the structure [35]. The reasons for this may be environmental factors, improper design, poor construction quality, lack of proper maintenance, and natural disasters like earthquakes, floods, or strong winds [36][30]. The increasing decay of infrastructure calls for a structural evaluation to make them in line with the exact design requisites [37].

2.4.1 Stages of bridge SHM system

The process of damage diagnosis in structural systems involves a sequential identification of the damage, followed by a determination of its location, type, and severity. According to [38], a comprehensive SHM system is structured into four different stages of damage identification, categorized as damage detection, damage location, damage typification, and damage extent. These stages are listed in Fig. 2-2.

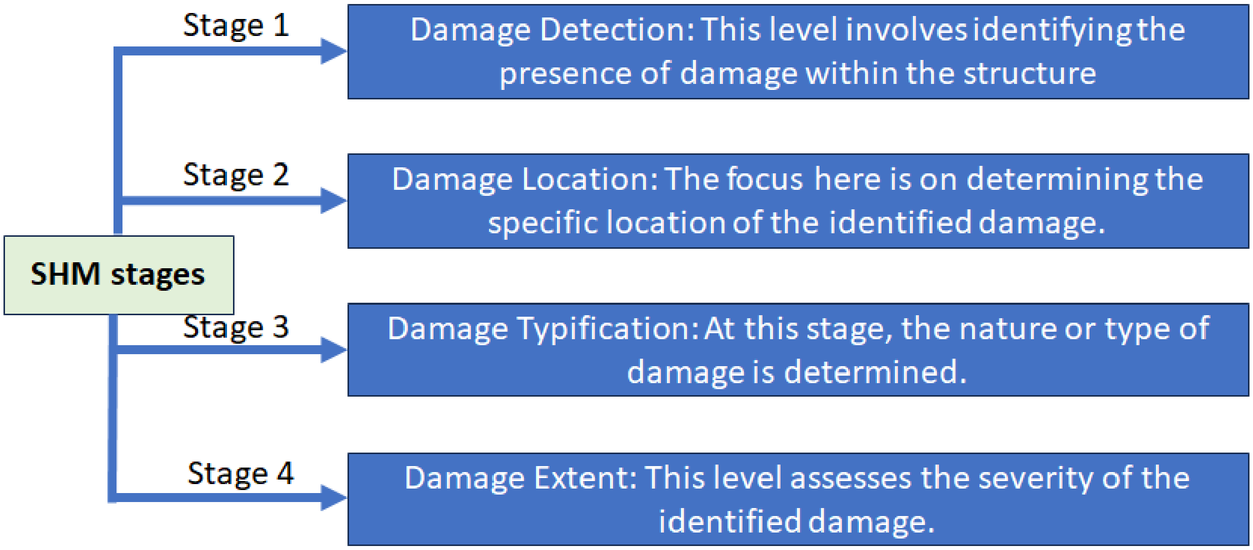


Fig. 2-2. Stages of the SHM system

Some researchers introduce an additional stage 5, which concerns predicting the remaining service life of the structure [38]. The hierarchical nature of these levels implies that the higher the level of assessment, the more detailed information the SHM system will provide about the structural condition. However, this comes at the cost of increased complexity in acquiring information, as each level requires knowledge from the preceding levels. Consequently, different levels of damage identification have varying requirements, including the types of sensors, monitoring algorithms, and the number of model parameters.

2.4.2 Principles of SHM procedure

The progress in SHM over the past two decades has led to the formulation of fundamental axioms or principles based on experimental studies supporting them [36][39]. As outlined in [40], adhering to the following principles is recommended for sound practices in SHM:

1. Principle I. Material Imperfections Existence: All materials inherently contain flaws or defects at the atomic microstructural level, such as hollow spaces, inclusions, and impurities.
2. Principle II. Baseline System Requirement: Assessing damage involves comparing two system states, and every SHM approach necessitates a baseline system. The training set depends on whether the goal is solely to detect damage or acquire detailed information about it (type, extension, location).
3. Principle III. Supervised and Unsupervised Learning: Unsupervised learning identifies damage, while supervised learning determines type and severity, using data from healthy and damaged structures, whereas unsupervised learning uses only healthy examples.
4. Principle IV-a. Limitation of Sensors: Sensors cannot directly measure damage. Feature extraction through signal processing and statistical classifications is required to convert sensor data into damage information.
5. Principle IV-b. Intelligent Feature Extraction: it aims to minimize measurement sensitivity to damage and operational and environmental conditions by focusing on damage-dependent responses.

6. Principle V. Time and Length Scales Influence SHM: The SHM sensing system's properties are determined by the time and length scales of damage initiation and evolution, which require special quantification for optimal operation.
7. Principle VI. Sensitivity vs. Noise Rejection Trade-Off: A trade-off exists between an algorithm's sensitivity to damage and its capability to reject noise. Extracted measurements encompass both damage effects and noise, requiring the separation of influences from each source.
8. Principle VII. Frequency Range and Damage Detection: The size of detectable damage from system dynamics changes is inversely proportional to excitation frequency, with higher frequencies increasing sensitivity to minor damage.
9. Principle VIII. Damage Increases Complexity: Damage to structures increases complexity, introducing non-linear behavior. Quantifiable measures of complexity can be developed by applying statistical and signal-processing concepts to damaged and undamaged systems.

These axioms collectively provide a foundational framework for effective and reliable practices in SHM.

2.4.3 Methods used for SHM of bridges

There are several different methods of SHM that can be used for bridges, including:

1. Visual inspections: This involves a physical inspection of the bridge, including the structure itself and any associated components such as bearings and joints.
2. Vibration monitoring: This involves the use of sensors to measure the vibration of the bridge under different loads, such as traffic or wind [41].
3. Strain monitoring: This involves the use of sensors to measure changes in the shape of the bridge, which can indicate structural distress or deformation [42].
4. Temperature monitoring: This involves the use of sensors to measure changes in temperature, which can indicate changes in the structure's stiffness or indicate the presence of cracks.

2.4.4 Recent trends in SHM of bridges

The SHM systems have experienced a tremendous change from the conventional bridge monitoring techniques which relied more on direct measurements of the bridge response using the traditional sensors on the bridge [43][44]. These conventional methods involve direct assessment of structural health using visual inspection techniques or simple handheld devices like portable sensors [45][46]. Nevertheless, these methods exhibit certain constraints, as they are highly dependent on manual intervention, causing several issues such as time-consuming processes, labor-intensive work, involvement of human errors, and challenged quantification of measured data [47]. Furthermore, they lack comprehensiveness and detailed damage assessment of bridges [48]. Considering these limitations, these methods were replaced by digitally advanced and robust sensors such as wired strain gauges, fiber-optic sensors, acceleration sensors, piezoelectric transducers, and Liquid leveling sensors for accurate and rapid monitoring of bridge health [49][50][51], but even the system using such tools has limitations concerning data management and 3D visualization of structural defects in real time.

2.4.5 Uses of the SHM system globally, in Poland and in Hungary

Many of the bridges that were used to be inspected using the traditional bridge inspection methods are now equipped with the SHM system partially or completely as the implementation of SHM systems can vary in scale and complexity, ranging from basic sensor networks to advanced monitoring technologies. Examples of SHM system equipped bridges include many famous like Golden Gate [52], Brooklyn, San Francisco-Oakland Bay in the USA, Jacques Cartier Bridge in Canada, Rio-Niterói Bridge in Brazil, Tower Bridge, Forth Bridge in the UK, Sydney Harbour Bridge in Australia [53], Akashi Kaikyō Bridge in Japan, Ponte Vecchio bridge, Rialto Bridge in Italy, Charles Bridge in the Czech Republic, Pont Neuf bridge in France, Great Belt Bridge in Denmark, Nijmegen Waal Bridge in Netherlands, Donaustadt Bridge in Austria, Øresund Bridge in Sweden/Denmark [54], Bosphorus Bridge in Turkey, Tsing Ma Bridge in Hong Kong, Nanpu Bridge, Jiaozhou Bay Bridge, Hangzhou Bay Bridge, Danyang–Kunshan Grand Bridge, Duge Bridge in China, Vinh Tuy Bridge in Vietnam and Penang Bridge in Malaysia.

In Poland, there are several bridges where the SHM system has been installed and implemented. These systems provide warning alerts and an opportunity for in-depth knowledge enhancement. Notable examples include the Redzinski Bridge in Wroclaw and the bridges over the Vistula River in Kwidzyn and Pulawy cities. The Redzinski Bridge, equipped with 222 installed sensors, sets a record in Poland [55]. This system is designed and sensors are placed to monitor various aspects such as deck vibrations, pylon, and suspension cables, as well as forces and deformations in selected points of the structure [56]. Similarly, the Kwidzyn Bridge and Kurow Bridge are recognized as the largest extradosed bridges in Europe, measurements focus on the deformation of the box superstructure, span deflections, and the horizontal movement of the pylon [57]. Meanwhile, the Pulawy Bridge, an arch structure opened in 2008, spans 212 meters between supports. Its monitoring system comprises three subsystems: weather, visual, and structural. A sophisticated weather observation system includes sensors measuring temperature, wind speed, direction, precipitation type, and surface condition. Connected to variable message signs, this information is transmitted to drivers for improved safety. Structural monitoring includes 68 deformation sensors, 30 accelerometers, and 10 inclinometers, measuring a total of 186 parameters in the arch and deck section.

Similarly, in Hungary, the most important bridges having the SHM system are the Megyeri Bridge, Petofi Bridge, Margaret Bridge, Erzsébet Bridge, and the Széchenyi Chain Bridge. The Margaret Bridge includes a sophisticated SHM system with sensors to monitor strain, temperature, and vibrations, enabling early detection of structural issues [58]. Similarly, the iconic Széchenyi Chain Bridge in Budapest is installed with the SHM system for monitoring displacement and corrosion, preserving its structural integrity [59]. These systems utilize real-time data to provide continuous assessment, ensuring the bridges' resilience against environmental and operational stresses.

2.5 Internet of Things used for SHM of bridges

In recent times, the applications of Internet of Things (IoT) technology have emerged as a handy tool in SHM systems of bridges. Numerous studies have underscored its significance, cited successful cases, and outlined various potential applications [60][41]. Ongoing advancements in IoT components, such as wireless sensors/networks and processing software packages, position it as an ideal technology for SHM, particularly in the context of bridges [61].

The IoT technology enables real-time monitoring of bridges through strategically positioned sensors capable of collecting data on various parameters like strains, temperature, corrosion, cracking, fatigue, and vibrations. The complete wireless sensor pack includes a sensor and a microcontroller (with or without the integrated communication facility), which communicates the actual state to the management unit for immediate action, ensuring continuous monitoring of the bridge's health and structural integrity. This whole sensor is then integrated with the web platform unit using LoRa, Bluetooth, BLE, ZigBee, GSM, Wi-Fi, etc. to facilitate remote data transmission. This platform then controls data collection and transfer for further processing. To ensure a constant power supply, an onsite solar unit connected to standby batteries can be used.

The integration of IoT technology in bridge SHM is increasingly crucial due to the necessity for swift evaluations of bridge behavior and integrity following events like collisions and extreme weather conditions. Traditional inspection methods, whether visual or involving non-destructive instruments, are commonly employed by transportation departments and state agencies but, these methods come with limitations of time and financial resources. The financial burden of bridge rehabilitation resulting from deterioration and environmental damage is enormous, rendering conventional examination methods impractical for real-time detection of hidden problems and active faults [62][63].

The IoT technology, with its comprehensive features, presents an opportunity for continuous SHM of bridges. Wireless sensor technology, coupled with remote monitoring and intelligent data collection units, overcomes challenges posed by wired sensors. Rapid data collection and processing become achievable, straightforwardly facilitating efficient analysis. The effectiveness of smart sensor networks in bridge SHM depends on the following three main features:

1. Wireless sensor systems to measure influential factors affecting deterioration,
2. The web platform that constantly recovers and wirelessly transmits accurate data to a central onsite control unit,
3. Remote monitoring enables the capability to interpret and cleanse the vast amount of collected data.

Developing compact, durable sensors with smart features and high accuracy is crucial for successful IoT technology utilization in bridge SHM [51][64]. This necessitates substantial investment and support for innovative research. The outcomes promise robust SHM systems for bridges and other essential structures, leading to significant savings in repair costs and human lives. The integration of IoT technology in SHM aligns with the global objective of creating smart cities [62]. Ensuring bridges remain functional during their intended service life post-extreme incidents requires strategic placement of sensors at critical locations, identified through sound structural analysis and finite element simulations [37].

2.5.1 Wireless smart sensors in SHM systems

Various IoT tools are currently available for SHM bridges, and each of them has certain advantages. These tools include various smart sensors, which are detailed below:

1. Micro-electrochemical systems (MEMS): Affordable micro-scale devices equipped with numerous sensors. They can be embedded at various locations in bridge elements to identify parameters such as corrosion of prestressing strands and rebars [65].
2. Nanotechnology: Employed in engineering and medical fields, nano-sensors can be used in SHM to observe material deterioration and cracking mechanisms. This allows for the identification of weaknesses and timely solutions before potential failures occur.
3. Fiber optic sensors: Optimal solutions for bridge instrumentation, particularly in areas prone to cracking. These sensors are user-friendly, reusable, and resilient after cracking. They provide accurate readings for monitoring structural integrity by measuring strains, vibrations, pressure, stresses, and temperature variations [66].
4. Piezo-ceramics: Actuator-type sensors capable of detecting damage locations in structural elements. When excited, these sensors vibrate, generating electric current related to the stiffness and damping properties of the structure [67].
5. Acoustic sensors: Ideal for monitoring stress/strain conditions in main cables of various bridge types (truss-bridges, suspension bridges, cable-stayed bridges). Offers real-time monitoring of signs of failure [68].
6. Magneto-elastic sensors: Used for remote detection of structure frequency, potential resonance occurrence, stresses, viscosity parameters, and excessive loading. Known for high sensitivity, endurance to high voltage, reliability, fast response, wide bandwidth, and cost-effectiveness.

Choosing the optimal sensing technology for SHM involves considering criteria such as system functionality, durability, ease of installation, intended response monitoring, and the severity of exposure conditions on the bridge. The primary objective is to develop practical monitoring technology with minimized wiring, easy installation, accessibility, maintenance/replacement ease, and reasonable cost compared to traditional inspection methods, eliminating the need for physical presence at the bridge.

Limitations of time and installation costs can significantly affect the overall inspection process of bridges. An economical sensing device or technology is characterized by a long maintenance period, typically lasting 5-10 years. Remote/real-time health monitoring uses multiple sensors with a digital network for data management including data recording, filtering, and processing, and result evaluation and decision-making. In periodic monitoring, collected data are transmitted to the control unit using wired and wireless data transmission. Depending on the bridge's condition, data collection and evaluation may be necessary after severe incidents or in real-time, especially for potential fatigue failures observed in fracture-critical structures. Data cleansing, a critical process, requires expertise from the bridge management unit engineers and can be programmed into the analysis software [69]. Similarly, data compression is also crucial, particularly when there's a need for data comparison throughout the bridge's service life.

2.5.2 Wireless smart sensor development

The development and implementation of an IoT-based wireless sensor for monitoring the health of bridges comprise wireless sensor networks, their communication solutions, and data transmission techniques. The major components of this system involve:

1. Design and integration of wireless sensors and data gateway.
2. Development of cloud platform terminal following IoT protocols.
3. Development of field installation and layout plan for sensors and gateways according to the design of the bridge SHM system [14], ensuring that sensors can automatically collect the required data and transmit it to the cloud platform using the local gateway.

Such systems can be controlled by using smartphones and tablets, but the developer mode can only be available on the web version of these applications. So, using the web version of the system, the web platform can be developed at the start, and after that communication between the sensors and the web platform can be established.

2.5.3 Wireless smart sensor deployment on bridges

There are several ways of deploying bridge sensors on bridges mainly including Information from previous studies, field conditions, and structural requirements supplemented with the experience of bridge inspectors, results of Finite Element Analysis (FEA), based on the maximization of the Fisher Information Matrix (FIM), based on the properties of the covariance matrix coefficients and using energetic approaches. The most commonly used methods that are used for the design of the SHM system include the results of FEA analysis and the expert opinions of system designers. Based on these methods the location and quantity of the sensors are defined, which can provide the on-site monitoring of the technical condition of the structural elements at selected measuring points of the bridge.

2.5.4 IoT-SHM hub-Web platform for SHM system

It involves the design of a data management system to transmit and automatically transfer the measured data to the cloud platform [70][71], considering established protocols and methodologies. For this purpose, the developed graphical interface and measurement scheme of sensors are connected to the wireless sensors. Then they can be made online by connecting to the web platform. This connection can be developed using codes and algorithms. One code for all the proposed sensors can be developed where the API of the sensors and the domain of the web platform are embedded. This code is then uploaded to the web application dashboard and communication is established over the Internet.

After successfully developing the connection between sensors and the web platform, the sensors under the SHM system are visible online on the dashboard. After this, automation action can be enabled for sensors that allow data recording. This initiates the real-time monitoring of the bridge. Thus, bridge managers can assess real-time data from the cloud platform throughout the operational lifespan of the bridge, enabling them to comprehend the health conditions of the bridge [41][72].

2.6 Chapter summary

This chapter introduces the concept of a BMS as a valuable tool for the maintenance and monitoring of bridges as it provides improved collaboration between bridge engineers and managers. The chapter highlights various benefits of this system such as enhanced collaboration and user-friendly interfaces. Within the framework of BMS, a comprehensive discussion of traditional assessment methods is done, while highlighting their limitations. These limitations include time-consuming and labor-intensive inspections that use manual measurement tools having minimal accuracy. Further, these methods have safety risks for inspectors in hazardous areas of deteriorating bridges which supports the imperative for robust Structural Health Monitoring (SHM) systems to ensure bridge maintenance, repair, and rehabilitation decisions. The advantages of SHM systems necessitate their installation for prolonged bridge functionality, offering time, human resources, and cost savings but even these systems have the limitations of being expensive, requiring specialized tools, equipment, personnel, and significant resources. Thus, the chapter introduces the concept of IoT technology and discusses its integration with SHM systems that improve bridge health monitoring systems effectively. It illustrates that these technologies can be integrated with the SHM systems and provide real-time data access for bridge managers to assess bridge health conditions. Thus, a robust foundation for the forthcoming PhD research is established, presenting practical insights applicable to the bridge industry.

In summary, this chapter serves as a foundational and comprehensive resource for the upcoming chapters, offering a detailed examination of bridge asset management and health monitoring strategies. It seamlessly transitions from traditional methods to the modern SHM tool, emphasizing the limitations of existing approaches and introducing applications of cutting-edge technologies such as IoT to enhance the effectiveness of bridge health monitoring systems.

3 BIM and digital technologies in bridge engineering

3.1 Introduction

This chapter introduces the concept of Building Information Management (BIM) methodology. It discusses its relevance with BrIM, understood as Bridge Information Management, which can be the future release of Bridge Management Systems (BMS) integrated with BIM and Structural Health Monitoring (SHM). For this purpose, state-of-the-art literature is being reviewed on the use of BIM and digital technologies in bridge engineering. It also reviews the detailed literature about the use of emerging technologies like Visual Programming for integrating Finite Element Models and BrIM models, the use of 3D reconstruction techniques for BrIM model development and model updating, and a detailed overview of Virtual, Augmented, and Mixed Reality (VR, AR, MR) for bridge health assessment and monitoring. Finally, the concept of a bridge Digital Twin is introduced by highlighting its general concept, its areas of application, and the benefits of using digital twins of bridges. DT has become an effective tool for improving productivity and implementing the principles of sustainable development throughout the entire life cycle of structures, both in the design, construction, and operation phases.

The use of immersive techniques is explored practically through a case study of a bridge that will be constructed in the future. Thanks to that, this chapter demonstrates how the practical implementation of VR/AR/MR in the field is possible and how cyber-physical devices aid the immersive experiences for the analysis of bridge design concepts and also for their technical condition assessment.

3.2 BIM versus BrIM as Bridge Information Modeling or Management

Global investment projects, often exceeding individual countries' capabilities, require improved management and technological innovations, with BIM methodology being a key innovation for digital and cyber-physical solutions. According to estimates [73], within 15 years there will be a doubling of expenditure on the so-called infrastructure megaprojects. Unfortunately, as the same analyses show, almost 98% of these projects are completed late (the average delay is approximately 20 months) and with a significant overrun of the assumed budget (an increase of up to 80% of the originally planned amount) [74]. There are many reasons for this state of affairs, but one of the most important is the low productivity of the construction industry worldwide. This is best demonstrated by failed investments in traditional and conservative construction in the public sector.

For example, the construction of Berlin's Brandenburg Airport was planned as early as 1991. However, implementation began after 15 years of design. The investment was estimated to be completed in October 2011 [75]. This date was then postponed many times, and the 2017 report indicated that the delay may even reach 2021. Construction costs in Germany have tripled from EUR 2 billion to EUR 7.3 billion, with the government creating a digital construction platform to develop national BIM strategies and implement BIM in public investments.

3.2.1 BIM definitions and the advantages of the Open BIM approach

Building Information Management (BIM) is an intelligent, smarted, and effective multi-dimensioning tool used to manage the information management of construction facilities. This information management is generated using certain software, developing the 3D models of the facilities and managing their assets. Currently, the major focus of the BIM approach is on 3D modeling therefore, it is usually termed as Building Information Modelling, but BIM is much more than just a 3D modeling tool; it is a collaborative process that involves the generation and management of digital representations of the physical and functional characteristics of a project. These digital models are used to inform decision-making throughout the project's lifecycle.

BIM, at its core, is a methodology. Nevertheless, the methodology comes with a plethora of tools and software. Closed BIM/Open BIM [77] separates the software-oriented and method-oriented activities. The open BIM orientation is mainly about ensuring the interoperability of BIM tools. This approach requires widely available and acceptable standards and open data exchange formats. These are described in three primary ISO standards [78][79]: ISO 16739, which contains the IFC (Industry Foundation Classes) data format description; ISO 29481, which describes processes in the form of IDM (Information Delivery Manual); and ISO 12006, which describes definitions or names in the form of IFD (Information Framework Dictionary).

An interesting trend related to BIM software is opening the Closed BIM. Software developers highlighted the benefits of extending software utilities to the BIM community. Producers often reveal the programs' APIs (Application Programming Interface), which allows the community to create customized add-ins to enhance the capabilities of software. Many commercial software publishes just part of the API, but some of them (e.g., Dynamo Visual Programming) are open source: all the details of programming implementations can be seen and utilized by users. With the web-oriented trends (e.g., Software as a Service), developers also create online platforms with web REST APIs (e.g., Forge, Bimplus), opening the platforms' capabilities to customized web applications.

3.2.2 The specificity of bridges and the Bridge Information Management proposal

In civil engineering, among the many classifications of construction types, there is a specific division into cubic and linear structures (Fig. 3-1). The first involves the construction of buildings in which their volume, i.e. cubature, is important. These are most often various types of buildings, regardless of their purpose. These objects, compared to linear ones, are rather point-like and are characterized by a relatively small area occupied, which can be measured in meters. No single spatial dimension is dominant. The only exceptions are the so-called skyscrapers, i.e. super-tall buildings in which the vertical dimension significantly exceeds the plan dimensions. However, in the case of linear objects, one dimension always dominates, which is its length, which dominates in the case of infrastructure projects, especially roads and bridges.

Observing the development of the BIM methodology, it is evident that the BIM appeared lately in infrastructure projects (i.e., roads, railways, bridges, and tunnels [80]). Where in the case of bridges it gave birth to the Bridge Information Management (BrIM) which is the subclass of the BIM [81]. In this dissertation, ter, “BrIM” will specifically be used for Bridge Information Modeling. The specificity of bridges and the BrIM is related to both the programming tools that are used to prepare BrIM models, as well as the devices and machines that are used during construction (surveying instruments and road construction machinery). Geographic information systems are used to manage this data, which will need to have a clearly defined connection with the BIM model of the facility under construction [82]. Further BrIM facilitates collaboration between different components of bridge construction, in particular to support clash detection, enhance visualization through 3D models, and integrate with project management tools. These tools are further equipped with features for detailed bridge monitoring, structural analysis, construction sequencing, and maintenance planning. Thus, the specificity of BrIM supports the operational phase with tools for facility management, health monitoring, renovation planning, and energy efficiency monitoring.

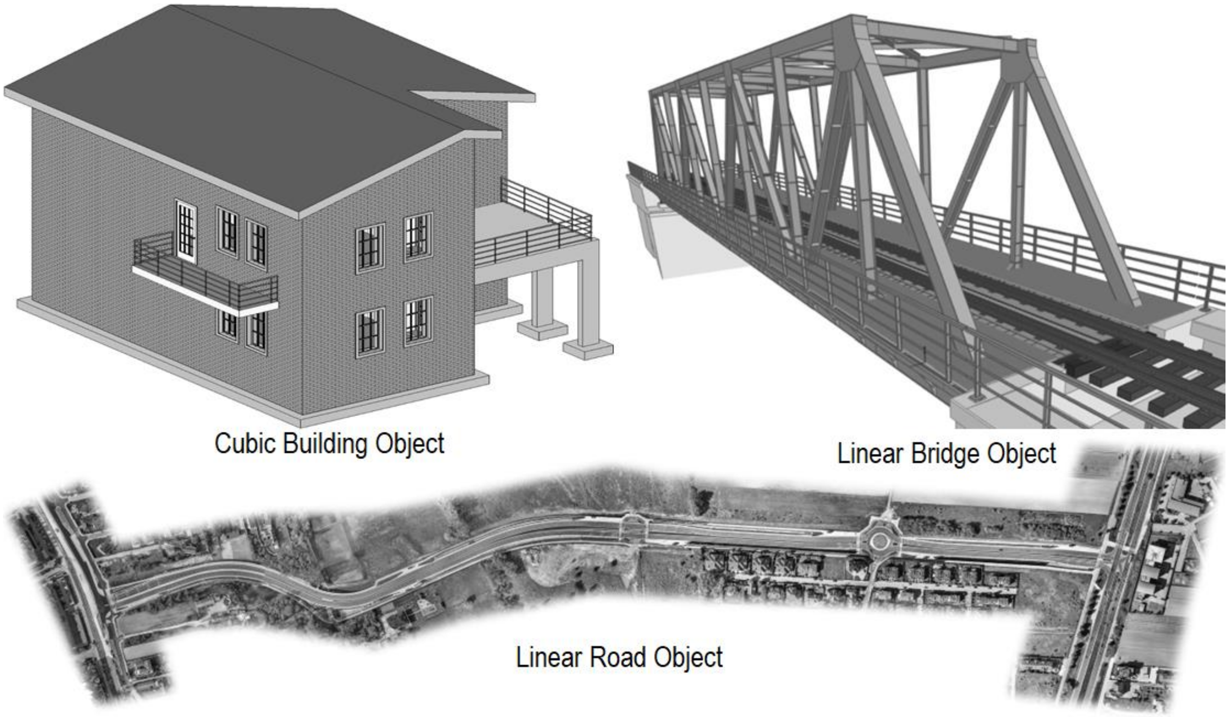


Fig. 3-1. Example of linear and cubic objects [83]

3.2.3 BIM for bridge management and monitoring

In the digitized world, bridges transform from static construction methods into services providing multidimensional connection: physical –communities, and digital –data. This transformation results from the requirements of bridge managers and the need to ensure the safety and comfort of bridge users, where the BMS offers its services, and people have started adopting them. This system forces connectivity and integration of bridges in the more synchronous digital dimension, especially in acquiring, processing, and sharing data. The bridge management system is now enabling bridges to cooperate with other objects to empower global holistic management and to constitute the digital networks of smart infrastructures. To enable that, we need a multi-industrial paradigm – the world is shifting towards BIM tools for BMSs.

In recent years, BIM has become the most flourishing technology in the building industry, and it has been extended to infrastructure engineering. This technology is a promising approach that can be used for the design, construction, and facilities management of structures, where a digital representation of the construction process is used to facilitate the exchange and interoperability of information [79]. The application of BIM results in cost reduction, quality control, and efficiency improvement throughout the life cycle of the project. A study [11] conducted by Stanford University highlighted the potential benefits of BIM tools in construction projects. According to this survey, the BIM implementation has the capacity to mitigate 40% of additional changes, lower contract prices by 10% through the identification and resolution of conflicts, and shorten project duration by 7%. With these advantages, BIM has also been adopted by commercial software, such as Autodesk Revit, ArchiCAD, and Allplan [80]. In addition, BIM has been successfully implemented in many bridge designs [81][82] and other civil engineering designs and management. However, its application in the maintenance phase started relatively late. McGuire and Atadero utilized BIM to manage the inspection and evaluate information [83]. Abudayyeh and Al-Battaineh adopted the as-built bridge information model for maintenance and management As-Built Information Model for Bridge Maintenance. Similarly, some research works also combined BIM with the traditional management system to improve maintenance efficiency [84][85][86]. Such studies concluded that the use of digital tools, especially BIM technology enables bridge management systems for the standardization and maintenance of bridges, as well as processes for processing facility data.

3.3 Selected digital technologies related to BIM

3.3.1 3D Reconstruction techniques and related data formats

The most crucial goal of BIM methodology is to collect, develop, and manage information about construction objects. This information is typically stored in BIM information models and can come from many different sources. When planning new facilities, the BIM model is created and developed during the creation of the project and then is successively updated and supplemented during construction and management processes. In the case of facilities that were designed and built before the implementation and use of the BIM methodology, it is necessary to use other techniques to obtain all the data needed to create the model. These may include 3D reconstruction techniques.

Typically, the modeling process starts with geometry, which so far in civil engineering has been obtained by traditional geodetic measurements during a building inventory. However, this method is very time-consuming and not consistently effective. Therefore, methods previously used in computer graphics and industrial applications are increasingly used in construction. This is a 3D reconstruction process that is the basis of reverse engineering, in which activities begin with accurately measuring an existing object and reproducing its 3D model [84].

3D reconstruction is a process that aims to recreate the shape and appearance of a real object in a virtual space. This process can be carried out using passive or active methods. Passive methods do not affect the reconstructed object. The input data in this method are sets of digital images or a video sequence. An example of the most frequently used passive technique in construction is photogrammetry, which, depending on the method of obtaining and using photos, is divided into flat (single-image) or spatial (two-image). Active methods reconstruct the 3D profile of an object using numerical approximation and build a model on this basis. Specific radiation is often emitted towards an object, and its reflection is measured. Visible light sources, lasers, radar waves, and ultrasound are used for this purpose. Laser scanning is an increasingly used technique in construction.

Photogrammetry has proven to be a valuable tool in bridge monitoring and inspection, utilizing photographic images to capture precise measurements of bridge structures. It is also an alternative method for obtaining point cloud data [85]. By analyzing multiple images taken from different angles, photogrammetry can reconstruct 3D models of the bridge, providing comprehensive information about its condition and geometry [86]. It is possible to create an accurate spatial representation of the photographed object. This requires a number of algorithms that combine subsequent photos into one orthophoto map and generate a point cloud.

The measurement principle of photogrammetry involves capturing a series of overlapping images of the bridge from various viewpoints. These images are then processed using specialized software that identifies common points in the photos and triangulates their positions to create a detailed 3D model [87]. The result is a high-resolution point cloud or mesh that accurately represents the geometry of the bridge. This model can be used to perform various analyses, including measuring dimensions, detecting deformations, and identifying damage such as cracks and corrosion. Additionally, photogrammetry can be employed to create precise models which are further used for the development of Scan-to-BIM models [88].

Photogrammetry is majorly described with its two types, ground-based and aerial photogrammetry. They differ primarily in the perspective and altitude from which the images are captured. Ground-based photogrammetry involves taking photographs from fixed points on the ground, allowing for detailed close-up views of specific parts of a structure, which is ideal for capturing fine details and inspecting lower sections of a bridge [89]. Whereas aerial photogrammetry involves capturing images from UAV drones or aircraft, offering a broader perspective that can encompass large areas and the entire structure from above, thus they are more suitable for structures like bridges [90]. This method is particularly useful for mapping extensive details of bridges and surrounding environments, providing a comprehensive overview that ground-based methods cannot achieve. However, ground-based photogrammetry typically provides higher-resolution images due to the proximity to the subject, whereas aerial photogrammetry can cover larger areas more quickly but may have lower resolution due to the greater distance from the subject [91]. Each method has its advantages and limitations, making them suitable for different aspects of bridge monitoring and inspection.

Laser scanning technology is an important tool for bridge monitoring and inspection, which uses laser beams to capture precise 3D measurements of different structural elements of a bridge [92]. Laser scanning provides detailed information about the condition and geometry of bridges, offering a comprehensive way to assess their damage states [93]. Laser scanning operates on the principle of Light Detection and Ranging (LiDAR), involving emitting laser pulses toward a target structure and measuring the time it takes for the pulses to return after hitting the surface [94]. This time measurement is then used to calculate the distance between the scanner and the surface which helps in capturing several points. By rotating the laser beam and capturing millions of points, a detailed 3D point cloud of the bridge structure is generated. This high-resolution point cloud can then analyze different structural elements, detect their deformations and damages, and identify signs of deterioration such as cracks and corrosion [95]. Additionally, it can be used to create accurate models that are compatible with BIM tools and can be used as a part of a bridge management system.

The accuracy of laser scanning depends on the equipment and conditions, typically ranging from 1 to 10 millimeters. High-precision scanners can achieve accuracies within a few millimeters, making them effective for detecting small structural cracks and critical deflections. The advantages of using laser scanning include high accuracy and detailed 3D modeling, reduced need for physical access to challenging areas, and rapid data collection as compared to traditional measurement methods [96]. However, the technology is expensive and requires a significant initial investment in buying equipment and software, and necessitates trained personnel to operate the scanners and manage large datasets. Moreover, weather conditions can also impact the performance of laser scanning, posing limitations in some scenarios.

Very often, when using scanning or photogrammetry, we talk about the use of aerial techniques (e.g. aerial photogrammetry). Until recently, it was very expensive and difficult to access, but after the spread of drones, it has become very popular and extremely frequently used [97]. UAV (Unmanned Aerial Vehicle) means unmanned aerial vehicle (UAV), which is defined by the Civil Aviation Office as an aircraft that does not require crew on board to fly. It is piloted remotely or flies autonomously. In everyday language, unmanned aerial vehicles are called drones. Until recently, drones were used only for military purposes. Currently, they have an increasing scope of civilian applications.

The possibility of using drones in the scanning process has opened up new possibilities in terms of access to hard-to-reach places in bridges and has significantly shortened the time of obtaining data for 3D reconstruction. They are equipped with many high-precision sensors such as inertial motion units and gyroscopes to recognize the attitude and attitude of the aircraft. The microcomputer enables autonomous navigation without much manual involvement of the pilot. Thanks to the availability of more accurate and cheap global GPS positioning systems, it is also possible to control the position of the drone in real-time.

3D reconstruction should ultimately lead to creating a model in a virtual 3D space that will reproduce the actual object as faithfully as possible. However, the problem is how to represent this model. The algorithms currently used in computer graphics use several representation methods. The most used are point clouds, polygonal meshes, and voxels [98].

A point cloud is a set of measured points in space, the position of which is recorded relative to established reference points. The data constituting the point cloud are most often obtained directly during laser scanning or indirectly from photogrammetry, which requires additional processing of raster images [99]. Each point in the cloud contains at least three coordinates (x,y,z). This method of representation usually generates huge amounts of data because of high resolution or point density and is used where high accuracy and fidelity of reproduction are required. However, the point cloud can be used to generate polygonal meshes that can reproduce the scanned or photographed surface of the object. Triangles or quadrangles are most often used for this purpose. Polygons can be additionally imaged (rendered) using smoothing and shading algorithms, which is impossible in point clouds [100].

3.3.2 Visual programming

It is essential to be able to create user-defined algorithms that specify the logic of a system's operation, particularly for domain experts with highly specialized needs. The trend of non-code solutions is a result of this requirement for customization. Conventional text-based programming can be substituted with non-code solutions. Their goal is to enable non-programmers to customize by providing a simple means of designing algorithms. One such solution is visual programming.

An alternative to conventional text-based programming that doesn't require code is visual programming. Its popularity is increased by its accessibility, particularly for non-programmers; with just a little knowledge, one may create scripts for complex tasks [101]. Many visual programming languages (VPL) are utilized in specialized disciplines, and visual programming concepts are widely employed in non-informatics domains [102].

Typical VPL algorithms comprise nodes, or blocks, that graphically describe the methods being used. The block operation's outcomes are communicated through the output fields, whereas the block input fields pass method parameters. The specific data type—numbers, texts, or instances of a defined class, such as Point, Line, and Surface—is frequently accepted in both the input and output fields. The blocks are wired together to form a logic network of methods. Simpler dataflow control and more user-friendly debugging are made possible by the script's graphical format and the methods' immediate return of results [103].

In the BIM environment, visual programming is becoming more and more common in the fields of architecture and civil engineering. Some useful modeling software additions are Dynamo for Autodesk Revit, Grasshopper for Rhinoceros3D, Marionette for Vectorworks, Allplan Visual Scripting for Nemetschek Allplan, and Bentley Generative Components. Although they can be used for various engineering tasks, parameterized geometry modeling is the primary purpose of VPL tools. Therefore, an extensive study has been done in this area.

[104] has emphasized visual programming use for Architecture, Engineering, and Construction (AEC) students, e.g., integrating a generative design with CAD can help in experimenting with new forms and shapes [105]. [106] developed VCCL (Visual Code Checking Language) to confirm code compliance of models, including IFC, while [107] verified code compliance of railway BIM design. [108] created the visual Query Language for 4D Building Models (vQL4BIM) to extract BIM models’ data. [109] used Grasshopper and EnergyPlus to forecast and visualize energy consumption in buildings. A similar combination of

software predicted aggregate energy requirements using GIS data and corrected multi-zone energy models [110]. [111] used visual programming for energy and shading analysis. Building energy performance was optimized by using Dynamo [112] and thermal analyses were performed [113], while Grasshopper facilitated daylight simulations [114], design of a zero-energy building [115], and forming a variable beam section [116].

Visual programming belongs to the arsenal of Artificial Intelligence (AI) methods that is gaining the interest of many scientific [117] and civil engineering communities. [118] identified six primary AI-based research areas of civil engineering: knowledge representation and reasoning (generating knowledge-based pattern systems instead of statistics and algorithms), information fusion (data integration from various sources, e.g., SHM sensors, to distill information), computer vision (image processing, videos, or point clouds), natural language processing (e.g., extracting information from texts in unstructured forms, chatting), intelligent optimization (looking for the optimal solution given an objective function; in civil engineering, often with genetic algorithms [117]), and process mining (analyzing processes distilled from structured reports generated by systems). The variety of research areas is reflected in use cases, where intelligent algorithms have been used, e.g., geometric optimization [119], FE model updating [120], cracks classification [121], and condition data extraction from inspection reports [122].

3.3.3 Integration of FEM and BrIM approach in bridge modeling

Bridge modeling started with FEM models, which, due to the capabilities of tools and computers, forced the use of simplifications. Mainly in terms of geometry and properties of structural elements (and material models, especially in the case of reinforced concrete) used in models (bar, plate, shell, etc.). BIM changed that approach and it is now possible to model the entire bridge with structural and non-structural elements with an almost realistic representation of the geometry and relationships between elements. A comprehensive bridge model, combining BIM and FEM properties, closely resembles a digital twin, with the main difference being the starting point, largely due to computer-aided design tool evolution.

The currently observed development of BIM tools indicates that it is now possible to integrate analytical elements, which, after connecting the FEM calculation engine to the program, can be used to analyze the behavior of the structure. At the same time, a realistic representation of the geometry and material properties of the physical part of the model is maintained. An example here would be Autodesk Revit [123].

In Autodesk Revit software, object classes that model physical structural elements, such as columns, slabs, and walls, contain both their geometric and analytical representations. These models are integrally linked. Changes to the structural model are immediately reflected in its analytical version. However, this relationship is one-way. This means that only the structural model influences the analytical one, not the other way around. However, it is possible to separate both models. The physical representation (geometric model) contains the standard geometry of the element with its shape and dimensions as well as BIM data. However, the analytical part consists of a separate, three-dimensional primitive that is intended to represent the computational element. It also contains the object properties needed for analysis, such as the type of material, boundary conditions, and assigned load. Unfortunately, the analytical model automatically generated in this way contains many geometric inaccuracies and often requires individual and tedious user intervention.

Generation of the FE model can be performed using direct or indirect integration methods. In the case of bridges, indirect integration methods are found to be more appropriate. These methods can be implemented using a Visual Programming interface, which is based on functional blocks connected in a specific order to perform desired tasks, including mathematical operations, creating, and manipulating geometries, as well as exchanging data between the BIM environment and other types of engineering software. VPL has already been used successfully in the automatic compliance check procedure [124][125], structural optimization [119], and life cycle sustainability assessment [126]. The use of the proposed algorithm allowed to automatic repair of the geometry of the bracings of the upper truss chord and technological supports. The algorithm correctly solved the selected connections, attaching beam-type bracing elements to the truss columns and technological support columns. At the same time, it is possible to execute subsequent iterations of the script on a selection of other model elements, ultimately bringing it to a state in which it will be considered by the user as suitable for performing FEM calculations. Additionally, all changes made can be undone and, if necessary, the entire model can be reset to its initial settings.

BIM models and their tools enable diverse, computationally complex, and sometimes unusual analyses. And they are not limited to the calculations often performed by designers using FEM. Increasing integration of both tools will allow for a close connection between the analytical model and its structural implementation in the BIM environment. Many different data and properties of the structural model can be accessed in a variety of ways for analysis of one, coherent environment. This may be, for example, the assessment of energy demand, acoustic background, lighting, indoor climate, carbon footprint, etc.

3.3.4 Reality-virtuality continuum and immersive technologies (VR, AR, and MR)

Until recently, the concept of Virtual Reality (VR) was primarily the domain of science fiction, and at computer exhibitions, it attracted crowds with the promise of exciting experiences that would occur after putting VR goggles on the head. The dynamic development of this technology and the exponential progress in computer computing power make it more and more common, and new concepts and solutions appear that allow users to explore various areas of the continuum of the real and virtual world. In addition, the concepts of AR (Augmented Reality) or mixed MR (Mixed Reality) have emerged. According to Paul Milgram [127], the area between the two extremes where both the real and virtual worlds are mixed is called mixed reality. It consists of both augmented realities, where virtual elements enrich reality, and augmented virtuality, where reality can complement virtual objects (Fig. 3-2).

The most famous of these technologies is VR. The user is fully immersed in the virtual space, which forces the senses to think that they are in a different environment than the real world. Using a head-mounted display, you experience a computer-generated world of images and sounds in which you can manipulate objects and move using touch controllers. The VR virtual reality environment is a new way to enrich project presentation methods, cooperation between design teams, and improve the design process. It also reduces the risk of collisions on construction sites and provides a more intuitive approach to assessing the correctness of proposed concepts. Users can navigate virtual environments using game controllers, hand controllers, or by moving their heads. The intuitive nature of these simulations allows you to navigate space and experience your design vision. These environments can be created using a variety of tools, including game engines such as Lumion, EON, and Unity, that fully visualize the virtual environment with freedom of movement within it.

Fig. 3-2. Reality-Virtuality continuum

Augmented Reality (AR) enhances real-world perception by overlaying digital information, and enhancing visual experience, and is now a standard feature in new smartphone models due to advancements in graphics and processor performance. In recent years, there has been an increase in interest in the use of AR techniques and also in construction. In this area, AR techniques bring benefits mainly in terms of simulation and visualization of objects or their elements [128], comparing the current state with the planned state during the implementation of construction investments [129], increasing the possibilities of cooperation [130], planning new investments and training [131]. User-assisted AR systems provide the opportunity to perform tasks simultaneously in real and virtual environments, along with the possibility of more efficient cooperation between several users (group collaboration) [132].

Mixed Reality (MR) combines real-world and digital elements. In mixed reality, the user interacts with and even manipulates physical and virtual objects and environments. MR is a hybrid of reality and virtual reality, thanks to immersive technology [133], which includes both augmented reality and augmented virtuality. This also allows people without engineering training to be involved in the design process. They are provided with a tool that allows them to familiarize themselves with the functionality of the future facility and make investment decisions. The first research works aimed at developing systems based on MR techniques were initiated in the early 1990s. Initially, these were systems supporting employees in factories and production lines. For example, when laying a large number of cables in assembled aircraft [134]. The use of MR increased the efficiency and intuitiveness of human actions. This is especially true when they are highly complex and require specialized knowledge. Such activities also include the design and inspection of facilities and technical devices.

Previously, devices isolated users from the outside world, but modern displays allow direct observation of surroundings, making them safer on construction sites. Microsoft HoloLens goggles are an example of MR-class devices. They are increasingly used not only for fun but also for visualizing designed structures. Both in the office and on the construction, site as shown in Fig. 3-3.

Fig. 3-3. Visualization of structures in Mixed Reality under field conditions

The presented VR, AR, or MR visualization techniques allow us to present the virtual world in a very intuitive way. These can be three-dimensional objects that can be viewed from any perspective, with textures that are indistinguishable from the actual textures of real objects, and at any scale. Moreover, elements that enrich reality using MR systems may have various forms, apart from particularly intuitive three-dimensional models: inscriptions, diagrams, photos, videos, or audio information. However, such use of these tools is only possible by linking BrIM models with solutions offered by manufacturers of increasingly better popular mobile devices such as smartphones and tablets. In the future, VR/ARMR technologies and new devices can revolutionize bridge inspection and health monitoring by providing real-time insights into structural integrity and health through immersive visualization and interaction.

By integrating such technologies with BIM and IoT technologies, bridge health monitoring is transitioned from traditional 2D representations to immersive 3D models, facilitating more accurate and detailed assessments. Many researchers have integrated the SHM systems with BIM technology [135][136][71] to visualize the SHM data [137][138][139] in 3D. This visualization is revolutionized by the involvement of Augmented/Mixed Reality (AR/MR) [140]. [141] have reviewed the application of AR for Advanced data management, and visualization of real-time SHM data. Similarly, [141][142] have proposed AR-based automated damage identification and quantification methodologies that use Artificial Intelligence (AI) models to detect and classify different damages and visualize the SHM data using integrative frameworks, and metadata in AR.

Engineers and maintenance personnel can use VR, AR, and MR to conduct virtual inspections, identify potential defects, and visualize structural changes over time. This innovative approach not only enhances the efficiency of bridge health monitoring but also contributes to more informed decision-making and proactive maintenance strategies. Several research works have highlighted the application of these tools for monitoring purposes. [143] carried out inspection information management using BIM-based models and interactive simulation in HL. Further, [144] used Microsoft HoloLens to detect potential problems in the target structures using thermal images. [145] studied the time delay of bridge Digital Twins (DT) services and proposed an Internet of Things (IoT)-based DT communication framework that can support smart bridge operation and maintenance.

3.4 The concept of a bridge Digital Twin

3.4.1 The general concept of a Digital Twin

Digital techniques not only improve the effectiveness of whole industries but are also beneficial on a smaller scale. BIM has already been proven to be a tool that provides commercial advantages to contractors. It has been observed by the Centre for Digital Built Britain and “The Gemini Principles” reflects [146] that BIM is expected to provide “new markets, new services, new business models, new entrants”. BIM, as a technical innovation, is seen as an export product, increasing the competitiveness of the domestic market. The same logic holds true for Digital Twin (DT) on the interdisciplinary level. Industries need to adopt and benefit from technological advances in order to expand economically. This is particularly true if the innovations are worldwide developments, such as digital twins.

A digital twin is an IT model replicating a physical object, considering its entire life cycle. It uses data from the device's history and expert information to report on its technical condition and optimize time or cost by performing calculations and creating operating scenarios.

The development and increasingly widespread use of digital twins is the result of an interdisciplinary approach to engineering and the achievements of IT techniques, including the assimilation of diverse data structures, machine learning, high level of performance in real-time simulation, process visualization capabilities, etc. This technology also shapes an industrial version of the Internet of Things, where physical objects can live and interact virtually with other machines and people [204]. In this context, they are referred to as "cyber objects" or "digital avatars", and a digital twin can also be an element of the CPS cyber-physical system concept [147].

Resource management and optimization of maintenance costs. Digital twins can help manage infrastructure assets. These issues are described in more detail below. Here you can only notice that the integration arises from needs precisely asset management, electronic registers of resources and the processes of degradation or improvement taking place in them, developing the knowledge base about resources and processing data collected during inspections or from monitoring systems, can be implemented in the form of a digital twin. In this way, it can simulate a specific network of road or railway infrastructure facilities. As such a twin matures, we are able to optimize the network's operation, adapting to various scenarios. This will make it easier for managers to make decisions regarding planning maintenance activities and setting a budget for the operation, renovation, or replacement of facilities.

3.4.2 Digital Twin areas of applications

The digital twin can interact with other systems and be used to validate and test the system before its actual installation [148]. It collects, monitors, and analyzes lifecycle data to improve operational and maintenance efforts in long-term asset management strategies. Also, the safety and reliability of transport systems can be assessed using digital twins, as is the case in the operation of modern railway switches [208]. By combining data recorded by sensors located in real objects with their digital models, the digital twin takes on a new meaning. Engineering activities have become even more human-oriented. A digital twin is a virtual representation of a real object or system throughout its lifecycle. Thanks to the solutions provided by technologies such as the Internet of Things, it is possible to use data obtained from the source object in almost real-time. There are several potential areas of application of digital twins.

1. Simulations at the design stage: Designers can use multi-industry digital models for complex, interdisciplinary simulations, enabling quick and inexpensive prototyping of new projects. This integration of models in a digital twin allows future users to participate without engineering experience, considering influences, such as static and dynamic loads, noise, environmental impacts, human interactions, lighting, etc.

2. Delivery logistics and traffic control. Real-time inventory tracking and delivery automation are in line with current demand on the construction site, which can also have its digital twin. These are also already-known examples of traffic control in cities and relatively simple solutions for urban parking networks that suggest the location of available spaces.

Operational activities in the field of reliability and safety. Linking digital models with increasingly used technical condition monitoring. Digital twins may be the next stage in the development of the SHM systems discussed above. They will enable operators to react quickly and reduce the risk of disruptions and threats. You can in these solutions use machine learning for prediction and anomaly detection and introduce autonomous decision-making algorithms, thus eliminating potential human errors.

3.4.3 Digital Twins of bridges

In the case of bridge structures, the concept of a digital twin may work best in simulating changes in its technical condition and mapping the processes taking place there. In this respect, the authors of the publication [149] proposed two interrelated digital twin models (Fig. 3-4). One is in the form of a digital BIM model that is named the Digital Twin Model (DTM), and the second is in the form of a model that was created using reverse engineering tools (reverse engineering). In this case, it was a reconstruction using photogrammetry and laser scanning methods. This model was named Reality Twin Model (RTM), because thanks to the possibility of cyclical repetition of the reconstruction procedure, it is possible to capture the current state of the 3D geometry of the structure, as well as the properties of the surface structure of the object's components. The results of each subsequent reconstruction are compared with the last version of the RTM model, and, on this basis, an automatic report is created containing the differences found that may suggest the fact that damage has occurred.

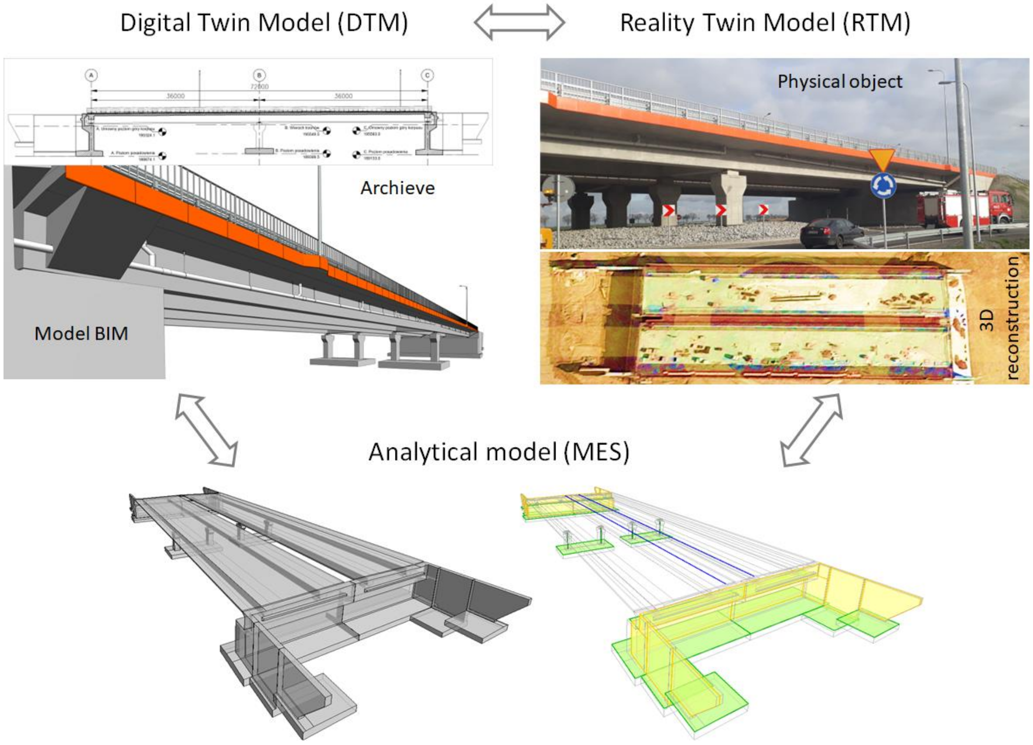


Fig. 3-4. The concept of a DT of a bridge according to [149]

The model comparison process also applies to both basic model types, i.e. DTM and RTM. Predefined markers are used, which were permanently attached to the actual bridge structure before the first scanning procedure. In addition, these models must be supplemented with an analytical FEM model, which is used to assess the impact of identified damage on the load-bearing capacity and other functional properties of the structure. For example, if defects, degradation, or material discontinuities (cracks) are identified, the parameters of the FE model are modified by reducing the moment of inertia, changing the elastic modulus, or introducing specific nonlinearities.

A digital twin of a real bridge facility can imitate the behavior of its physical counterpart, provided that the user (owner or manager) is provided with easy access to data collected during the life cycle, which may relate to load history, climatic events, oversize crossings, or degradation processes. In this way, it becomes a data repository and knowledge base, constituting an integral part of a comprehensive inspection, technical condition monitoring, and decision-making strategy. In their current state of development, digital twins can already be used to improve the security and reliability of infrastructure. In some way, they will also contribute to improving the quality of new, planned facilities. However, their creation and use still involve high costs, which result from the need to assemble and operate complex electronic systems and collect, share, and process huge amounts of data. Therefore, we need platforms that integrate various tools, environments, models, and formats for recording and sharing information.

3.5 Immersive techniques in the visualization of bridge concepts

3.5.1 Introduction to the case study

This study is pioneering the concepts of the implementation of VR/AR/MR not only for the selection of futuristic bridge designs but also for their onsite visualization at a scale. It is one of the first attempts in central Europe that use such decision-support techniques for the construction of new bridges [150]. The said concept is used in this study to help the designers and clients in the design phase of a bridge construction planned in the southeastern part of Poland. In this way, this research provided additional support to the client in selecting the variant to be used in subsequent and final design stages. It helped to visualize the variants proposed by the designer in the VR and MR environment that can aid decision-making in the selection as well as updating of bridge designs.

3.5.2 The design concepts of the future bridge

The subject bridge of this experiment is situated in the South-East of Poland in a town called Sanok over the San River. The bridge will be the only way to cross this river and will provide access to the other riverbank. Being close to a famous museum and city castle, the bridge will also be an attraction for tourists, so authorities are highly concerned about its aesthetics. Therefore, special consideration is given to its visualization against the canopy of mountains. Designers prepared two different variants and authorities have to select one of them. It was hard to imagine which variant would be the most suitable and would add beauty to the town. Both variants are presented in the form of side view and cross sections in Fig. 3-5.

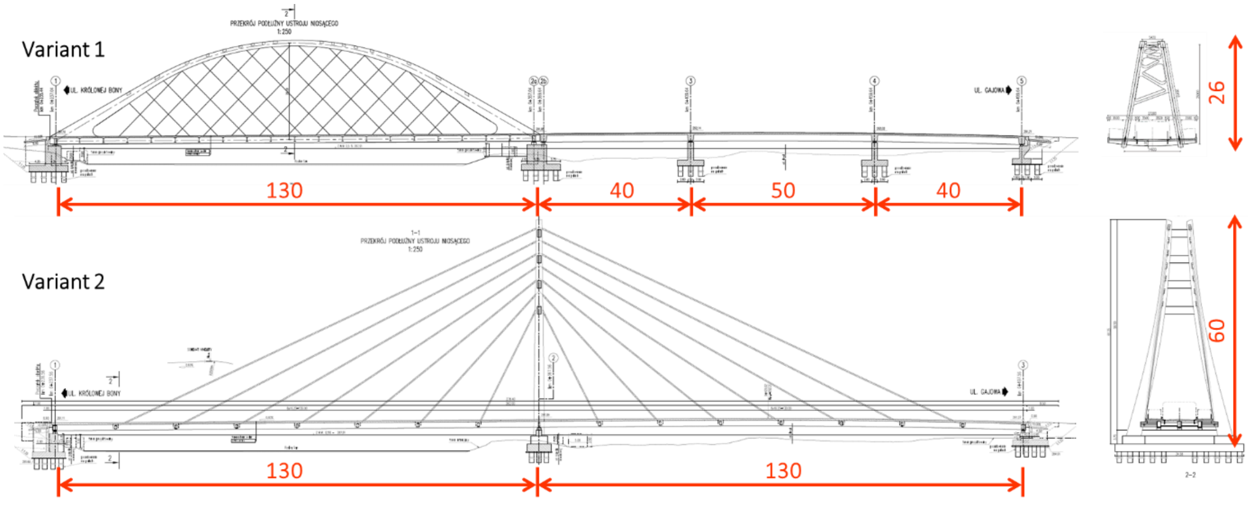


Fig. 3-5. Comparison of the two variants in the form of 2D drawings

The Variant “1” includes the arch model with the main span of 130 m and three approaching spans. The Variant “2” is a cable-bridge having two symmetrical spans and 60 m high pylons.

Thanks to the applications of VR and MR, this purpose can be fulfilled with the visualization of the bridge true to scale. I prepared the BrIM models of this bridge and presented all of them using the VR application with all the details of the future bridge. The VR demonstration involves the street and bird's-eye view visualization of bridge designs. It implemented both models at the real scale, so every structural element was visualized with full structural details. The main details of these two variants along with the visibility from different points are shown in Fig. 3-6.

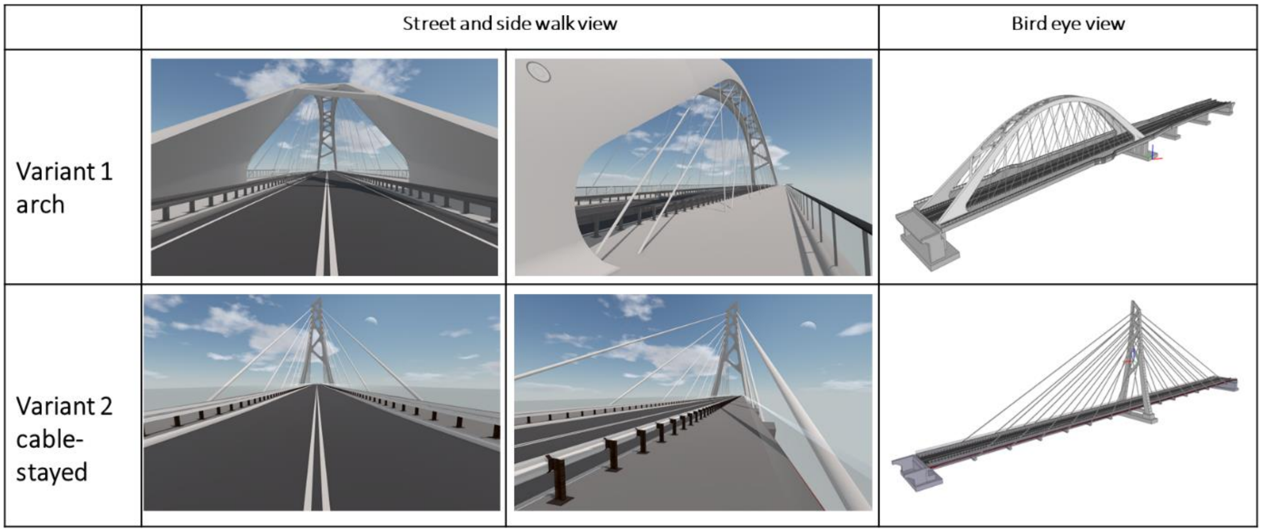


Fig. 3-6. Comparison of the two variants in VR

3.5.3 Devices used for the implementation of immersive techniques

To implement the VR/AR/MR application, several cyber-physical devices are in practice, but the most suitable devices that supported this research are Oculus Quest (OQ), Trimble XR10 helmet integrated with Microsoft HoloLens (HL), and Site Vision (SV) which are shown in Fig. 3-7. These devices use certain applications and platforms such as Trimble Connect (TC), which provides a database of 3D projects from where the models can be visualized in the MR [151]. They allow users to project the 3D model into the real world and show them at the exact location and scale. This implementation can also be facilitated with the possibility of collaborating with other stakeholders by using gestures and voice commands [152] in HL.

Oculus Quest-2 (VR)

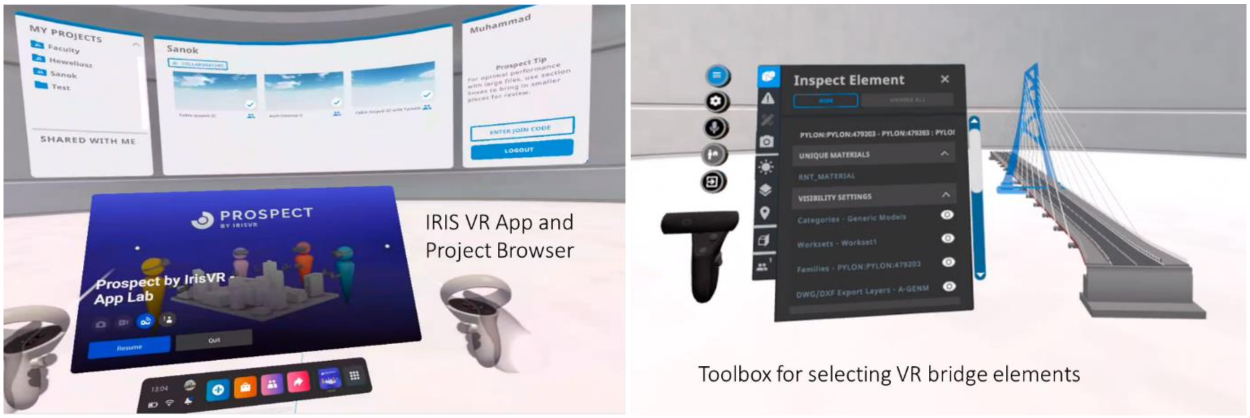
Trimble XR10 with MS HoloLens-2 (MR)

Trimble Site Vision (MR)

Fig. 3-7. Devices used in the immersive techniques case study

This research uses the Oculus Quest-2 headset (OQ) with a prospect iris VR application [153] for VR-based visualization of bridges. The OQ offers a user-friendly interface with over 100 VR apps, Wi-Fi server access, project cloud connectivity, screen recording, and casting capabilities. With a built-in storage of 128 GB, the device provides the possibility of a large database inside the device which can help use it for complex designs of bridges [154].

The device uses Prospect IRIS VR to visualize bridge models, create a cloud database of projects, and allow stakeholders to collaborate on each project. It also enables virtual meetings with remote access via headsets. Further, this application offers a user-friendly interface for viewing model details, taking pictures in VR, and adding different viewpoints for visualization or marking details for further updates in the design. It also supports day and night modes, allowing users to navigate through the model with real visibility of structures with different light conditions. Different functions of this application and the project database of the OQ headset are shown in Fig. 3-8.



IRIS VR App and Project Browser

Toolbox for selecting VR bridge elements

Fig. 3-8. Project database with different functions of the VR app

The MR implementation using HL involves assigning BrIM models to ground coordinates of reference points and developing QR codes for them. The TC application allows functions like cloud data generation, QR code generation, and URL addition. The model can be then visualized in the real world and MR, and collaborators can be called from the MR headset to show progress. To implement the model at a true scale, two functions, model alignment, and QR code placement can be used. These functions ensure the model is placed at the correct location with the actual size. However, there are certain limitation of HL devices that limits their functionality for certain types of bridges.

SV is a useful MR device that overcomes distance and number of elements limitations of HL and resolves 3D model visualization issues using a smartphone. It features GNSS receivers, GNSS positioning, EDM/AR positioning, and EDM distance measurement. The device's hardware includes an antenna that connects directly to satellites using cables and GPS, a smartphone device, a cable that connects the antenna to the mobile device, and the batteries that provide power to the SV setup. After mounting the mobile device onto the SV, it can be connected to the antenna using a cable. The device's Bluetooth function connects the catalyst to the mobile device. The SV app confirms the connection and starts connecting the device to external satellites, but SV cannot be fully functional inside buildings or under bridges due to a lack of satellite connections. Once the satellite connections are established, the device starts the synchronized orientation according to the surrounding environment.

3.5.4 Use of VR for the assessment of bridge concepts

The success of the futuristic Bridge Information Modeling (BrIM) for bridges depends mainly on its visualization performance, which has been revolutionized by the applications of VR [83]. Starting from the concept design, virtual models take over and provide an interactive environment where stakeholders feel like they are using their models in reality. By providing this interactive platform, VR allows the visualization of the different stages of model development, real-time execution of construction stages, management and collaboration during construction, visualization of the final model after construction, and the effective use of the facility [131]. This way, it not only reduces the assumptions involved in the construction of bridges but also allows different points of view to conclude the final model that can be visualized on a real scale with real scenarios [130]. Considering the advantages of VR technology, this PhD research successfully executed VR-based field experiment in collaboration with an industrial partner, as a case study to demonstrate the design concepts of a future bridge. In this experiment, different designs of a bridge proposed by the designers were presented in a VR environment using a VR headset and a comparison of different variants was carried out in a virtual environment. This immersive visualization helped the clients in the selection of the final design for the construction of the bridge.

BrIM models can be uploaded using the plugins in Autodesk Revit or any other software while the IFC model can be uploaded using the project upload tab. Uploaded models can be launched in OQ to access the model details. Models can be rotated and moved to 360° in VR space. Using the joystick of the right controller street view can be activated where the left controller will act as a project menu bar (Fig. 3-9d). Major working of the model can be accessed using the project detail option shown in Fig. 3-9b whereas Fig. 3-9a shows the database of all the variants of the subject bridge. During the VR implementation, both variants were launched one by one, using two sets of OQ, one for the client and one for designer representatives (Fig. 3-9).

After carrying out the visual analysis of both variants in VR, stakeholders decided to select Variant 2 (cable-stayed bridge) as a final design, as the selected variant offers esthetically better visuals of the landscape and tourist attraction around the bridge location. Thus, the implementation of VR aided the selection of the future design of a bridge concept.

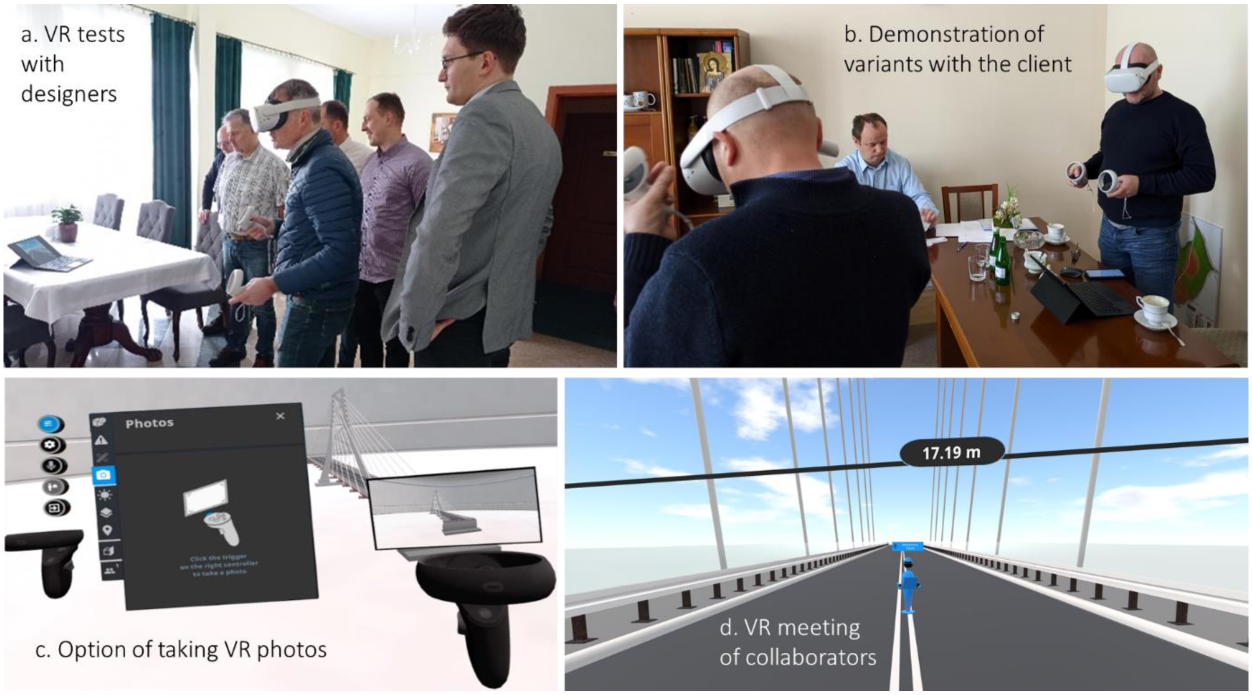


Fig. 3-9. VR tests with VR collaboration of designers and client representatives

3.5.5 Use of MR for the immersive visualization of bridge concepts

After the selection of one of the designs, the MR experiment was performed to visualize the selected variant of the bridge. For this purpose, four observation points were considered, which are shown in Fig. 3-10.

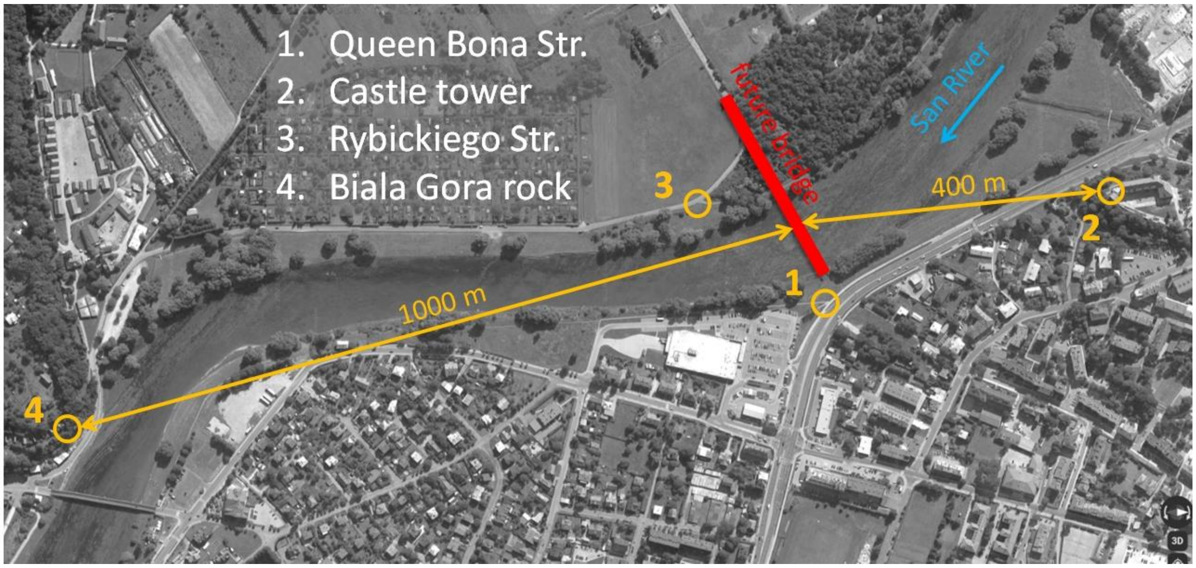


Fig. 3-10. Location and marking of the indicated observation points

Out of the selected points, no. 1 and 2 were of the greatest importance for the entire project. They are the easiest to access and the most frequently visited. Therefore, MR experimentation was carried out at these points. At point no. 1, closest to the crossing, the experiment was fully performed with both MR devices.

First, it was HL, where the operation in the field is carried out using gestures and a virtually displayed menu. Such a menu is usually displayed after recognizing a raised wrist and hand motions, Fig. 3-11. After loading the model from the TC project database, the process of its localization and calibration starts. A prepared QR marker with the exact coordinates of the bridge was used for this purpose. The model of this marker was first placed in virtual space, and its real image was placed in the real terrain at the same coordinates as in the model by scanning the QR code using the marker scanning technique.

Users without the HL had the opportunity to preview the MR views cast on the tablet from the HL as shown in Fig. 3-11. The tablet, used for this purpose, was connected to HL via the http protocol over a local WiFi network. The environment was mapped by the built-in cameras of the HL. The video on the tablet screen demonstrated the visualization of the real environment and the virtual model. This way not only the user of HL was immersed in the MR but the people attending this demonstration were also able to see the MR implementation of the bridge. Fig. 3-11 shows the menu of the TC application and the main menu of the HL device. The navigation function that is used in MR can be observed by recognizing the movements and gestures made by the user with his hands. Finally, a view of the model in its natural environment was shown, but unfortunately, a part of the bridge was visible due to the distance and number of elements of the HL device.

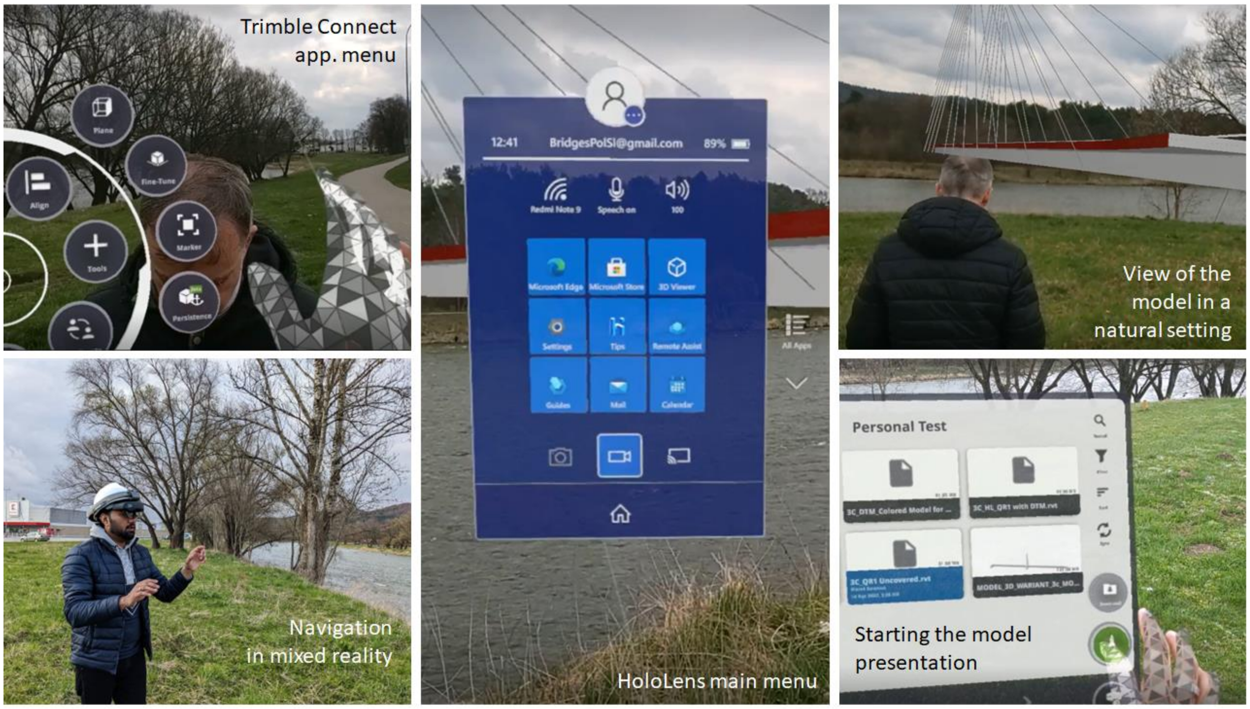


Fig. 3-11. Model visualization using the Trimble HoloLens device at point no. 1

As the user approaches the model, other details could also be displayed. It can therefore be assumed that the HL device does not work well in open areas with longer-span structures. Such an open area without any characteristic objects with flat surfaces does not allow for full visualization of a larger model and its precise display.

To overcome such limitations of the HL device, a SV device with a smartphone was further used at the same points in the terrain. It served not only as an interface to support dedicated TC applications but also projected real and virtual objects on the screen (see Fig. 3-12 and Fig. 3-13). The surrounding terrain was recorded by the smartphone's built-in camera, and virtual objects of the bridge model were placed on this image. This device worked better in open spaces and with large objects. Even moving the user with the SV antenna did not interfere with the displayed view of the bridge because the model was continuously updating itself in real time. It was easy to display the entire model with all the details, and the display was stable too, Fig. 3-12. These limitations resulted from the large dimensions and a large number of details of the bridge model. Users could see that the model of the bridge span is above the ground in the way it will eventually be built.

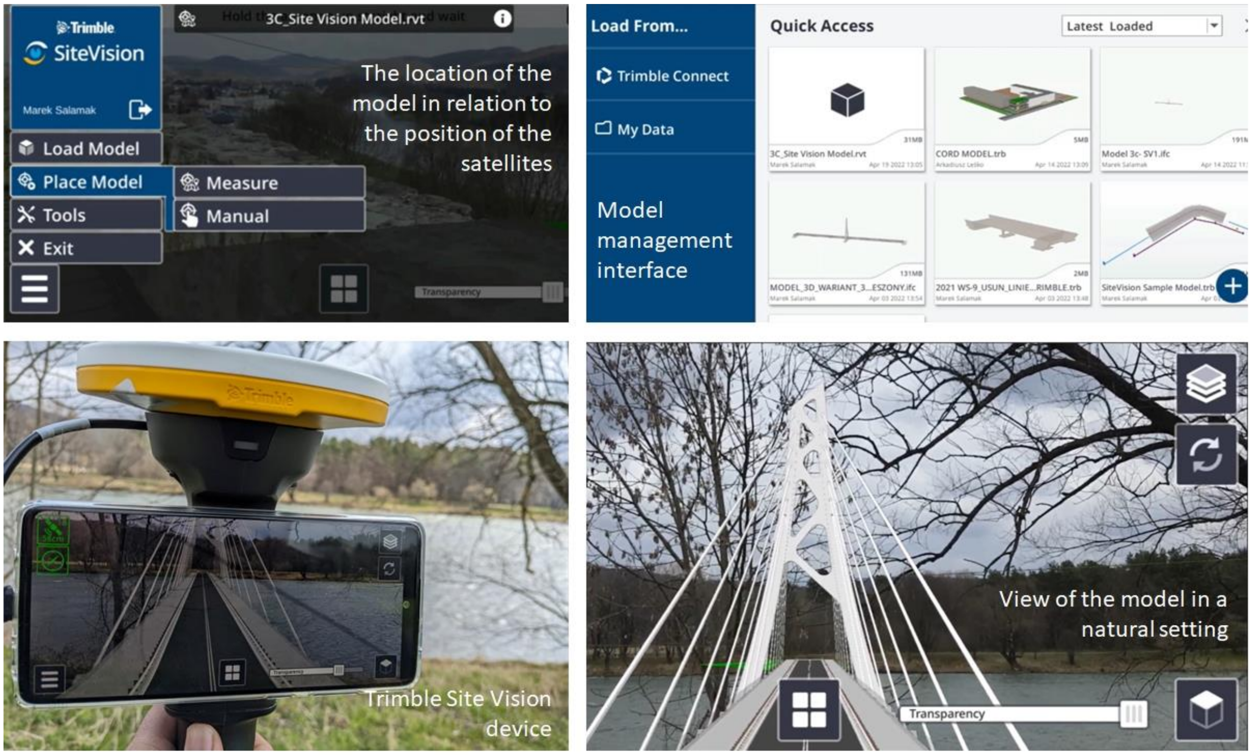
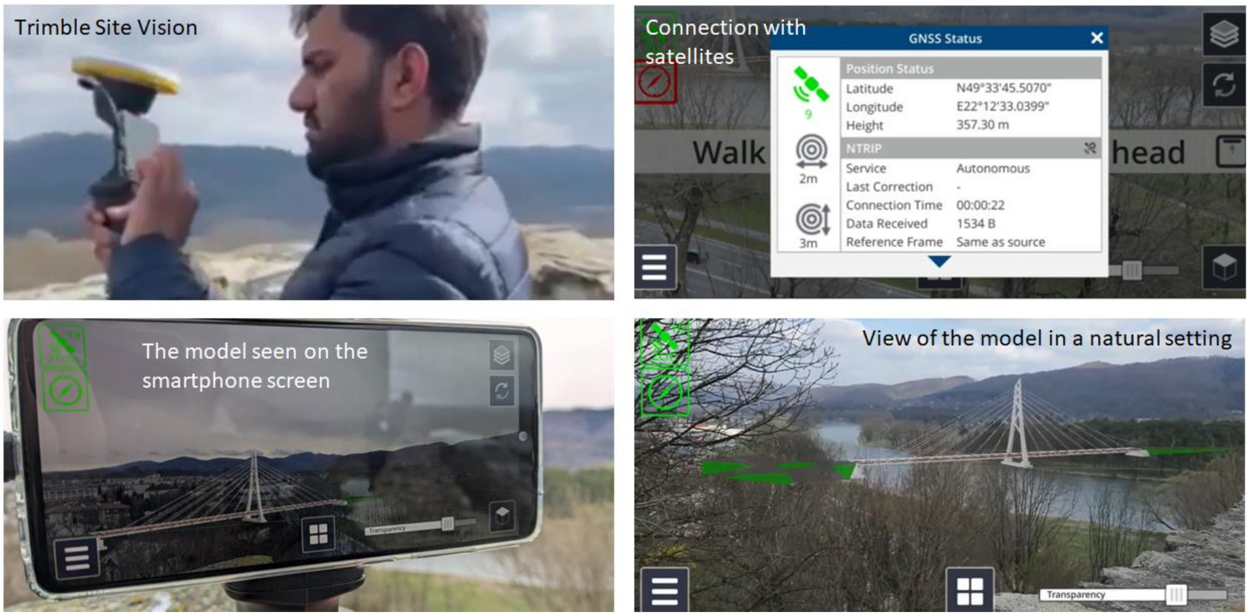


Fig. 3-12. Model visualization with the Trimble Site Vision device at point no. 2

An attempt to visualize the access road to the bridge and the surrounding roundabout helped to see how the terrain would ultimately look at the site of the planned crossing. Participants of the experiment could see that the plane of the road was above their eye level. The roundabout will be raised almost two meters above the existing terrain. Near the roundabout (point no. 1), it was possible to retrieve the planned longitudinal axis of the bridge using SV, which helped the visualization of the full length of the bridge with its pylon visible on the screen, Fig. 3-12. However, from a greater distance (point no. 2), the model had proportions closer to the designed ones, and the landscape behind the bridge was imagined to be as true as it will look after the construction of the bridge. The orientation of the bridge from this location was closer to the accuracy as it was from several dozen meters, which can be seen in Fig. 3-13.



Position Status
Latitude N49°33'45.5070"
Longitude E22°12'33.0399"
Height 357.30 m
NTRIP
Service Autonomous
Last Correction -
Connection Time 00:00:22
Data Received 1534 B
Reference Frame Same as source

Fig. 3-13. Visualization of the model with the Trimble Site Vision device at point no.1

3.5.6 Working limitations of MR/AR devices and suggestions

Both HL and SV are no doubt promising devices, but their full capacity is still in operation. As mentioned earlier, HL has the major limitation of distance mappings as it can map the surrounding up to 5 m. Besides this, its functionality and visualization are reduced in the sun, so a cloudy environment is best suited to perform such types of experiments. Moreover, in very cold weather sometimes the device hangs and shuts down automatically. Another important limitation of the HL device is the short operating time that forces the use of a portable power supply.

Similarly, SV has the limitation of its use only in the open air as it needs direct connections with satellites. Moreover, during the orientation settings device requires some adjustment of the antenna by walking on the ground, so, it is very challenging in case of limited space availability. Other issues involve the precision of orientation and scaling of the model and accurate measurement of designated coordinates, which takes a long time for their adjustments, therefore, bigger marking points with enough space availability can reduce the limitations and help to achieve better results. Several factors influence the placement, especially the connections to GNSS satellites and the orientation parameters of the device. Besides these limitations, the implementation still worked well from a long distance and was found to be very close to the real placement of the bridge which was also acknowledged by the designers too.

3.6 Chapter summary

This chapter provides an in-depth knowledge of BIM and related digital technologies in the context of bridge engineering. The integration of Building Information Management (BIM) methodology, 3D reconstruction techniques, Digital Twins, and immersive technologies like Virtual Reality (VR) and Augmented Reality (AR) offer substantial benefits to bridge engineering. BIM facilitates intelligent project management by developing digital models for informed decision-making, leading to cost reduction and enhanced efficiency throughout a bridge life cycle. 3D reconstruction techniques, including laser scanning and photogrammetry, play a critical role in creating detailed and accurate models of bridge structures, aiding in precise measurements, deformation identification, and damage detection. Similarly, Digital Twins (DT) provide a virtual representation of bridges, enabling asset management, maintenance cost optimization, and real-time monitoring for improved operational strategies.

Further, Immersive technologies like VR and MR enhance visualization capabilities in bridge engineering, allowing stakeholders to experience designs interactively for better decision-making. VR offers an immersive experience that aids in design selection, while MR techniques overlay digital information onto physical objects, enhancing realism in design perception. A case study, discussed in this chapter, demonstrated the effective application of VR and MR in visualizing different bridge design variants, providing stakeholders with true-scale experiences for final design selection. Challenges remain in device limitations, distance mapping, and operational conditions, requiring further enhancements for accurate bridge visualization and improved implementation of MR and AR technologies in the field of bridge engineering and monitoring. The literature reviewed in this chapter will help to explain the research narrative in the subsequent chapters of this thesis.

4 Analytical and asset bridge modeling with SHM systems and IoT sensors

4.1 Introduction

This chapter discusses the bridge modeling techniques, primarily analytical and 3D modeling techniques. The analytical modeling involves an extensive discussion of the application of Finite Element Analysis (FEA) for bridge damage assessment. The primary objective is to identify the damaged state of the bridge for proposing a robust Structural Health Monitoring (SHM) system. Two case studies are presented in this chapter to practically apply the analytical modeling techniques validated by bridge load testing methods for damage assessment and the proposal of an SHM system. While focusing on 3D modeling of the bridges, their integration with analytical modeling techniques is also discussed. It enlightens the first new scientific result of this dissertation by integrating Finite Element Modelling and Bridge Information Management (BrIM). This integration develops a BIM-based FE model that can be used for the analysis and design of bridges.

Moreover, this chapter also focuses on integrating advanced technologies, mainly BIM, SHM, IoT, and MR, to address their significance in the ongoing advancement of the SHM domain. For this purpose, the development of wireless sensors, comprising DHT 22 and 3-axis gyroscope sensors using ESP32 microcontroller and IoT web platform, is discussed in detail. Further, the chapter demonstrates a lab-scale simulation of a bridge SHM system, showcasing how the real-time SHM of a bridge can be performed using IoT and BIM technologies. This way the second new scientific result is documented. Another major topic of discussion in this chapter is the integration of the developed IoT system with Mixed Reality (MR) through 3D game engines encompassing the development of the dedicated MR application, its deployment to MR headsets, and the development of a comprehensive framework for MR-based SHM of bridges, highlighting the innovative approach for bridge health monitoring aided by IoT capabilities.

4.2 Assessment of the structural health of the bridge and the impact of damages

4.2.1 Analytical modeling of bridges with the impact of damages

In the first stage of development, the computational capabilities of computers and limited methods of operating in virtual space forced the use of a large number of simplifications in modeling. Especially in terms of mapping the bridge geometry. In fact, there was a complete separation of tools used to create the most faithful geometric models from increasingly advanced computer systems, which were intended mainly for performing various types of analyses of bridge structures (static-strength, dynamic, non-linear, etc.). Initially, the force or displacement method was implemented for these analyses.

Shortly after OC Zienkiewicz [155] published the assumptions of the Finite Element Method (FEM), they were completely replaced by the new approach. This approach was much better suited to creating algorithms and computational procedures using increasingly faster and more memory-capacious computers. Unfortunately, simplifications were also needed in the description of the geometry, which resulted mainly from the weaknesses and limitations of the first interfaces for operating these programs. The geometry of the model and the connections between its elements were presented symbolically in relation to the actual structure. The priority was to reproduce the conventional division into finite elements, their stiffness resulting from the cross-sections and the material used, as well as mutual relationships, again in a conventional topology of nodes. Even if, over time, FEA programs allowed the analysis of three-axis models in three-dimensional space (class objects), the way of visualizing them was still greatly simplified.

The analytical part consists of a separate, three-dimensional primitive that is intended to represent the computational element. It also contains the object properties needed for analysis, such as the type of material, boundary conditions, and assigned load. Unfortunately, the analytical model automatically generated in this way contains many geometric inaccuracies and often requires individual and tedious user intervention. To overcome this limitation, several analytical modeling tools are directly used these days which help to create and analyze the analytical models.

The term "damage" hereinafter used describes effects that cause deterioration of the condition of the bridge. The concept of the condition of a bridge structure is a general term including technical condition, usefulness, and aesthetics of the structure. However, the concept of technical condition is understood as the level of compliance of the current values of the technical parameters of the object (geometry, material features, etc.) with the designed values. However, usability is a term characterizing the level of compliance of the current values of the object's operational parameters (load capacity, movement limits, permissible movement speed, etc.) with the required values of these parameters. The qualitative and quantitative description of the damage and its location may concern the assessed structural element or equipment in a specific place and along its entire length. The concept of a structural element refers to the component of a bridge that is used to transfer loads (deck, girders, bearings, supports). Equipment elements, on the other hand, include additional bridge components that serve to meet functional, safety, and durability requirements.

Many methodologies are in practice for the detailed evaluation of bridges. In this regard, in-situ measurements and Non-Destructive Testing (NDT) evaluations have been the most adaptable methodologies since long [156][20]. These evaluations have provided us with the specifications and properties of the material and information about significant deterioration effects phenomenon [157][158]. It further involves numerical models for static and dynamic analysis of bridges. In addition to strength and stability issues, special consideration should be given to a broad range of important factors such as dynamic and seismic behavior, long-term deformations, fatigue, and durability (functional efficiency) issues, that can be effectively analyzed using the 3D nonlinear FE modeling technique [159][160][161]. Safety assessment procedures using Finite Element (FE) modeling represent the sound basis for selecting intervention techniques and controlling the efficiency of the applied interventions [162]. Numerous deficiencies of existing Reinforced Concrete (RC) bridges are due to the absence of detailed durability rules in the original design, which can be verified by carrying out static and 3D nonlinear structural analysis [18].

4.2.2 Bridge damage assessment tools used for structure monitoring

Deterioration and damage of bridges are the results of aging and downgrading of the structure. The reasons for this may be environmental factors, improper design, poor construction quality, lack of proper maintenance, and natural disasters like earthquakes, floods, or strong winds [163][164]. The increasing decay of infrastructure calls for their damage assessment to make them in line with the exact design requisites [165]. For this purpose SHM framework is utilized to observe and evaluate the existing condition of civil infrastructure, which has been broadly evolved to monitor the safety, serviceability, and sustainability of existing structures like bridges [166].

In addition to the bridge assessment methods discussed in Section 2.3, FE analysis is also used to analyze the bridge damages and further helps to design the SHM systems of the bridges which identify the locations of damage measuring devices [167]. The effects of influencing factors such as live load, temperature, and wind can be analyzed in the numerical model to determine the type and location of sensors in the planned SHM system [168][50]. This approach allows the selection of optimal and efficient damage assessment devices [169]. For example, strain needs a special measurement method for testing and early identification of structural defects in bridges [170].

Different novel techniques, including infrared (IR) thermography and digital image correlation (DIC), are preferable when it comes to assessing the damages caused by the strain [171]. For the monitoring of such damages, Fiber Bragg Grating (FBG) using fiber optic sensing techniques is widely used and highly efficient to measure strain under the effects of dynamic loads [172][173]. Displacement is another critical parameter in the case of bridge damage monitoring as it reflects the overall stability and behavior of a bridge [174]. Efficient measurement of deflection is carried out by using an inclinometer because of its high precision and easy handling. [175]. However, these inclinometers have special hardware requirements, which limits their use for special bridge sites. Therefore, to overcome the limitations of certain contact sensors, and the measurement of vertical displacements, the use of special Liquid Leveling Sensors (LLS) is vital [176]. This is also because these Liquid Leveling Sensors (LLS) offer contactless services with the measurement of 3D field dynamic deflection [177].

Another critical damage in RC bridges is the development of cracks, which can be caused by overloading, the carbonation process, and corrosion of rebars in an aging bridge structure [178][179]. The formation of new cracks and the propagation of existing ones not only reduce the stiffness, load-bearing capacity, and durability but also shorten the service life of bridges [180][181]. Many traditional mechanical methods allow for spot measurement of cracks up to 7 mm at the places where cracks have already been identified [182]. However, simple crack scales or gauges are inefficient for the detection of new cracks along with the propagation of cracks in new areas [183]. Many smart deformation monitoring techniques are in practice to monitor such damages nowadays, among which smart film for crack monitoring is an effective one [184] but their high sensitivity limits their applications for some typical usage in bridges. Distributed Fiber Optic Sensing (DFOS) is found to be the most effective method for deformations monitoring of RC bridges [185]. It can effectively detect the length, width, shape, location, and propagation of cracks in an existing bridge along with the measurement of the deformation parameter [186][187][65][188]. Some researchers [189][190] have highlighted the monitoring of cracks using deep machine learning algorithms that involve the basics of fiber optic sensing. These sensors provide a continuous profile of light scattering processes, over a certain optical fiber range, that allows users to set the parameters for measurements of deformations as per their requirements [191][192]. In addition to that, another important parameter in bridges in bridge damage assessment and monitoring is the assessment of moving weights especially when the load-bearing capacity of the structure is under design [42]. Imposing proper regulations of truck weights reduces the surface damage in bridge structures which in turn reduces the pavement maintenance costs and provides a check over the load-bearing capacity of bridges [193][194]. Consequently, the mentioned methods provide a data set of the most advanced techniques used to monitor bridge damages and introduce robust and heavy-duty damage monitor device sensors that can give rise to a proper SHM system, as proposed in this research paper.

4.2.3 Bridge load test in the process of FE model update and SHM system calibration

The base of the SHM system lies in its proper installation and validation before functional use. Therefore, the SHM system always requires reliable information about the serviceability and performance parameters of the bridge [35]. This is only possible by the periodic calibration and/or experimental validation of the SHM system. Considering the safety procedures and recent developments in the bridge industry, it is critical to adopt proper health monitoring of bridges [195], as it requires the use of reliable data that can improve the operability and effectiveness of the bridge throughout its life. Therefore, authentication of the installed SHM system, especially the new bridges, is extremely important for the start of their operational life [196]. Considering this fact, performed load testing results are used in this study for performance evaluation and validation of installed SHM as it has been done in the previous studies [197][198][199][200].

Static load tests are usually done by loading the bridge with fully loaded trucks which in turn yields the maximum vertical displacement of the spans [22][201]. Besides this, dynamic testing involves the evaluation of the modal parameters, for instance, the time period of the structure, resonance frequency, free vibration frequencies, and their respective mode shapes with corresponding damping ratios [202][203][33]. Additionally, the comparison of these values with numerically evaluated values is mandatory to check the first vibration frequency that should be comparable with the numerical values [204],[205]. This way dynamic load testing helps to predict the type and location of vibration-measuring devices. Moreover, load tests are also useful for the verification of FEA results and FE model updating [206] which also helps in the decision-making for a proper SHM system of the bridge [207]. Results reported from many of the load tests have focused on the improvements in analysis and design procedures, verification of design code provisions, and FEA of bridges which are important for the diagnostics of damages [208][209][210]. Therefore, the effective utilization of load test results involves the comparison of the measured values with the calculated ones. The calculated values are extracted from FEA [211],[212] i.e. the displacement results and their residual values after unloading the bridge [213],[120]. This comparison confirms the validity of FEA. If the difference between measured and calculated values is less than 10%, there is no need to update the FE model [214], [215],[120], otherwise, FE model updating is required.

4.3 Bridge damage assessment using FE nonlinear analysis and proposal of SHM system

4.3.1 Introduction to a case study of an RC bridge in Hungary

To practically implement the discussed bridge damage assessment methodologies, a case study of a reinforced concrete bridge is carried out in this research. This case study is based on the implementation of different damage assessment techniques like static linear and 3D nonlinear analysis methods to analyze the existing damage state of the bridge and provide the basis for the SHM system of the bridge.

The subject bridge is a 50-year-old box girder facility, located over a dam in eastern Hungary. Overall, the bridge structure contains five spans, each of 27.6 m making a total length of 138 m. The superstructure is a continuous RC double box girder having a 20 cm top slab (separated by the expansion joints at each support) and a 16 cm bottom slab, connected by the 40 cm thick deck walls. These walls are additionally the elements of the hydro-technical infrastructure providing the access for inspection of hydro-technical works. For this reason, the outer deck walls of the webs have openings located above the support walls. This results in a local reduction of the girder stiffness in the area of the support wall connections. The girder is supported on concrete support walls of 20 cm via the set of three steel plate bearings placed under the box webs. The cross-section and span layout are shown in Fig. 4-1.

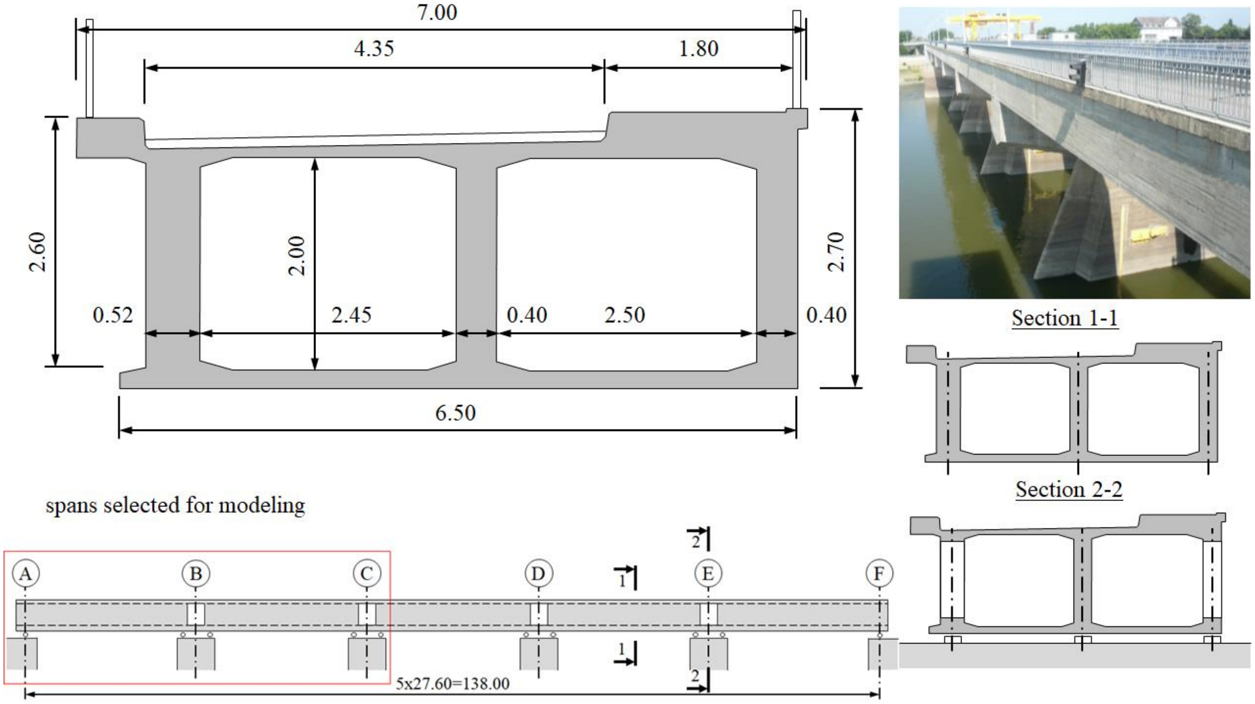


Fig. 4-1. Bridge cross-section and span layout

The first two spans (A-C) of the bridge, over the waterbed are considered in this research work because on one side, the maximum moment is experienced at the central support while on the other side, different crack patterns can be observed in both the spans.

The bridge's structural assessment has been done several times in the past but similar defects were addressed in every archival report. These reports suggested certain strengthening or complete dismantling. The archival reports from 1998 showed the presence of cracks for the first time, since then every report has mentioned these cracks, with a significant increase in the location of cracks. The technical condition has not been improved so far. As the infrastructure is to be used only for the next 15 years, the overall reconstruction is economically and technically irrational in this case. Therefore, the implementation of the SHM system is found to be a viable solution for the above-mentioned case. This system would enhance safe bridge operation for the next 15 years, reduce inspection costs, and monitor certain defects, especially cracking.

4.3.2 Damage assessment using analytical modeling

Static linear analysis is carried out using AXIS VM software to calculate internal forces and check for the displacement capacity of the bridge in accordance with the Eurocode standard. So, for this strength-based design, an elastic model of two spans (A-C) is developed as a shell element. Loading of the structure includes the application of live loads as 7 kN/m² (taken from the standard load given in the EC for this type of bridge structures), permanent loads (besides self-weight) as 1.9 kN/m², moving loads (vehicular load) as a concentrated and a distributed load of 300 kN and 4 kN/m² respectively, and the temperature loads as +20/-60 °C by considering the thermal expansion effects. The supports' (bearings) stiffness is considered to be quite stiff against vertical movements without any calculations because there is a solid concrete structure under it. These bearings are supported by 20 cm thick support walls. Connections between the deck walls and bearings are kept pinned at support A, while the roller is at B and C, as per the actual conditions at the bridge. The supporting walls have a fixed connection with maximum stiffness at support A and relatively less stiff supports at B and C. Actual reinforcement is added to the bridge model, just to analyze the internal forces and cracking in the bridge (Fig. 4-2).

Since the current analysis is aimed at finding the displacements, so, the results of displacements rather than the forces are required to fulfill the damage limit state. A detailed analysis shows that the maximum vertical deflection is almost 6 mm at the center of the span AB (Fig. 4-2). Bridge condition assessment is based on comparisons between calculated displacement results and the code criteria, therefore, by applying the maximum deflection criteria according to the EC (L/400 = 27600/400 = 69 mm), the maximum deflection is found to be less than this limit value. Thus, the bridge is showing satisfactory performance against displacement damage.

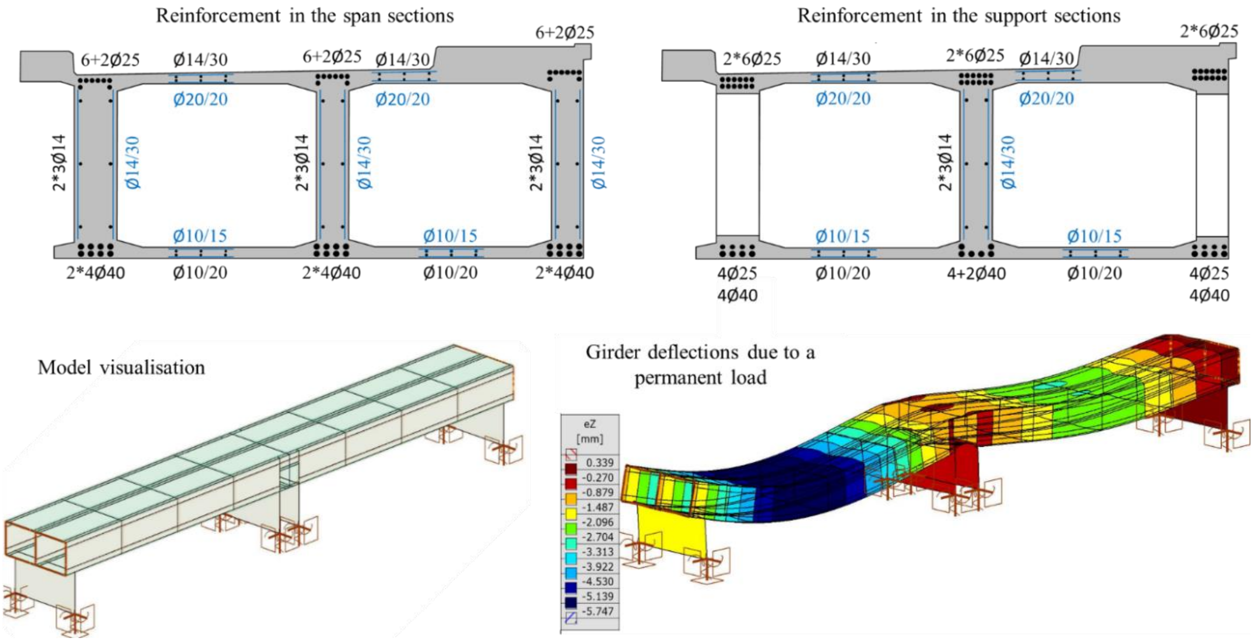


Fig. 4-2. Typical reinforcement and linear elastic static model of the bridge created in AXIS VM software

However, cracks observed on the bridge are one of the major problems. The complete calculated crack profile (with ranges) in the top and bottom slab (wk(t), wk(b)) is shown in Fig. 4-3.

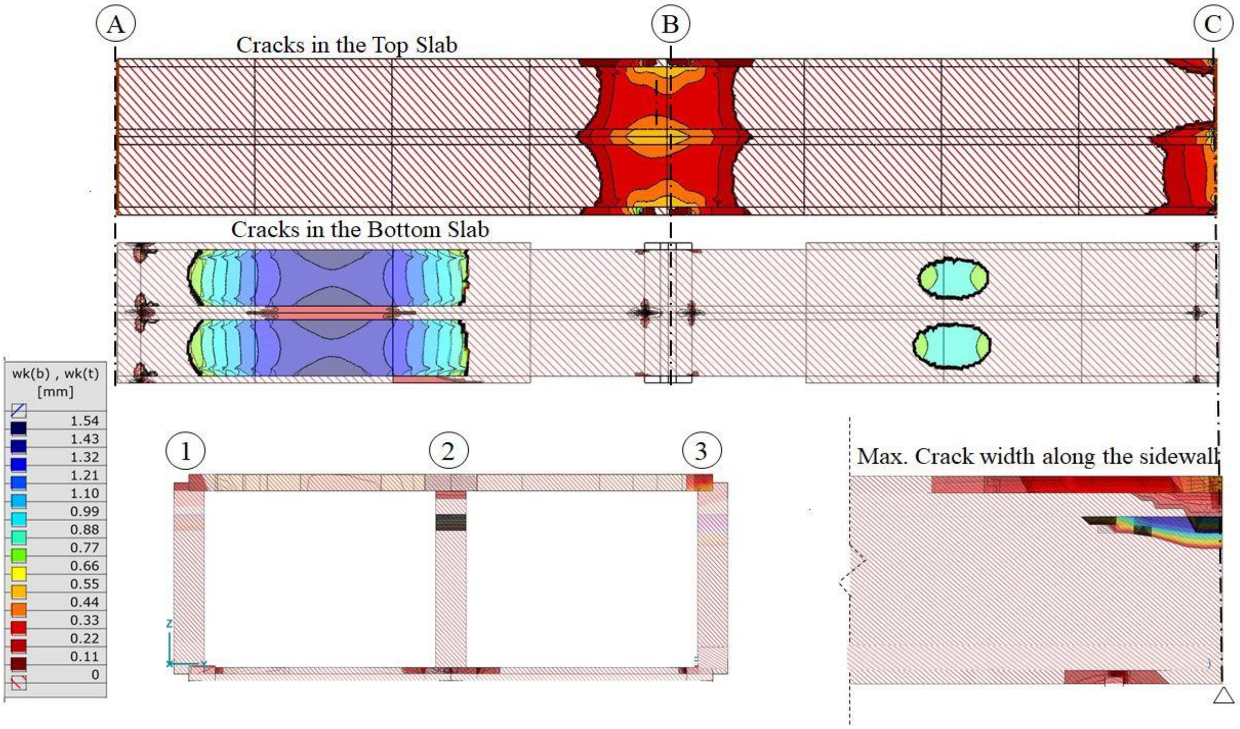


Fig. 4-3. Visualization of calculated critical crack widths

The cracks in the middle of the span in the bottom slab (0.80-0.99 mm), and at the support in the top slab (0.10-0.33 mm) seem to be reasonable because these are the locations of the highest bending moment.

Cracks in the side wall of the deck below the top slab, at the end of the span, are critical (reaching up to 1.54 mm), as thermal changes are applied to the bridge. Moreover, these are the places where the highest shear stresses are transferred from the slab to the deck wall producing cracks of maximum width. This maximum crack width is due to several reasons. First, in the numerical model, there is a peak stress at some points, however in the real structure these stresses will be lower e.g., if a small crack appears, the stiffness will be reduced there, and the internal forces will be redistributed because of that, furthermore, having actual structural thicknesses will result in different internal forces than in the numerical model, where everything is represented by single lines or surfaces). Secondly, in the model, numerical calculations are done at the design level, considering weaker material properties and higher design loads. These loads are considering the fact that the bridge is operated under full traffic, and to be satisfactory according to EC. Based on the analysis, a lot of mainly diagonal cracks were also observed within the walls on the real bridge, in several cases exceeding the limit value from EC (0.3 mm), and reducing stiffness. It also confirms the necessity for retrofitting the bridge.

3D Non-linear analysis is carried out using ATENA software based on non-linear material properties. This analysis overcomes the limitations of linear elastic analysis and provides more accurate results, by taking into account material and geometric nonlinearities. The geometric and material model starts with the material selection followed by macro-element generation, material assignment, loading of structure, meshing, and analysis setup.

In this analysis, modeling is done on the principle of shell element theory with the cross-section of 2D macro-elements. A smeared cracked material approach is used for the concrete. As per the findings of in-situ measurements, concrete with an elastic modulus of a lower range value (31.7 kN/mm²) is selected. This material selection is based on the applications of Biaxial Compression-Tension Failure, where the tensile strain is experienced within the concrete under the effect of poison ratio (0.2) in x-y directions. In this way, the selected concrete is fully complying with the nonlinear biaxial stress-strain law. Cracked concrete is supposed to be a homogeneous material with orthotropic behavior. At different section levels of structural damage, a shear-sensitive model accounts for the axial force-bending-shear interaction (N-M-V). This methodology is very effective as it is based on a hybrid approach. On one side, it considers the multiaxial stress generation in macro-elements, and on the other side accounts for the nonlinearities produced by cracking and the anisotropy of concrete.

The loading of the structure is done in 40 intervals of nine load cycles (different load types) starting from zero to their maximum value. Load values are the same as defined in the case of static analysis. A thinner mesh of size 0.05 m is used to get refined results. The analysis is carried out within the framework of the Newton-Raphson method with tangent stiffness properties of finite elements. In this method, non-linear algebraic equations are used to solve the non-linear finite element problems using the selected iterations.

After running the analysis, the results are obtained in the post-processing phase. Maximum deflection is calculated to be 20 mm, while the minimum deflection is 5.4 mm. As the maximum deflection is less than the limit value mentioned before, thus the structure meets the deflection criteria [216]. Cracking is critical also in this analysis. The maximum crack width is found to be 0.62 mm along the sidewall of the deck at support C, which is higher than the limit value of 0.30 mm. These results are comparable to the linear elastic analysis where the critical crack width is found exactly at the same location, and maximum deflection is slightly smaller, as expected.

The Load Displacement (LD) curve highlights the overall response of the bridge against the applied loads. As the shear is considered to be linear and bending is due to non-linear interactions, the load-bearing capacity of the bridge keeps on increasing linearly until the appearance of shear cracks. These cracks appear when the structure experiences a higher load level (around 14.7 kN/m²). The cracking pattern and deflected shape of the bridge with the LD curve are shown in Fig. 4-4.

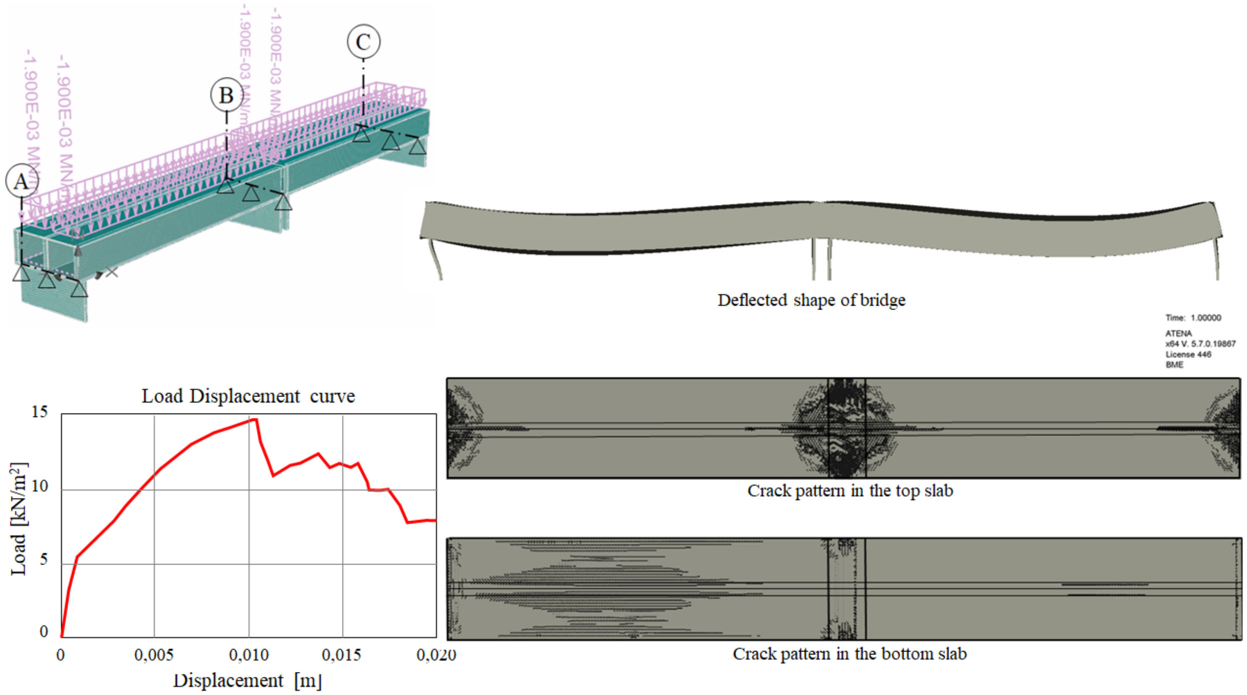


Fig. 4-4. Nonlinear analysis results and deflected shape of the bridge

At this stage, the model experiences bending failure not only because of the crushing of concrete but also due to the yielding of longitudinal reinforcement. So, the load value suddenly falls to 11.2 kN/m². After this, a resuming mechanism takes place which tries to stabilize the load-bearing capacity of concrete but fails to do so. Thus, the fractured concrete and yielded steel reinforcement cause an increase in displacements without further increase of load-bearing capacity of the bridge until stirrups fail, leading to the attainment of maximum displacement (20 mm). In general, the extracted LD curve (Fig. 4-4) represents the experimental behavior of materials precisely until the cracking of concrete and yielding of steel.

Conclusively, two major concerns are highlighted by 3D non-linear analysis results. One of them is cracking, and the other one is displacement. The bridge has sufficient bending and shear capacity in the Ultimate Limit State; therefore, analysis results are satisfactory here as well. This analysis also proves the safety of the bridge against deflection damage as the maximum value (20 mm) is below the allowable limit (L/400 = 69 mm). Verification of stresses in SLS is also exhibiting satisfactory values. The cracks at the mid supports of two spans are very critical due to a stiff resistance against the vehicular loads. Finally, the extracted crack pattern of slabs is quite similar to the crack profiles drawn by static analysis. These results are more accurate and closer to the conclusions of the in-situ measurements. Further, it can concluded that the issues related to the bridge affect serviceability, which has so far been dealt with by introducing traffic restrictions, but due to uncertainties of the bridge behavior (e.g. how damaged expansion joints work), a better understanding of structural conditions and behavior can only be achieved by bridge monitoring.

4.3.3 Proposal of the SHM system

Based on the inspection results, material tests, and assessment of the technical condition of the bridge described above, it is observed that the structure exhibits considerable damage; indicating a reduced load-bearing capacity of the box girder. Therefore, with such reduced functional properties and durability, the structure's degradation level will accelerate over time, which either calls for an extensive renovation or the complete replacement of the spans. Therefore, long-term plans assume the reconstruction of the entire infrastructure, however, until then, the bridge must guarantee safety. Furthermore, the assumed operating life of the existing components is approximately 15 years. Therefore, replacing spans or a thorough repair with reinforcement is not an economical solution. Thus, a solution is proposed in this research that will extend the life cycle of the bridge with minimal repair costs while reducing the risk of failure.

The proposal is to install a SHM system. Several assumptions are made while planning this system. First, the system should be in operation for 15 years and be able to alert the authorities when a sudden drop in the load-bearing capacity is observed. The second assumption applies to the restrictions on traffic organization on the bridge by determining the load limit (up to 300 kN), speed (up to 30 km/h), and the weight monitoring of passing vehicles. The third provides information about the load-bearing capacity that will be obtained using at least two different techniques in several critical places like deck connections with its walls and opening of the deck walls and supports. Lastly, it is assumed that together with the installation of the SHM system, protective work should be performed, particularly anti-corrosion protection of the exposed reinforcement and injection of the indicated cracks. Therefore, it is proposed that the planned system should record the deformation of the structure by measuring the vertical displacements of the spans and the deformation of the box girder at the places highly exposed to cracks. This system consists of a set of sensors, weight in motion system on both-sided access roads of the bridge, power wirings, and electronic gadgets data acquisition. Another integral part of this system is the software data analysis, providing the visualization and tracking of crucial information associated with the behavior of the structure.

The proposed SHM system provides for the installation of two essential measuring devices. The first are sensors for measuring vertical displacements. Their task is to monitor changes in the grade line. For this purpose, a series-connected Liquid Levelling Sensor (LLS) has been proposed; that uses the communicating vessel principle (Fig. 4-5). Together with the reference station, they will form a hydrostatic system for measuring changes in displacement in relation to the reference point on the extreme supports.

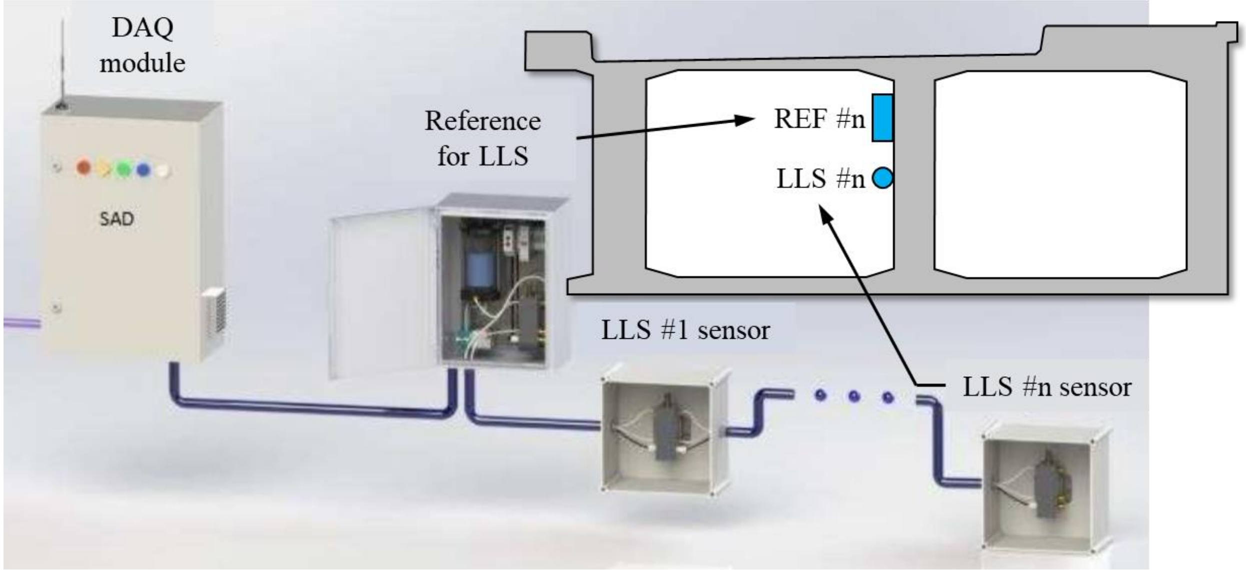


Fig. 4-5. Liquid Levelling Sensors for measuring vertical displacements of spans

The second device will be fiber optic sensors for geometrically continuous measurements, type DFOS (Distributed Fiber Optic Sensing). These are sensors in the form of composite reinforcing bars with a diameter of approximately 5-6 mm called Epsilon Rebar. The key feature of the Epsilon Rebar is that it is made of one composite material. Its cross-section is monolithic, without any intermediate layers. They guarantee accurate strain transfer from the concrete to the optical fiber inside the sensor. In addition to that its external surface is ribbed to provide appropriate mechanical bonding with the surrounding concrete. Sensors will be placed in grooves approx. 7-8 mm wide and of the same depth. Their location on the cross-section of the box girder is shown in Fig. 4-6.

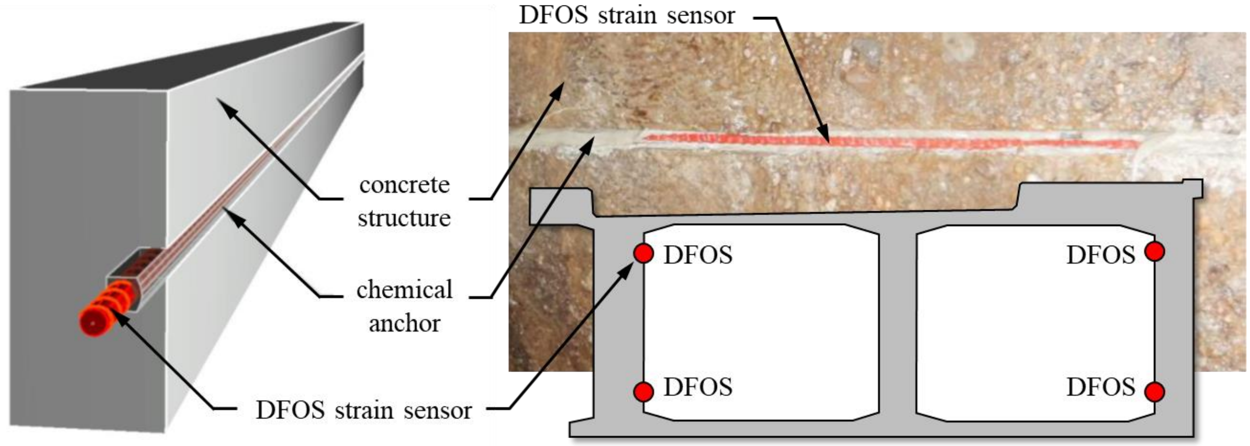


Fig. 4-6. DFOS sensors on the cross-section of a box girder

The four outer corners of the girder box are indicated at the contact of the outer webs with the upper and lower plates. The final location of the bar sensors should be determined in situ. It should fit in the concrete cover during installation without damaging the existing reinforcement. The resin adhesive composition carries out the transfer of deformations from concrete to the sensors. Therefore, the sensors should enable the measurement of strains, i.e., because of changes in the width of the cracks and temperature. Moreover, using the knowledge of the distance between the sensor axes, it is possible to determine the deformation of bridge spans understood as its displacement Epsilon Rebars.

In addition to the described set of sensors, two Weigh in Motion (WIM) devices are also planned to be used. To initiate and close measurement sessions, they should be integrated with the main data acquisition system (DAQ). Each vehicle passing the WIM device can force the entire system to record the measurement data. In turn, driving through the second WIM device will end the registration process. The locations of all significant components of a planned SHM system are shown in Fig. 4-7.

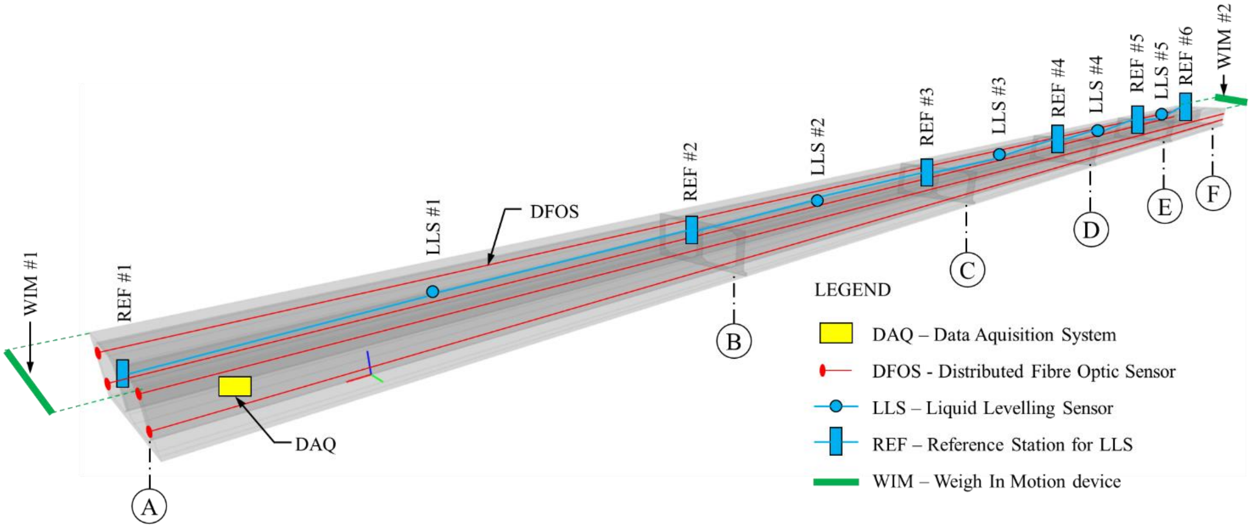


Fig. 4-7. Location of the essential elements of the SHM system

So, the recorded data must be pre-processed in order to determine the extreme values and to be archived. Subsequently, SHM system management software modules will later make use of such reduced signals and will be transferred to the reporting and visualization module. Users will receive periodic reports via email. They will also have authorized access to the running application that will be used to clearly present data in tabular and graphical form over time. It will also show alarm conditions and threshold violations. Later, the data will be synthesized according to a specific conversion algorithm in additional modules – diagnostic, alarm, and expert.

4.3.4 Case study conclusions

The findings of this case study can be concluded with the comparison of results extracted from three different types of analysis methods and their recommendations for the development of an SHM system that can be installed on RC bridges having a similar situation as considered in this case study. Analysis results yield the following observations:

1. Out of limit crack width, calculated as 0.4 mm in case of in-situ investigations, 1.5 mm in case of linear elastic static analysis, and 0.6 mm in case of non-linear analysis, exceeds the EC limit (0.3 mm).

2. High values of temperature and humidity variations cause cracking and weathering of concrete.
3. Extensive corrosion of steel bars was observed which is due to the small concrete cover.
4. Bridge deflection is observed in the safe zone as it is calculated to be 6 mm in the case of linear elastic analysis and 20 mm in the case of non-linear analysis, so both values are below the EC limits (69 mm) bridge.
5. The bending and shear capacity of the bridge in the Ultimate Limit State and stresses in Serviceability Limit State, satisfy the criteria according to the guidelines of EC.

The above results are more refined in 3D non-linear analysis and have closer values to the in-situ investigation. Hence, a 3D non-linear analysis is highly recommended for the damage assessment and evaluation of bridges.

Further, to monitor associated damage and to ensure safer operations of the bridge, a SHM system is proposed in this study. This system includes the installation of a Liquid Levelling Sensor (LLS) for the measurement of vertical displacement, Distributed Fiber Optic Sensors (DFOS) for deformation monitoring, and Weigh in Motion devices for monitoring moving loads on bridges. Installation of this system is subject to the following measures.

1. The system will be in operation for 15 years and will alert the authorities when a sudden drop in the load-bearing capacity is observed.
2. Load (up to 300 kN) and speed limits (up to 30 km/h) are recommended with monitoring of passing vehicle weight.
3. One directional traffic flow is to be implemented on the bridge,
4. Together with the SHM system, protective works, particularly anti-corrosion protection of the exposed reinforcement and injection of the indicated cracks should be performed.

Although the proposed concept of the SHM monitoring system would allow for extending the life cycle of this overloaded structure (of course, while ensuring an appropriate level of safety), unfortunately, the owner of the bridge did not decide on such a solution. Therefore, it was necessary to find another testing ground. For this purpose, an extradosed bridge in Poland was considered for further research phases of this dissertation.

4.4 Bridge model update and SHM calibration using field load testing

4.4.1 Introduction to a case study of an extradosed bridge in Kurow (Poland)

Once the analytical models are created and the associated SHM system is proposed and installed on the bridge, there arises a need for the verification of the generated analytical models and the calibration of the installed SHM system. For this purpose, this research uses the bridge load testing technique to fulfill said purposes at once. This case study is used to show the FEM model of the bridge together with the SHM system and the load test as a process that can be used to update the model, i.e. the birth of the digital twin.

A newly constructed bridge along National Highway 75 in Poland was selected for this study. This bridge consists of a four-span, continuous extradosed structure with a box girder superstructure made of C60/75 concrete. The bridge spans are 100 + 200 + 200 + 100 m, making a total of 600 m.

The bridge was designed following the LM1 load model according to the EC1 standard [217] (with the adaptation coefficient α = 1.00) and for class A according to the PN 85/S standard [218]. The overall width of the structure in the span cross section is 17.68 m and 23.0 m at intermediate supports. A dual carriageway road, 8.60 m wide (between curbs) runs through the structure, there is also a 4.0 m wide pedestrian and bicycle lane. The layout of the bridge with complete detailing of its superstructure and cross-section is shown in Fig. 4-8.

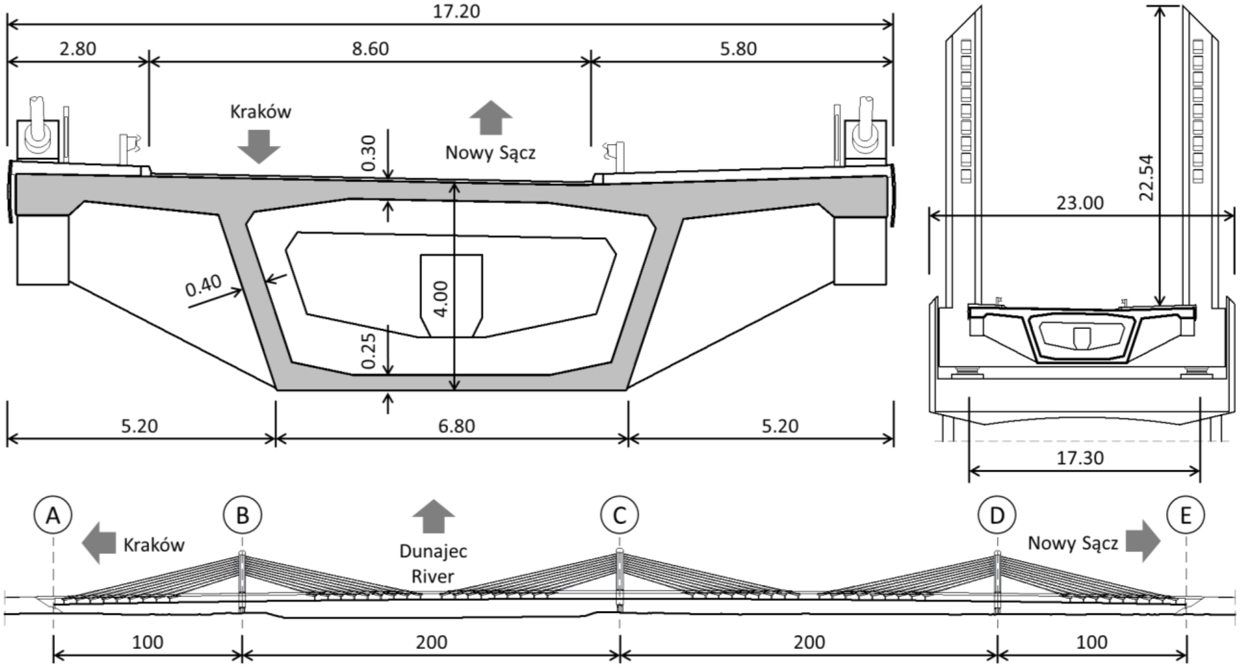


Fig. 4-8. Kurow Bridge cross-section and span layout

4.4.2 Updating the material model of as-built concrete and its modulus of elasticity

The dependence of the modulus of elasticity of concrete on the type of aggregate used is taken into account in EC-2 by the coefficient α_E. The modulus of elasticity E_{cm} for concrete is thus calculated by multiplying the values by the coefficient α_E. In the case of the used aggregate, the α_E coefficient is 1.2. Considering the influence of air entrainment in the analyzed structure, α_E is finally assumed to be equal to 1.2. Considering the concrete strength tests after 28 days of curing and the type of aggregate used, the forecasted modulus of concrete elasticity as a function of age can be determined based on the formula:

$$E_{cm}(t) = 22 \cdot \left(\frac{f_{cm}}{10} \cdot e^{s\left(1-\sqrt{\frac{28}{t}}\right)} \right)^{0,3} \cdot \alpha_E \qquad [GPa] \tag{5-1}$$

where: f_{cm} is the average 28-day compressive strength of concrete in [MPa],

s = 0.25 is a factor depending on the type of cement (CEM II / AS 52.5 N),

t – is the age of concrete ≥ 7 in days,

α_E = 1.2 is a factor as discussed above.

The calculated modulus of elasticity E_{cm} of the concrete is found to be higher than the E_{cm} as per EC. The comparison of both of these values is presented in the graphs of Fig. 4-9, showing that the resulting increase in the stiffness of the structure can be considered by reducing the theoretically calculated deflections by a reduction factor of 0.73 (Table 4-1).

Table 4-1. Reduction factor of predicted modulus of elasticity according to EC-2

Age of Concrete	*Average strength*	*Characteristic strength*	*Concrete class*	E_{cm}	E_{cm} *as per EC standard*	*Reduction factor*
t	f_{cm} (t)	f_{ck} (t)	[-]	[-]	[-]	E_b / E_{cm} (t)
[days]	[MPa]	[MPa]	[-]	[MPa]	[MPa]	[-]
385	103	99	C 60/75	53.7	39	0.73

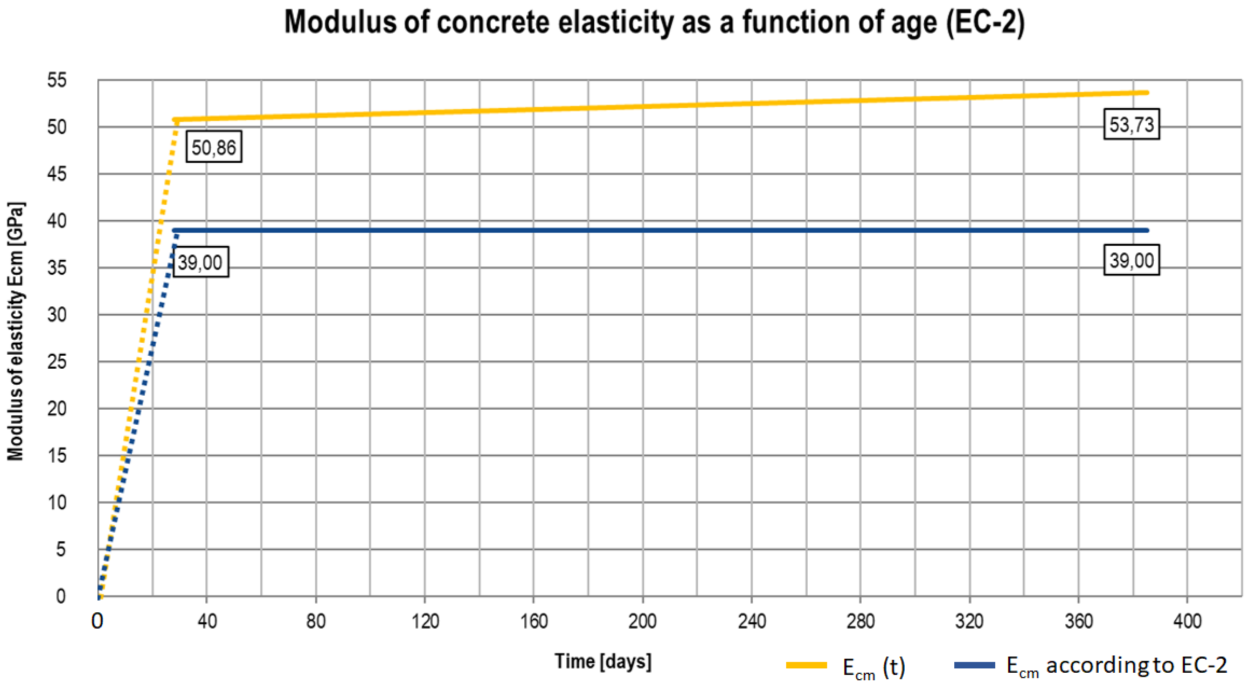


Fig. 4-9. Modulus of concrete elasticity as a function of age according to EC-2

4.4.3 Creating a BrIM 3D model

The BrIM model of the bridge is developed using Autodesk Revit software (Fig. 4-10). Where all the geometric details are collected from the CAD files of the bridge archival. The 3D geometry of the bridge is developed by incorporating alignment, profile, and cross-section details as shown in Fig. 4-8. All the structural elements, including pylons, extradosed cables, deck, piers, RC box girder, and abutments, are modeled using the details of the analytical model shown in Fig. 4-10, and all the materials properties are assigned as per the archives. As the bridge model is quite complex the electrical and plumbing system (MEP) is not modeled because this way the model could be very heavy which could cross the limits of the number of elements in the Mixed Reality tools. Thus, MEP details are not discussed here. With all the mentioned geometric details BrIM model is developed (as shown in Fig. 4-10) and exported to the relevant tools for further processing.

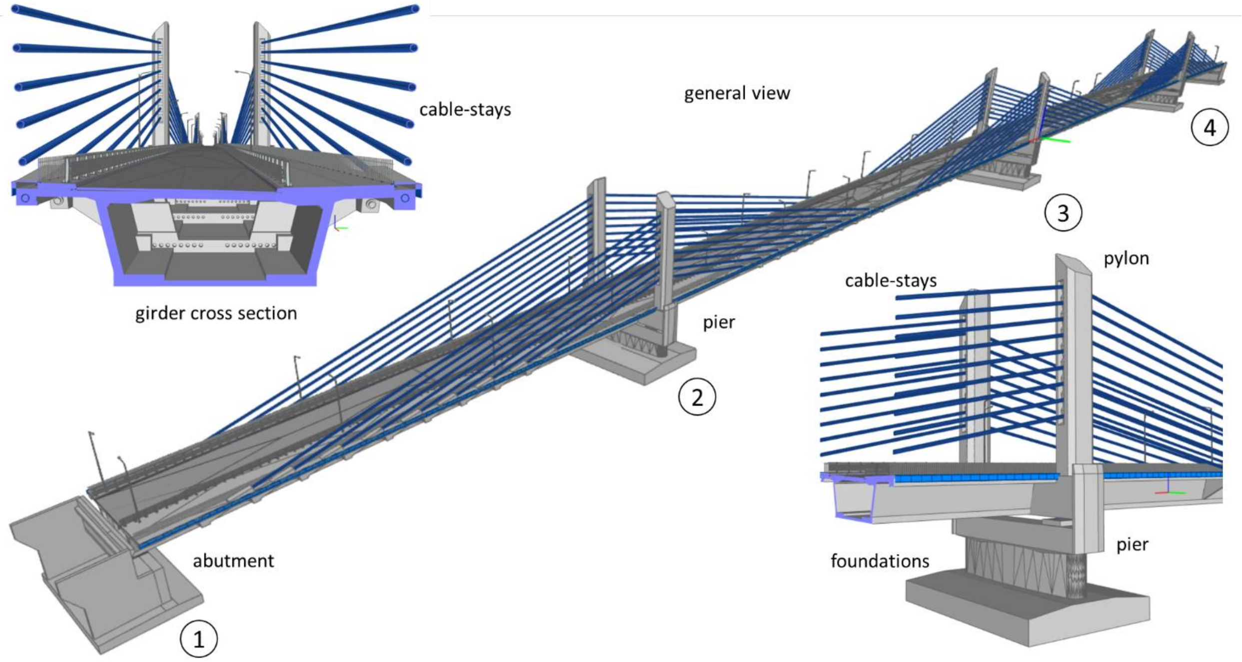


Fig. 4-10. BIM model of the extradosed bridge in Kurow

This model provides a base for the novel solution proposed in this research that helped the generation of an accurate parametric FE model, as well as suggested efficient visualization of real-time sensor data. Visualization of SHM data is very handy for bridge inspectors as they can see the real-time condition of the bridge by interpreting the information provided by sensors regarding the bridge's health. The integration between BIM and FE models ensures a coherent database with the ability to generate and update structural models in an automatic or semi-automatic way.

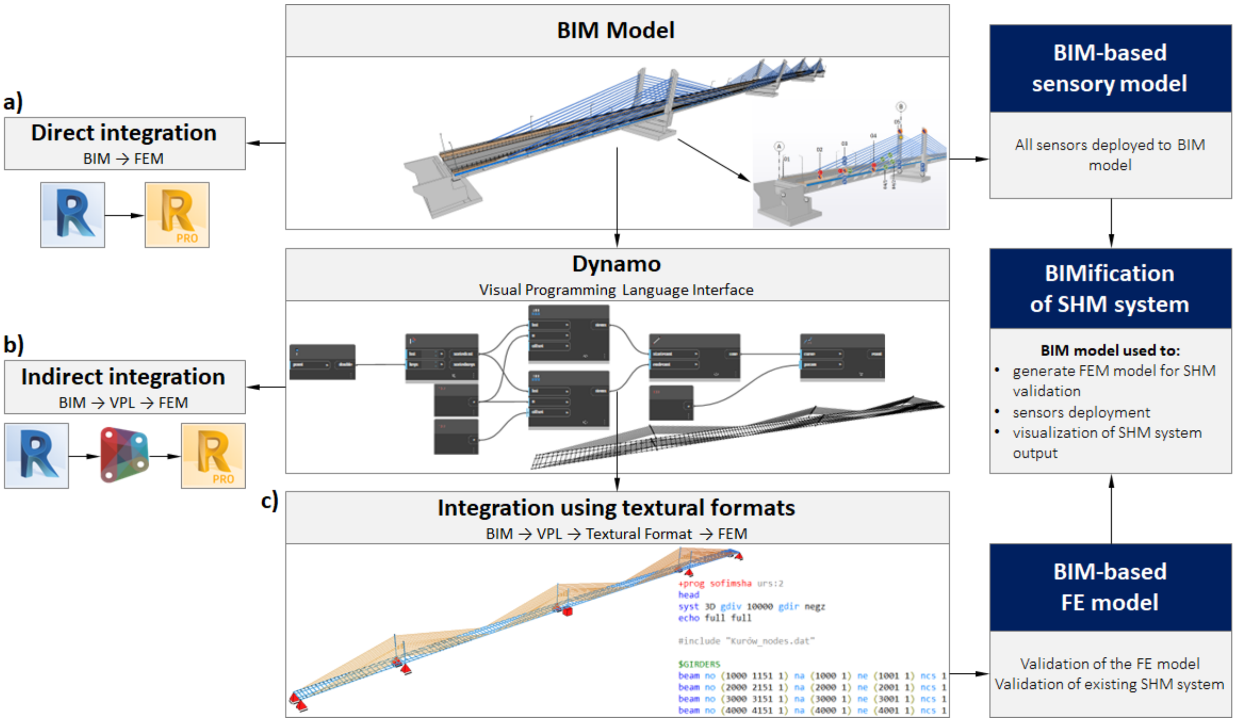
4.4.4 BIM-based automated method of FE model generation

The final changes to the FE model can be incorporated according to the results of the in-situ measurement. In this way, updating the FE model requires some iterative steps where it becomes necessary to make changes in the geometry of the FE model and the properties of elements or materials. In most of the software, the said job is cumbersome and consumes a lot of time. To overcome this issue, an integrated FE model generation technique is developed in this research. It uses the BrIM model as a source file and transforms its geometry into the topology of the FE model. The future direction of this work focuses on the material assignment, load application, and running the FEA using the BrIM-based model, which can lead to the comparison of BIM-based FEA results with the traditional FEA.

The generation of the BIM-based FE model can be performed using direct or indirect methods. Direct integration (Fig. 4-11a) involves closed solutions provided by BIM and FEM software. Linear elements, including beams, columns, pylons, or cables, can be translated into analytical counterparts created automatically in the structural analysis environment. It is observed that this method generates valid models only when the topology of both the BrIM and the FEM models is similar in terms of the number of elements, their shape, orientation, and relations. Moreover, the direct generation of the structural model requires dividing the BrIM model into pieces, including elements that are not explicit in the real structure, e.g., longitudinal, and transversal beams. Introducing such a topology in the BIM environment, especially for structural analysis purposes, is not a valid approach, as it requires additional, separate, and virtual elements to the BrIM model, which can disturb its semantics, performance, and usability in other aspects, e.g., quantity take-offs. Therefore, indirect methods were used in this research.

In this approach, the VPL interface is used in this dissertation to retrieve data on the geometry of spans, pylons, and cables directly from the BrIM model and convert them into a set of curves and points, including additional lines for longitudinal and transverse components of the structural model. This geometric representation can then be used to generate FE models using additional packages in Dynamo (Fig. 4-11b) or textural formats readable by structural analysis software (Fig. 4-11c). Dynamo script outputs generic node coordinates, allowing data exchange between BIM and FEM environments. Visual programming enables parametric model creation with open, adjustable code, enabling universal implementation in other frameworks. Using a visual interface, a file is generated that contains the coordinates of all the nodes. This file is written in the syntax of the CADINP language used in FE software.

The robustness and modifiability of direct methods are limited and depend on the maturity of the software used. Direct methods are usually software-specific and closed implementations delivered as ready-to-use tools in a software interface, defined in compiled and inaccessible source code that cannot be adjusted or extended to perform specific, out-of-scope tasks. In the given example and software, the BrIM model topology cannot be directly transformed into the FE model due to inconsistencies in the structure of both models. The single cross-section of the superstructure extruded along the road alignment creates a solid span and would be seen as a single linear element in the FE model. The topology of the span requires divisions into sections of parametric density defined in the open VPL code. Furthermore, two series of 1D elements are created for the left and right sides of the box girder with neglected vertical alignment in the FE model. These basic rules may not be fully covered by direct methods of data exchange, depending on the specificity and maturity of the software. In the case of the bridge FE model, due to the irregularity, complexity, and curvature of the BrIM model geometries, direct methods of exchange can give incorrect output. Hence, open indirect solutions are recommended and presented in our approach that can be extended or modified, if required, and give the output that is not limited to specific FEA software. The use of indirect methods also has other advantages. In this way, not only the time is saved but it is also very easy to update the FE model according to the results of the load testing. The openness and transparency of the source code are maintained, which is one of the key features of the BIM methodology, e.g., IFC-based (Industry Foundation Classes) data delivery and exchange. The said approach can be the basis for BIM-based bridge FEA and, in the future, can help designers work on the BrIM model to carry out FEA.



```
+prog sofimsha urs:2
head
syst 3D gdiv 10000 gdir negz
echo full full

#include "Kurów_nodes.dat"

$GIRDERS
beam no (1000 1151 1) na (1000 1) ne (1001 1) ncs 1
beam no (2000 2151 1) na (2000 1) ne (2001 1) ncs 1
beam no (3000 3151 1) na (3000 1) ne (3001 1) ncs 1
beam no (4000 4151 1) na (4000 1) ne (4001 1) ncs 1
```

Fig. 4-11. Diagram of an automated BIM-based method for generating a FE model

After the development of the FE mode, linear elastic static analysis is carried out to calculate internal forces and span displacement. These parameters are required in this study to provide locations of measurement points for the field load testing. Further, these results are considered as theoretical calculations to compare with the experimental ones (results of load testing). In the design, the calculation model takes the standard parameters of the concrete elasticity modulus into account, according to EC-2 [216].

Using the structural model, calculations are carried out to determine the values of displacement and the maximum bending moments in the spans and cross-sections of the box girder. These values are further compared against the code limits and measured values of load tests. The results show that the bridge has sufficient moment capacity. The calculations ignored the influence of axial forces due to their low values and normal stresses in the considered cross-sections. Based on our own experience, the model results could be enhanced if we use more realistic concrete strength (instead of the standard value) as per the real situation (e.g., measurements on the existing bridge). Moreover, the results of the static analysis indicate a slightly higher flexural stiffness of the structure, necessitating the need for the modification of the modulus of elasticity. The modulus of elasticity of concrete is the measure of concrete’s stiffness and is an important factor in calculating the flexure stiffness of the structure. It needs to be quantified as per the required reduction factor, described according to EC. This modification is also considered during the development of the FE model, thus, the FE model with the corrected value is considered in this research. This correction is described in the section below.

4.4.5 Static load testing with FE model updating

Static and dynamic load testing of the bridge was performed in this research to validate the FE model and to check for the sufficiency of the bridge monitoring system. Using the FE model, calculations are made to determine the values of bending moments in the box girder to define the load test patterns and location of measurement points. Further, the results of the load test are compared with the FEA results to validate the FE model.

Based on the numerical calculations, twelve load tests, designed to examine the static measurements of the newly constructed bridge in each span, were performed. These tests were performed to check the transverse load distribution and torsional stiffness of the structure. These tests included four basic span tests (S1-S4) selected on the basis of the maximum span load condition, three support tests (P1-P3) selected on the basis of the maximum support cross-section load condition over intermediate supports, three support reaction tests (R1-R3) causing maximum reactions to intermediate supports and two asymmetrical span tests (N1 and N2). For the scheme "S" twelve trucks were placed at the center of each span, for "P" four trucks were on each side of the support at an equal distance, for "N", twelve trucks were at the center of the bridge, and for "R" eight trucks at the axis of the support. The loading arrangement of the bridge along its cross-section is shown in Fig. 4-12. The truck placement details for schemes S, P, and R are shown in Fig. 4-12a), for scheme N1 in Fig. 4-12b), and for N2 in Fig. 4-12c). The weight of each vehicle was around 32 tons with ± 5% load variation margin giving a total weight of 384 tons.

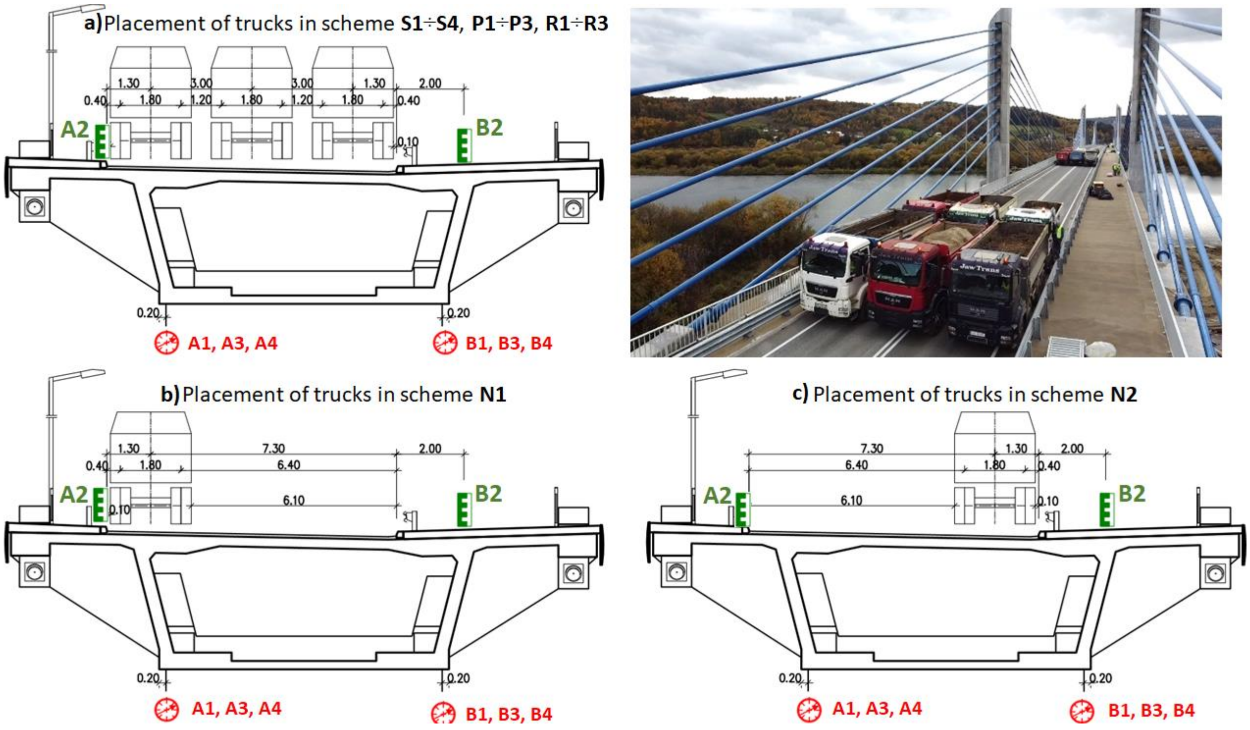


Fig. 4-12. Transverse arrangement of the load test trucks and location of measurement points

During the static load test, the displacement of the box girder was measured at two points of its cross-section (under the webs) in the loaded spans, and the settlement of the adjacent supports was also measured under load. Displacement of the girders in spans one, three, and four was measured with a dial gauge having a resolution of 0.01 mm. The measurement in span two was carried out using precise leveling from the top, due to river flow underneath, having a resolution of 0.05 mm. Measurement of support settlements was performed simultaneously with the measurement of deflections.

Displacement sensors and precise leveling (at each support) were used to measure the bridge displacements during the static tests. These sensors were placed according to the placement of trucks (static loads), and accordingly, measurements were taken. The markings of the measurement points and the location of these sensors are shown in Fig. 4-13. The displacement sensors were placed on each beam (L and R) at the center of each span and are highlighted in Fig. 4-13b and Fig. 4-13d. Similarly, the precise leveling sensors were placed at each of the supports on both sides as shown in the cross sections of Fig. 4-13a and Fig. 4-13c. The first series of measurements were done in an unloaded state. Subsequent series (not less than three) were carried out at regular intervals (every 10 minutes) until the movements stabilized. The stabilization of displacements is understood as a situation where the difference between the indicated and its previous displacement does not exceed 1% of the measurement increment. At this point, the structure was unloaded, and a series of readings were made again.

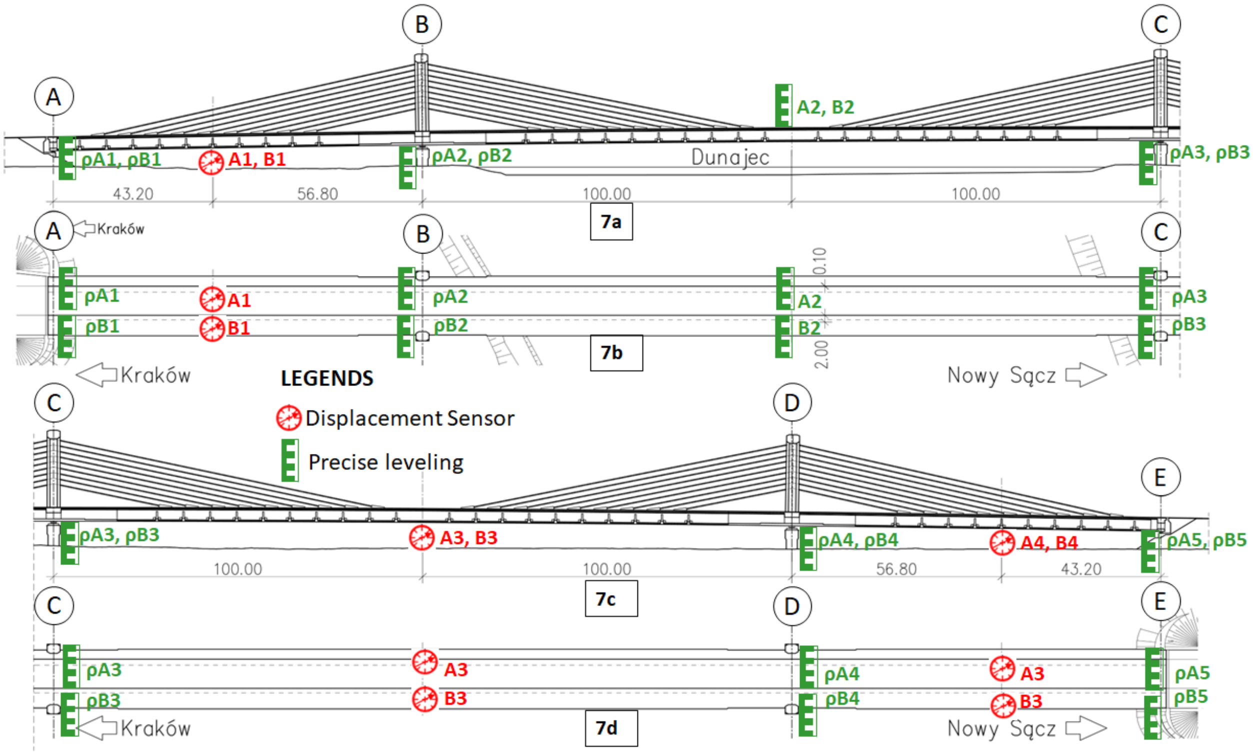


Fig. 4-13. Location of measuring points and installed sensors during the static load test

Based on the deflection readings recorded during the test, vertical displacements of the webs were calculated at different positions in the span. Each time, the displacement values were referred to the initial state, before loading. Selected representative results of displacement measurement are listed in Table 4-2.

Table 4-2 Maximum measured deflections of the box girder in case of selected load schemes [mm]

Static load scheme	*S1*		*S2*		*N1*		*N2*	
Span	1		2		2		3	
Measurement point	A1	B1	A2	B2	A2	B2	A3	B3
Total displacement, U_t	29.1	28.2	119.3	117.9	101.0	95.6	93.5	94.6
Permanent Deflection, U_p	-0.1	-0.3	4.3	4.8	2.1	2.1	-0.2	-0.2
Elastic Deflection, U_e	29.1	28.2	115.1	113.1	98.9	93.6	93.5	94.6
Measured Deflection, U_d	34.3	33.05	127.2	124.6	109.4	104.4	106.2	108.1
Permanent/Total, p	0%	0%	4%	4%	2%	2%	0%	0%
Elastic/Measured $U_d(k)$	85 %	85%	90%	91%	90%	90%	88%	88%
Average difference of %	86%				89%			

The values determined here are subjected to successive stages of loading and unloading of the structure during load tests. So, after completing the measurements, measured total displacements (Ut) and permanent displacements (Up), the elastic displacements or deflections (Ue) were determined and compared with the corresponding theoretically calculated (based on FEM analysis) values (Ud). The comparison between them is expressed as a percentage of the difference between theoretical values (FEM) and measured ones. Following standard conditions are applied to carry out these comparisons [219]:

- the ratio of permanent deflections U_p to total deflections U_t: $p = \frac{U_p}{U_t} < 10\%$ (5-2)
- the ratio of elastic deflections U_e to design (theoretical) deflections U_d: $k = \frac{U_e}{U_d} < 100\%$ (5-3)

From the results enlisted in Table 4-2, it can be observed that the stiffness of the spans is in accordance with the properties of the concrete used. The elastic deflections of the maximum loaded box girder in each span are slightly smaller than the theoretically calculated (amount to 85% and 90%) values. On average, elastic deflections of the tested spans constitute about 86% of the calculated values. c and showing the sufficiency of existing sensors measuring the static parameters of the SHM system.

So, after the modification of the elastic modulus of concrete, the FE model was validated by comparing the results of the field test with the numerical output, especially displacements. These values were further compared against the code limits and measured values of load tests (Table 4-2). Further, the consistency of the stiffness values was also checked. Thus, a comparison of permanent and total deflection from Table 4-2 was checked against the standard condition of not exceeding the level of 10% [120]. In this way, load-test results validated the developed FE model and showed that there is no need for the FE model updating.

4.4.6 Identification of dynamic parameters

Dynamic load testing was carried out to identify the dynamic properties of the bridge superstructure. During the test, modal parameters (natural frequency, mode shape, and damping ratio) associated with basic modes of vibration were identified. Identification of modal parameters was performed on the basis of acceleration signals processed using the Operational Modal Analysis (OMA) framework.

To perform the dynamic load testing, Peltron inductive linear displacement sensors (LVDT) were used to record dynamic displacements of the bridge and were placed at the marked locations in Fig. 4-14 (green color). LVDTs were attached to the bottom slab of bridge decks and measurements were taken beneath the bridge. Similarly, PCB Piezoelectric high sensitivity accelerometers (IEPE) were used to record the vibrations of the bridge on each side of the roadway with the location marked in Fig. 4-14. (red color). The test results were recorded electronically as time signals of vertical displacements and vertical (z) and transverse (y) accelerations. The measurement system also included a laptop computer and Siemens LMS SCADAS Mobile data recorder as shown in Fig. 4-14. Further, an artificial obstacle was placed at the route of the truck to produce some excitation for the OMA of the bridge. This obstacle is shown in the span DE of Fig. 4-14.

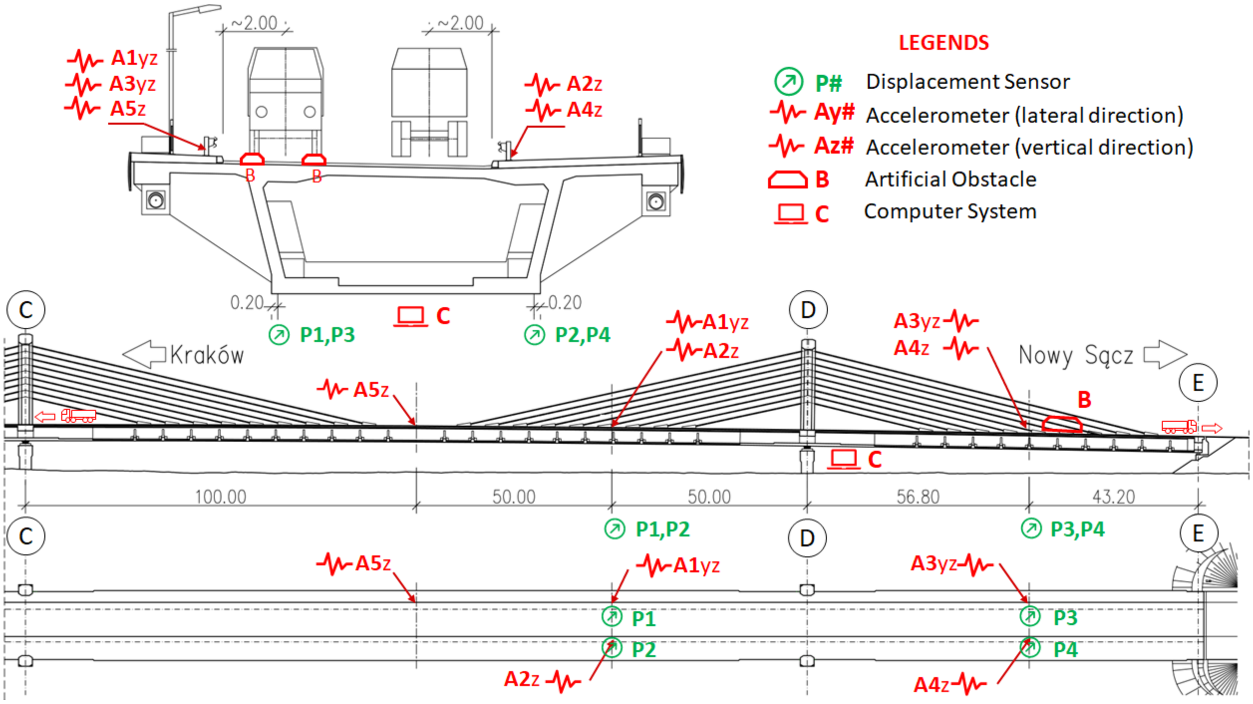


Fig. 4-14. Arrangement and placement of sensors along the bridge cross-section used in the dynamic load test

Measurements of dynamic load testing have unambiguously identified four natural frequencies which are shown in Fig. 4-15. In the case of the mode shapes, only FE analysis results gave valuable information, so, mode shapes from FE analysis were considered. As observed in Fig. 4-14, sensors number (only five vertical accelerometers) and placements (only two spans) limit our options to visualize mode shapes from

OMA, thus, only the comparison of frequencies was carried out without a comprehensive comparison of shapes using e.g. CoMAC (Coordinate Modal Assurance Criteria).

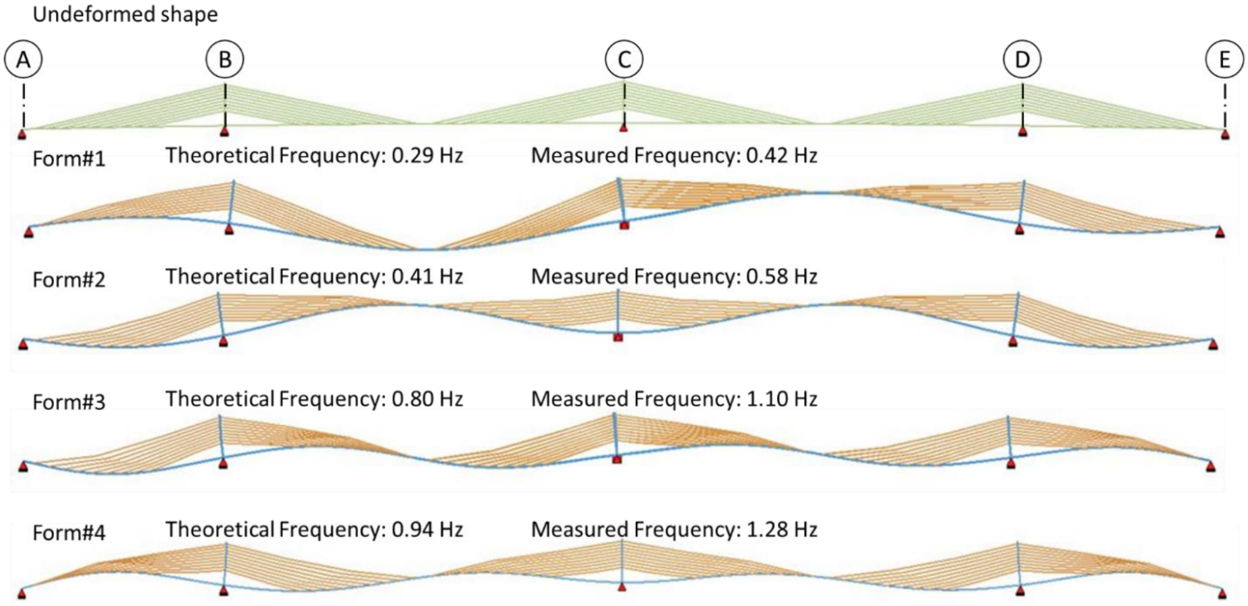


Fig. 4-15. Mode shapes from the FE model, preliminary theoretical and real identified natural frequencies

The lowest identified natural frequency is 0.42 Hz which is higher than the theoretically calculated 0.29 Hz. Although the stabilization diagram (Fig. 4-16) shows numerous peaks that indicate other natural frequencies, due to their proximity in the frequency domain and the complex shape of the sought forms, unambiguous identification is not possible. Thus, it would be necessary to use a larger array of sensors spread around key locations in a whole superstructure. This conclusion points toward the need for some additional accelerometers with more measurement points at the bridge.

The stabilization diagram shown in Fig. 4-16 gives better insight into superstructure dynamic properties. It shows the stability of four poles as f - only frequency stable compared to previous row; d - frequency and damping are stable; v - frequency and modal vector are stable; s - frequency, damping, and modal vector are stable". Here the model vector is considered between 40-60, which highlights the number of modes used to describe Frequency Response Functions (FRFs). It can be clearly seen that the most excited frequencies lay around 2.5 Hz but as stated previously, a relatively small number of sensors have limited mode observability.

Another metric of the dynamic behavior of the bridge is the dynamic amplification factor (DAF), here defined as the ratio of the maximum deflection on a given drive (30, 50, 70 km/h) of one vehicle to the maximum deflection in the same measurement section while driving the same route at a quasi-static speed of up to 10 km/h. The DAF peaked at 1.05 at 70 km/h concluding that the bridge has a small dynamic susceptibility to excitation by heavy vehicles [220].

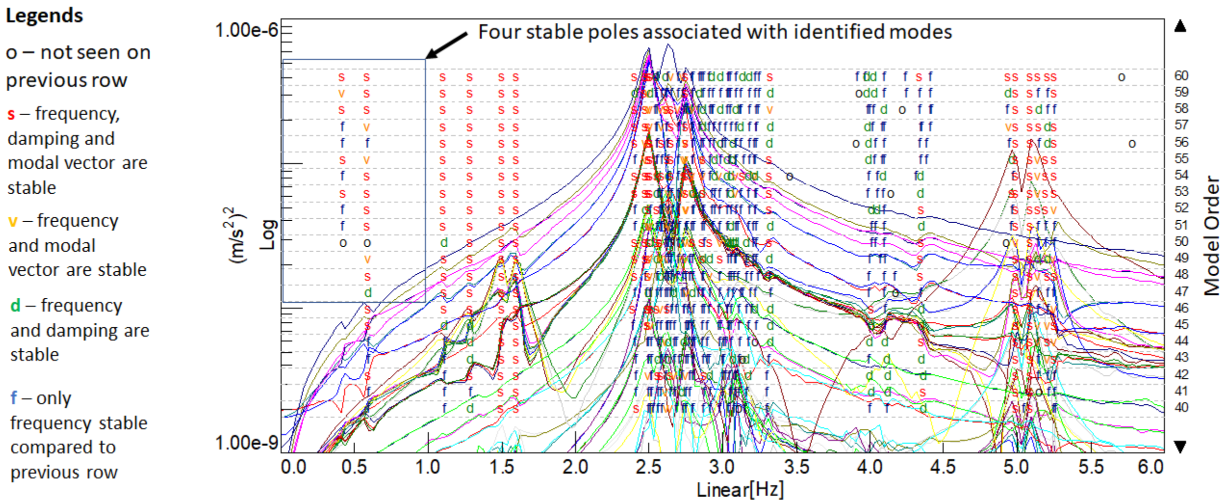


Fig. 4-16. Stabilization diagram of SSI-COV identification algorithm

Observation of these results, in the natural frequency domain, shows that the structure has a slightly higher stiffness than assumed in the model. Thus, the trend observed in static tests is also confirmed. As already mentioned, the results of the dynamic tests highlight the need for a greater number of accelerometers and dynamic measurement locations because of the higher difference in the measured and theoretical natural frequencies. Fig. 4-14 shows that only five sensors were used along the cross-section of the bridge. Out of these five sensors, two sensors measured both longitudinal and transverse vibrations, two measured vertical vibrations, and one sensor measured lateral. Using a greater number of sensors could increase the observability of the higher modes. Therefore, the results, with the given number of sensors and differences in their locations, are not very conclusive in the case of field measurement. Resultantly, the analysis is more reliant on the outcomes of the FE analysis which is recommended in this research.

4.4.7 Overview of the bridge SHM system

The SHM system of the bridge was planned to continuously monitor the technical condition of the structure. Considering the need, the SHM system was designed for the installation of sensors at selected measurement points. The major purpose of this system was to assess rheological phenomena, assessment of structural behavior of the bridge under operational loads, observation of the operationality of bridge box girders and suspension system, identification of structural damages, and monitor of loading conditions of the bridge. In this way, the SHM system can perform deformation measurements, synchronous dynamic measurements (Dynamic deflection and accelerations), structural response measurements under the operational loads, and monitoring of temperature, humidity, and wind effects on the structure.

To monitor the different parameters of bridge health certain devices like Vibrating wire strain gauges, Liquid Levelling Sensors (LLS), LVDTs, MEMS accelerometers supplemented with weather monitoring control stations and a Data Acquisition System (DAQ) are part of this SHM system. Their complete details, types, and location points are enlisted in Table 4-3.

Table 4-3. Details of installed sensors on the Kurow bridge

Sensor name	*Measurement parameter*	*No. of sensors*	*Location in Span#1 (5-15)*
Embedded wire strain gauge (WSG)	Deformation in pylons and slab	28	03,05
Liquid Levelling Sensors (LLS)	Vertical displacement	15	02, 03, 04
LVDTs (LVD)	Displacement at supports	10	A, B
Inclinometers (INC)	Angular displacement	20	02, 03, 04 & B
MEMS accelerometers (ACC)	Acceleration monitoring	28	03 & 1st, 3rd cable
Meteo station (MET)	Temp, Humd, and wind	01	Center of bridge

The above-mentioned sensors contribute to the SHM system of the bridge, which is the major focus of this study. The BrIM model of the bridge is selected to show the location of these sensors. For simplicity, the BIM-based SHM system for one span of the bridge is visually elaborated in Fig. 4-17, which will be further used for the automation of the SHM system.

After the evaluation of load testing results, it can be concluded that the type of sensors measuring the dynamic parameters of the SHM system suffice the needs of the existing SHM system whereas there is a lack of the number of sensors, and measurement location for dynamic parameters, therefore existing SHM require more of such devices for reliable monitoring of dynamic parameters.

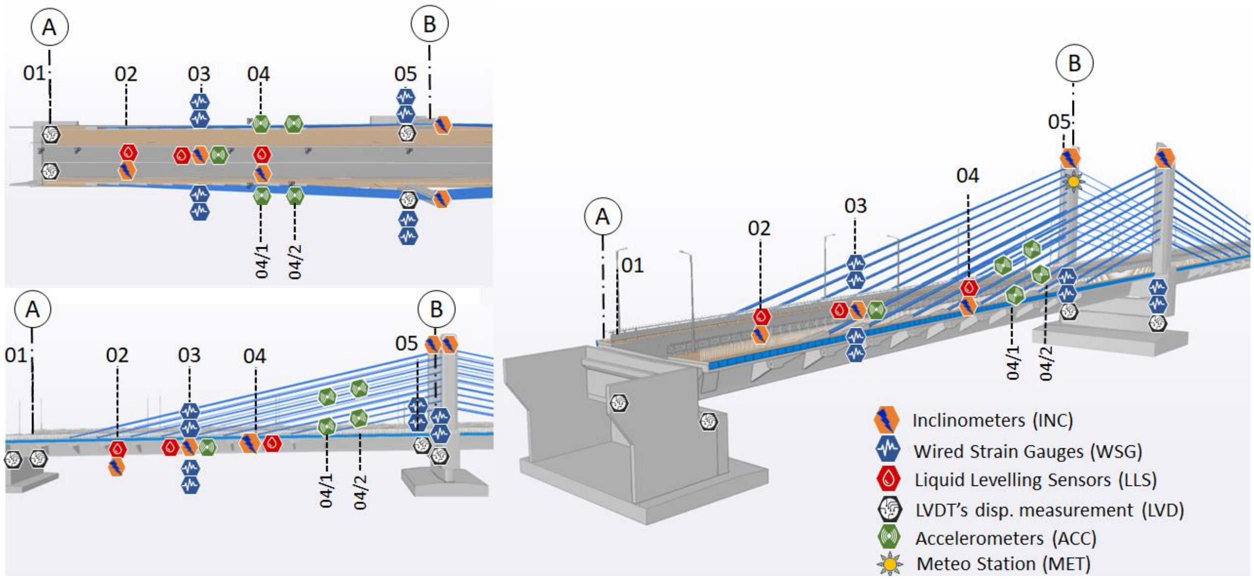


Fig. 4-17. SHM model of the Kurow extradosed bridge with the location of installed sensors

4.4.8 Case-study conclusions

The first new scientific achievement of this dissertation has been achieved in this case study through the automatic generation of the FE model. Since FE model development is an iterative and time-consuming process, this solution will ease the process of numerical modeling. It has been done using the applications of BIM technology, where a novel Visual Programming Language (VPL) script is developed using the indirect integration method in Dynamo. This script is based on functional blocks connected in a specific order to perform desired tasks, including mathematical operations, creating, and manipulating geometries, and exchanging data between the BIM environment and other types of engineering software. These building blocks can generate the geometry of any FE model enabling the integration between BIM and FEM environment. This integration results in the automation of FEM frameworks.

Further, the case study analyzes the existing SHM system of the bridge. For this purpose, FEA and field load testing techniques are employed. The results of both static and dynamic measurements are compared with the numerical calculations and the percentage difference in results is compared with the findings of EC. Whereas the comparison of permanent and total deflections constitutes from 0% to 6% and, therefore, meets the standard condition of not exceeding the level of 10% [120]. Such results prove that the stiffness of the spans is consistent with the values of the calculation model, thus validating the FE model of the bridge and showing the sufficiency of existing sensors measuring the static parameters of the SHM system. In the case of dynamic measurements, the high modal density values and the limited number of accelerometers are limiting factors in the case of the modal identification process, thus requiring more dynamic measurement devices for the installed SHM system of the bridge. After analyzing the SHM system of the bridge, the research tried to link this system with the Internet of Things (IoT) technology for automation of the bridge monitoring system.

4.5 Smart IoT sensors integrated with a bridge SHM system

With the fast-growing trends in the construction industry, the applications of IoT technologies have proven to be a game-changer, especially in the infrastructure monitoring domain. The integration of IoT technology has a transformative impact on monitoring and remote real-time management of the infrastructure. This way it plays a pivotal role in ensuring the resilience and efficiency of urban infrastructure. IoT-enhanced infrastructure monitoring involves heavy-duty robust wireless sensors that are deployed to the physical infrastructure to collect real-time data and are connected to internet platforms for data management. This platform further helps in the processing of the data for decision-making, predictive maintenance, and overall management of urban infrastructure. There are three basic components of this IoT system.

4.5.1 Development of the wireless sensors

Choosing the optimal sensing technology for infrastructure monitoring involves considering criteria such as system functionality, durability, ease of installation, intended response monitoring, and the severity of exposure conditions on the bridge. The primary objective is to develop practical monitoring technology with minimized wiring, easy installation, accessibility, maintenance/replacement ease, and reasonable cost compared to traditional inspection methods, eliminating the need for physical presence at the bridge. Limitations of time and installation costs can significantly affect the overall inspection process of bridges. Considering the advantages of such a system, I have developed IoT wireless sensors that have been successfully tested at the laboratory scale and made compatible with the field conditions of the bridges. Three major components of IoT-based SHM systems are considered in this research:

1. Wireless sensors.
2. Wifi enabled microcontroller.

3. IoT-based web platform.

These three elements work together to create a reliable Internet of Things-based bridge health monitoring system. The key components of wireless sensors, the employed technique, sensor and programming language datasheets, and the creation of a web platform with the Arduino IDE are discussed in this section. It is important to note that the Arduino IDE programming platform is chosen for this study due to its user-friendly interface and ease of developing connections between the web platform and the sensor.

4.5.2 Wireless sensors

In this research, three different types of sensors are used for monitoring the relevant parameters. These sensors include a DHT22 temperature and Humidity sensor and a 3-axis digital output gyroscope for the monitoring of vibrations. Table 4-4 shows the datasheet of the DHT11/22 temperature and humidity sensor, and Table 4-5 shows the specifications of gyro sensors.

Table 4-4. Datasheet of Temperature and Humidity sensors [221]

Model	*DHT22*
Power supply	3.3-6V DC
Output signal	digital signal via single-bus
Sensing element	Polymer capacitor
Operating range	humidity 0-100%RH; temperature -40~80Celsius
Accuracy	humidity +-2%RH(Max +-5%RH); temperature <+-0.5Celsius
Resolution or sensitivity	humidity 0.1%RH; temperature 0.1Celsius
Repeatability	humidity +-1%RH; temperature +-0.2Celsius
Humidity hysteresis	+-0.3%RH
Long-term Stability	+-0.5%RH/year
Sensing period	Average: 2s
Interchangeability	fully interchangeable
Dimensions	small size 14*18*5.5mm; big size 22*28*5mm

Table 4-5. Datasheet of 3-axis digital output gyroscope [222]

Chip	*MPU-6050*
Power supply	3~5V Onboard regulator
Communication mode	standard IIC communication protocol
Chip built-in	16bit AD converter, 16bit data output
Gyroscopes range	+/- 250 500 1000 2000 degree/sec
Acceleration range	+/- 2g, +/- 4g, +/- 8g, +/- 16g
Pin pitch	2.54mm

4.5.3 Wi-Fi enabled microcontroller

This research used an ESP-32 microcontroller to enable the wireless functionality of the used sensors. This microcontroller is just like a chip having Wi-Fi and Bluetooth connectivity modules which are embedded in the chip for activating the sensor through the processor – in other words, this chip is the hub of the IoT sensors. The original ESP32 chip had a single-core Tensilica Xtensa LX6 microprocessor. The processor has a clock rate of over 240 MHz, which can be used for a relatively high data processing speed. The specifications of the microcontroller are listed in Table 4-6.

Table 4-6. Datasheet of ESP-32 microcontroller [223]

ESP-32	*Description*
Core	2
Architecture	32 bits
Clock	Tensilica Xtensa LX106 160-240MHz
WiFi	IEEE802.11 b/g/n
Bluetooth	Yes - classic & BLE
RAM	520KB
Flash	External QSPI - 16MB
GPIO	22
DAC	2
ADC	18
Interfaces	SPI-I2C-UART-I2S-CAN

4.5.4 Sensor development methodology

In order to effectively use the DHT 22 and gyro sensors, the sensors should be connected to the microcontroller. To ensure this connection 4.7k Ohm resistor, a breadboard, and Jumper wires are used. The schematic diagram of the sensors and microcontroller assembly is shown in Fig. 4-18.

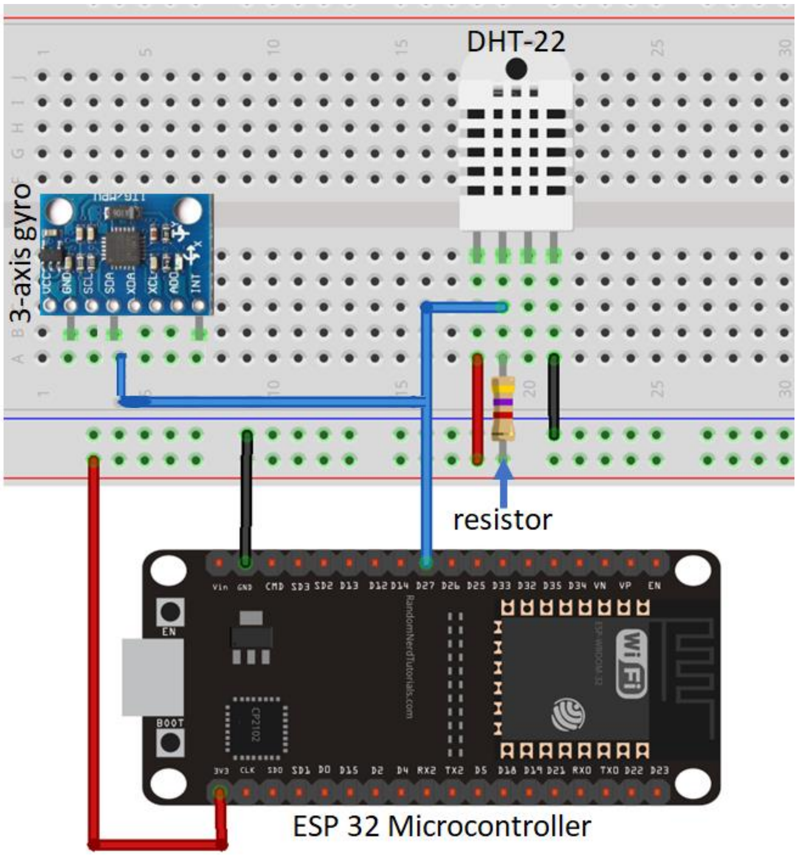


Fig. 4-18. Circuit diagram of the sensor-microcontroller hardware connection

After installing the libraries, the Arduino programming platform is used in Arduino IDE, which consists of several functions, variables, and structures based on the C++ language. This programming helps to set the parameters of the used sensors using Serial Communication Protocols and send the data accordingly to the serial monitor for visualization.

As two different types of sensors were used in this research, two different codes were developed to activate the sensors' measurements. The codes for the DHT sensor and the 3-axis gyro are attached as GitHub/THS(Annex-A) and GitHub/3GS(Annex-B). After successfully deploying the code, the sensors start the measurements, and the real-time results are visualized in the serial monitor.

4.5.5 IoT-based web platform

To develop an IoT-based SHM system, a dedicated web platform is developed in this research which actively communicates with the ESP-sensor system to measure and manage the sensor's data. The IoT-based web platform for the SHM system is developed using a free version of a web application (Blynk) [224]. This application is available in both smartphone and web versions, but the developer mode is available only on the web version. So, using the web version of the application, the web platform is developed, and after that communication between the ESP-sensors system and the web platform is established again using the Arduino code GitHub/AWP(Annex-C).


Kurow Bridge SHM System Online

Temperature 20.8 °C

Humidity 56.1 %

Fig. 4-19. The IoT-based web platform of the SHM system

The development of the IoT web platform starts with a project creation, where one device having three sensors (temperature. Humidity, and vibration sensor) is added to the dashboard. On the dashboard, each sensor is created with its own domain, and its measurement features are enabled according to its datasheet. Thus, the measurement parameters of each sensor, i.e., its measurement limits, units, graph axis, and frequency of measurement are manually developed. After developing the graphical interface and measurement scheme of sensors, they are made online by connecting to the web platform. This connection is developed using Arduino code (GitHub/AWP)(Annex-C). One code for all three sensors is developed where the API of the sensors and domain of the web platform is embedded. This code is then uploaded to the web application dashboard and communication is established over the Internet. After successfully developing the connection between the ESP sensor system and the web platform, the sensors under the SHM system are visible online on the dashboard. After that, the automation action is enabled for sensors that allow data recording, which initiates real-time monitoring. The dashboard of the developed IoT-based based platform is shown in Fig. 4-19.

4.5.6 Integration of IoT-based system with BrIM models

The best utilization of the IoT tools can only be attained if they are integrated with the BrIM models. This way 3D visualization of the developed sensor along with real time data monitoring can be performed right on the bridge model. A thorough literature on this topic is discussed in section 2.5 of this dissertation. This section discusses the integration of the developed IoT-based web platform with the BrIM model of a bridge.

The initial plan of this research included the field installation of the developed sensors on the Kurow bridge and data measurement in the field condition, but unfortunately, permission to physically access the bridge SHM system was not granted, so, a lab-scale bridge model was used over which the developed IoT sensors were installed and simulation of the bridge SHM system with the developed wireless sensors was performed at the lab scale.

In this scenario, the BrIM model (developed in section 4.4.2) of the bridge is used as a base file over which the developed wireless sensors are deployed in the virtual space. The job is done using the application (Trimble Connect) in the MR environment. The web-supported domain of this application is used throughout this process. The BrIM model of the bridge is uploaded to the application platform as the IFC formats or .rvt files, directly through the BIM software (Autodesk Revit). After uploading the model, the locations of the selected sensors according to the layout shown in Fig. 4-20 are marked on the uploaded BrIM model. At these locations, small icons representing each sensor are then generated. All these icons are now the virtual representation of the actual sensors installed on the bridge. Each icon in the BIM environment is developed with several functions. The major task is to develop the URL access for each icon, which is done using the interface of the MR application. This function allows the user to embed the URL or IP address of the web platform dashboard, where recorded data is available in graphical format, so, after developing this communication path in the BrIM model, the MR application developed direct access to IoT-based web platforms. Clicking the sensor icon on the BrIM model redirects to the sensor dashboard on the web platform where real sensors are sending data in graphical formats. Graphs of each measurement parameter can be seen in Fig. 4-20. In this way, data with different options (real-time, one hour, one day, seven days, one month, and three months) can be visualized remotely. Clicking each graph shows the details of measured data from where the data can be downloaded as .CSV file.

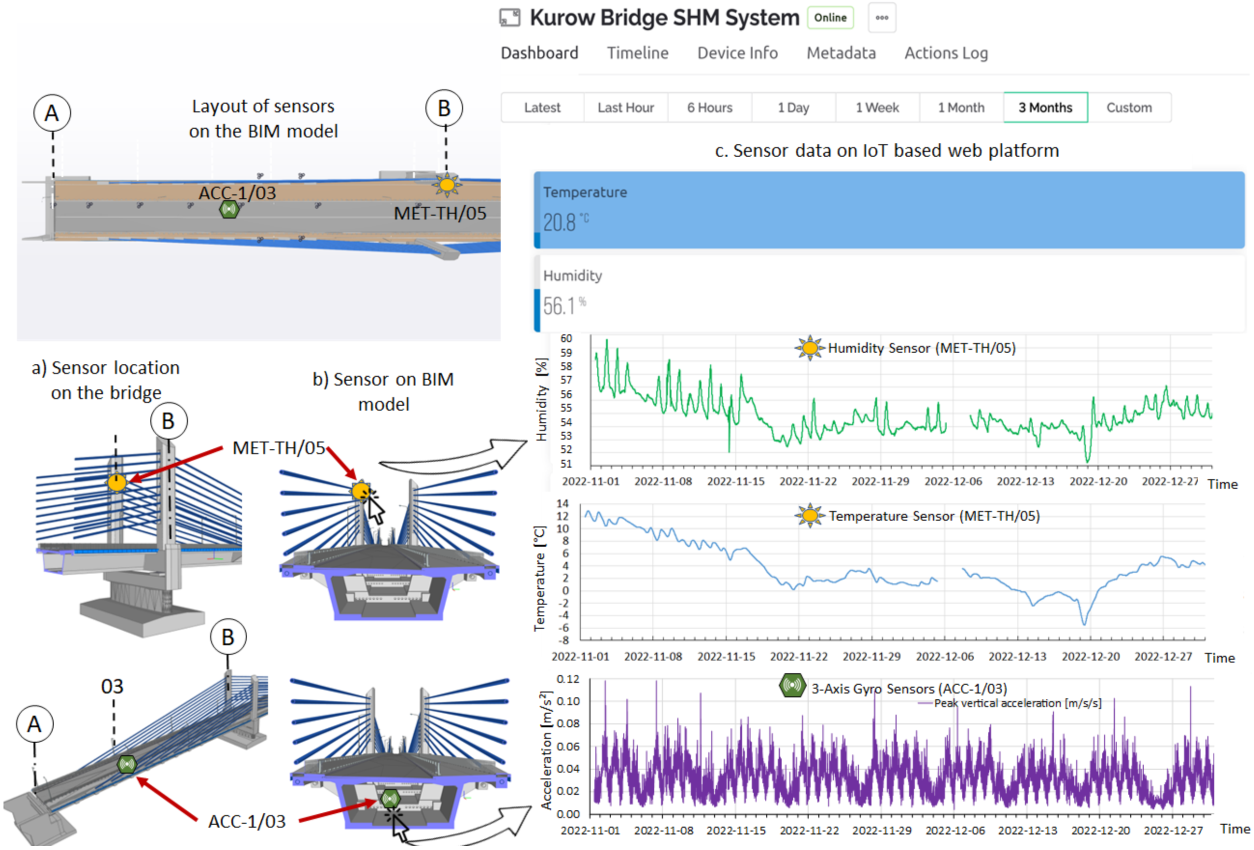


Fig. 4-20. IoT-based SHM system of a bridge

4.6 Development of the MR-based SHM system using a customized application

4.6.1 Wireless smart sensor and MR environment

Automation of SHM systems is currently trending in bridge monitoring because of their remote applications but the major aspect of this automation lies in the 3D visualization and on-field assessment of SHM data. For this purpose, Mixed Reality (MR) offers its service. This MR-enhanced solution increases the potential of a traditional SHM system using the applications of MR. Currently, MR applications in the construction industry are only used for machine control on construction sites, concrete pouring, reinforcement detection, onsite clash detection, and worker's field safety. So far, very limited research is available that tries to implement this technology in bridge monitoring, thus, this section discusses a novel way to develop an immersive MR-based SHM system.

This immersive SHM system includes developed wireless IoT sensors that integrate real-time sensor data from the installed sensor network and process it through the web platform in real time. The integration of SHM data with MR using MR headsets creates a seamless real-virtual blend. Holographic overlays highlight critical areas and gesture controls enable online data management. This way it helps to manage the technical condition of the bridge with real-time alerts, remote/onsite monitoring, cloud integration, data visualization, system calibration, and maintenance procedures to ensure the system's accuracy, reliability, and functionality while offering an advanced solution for monitoring of bridge health in real-time. To achieve these goals, the VR model of the same bridge (Kurow extradosed bridge) is created from the BrIM model, and the BIM-based sensory model is developed (embedded with the web address of the IoT platform). In this way, sensor data can be managed and visualized using MR devices.

4.6.2 Limitation of MR devices HoloLens to access IoT web portal

I performed several field tests for bridge health monitoring using an MR device HoloLens (HL). During these field experiments, some results weren’t successfully achieved which helped to identify the limitations of HL. When the BrIM model supplemented with virtual sensors was uploaded to HL and implemented in MR, it was encountered that the virtual sensors (with the embedded URL of the SHM platform) were not functional in the MR environment. Several attempts were made to activate the sensors in the MR environment, but no success was achieved. To address this limitation, some literature was reviewed which proposed a solution to this problem using UNITY [225]. UNITY 3D has the capabilities of MR application development which can address the limitations of MR devices.

4.6.3 Development of an MR application for the MR-based SHM system

The basic objective of this application development is to overcome the limitations of MR devices like HL by developing a novel way of linking the IoT platform of the bridge SHM system with its MR model. For this purpose, the BrIM model of the bridge is used as a source file in a 3D game engine (UNITY 3D). In order to use this model in the MR, the Mixed Reality Tool Kit (MRKT) is integrated and configured with the project. This configuration helps to develop the Universal Window Platform (UWP) which defines the build settings of the app and links it with VR/MR platforms, Android, and WebGL platforms. In this research, UPW is developed for HoloLens, so the target device is set to HoloLens with ARM 64-built Architecture, which defines the architectural configuration of the project. After developing the build settings, SHM sensors are virtually developed using Canvas meshes. Canvas helped to generate these sensors as a clickable button in order to integrate them with real sensors of the bridge.

After adding sensors to the application virtually, they are integrated with the IoT platform of the SHM system, for which a C-sharp script is developed in MS Visual Studio. This script can connect the sensor to any of the web platforms. The script is kept generic by adding multiple web addresses to each sensor. After developing the script in VS, it is attached to the UNITY so that it can be further linked to each sensor. In this way, each virtual sensor is linked with the real sensor’s data. To run this application, play mode is switched on, and clicking each sensor opens the SHM data in the web browser.

4.6.4 Deployment of MR app to HoloLens

After successful testing of the developed app in UNITY, it is then deployed to HL. Deployment of the developed app involves setting up HL settings and pairing the app with the target HL device. For this purpose, firstly, build settings are set to the “build” option in UNITY to develop a .sln (Visual Studio file) file that can open the project in VS. After opening the project in VS, the first thing is to pair the device with the HoloLens over the Wi-Fi network. It can be done by turning on the developer mode of HoloLens and retrieving a code that after adding to the VS project connects UNITY with the HL. After that, the IP address of the HL is added to the VS project for debugging. This started the deployment of the application to HL and after successful deployment, the application icon appeared in the main menu as shown in Fig. 4-21.

After the deployment of the application in the UNITY, it was opened and tested at the lab scale. All the SHM devices were found to be at the exact locations of the actual sensors. Clicking the sensor opens the IoT platform where real-time data is continuously monitored and stored. This data can be visualized over a certain period (1 hr., 6 hr., 1 day, 1 week, and 3 months) (Fig. 4-21). Data can also be stored in HL as a .CSV file which can further be transferred to any workstation. This way visualization of SHM data can be performed onsite or remotely and data can be transferred to the project team over the Internet. The schematic layout of this whole process is shown in Fig. 4-21.

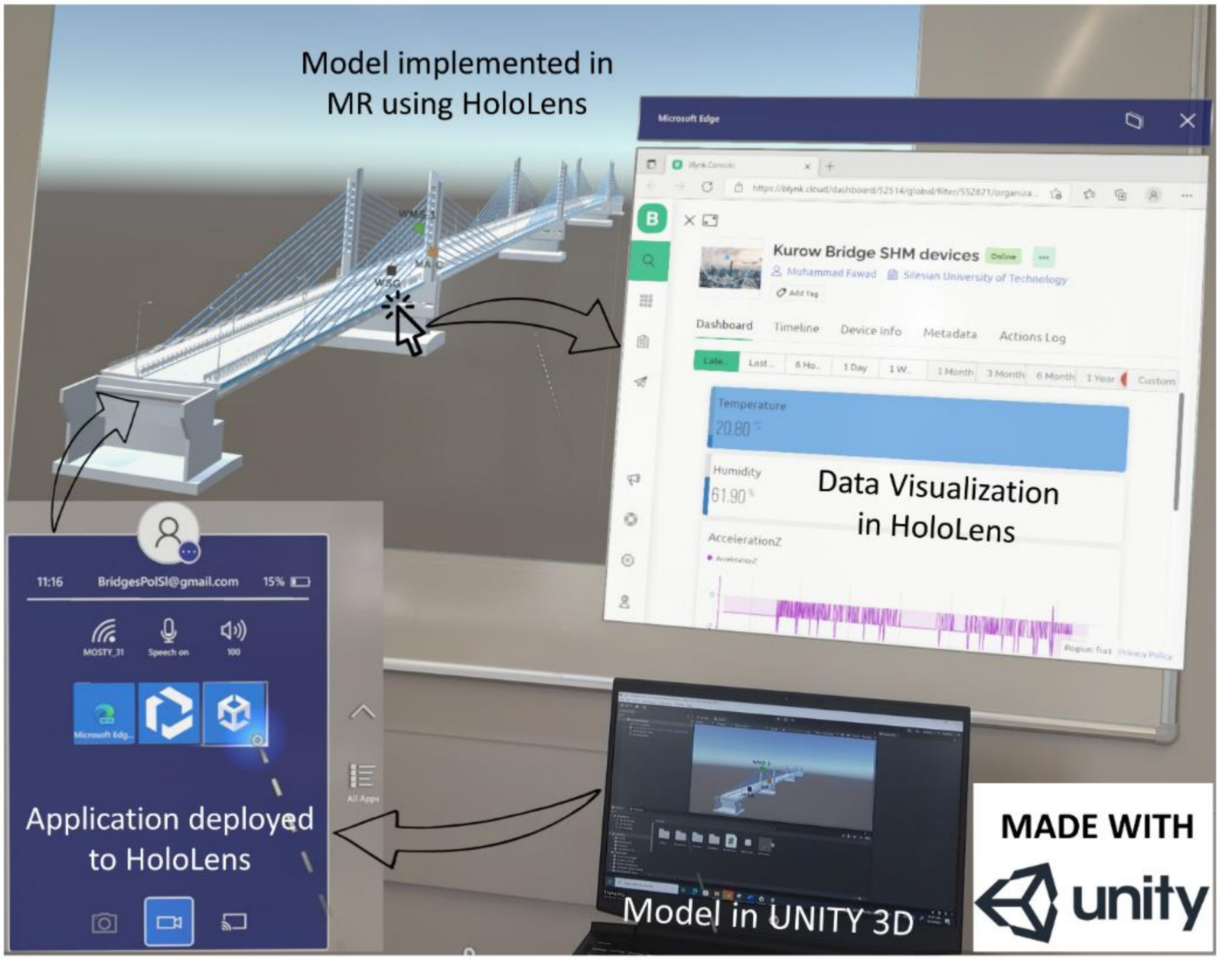


Fig. 4-21. MR-enhanced bridge SHM and visualization of SHM data in HoloLens

The success of the developed MR-based SHM system requires long-term performance monitoring and evaluation in real-world scenarios. The successful implementation of this system requires several key factors, i.e. Long-term stability, periodic calibration of system accuracy and precision, adaptability, and scalability, maintenance of sensors network and IoT platform, user feedback and industrial surveys, data integration, and regular updating of the MR- application. Once the system is installed on a bridge, the in-depth analysis of these aspects through the bridge inspection activities, data processing, and regular system modification will offer the real benefits of this promising system in bridge monitoring.

4.6.5 Cost and benefit analysis of traditional SHM system with the immersive SHM system

This research is primarily "applied" in nature and aimed at benefiting the stakeholders of the bridge industry. To further elaborate on the benefits of the proposed MR-based SHM system over the traditional system a thorough cost-benefit analysis comparing both the bridge monitoring methods is presented in Table 4-7.

Table 4-7. Cost-Benefit Analysis of MR-based SHM System and Traditional System

Cost to benefits	*MR-based SHM System*	*Traditional SHM system*
Initial cost	High initial cost for IoT sensors, software, hardware, and system integration	Comparatively low initial cost of conventional sensors and other equipment
Software development	One-time system/application development cost. No/limited wiring and electricity cost.	No direct costs for system development but wiring and electricity costs are relatively high
Specialized staff training	Skilled staff/training equipment required for training of staff on MR+IoT technologies	No requirement for modern technologies so minimal training costs
Maintenance costs	Minimal costs for system updates as automated systems update software, automated sensor calibration, and technical support	Routine maintenance costs/equipment parts incurred are high
System capabilities	Real-time monitoring, immersive visualization	Lacks immersive visualization/real-time monitoring
Monitoring options	Onsite and offsite monitoring capabilities	Only offsite monitoring options
System efficiency and accuracy	Highly efficient data collection and processing capabilities with higher accuracy	Slower data collection with relatively low accuracy
Worker's safety	Lesser/minimal physical interaction with onsite visualization capabilities makes it potentially safer	No visualization of potential damages increases safety risks and associated costs
Long-term financial benefits	An automated system with minimal manpower and early damage detection saves money	Periodic maintenance and auxiliary costs increase the long-term costs
Risk factors involved	Potential risks connected to technological reliability and system failures	Major risks are associated with safety, electricity usage, and data reliability
Total cost	System costs include high initial costs, additional devices and equipment, staff training costs, and lower maintenance/repair costs.	Lower initial costs but higher maintenance/repair costs
Total benefit	Higher safety, accuracy, and automated monitoring with enhanced safety and potential time savings	It simplified the system but was more time-consuming and compromised safety

The table explains a detailed comparison of the costs and benefits associated with the MR's implementation in bridge monitoring. This comparison provides valuable information for decision-making in the field of infrastructure management. Additionally, it is essential to consider the existing condition of the bridge, its design parameters, specific safety requirements, and monitoring goals when evaluating the system requirements and making decisions based on the presented analysis.

4.7 Chapter summary

This chapter enlightens the analytical and BrIM modeling techniques of bridges to propose the SHM system of the bridge. As a major novelty, the SHM system is further linked with the IoT technology to develop an IoT-integrated SHM system. Majorly analytical and BrIM modeling approaches are explored. The first part of the chapter discusses analytical modeling with a detailed discussion on the use of FEA for numerical analysis of bridges, specifically applied to damage assessment of the bridge. This assessment models the bridge damage state and identifies the damage-prone areas of the bridge facilitating the proposal of a SHM system. This way FEA helps to propose a SHM system of a bridge but the proposal of such a system without its validation and also without the verification of numerical analysis results may involve some risks of the errors. Therefore, field load testing is recommended to ensure the accuracy of the FE model and validate the proposed SHM system. The practical application of these techniques is demonstrated through a case study of an RC bridge. The case study employs an analytical modeling approach, utilizing static and 3D nonlinear analysis for the damage assessment of the bridge which is found to be extensive cracking. Subsequently, a sophisticated SHM system is proposed for effective monitoring of bridge damage. As the authorities were not interested in installing the SHM system, so, another case study was considered for further research.

The second case study explores an extradosed bridge in Poland, where the BrIM model is developed to generate an accurate parametric FE model using the VPL algorithm in dynamo. Thus, the dissertation successfully achieved the first new scientific result. This FE model is further used to simulate the bridge static and dynamic parameters which are further compared with the load testing results for the verification of the FE model. Further, this chapter discussed the SHM system of the bridge which is currently installed on the bridge for continuous monitoring of the bridge's health.

Further, the integration of BrIM, SHM of bridges, IoT, and MR technologies is performed. The major emphasis is on the applications of IoT technology in a comprehensive bridge monitoring and management system, showcasing how IoT tools can facilitate real-time health monitoring of bridges. For this purpose, wireless sensors are developed and linked to the IoT-based web platform (developed from scratch). To practically demonstrate the developed IoT-enhanced SHM system, a lab-scale simulation of bridge SHM was performed, where, the IoT-based sensor system is integrated with the BrIM model of the bridge, successfully implementing real-time SHM of the bridge. This way the second new scientific result is also achieved in this chapter. Due to limited access to the discussed extradosed bridge, the implementation of immersive technologies was not carried out physically at the bridge. For this purpose, another case study of a concrete arch bridge was considered, which is discussed in the next chapter.

5 Development of Immersive Bridge Digital Twin Platform

5.1 Introduction

Deeply rooted in the capabilities and adaptability of Digital Twins (DT) for bridge health monitoring and their integration with Mixed Reality (MR), this chapter discusses the modeling techniques used for a case study. As an essential component of this PhD research work, the use of 3D reconstruction techniques helps in capturing and synthesizing spatial data to develop a comprehensive Bridge Information Model (BrIM) of the bridge. This study helps not only to showcase the technical benefits of 3D reconstruction but also to highlight its potential to revolutionize the field of structural assessment and maintenance. Furthermore, the analytical model is used to analyze the existing condition of the bridge along with the identification of bridge damages, which further leads to the proposal and installation of a bridge SHM system, according to which bridge health monitoring is performed and further linked with DT and MR technologies for the development of an Immersive Bridge Digital Twin Platform (IBDTP). This platform can automate the SHM of the bridge and can engage users in immersive decision-making processes using Mixed Reality (MR) technology. The functions of the IBDTP are applied to a real-life bridge and its practical applications are explored for management and 3D visualization of SHM data.

5.2 Description of the case study bridge (Panewnicka bridge) and its modeling

For the practical implementation of this research, the case study of a concrete arch bridge (Fig. 5-1) is considered as a physical asset. The bridge is a single-span concrete arch with a two-directional traffic flow. The theoretical length of the bridge is 37.60 m, with a 0.30 m thick concrete deck slab. Two prestressed concrete girders are 9.72 m apart making the whole width of 13.68 m. Two concrete arches on each side of the bridge are connected to the deck slab through steel hangers. The choice of this bridge is critical for this research due to its distinctive design and inclusion of certain structural elements like deck, arches, and hangers. These elements make it an ideal research subject.

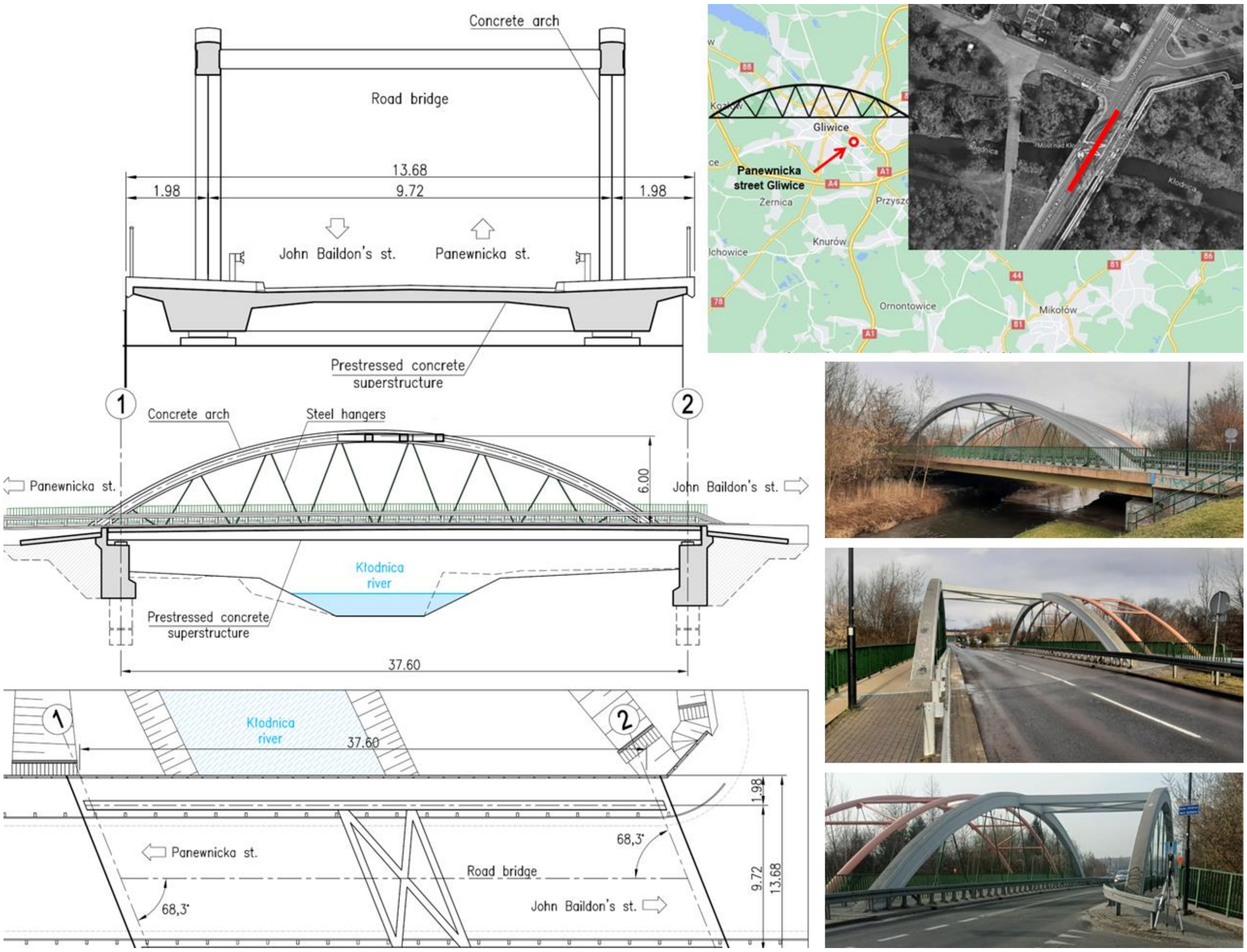


Fig. 5-1. Concrete arch bridge used as a case study

5.3 3D model (BrIM) development based on the 3D reconstruction data

To effectively update and develop a BrIM model of a bridge structure, precise measurement of the construction is necessary. The scan-to-BIM process aids in this, resulting in a digital representation of the structure, which is then used to prepare BIM models.

The Scan-to-BIM is a sophisticated procedure that uses state-of-the-art laser scanning technology that accurately captures the details of a physical asset’s structural composition [113]. This points-based dataset is subsequently transformed into a high-fidelity digital 3D model, which is then subjected to further refinement, and processing to develop a comprehensive BIM model of a bridge [114]. In this context, BIM models serve as a handy tool for enhancing the management and maintenance of bridge facilities by optimizing the maintenance processes and providing real-time monitoring of a structure's operational performance [182][183]. This not only enhances the operational efficiency of structures but also minimizes the risk of unexpected problems that contribute to the extended lifespan and sustainability of the structures by adding aids in cost-effective bridge management [184]. The Scan-to-BIM process involves three steps explained in Fig. 5-2.

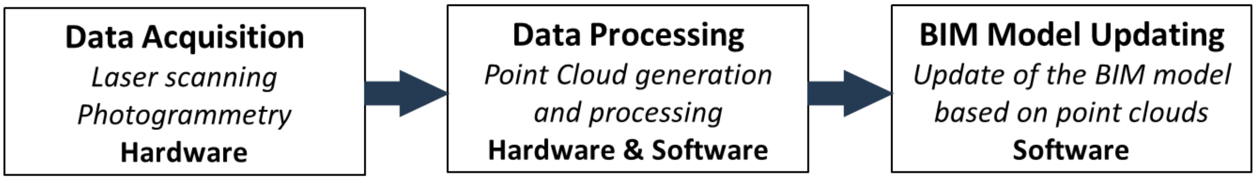


Fig. 5-2. Steps of the BIM reality model updating process

1. Step 1: Scanning

The first step in the Scan-to-BIM process involves the precise surveying of the bridge using specialized reconstruction techniques such as laser scanning and photogrammetry. The laser scan emits laser beams and accurately captures the reflected signals, enabling the accurate determination of distances and spatial coordinates of surface points. Subsequently, these collected data are transformed into a comprehensive 3D point cloud, representing the structural layout of the bridge under examination. These point clouds are then aligned to a common reference point, which is a fundamental prerequisite before proceeding to create a BrIM model [186].

2. Registration

The gathered scan data is then stored in a point cloud format, serving as a foundation for subsequent transformations into 3D and BrIM models. Common file formats for this purpose include .e57 and .rcp files supported by Autodesk, widely recognized for their efficiency in exchanging laser scan data. The precise alignment of the point cloud data is carried out by linking and harmonizing data collected from various scanning sessions or different scanning devices [187]. Registration can be accomplished manually or with partial automation through specialized software. Manual registration involves using visual cues within the data to establish connections, while automated methods employ algorithms to automatically compare and register data based on geometric or textual features. In this research manual registration was performed as the dataset was not big enough to go for the automated methods. This step significantly laid the foundation of the resulting BrIM model, ensuring the accuracy and fidelity of the final BIM model [188].

3. Step 3: Modeling

Following the exportation and precise registration of data, the process of creating digital 3D and BIM models commenced. This phase is carried out using specialized Computer-Aided Design (CAD) software, such as Revit or ArchiCAD. The major task involves exporting the point clouds into modeling software i.e., Autodesk Revit. For this purpose, specialized software i.e., Autodesk Recap can be used which can directly convert point cloud file (.e57) into a .rcp file format, compatible with Autodesk BIM modeling software. Then using the ground coordinates of the developed point clouds, different structural elements are drawn [189]. This way accuracy of the developed BIM models can be ensured closer to reality [190]. The developed BrIM model using the Scan-to-BIM approach can be known for its millimeter-accurate digital replication methodology and is an important tool for efficiently creating digital twins of existing bridges.

5.3.1 Use of laser scanning and photogrammetry methods for 3D reconstruction of a bridge

The use of laser scanning, and photogrammetry methods develops the Scan-to-BIM approach for 3D modeling (BrIM modeling) of the bridge structure. For the laser scanning, high-accuracy automated two 3D laser scanners were used to acquire data: the Z+F IMAGER 5010X and the Leica BLK360 [226][227]. In addition to the acquired point cloud, the scanners also captured 360-degree High-Dynamic Range (HDR) images. As can be seen on the left side of Fig. 5-3 the data obtained from the 3D scanners was not sufficient. It was necessary to use low-altitude photogrammetry to accurately replicate the top surface of the bridge's arch girders. For this purpose, a DJI Mavic 3 Enterprise UAV with an RTK module was used. It helped to create a coherent 3D model of the bridge [228] as shown in Fig. 5-3.

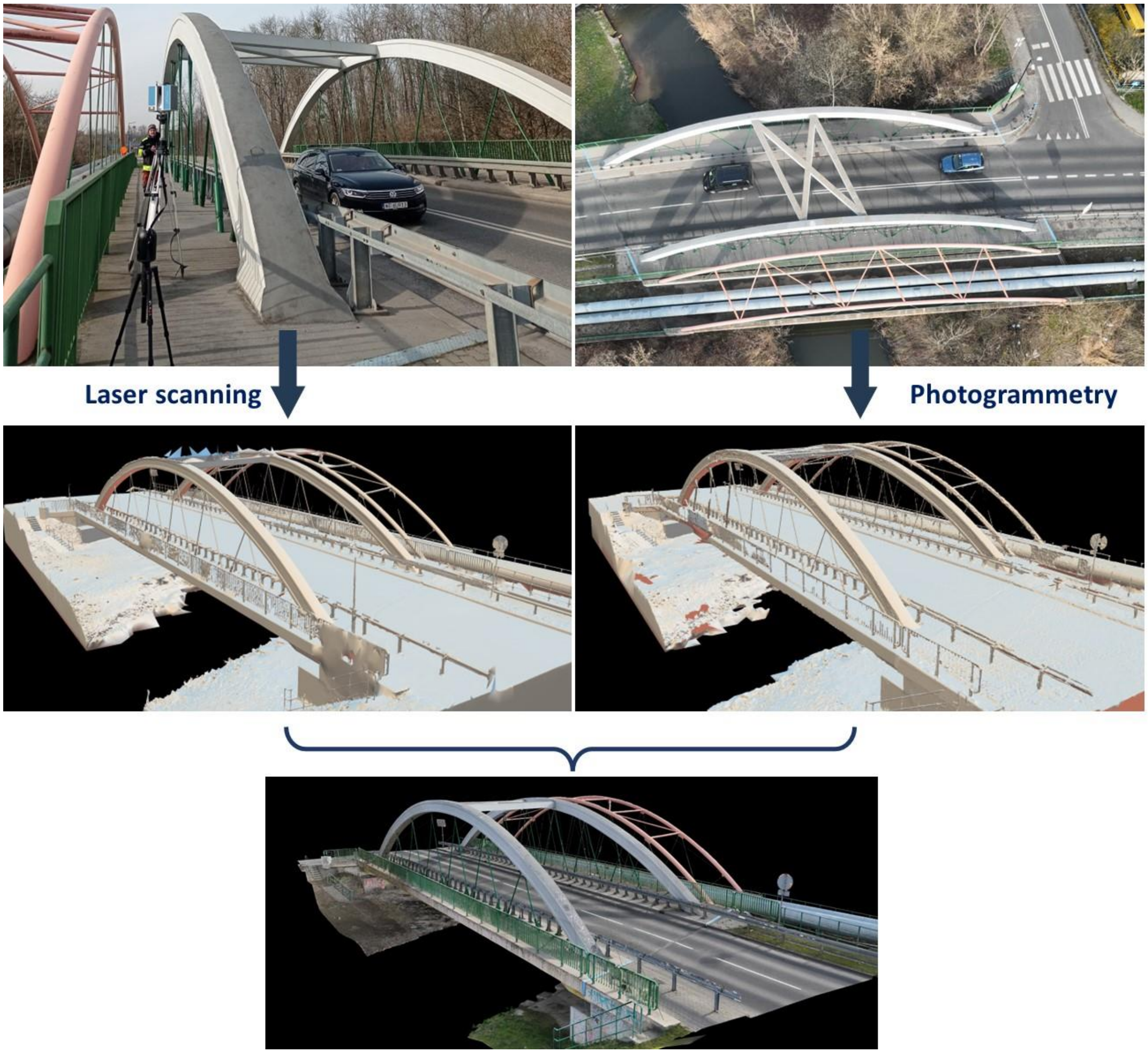


Fig. 5-3. Data acquisition and processing for generating a point cloud

3D scanning of the bridge involved several steps starting from setting up the laser scanner. In the case of the subject bridge, the Z+F scanner was set up in 24 locations, and the Leica scanner in 26 locations, to fully scan the bridge. The major precaution used in this method was to keep the sequence of 3D scans with certain overlapping areas. Therefore, a significant number of points were selected due to the objective of comparing the performance of both scanners. After each scan, the point clouds were configured with the previously scanned area, and 3D overlapping was performed on the mobile/tablet device. Further, the 22 survey points were measured with a tachymeter to position the point cloud in the national coordinate system. In order to obtain a sufficient amount of photogrammetric data, approximately 450 photos were taken using a DJI drone following a pre-determined, automated flight path. The photos were taken vertically downward and at an angle. Initially, in-situ combined point clouds from the scans were calibrated, optimized, and cleaned using computer software. The prepared point cloud was then merged with data obtained from the drone flight, which allowed for the creation of a combined model using the Reality Capture software. The parameters of the point cloud met the accuracy requirements for reconstructing the bridge.

5.3.2 BrIM model updating based on generated point clouds

Two specialized CAD software programs, Autodesk Revit and Tekla Structures, were used to update the BrIM model. There are several types of point cloud formats, each used for different applications and software, therefore, it was necessary to use two different point cloud formats: .e57 for Tekla and .rcp for Revit. The .e57 format point cloud was obtained directly from the scanner software, while the .rcp format was converted using Autodesk Recap. After importing the point clouds into the software, it was necessary to verify the current BrIM model. Many differences were observed between the actual geometry of the structure and the assumed geometry in the existing model. Based on precise 3D modeling tools, an updated model reflecting the actual geometry of the structure was created. The final BrIM model developed using the 3D reconstruction techniques is shown as the BrIM model in Fig. 5-4.

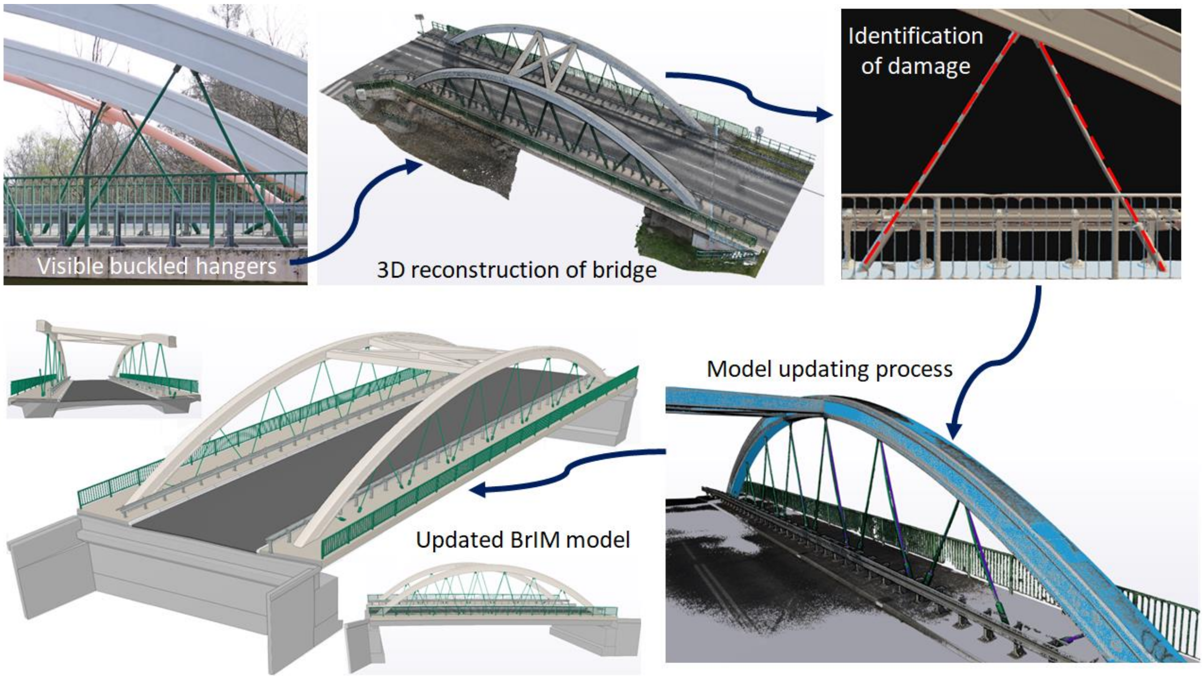


Fig. 5-4. 3D reconstruction techniques used for damage detection and BrIM model updating

Applications of the used 3D reconstruction techniques are crucial in crafting solutions for bridge assessment and monitoring. Therefore, the developed BrIM model promotes the evolutionary approach, which will be further used to integrate the bridge assessment methods with the immersive techniques. Additionally, it helps to integrate the bridge SHM system with IoT tools to smartly monitor the bridge's health. Thus, the developed 3D model will be used in the subsequent chapters to develop the BIM-based framework for automated Structural Health Monitoring and its digital twinning. This framework prepares bridge engineering to contribute to multi-industrial cooperation, thrive in the global market, and adapt to future tasks.

5.4 Finite Element Modeling of bridge

Finite Element Analysis (FEA) analysis of the bridge is carried out to calculate internal forces and displacement. These parameters helped to design the SHM system of the bridge which provides a physical system for the development of the DT model. SHM system is designed according to the maximum valued location of these numerical parameters.

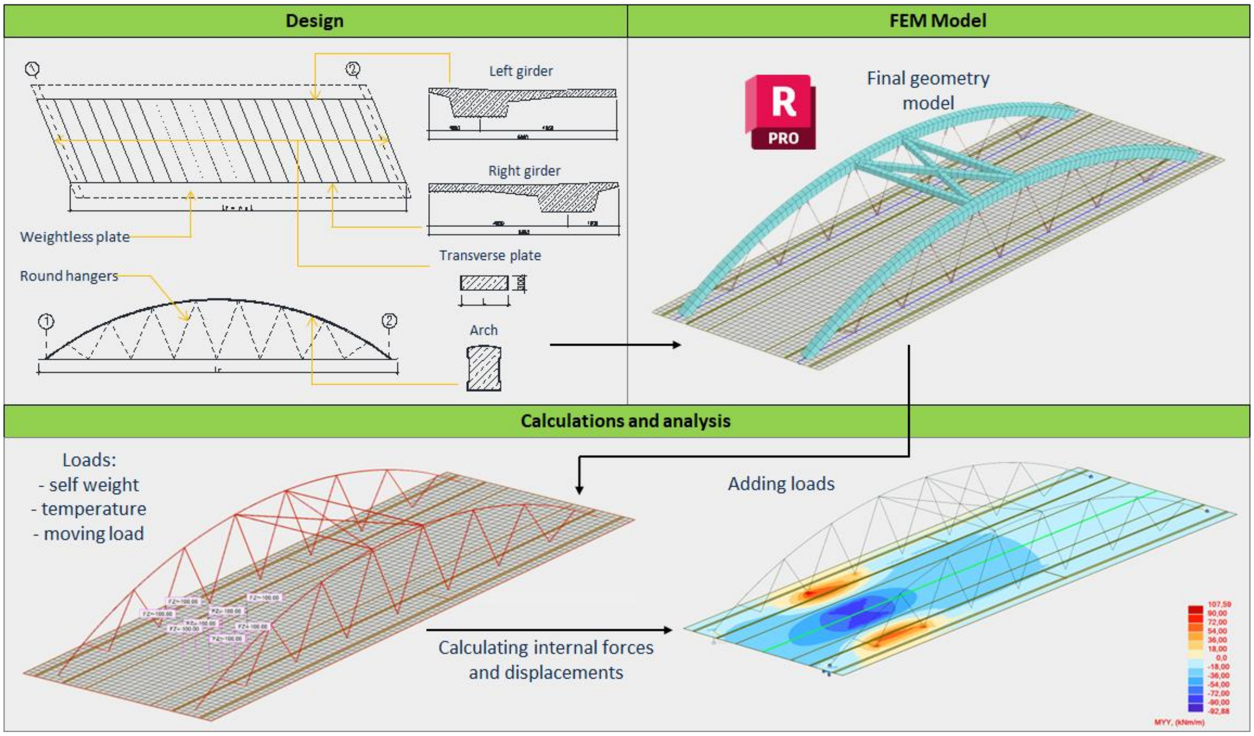


Fig. 5-5. FE model and used the geometry of the bridge

To perform the static analysis, a linear elastic model of the bridge is developed using shell and line finite elements. The geometric characteristics of the bridge deck are adopted in accordance with the geometry shown in Fig. 5-5. The modular geometry includes the bridge deck slab of C60/75 concrete, held by the edge girders on both sides of the deck slab. Similarly, diaphragms are also a part of bridge geometry that helps to resist the lateral forces and transfer loads to the support. The values of the torsional moment are calculated throughout the girder, for ease of managing the geometry of the structure. Further, the bridge structure includes concrete C60/75 arches on both sides of the bridge deck. These arches hold the bridge deck through tied steel hangers. The cross-sections of the hangers are reduced to a circular cross-section having a diameter resulting from the total cross-sectional area of the circular solid steel section. In the design, the calculation model takes the standard parameters of the concrete elasticity modulus into account, according to EC-2 [219]. The loading of the bridge is applied as per [217], including self-weight, superimposed dead load, uniform temperature load ranging from -29°C to 31°C (range for the area), and a vehicular load of 32 t (calculated for the heaviest vehicles passing over the bridge). The developed FE model of the bridge is shown in Fig. 5-5.

FE analysis results are evaluated to calculate bridge internal forces and displacements. For this purpose, the results of displacement rather than the forces are considered to fulfill the damage limit state. Analysis shows that the maximum vertical displacement at the center of the bridge deck is 28.7 mm. Bridge condition assessment is based on displacement comparisons between calculated results and the code criteria, so, by applying the maximum deflection criteria as per the EC-2 [219] (L/400 = 37600/400 = 94 mm) maximum deflection is found to be less than the limit value. Thus, the bridge is showing satisfactory performance against the bridge deflection. Similarly, the crack width was also checked against the code limits of 0.3 mm, but no significant cracks above 0.20 mm were observed in the analysis. This way the analysis satisfies the crack width limits for the bridge deck, girders, and concrete arches.

5.5 Design and installation of bridge SHM system with IoT sensors

The FE analysis results helped to identify the maximum valued locations of longitudinal, vertical, and angular deflections of the bridge. According to these results, the expansion joint at support A is found to be the best-suited place for the installation of crack monitoring devices because the expansion joint offers the maximum longitudinal moments. Further, the deflection diagram of the bridge is carefully observed to check for the rotation angles. The difference in rotation angles varies from constant negative to constant positive, with a sharp change at a distance of 0.5 m from the left bearing of support A, which can be observed as the potential location for the damage [240], so the rotation measurement devices are proposed to be installed at this location. For monitoring of the vertical displacement, the deflected shape of the bridge deck was observed, proposing that the displacement sensor should be installed at the center of the bridge deck. Additionally, temperature and humidity monitoring were also planned as the FE results show the critical deflections with a temperature gradient.

Based on the proposal of the SHM devices, heavy-duty, robust IoT sensors were used in this research. These sensors were provided by the industrial partner (TPI Ltd Poland). These sensors included:

1. FlatMesh 3G Gateway: to communicate with the wireless sensors and Sencieve web monitor,
2. 1x FlatMesh Crack Sensor Node (CM): for the measurement of longitudinal displacement,
3. 1x FlatMesh Tilt Meter Node (TM): for the measurement of rotation angle showing the bridge rotation in 3-axis,

4. 1x FlatMesh Optical Displacement Sensor Node (LD): for the measurement of vertical displacement and rotation at the center of the bridge deck.

In addition to the listed sensors, an IoT-based web platform was also part of the monitoring system which helped to monitor and manage the SHM data. This web platform provided an extensive data storage capacity, allowing for the graphical representation of acquired data and facilitating the seamless extraction of data in any file format. The complete SHM plan along with these installed sensors is shown in Fig. 5-6.

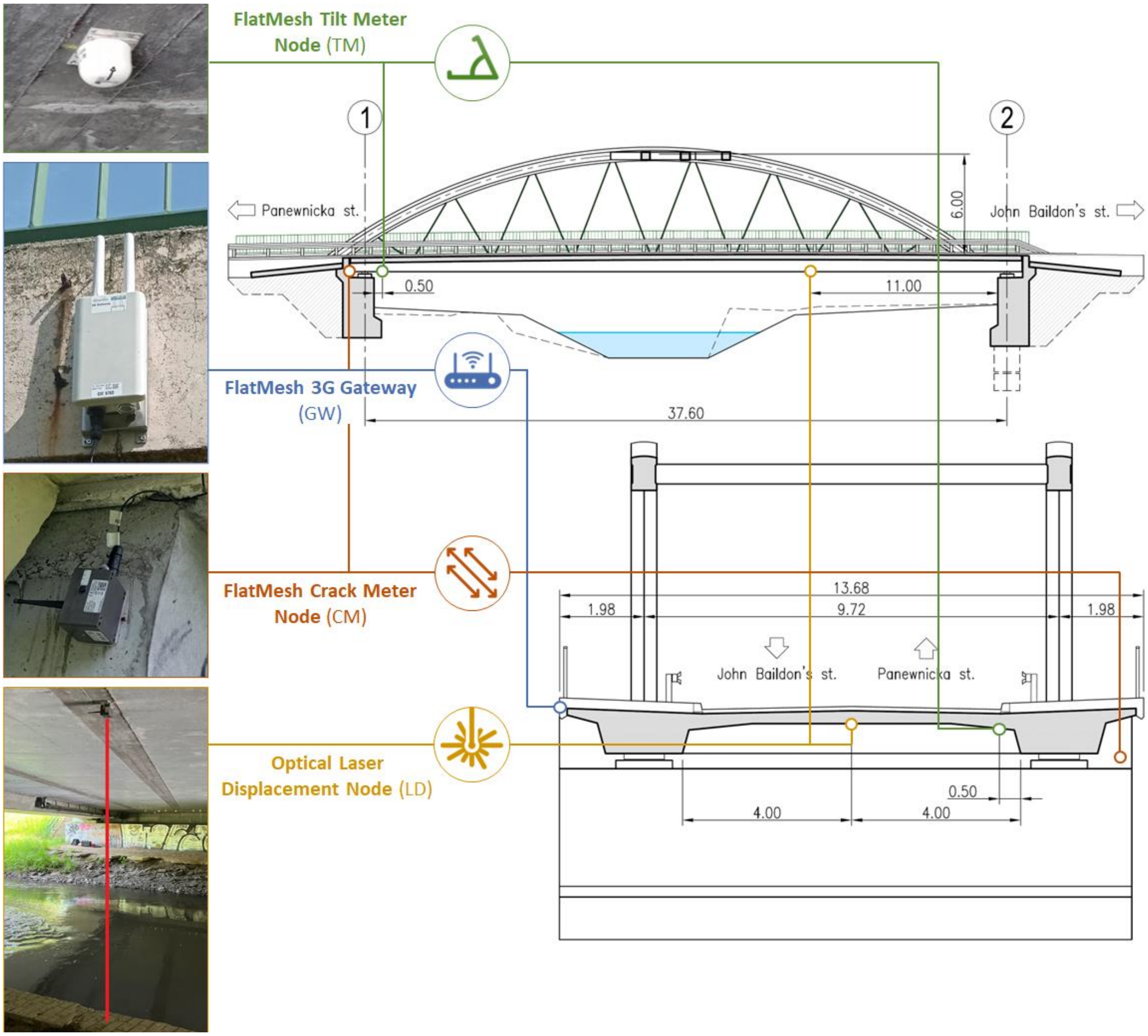


Fig. 5-6. SHM system installed on the bridge

5.6 Data collection, processing, and damage identification

5.6.1 Field data measurements

The installed sensors included the CM having built-in temperature measurement devices, so it measured the longitudinal displacement of the bridge deck along with the temperature at a frequency of 30 minutes.

Similarly, the TM measured the rotation angles of the bridge deflection in x, y, and z directions accompanied by the temperature sensing device measuring at a frequency of 30 minutes. Further, the LD sensor measured the vertical displacement of the deck accompanied by the measurement of rotation angles and the temperature. All the measurements with the LD sensor were recorded at a frequency of 5 minutes. The complete details of these sensors are listed in Table 5-1.

Table 5-1. Details of the installed sensors and their measurement parameters

Measurement Parameters	*Crack Meter (CM)*		*Tilt Meter (TM)*		*Laser Displacement (LD)*	
	Parameter	Measured Frequency [min]	Parameter	Measured Frequency [min]	Parameter	Measured Frequency [min]
Displacement [mm]	✓	30			✓	5
Temperature [°C]	✓	30	✓	30	✓	5
X-axis rotation [deg]			✓	30	✓	5
Y-axis rotation [deg]			✓	30	✓	5
Z-axis rotation [deg]			✓	30	✓	5

Initially, 20 days of data were recorded for further evaluation. Following the data retrieval from the web platform, a data fusion was performed using DataFusion in Python library which allowed the data binding through DataFrame API against the data stored in the .CSV files, and run it in a multi-threaded environment, which helped to integrate the diverse sensor data, resulting in a more consistent, accurate, and useful dataset [62][241]. Using this approach, the problem of different frequencies of the data set was resolved and a reliable and convenient dataset was developed for further processing. This consolidated dataset was subsequently used to generate a time series graph to facilitate graphical interpretation. For the listed parameters in Table 5-1, temperature and displacement measurements showed interesting trends detailed in Fig. 5-7.

All the sensors were used to monitor the temperature variations at different locations of the bridge; thus, different temperature values can be observed in Graph A of Fig. 5-7. Notably, the maximum values of the temperature are recorded by the CM (crack meter) fluctuating between 11°C to 34°C indicating a temperature gradient exceeding 20°C. Following this, the tilt meter recorded the temperature from 19°C to 24°C displaying a relatively low temperature gradient whereas the laser displacement sensor recorded the lowest gradient of the temperature. This substantial temperature variation caused the sudden expansion and contraction along the bridge which can somehow be compromised by the concrete but not by the solid steel sections of the hangers, causing the buckling hangers to be mostly exposed to the sun.

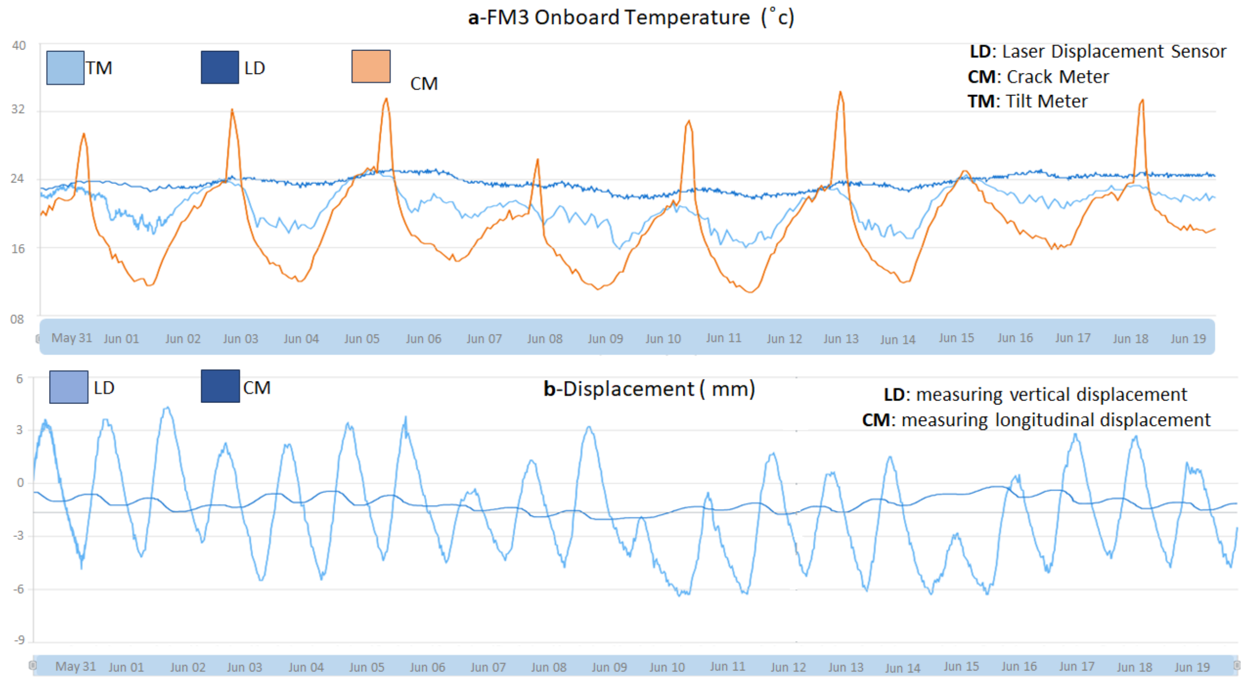


Fig. 5-7. Graphical representation of fusion data recorded by the SHM system

Besides this, the results of the displacement values were also monitored at the center of the bridge deck using the LD sensor to compare the results with the calculated values of the FE model. The comparison of both measurements is listed in Table 5-2.

Table 5-2. Comparison of measured and calculated results

	Calculated value	*Measured value*	*Difference [%]*
Vertical displacement U_z [mm]	4.73	4.3	10%

Thus, a comparison of measured and calculated displacements presented in Table 5-2 is checked against the standard condition of not exceeding the level of 10% [120]. In this way, SHM results validate the FE model and verify that there is no need for the FE model updating.

5.6.2 Simulation of the cause of hanger buckling

The buckling of the hangers is observed as one of the major problems in the case of this bridge. The buckling of some hangers was even visible with the naked eye thus it was important to simulate the buckling results according to the FE analysis.

In order to simulate the effects of buckling, an additional prestressing load case is also included in the FE model developed in section 5.4, where the point load in the longitudinal direction (points of prestressing application along the bridge deck) and vertical uniformly distributed loads (considering the eccentricity and curvature of the prestressing cables) are applied. Seven cables were used to apply the prestressing along the bridge, so the load application for all seven cables is considered. This way, the buckling of the hangers is simulated (Fig. 5-8) in all the load cases and then the comparison of different load cases is carried out to identify the maximum buckling value.

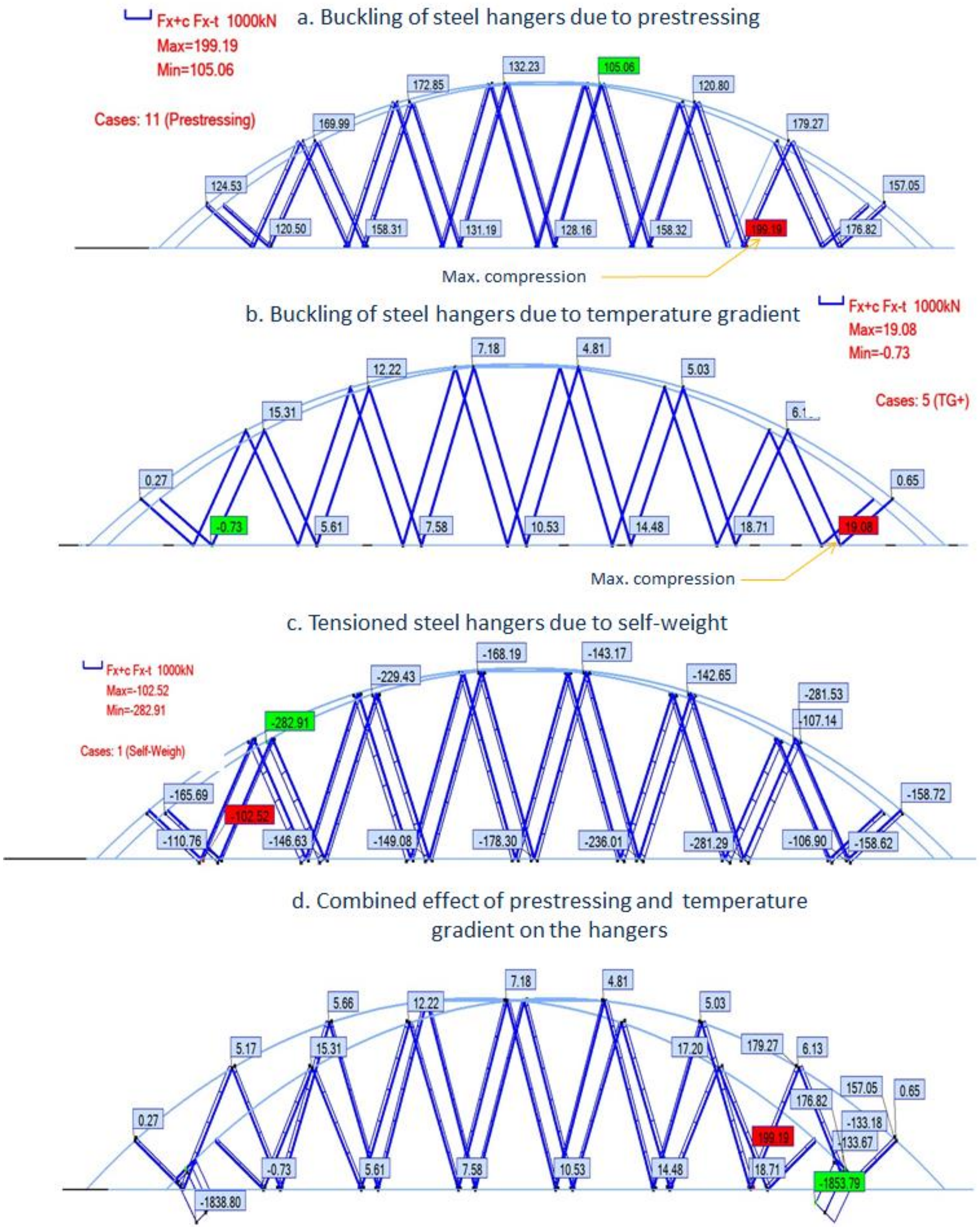


Fig. 5-8. Hangers buckling profiles due to max truckload and temperature gradient

In this simulation, the results of forces in the hangers are considered. The normally simulated results must include tensioned hangers, but it is observed in some load cases that the hangers are in compression which causes the buckling in them. The FE analysis results simulate that hangers are in compression due to prestressing with a maximum compression force of 199.19 kN (Fig. 5-8a) which is in the third hanger from the right. Physically the same was also observed as the most buckled hanger on the bridge. Similarly, the same effect is also observed in the temperature gradient loading, but the compressive forces are much lower (19.1 kN, Fig. 5-8b) in the hangers. Thus, it can be concluded that the prestressing forces are causing the major buckling of hangers which increments due to temperature variations over time. The compression forces due to prestressing and temperature gradient are shown in Fig. 5-8d, where these values are also compared against the self-weight of the bridge Fig. 5-8c.

The reason for this buckling is that the span of the bridge is very small, and the bridge deck is too stiff compared to a normal and oversized. It has been the case that at the time of construction, the modulus of elasticity of the young concrete was not yet as high as stated in the standard. The compression effect then causes the span to rise significantly upwards. At the top, the hangers are attached to a rigid reinforced concrete arch. As a result, some hangers stopped working in tension and compression occurred, which caused them to buckle. Temperature changes now only increase or decrease this effect, which is also confirmed by the FE analysis. Thus, FE analysis helped to identify the reason for the buckling of the steel hanger, for which load case pertaining to prestressing is found to be the major contributing factor.

5.7 Development of Immersive Bridge Digital Twin Platform

5.7.1 MR-based Digital Twinning of the SHM system for Immersive Bridge Digital Twin Platform

For the development of the digital twin platform of the bridge SHM system, a 3D game engine is used. For this purpose, the BrIM model of the bridge is used as a source file in the UNITY game engine. The development starts by setting up a 3D project in UNITY. Once the project is developed and opened in the Universal Window Platform (UWP), some basic settings need to be configured which define the build settings of the project. The major objective is the integration of DT with the MR devices so build settings are adjusted for MR platforms. This way, UPW is developed for HoloLens (HL), so the target device is set to HL with ARM 64-built architecture, which defines the architectural configuration of the project.

The UNITY hub provides the creation of bridge models from scratch or by adding a 3D model as an asset to the project. The model is exported from the BrIM model, ensuring visualization during gaming sessions. All assemblies are imported, providing geometric and mechanical properties for SHM device development.

SHM devices utilize "Canvas" meshes to identify structural elements of bridges, where sensors are installed. A User Interface (UI) is established, generating a canvas with clickable buttons. These buttons create virtual sensors embedded with Visual Studio codes for automation, connecting the virtual sensor to the physical sensor via the IoT platform. Thus, clicking the virtual sensor opens the database of the physical sensor on the IoT platform. This way the digital twin dashboard is equipped with SHM devices in the virtual environment.

After adding all the proposed devices to the digital twin dashboard, the Bridget Digital Twin Platform is ready for further development of the immersive solution. The dashboard of this BDTP with different features along with the real-time data visualization of the SHM devices is shown in Fig. 5-9.

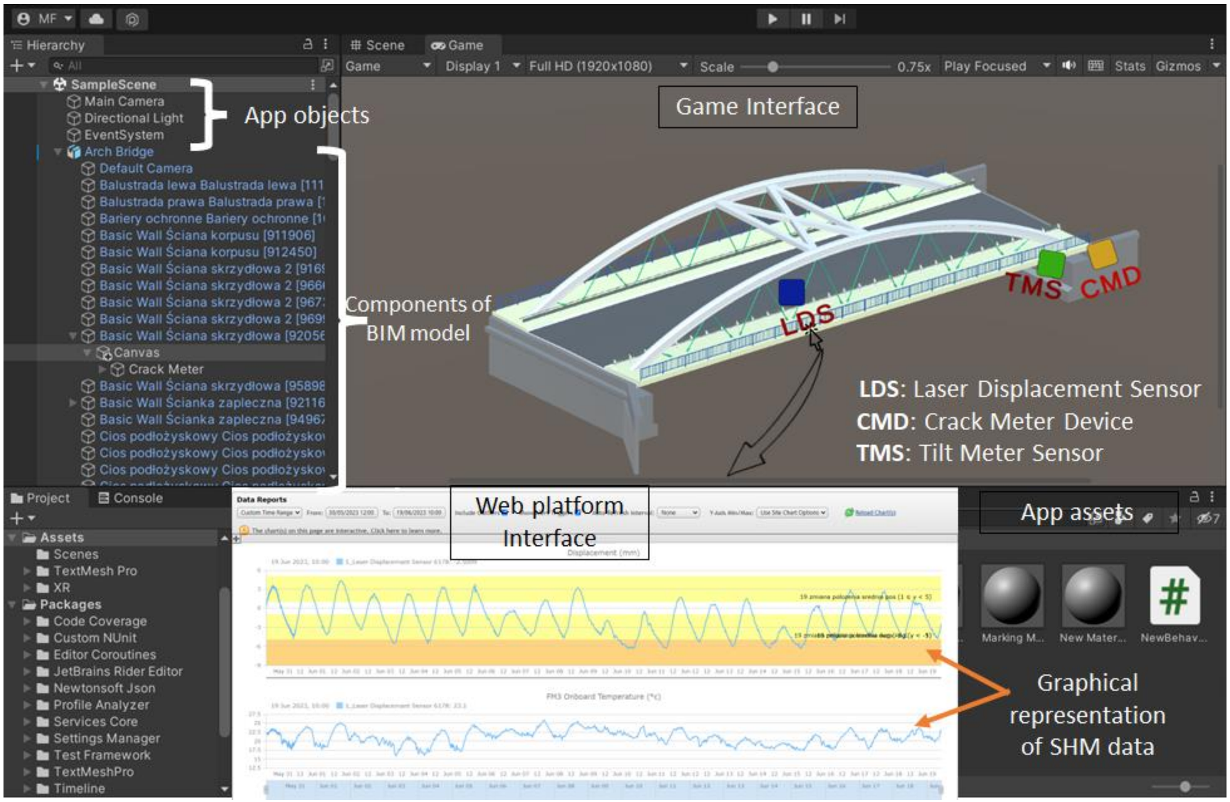


Fig. 5-9. Dashboard of DT model of bridge SHM system

5.7.2 Application development and deployment to MR headset

After successfully testing the DT model in the 3D game engine, the development of the MR application is initiated by creating a UNITY project supplemented with Mixed Reality Tool Kit (MRKT) and Universal Window Platform (UWP). These computing platforms help to customize the applications that can run on the Windows system and MR platforms. DT model is used as the base 3D model of this application and all functions of DT model are imported as assets to this application. The real-time functionality of the application is developed using the virtual buttons as a connection between the virtual and real world. To import the actual reality, an MR development plugin is used (Vuforia) [242]. This plugin enables its own camera to convert the DT model from the gaming environment to MR. So, when the user switches to the game mode, the MR application connects the virtual SHM system to the real SHM system which can be visualized in the MR in the gaming environment.

After developing the MR application, an important phase is to successfully deploy this application to the MR headset. For this purpose, the target device in UPW is selected for the HL. Then the project is built as an application that generates a Visual Studio (VS) .sln file. This file is then used to open the project and the system is paired with the HL device over the Wi-Fi. This step requires turning on the developer mode of the

HL device and retrieving a code that connects the system with the HL. After the IP address of the HL is added to the VS project for debugging, the application starts the deployment process. So, debugging of the application is started in VS which automatically starts the deployment of the application to the HL. After successful deployment, the DT model can be visualized in the app menu of HL, where it can be operated independently.

5.7.3 In-situ model and platform application tests

After the deployment of the application, it was tested on the case study bridge. All the SHM devices were found to be at the same location where the actual sensors were installed. Clicking each sensor communicates with the web platform of the SHM system and real-time data can be visualized in a graphical format as shown in Fig. 5-10. This data can be interpreted as per user requirements, which can be set in real time. Data can also be stored in HL as a .CSV file which can further be transferred to any workstation. This way a complete visualization of SHM data can be performed onsite or remotely and data can be shared with project partners over the Internet. The field demonstration includes running the app in the HL and visualizing data with just a click which popped up the sensor data in MR with the possibility of changing certain parameters as per the inspection's requirement. The outcomes of the field demonstration and the implementation of the DT model using the MR application in an MR headset can be seen in Fig. 5-10.

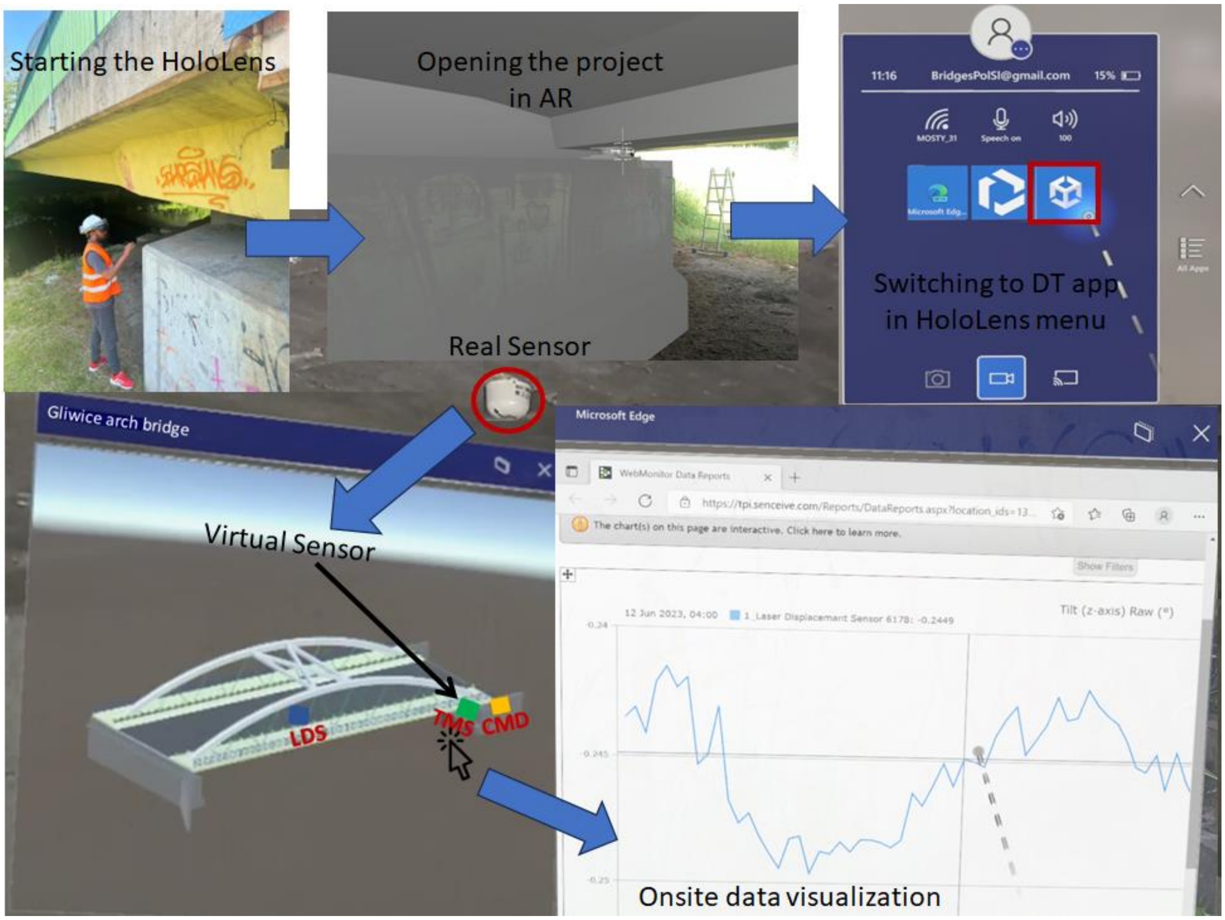


Fig. 5-10. DT model of bridge SHM system in Mixed Reality

This way the integration of both MR and DT technologies shows the potential tools to facilitate the fusion of virtual and physical, which is a growing trend in the construction industry. Since SHM of bridges needs practical implementations of cutting-edge technologies like DT and MR, so, the automated SHM system in the immersive MR environment kick-starts this boom. Further, it can be observed that MR-enhanced DT of bridge SHM systems not only helps the real-time monitoring of bridge health but can also step towards the digitization of the bridge industry and across sector digital construction. This fusion of SHM, Scan-to-BIM, DT, and MR has turned the conceptual designs into a mature BIM framework that can push BIM implementation stages to a new level and reciprocate its applications. This can bring more unified and integrated applications of MR-based Digital Twinning into bridge engineering.

5.8 Chapter summary

This chapter has discussed the case study of a concrete arch bridge and applies the 3D reconstruction techniques (laser scanning and photogrammetry) and data formats (point cloud) to develop and automatically update the BrIM 3D model. Further, the FE analysis is used to analyze the existing damage state of the bridge which identifies prone zones for monitoring bridge damages [243][37], thus bridge health monitoring system is proposed [71]. This system involved the installation of IoT sensors including crack meter, tilt meter, and optical laser displacement sensors which are used for monitoring longitudinal and vertical displacement, rotation angles of the bridge deck, and monitoring of bridge cracks. An additional gateway sensor is also installed which acts as a data communication network. After the installation of sensors, measured data is compared with the results of FEA to verify the FE model and simulate the results of bridge damage. As buckling of steel hangers is observed as the major problem, FEA is further used to simulate the reason for the buckling, which comes out to be the prestressing of the bridge deck where temperature changes increase or decrease this effect.

Further, this chapter integrates the proposed SHM system with BIM, IoT, and MR technologies to develop an Immersive Bridge Digital Twin Platform (IBDTP). For this purpose, the IoT-based web platform is linked with the BrIM reality model of the bridge to lay down the foundations for the development of IBDTP. The bridge digital twin platform, developed in the UNITY game engine, embeds virtual sensors of the bridge SHM system in the BrIM reality model, enabling real-time communication between the virtual and real systems, resulting in the automatic functionality of the bridge SHM system.

This DT is then used to develop the MR application which is further deployed to the MR headset to perform the immersive bridge health monitoring. This way the developed IBDTP helps to achieve the third new scientific result of this dissertation where both MR and DT technologies showcase the fusion of virtual and physical assets, by performing real-time automated SHM of the bridge in the immersive environment.

6 Conclusions and recommendations

6.1 Discussion of results to achieve research objectives

Recently, digital transformation and Industry 4.0 have revolutionized bridge monitoring and inspection procedures by providing smart solutions. The use of a smart SHM system is one such solution that is becoming powerful with the competencies of BIM tools, Artificial Intelligence (AI), Internet of Things (IoT), and Virtual/Mixed (VR/MR) technologies. This PhD research has carried out a detailed study on the use of such smart health monitoring procedures and provided some state-of-the-art findings in this domain. The results of these findings are discussed in this chapter regarding the research objectives defined in chapter 1.2.

6.1.1 Use of Analytical and BrIM modeling for the bridge asset management

In the past times, limitations in computer capabilities and use of virtual space operations necessitated simplified modeling techniques i.e., computational bridge modeling, particularly in the development of bridge geometry for further analysis. After that FE modeling replaced earlier methods, offering better adaptability to evolve modern computation technologies for the analysis and design of bridges. The FEM technique, representing computational elements, has played a pivotal role in the analysis of bridge health conditions and helped in the development of bridge monitoring procedures. Now, they are synchronizing with modern tools to manage bridge damage information and provide automated solutions. To achieve this goal, BIM is transforming bridge analytical modeling, integrating 3D models with FEM techniques for enhanced visualization and detailed structural information. BrIM models, while approximating reality, play a critical role in bridge health data management. The accuracy of computational and BrIM models significantly impacts the reliability of analyses and damage identification procedures.

To practically demonstrate the adaptability of analytical modeling tools in bridge damage detection, this research uses three case studies of real-life bridges. In one of the case studies discussed in section 4.3, it can be observed that the analytical modeling techniques (static linear and 3D non-linear analysis) are used not only to identify the bridge damages but also to verify the observations made by traditional bridge inspection methods (visual inspection, in-situ bridge testing). In this case study cracking is observed as the major problem, which is a commonly observed issue of concrete structures built over the waterbed. Whereas the other parameters like deflection of bridge, bending, and shear capacity in the Ultimate Limit State and stresses in the Serviceability Limit State, are satisfying the criteria according to the guidelines of EC standard. These results show the need for proper bridge health monitoring and management where BIM technology offers its application. To integrate the analytical methods with the BIM tools, this research has offered a novel solution of BIM-based automated FE modeling, which not only brings the analytical and BrIM models to one platform but also provides a framework for bridge asset management. In this regard, the case study of an extradosed bridge discussed in section 4.4.1, proposed the novel technique of generating automated FE models of the bridge using the BIM methodology. In this case study Visual

Programming Language (VPL) interface is used to retrieve data on the geometry of spans, pylons, and cables directly from the BrIM model and convert them into a set of curves and points, including additional lines for longitudinal and transverse components of the structural model. This geometric representation can be used to generate FE models using additional packages in VPL Dynamo or textural formats readable by the structural analysis software. Using a visual algorithm, a file is generated that contains the coordinates of all the nodes. This file is written in the syntax of the CADINP language used in FE software. Thus, an automated FE model was developed (the first new scientific result of this dissertation) which helped in the analysis of the bridge condition and provided a platform for managing the bridge health information extracted from the FE analysis directly in the BrIM model.

This integrated approach emphasizes the parallel development of 3D modeling and BrIM processes, highlighting the importance of integrated and automated solutions that can be used in bridge management systems. BIM methodology aligns 3D models with FEM for comprehensive structural evaluation, incorporating geometric and technical data. Using this integrated technique adheres to established procedures, often outlined in Building Execution Plans (BEP) responding to Employer Information Requirements (EIR).

6.1.2 Proposal of advanced SHM system and their validation

Another objective of this PhD research is the development of a comprehensive plan for the design of the bridge SHM system and its validation using field-testing methods. This milestone can directly be linked to the objective I discussed in the previous section, where a FEM/BIM integrated approach helps to analyze and manage bridge damage using a single platform. This platform is further used to develop and propose the bridge SHM system.

In case the bridge damages are identified, and its reduced load-bearing capacity is verified, it becomes evident that the structure's degradation level will accelerate over time, which either calls for an extensive renovation or the complete replacement of the bridge spans. In such cases, long-term plans assume the reconstruction of the entire infrastructure, however, until then, the bridge must guarantee safety which can only be ensured by installing a proper SHM system on the bridge. In other cases of long-span important bridges, which are very critical for the society and economy of a country, the use of a proper SHM system is ensured from the very first day of the bridge’s life as the safety of such bridges cannot be compromised under any circumstances.

For both cases, this research has provided the applied solution by providing a detailed framework of the bridge SHM system. For the first case, a study discussed in section 4.3.3 was included in this research, where it can be observed that the structure exhibits considerable damage, indicating a reduced load-bearing capacity of the box girder. Due to extensive cracking and reduced load-bearing capacity the reconstruction of the entire infrastructure is planned after 15 years but to ensure the safety of the bridge until then, the bridge SHM plans are presented that will extend the life cycle of the bridge with minimal repair costs while reducing the risk of failure. This system includes the installation of a Liquid Levelling Sensor (LLS) for the measurement of vertical displacement, Distributed Fiber Optic Sensors (DFOS) for deformation monitoring, and Weigh in Motion devices for monitoring moving loads on bridges. So SHM system with the practical implementation of the above devices can enhance safe bridge operations for the next 15 years, reduce inspection costs, and monitor certain defects, especially cracking.

For the second case the case study, discussed in section 4.4.7, of a newly constructed extradosed bridge is considered over which the SHM system is already installed during the construction of the bridge. In such cases, it becomes important to validate the installed SHM system, whether it is accurately monitoring the bridge's health, and whether all the devices are mounted at the exact locations where they need to be installed. For this purpose, static and dynamic load testing methods were employed to check the numerical calculations, and the percentage difference in results is compared with the calculation results according to EC standards. The static load testing results proved that the stiffness of the spans is consistent with the values of the calculation model, thus validating the need and location of the existing sensors measuring the static parameters of the SHM system. In the case of dynamic tests, it was concluded that the type of sensors measuring the dynamic parameters of the SHM system is sufficient for the needs of the existing SHM system whereas there is a lack of the number of sensors and measurement location for dynamic parameters, therefore it was proposed that the existing SHM require more of such devices for reliable monitoring of dynamic parameters. This way, this research provided a comprehensive overview of the bridge SHM system supported by the results of the analytical modeling and field load testing techniques which ensures the safer bridge operation for both the existing and newly constructed bridges.

6.1.3 Integration of SHM, BIM, and IoT technology for smart bridge health monitoring

The next objective of this PhD research is to discuss the fast-growing trends in the construction industry that call for smarter, less time-consuming, and cheaper solutions for effective and efficient bridge health monitoring. In this regard, the applications of IoT technologies have proven to be game changers, especially when they are integrated with the SHM system of the bridge. This integration has a transformative impact on monitoring and remote real-time management of the infrastructure. In this way, it plays a key role in ensuring the resilience and efficiency of urban infrastructure.

The integration of SHM and IoT technologies can be employed using BIM methodology, especially in the case of bridges. SHM system deploys sensors for real-time bridge health monitoring, with IoT facilitating seamless data transmission and management. Whereas the real-time data visualization and virtual representation of bridge conditions are enhanced by BIM technology, ensuring accurate alignment with the physical structure. The integration enables predictive maintenance, reducing costs and enhancing safety. This integrated system showcases the actual contributions of BIM methodology by bringing the application of IoT tools to SHM platforms. The system serves as a decision support tool for stakeholders, empowering informed decisions.

Considering the importance of IoT-enhanced SHM systems, this research linked the SHM systems discussed in the previous section with the IoT tools using the BIM platform. To take full advantage of the promising IoT technology, not only the developed IoT platforms are used in this research, but a proprietary IoT system has also been developed in this research. This system involved the development of wireless sensors embedded with a web platform controlling not only the wireless sensors installed as part of an SHM system but also facilitating real-time data monitoring and management. The development of this IoT system is discussed in section 4.5.1 of this thesis in detail. After the successful development of the wireless sensors and connected IoT-based web platform, the system was tested at a lab scale for the case study of the bridge SHM system discussed in section 4.6. In this study, BIM methodology offered a bridging role between the SHM system of the bridge and developed IoT-based wireless sensors (second new scientific result). The bridge SHM system utilizes IoT technology to create a virtual sensory model, enabling real-time communication with real sensors, and enhancing system monitoring efficiencies and maintenance. In this integrated system, comprehensive data integration includes SHM measuring the structural data, IoT collecting diverse data sources, and BIM integrating SHM and IoT data to provide a holistic view of infrastructure health. Predictive maintenance thus can be performed by such systems in real-time with clear visualization of damages in tabulated and graphical formats. Overall, this integration creates a comprehensive approach, enhancing the safety, reliability, and efficiency of infrastructure while optimizing maintenance efforts and resource utilization for smart infrastructural health monitoring.

6.1.4 Use of Mixed Reality and Digital Twins for the development of the Immersive Bridge Digital Twin Platform (IBDTP)

The major milestone of this PhD research is to develop an immersive automated SHM system. The automation of SHM systems is currently trending in bridge monitoring because of their remote applications but the major aspect of this automation lies in the 3D visualization and on-field assessment of SHM data. For this purpose, MR offers its service. This MR-enhanced solution increases the potential of a traditional SHM system using the applications of MR. The automation part of the immersive SHM system involves the application of Digital Twin technology, which offers the possibility of automatic data collection from the sensors, making autonomous decisions, and proactive maintenance, while aided by real-time data collection from sensors and IoT technology.

Currently, MR applications in the construction industry are only used for machine control on construction sites, concrete pouring, reinforcement detection, onsite clash detection, and worker's field safety. Considering that such an integrated and holistic application is not available in the current body of knowledge related to bridge health monitoring, this study intends to develop the Immersive Bridget Digital Twin Platform (IBDTP) to improve infrastructure management and monitoring and showcase its potential for running future infrastructure projects.

To practically demonstrate the applications of MR technology, this research carried out a field experiment (discussed in section 3.5 whereby using the MR technology and associated MR devices helped the visualization of different variants of a future bridge in MR which made the selection of the final bridge design easy.

Further, the practical use case of MR technology for bridge health monitoring systems is discussed as the development of an IBDTP in section 5.7 of this dissertation. This approach allows the infrastructure managers to automate the SHM of bridges and engage them in immersive decision-making processes using MR. The development of this MR platform can be documented as the major novelty of this research work.

For the development of the IBDTP, the geometric reality model of bridges based on parametric BIM designs was adopted. For the continuous monitoring of the bridge's health, the SHM system of the bridge was proposed, and sensors according to the proposed system were mounted on the bridge. With the system installed on the bridge, a novel 3D game engine aided by IoT technology was used as part of IBDTP and is deployed using MR hardware to enable an immersive decision-making environment for infrastructure managers and seamless communications between the virtual and real sensors. The developed IBDTP was successfully tested on the real bridge using the MR headset (third new scientific result). Results show that the measurement data collected and presented in IBDTP improves the infrastructure managers' accessibility to major damage data of the bridge to plan for future interventions.

The proposed IBDTP not only pioneers the immersive Digital Twin of the bridge SHM system but also addresses the limitations associated with traditional SHM methods, particularly concerning data management and the visualization of 3D structural data. Moreover, it provides a comprehensive framework as a base to guide future practices of digital twining of infrastructure to enable proactive decision-making of infrastructure managers. Moreover, the functions of the IBDTP can be potentially scaled for different types of bridges and critical infrastructure, substantially improving the traditional SHM in terms of data management and 3D structural visualization.

6.2 Final Conclusions

This research explores the advancements in Bridge Management Systems (BMS) for Structural Health Monitoring (SHM) of bridges, focusing on the use of Building Information Management (BIM) methodology for asset management and predictive decision-making. The study also explores the use of Virtual and Mixed Reality (VR/MR) for visualization of future bridge design concepts. The integration of these technologies with BIM, the Internet of Things (IoT), and MR technology has led to the development of an online web platform for bridge SHM systems, utilizing wireless sensors for bridge health monitoring, visualization of SHM data, and periodic maintenance. The final conclusions of this research are listed below.

- Finite Element Modeling (FEM) has played a critical role in analyzing bridge health conditions, supporting the development of bridge monitoring techniques. It has allowed for detailed structural condition assessment and damage detection, helping to identify the location of damage-prone areas where monitoring devices should be installed.
- Building Information Management (BIM) has transformed bridge analytical modeling techniques by integrating 3D models with FEM methods. This integration enhances full-scale structural damage mapping, emphasizing the critical role BIM plays in bridge health data management.

- The case studies included in this research use analytical modeling techniques, including static linear and 3D non-linear analysis, to identify bridge damages along with the verification of the observations made by traditional inspection methods.
- The FEM analysis helps in the identification of bridge damages and verification of reduced load-bearing capacity which are crucial indicators of structural degradation. It identifies the need and quantity of measurement points for bridge health monitoring thus, helps in the proposal of a bridge SHM system. This research provides a detailed framework for a bridge SHM system that extends the life cycle of bridges with minimal repair costs and reduced failure risks.
- Static and dynamic load testing methods can be employed to validate the accuracy and effectiveness of the installed SHM system.
- Thus, a thorough overview of bridge SHM systems, supported by analytical modeling and field load testing techniques can ensure safer bridge operations for both existing and newly constructed bridges.
- For the integration of BIM and FEM approaches, the research proposes a novel technique of BIM-based automated FE modeling. In a case study (4.4.4), a Visual Programming Language (VPL) interface is used to retrieve data from the BrIM model and convert it into a set of points, lines, and curves for automated FE model generation. This approach facilitates efficient bridge condition analysis and health information management.
- The BIM-FEM integrated approach emphasizes the parallel development of 3D modeling and BIM processes, highlighting the importance of automated solutions in bridge management systems.
- Once the SHM is proposed and their installation is validated, then the smarter, time-saving, and cost-effective solutions for bridge health monitoring are needed where, the application of IoT technologies, particularly when integrated with BIM and SHM technologies, has proven to be transformative. This integration facilitates real-time monitoring and remote management of bridges, ensuring infrastructure resilience and efficiency.
- BIM methodology, especially in connection with IoT, serves as a bridge for such an integration. By deploying sensors for real-time monitoring and utilizing IoT for data transmission, BIM ensures an accurate virtual representation of the physical structure, enabling real time health monitoring and data visualization.
- The research utilizes existing IoT platforms for the development of a proprietary IoT system. It involves the development and use of wireless sensors embedded with a web platform for real-time data monitoring and management, showcasing innovative approaches to bridge monitoring strategies.
- The developed integrated system, including wireless sensors and the novel IoT web platform, is tested with the lab-scale simulation of a bridge SHM system. This testing demonstrates the practical application and feasibility of the integrated approach. In this system, BIM methodology serves as a bridging platform between the physical sensors of the SHM system and the virtual replicas. This connection enables real time data visualization, offering various data analysis options for continuous monitoring, maintenance, and safety measures.

- Overall, the integration of SHM, IoT, and BIM creates a comprehensive approach that enhances the safety, reliability, and efficiency of infrastructure. It optimizes maintenance efforts and resource utilization, providing a smart solution for infrastructural health monitoring.
- The use of Mixed Reality (MR) technology in bridge design visualization facilitated the visualization of different bridge variants, simplifying the selection of the final design.
- The integration of bridge health monitoring systems with MR is relatively unexplored. Thus, an immersive SHM system is developed in this research which integrates MR and BIM methodology, aiming to enhance the capabilities of traditional SHM systems, particularly in terms of 3D visualization and on-field assessment of data.
- The automation aspect of the immersive SHM system can be enabled using the Digital Twin (DT) concept, facilitating automatic data collection from sensors, autonomous decision-making, and proactive maintenance. Real-time data collection of the sensors is ensured using the applications of IoT technology which further enhances the system's efficiency.
- The Immersive Bridge Digital Twin Platform (IBDTP) is developed using 3D game engines (UNITY 3D). This platform integrates geometric reality models based on parametric BIM designs, SHM systems, and MR technology, creating an immersive decision-making environment for infrastructure managers.
- The IBDTP enhances infrastructure management by overcoming traditional SHM limitations, improving data management and bridge monitoring visualization, and providing a comprehensive framework for digital twinning.
- The IBDTP's functions can be potentially scaled for different types of bridges and critical infrastructure, offering a promising avenue for improving traditional SHM practices.

6.3 New scientific achievements

6.3.1 Result 1: Automated development of BIM-based FE models of bridges

I developed the BIM-based FE model using a novel dynamo algorithm [41]. To achieve the automated FE model development, I tested the direct integration method, where linear structural elements, including beams, columns, pylons, or cables, were translated into analytical counterparts created automatically in the structural analysis environment, and the indirect approach, where the geometry of spans, pylons, and cables is converted directly from the BrIM model into a set of curves and points, including additional lines. A comparison of these approaches concludes that direct methods are limited due to software maturity and inconsistencies in BrIM model topology, therefore I used the indirect method with the Visual Programming Language (VPL) interface to retrieve data on the geometry of spans, pylons, and cables directly from the BrIM model and converted them into a set of curves and points, including additional lines for longitudinal and transverse components of the structural model. The .txt file containing the script of these points, lines, and curves was then imported into FE software that automatically created the FE model of the bridge.

6.3.2 Result 2: IoT-BIM enhanced smart Structural Health Monitoring of bridges

I developed a novel technique for integrating Structural Health Monitoring (SHM) and Internet of Things (IoT) technologies for bridges using BIM technology. With this technique, I connected the SHM system of a bridge with the IoT tools using the BIM platform. For this purpose, I applied some existing IoT platforms and also developed a proprietary IoT system myself from scratch. I developed the virtual sensory model of the bridge on the BrIM model and linked the IoT platform to the BrIM model. In this way, the BrIM model not only controlled the wireless sensors installed as part of an SHM system but also facilitated real-time data monitoring and management. I tested the system for the case study of an existing bridge SHM system. In this integrated system, the SHM system measures the bridge health data, IoT manages the various data sources, and BIM integrates the SHM and IoT data to provide a holistic view of infrastructure health. Predictive maintenance can thus be performed by such systems in real time with clear visualization of damages in graphical formats, improving the safety, reliability, and efficiency of infrastructure while optimizing maintenance efforts and resource utilization for smart infrastructural health monitoring [41][71].

6.3.3 Result 3: Development of Immersive Bridge Digital Twin Platform (IBDTP)

I developed the immersive Digital Twin of the SHM system for an existing bridge. For this purpose, I developed and used the geometric reality model of a bridge based on parametric BIM design. I proposed the SHM system of the bridge (using FE analysis), installed the SHM devices (IoT sensors provided by the industrial partners) according to the proposal, and performed SHM of the bridge. I used the physically installed system as a reality model and developed a virtual replica of the same system in the 3D game engine (UNITY 3D) integrated with IoT technology. I further used this virtual reality model to develop the Digital Twin (DT) model of the bridge SHM system by establishing a connection between the physically installed system and the virtual system. After successfully developing the DT model, I converted this DT model into a Mixed Reality (MR) application using the same 3D game engine to develop an Immersive Bridge Digital Twin Platform (IBDTP) and deployed it to the MR headset (HoloLens). I then physically tested the developed IBDTP on a real bridge using the MR headset. The developed IBDTP provides the ability to automatically collect data from the sensors and visualize the SHM data in the field to make autonomous decisions and support the proactive maintenance of bridges.

6.4 Practical applications of the research work

This PhD explains the demonstrative nature of an MR-based SHM system for a bridge. The scalability and generalizability of this technique was a challenging task. Different types of bridges i.e., suspension, arch, and cable-stayed bridges behave differently in different conditions. Therefore, basic consideration was given to the sensor installation, data integration process, MR-interface adaptability, adaptability in data visualization, and user interface management. The developed framework uses the VR background, which unifies the number of elements, thus, any kind of bridge with a different number of elements is considered as a single unit so the issue of geometric complexity is resolved. Further, the IoT interface houses all kinds of sensors and facilitates the data integration processes. It involves robust algorithms for data visualization, data processing, and data transfer, accommodating complex and cumbersome data management. Moreover, the developed framework was customized from scratch, so it is customizable and adaptable in nature, which can be easily modified as per the bridge design and monitoring requirements.

6.5 Major challenges and the associated recommendations for future research

The major challenge associated with this research includes the limited capabilities of MR headsets. To date, the available headsets have the limitation of the number of elements (< 10k) in the BrIM models that can be visualized in MR. In the case of bridges, sometimes the number of elements in the BrIM models is much higher than this limit. So, this issue has been addressed in the designed framework where the bridge model is imported with the VR background, this way the whole structure acts as a single unit, and individual elements are not counted in numbers, which overcomes this problem. Besides this, there still exists an issue of using HoloLens in bright sun which causes visualization issues during the daytime. To resolve this issue, it is recommended to carry out the field experimentation either during overcast weather conditions or should be done close to the sunset timings, to have better visualization of data.

Additionally, the accuracy and reliability of wireless sensors integrated with MR applications may be affected by environmental factors such as temperature, humidity, and vibration. Therefore, further research is needed to overcome these limitations.

Moreover, this research provides a comprehensive framework as a base to guide future practices of digital twining of infrastructure to enable proactive decision-making of infrastructure managers. Future work can be conducted to resolve interoperability issues among different modeling systems and additional real-world case studies can be investigated to validate the potential of the proposed IBDTP. Additionally, it can be observed that the cost of an MR-based SHM system is a point of discussion that needs extensive study with the proper implementation of such systems at different types of bridges, so, research including such findings can add value to the MR-based health monitoring of bridges.

Besides this, the research scope can also be extended to the Life Cycle Assessment (LCA) of bridges where the integration of circular economy can be incorporated, and a framework can be established that can help in the achievement of sustainable development goals in the life cycle assessment of bridges.

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Abstract (in English)

BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates

In recent times, digital transformations and Industry 4.0 have revolutionized bridge monitoring and inspection procedures by providing smart solutions. The use of smart Structural Health Monitoring (SHM) is one such solution that is becoming powerful with the competencies of Building Information Management (BIM) tools, Artificial Intelligence (AI), Internet of Things (IoT), and Virtual/Augmented/Mixed (VR/AR/MR) technologies. This PhD research has carried out a detailed study on the use of such smart health monitoring procedures and provided some state-of-the-art findings in this domain.

The research provides a state-of-the-art review of the literature available for SHM of bridges from the design phase to the development of immersive solutions for SHM. The study covers the exploration of Bridge Management Systems (BMS) in detail with the specifics of technological advancement in BMSs over the period of time. The exploration of the BMSs discusses the use of traditional bridge inspection methods for the extraction of bridge health data which are replaced by the dedicated SHM system due to advancements in the analytical and 3D modeling techniques.

In the quest to use digital technologies for BMS, the study explores the applications of BIM methodology for an in-depth analysis of its application for the management of bridge assets. It helps the understanding of basic principles of BIM tools that can be applied to the SHM domain to collect, manage, and analyze the structural health data and helps in predictive decision-making. This study emphasizes the use of BIM technology to transform bridge analytical modeling techniques by integrating 3D models with FEM methods. This integration enhances full-scale structural damage mapping, emphasizing the critical role BIM plays in bridge health data management. Further, the research proposes a novel technique of BIM-based automated FE modeling. In a case study, a Visual Programming Language (VPL) interface is used to retrieve data from the BrIM model and convert it into a set of curves and points for automated FEM model generation. This approach facilitates efficient bridge condition analysis and health information management.

The study also explores the concepts of Virtual, Augmented, and Mixed Realities (VR/AR/MR) for the visualization of bridge concepts planned to be constructed in the future. This approach pioneered the use of such technologies for the assessment of bridge design concepts. To further integrate the VR/MR tools with the SHM systems of the bridges, applications of Internet of Things (IoT) technology are explored. This exploration results in the possible solution of developing an online web platform for bridge SHM systems that can utilize wireless sensors not only for bridge health monitoring but also for periodic maintenance of bridges. Further exploration of this domain provides the possibilities of integrating MR technology with this web based SHM system using the platform of BIM methodology. This way the integration of several

advanced tools like SHM, BIM, IoT, and MR yields a novel Immersive Bridge Digital Twin Platform (IBDTP) that can facilitate the fusion of virtual and physical assets and can perform real time automated SHM of the bridge in the immersive environment.

The IBDTP improves infrastructure management by overcoming the limitations associated with traditional SHM methods, particularly in terms of data management and the visualization of bridge monitoring data. It provides a comprehensive framework for the digital twining of infrastructure, enabling proactive decision-making by infrastructure managers. The IBDTP's functions can be potentially scaled for different types of bridges and critical infrastructure, offering a promising avenue for improving traditional SHM practices. The research suggests that the developed platform can serve as a base to guide future practices of digital twinning in the field, contributing to advancements in infrastructure monitoring and decision-making.

The outcomes of this study have the potential for broader applications, particularly in automation processes and the implementation of digital twins within the construction sector. Although the primary emphasis lies in the domain of bridges, it's important to acknowledge that the principles of this research are transferable to other structural domains, including buildings and various infrastructure projects.

Abstract (in Polish)

BIM-based Framework of Bridge Health Monitoring Supported by Immersive and 3D Reconstruction Techniques for Analytical and Asset Model Updates

W ostatniej dekadzie transformacja cyfrowa i strategia kryjąca się pod hasłem Przemysł 4.0 (Industry 4.0) mocno zmieniły procesy inspekcji i monitoringu stanu technicznego obiektów mostowych (SHM, Structural Health Monitoring), wprowadzając zupełnie nowe i inteligentne rozwiązania. Zastosowanie systemów SHM staje się jeszcze bardziej efektywne dzięki możliwościom nowych narzędzi do modelowania informacji o budowli (BIM, Building Information Modeling), sztucznej inteligencji (AI, Artificial Inteligence), Internetu rzeczy (IoT, Internet of Things) oraz technologii wirtualnej, rozszerzonej i mieszanej rzeczywistości (VR/AR/MR, Virtual/Augmented/Mixed Reality). W ramach niniejszej pracy doktorskiej przeprowadzono szczegółowe badania nad wykorzystaniem tych nowoczesnych i inteligentnych narzędzi do opracowania nowych procedur oraz zintegrowanych platform monitorowania stanu technicznego obiektów mostowych.

Przeprowadzone badania dostarczyły wiedzy pozyskanej najpierw na podstawie studiów dostępnej literatury na temat monitorowania stanu konstrukcji mostów, od fazy projektowania aż do opracowania immersyjnych rozwiązań dla systemów SHM. Objęto nimi eksplorację systemów zarządzania mostami (BMS, Bridge Management System) wraz z oceną postępu technologicznego w tym zakresie. Eksploracja systemów BMS rozpoczęła się od prób usprawnienia tradycyjnych metod inspekcji mostów, które są coraz częściej uzupełniane lub nawet zastępowane przez dedykowane systemy SHM. Wynika to m.in. z szybkiego postępu w zakresie technik analitycznych, modelowania 3D i cyfryzacji procesów budowlanych.

W dążeniu do wykorzystania cyfrowych technologii w systemach zarządzania mostami, zbadano też możliwość zastosowania metodyki BIM i wykorzystywanych w niej modeli informacyjnych. Wykazano, że modele i narzędzia BIM można wykorzystać również w domenie SHM, np. do gromadzenia, zarządzania i analizowania danych opisujących strukturę obiektu mostowego, ale też do rejestracji stanu technicznego jego konstrukcji. I to z możliwością predykcji oraz wsparcia procesów decyzyjnych. W badaniu wykazano zalety metodyki BIM w procesie przekształcania technik modelowania analitycznego konstrukcji mostów poprzez integrację modeli 3D z metodami i narzędziami MES. Integracja taka usprawnia mapowanie nie tylko topologii i parametrów modeli MES, ale również zidentyfikowanych uszkodzeń elementów konstrukcyjnych. W pracy zaproponowano nowatorską technikę zautomatyzowanego modelowania MES opartego na modelu BIM. W studium przypadku wykorzystany został język programowania graficznego (VPL, Visual Programming Language), który służył do pobierania danych z modelu BrIM 3D i konwertowania ich na zestaw krzywych i punktów do automatycznego generowania modelu MES.

W rozprawie przedstawiono również badania nad wykorzystaniem kontinuum rzeczywistości wirtualnej, rozszerzonej i mieszanej (VR/AR/MR). W początkowym etapie była to wizualizacja koncepcji projektowanych mostów, a w toku dalszych prac – również integracja narzędzi VR/MR z systemami SHM

konstrukcji. Systemy te uzupełnione zostały przez układy sensoryczne zgodne z wymaganiami technologii Internetu Rzeczy (IoT, Internet of Things). W wyniku tych badań opracowano demonstracyjne rozwiązanie w postaci internetowej platformy systemu SHM obiektu mostowego, która może obsługiwać bezprzewodowe sensory. Dalsza eksploracja tej domeny dostarczyła możliwości integracji technologii mieszanej rzeczywistości (MR) z utworzonym systemem SHM poprzez użycie modelu i elementów metodyki BIM. W ten sposób osiągnięto złożoną integrację kilku zaawansowanych narzędzi i rozwiązań technologicznych, jak SHM, BIM, IoT i MR. W efekcie zaowocowało to utworzeniem nowatorskiej immersyjnej platformy cyfrowego bliźniaka nazwanej tutaj IBDTP (Immersive Bridge Digital Twin Platform). Platforma ta może ułatwić użytkownikowi pracującemu na moście w terenie, korzystanie z wirtualnych i fizycznych zasobów przez użycie immersyjnego środowiska MR. Może także zapewnić mu dostęp do danych rejestrowanych przez system SHM mostu w czasie rzeczywistym.

Docelowo platforma IBDTP będzie mogła usprawnić zarządzanie infrastrukturą mostową poprzez przezwyciężenie ograniczeń związanych z tradycyjnymi metodami SHM, a w szczególności w zakresie zarządzania i wizualizacji danych monitorowanego mostu. Opracowany demonstrator zapewnia kompleksowe ramy dla cyfrowego powiązania fizycznego obiektu mostowego z jego cyfrowym odpowiednikiem (cyfrowym bliźniakiem). Nowe funkcje platformy IBDTP mogą być potencjalnie skalowane dla różnych typów mostów i infrastruktury krytycznej, oferując poprawę skuteczności tradycyjnych metod inspekcji i pokonanie dotychczasowych ograniczeń w stosowanych obecnie systemach SHM. Rezultaty zrealizowanych badań mają też potencjał do szerszych zastosowań. Chodzi o procesy automatyzacji i wdrażania cyfrowych bliźniaków w całym sektorze budowlanym. Chociaż główny nacisk w rozprawie położono na obiekty mostowe, to należy zaznaczyć, że zdobyte w ten sposób doświadczenia i opracowane metody mogą zostać przeniesione również na inne rodzaje konstrukcji budowlanych.

Appendix A. Code for wireless Temperature and Humidity sensor

Listing A. Arduino code for wireless Temperature and Humidity sensor

```
const int refresh=3;//read every 3 seconds
boolean showSerial =true;//true or false
unsigned int unit=0;//0=C, 1=F, 2=Humidity
char *title[]={"Temperature","Temperature","Humidity"};
char *unitText[]={"&deg;C","&deg;F","%"};
#include "DHT.h"
#define DHTPIN 32
//#define DHTTYPE DHT11   // DHT 11
#define DHTTYPE DHT22   // DHT 22  (AM2302), AM2321
//#define DHTTYPE DHT21   // DHT 21 (AM2301)
DHT dht(DHTPIN, DHTTYPE);
float temperatureValue,temperatureFValue, humidityValue;//
// ****** DHT settings end (Robojax.com)
#include <WiFi.h>
#include <WiFiClient.h>
#include <WebServer.h>
#include <ESPmDNS.h>
const char *ssid = "----------";
const char *password = "-----------";
WebServer server(80);
void sendTemp() {
  String page = "<!DOCTYPE html>\n";
  page +="<html>\n";
  page +="<head>\n";
  page +="<title>Robojax DHT</title>\n";
  page +="    <meta http-equiv='refresh' content='";
  page += String(refresh);// how often temperature is read
  page +="'/>\n";
  page +="<head>\n";
  page +="<body>\n";
  page +="<h1>Temperature and Humidity Sensor</h1>\n";
  page +="<p style=\"font-size:50px;\">";
  page +=title[unit];
  page +="<br/>";
  page +="<p style=\"color:red; font-size:50px;\">";
 if (DHTTYPE ==DHT11){
  page += String((int)temperatureValue);
}else{
  page += String(temperatureValue, 1);
}
  page +=unitText[unit];
  page +="</p>\n</body>";
```

```
  page +="</html>\n";
 server.send(200,  "text/html",page);
}
void handleNotFound() {
  String message = "File Not Found\n\n";
  message += "URI: ";
  message += server.uri();
  message += "\nMethod: ";
  message += (server.method() == HTTP_GET) ? "GET" : "POST";
  message += "\nArguments: ";
  message += server.args();
  message += "\n";
  for (uint8_t i = 0; i < server.args(); i++) {
    message += " " + server.argName(i) + ": " + server.arg(i) + "\n";
  }
  server.send(404, "text/plain", message);
}
void setup(void) {
  // Robojax.com code for ESP32 DHT11 DHT22
   dht.begin();
  Serial.begin(115200);
  WiFi.mode(WIFI_STA);
  WiFi.begin(ssid, password);
  Serial.println("");
  // Wait for connection
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("");
  Serial.print("Connected to ");
  Serial.println(ssid);
  Serial.print("Open: http://");
  Serial.print(WiFi.localIP());
  Serial.println(" to read temperature");
  if (MDNS.begin("robojaxDHT")) {
    Serial.println("MDNS responder started");
    Serial.println("or open http://robojaxDHT");
  }
  server.on("/", sendTemp);
  server.on("/inline", []() {
    server.send(200, "text/plain", "this works as well");
  });
  server.onNotFound(handleNotFound);
  server.begin();
```

```
  Serial.println("HTTP server started");
  //see video https://youtu.be/JXCcmZUmzy8
}
void loop(void) {
  //Robojax.com code for ESP32 DHT11 DHT22
  server.handleClient();
  temperatureValue = dht.readTemperature();// Read temperature as Celsius (the default)
  humidityValue = dht.readHumidity();// Reading humidity
  temperatureFValue = dht.readTemperature(true);// Read temperature as Fahrenheit (isFahrenheit = true)
  if(unit ==1)
  {
   temperatureValue =temperatureFValue; //
  }else if(unit==3)
  {
    temperatureValue =humidityValue;
  }else{
    temperatureValue =temperatureValue;
  }
  if(showSerial){
      Serial.print(title[unit]);
      Serial.print(": ");
      if (DHTTYPE ==DHT11){
     Serial.println((int)temperatureValue);
      }else{
       Serial.print(temperatureValue,1);
      }
  }
  Serial.println();//just adds new line
  delay(300);// change this to larger value (1000 or more) if you don't need very often reading
  }
```

Appendix B. Code for 3-axis accelerometer (gyro)

Listing B. Arduino code for 3-axis accelerometer

```
/********************************************************************************/
#include <Wire.h>
#include "MMA7660.h"
MMA7660 accelemeter;
void setup()
{
        accelemeter.init();
        Serial.begin(9600);
}
void loop()
{
        int8_t x;
        int8_t y;
        int8_t z;
        float ax,ay,az;
        accelemeter.getXYZ(&x,&y,&z);
        Serial.print("x = ");
    Serial.println(x);
    Serial.print("y = ");
    Serial.println(y);
    Serial.print("z = ");
    Serial.println(z);
        accelemeter.getAcceleration(&ax,&ay,&az);
    Serial.println("accleration of X/Y/Z: ");
        Serial.print(ax);
        Serial.println(" g");
        Serial.print(ay);
        Serial.println(" g");
        Serial.print(az);
        Serial.println(" g");
        Serial.println("*************");
        delay(500);
}
```

Appendix C. Code for the communication between Blynk server and wireless sensors

Listing C. Arduino code for communication between Blynk server and wireless sensors

```
#define BLYNK_TEMPLATE_ID "TMPLiQfymOsk"
#define BLYNK_DEVICE_NAME "MuhammadDevice"
//
//#define BLYNK_TEMPLATE_ID "TMPLiQfymOsk"
//#define BLYNK_DEVICE_NAME "MuhammadDevice"
// Fill-in information from your Blynk Template here
//#define BLYNK_TEMPLATE_ID           "TMPLxxxxxx"
//#define BLYNK_DEVICE_NAME           "Device"
#define BLYNK_FIRMWARE_VERSION        "0.1.0"
#define BLYNK_PRINT Serial
//#define BLYNK_DEBUG
#define APP_DEBUG
// Uncomment your board, or configure a custom board in Settings.h
//#define USE_SPARKFUN_BLYNK_BOARD
//#define USE_NODE_MCU_BOARD
//#define USE_WITTY_CLOUD_BOARD
//#define USE_WEMOS_D1_MINI
#include "BlynkEdgent.h"
#include "DHT.h"
#include <Wire.h>
#include "MMA7660.h"
MMA7660 accelemeter;
#define DHTPIN D7     // Digital pin connected to the DHT sensor
// Uncomment whatever type you're using!
//#define DHTTYPE DHT11   // DHT 11
#define DHTTYPE DHT22   // DHT 22  (AM2302), AM2321
//#define DHTTYPE DHT21   // DHT 21 (AM2301)
DHT dht(DHTPIN, DHTTYPE);
////////////////////////////////////////////////////////
//ddd();
void setup()
{
  Serial.begin(115200);
  delay(100);
  BlynkEdgent.begin();
//  BlynkEdgent.begin();
  accelemeter.init();
  Serial.println(F("DHTxx test!"));
  dht.begin();
}
```

```
void loop() {
  BlynkEdgent.run();
  ddd();
  Grov();
}
//////////////
void ddd(){
    // Reading temperature or humidity takes about 250 milliseconds!
  // Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
  float h = dht.readHumidity();
  // Read temperature as Celsius (the default)
  float t = dht.readTemperature();
  // Read temperature as Fahrenheit (isFahrenheit = true)
  float f = dht.readTemperature(true);
  // Check if any reads failed and exit early (to try again).
  if (isnan(h) || isnan(t) || isnan(f)) {
    Serial.println(F("Failed to read from DHT sensor!"));
    return;
  }
  // Compute heat index in Fahrenheit (the default)
  float hif = dht.computeHeatIndex(f, h);
  // Compute heat index in Celsius (isFahreheit = false)
  float hic = dht.computeHeatIndex(t, h, false);
  Serial.print(F("Humidity: "));
  Serial.print(h);
  Serial.print(F("%  Temperature: "));
  Serial.print(t);
  Serial.print(F("°C "));
  Serial.print(f);
  Serial.print(F("°F  Heat index: "));
  Serial.print(hic);
  Serial.print(F("°C "));
  Serial.print(hif);
  Serial.println(F("°F"));
    // You can send any value at any time.
  // Please don't send more that 10 values per second.
  Blynk.virtualWrite(V1, h);
  Blynk.virtualWrite(V0, t);
}
void Grov()
{
  int8_t x;
  int8_t y;
  int8_t z;
  float ax,ay,az;
```

```
  accelemeter.getXYZ(&x,&y,&z);
   Serial.print("x = ");
    Serial.println(x);
    Serial.print("y = ");
    Serial.println(y);
    Serial.print("z = ");
    Serial.println(z);
    accelemeter.getAcceleration(&ax,&ay,&az);
    Serial.println("accleration of X/Y/Z: ");
  Serial.print(ax);
  Serial.println(" g");
  Serial.print(ay);
  Serial.println(" g");
  Serial.print(az);
  Serial.println(" g");
  Serial.println("*************");
  Blynk.virtualWrite(V2, ax);
  Blynk.virtualWrite(V3, ay);
  Blynk.virtualWrite(V4, az);
  delay(50);
}
```