# Development of a BIM-Enabled Digital Twin for IoT-Based Structural Health Monitoring and Analysis

**FINAL YEAR PROJECT UG 2020**

**By**


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Final Year Project Titled

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has been accepted towards the requirements for the undergraduate degree

in

**CIVIL ENGINEERING**

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***This thesis is dedicated to our parents.***

*For their love, support and prayers throughout our lives*

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## ABSTRACT

This report presents a unique approach to structural health monitoring and monitoring of environmental parameters in real-time. The study aims to develop an alternative to visual inspection of structures located in remote areas by creating a real-time digital twin of the bridge model that collects sensor data and transfers it to the BIM Model to monitor damage. Temperature and humidity sensors monitor the changes in the environment whereas, data from ultrasonic sensors is used for crack detection and monitoring of deformation in structure. The study first explores the data acquisition process where DHT11, Ds18b20, and HC-SR04 sensors are attached to the bridge beam at L/3 distance. The sensors are connected to Esp 32 with its battery provided by a power bank. The collected data is transferred to Google Sheets through Wi-Fi and used to update the Excel sheet. Dynamo receives data from Excel and displays it on the BIM Model in Revit. Thresholds for environmental monitoring are set according to the temperature and humidity values that affect concrete. Revit Model displays these values in the form of color coding that indicates whether the actual values have exceeded or are below the parameters set for optimum concrete strength. The values from ultrasonic sensors are used for crack detection and determining the height of the beam above the structure to monitor the deformation of the bridge beam. The thresholds for damage detection are set according to the simulations run on Ansys. The BIM Model indicates the exact location of the crack and whether the structure has crossed the critical limit for deformation. Validation of the research study was conducted on the bridge model constructed in SCEE. An FEM model of the structure was also created on Ansys to determine the critical failure of the beam when different values of load are applied. A webpage was also made that displays the sensor values as well as the BIM Model in an easy-to-use dashboard system.

**Keywords:** Structural Health Monitoring, Digital Twin, Ultrasonic Sensors, Temperature sensors, Humidity Sensors, Real-time Monitoring, IoT in Structural Engineering, Building Information Modelling (BIM), Finite Element Model, Environmental Monitoring, Crack and Failure Detection, Deformation of Structure, Cost-effective Analysis of Bridge Structure, Revit Model.

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# CHAPTER 1

# INTRODUCTION

## Background

Civil structures and historical buildings are prone to damage due to environmental effects and after natural disasters such as earthquakes and floods. In fact, Pakistan is in one of the most earthquake prone regions of the world with a PGA of 0.4g or more. However, many buildings located in remote areas are difficult to monitor due to high transportation costs and difficult access. Often, damage is detected when structures reach the end of their life span.

Adobe buildings are the most vulnerable of all the building types in Pakistan and these are built in rural areas, where there is very little knowledge in local communities about hazards and their consequences [1]. Hence, there is a need to develop a low cost and effective approach to monitor these structures located in remote areas and historical buildings for early damage detection, without site visit, to generate early warning signs and facilitate early maintenance. Currently, damage detection is carried out by remote sensing and GIS software, however, the system does not give accurate data for remote locations. Moreover, 63.62% of Pakistan’s population lives in rural areas where houses are prone to collapse from seismic damage.

Digital twin technology and structural health monitoring allow monitoring of environmental data and early damage detection of buildings in real time without the requirement of a site visit. A digital twin is a virtual model replicating the characteristics and behavior of a real-world physical object serving as a real-time digital counterpart. Digital Twin is increasingly being explored as a means of improving the performance of physical entities through leveraging computational techniques, themselves enabled through the virtual counterpart [2].They are built by incorporating all the required information in a digital space hence, they make costly and risk-associated processes simpler and achievable. A digital twin replicates each component in addition to their interaction with each other and the external environment, making digital transformations possible. This is made possible by sensors integrated into the real world that send real-time information regarding development, production, and operation to the digital twin model. Digital twin technology is becoming increasingly popular in the manufacturing, transportation, and healthcare industries to monitor operations, simulate environments, and optimize performance. In the construction industry, digital twin models facilitate site management to determine how structures behave under different wind loads or earthquakes. Despite the emerging new data capturing technologies and advanced modeling systems, the process of digital twin modeling for existing buildings still lacks a systematic framework [3].

To implement digital twin technology effectively for monitoring bridges and other vulnerable buildings in Pakistan a network of sensors on buildings can be deployed to collect data on structural health parameters such as vibrations, cracks, temperature, humidity, and seismic activity. These sensors form the backbone of the SHM system, providing continuous and real-time data [4]. An effective communication network also needs to be ensured for reliable data transmission from sensors to a central database through IoT (Internet of Things) technologies. In remote areas, where traditional communication networks may be unreliable or non-existent, alternative solutions such as satellite communication or long-range radio waves can be used [5]. Cloud computing can then be utilized to store, process, and analyze the large volumes of data received from the sensors. Cloud platforms offer scalability and flexibility, allowing for the handling of big data and complex analytical tasks. Advanced algorithms and machine learning models can be applied to detect patterns, predict potential issues, and provide actionable insights [6]. To monitor the collected data in real-time, a detailed 3D model of the bridges and buildings can be developed, incorporating real-time data to reflect the current state of the structure. This model serves as a digital replica, capturing every detail and dynamic behavior of the physical asset. By simulating the building's response to various environmental factors and load conditions, the digital twin can help in understanding its performance under different scenarios [7]. Interpretation of this data can be done by dashboards and graphical representations can make complex data easily understandable, facilitating informed decision-making by stakeholders [8].

Adopting digital twin technology for structural health monitoring in Pakistan's remote and earthquake-prone areas can significantly improve the safety and longevity of vulnerable buildings. Although it is important to ensure accurate and reliable data from sensors, especially in harsh environmental conditions. Regular maintenance and calibration of sensors are necessary to maintain data quality for accurate monitoring. However, this technology facilitates real-time data and advanced analytics that allows early damage detection, timely maintenance, and hence, efficient resource utilization. The integration of digital twins and SHM systems presents an innovative and cost-effective solution to the challenges faced by Pakistan's rural and historical bridges and buildings, ensuring their preservation, effective maintenance and the safety of their occupants for generations to come.

## 1.2 Research Significance

The integration of BIM with real-time data from the Internet of Things (IoT) devices is already a powerful paradigm for numerous applications to improve construction and operational efficiencies. Currently, there is no benchmark set for the assessment of historical structures [4]. To do that, these organizations have to perform one or another form of SHM and are driven by the prospective life-safety and economic benefits of this technology. SHM has the potential to reduce the unpredictability attached with construction process and notably lessen the economic and human losses incurred during a seismic activity. The data based on qualitative and quantitative is important before taking any treatment decision for safety evaluation [5]. In addition to that, many components of the technical infrastructure are nearing the end of their actual design life. Due to financial constraints, the use of these structures is exceeding their design life and, in this scenario, the ability to constantly monitor these structures is becoming extremely crucial.

It is necessary to examine each structure component in its state and consider it as a whole in the assessment process while evaluating structural deterioration and damage[6]. With SHM, it will become possible for the current maintenance practices to evolve into cost-effective condition-based maintenance philosophies. This will entail a sensing system that notifies the operator that damage has been detected in a structure. However, life-safety and economic advantage will only be gained if the proposed SHM provides sufficient warning in a timely fashion so that corrective measures can be taken before damage turns into failure. This requires complicated monitoring hardware to be attached to the system and an equally compatible data analysis process to interrogate the structure. It is also important that the monitoring system being used is at least as accurate as the structure or the target system.

Apart from this, SHM has the potential of increasing the time intervals between scheduled maintenance and enable the equipment to stay in the field for a longer period and generate revenue in the time it would otherwise take for it to be taken back to the manufacturer for inspection.

The topic of SHM is of interest to a wide range of industries and government agencies. Several technical disciplines, however, need to be integrated to properly address SHM problem. Finally, the initiation of specialized courses on SHM technologies and methodologies is attestation to the keenness expressed by the industry.

## 1.3 Problem Statement

Pakistan is prone to severe floods such as the 2022 flood that submerged one third of country affecting 33 million people rendering many homeless. Natural disasters like these weaken the structure of many buildings. Current damage detection includes visual inspection that is both time consuming and inefficient in terms of cost for remote areas. Moreover, many historical buildings such as those located in Karachi need real time monitoring to detect damage so that buildings can be promptly evacuated.

The aim of this research is to develop a low-cost real-time monitoring system to monitor the environment and damage of buildings prior to collapse to notify occupants and take timely action. The data can be used for post disaster analysis and monitoring the environment for structures located in remote areas.

## 1.4 Objectives

There are three main objectives of this study. These are:

- To Visualize environment data on BIM model in real-time.
- Visualize sensor data on BIM model in real-time and determine if threshold values are exceeded.
- Detect cracks in Structure.

## 1.5 Scope of Work

The research focuses on developing a cost-effective model designed to provide early notifications of damage and real-time data on the environmental conditions surrounding bridge structures. This innovative model leverages advanced sensor technology to continuously monitor various parameters critical to the structural health and safety of bridges. The sensors, which are both embedded within the concrete and strategically installed on the bridge surface, play a pivotal role in capturing comprehensive data. By embedding sensors within the concrete, the system can detect internal stresses, cracks, and temperature changes that are not visible on the surface. These internal sensors monitor the micro-level changes in the bridge's material, providing early warnings about potential structural weaknesses before they manifest as visible damage. Surface-installed sensors, on the other hand, measure external factors such as vibrations, load distribution, and environmental conditions like humidity and temperature fluctuations. Together, these sensors create a detailed and holistic view of the bridge's health. The real-time data collected by these sensors is then transmitted to a centralized processing unit. Here, sophisticated algorithms analyze the data to identify patterns and anomalies that could indicate early signs of damage or deterioration. This immediate analysis allows for prompt notifications to be sent to bridge authorities, enabling them to take swift preventive actions to mitigate any detected risks. One of the standout features of this research is the integration of the sensor data with Building Information Modeling (BIM) technology. BIM is a digital representation of the physical and functional characteristics of a structure. By visualizing the real-time sensor data on the BIM model, engineers and maintenance teams can see a dynamic, up-to-date representation of the bridge's condition. This visualization helps in understanding the exact location and nature of any potential issues, making maintenance more efficient and targeted. Furthermore, the cost-effectiveness of the model is a key consideration. By using readily available and affordable sensor technology, the research aims to develop a solution that can be widely implemented without requiring extensive financial investment. This makes it feasible for use in a variety of bridges, including those in regions with limited resources or older structures that might not otherwise benefit from advanced monitoring systems.

## 1.6 Overview of Chapters

**Chapter 2 – Literature Review** offers a comprehensive overview of existing knowledge in this field, as well as the threshold values that cause damage.

**Chapter 3 – Methodology** introduces our unique approach that combines real time data from temperature, humidity and ultrasonic sensors. It includes the code designed to take input, dashboard used to display values and the BIM Model to visualize data.

**Chapter 4 – Results and Validation** presents the results of the BIM Model, including results to validate the case study. It also includes the cost analysis and interface developed.

**Chapter 5 – Conclusion** contains the conclusion of the study.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 IoT Sensors and BIM Integration

Structural health monitoring plays a critical role in ensuring the safety and longevity of infrastructure. This research paper aims to explore the integration of digital twin technology and IoT sensors for structure health monitoring, with a focus on crack detection [7]. The paper discusses the concept of a true digital twin, which combines a virtual representation of the structure with real-time data from IoT sensors [8]. This integration allows for the continuous monitoring of the structure, capturing real-time data on factors such as strain, temperature, and vibrations. This data is then used for predictive analysis, enabling the detection of cracks and other structural issues at an early stage. The proposed research paper highlights the potential of digital twin technology and IoT sensors in revolutionizing structure health monitoring.

## 2.2 Thresholds for Damage Detection

Building Information Modeling (BIM)-based SHM systems often use offline data processing techniques to analyze and visualize structural health data [9]. Thus thresholds are set to measure parameters that indicate possible damage or the need for maintenance actions. They are determined by the different factors such as the material properties, design specs, environmental conditions, and the data of the historical performances.

Temperature Thresholds: The materials used in construction have their own thermal properties and they react to the changes of temperature in a predictable fashion. Exposure of concrete to elevated temperature affects its mechanical and physical properties [10]. In the operation and maintenance phase in building life cycle, the building status data such as temperature, humidity, air quality, energy consumption, etc. must be corrected to manage building effectively because they can be data to diagnose building status and the result can help decision making to manager [12]. Research and simulations can enable us to discover the range in which a structure can operate without being affected by thermal stress that would cause cracking or any other kind of damage to the structure. These safe operating ranges are the first step in the process, and afterwards the monitoring system is used to set up the temperature thresholds. However, apart from data from sensor, settlement thresholds can be set to monitor the downward movement of a building upon the ground it is constructed. It is common for some settlement to be happening, but if the settlement is too much, it means that the structure might fail. Simulations, such as the finite element analysis (FEA) in ANSYS or other engineering software, engineers can foresee how much settlement is permitted before it affects the structural integrity of the building. These predictions are the outcome of the soil properties, the building load, and other related factors, and they assist in determining the settlement thresholds.

BIM provides detailed geometric and semantic information and IoT contains the management and analysis of the actual condition. Hence, after given thresholds are set, the IoT-based monitoring system can continuously collect data from sensors which are either embedded in or attached to the structure. The information on the thresholds that have been surpassed will automatically send the facility managers or engineers a message that there is a potential problem, thereby, they will be able to do the inspections and interventions promptly.

## 2.3 Current Practices in Pakistan

Building Information Modeling (BIM)-based digital twin technology for IoT-based structural health monitoring and analysis is an emerging field worldwide, including in Pakistan. The integration of BIM with digital twins and IoT for structural health monitoring is gaining popularity due to its potential to significantly enhance the life cycle management of infrastructure. This innovative approach enables continuous monitoring, real-time data processing, and predictive maintenance, which are crucial for ensuring the safety, durability, and efficiency of structures.

In Pakistan, the building industry is gradually embracing new technologies, but the rate of adoption is generally slower compared to developed countries. Economic constraints, a shortage of skilled professionals, and limited awareness of the latest technological advancements are significant barriers. Despite these challenges, BIM is being used in Pakistan primarily for its benefits in construction projects. Its adoption, however, remains limited to large-scale or well-known projects, where the government and private sector stakeholders are beginning to recognize its potential to improve efficiency and reduce costs [1].

The concept of digital twins is still under development in Pakistan. Digital twins are sophisticated digital models that mirror real-world entities or systems and their behaviors. These models are used for creating, evaluating, and managing systems. Although the application of digital twins is not yet widespread in Pakistan, interest is growing, particularly in manufacturing and smart city projects. Digital twins can revolutionize how infrastructure is managed by providing a virtual environment for testing and optimizing structural performance without the risks associated with physical testing [2].

IoT technology is being utilized across various sectors in Pakistan, including agriculture, manufacturing, and urban development. In the context of structural health monitoring, IoT devices such as sensors play a crucial role in monitoring the condition of buildings and infrastructure. These sensors collect data on parameters like vibrations, strain, temperature, and displacement, which are essential for assessing structural health. However, the integration of these systems into a comprehensive monitoring and analysis platform is still in the developmental stage [3].

The research landscape in Pakistan is rapidly evolving, with universities and research institutions increasingly focusing on BIM, digital twins, and IoT. Faculty and students are engaging in pilot projects and studies to explore the practical applications and benefits of these technologies for structural health monitoring. These research initiatives are crucial for advancing the understanding of how digital technologies can be leveraged to enhance infrastructure resilience and management in Pakistan [4].

The regulatory framework for the adoption of advanced construction technologies like BIM and IoT is undergoing revision in Pakistan. The government is in the process of formulating policies that promote the use of these technologies to improve the quality, efficiency, and sustainability of construction projects. Such policies are expected to provide a supportive environment for the adoption of BIM-enabled digital twins and IoT, encouraging more widespread use across the construction industry [5].

Digital twins can integrate data from various IoT sensors embedded in bridge structures. These sensors can monitor a range of parameters including strain, temperature, vibration, and displacement. The digital twin model processes this data in real-time, providing engineers with a comprehensive understanding of the bridge's condition. This capability is particularly valuable in earthquake-prone regions of Pakistan, where real-time monitoring can provide critical information for emergency response and disaster management.

The adoption of BIM-enabled digital twins and IoT in Pakistan faces several challenges. The high cost of technology, the need for professional training, and resistance to change within the industry are significant obstacles. Additionally, issues related to privacy, security, and the compatibility of various systems and technologies must be addressed. Overcoming these challenges requires coordinated efforts from stakeholders, including the government, industry, and academia [6].

One of the critical advantages of integrating BIM with digital twins and IoT for structural health monitoring is the ability to process data in real-time. This capability is essential for making timely decisions regarding the maintenance and operation of structures. Developing robust IT infrastructure and incorporating advanced analytics technologies are necessary to handle the vast amounts of data generated by IoT sensors. This data-driven approach enables predictive maintenance, allowing for the identification of potential issues before they become critical. By analyzing long-term data trends, it is possible to predict when a structure will require maintenance, thereby shifting from reactive to proactive maintenance strategies [7].

Several pilot projects in Pakistan illustrate the potential of BIM-based digital twin technology for structural health monitoring. For instance, the Lahore Orange Line Metro Train project, which incorporates BIM for design and construction management, could benefit from integrating digital twins and IoT for ongoing structural health monitoring. Similarly, smart city initiatives in

Islamabad and Karachi are exploring the use of digital twins to manage urban infrastructure more efficiently [8].

The integration of BIM, digital twins, and IoT for structural health monitoring and analysis represents a significant advancement in the management of infrastructure in Pakistan. While the adoption of these technologies is currently in its early stages, the potential benefits in terms of enhanced safety, efficiency, and cost savings are substantial. By addressing the challenges of high costs, professional training, and regulatory support, Pakistan can leverage these technologies to build more resilient and sustainable infrastructure.

## 2.4 Summary of Research Gap

Digital twin framework for the existing buildings which is one of the current problems mainly arises when the building is originally constructed in no plans or plans that are difficult to be integrated with modern technology, since the building structure is one of the oldest. In addition, these tailing programs are limited relative to their unable to do the data collection, since there are not exist the records taken from the past and there are the technology mismatched problems as the old technology is exchanged with the new technologies. The crucial issue in visualization lies in the difficulties in analyzing raw sensor data, thus one of the ways to deal with this is to improve the visualization of sensor data, which in turn would greatly be favorable for user comprehensibility and enhanced user efficiency and enable them to make clearer decisions in regards to smart building management[14].

The integration of digital twin technology for existing buildings presents several challenges, particularly when dealing with historical structures that lack detailed architectural plans or have plans that do not align with modern technological standards or with plans that are difficult to integrate with contemporary technologies. This absence of detailed documentation complicates the creation of accurate digital twins, which require precise information about the building's structure and systems. Modern techniques like Building Information Modeling (BIM) can be used to generate accurate models of these structures, yet the process is often complex and resource-intensive. Moreover, bridges in Pakistan often rely on outdated technologies that are incompatible with modern digital twin systems. For instance, analog systems and mechanical components that were common in older constructions do not easily interface with digital sensors and IoT devices. This technological gap necessitates substantial retrofitting and modernization efforts to bring these buildings up to the required standard for digital twin integration. This is made worse by historical lack of systematic data collection further complicating the integration process. Unlike new buildings equipped with sensors from the outset, older buildings may not have any pre-existing data on structural performance, environmental conditions, or usage patterns. This absence of data necessitates the deployment of new sensor networks, which can be both costly and logistically challenging. Another critical issue in leveraging digital twin technology is the difficulty in analysing raw sensor data. The huge volume and complexity of data generated by modern sensors can be overwhelming. Improved visualization techniques are essential to make this data comprehensible and actionable for building managers and stakeholders. Effective visualization tools can transform raw data into intuitive graphs, charts, and 3D models, enhancing user efficiency and decision-making capabilities.

Integrating digital twin technology into existing buildings is a complex but highly beneficial endeavour. By addressing challenges such as the lack of original plans, technological mismatches, and data collection limitations, building managers can utilize the full potential of digital twins. Improved data visualization plays a crucial role in this process, making sensor data more accessible and actionable. With strategic retrofitting, advanced digital reconstruction techniques, and effective stakeholder collaboration, the benefits of digital twin technology can be realized, leading to more efficient, sustainable, and resilient building management.

# CHAPTER 3

## METHODOLOGY

The methodology can be broadly classified into three main phases: Data acquisition, Data Transfer and Data Visualization.

1. **Data Acquisition:** The first stage is data acquisition from humidity, temperature, and ultrasonic sensors. Humidity and Temperature acquire environmental values whereas ultrasonic sensor detects damage in the structure.
2. **Data transfer:** Once the data is acquired from sensors, the next step is to transfer it in real-time to dynamo script through google sheet and excel.
3. **Data Visualization:** The next step is to visualize data in the form of a BIM model. The BIM model displays values in the form of color coding on the virtual model as the values change in the external environment. Ultrasonic Sensor also detects damage in the structure for early crack identification.

The Complete system architecture is illustrated in the figure below:

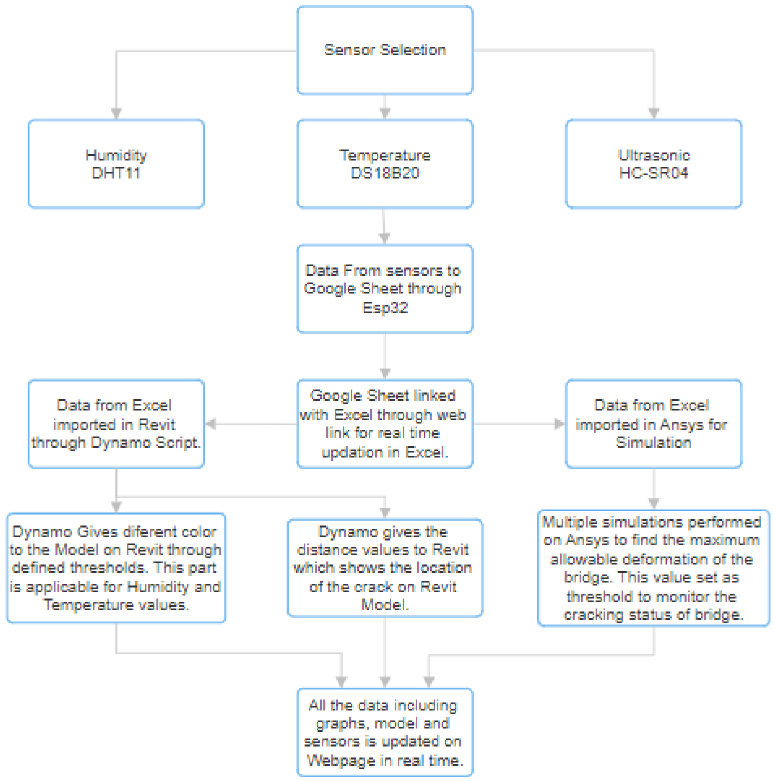


*Figure 1. Flowchart of the Methodology*

## 3.1 Data Acquisition

In the pursuit of achieving a precise and efficient Structural Health Monitoring (SHM) model, the foundational step encompasses data acquisition. The strategic selection and placement of sensors play a pivotal role in ensuring the accuracy and effectiveness of SHM. Real-time data collection forms the bedrock of data acquisition, facilitating subsequent analysis through archival storage. This seamless orchestration automates data transfer for further stages of structural evaluation. In this paper, data acquisition includes environmental impact data and ultrasonic data. This data set will help in further detailed analysis of damage in a structure, especially in cases where environmental factors need to be separate from the other data, like vibrations data.

### 3.1.1 Environmental Data Collection: Temperature and Humidity Sensing

Data acquisition stands as a critical step in monitoring the structural health of a bridge, enabling close observation of the impact of loads and environmental factors. In this research, environmental data, including temperature and humidity, are collected. The DHT11 sensor is employed for temperature and humidity measurements at each one-third point of bridge, operating within a temperature range of 0°C to 50°C with an accuracy of ±2°C. Its humidity measurement capability spans from 20% to 90% RH with an accuracy of ±5% RH, rendering it ideal for monitoring concrete moisture levels during curing. With a response time of approximately 2 seconds for humidity and 5 seconds for temperature, the DHT11 sensor ensures timely data acquisition.

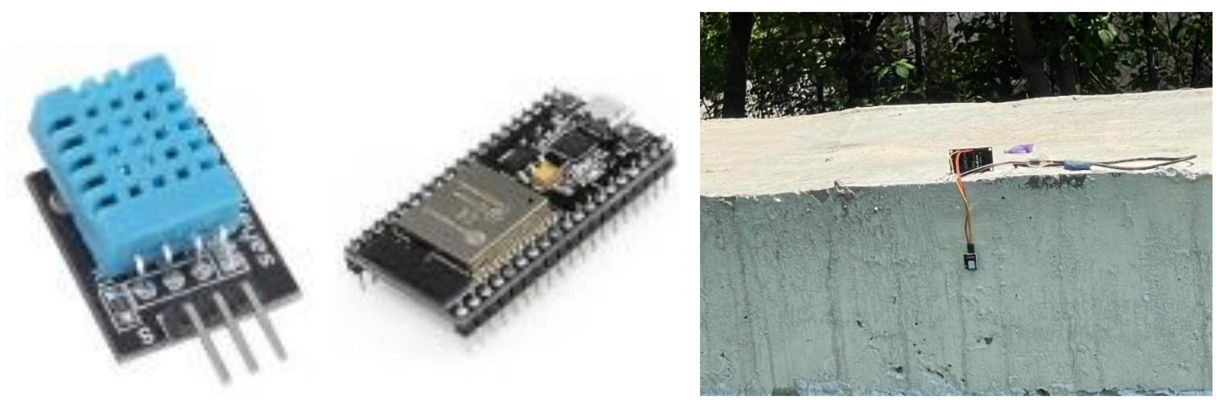

*Figure 2. (a) Temperature and Humidity Sensor DHT11, (b) ESP 32 Wi-Fi modular, and (c) Temperature and Humidity Sensor at 2/3$^{rd}$ location of bridge*

The threshold values for environmental sensors are established based on the optimal conditions for concrete health. The humidity sensor plays a crucial role in detecting the relative humidity of concrete, influencing cement hydration rates during constructions phase. So, a threshold for humidity of 80% RH is set to ensure optimal strength, as cement hydration slows down significantly below this level. For structures exposed to low humidity, such as in the initial stages, the hydration process is markedly inhibited. Experimental results by Jensen indicate that the hydration degree of $C_3S$ significantly decreases at lower relative humidity levels, with almost no hydration occurring below 43% RH. While the value of temperature is monitored constantly without setting any threshold, as these temperature changes value are crucial. As environmental temperature initiates various changes in the structural and material properties of RC structure. The variations in structural properties include reduction in natural frequencies from 5 to 12% of the baseline natural frequency of the structure. The Elastic modulus of the structure is also reduced due to elevated environmental temperatures. This similarity in structural behavior is identical to the response obtained when there is some damage in the structure hance leading to misleading early warnings in the SHM systems.

***Table 1.** Color Code for variation of temperature.*

| Color | Range |
|---|---|
| -20 to 100 | Green |
| -40 to -20 & 100 to 250 | Orange |
| Others | Red |

***Table 2.** Color Code for variation of Humidity.*

| Color | Range |
|---|---|
| 30-70 | Green |
| -20-30 & 70-80 | Orange |
| 0-20 & 80-100 | Red |

*Figure 3. Color code for Temperature and Humidity*

### 3.1.2 Ultrasonic Sensor Application

Ultrasonic sensors, a non-contact type, are deployed beneath the bridge to assess the maximum deformation and horizontally to detect crack locations, offering valuable insights for structural health monitoring. In this research HC-SR04 sensor, is utilized for distance measurement, it emits ultrasonic waves through a piezoelectric transducer to identify internal cracks within concrete. By determining the distance at which cracks appear, the HC-SR04 sensor contributes crucial data for assessing structural integrity.


***Figure 4.*** *(a) Ultrasonic sensor HC-SR04, and (b)Ultrasonic sensors placement at horizontal position in bridge.*

## 3.2 Data Transfer

In order to automate the whole process and make distant data collection possible, an ESP-32 Wi-Fi modulars are used. So, in Data transfer stage, data transferred from ESP-32 to google sheet in real-time. Data is then updated on excel and transferred to dynamo. Dynamo displays data for temperature and humidity sensors in the form of color coding at every L/3 distance. The model changes color when sensor values exceed above or below threshold value. Simulations are run on Ansys to develop an FEM Model that determines the max deformation of the structure. Ultrasonic sensor updates the distance of the bridge beam above the ground to monitor if the bridge crosses its threshold for maximum deformation.

### 3.2.1 Sensor to Google Sheet

Humidity, Temperature and Ultrasonic sensors are connected to the ESP-32. The ESP-32 is a versatile microcontroller chip that integrates Wi-Fi and Bluetooth capabilities. It's commonly used in IoT (Internet of Things) projects due to its low cost, low power consumption, and built-in connectivity features. ESP-32 is programmed using the Arduino Integrated Development Environment (IDE), which is a popular platform for writing, compiling, and uploading code to microcontrollers. The programming language used is based on C++, with specific libraries and functions provided by the Arduino framework for interacting with the ESP-32's hardware features and peripherals. The ESP-32 reads data from the connected sensors using its GPIO (General Purpose Input/Output) pins. The code written in Arduino IDE defines how the microcontroller interacts with each sensor and collects data from them. The ESP-32's built-in Wi-Fi module enables it to connect to the internet wirelessly. This is crucial for uploading data to online services such as Google Sheets. Using the ESP-32's Wi-Fi capabilities, the collected sensor data is uploaded to a Google Sheet. This is typically achieved by sending HTTP requests to Google's APIs, specifically the Google Sheets API, which allows for programmatically updating spreadsheet data. Google Sheet serves as a central repository for the collected sensor data. Each time new data is collected, it is appended to the spreadsheet, creating a log of historical data over time. Lastly, the spreadsheet is linked with Excel through web link.

### 3.2.2 Excel To Dynamo

The sensor data collected and stored in the Google Sheets is exported to an Excel spreadsheet. This can be achieved using various methods, such as Google Sheets add-ons or scripts, which automate the process of exporting data to Excel format, which will help in further analysis of data in Revit. Revit is a Building Information Modeling (BIM) software commonly used in architecture, engineering, and construction (AEC) industries for designing and managing building projects. Dynamo is a visual programming platform integrated with Revit that allows users to automate tasks and manipulate BIM data. In Dynamo, two separate scripts are created for integrating the sensor data into the Revit BIM model:

Script for Humidity and Temperature Data: This script is designed to read data from an Excel spreadsheet that contains detailed records of humidity and temperature values, which are critical environmental parameters influencing the structural behavior and integrity of bridges. The script processes these values and applies a color-coding system to elements within a Revit model, based on predefined threshold values. This color-coding system visually represents the different environmental conditions affecting the bridge, making it easier for engineers and maintenance teams to interpret the data and identify areas of concern. Upon extracting the humidity and temperature data from the spreadsheet, the script maps these values to corresponding elements in the Revit model. Each element of the bridge structure, such as beams, columns, and decks, can be individually assessed for its exposure to varying environmental conditions. The script uses a set of predefined threshold values to determine the color assigned to each element. For instance, if the temperature recorded for a particular section of the bridge exceeds a certain high threshold, the script will color that section red within the Revit model. This red coloring serves as a visual alert, indicating that the area is experiencing high temperatures that could potentially impact its structural integrity. Conversely, areas with lower temperature readings may be colored green, signaling that they are within a safe temperature range. Intermediate temperature ranges might be represented by other colors, such as yellow or orange, to provide a gradient of temperature exposure. Similarly, humidity values can be visualized using a different color scheme, allowing for a comprehensive environmental assessment of the bridge. This visual representation in the Revit model facilitates further analysis by highlighting areas where environmental conditions might lead to behavioral changes in the bridge structure. High temperatures can cause expansion in materials, potentially leading to stress and deformation, while low temperatures might result in contraction and brittleness. Humidity can contribute to corrosion and weakening of materials, especially in metal components. By color-coding the model based on these environmental factors, engineers can quickly identify which parts of the bridge are at risk and require closer inspection or preventive maintenance. Additionally, this approach enables the analysis of temporal changes in environmental conditions. By comparing the color-coded models over different time periods, engineers can track how temperature and humidity variations impact the bridge's structural health over time. This data-driven approach supports proactive maintenance strategies, ensuring that potential issues are addressed before they escalate into serious problems.

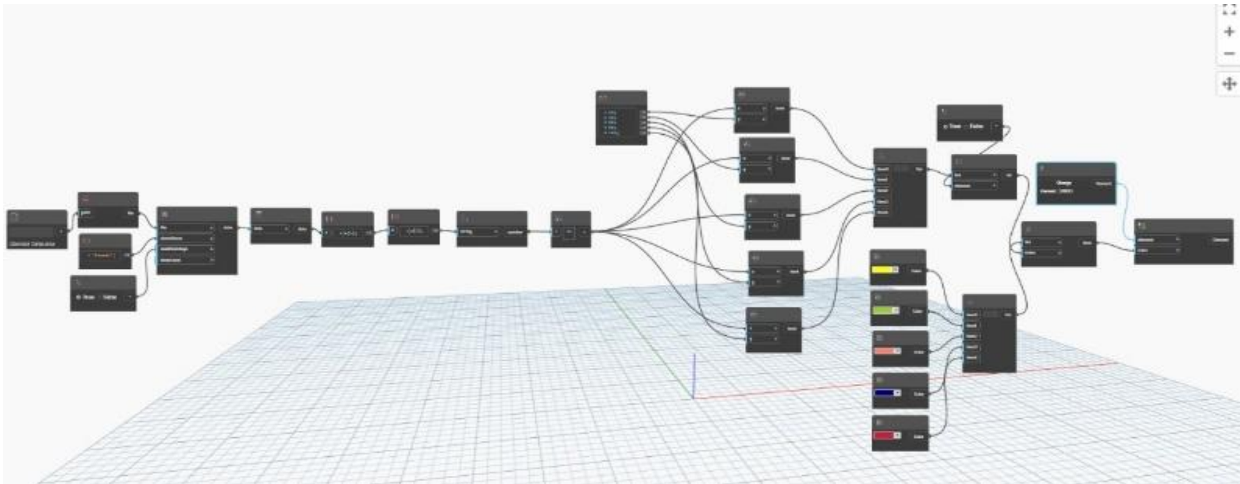

***Figure 5.*** *Dynamo Code for Temperature and Humidity Sensors*

Script for Ultrasonic Data: This script is designed to read ultrasonic data from an Excel spreadsheet, a task that involves extracting detailed information about distance values which likely represent the locations and dimensions of cracks within a bridge structure. Ultrasonic data is commonly used in structural health monitoring to detect anomalies and defects, as ultrasonic waves can penetrate materials and reveal internal flaws that are not visible to the naked eye. Upon reading the spreadsheet, the script processes these distance values to pinpoint the exact locations of cracks. Each distance measurement corresponds to a specific point along the bridge where ultrasonic sensors have detected a potential issue. These values are crucial for determining both the position and the severity of the cracks, providing a detailed map of where the structural integrity of the bridge may be compromised. Once the script has extracted and analyzed the distance data, it integrates this information into a Revit model. Revit, a powerful Building Information Modeling (BIM) software, is used to create detailed and dynamic digital representations of physical structures. By inputting the ultrasonic data into Revit, the script enables the visualization of the cracks within the bridge model. This process involves translating the numerical data from the Excel spreadsheet into spatial coordinates that Revit can interpret, effectively overlaying the detected cracks onto the 3D model of the bridge. The integration of ultrasonic data into the Revit model offers several significant advantages. First, it provides engineers and maintenance teams with a clear and precise visual representation of where cracks are located, making it easier to assess the extent of the damage. Second, this visualization helps in planning targeted maintenance and repair activities, ensuring that resources are directed to the most critical areas. Lastly, having a digital record of crack locations and their progression over time supports ongoing monitoring and future inspections, contributing to the overall safety and longevity of the bridge.

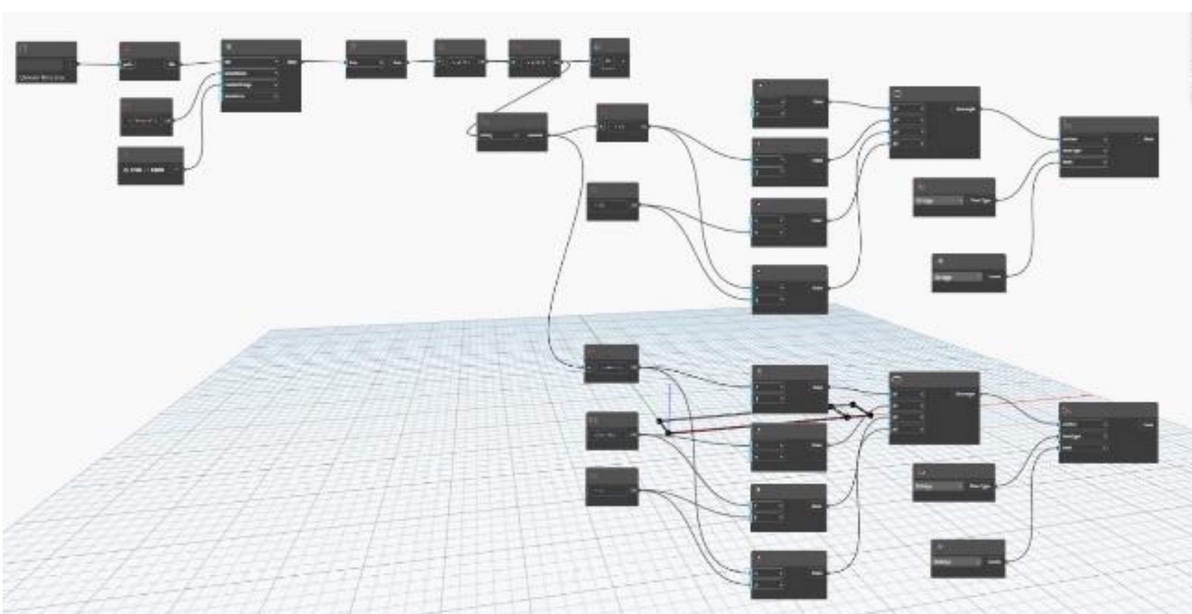

***Figure 6.*** *Dynamo Code for Ultrasonic Sensors Data*

Both Both scripts are engineered to dynamically update the Revit model in real-time as new data is imported from the Excel spreadsheet, ensuring that the model always reflects the most current sensor readings. This real-time synchronization is crucial for maintaining an accurate and up-to-date digital representation of the bridge's condition.

As sensor data changes—whether it's temperature, humidity, or ultrasonic readings—the scripts automatically process the new information and adjust the Revit model accordingly. For temperature and humidity data, the script continuously monitors the values recorded by the environmental sensors. When a new set of data is imported, the script re-evaluates each element of the bridge model against the predefined threshold values. If there are any changes in the temperature or humidity readings that cross these thresholds, the script updates the color coding of the corresponding elements in the model. For instance, if a section of the bridge that was previously green (indicating safe temperature) now records a temperature above the high threshold, it will be recolored to red to signal the elevated temperature.

Similarly, for ultrasonic readings, the script assesses the data to detect any new or progressing cracks within the bridge structure. As new ultrasonic data is imported, the script identifies the specific locations and dimensions of the cracks and updates the Revit model to reflect these changes. This could involve highlighting new cracks, showing the progression of existing cracks, or even indicating areas where cracks have been successfully repaired.

The real-time update capability of these scripts offers several significant benefits. Firstly, it provides engineers and maintenance teams with an immediate and accurate visual representation of the bridge's current state, allowing for swift identification and assessment of potential issues. This immediacy is crucial for timely decision-making, especially in the case of emerging structural problems that require prompt attention to prevent further deterioration or failure.

Secondly, the continuous updating of the Revit model enhances the ability to monitor trends and patterns over time. By maintaining a dynamic and current model, engineers can track how environmental conditions and structural changes evolve, enabling more informed predictions about future maintenance needs and potential risks. This proactive approach supports long-term planning and resource allocation, ensuring that maintenance efforts are both efficient and effective.

Lastly, real-time updates ensure that all stakeholders have access to the most recent and relevant information. Whether it's engineers on-site, maintenance teams, or decision-makers in an office, everyone can rely on the Revit model as a single source of truth for the bridge's condition. This collaborative tool enhances communication and coordination across different teams, improving overall project management and execution.

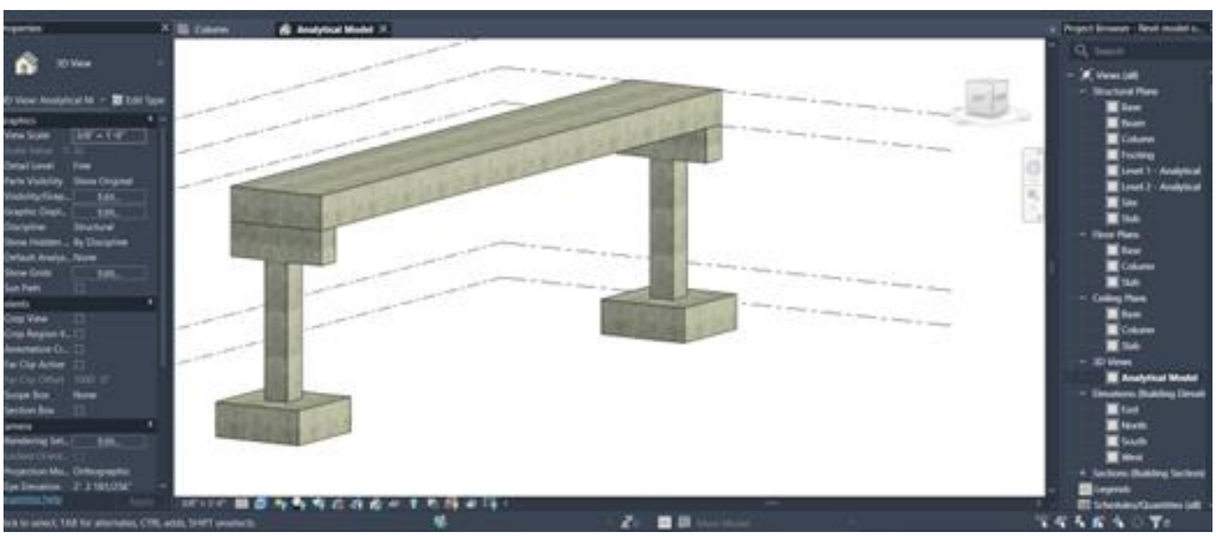

***Figure 7.*** *Revit model of bridge*

## 3.3 Data assessment for deformation and crack detection

The BIM model, which represents the bridge structure with real-time data in Revit, is converted into a Finite Element Model (FEM). This conversion process involves translating the geometric and material properties of the bridge elements from the BIM software (Revit) into a format compatible with finite element analysis (FEA) software, such as ANSYS, by utilizing the industry foundation class (IFC). ANSYS is a powerful simulation software suite used for engineering analysis, including finite element analysis (FEA). In this case, the FEM model of the bridge is imported into ANSYS, where deformation simulations are performed under various loading conditions. These simulations help predict how the bridge structure will deform and respond to external forces such as traffic loads, wind loads, etc. During the deformation simulations, ANSYS calculates the maximum deformation points within the bridge structure. These points represent areas of the bridge that experience the highest levels of deformation under the applied loads. Identifying these critical points is crucial for assessing the structural integrity and performance of the bridge. Once the maximum deformation point(s) are determined, a threshold value is established based on the maximum allowable deformation that the bridge can withstand before failure. This threshold value serves as a critical criterion for monitoring the health and safety of the bridge structure. The ultrasonic sensors installed on the bridge continuously monitor the structural integrity by measuring the distance to various points on the bridge surface. These measurements are compared against the threshold deformation value obtained from the ANSYS simulations. If the ultrasonic readings indicate that the deformation at any point on the bridge exceeds the threshold value, it suggests that the bridge has experienced excessive deformation and may be at risk of failure.

## CHAPTER 4

# RESULTS AND VALIDATION

## 4.1 Results

The results of this study have been displayed on a webpage in the form of a dashboard that displays all of the sensor data in real time for bridge monitoring. The values from sensors are shown in the form of both: graph and table. The data values from ultrasonic sensor are displayed as a graph of deformation against time as illustrated in the diagram below. The webpage also displays the FEM Model of the bridge.


***Figure 8.*** *Website Interference of the Bridge model for real-time assessment of bridge, webpage:* *http://sensorsbms.netlify.app*

After placing all the sensors on the bridge, we successfully create an automated model, which transfer the temperature and humidity data constantly, for illustration the temperature data and humidity data of the bridge for few hours are shown in figure below:

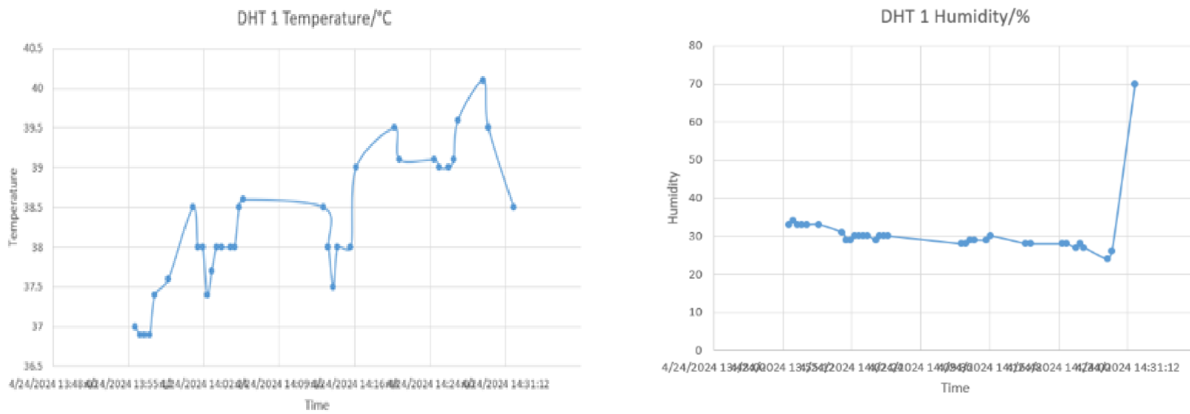


***Figure 9.*** *(a) Temperature Data Collection for the bridge of 2 hours, and (b) Humidity Data Collected from bridge for 2 hours, where DHT 1 shows the positions of sensor mean at first 1/3^rd^*

After displaying all temperature data, the Revit model is tested by varying the temperature randomly, as currently the weather is almost constant, so an arbitrary value is given to the model to check the efficiency and response of the model.

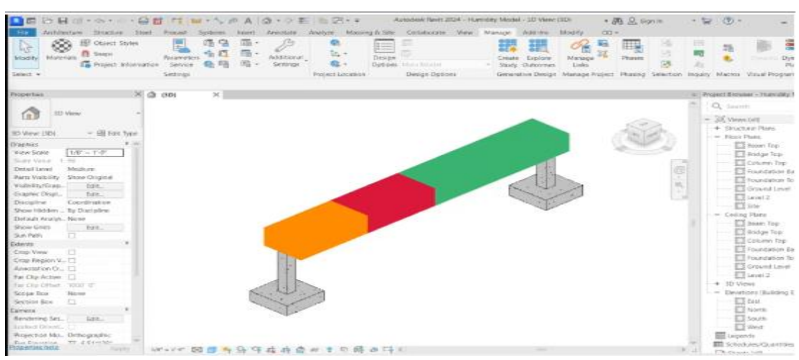

***Figure 10****. Revit Model to display the change of color with variation of temperature.*

An ultrasonic sensor data is collected from the bottom of the bridge is used to assess the deformation of the bridge at the center of the bridge, while the threshold is set by performing the Ansys modelling and calculate the deformation at which the bridge loss its strength. As the bridge is not deformed in reality, so in order to detect the damage a ultrasonic one end is displaced from the bottom of the bridge to a failed displacement point (which is obtained from the Ansys model), to check the working of the Revit model. As it can see from Figure 10, the value of ultrasonic displacement is dropped from the threshold indicating the deformation exceedance from safety level, which is indication of damage and failure.

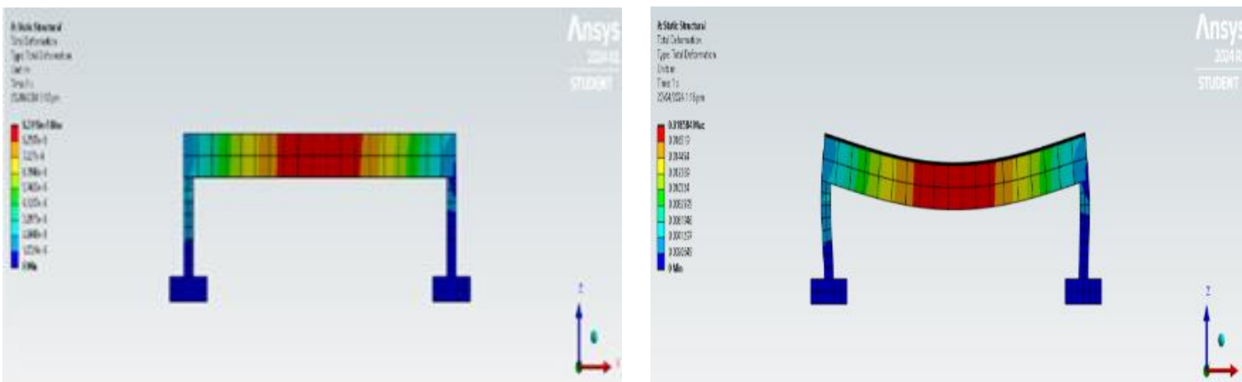


***Figure 11.*** *Ansys Model (a) Before Bridge Deformation, at healthy state, and (b) Bridge Modelling at deformation failure*

As the ultrasonic sensors are also placed at the sides of the bridge, to locate the crack in bridge. The following figure shows, how the location of crack will be displayed in model and generate warning system, in case of crack occurrence.

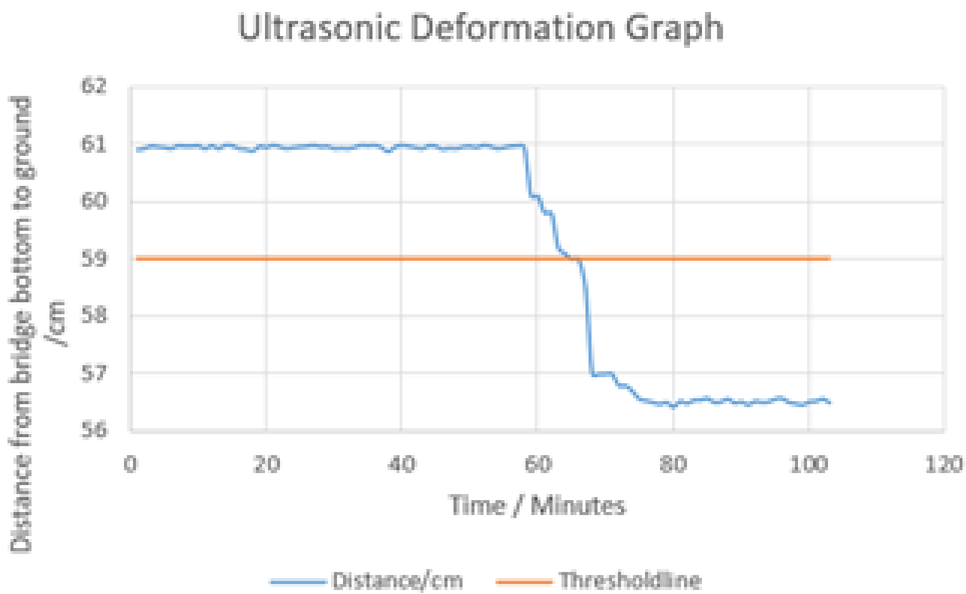


***Figure 12.*** *Deformation assessment using Ultrasonic Sensor*

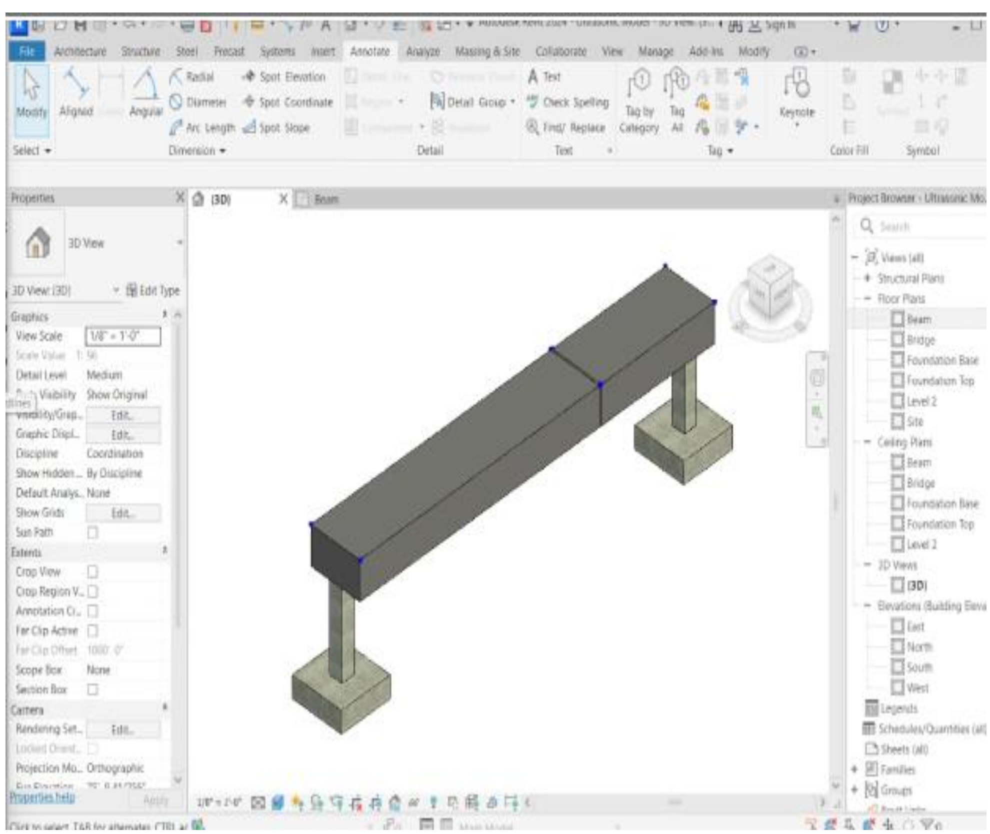

***Figure 13***. *Crack Location identified by ultrasonic sensors placed on sides of bridge.*

## 4.2 Validation

It is of utmost importance to ensure that once a hypothesis has been formulated or an experiment has been conducted to advance a research theory, the validity of the hypothesis or experiment is also confirmed through real-world application. This validation process involves applying the hypothesis to a structure, material, or object to verify and authenticate the results obtained from the experiment. Result validation, as this process is known, is a critical step in the scientific method as it ensures that the findings are reliable and applicable in practical scenarios. By subjecting the hypothesis to real-world conditions, researchers can validate the credibility and feasibility of their theoretical work, contributing to the robustness of scientific knowledge.

### 4.2.1 Overview of the Process for Humidity and Temperature data

To validate the theory and results in our research, we performed a validation experiment on a bridge. The purpose of this validation experiment was to test the working of our system by using Humidity and Temperature data from sensors. The Humidity and Temperature sensors used in the validation experiment transmitted the data wirelessly for us to further process it into actionable input. The bridge on which the sensors were installed is built in SCEE, NICE, NUST.

After the sensors were connected with the proper instruments, real-time raw data was collected from them. This was done to ensure that the data acquired from the sensors can be used to monitor in real-time. The wireless transmission of the data was of great significance in this regard. The sensors were programmed to send numerous live readings over a set amount of time and the readings were then almost instantaneously processed to obtain the results.

The results were analyzed by Revit. Revit is a software for making 3D renders of structures. The software would be used to visualize the environmental parameters of the Bridge. Revit assigns color coding to the structure according to the set thresholds. As shown in Figure 10 above.

### 4.2.2 Overview of the Process for Ultra-Sonic data

To validate the theory and results in our research, we performed a validation experiment on a bridge. The purpose of this validation experiment was to test the working of our system by using Ultrasonic data from sensors. The Ultrasonic sensors used in the validation experiment transmitted the data wirelessly for us to further process it into actionable input. The bridge on which the sensors were installed is built in SCEE, NICE, NUST.

After the sensors were connected with the proper instruments, real-time raw data was collected from them. This was done to ensure that the data acquired from the sensors can be used to monitor in real-time. The wireless transmission of the data was of great significance in this regard. The sensors were programmed to send numerous live readings over a set amount of time and the readings were then almost instantaneously processed to obtain the results

The results were analyzed by Revit. Revit is a software for making 3D renders of structures. The value of the data can be used to evaluate the location of the crack and this can be visualized on the Revit Software. As shown in Figure 13 above.

FEM model was created on Ansys and through multiple simulations the failure deformation of the bridge was determined

# CHAPTER 5

# CONCLUSION AND RECOMMENDATIONS

## 5.1.Conclusion

Significant improvements in infrastructure safety and maintenance are achievable with the combination of IoT sensors and digital twin technologies for structural health monitoring, or SHM. Continuous monitoring of structures is possible with the development of a true digital twin, which blends virtual models with real-time sensor data. This method improves the overall safety and lifespan of infrastructure by facilitating the early detection of cracks and other structural problems.

The findings of the study support the viability and efficiency of this coordinated strategy. A thorough understanding of the bridge's condition can be obtained via the dashboard designed to show sensor data in real time. It is simple to comprehend and analyze the graphs and tables that provide sensor data, such as temperature and humidity.

The use of ANSYS software for finite element modeling (FEM), precise evaluation of structural displacement and fracture identification are made possible. Potential structural failures can be identified and alerted to by the system by establishing thresholds based on the FEM simulations.

In summary, this study highlights how digital twin technology and Internet of Things sensors might transform the process of structural health monitoring into a much simpler and comprehension assessment technique of timely damage detection. By putting these innovations into practice, infrastructure may become more sustainable and safer, which will eventually benefit society.

## 5.2 Potential Benefits

### 5.2.1 Bridge Management System

An IoT-based bridge management system offers numerous potential benefits, significantly enhancing the safety, efficiency, and longevity of bridge infrastructure. By utilizing a network of sensors and connected devices, such systems can continuously monitor the structural health of bridges, detecting issues like cracks, vibrations, or stress in real-time. This real-time data enables proactive maintenance, reducing the risk of catastrophic failures and extending the lifespan of the bridges. Additionally, IoT-based systems can optimize traffic management by providing up-to-date information on bridge conditions, helping to prevent congestion and improve overall transportation efficiency. These systems also facilitate better resource allocation, as maintenance efforts can be precisely targeted where needed most, ultimately leading to cost savings and improved safety for both vehicles and pedestrians.

### 5.2.2 Crack and Failure Detection

By constantly monitoring the bridge's structural integrity, the IoT-based bridge management system can detect the development of cracks, corrosion, and other signs of weakness at their earliest stages. Sensors embedded in various parts of the bridge continuously measure factors such as stress, strain, displacement, and environmental conditions. For instance, accelerometers can detect unusual vibrations that might indicate structural instability, while strain gauges measure the deformation of bridge materials under load. This early detection is crucial because it allows maintenance teams to address minor issues before they escalate into major problems. When a crack begins to form, or when material fatigue is detected, the system can immediately alert engineers to the precise location and severity of the issue. This targeted approach means that maintenance can be performed quickly and efficiently, reducing the risk of catastrophic failures that could result in significant property damage, injuries, or even loss of life. Furthermore, by addressing these issues early, the overall structural health of the bridge is maintained, ensuring that it remains safe for use by vehicles and pedestrians. Preventative maintenance not only extends the lifespan of the bridge but also enhances public confidence in the safety of the infrastructure. In addition, the system's ability to provide real-time data means that, in the event of an unusual incident such as an earthquake or a heavy storm, engineers can rapidly assess any impact on the bridge's integrity. This swift response capability is vital for making informed decisions about temporary closures or load restrictions to protect public safety. Thus, the continuous monitoring and early detection facilitated by IoT-based systems play an essential role in maintaining the structural integrity and safety of bridges.

### 5.2.3 Broad Applicability

The beauty of this system lies in its remarkable versatility. IoT-based bridge management systems are designed to be adaptable and scalable, making them suitable for implementation on any bridge, regardless of size, location, or design. This adaptability stems from the modular nature of the sensors and the flexibility of the data processing algorithms, which can be customized to meet the specific needs of different types of bridges, whether they are small rural overpasses or massive urban suspension bridges. This versatility is a significant advantage for bridge authorities and infrastructure management teams worldwide. For instance, in urban environments with heavy traffic and complex structural demands, the system can be configured to handle high data volumes and provide detailed analyses of stress distribution and load-bearing capacity. In contrast, for rural or remote bridges that might face environmental challenges such as extreme weather conditions or limited maintenance access, the system can focus on monitoring factors like temperature fluctuations and corrosion rates. Moreover, the system's ability to integrate with existing infrastructure means that it can be retrofitted to older bridges without requiring extensive modifications. This is particularly valuable for countries with aging infrastructure, where the cost and logistics of rebuilding or extensively renovating bridges are prohibitive. By implementing an IoT-based monitoring system, these older structures can be maintained and managed more effectively, enhancing their safety and longevity without the need for significant reconstruction. Additionally, the system's global applicability makes it an invaluable tool for diverse geographic and climatic conditions. Whether in seismic zones where bridges need to withstand frequent earthquakes, in coastal areas facing corrosive saltwater exposure, or in regions with heavy snowfall requiring constant load assessment, the IoT-based system can be tailored to provide relevant data and predictive insights. This ensures that bridge authorities can make informed, data-driven decisions to enhance safety and performance in any environment.

### 5.2.4 Particularly Effective in Remote Area

Places like Skardu and Kashmir face unique challenges when it comes to maintaining their bridge infrastructure. These regions are often characterized by their remoteness, rugged terrain, and harsh weather conditions, making it difficult and sometimes dangerous to conduct regular bridge inspections. Traditional inspection methods in such areas require significant time, effort, and financial resources, often involving long travel distances and specialized equipment to reach and assess each bridge. This logistical complexity can lead to infrequent inspections, increasing the risk of undetected structural issues that could compromise safety. The real-time data provided by the system enables proactive monitoring, allowing bridge authorities to detect and address issues as soon as they arise, rather than waiting for periodic inspections. This is particularly crucial in remote areas where adverse weather conditions, such as heavy snowfall, monsoon rains, or earthquakes, can rapidly deteriorate bridge conditions. The system's ability to provide immediate alerts and detailed diagnostics helps ensure that necessary maintenance can be planned and executed promptly, even from a distance. Furthermore, the IoT-based system minimizes the need for physical inspections, which are challenging and costly in these areas. This not only enhances the safety of maintenance personnel but also significantly reduces operational costs. The system's data-driven approach ensures that resources are used efficiently, focusing efforts on bridges that truly need attention, rather than adhering to a fixed inspection schedule.

### 5.2.5 Addresses earthquake and landslide risks through proactive monitoring

In regions prone to earthquakes and landslides, bridges face significant vulnerabilities due to the intense and sudden forces exerted by these natural disasters. Earthquakes can cause rapid ground shaking, leading to severe structural stress and potential damage to bridge components, while landslides can exert heavy loads and shift bridge foundations. These extreme events can compromise the integrity of bridges, posing serious safety hazards for both pedestrians and vehicular traffic. Furthermore, the early warning capability of the system is vital for disaster preparedness and response. Authorities can use the data to model and predict the impact of ongoing seismic activity or unstable terrain, allowing them to take preemptive actions. For instance, in the event of an anticipated aftershock following an initial earthquake, the system can help determine which bridges are most at risk and prioritize them for immediate inspection or closure. By providing continuous monitoring and early warnings of potential damage, the system helps authorities promptly identify and address vulnerabilities, preventing minor issues from escalating into major safety hazards and enhancing overall disaster resilience.

## 5.3 Sustainable Development Goals



**Addresses SDG 9: Industry, Innovation and Infrastructure**

Promotes development of sustainable infrastructure through real-time monitoring and preventative maintenance. This system aligns perfectly with SDG 9's focus on developing sustainable infrastructure by promoting a proactive approach to bridge maintenance. By identifying and addressing potential problems early on, the system extends the lifespan of bridges, reducing the need for frequent repairs and reconstructions. This not only saves resources but also minimizes environmental impact.

**Addresses SDG 11: Sustainable Cities and Communities**

Enhances bridge safety and resilience, contributing to safer and more sustainable communities. Safe and reliable bridges are essential for connecting communities and facilitating the flow of goods and services. This real-time monitoring system directly contributes to SDG 11 by enhancing bridge safety and resilience. By ensuring the structural integrity of bridges, the system promotes safer transportation networks and contributes to the development of more sustainable communities.

## 5.4 Cost Analysis

**Breakdown of Project Costs:**

Total Expenditure: PKR 8,290 (This is a relatively cost-effective solution compared to the potential consequences of bridge failure)

Sensor Costs: PKR 7,150 (largest cost component) Sensors are the heart of this system, as they are responsible for collecting the vital data on the bridge's health. While they represent the largest cost factor, advancements in sensor technology are constantly driving down prices.

Other Technical Equipment: PKR 1,140 (connecting wires, etc.) In addition to the sensors, other technical equipment is needed, such as connecting wires and potentially a data transmission unit. These additional costs are minimal compared to the overall benefits of the system.

## 5.5 Future Recommendations

Incorporate data from accelerometers, load cells, inclinometer, and temperature sensors. Currently, the data from ultrasonic sensors is used for crack detection. Load cells and accelerometers allow vibrations to be monitored when the load is applied for a comprehensive study of changes in the strength of the structure over time. Hence, the behavior of the structure under different types of static and dynamic loading can be determined to obtain a threshold as well as real-time values of load and strength for the structure. Temperature sensors embedded in concrete, for example, allow maturity index to be calculated that can be used to compute the in-place strength of the structure. These parameters will enable engineers and stakeholders to make sound decisions about the structure in post-damage scenarios.

Artificial neural networks can be used to improve the model's performance by running simulations on collected data and allowing it to predict damage based on collected data. The model can be trained with images of cracks to identify the type of crack that appears in the structure. Data from other sensors can be used to predict the behavior of the structure in post-damaged conditions.

Use of Raspberry Pi to improve performance and expand storage. The model currently runs on battery power provided by a power bank. The use of Raspberry Pi will allow seamless data transfer and enhance the system's capability to store a large amount of data in Google Sheets for real-time monitoring.

Transfer data to Ansys to run FEM analysis in real time. Currently, the data is transferred to the Revit Model and the thresholds have been set to identify the location cracks and whether the structure has deformed. However, data transfer to Ansys will allow engineers to visualize the actual deformation when loads are applied at different points in the bridge beam.

# CHAPTER 6

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