BUILDING INFORMATION MODELING-ENHANCED VISUALIZATION TOOL FOR STRUCTURAL HEALTH MONITORING

by

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Dedicated to my family

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Abstract

With growing number of modern complex infrastructure, robust and autonomous condition assessment of large-scale structures under operational loads and extreme climatic events has garnered significant attention. Data-driven structural health monitoring (SHM) techniques offer valuable information of existing health of the structures, maintain the safety and their uninterrupted use under varied operational conditions by undertaking risk and hazard mitigation promptly. However, just data-driven approaches are not enough to monitor a large amount of SHM data and conduct systematic decision making for future maintenance. Recently, Building Information Modeling (BIM) has become a valuable tool for design, production, construction, facility management and life-cycle analysis of buildings and bridges. Such a hybrid information modeling platform integrates the architectural, engineering and construction systems of a structure into one place allowing all users to incorporate various features effectively and accurately. In this thesis, a BIM-enabled system is utilized as a promising computing environment and integrated digital representation platform of SHM that can visualize a considerable amount of sensor data and subsequent structural health conditions over a prolonged period.

In this research, three-dimensional Autodesk Revit® models of a large-span bridge and a pedestrian bridge in Thunder Bay, Ontario are developed to enable automated sensor data inventory into the BIM environment. Such automated tool facilitates achieving systematic maintenance and risk management, while avoiding manual errors resulting from visual inspections of the structures. The proposed integrated tool allows the practicing engineers in organizing, processing, and visualizing the sensor data from the monitoring system, updating relevant finite element (FE) models, and providing valuable feedback for structural retrofitting in a single platform. The data acquisition was performed on various seasons of the year to check the performance of the structure under various temperatures and traffic loading conditions. The results reveal that the proposed method can be considered as a user-friendly and economic framework for condition assessment of large-scale structures in ease.

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Chapter 1

Introduction

The chapter presents the effectiveness and associated challenges of Structural Health Monitoring (SHM) to efficiently maintain and retrofit large-scale critical structures under operational structural damages. Long-term SHM utilizes a significant amount of vibration data during the in-service condition of large-scale structures including building and bridges. Building Information Modeling (BIM) has emerged as a powerful tool for planning and monitoring of the structures, starting from its construction till the end of its design life. Recent developments of the BIM technology help in identifying the damages in the structures by interfacing the long-term SHM data with the BIM model. While discussing the potential approaches of integrating SHM with the BIM tools, several limitations are identified. The gap areas of the existing literature are discussed followed by the objectives of the proposed research.

1.1 Structural Health Monitoring

Structural health monitoring (SHM) [1] is referred as a measuring tool to detect the critical responses of a structure and subsequently track and evaluate any unusual symptoms, serviceability, and safety of the structures. The accuracy of structural identification relies on different signal processing techniques to extract the structural parameters, identify the structural condition, locate the damage and quantify its severity. Most of the traditional methods require visual inspection by the trained engineers. Recently developed SHM techniques utilize the vibration data that are measured by inexpensive sensors thereby improving the accuracy of damage detection capability compared to the visual inspection. Most of the large-scale infrastructure like bridges, highways, and high-rise buildings deteriorate with distinct reasons including unusual traffic loads and other environmental impacts. They require not only a critical inspection but also thorough continuous monitoring of the structure to detect the changes of structural parameters and early detection of unsafe condition using real-time data [2].

A structure deteriorates with time due to natural disasters, excessive operational loads, cyclic freezing, thawing, corrosion and many other factors. The early identification of damages facilitates prevention of catastrophic failure [3]. Inspection engineers typically assess these structures manually, but a network of sensors can automatically evaluate the integrity of the structure and locate the damage which could significantly reduce the operational costs while improving the public safety [4]. Even though, if a structure manages to survive against the natural disaster, it is necessary to check its serviceability on a continuous basis. Output-only vibration testing [5, 6, 7] uses responses data obtained from the accelerometers placed optimally [8] throughout the structure to determine existing conditions of the structure.

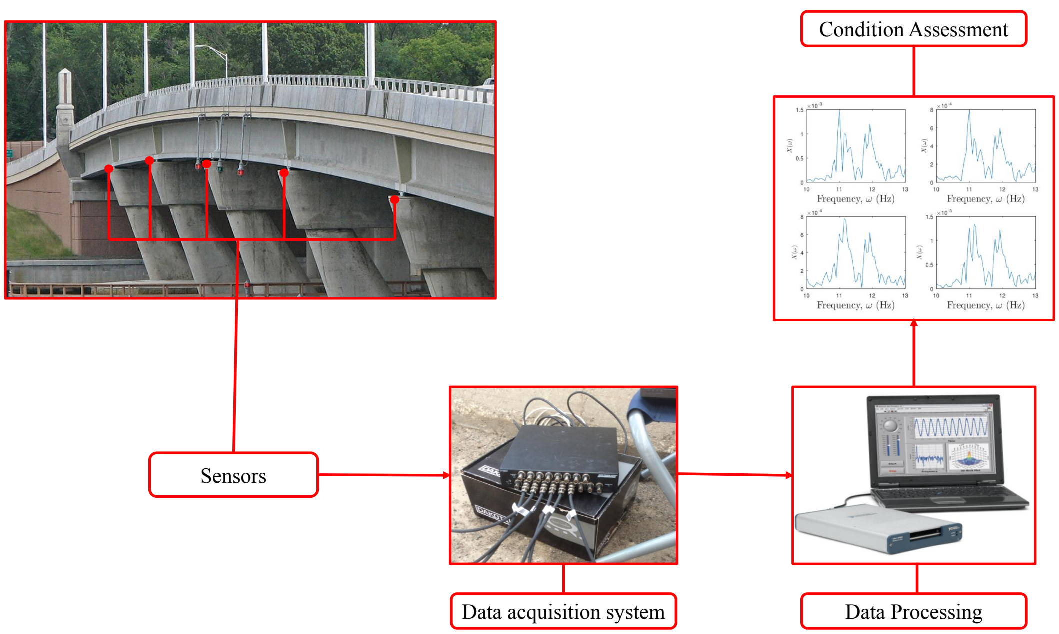


Figure 1.1: Key steps of the SHM.

Fig. 1.1 presents the four key phases of long-term-continuous SHM system. The SHM is initiated by collecting data followed by system identification and condition assessment leading to strategic future maintenance and retrofitting of the structure. For example, the research [9] from the Australian network of Structural Health Monitoring proposed various software products and algorithms for assessing the vibration based structural damage identification under various service conditions. Apart from operational conditions, the impact of earthquakes can lead to collapse during aftershocks. After natural calamities, it is also necessary to assess the emergency facilities, evacuation routes, including bridges and highways for occupant safety. A dense combination of sensors in SHM increases the performance of damage identification as well as better infrastructure management of critical facilities [10].

Bridges in North America experience accelerated deterioration and are exposed to wear and tear due to extreme climatic events. Regular maintenance is required mainly for joints and bearings as they suffer from premature wear before deterioration. Although the long-span bridges require regular maintenance which includes comprehensive visual inspections, the sensor measurement offers additional information to interpret the damages than visual inspections. Moreover, the monitoring system facilitates the infrastructure owners by providing more up-to-date health status of the bridges which can provoke for immediate inspections [11]. Critically, SHM of bridges is characterized by three major components: (a) damage detection, (b) prognostics and (c) risk assessment. Till date, most of the research on SHM has been focused on developing the sensor technologies to measure data and detect the damages, their severity and locations [12, 13].

Sensor technologies have immensely developed in the monitoring and management of civil structures. For large structures, it is now possible to collect a significant amount of rich quality data. Law et al. [14] discussed the data management framework for bridge monitoring application where the authors investigated nonstructural query language interface in Telegraph Road bridge in Michigan that was connected with several accelerometers. SHM relies on system identification [5, 15] and consists of finding the parametric physical models which fit the structural responses. These types of approaches lack efficiency in the analysis, capturing data, sharing, storing, transfer and visualization of structural response [16]. A substantial amount of big data and images resulting from long-term SHM sets further challenges for data interpretation. The data processing framework including storage, transmission, and manipulation associated with big data becomes impractical [17]. Various literature and research work implied a strong focus on huge data sets through different software platforms.

Zhou et al. [18] proposed advanced concepts for bridge safety evaluation and technologies required for current obligations. Due to the size of structures, the number of measuring points is reduced to achieve the effective damage detection. To perform the SHM, a long-span Caijia Jialing River bridge of 1250m length located at Liangjiang, China was considered as a case study. The approach expanded the usage of innovative ideas and concepts to achieve practical safety evaluation and structural damage prognosis using sensors. To justify the long-term SHM, Catbas et al. [19] analyzed a long-span bridge and determined the structural reliability due to temperature over a long period of time. The longest cantilever truss bridge in the US was extensively instrumented and monitored under traffic, wind, and temperature. The authors emphasized long-term SHM over more locations on the bridge to characterize the temperature induced strains in the structure. Due to large data sets during testing as shown in Fig. 1.2, it is also difficult to assess and predict the uncertainties of the structural parameters of the structure based on the long-term monitored data. This demands the need for a visualization tool to regulate the possible damages in the structure based on long-term monitored data.

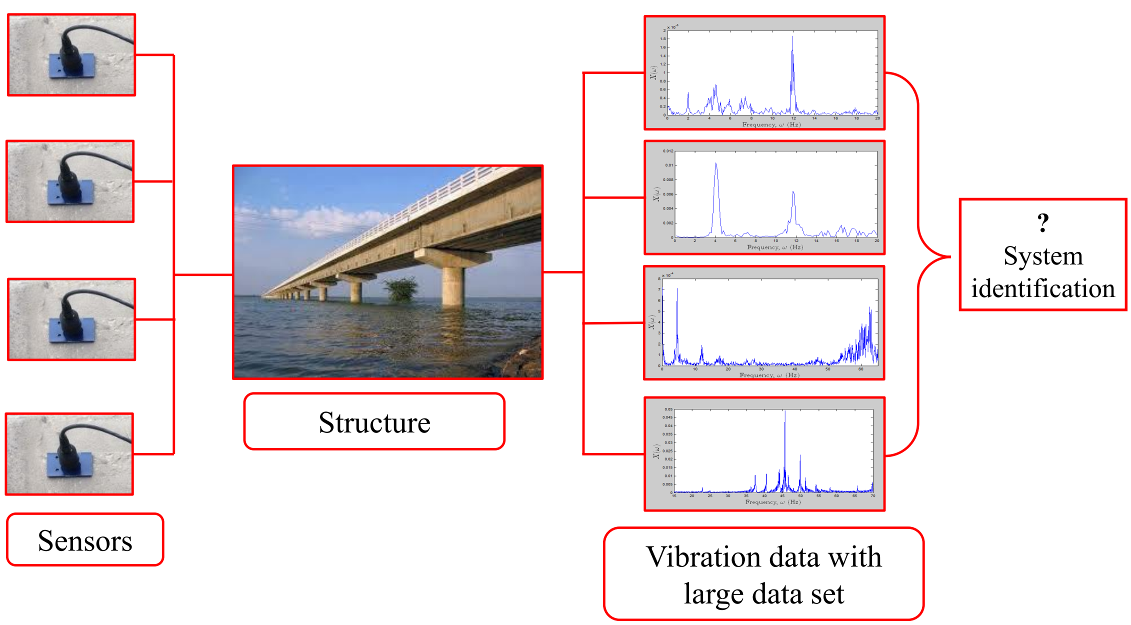


Figure 1.2: Problems associated with big data.

Omenzetter and Brownjohn [20] used several existing time series analysis (e.g., univariate/multivariate models) to understand the strain data recorded from a long-span bridge. The proposed method detected the unusual events in the data, however, did not provide the characteristics of the damage such as the damage nature, severity or location of the damage. Orcesi and Frangopol [21] explained the importance of monitoring fatigue life of different components of a bridge. Hu et al. [22] discussed the requirements for bridge health monitoring. The combination of multiple sensors interfaces the physical quantities such as acceleration, temperatures, and strain during the SHM. The system was deployed in the Zhengdian Highway bridge, based on the wireless sensor network. Li et al. [23] employed SHM system for Binzhou Yellow River highway bridge with a total of 141 sensors using several types of data acquisition systems, data transmission and data management systems. The SHM system is performed under heavy truck loading to provide information for planning and maintenance activities and alert the future construction policies for cable-supported bridges. Through the SHM, analysis of the measured data indicated that the bridge experienced light vibration under regular traffic and is reliable at the current stage. Bas et al. [24] aimed to develop advanced SHM system for the long-span bridges.

Ko and Ni [25] discussed the current practices towards long-span bridge health monitoring and addressed the existing challenges of the SHM. The use of fiber optic sensors provides a promising effort in extracting temperature and strain measurements. The structure experiences environmental and operating conditions such as traffic, humidity, wind, and solar radiation. Therefore, it is necessary to include both vibration-based sensors and temperature sensors to measure the full cycle of in-service environmental conditions. Min and Santos [26] performed SHM on Sao Joao Bridge, Oporto using Stochastic Subspace Identification technique and cluster analysis. The bridge was monitored since its construction in 1991, and the strains, temperatures vertical displacements, rotations and horizontal displacements were measured. The operational modal analysis was performed to achieve accurate natural frequencies, mode shapes and modal damping ratios under its operational conditions. Wong [28] distinguished SHM of large-span bridges into six modules: (a) sensory system (b) data acquisition (c) data processing (d) structural evaluation (e) inspection and maintenance (f) management of structural health data. To achieve this appropriate customized approach, software systems were developed to measure the data from bridge health monitoring evaluation.

1.2 Building Information Modeling

Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a structure [29]. It is a platform that shares the information of a facility from its construction till its demolition. BIM is not only a computer-aided design (CAD) tool but also a 3D modeling and information management software which enables engineers and architects to work seamlessly on the same project remotely. BIM integrates various aspects of engineering design through three-dimensional spatial representation. BIM-based designing tools offer extraction of different views of a structure or a model for production and other uses. Each BIM model can carry attributes by providing their key features and can perform cost estimation and material ordering. Fig. 1.3 provides a basic layout of information sharing through BIM for a complex structure. It benefits owners and contractors more as the model can foresee potential problems before the construction phase. The comprehensive list of BIM software are Autodesk Revit Architecture®, Graphisoft ArchiCAD®, Graphisoft ArchiCAD®, Nemetschek Allplan Architecture®, Nemetschek Vectorworks Architect®, Bentley Architecture®, 4MSA IDEA Architectural Design® (IntelliCAD), CADSoft Envisioneer®, Softtech Spirit®, RhinoBIM®.

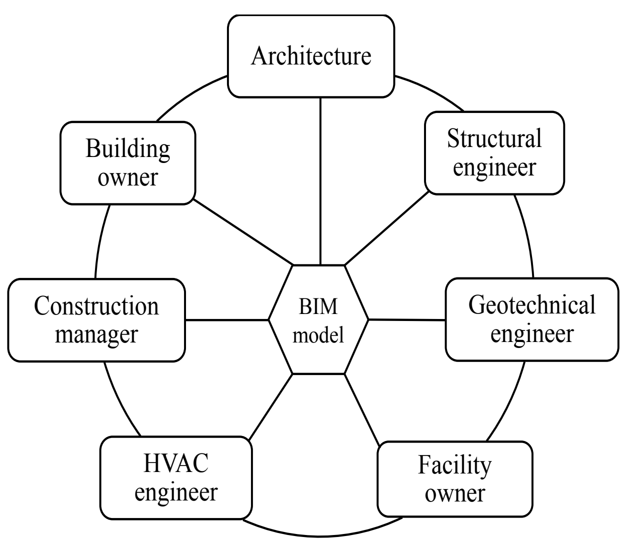


Figure 1.3: Conceptual framework of building information modeling.

BIM is a hybrid modeling approach for conceptual and detailed design, production, construction, facility management, life-cycle analysis, and long-term management of new and in-service structures. It is not merely a software enviroment but also a series of visualization tools, providing a better understanding of a building project, helping the design and construction team to convey the information to the client. The digital model of the structure is made up of structural objects related to it. With all the information about every component of the structure being brought together in one place, it enables users to access the information of the structure at any point of project life-cycle. The architectural spaces, systems, energy supplies and services can help prevent errors creeping in all stages of development and construction, safeguarding danger and consequently inconsistencies can reduce.

Figure 1.4: Factory time-line viewed in Naviswork [30].

Traditional BIM models primarily focus on design and life cycle analysis of a new building. Fai et al. [30] explored the use of BIM for documentation of heritage buildings and cultural landscape in a village of an area of 600-hectare. In Fig. 1.4, an accurate topographical analysis is generated by integrating a digital elevation model with terrestrial laser scanning using digital and paper-based texts. A research project for the accelerated delivery of bridges [31] explained the electronic communication of bridge life cycle information to develop real-time monitoring that incorporated the planning, design, construction, and maintenance phases of bridges into one single entity for multiple users.

The execution and use of digital construction through BIM for better productivity, efficiency, quality, and sustainability was explained by [32]. The authors explained different BIM implementation phases which include preparation phase, the roll-out phase, and post-implementation phase of the construction practice. The focus on preventing injuries, fatalities, and improvements in safety have grabbed massive attention in the construction industry. Seokho et al. [33] identified the lack of BIM models in productivity loss during design and construction and opportunities for improved safety practices with the design of scaffold and form-work. The research included a series of scaffolding and form-work of BIM objects that designers and constructors can freely access using various platforms, and safe and efficient methodologies integrate BIM objects for design and construction. To overcome the problems of the conventional construction management practices, Yalcinkaya and Arditi [34] discussed different construction management categories like budget management, decision management, safety management and another nine areas of construction management. With the BIMs takeover of design and construction activities, it would be beneficial for all parties to have a mutual understanding of updated construction management duties and responsibilities during all phases of the construction project. Bhusar and Akhare [35] conducted environmental impact-based life cycle assessment and developed a model which connects the BIM software and structural analysis software in their work. The Revit® model was exported into Robot Structural Analysis® (RSA) software to perform structural analysis. This approach of BIM helped to keep all the essential information of design, analysis, and documentation in one place which helps in better communication between different parties.

Even though BIM data is stored and transformed through Autodesk Revit® files, Zhao et al. [36] proposed a framework for BIM through a private platform. The integration of BIM and cloud computing resulted in a higher performance at lower cost. The BIM integrated service platform is used for data integration and model information extraction for multiple users. A NoSQL database is used to store the data. In the end, the users were able to store relevant data on their servers while the overall data was virtually integrated through cloud computing platform. Anil et al.

[38] analyzed a structure that was heavily impacted by the earthquake and used BIM as a key tool to provide accurate geometric, reinforcement and material properties. The transformation of the structure caused by the seismic activity is developed as 3D images using BIM.

Even with the advancement of communication technology, the point cloud services still not able to provide highly accurate physical measurements. To overcome this drawback, Jung et al. [39] developed a 3D-modeling of indoor structures like windows and doors using BIM from point cloud services. To develop this study they used a seminar room to acquire the geometric parameters of the room using laser scanning. A mathematical method was proposed to develop the windows and doors in the design. Infrastructure asset management optimizes costs, risk, and performance of assets throughout their life-cycle. BIM for infrastructure asset management delivers value by sustaining the creation, collation, and exchange of data. Fanning [59] documented the current utilization of BIM practice by providing a case study of two bridge construction projects one with BIM and another with traditional manner. BIM on bridge projects improves the efficiency and effectiveness of design and construction. The proposed study [41] focused mainly on the complexity and uncertainties of the structure; BIM aided designs, optimization of construction schedules, and construction management tools. For effective collaborative design, construction, and maintenance a 3D model with metadata shares information of the design [62].

The key benefit of BIM lies in its accurate geometrical representation of building components to make decisions and perform facility maintenance. Out of many existing BIM software, Autodesk Revit® has 2D capabilities of the AutoCAD® as well as attributes associated with 3D modeling design. In case of historical and heritage buildings with absence of the drawing sheets and blueprints, Autodesk Revit® allows communication with third-party sources which makes it possible to generate the models in the cloud by gbXML format file [43]. Autodesk Revit® allows the simulation, analysis, and comparison of all projects in a global view for the optimal visualization of the heritage buildings. The interactive management of the structural elements provides a seamless visualization tool.

Autodesk Revit Architecture® is the most widely used BIM tool for architectural design. It includes routines to extract quantities automatically from the model. On selecting the elements to be identified, it defines the measurement parameters [44]. The Autodesk Revit® allows selection of all object types in the model database, thereby making it possible to extract properties related to all types of materials. Autodesk Revit® Structure provides components for a significant element types such as beams, columns, walls, and slabs. In addition to those, Revit Precast tools provide components to reinforce foundations and different other types of structural connections between beams and columns including corbels and joist hangers, and between columns and foundations [45].

1.3 Applications of BIM in SHM

Bridges and buildings are one of the large infrastructure in the construction industry that need monitoring against environmental and climatic changes, excessive loadings and human-made activities. For the last two decades, SHM is developed as a useful tool to monitor the condition of the structures. The active monitoring of the structures follows appropriate tools like data management, data storage, damage detection and data retrieval. The data management is substantial since it is proved as an inter-operable building model and specifications of the building objects for better exchange of data. The organization of all the raw data and preprocessed data, during the assessment of the structure, can add up hundreds of gigabytes of data which can lead to misalignment of data. Simulating the sensor data of bridges using BIM models will visualize all the sensor information which can make the proper advantage of data interpretation and detects the damages in the model. BIM uses a static data source to assess the structure. Therefore, extending the application of BIM model from static to dynamic model by linking the sensor data will give effective results to assess and interpret the ongoing performance of the structure.

In traditional methods, bridge maintenance decisions are made based on the engineering judgment. Consequently, acquiring more extensive and detailed data in a real-time inspection can result in better management decisions. Mcguire [46] developed a bridge information modeling and evaluation method to evaluate the damage location and structural performance. The authors developed various tools to investigate the effects of damage on bridge members attempting to document the location of damage through electronic media that can prioritize better decision making and public safety. Shakramanyan et al. [47] discussed the three stages of a real-time structural monitoring system that followed the design, construction and maintenance stages using sensors and performed analysis using "SODIS building M" software as shown in Fig. 1.5.

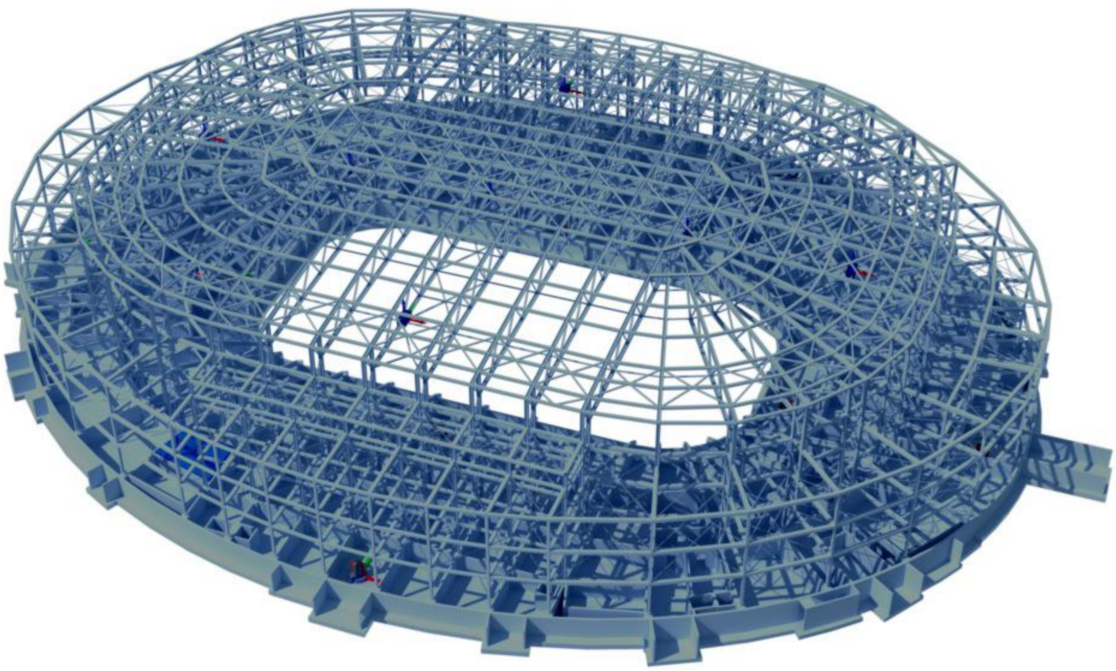


Figure 1.5: BIM model of the Maly Ice Arena in Sochi [47].

There has been several implementation of BIM for facility management. For example, Chen and Chu [48] developed a time-dependent vehicle routing problem using BIM approach. The graphs were developed for different building routes to acquire best decisions by using Autodesk Revit®, MATLAB®, and C-programming. Even though the proposed case study could produce escape sequences for rescue management, the application of BIM has limited use in the development of real-time information retrieval and modeling of pedestrian and risk flow in the time-dependent model. Delgado et al. [49] used BIM for visual sensor information for an effective action. A precast concrete bridge located in Staffordshire, UK was used as a case study. The modeling and visualization of the monitoring data were performed using Revit®. The values of the strain attributes of each sensor entity were linked with the material attribute of the BIM model. Banfia et al. [50] included 3D digital surveys, parametric modeling and monitored data sets for documentation and visualization of SHM information. A 3D web share cloud technology was used to develop a 3D model of a bridge. With the implemented digital information, SHM allows the management of the structure using the user-friendly software. A semantic rich BIM model can facilitate more streamlined approaches to SHM and data management and can generate changes in structural behavior [51]. With the current opportunity, before performing any analysis, the BIM model can be inspected directly and can deliver necessary safety precautions. Marzouk [52] discussed the successful implementation of BIM on bridges through bridge information modeling.

Despite the trending developments in the intelligent SHM, it is still not possible to digitally represent the sensor information. Kay and Eike 2015 [53] discussed the opportunities and challenges towards the digital representation of SHM systems using Industry Foundation Class (IFC) which was used to bridge the gap between sensor models and BIM. Maximilian and Kosmas [54] explained the different methodologies to perform the SHM. By integrating and monitoring the related information into BIM helps in categorizing, documenting and updating monitoring related to information throughout the life cycle of the structure. Traditional approaches take a long time to exchange the data with limited access as well as errors associated with manual data. Integrated design and delivery solutions priority theme uses collaborative work process and enhanced skills with integrated data and knowledge management to boost the structural efficiency [55]. The successful use of integrated design and delivery system changes the project phases from conceptual planning and business formulation to all stages of design, construction, operation, commissioning and decommissioning.

The methods of manual checking is no longer efficient for massive and complex structures as it consumes more time and labor. Park 2015 [56] focused on resolving building safety issues through BIM. BIM-based quality control is of three types: physical quality control; consistent quality control; data quality control. BIM-based quality control ensures the safety of both individual independent models, as well as models with integration. To organize the multi-scale image system, [57] proposed an approach and developed a web-based tool named *BridgeDex* within a geographic information system. Using the developed tool, users can view the spatial and temporal information of the bridge by linking the images with the bridge metadata, including inspection notes, drawings, and possible test results of the structure.

For long-span structures, visual inspection techniques facilitate real-time maintenance to improve the overall safety of an aging structure. Chan [58] proposed an approach for bridge asset management systems using an unmanned aerial vehicle. Using the images captured by the UAV and a BIM model, the bridge inspector identifies damage location and rate of progressive deterioration of the structure. [59] investigated the current utilization of BIM practices in bridge construction and inspection. The application of BIM reduced the expenses of the project when compared with the non-BIM-based practices. Grosso [60] utilized a 3D BIM model that are updated by adding time data (4D), cost data (5D), facility management (6D) and sustainability (7D) for better functioning. Even though many BIM models are configured up to 5D, the problem of extending the model towards facility management stage involves several drawbacks. Through BIM family parameters and shared parameters, the sensor data visualize on Revit® and Navisworks® (4D) platforms. The main limitation identified was the absence of standard interface between SHM and BIM tools. Bridge inspections require survey data to undertake visual inspections and structural assessment. Minehane [61] used laser scanning that offers safety and remotely accesses comprehensive information without direct contact with the structure. It also allowed rapid decision making and evaluation to satisfy building safety requirements. For effective collaborative design, construction, and maintenance, a 3D model with meta-data shares information of the design [62]. This interoperability enhances the design revision process and communication for better productivity.

1.4 Gap Areas

1. The BIM implementation for SHM is mostly limited to small-scale structures, and there are insufficient real-life implementations of BIM technology in SHM.

2. There is a lack of BIM models to visualize and monitor the entire life-cycle of structures with the SHM information. There are very limited research on detailed documentation to track progressive maintenance strategies and their

subsequent effectiveness in improving the overall health of structures. The resulting shortage of the accurate information of structural health leads to incorrect decisions regarding maintenance, retrofitting and facility maintenance of the bridges.

3. Even with the access of accurate and comprehensive information of several failure modes, it is still challenging to accurately quantify uncertainties occurred during the life-cycle analysis of a bridge. Therefore it is necessary to consider maintenance strategies to quantify the overall benefit of monitoring of large span bridges.

1.5 Thesis Objectives

Based on the above gap areas, following key objectives are identified to pursue in the current thesis.

1. To integrate SHM with BIM for better visualization of diagnosis and prognosis information, thereby pursuing better damage assessment of the entire structure.

2. To develop decision-making tools of SHM within the BIM to identify the structural performance under various weather and operational conditions.

3. To come up with an integrated model that shows the complete sensor information and diagnostic results for the entire life-cycle of the structure that would be beneficial for the infrastructure owners.

The thesis is outlined as followed. Firstly the background of SHM and BIM is presented in **Chapter 1** followed by the formulation of the proposed algorithm in **Chapter 2**. In **Chapter 3** and **Chapter 4**, experimental and full-scale studies are demonstrated in a long-span bridge and a short-span bridge, respectively. Finally, the conclusions of the proposed research are discussed in **Chapter 5**, and then the major contributions and recommendations of future work are presented.

Chapter 2

Proposed Framework

This chapter provides an overview of the proposed research and the methodologies implemented to visualize the SHM information within the BIM through Autodesk's Revit®. The applications of Revit® are explained in the context of tool development. The approach uses Revit® and MATLAB® as base platforms to integrate the sensor information with the diagnostics results. Unlike other Autodesk software, Revit® has a capability of designing 3D-models as well as can perform facility maintenance through time-to-time monitoring of the model with the updated model of the selected infrastructure. The dynamic behaviour of the structure is then analyzed using the sensor data in MATLAB®.

2.1 Proposed Methodology

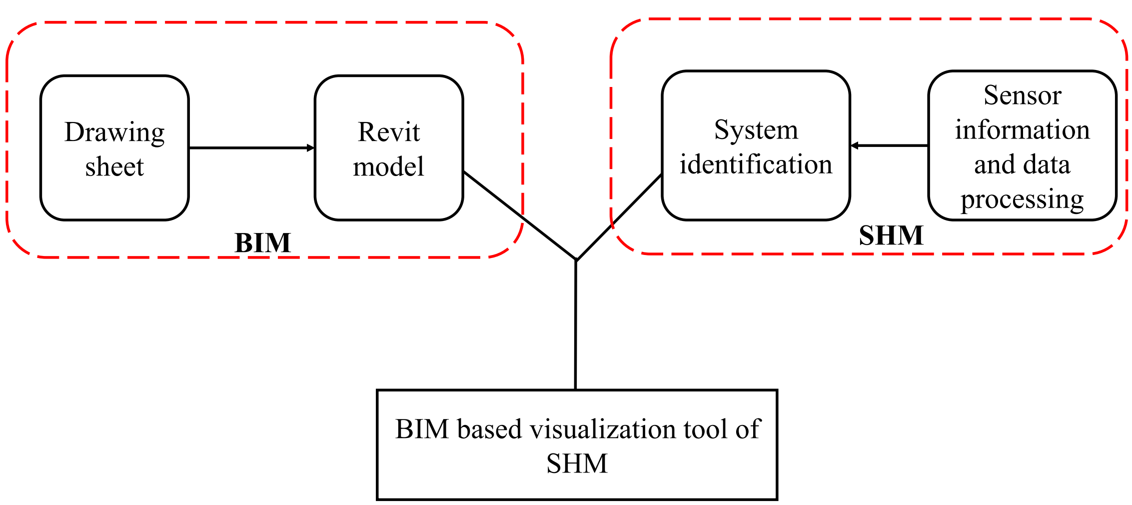


Figure 2.1: Layout of the proposed framework.

The proposed framework harnesses the relative merits of SHM and BIM to develop the visualization tool for monitoring of large-scale infrastructure. The data and system identification information of SHM are systematically embedded with the BIM software such that long-term health monitoring information can be visualized in ease and used for maintenance and decision making purpose. As shown in Fig. 2.1, the proposed research is consisted of four key steps (a) drawing sheet, (b) BIM model, (c) sensor data, and (d) data processing [64].

Both AutoCAD® and Revit® are used to develop 2D drawings such as elevations, floor plan, side views and object features. They differ in their performance through graphical representation. AutoCAD® uses basic geometry to represent real-life objects, whereas Revit® uses object-based elements which are featured with real attributes. For the approach presented in this thesis, a structural model is developed that closely represents the real-life structure. The data represented in attributes define the physical, geometrical and abstract properties of the structure. As shown in Fig. 2.2, with the help of 2D drawings, the structure is developed into a 3D model with all the generic parameters and properties using Revit® (BIM). This model provides the real-time appearance of the structure with all the material properties as well as model updating during its service period.

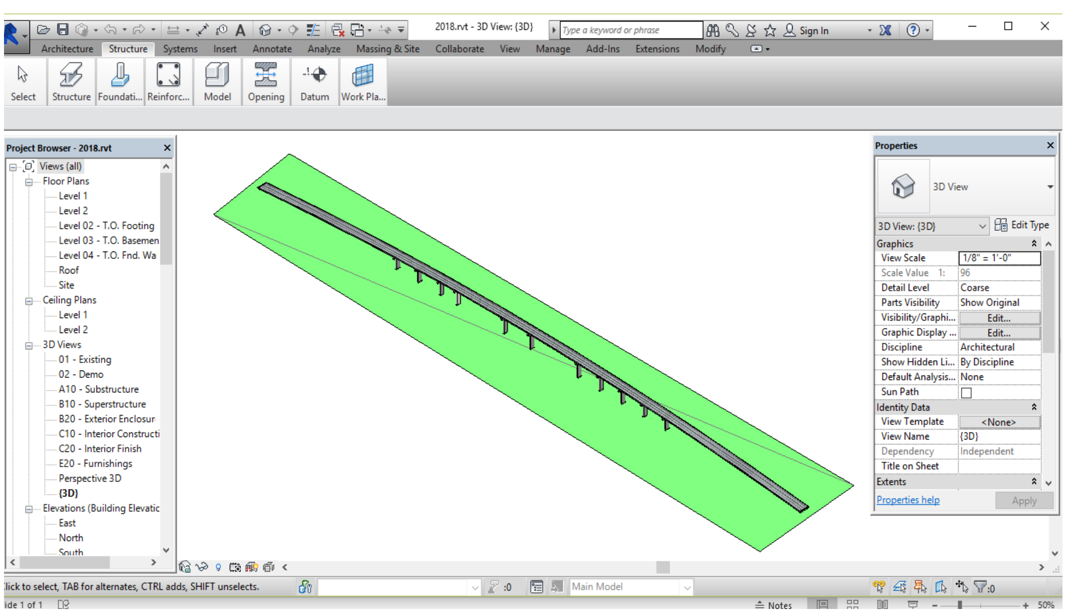


Figure 2.2: Graphical representation of the test structure in Revit® with its key features.

The integration of finite element analysis in BIM software offers a better alternative for monitoring complex structures. In particular, BIM simplifies the modeling work through robust exchange of design information using Robot Structural Analysis®. The structural analysis tool, namely Autodesk Robot Structure®, is fully integrated with Revit® and BIM platform. BIM allows different plugins and addons to integrate Autodesk Revit® with Robot Structural Analysis®. The integration of the Robot Structural Analysis® application with BIM is implemented as a series of *structural* class for direct access to the users. The structural *analysis* object creates a collection of structural *result* objects corresponding to the collection of input structural objects.

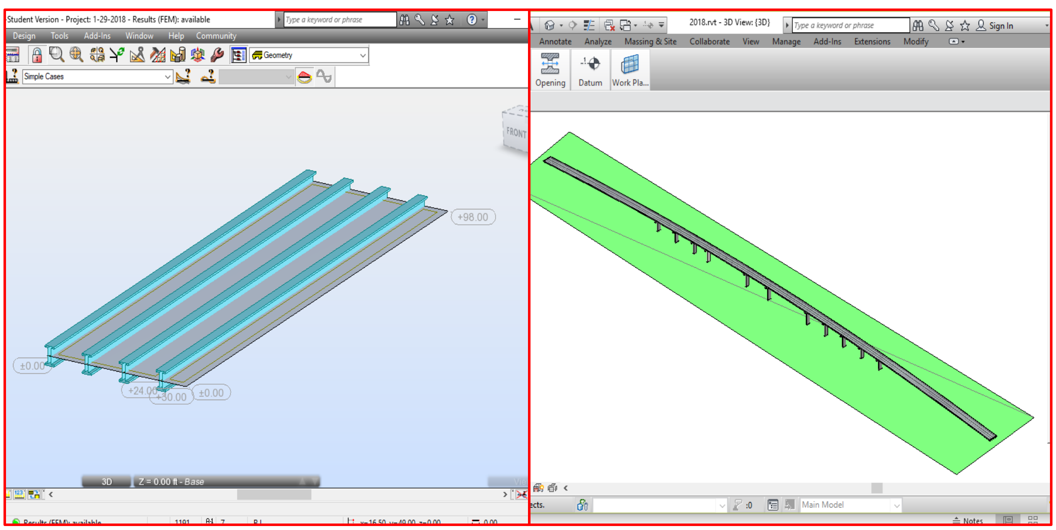


Figure 2.3: Robot structural analysis® and the Revit® model.

The BIM platform reduces the working space for structural analysis by linking its model to other structural analysis software. The integration between Revit® and Robot structural analysis® (RSA) allows bi-directional data exchange between both the platforms. The BIM platform reduces the working space for structural analysis by linking its model to other structural analysis software. Robot Structural Analysis® (RSA) as shown in Fig. 2.3 is one of those softwares that links to the current BIM platform. With the integration tool, the results of static analysis and the required calculated deflections are transferred to the Revit® model. Modeling a structure in Revit® helps to visualize the relationship between real-time structure and its analytical simplification. The obtained results from RSA® are saved as readable files for the parental platform.

Apart from performing the static analysis, the results from dynamic analysis helps in monitoring the structure during its service period. Sensors connected to the bridge are utilized to collect vibration response of the structure under different operating conditions. The collected data is processed using MATLAB® and modal responses are extracted using a popular system identification method, namely Second Order Blind Identification (SOBI) method [66]. The modal identification is facilitated with the FE model of the structure, and the FE model is compared with the experimentally obtained modal parameters. All the results are projected in the BIM model. These results help in monitoring the performance of the structure during the different period of data collection. The comparison between the recorded modal frequencies and the Finite Element (FE) model gives a better understanding of the evolution of structural damage.

2.2 Summary of the Approach

1. Convert the two-dimensional (2D) drawing of a structure into a three-dimensional (3D) BIM model.

2. Export the designed BIM model into RSA® to perform static analysis.

3. Collect the vibration data of the real structure using appropriate instrumentation.

4. Assign the required sensor information in Revit® model to visualize the data and process information.

5. Analyze the collected data using a system identification method through MATLAB®.

6. Compare the static and dynamic analysis of the structure using the FE model and system identification.

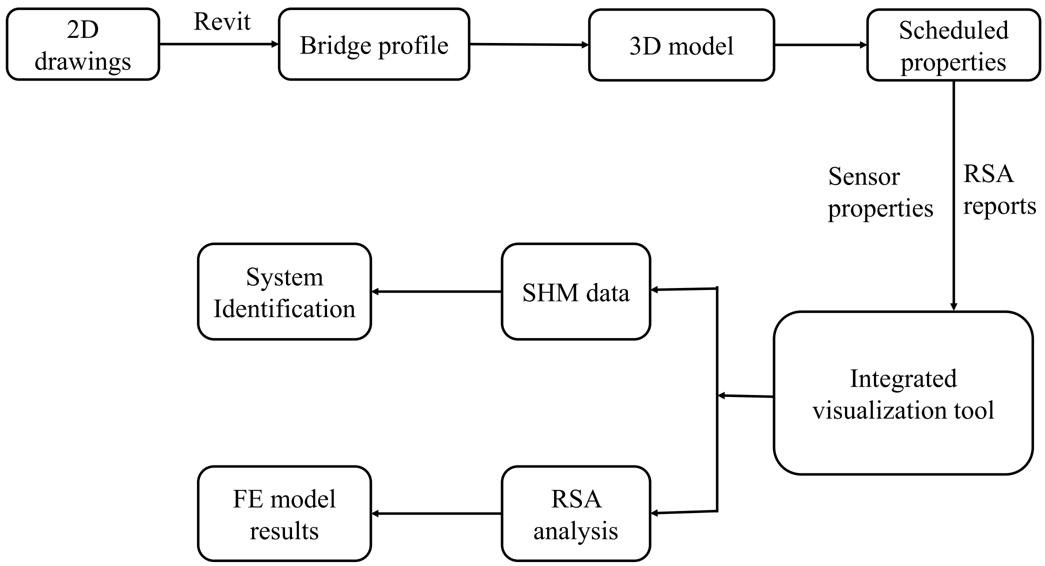


Figure 2.4: Detailed flowchart of the proposed integrated tool.

2.3 System Identification Method

One of the important steps of the proposed tool is to compare system identification results of the periodically collected data. In this research, one of the popular blind source separation-based methods [6, 65], namely second-order blind identification (SOBI), is adopted which is briefly introduced in the following section. The SOBI method is primarily based on second-order statistics of the signal.

2.3.1 Second-order blind identification

The basic dynamics of a structure can be considered as a linear, classically damped, and lumped-parameter n degrees of freedom system, subjected to an excitation force, $\mathbf{F(t)}$.

$$\mathbf{M\ddot{x}(t)} + \mathbf{C\dot{x}(t)} + \mathbf{Kx(t)} = \mathbf{F(t)}, \tag{2.1}$$

where $x(t)$ is a vector of displacement coordinates at the degrees of freedom. M, C and K are the mass, damping and stiffness matrices of the system respectively, and $\mathbf{F(t)}$ is the input excitation to the system that is assumed to be Gaussian and broadband. The solution to Eq. (2.1) can be written in terms of superposition of vibration modes with the following matrix form [65]:

$$\mathbf{x} = \mathbf{A}\mathbf{s}, \tag{2.2}$$

where, $x \; \epsilon \quad m \; \times \; N$ is the measurement matrix composed of the sampled components of x, $s \; \epsilon \; n \; \times \; N$ is a matrix of the corresponding modal coordinates, $\mathbf{A_{m\times n}}$ is the modal transformation matrix and N is the number of data points of the measurements. The column of $\mathbf{A}$ matrix are linearly independent, and they represent the modeshape matrix of structure. The SOBI method [66] aims to formulate two covariance matrices $\mathbf{R_x(0)}$ and $\mathbf{R_x(p)}$ evaluated at the time lag zero and p from the observed measurements, then simultaneously diagonalize them in order to find unknown mixing matrix, $\mathbf{A}$. The key steps of the SOBI method are as follow;

$$\begin{aligned}
\mathbf{R_x(0)} &= E[\{\mathbf{x(n)}\}\{\mathbf{x(n)}\}^{\mathbf{T}}] \\
&= \mathbf{A}\mathbf{R_s(0)}\mathbf{A}^T \\
\mathbf{R_x(p)} &= E[\{\mathbf{x(n)}\}\{\mathbf{x(n-p)}\}^{\mathbf{T}}] \\
&= \mathbf{A}\mathbf{R_s(p)}\mathbf{A^T}
\end{aligned} \tag{2.3}$$

where

$$\mathbf{R_s(p)} = E[\{\mathbf{s(n)}\}\{\mathbf{s(n-p)}\}^{\mathbf{T}}] = \mathbf{I} \tag{2.4}$$

The measured responses $\mathbf{x(n)}$ are zero-mean, and the whitening is obtained as follows. The singular value decomposition is used to diagonalize $\mathbf{R_x(0)}$:

$$\mathbf{R_x(0)} = E[\{\mathbf{x(n)}\}\{\mathbf{x(n)}\}^{\mathbf{T}}] = \mathbf{V_x}\lambda_{\mathbf{x}}\mathbf{V_x}^{\mathbf{T}} \tag{2.5}$$

where, $\mathbf{V_x}$ is the eigenvectors matrix and $\lambda_{\mathbf{x}}$ is the eigenvalue matrix. The whitened signals are then computed as shown in equation (2.6) where, $\mathbf{Q}$ is realized as whitening matrix,

$$\begin{aligned}
\bar{x}(n) &= \lambda_{\mathbf{x}}^{\mathbf{-1/2}}\mathbf{V_x}^{\mathbf{T}}\mathbf{x(n)} \\
&= \mathbf{Q}\;\mathbf{x(n)}
\end{aligned} \tag{2.6}$$

The reason for whitening is to remove the correlation between the measured responses.

$$\mathbf{R_{\bar{x}}} = E[\{\mathbf{\bar{x}(n)}\}\{\mathbf{\bar{x}(n)}\}^{\mathbf{T}}][\mathbf{A}] = \mathbf{I}. \tag{2.7}$$

Due to whitening process $\mathbf{R_x(p)}$ becomes $\mathbf{R_{\bar{x}}(p)}$, which is given by:

$$\begin{aligned}\mathbf{R_{\bar{x}}(p)} &= \frac{1}{N}\left[\sum_{\mathbf{n=1}}^{\mathbf{N}} \mathbf{\bar{x}(n)\bar{x}(n-p)^T}\right] \\ &= \mathbf{QR_x(p)Q}^T = \mathbf{QAR_s(p)A}^T\mathbf{Q}^T.\end{aligned} \tag{2.8}$$

Eq. (2.8) reveals that whitened covariance matrix at a particular time-lag can be diagonalized; therefore the product $\mathbf{QA}$ is realized as unitary matrix and can be determined. During the orthogonalization process, the whitened covariance matrix $\mathbf{R_x(p)}$ is diagonalized whose eigenvalue decomposition satisfies

$$\mathbf{V_{\bar{x}}R_{\bar{x}}(p)V_{\bar{x}}}^T = \lambda_{\mathbf{\bar{x}}} \tag{2.9}$$

The diagonal matrix $\lambda_{\mathbf{\bar{x}}}$ has distinct eigenvalues, thus the mixing matrix can be estimated by the following equation,

$$\mathbf{\hat{A}} = \mathbf{Q^{-1}V_{\bar{x}}} = \mathbf{V_x}\lambda_{\mathbf{x}}{}^{\mathbf{T}}\mathbf{V_{\bar{x}}}. \tag{2.10}$$

In order to find the unitary matrix $\mathbf{QA}$ that diagonalizes the whitened covariance matrix $\mathbf{R_{\bar{x}}(p)}$ at one or several non-zero time lags, the SOBI carries out an approximate joint diagonalization approach based on Givens rotation technique. Consequently, the associated problem becomes to find minimum performance index $\Im$, such that unitary diagonalization satisfies $\mathbf{D} = \mathbf{V^TR_{\bar{x}}(p)V}$ [66],

$$\Im(V,p) = \sum_{p} \sum_{1 \leq i \neq j \leq n_s} ||D_{ij}^p||^2, \tag{2.11}$$

where, $\mathbf{V}$ is the unitary matrix and also the joint approximate diagonalizer for all p-shifted covariance matrices $\mathbf{R_x(p)}$ [66]. Therefore, the estimated sources can be obtained once the estimated mixing matrix is calculated,

$$\mathbf{\hat{s}(n)} = \mathbf{\hat{A}^{-1}x(n)}, \tag{2.12}$$

where, $\mathbf{\hat{s}(n)}$ contains the modal responses in time-domain from which the modal frequencies and damping ratio can be obtained [67, 68].

Chapter 3

Case Study: Large-span Bridge

In this chapter, the proposed method is validated using a long-span bridge located in Thunder Bay, Ontario. This chapter demonstrates the application of the proposed tool developed in this thesis. The model developed in Revit® is integrated with the sensor information of the SHM. All the results are shown in a user-friendly format and integrated with the visualization platform of Revit®. The results of the structural analysis obtained from RSA® are compared with the system identification results of the SHM data.

3.1 Bridge Description and Instrumentation

Figure 3.1: Large-span bridge, Thunder Bay.

The selected large-span bridge is located in Thunder Bay, Ontario as shown in Fig. 3.1. The reinforced concrete bridge is approximately 1000 ft long and 24 ft wide. Since its construction, the bridge has seen a significant increase in heavy traffic between the City and the Marina. This bridge was instrumented with vibration sensors in winter 2017 [15] and spring 2018, respectively and the collected long-term data and the evolution of structural health is demonstrated here to illustrate the proposed tool.

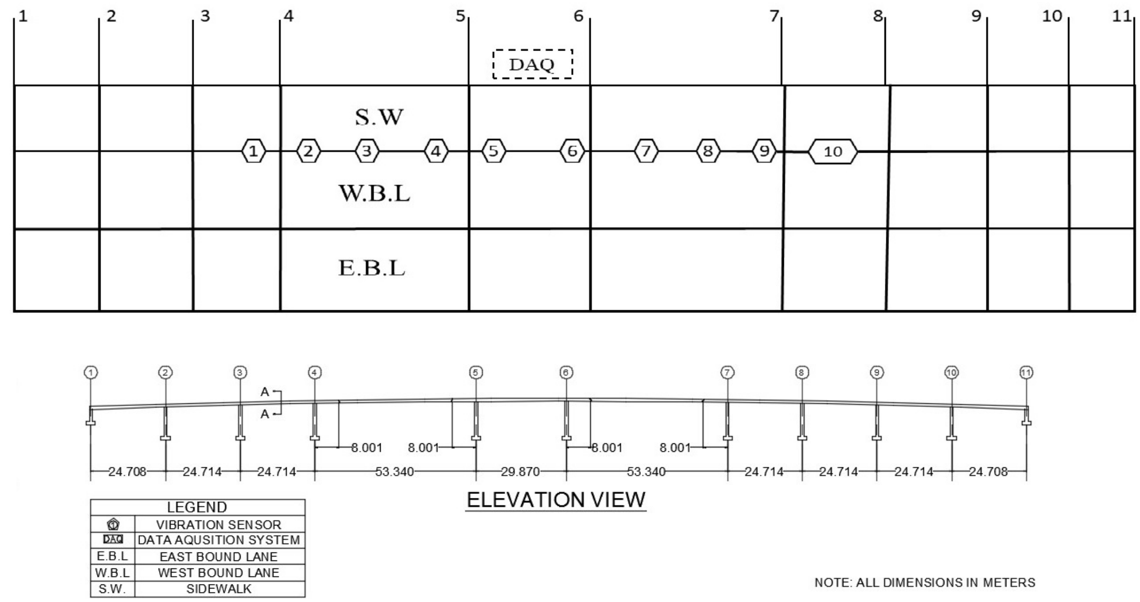


Figure 3.2: Location of the sensors and layout of the bridge.

The vibration testing was performed on the bridge on January 20th, 2017 between 9am - 12pm and on April 23rd, 2018 between 9am - 12pm. The temperature during the test was around to -5°C, and 15°C in 2017 and 2018, respectively. Ten sensors were placed along the walkway on the North side of the bridge, and the sensors were set up to measure uniaxial vibration in the vertical direction. Each sensor has a sensitivity of 10V/g. The spacing of the sensors and the location of the Data Acquisition (DAQ) System is shown in Fig. 3.2. The data collection was performed through DAQ by connecting it with sensors using BNC cables and with a laptop using a USB cable.

A various number of vehicles travelled across the bridge at different speeds during the tests. The duration of each test was between 30 seconds to 2 minutes, and sampling frequency was set to 200 Hz. As shown in Fig. 3.3, sensors were installed on the walkway, located close to one side of the bridge. As shown in Table 3.1, twelve tests were performed with a different class of vehicles such as cars (3000 lbs), trucks (20000 lbs) and large trucks (40000 lbs) at various speeds. The vehicles and the tests are documented in chronological order of occurrence. The description of the test details is mentioned in Table 3.1.

Table 3.1: Test details

Test No.	Car	Truck	Large Truck	Total Nos. of Vehicles	Total Weights (lbs)
1	4	1	1	6	72000
2	6	1	2	9	118000
3	2	0	0	2	6000
4	0	1	0	1	20000
5	7	1	2	10	121000
6	3	0	1	4	49000
7	14	2	3	19	202000
8	2	1	0	3	26000
9	0	0	1	1	40000
10	4	2	0	6	52000
11	6	1	1	8	78000
12	2	1	0	3	26000

Figure 3.3: Sensors (highlighted using yellow box) placed on the side walk and the vehicles running on the bridge during the test.

3.2 Data Processing and System Identification

Measured sensor data is shown in Fig. 3.4(a) under a typical traffic condition. The time-domain data is processed through a Fast Fourier Transform (FFT) and is shown in Fig. 3.4(b). The frequencies corresponding to peak response amplitude are selected using the peak picking method. In this way, the preliminary modal frequencies are identified. As shown in Fig. 3.5, vibration response for sensor 5 are plotted for a maximum and minimum number of vehicles. The results clearly reflect that the response increases significantly with more number of vehicles. Even though the number of vehicles passed through both the sensors is same, sensor 5 experienced more vibration than sensor 6.

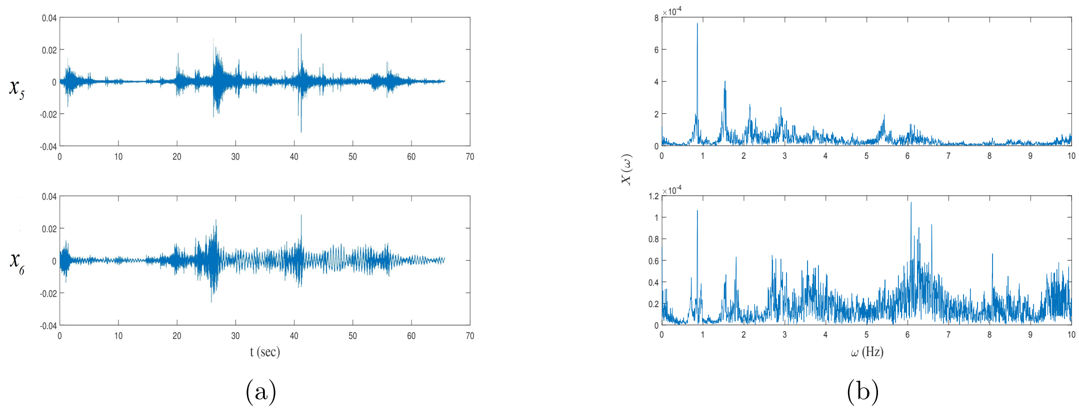


Figure 3.4: (a) Typical vibration data and (b) Fourier spectra of the measured data.

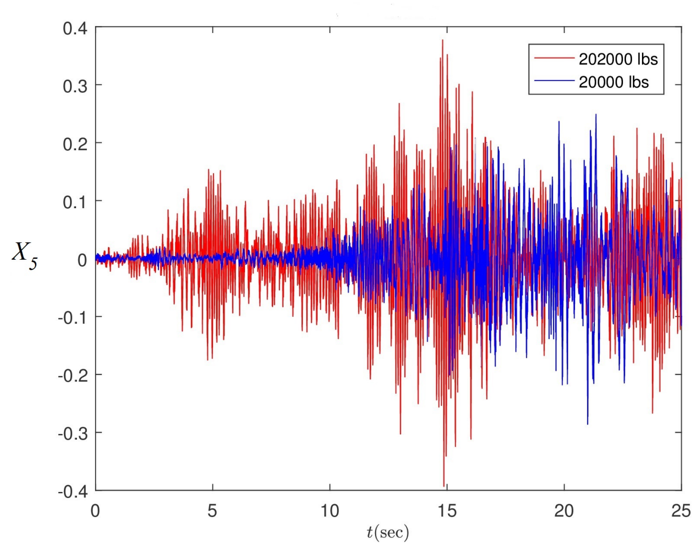


Figure 3.5: Time-history of mid-span sensor under maximum and minimum weights.

The collected structural response is processed in MATLAB® from time-history data to FFT. The maximum observed vertical acceleration for all sensors is 0.32 cm/s^2. Depending on the first flexural frequency, the code sets limits on acceleration from a serviceability perspective. For a first vibration mode of approximately 2 Hz, the code defines the maximum acceptable acceleration as 0.4 m/s^2 or 40 cm/s^2. The collected data falls well within these guidelines and thus is acceptable based on the typical traffic experienced by the bridge. It is expected that very heavy loading (e.g., wind turbines) crossing the span would excite much greater acceleration within the span.

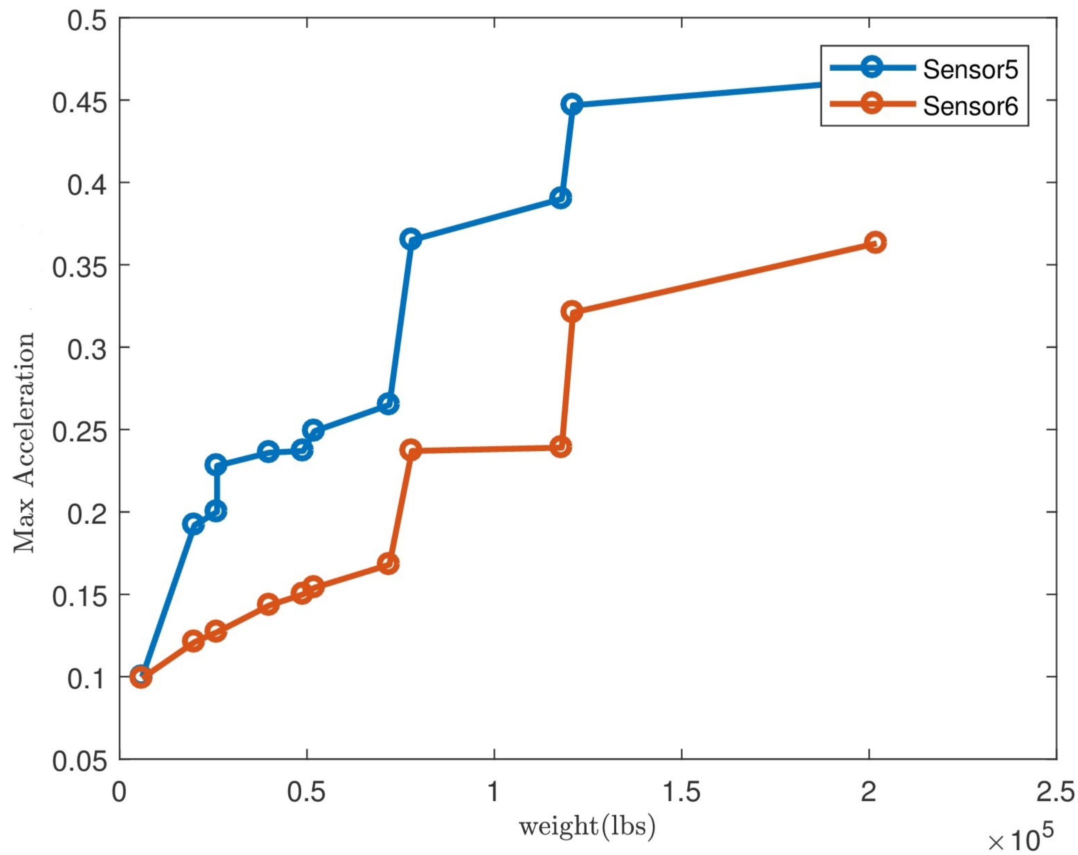


Figure 3.6: Peak vibration response of mid-span sensors under different traffic.

In order to correlate the amount of vehicular weight that passed over the bridge during each test, vehicle's weights were assumed for each type of vehicle from the website of the Department of Transportation. As shown in Fig. 3.6 the estimated maximum acceleration against vehicle weight for sensor 5 and sensor 6 are plotted and the root-mean-square (RMS) values of the accelerations of each test are plotted as shown in Fig. 3.7. The RMS value is higher for heavier vehicles, which caused more excitation, across the bridge during the test.

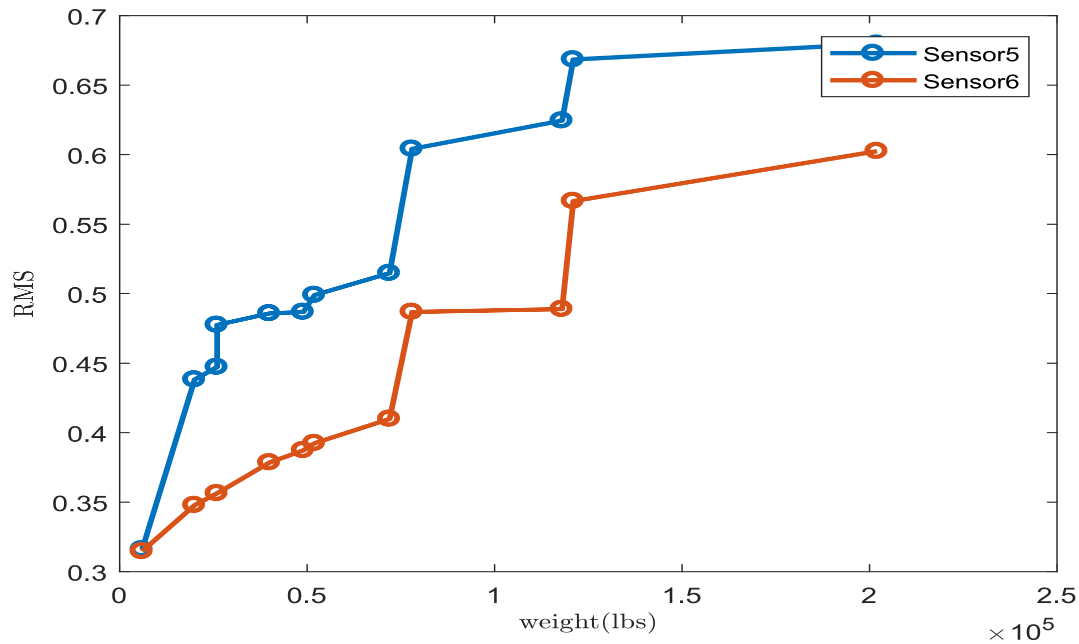


Figure 3.7: RMS acceleration of mid-span sensors under different traffic.

Once the preliminary data analysis is performed, the vibration data is processed through the Second-order Blind Identification (SOBI) method. The SOBI method has shown significant potential in ambient system identification to identify modal parameters of the structures, without the knowledge of excitation. The SOBI method is employed to perform a condition assessment to identify natural frequencies for both 2017 and 2018. The resulting typical modal responses are shown in Fig. 3.8.

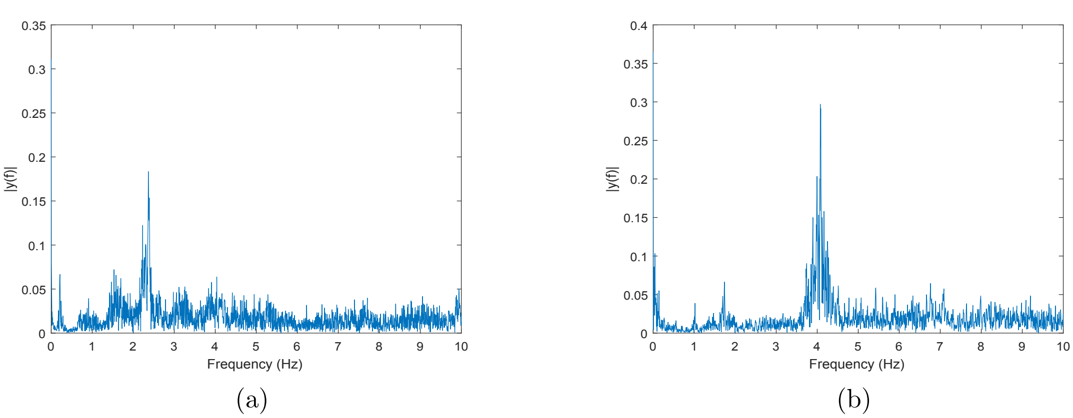


Figure 3.8: Sample modal response of measured data

Table 3.2: Comparison of FE model with the identified frequencies (Hz).

FE	2017	2018
2.34	2.33	2.33
2.4	2.5	2.42
3.7	3.9	4.05
5.8	5.5	5.5
7.6	7.8	7.7

3.3 Development of the BIM Model

After the data analysis is performed, the primary task is to integrate the sensor information into a user-friendly software which can provide easy access for long-term monitoring. For the current case study, Revit® is utilized as the BIM platform to integrate the SHM information. All the physical, geometric and material properties are approximately assigned to the model according to the real bridge. The sensor parameters are assigned to determine the type, location, extent, and rate of damage in the structure. Real-time maintenance and decision making are the main objectives of visualizing data acquired by the proposed monitoring systems.

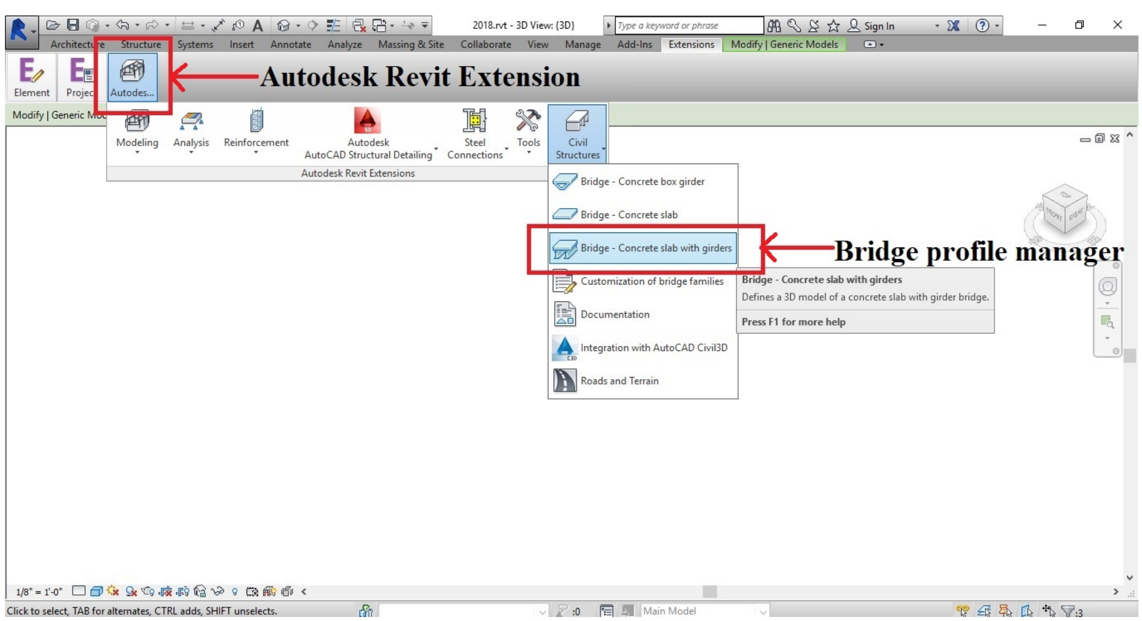


Figure 3.9: Autodesk bridge extension in Revit®.

As shown in Fig. 3.9, the Autodesk Revit® *extension* enables to generate 3D models automatically using their limited capability to perform structural analysis and design. The current structure is designed with sophisticated geometry, including road profiles, decks, abutments, piers, alignments and existing ground surfaces. Through bridge extension, the roads and terrain definitions provide feasibility to create road objects to topography in Revit®.

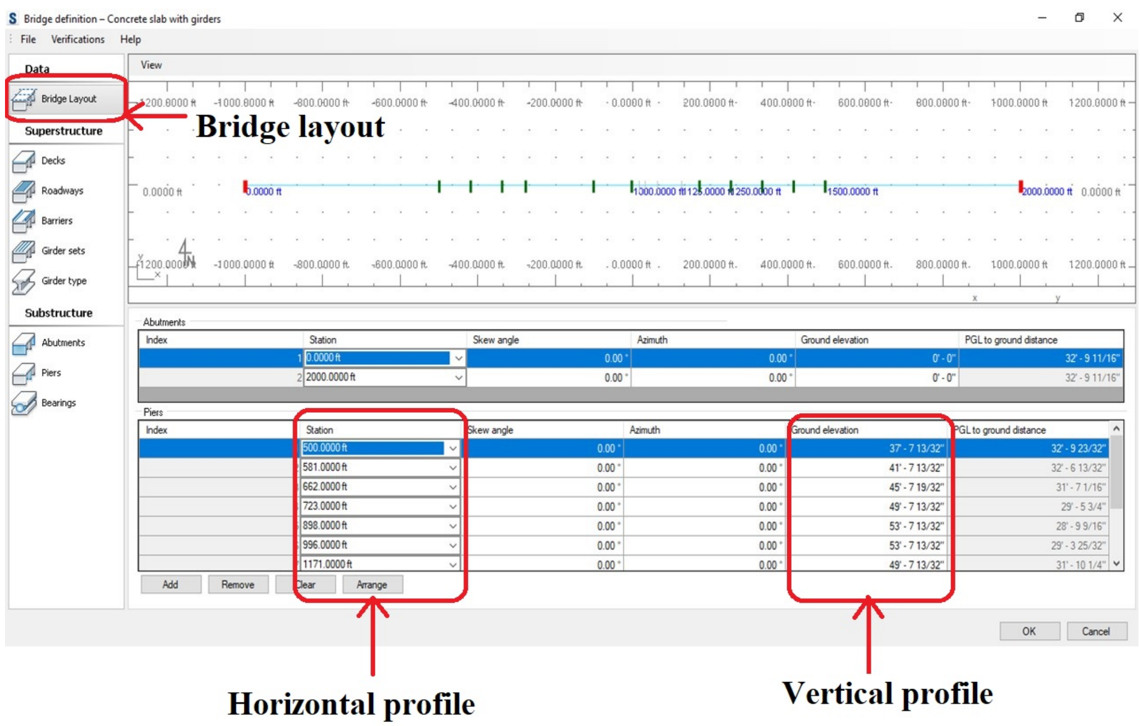


Figure 3.10: Layout of the bridge in Revit®.

In order to develop a bridge profile and alignments, the bridge profile manager provides the right tools to perform the task easily. The bridge profile predefines the set of properties and graphical representation of bridge family. In the Revit interface, through bridge profile manager, many of the components such as piers, abutments, decks are available a the click of the button in a customized manner. The extensions parameters import roadway model and present the model in tabular and graphical form. The data includes the vertical, horizontal profiles, cross sections and topology. As shown in Fig. 3.10, the bridge profile is used to define horizontal and vertical profiles, roadway, deck, abutments, piers, bearings, and railings. The bridge profile defines geometry via tabular input with well-defined names for variables and creates deliverables in a 3D model content. As shown in Fig. 3.10, using the bridge layout, the organization of vertical and horizontal profiles are developed by assigning the layout dimensions of the bridge.

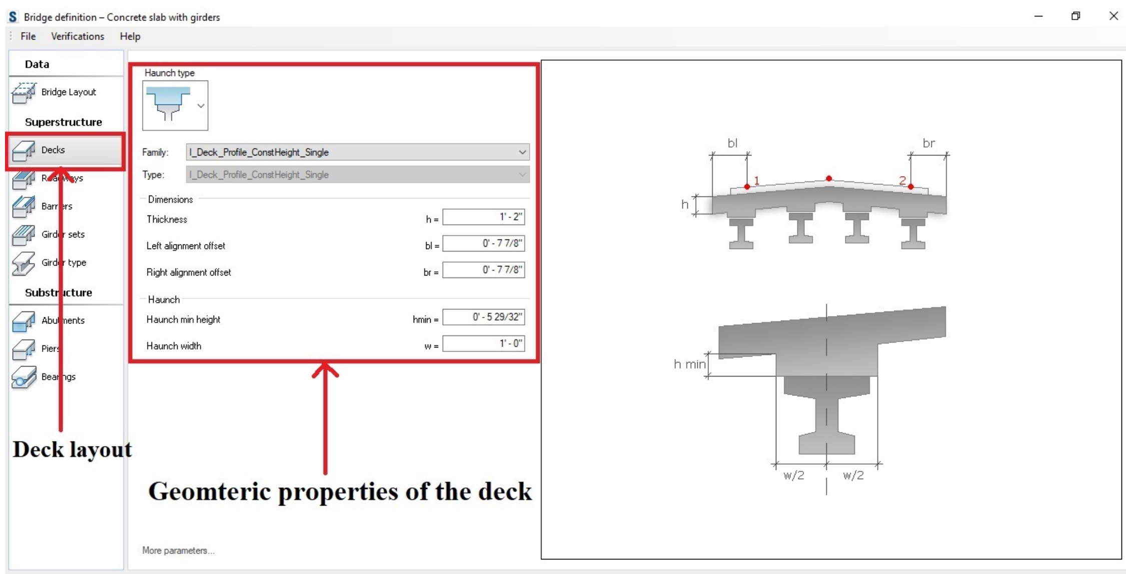


Figure 3.11: Deck layout of the bridge in Revit®.

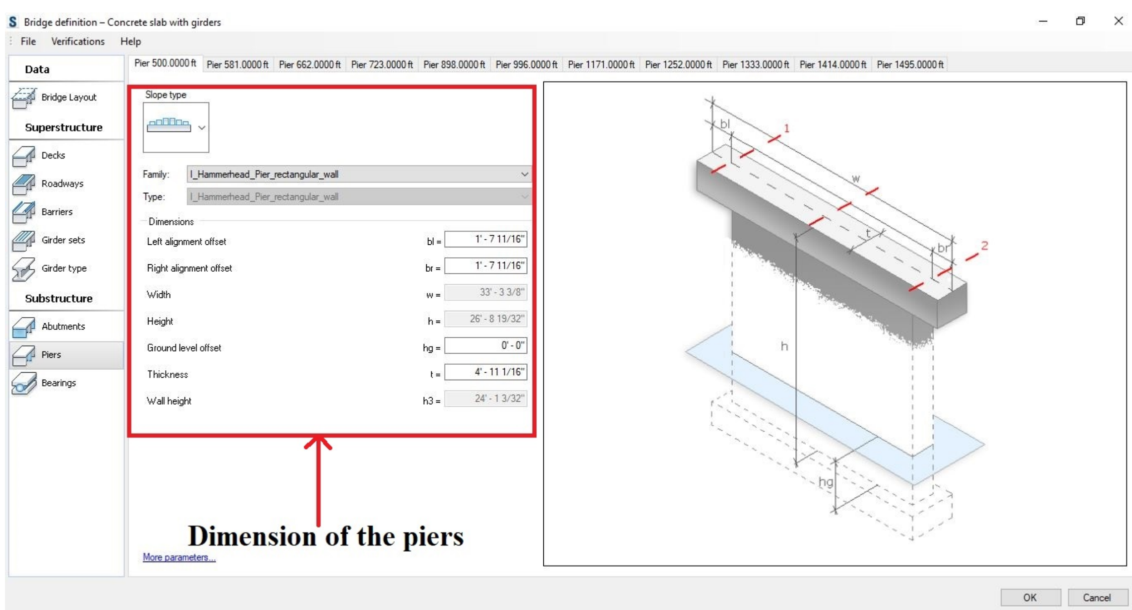


Figure 3.12: Alignment of piers of the bridge in Revit®.

The *Deck* menu as shown in Fig. 3.11 is used to define the geometry of the deck and beams. Using the available drawings of the test bridge, the super-elevation, width, and slope for each lane are defined in the dialog box which allows one to add an offset or skew angle to the first and last profile of the bridge deck. The deck profile is oriented with a concrete deck profile to generate the reinforcement to the model. As shown in Fig. 3.12, *pier* option defines the geometry and station of the piers. It configures the *pier number*, *pier choice*, *family type*, *type of foundation* and *family* that need to be projected to visualize them in the drop-down list. The current Revit® extension creates a various predefined list of color scheme system for areas and keynote text files for piers, decks, bearings and provides user-defined families to represent each structural object and generates fundamental documents for the entire model as shown in Fig. 3.13, which represents plan views, section views and elevation views with respect to the available drawing sheets.

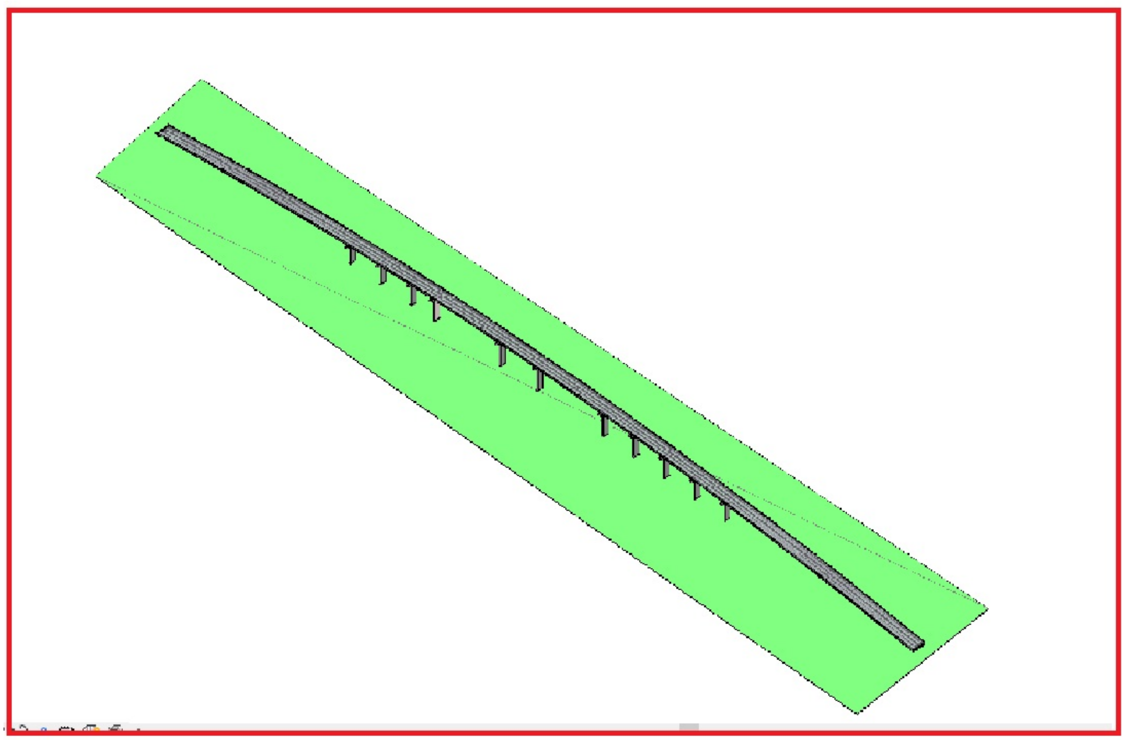


Figure 3.13: Revit® model of the bridge.

3.4 Robot Structural Analysis

Once the model is developed in Revit®, the structural analysis is performed using the Robot Structural Analysis® (RSA). RSA is Autodesk's FEM structural analysis program that has the capability to analyze the most complex models with powerful finite element auto-meshing, nonlinear algorithms. However, it does not contain the provision of the Canadian Highway Bridge Design Code (CHBDC). Thus the designed load combinations are manually entered in the software.

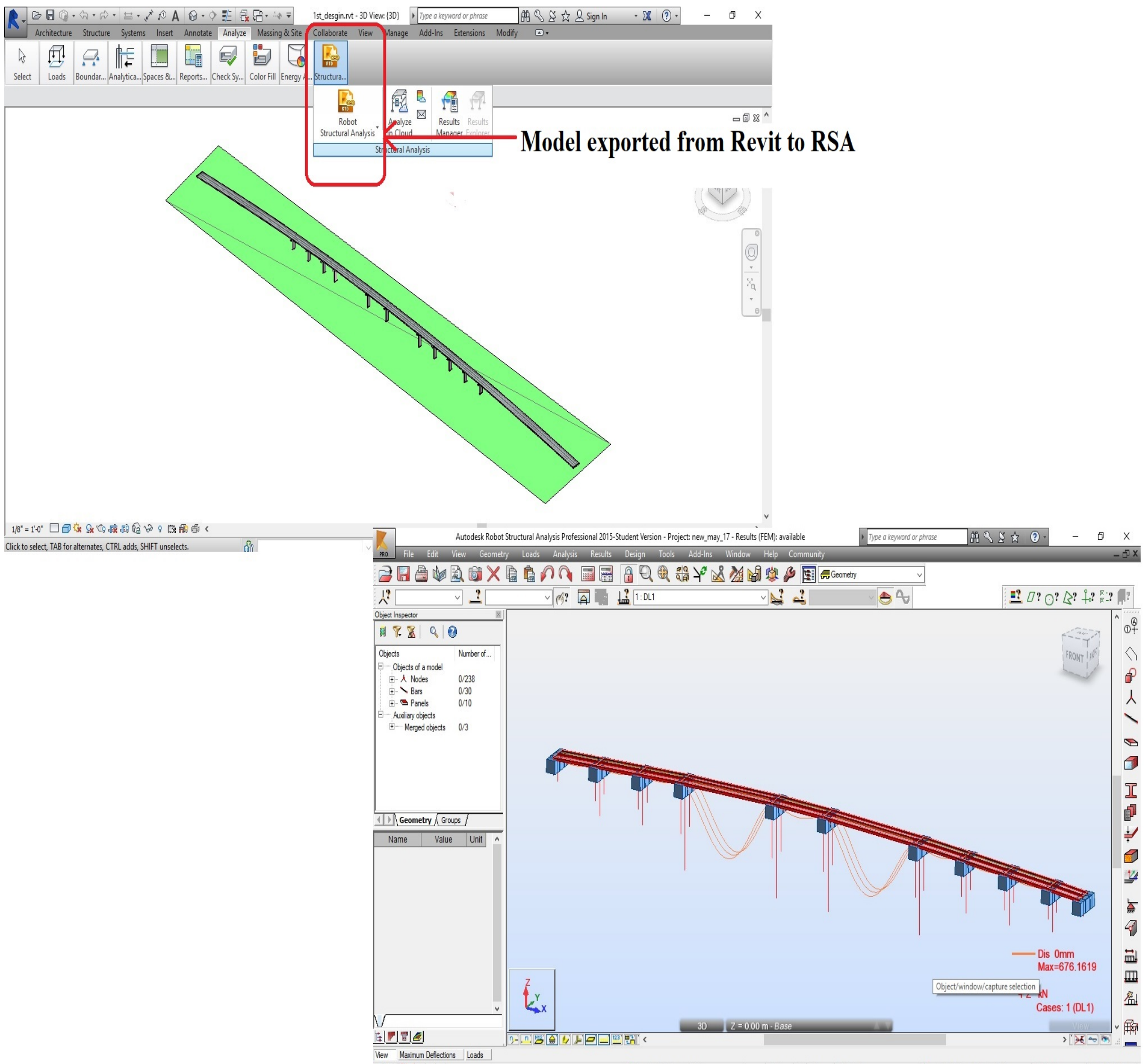


Figure 3.14: Transformation of the BIM model from Revit® to RSA®.

The designed Revit® model is exported to RSA® as shown in Fig. 3.14 to perform analysis. The non-linear static analysis through RSA® considers the second-order effects, due to change in stiffness and moments generated due to the applied vertical forces at nodes. The current software allows the simple and adequate analysis of many types of structural elements such as tension and compressions members, plastic hinges, cables, supports. To perform the analysis, design loads are considered from the CHBDC code. A combined live load, dead load, and thermal load are applied on the model to extract the maximum deflection under different seasons. The live load and dead load factors are estimated from *clause 3.5 of Table 3.2 and Table. 3.3* and the design live load is estimated from *clause 3.8.3.1.2* for CL-W trucks and unit material dead weight is extracted from *clause 3.6 of Table 3.4*. The thermal load effect is applied as the average temperature for every month. Upon further analysis, the software generated the graphical information which includes the forces, stresses, displacements, reactions and moments. The graphical representation of results and tables allows viewing of the specific nodes, bars, and members. For the current research, the maximum deflection from the applied load combination is identified for each panel of the bridge to compare the results with the identified frequencies from SHM. As shown in Fig. 3.14, the maximum deflection is observed at the panel 4 and panel 5 due to their larger span length and applied load combinations.

3.5 BIM-integrated Visualization Tool

Visualization of sensor networks and structural data is one of the most pivotal aspects of SHM. The visualization tool communicates efficiently and effectively between disparate groups working on a single project. The current approach fosters communication by creating sensor properties through scheduled parameter table. Despite the advancements in software technology, Revit® does not have the ability to read all the outputs from the simulation software (MATLAB® and RSA®). For successful integration of the information, all the output results are converted into the corresponding readable files. The sensor data, FFTs, and system identification results of the sensor data are converted into excel and jpeg files for the better interpretation and results of the RSA® are converted into pdf files. The SHM information including sensor number and location, time, data sheet and identification results are assigned to the sensor properties.

To integrate the SHM information during its service life, different parameters are assigned on sensors in Revit® model as shown in Fig. 3.15 which enables better understanding of the structure in a 3D oriented view. The identities of the structural objects such as *type*, *image*, *manufacturer*, *URL*, *description*, *cost*, *assembly code* are inserted in the model such that these parameters appear in the sensor properties. For each type of entity, the various attributes are defined depending on the data and attributes. The sensors are organized in their prescribed locations. Revit® visualizes the sensor schedule table including all the sensors as well as their entitled properties.

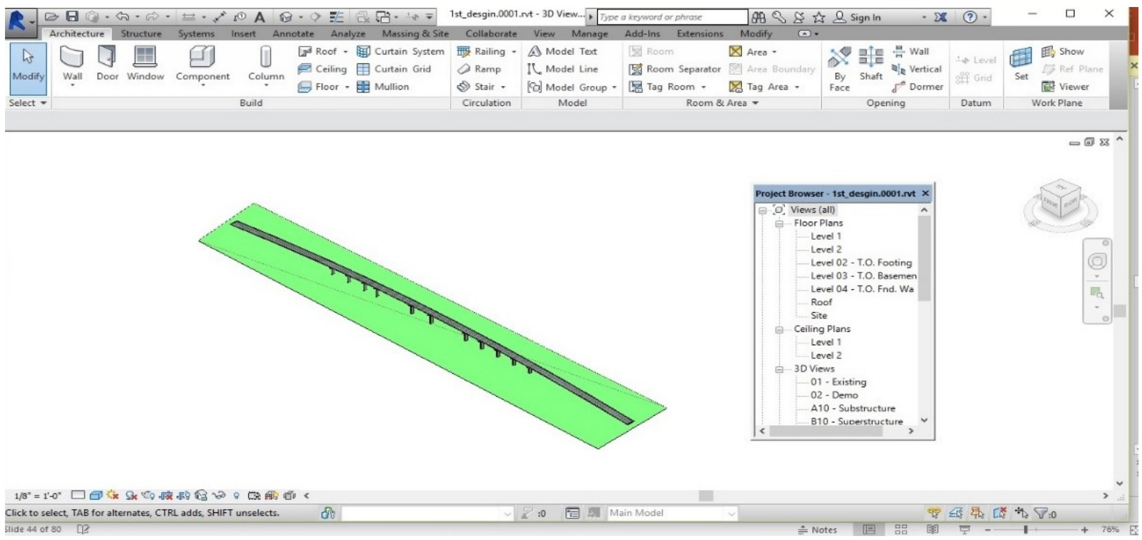


Figure 3.15: The Revit® model.

As shown in Fig. 3.16, the properties of the sensor are assigned through *"scheduled parameter"* command. Through the shared parameter command, the sensor properties are added by selecting *"Add parameter"* command, which allows assigning all the required information to the sensor entity as shown in Fig. 3.16. For the current case study, different structural properties including forces, sampling frequency, MATLAB® figures, sensor data, time of the test, deflections and other information are added to the sensor properties. One of the exciting features of the sensor schedule table is that, when a specific sensor is selected on the model, the selected sensor automatically highlights all the essential vital parameters assigned to the specific sensor. As shown in Fig. 3.17, the SHM data is visualized with all information. The corresponding results from the MATLAB® and RSA® are shown in the table through URL.

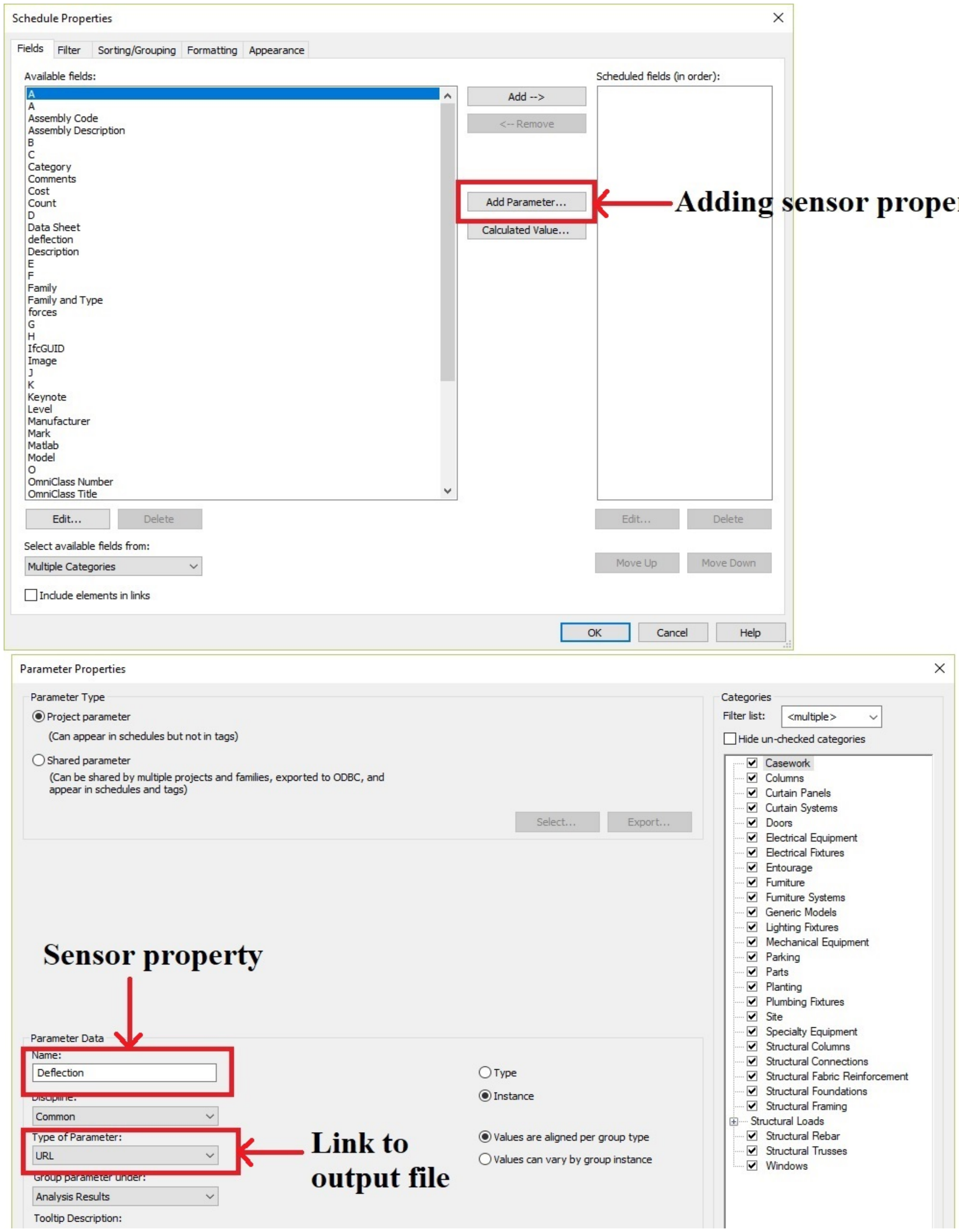


Figure 3.16: Sensor properties added to the Revit® model.

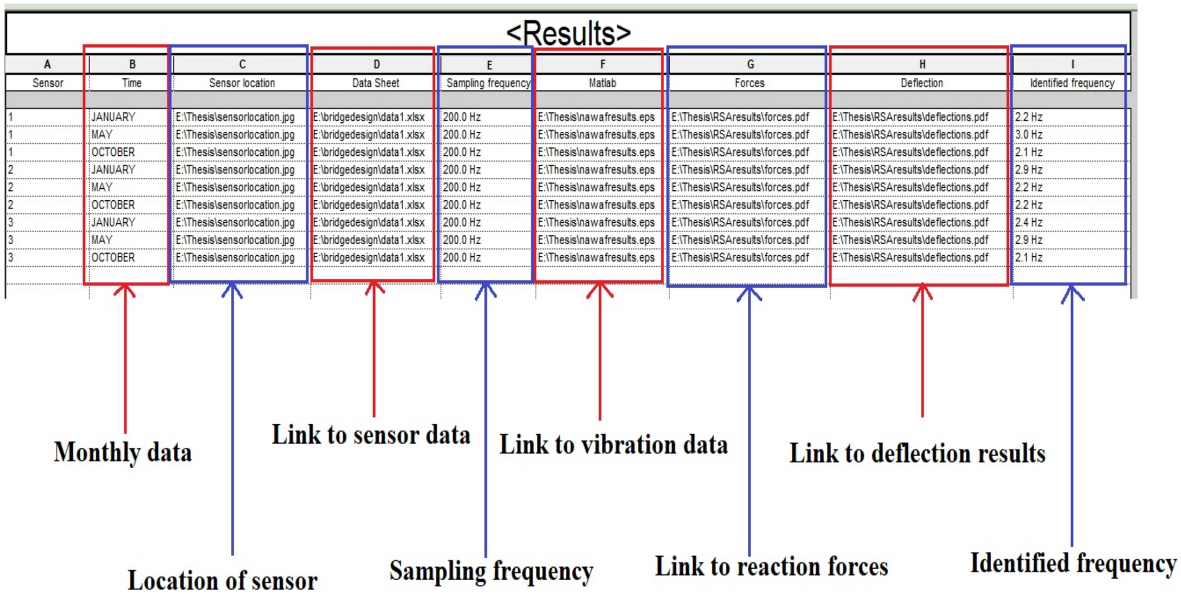


Figure 3.17: Integrated visualization tool.

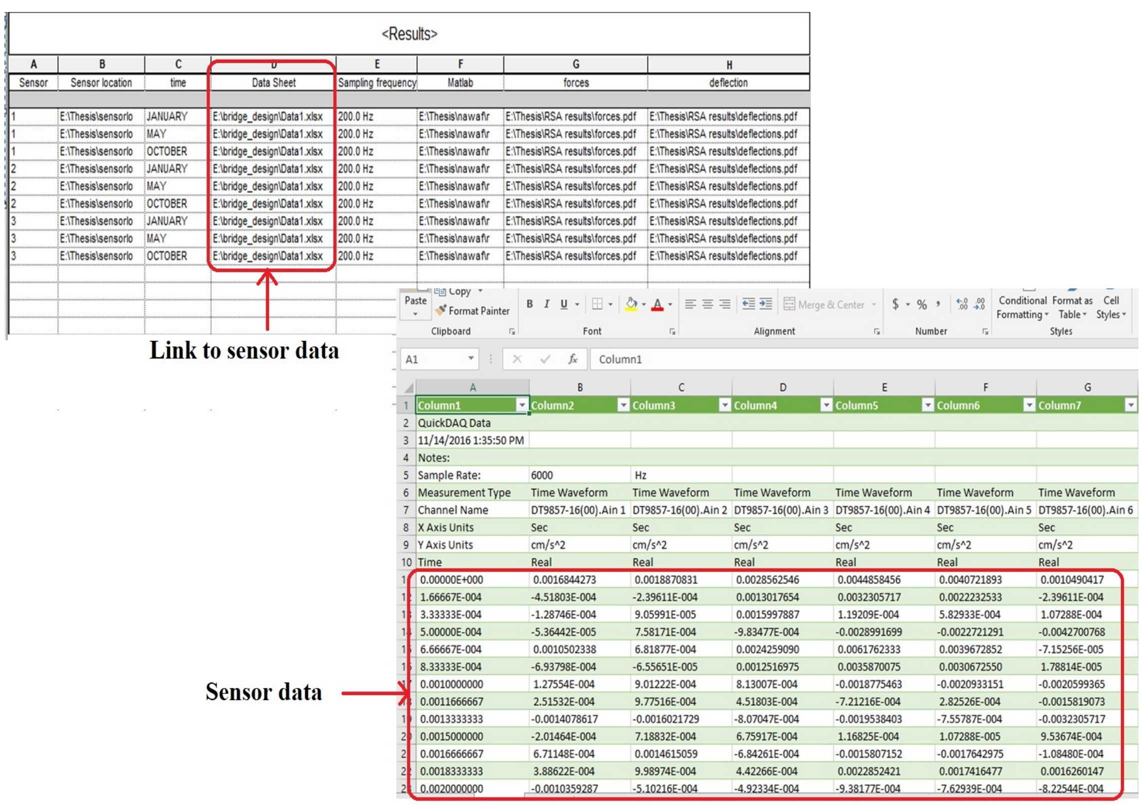
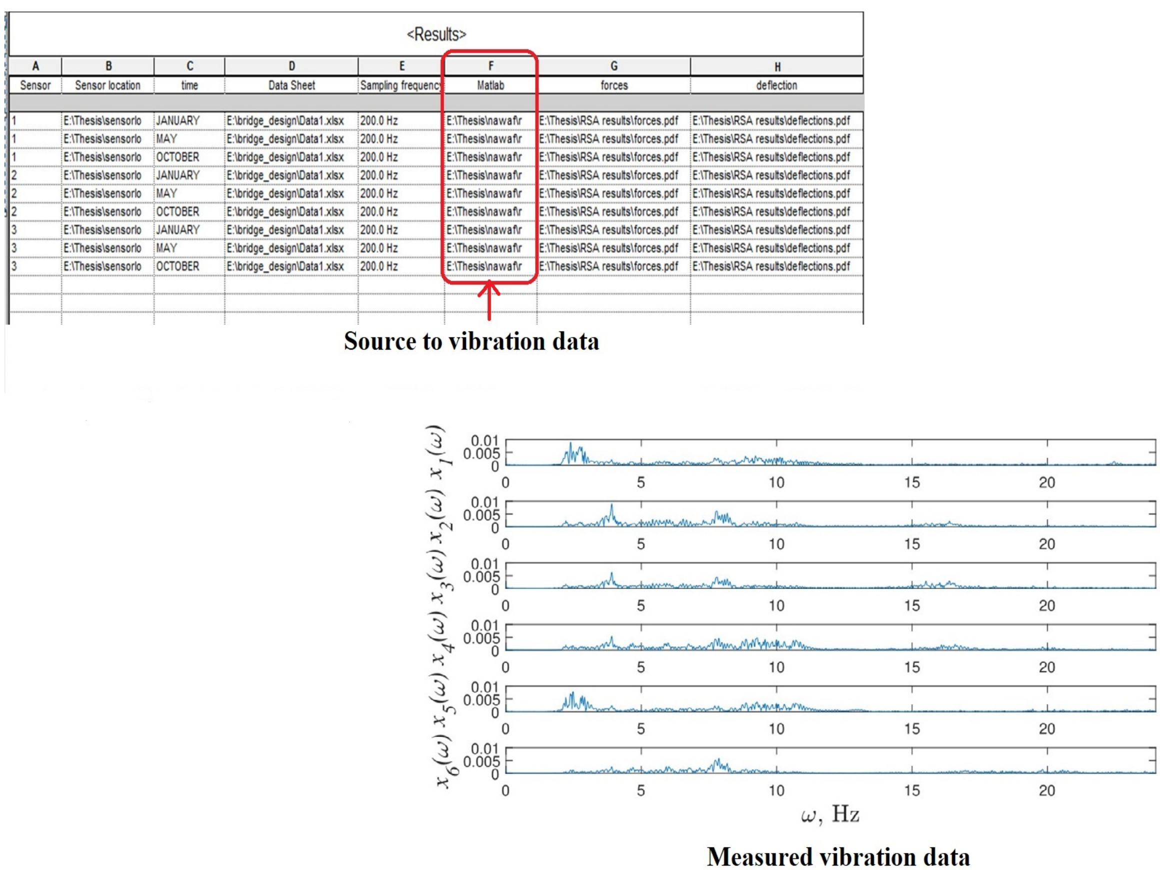


Figure 3.18: Visualization of sensor data.

The acquired sensor data as shown in Fig. 3.18 includes all the sensor entities that are featured directly in the BIM model to enable the data interpretation. The sensor information during the testing is obtained in the form of text files. To make it user-friendly, the information is exported into an excel file. Upon selecting the file name, the URL of the parameter links to the source file and the application generates the sensor data as shown in Fig. 3.19. In the analysis of the bridge, several parameters are evaluated. Those parameters are natural frequency and maximum acceleration. The natural frequencies are traced by processing the vibration data using FFT in MATLAB®. Since, Revit® is unable to read a MATLAB® output file, the FFT plots are linked to the scheduler parameter table through *url*. On clicking the cells, the FFT plots are displayed in their parental platform. The converted file is linked to the sensor entity in Revit® in further is used to monitor the structural performance.



<Results>

A	B	C	D	E	F	G	H
Sensor	Sensor location	time	Data Sheet	Sampling frequency	Matlab	forces	deflection
1	E:\Thesis\sensorlo	JANUARY	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
1	E:\Thesis\sensorlo	MAY	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
1	E:\Thesis\sensorlo	OCTOBER	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
2	E:\Thesis\sensorlo	JANUARY	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
2	E:\Thesis\sensorlo	MAY	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
2	E:\Thesis\sensorlo	OCTOBER	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
3	E:\Thesis\sensorlo	JANUARY	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
3	E:\Thesis\sensorlo	MAY	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf
3	E:\Thesis\sensorlo	OCTOBER	E:\bridge_design\Data1.xlsx	200.0 Hz	E:\Thesis\nawafir	E:\Thesis\RSA results\forces.pdf	E:\Thesis\RSA results\deflections.pdf

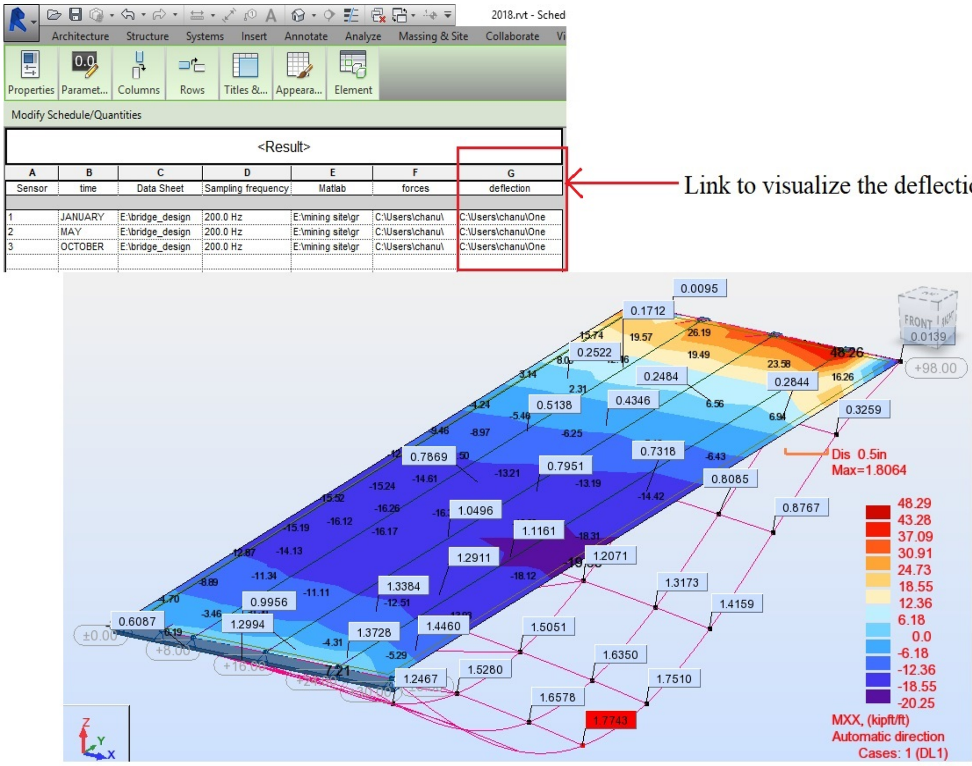
Figure 3.19: Visualization of the analyzed data.

3.6 RSA-enhanced Comparison

The enhanced features of RSA® software enable to simulate and analyze the structures with enormous algorithms. The simulation can be run directly in RSA®, or the structure can be exported to Autodesk Simulation. The load simulation feature allows to simulate the wind flow around the structure and also allows the live load and dead load simulations. The enhanced feature of Robot is useful for large structures with complicated geometry. The results of this simulation are used for further analysis. The structure is designed under different load combinations. The loads are categorized based on the regular seasons in a year. In January, a lot of snow occurs which also adds up along with the live loads and dead loads. Whereas, for the other seasons (May, October), the snow load is replaced with heavy wind loads and traffic loads. Based on these assumptions, and load combinations from the CHBDC, structural analysis is performed.

Once the analysis is performed the software generates a model to identify the structural behavior. After the analysis is performed, the results are converted into the pdf format which provides a better understanding of the structural behavior and eliminates the requirement of another design software. These results are separated based on the outputs like reaction forces, moments, and deflections. The converted pdf format of the RSA® file is linked to the sensor entity to characterize the performance of the structure. The structural integrity is developed by exporting the images and reports of the RSA® work-space into Revit®. The output source files are formatted as pdf format and are linked to the cells of reaction forces and deflections. On clicking the cells, the scheduled parameter table generates the necessary outputs that are required to access the performance of the structure.

Fig. 3.20 shows the representation of deflections in the structure. The deflection results are obtained to give the prolonged characterization of the structure regarding static analysis. The resulted deflection values are useful in finding the stiffness of the structure throughout its length. Thus, the obtained results are converted into pdf format and linked to the sensor entity. Stiffness values from the sensor information and the static analysis help in analyzing the performance of the structure during its service period and also helps in monitoring the structure throughout its life period.



<Result>

A	B	C	D	E	F	G
Sensor	time	Data Sheet	Sampling frequency	Matlab	forces	deflection
1	JANUARY	E:\bridge_design	200.0 Hz	E:\mining site\gr	C:\Users\chanu\	C:\Users\chanu\One
2	MAY	E:\bridge_design	200.0 Hz	E:\mining site\gr	C:\Users\chanu\	C:\Users\chanu\One
3	OCTOBER	E:\bridge_design	200.0 Hz	E:\mining site\gr	C:\Users\chanu\	C:\Users\chanu\One

Filtering	Bar	Case
Full list	1to6	1 3
Selection	3to6	1 3
Total numb-er	4	2
Selected nu-mber	4	2

Bar/Case	UX (in)	UY (in)	UZ (in)
3/ 1	-0.0236	-0.0279	-2.7186
3/ 3	-0.0044	0.0400	0.0590
4/ 1	0.0229	-0.0252	-2.6357
4/ 3	-0.0018	-0.0137	0.0609
5/ 1	0.0228	-0.0294	-2.5517
5/ 3	-0.0018	-0.0099	0.0610
6/ 1	0.0243	-0.0241	-2.4668
6/ 3	-0.0036	-0.0392	0.0593

Figure 3.20: Report of deflections obtained from the RSA®.

All the results from RSA® are reported in pdf formats as shown in Fig. 3.20 and Fig. 3.21. The obtained results imported into the Revit® software provide the primary basis of collected information and analyzed results. The results replicate the behavior of the structure and mobilize the necessary remedies to avoid fatalities in the structure. The key importance integrating the SHM technique and a numerical model is well established in this work. The given approach identifies the damage states during the structural diagnosis and also characterized the evolution phase, based on the analysis and interpretation through a numerical model of the structural system through the given sensor parameters.

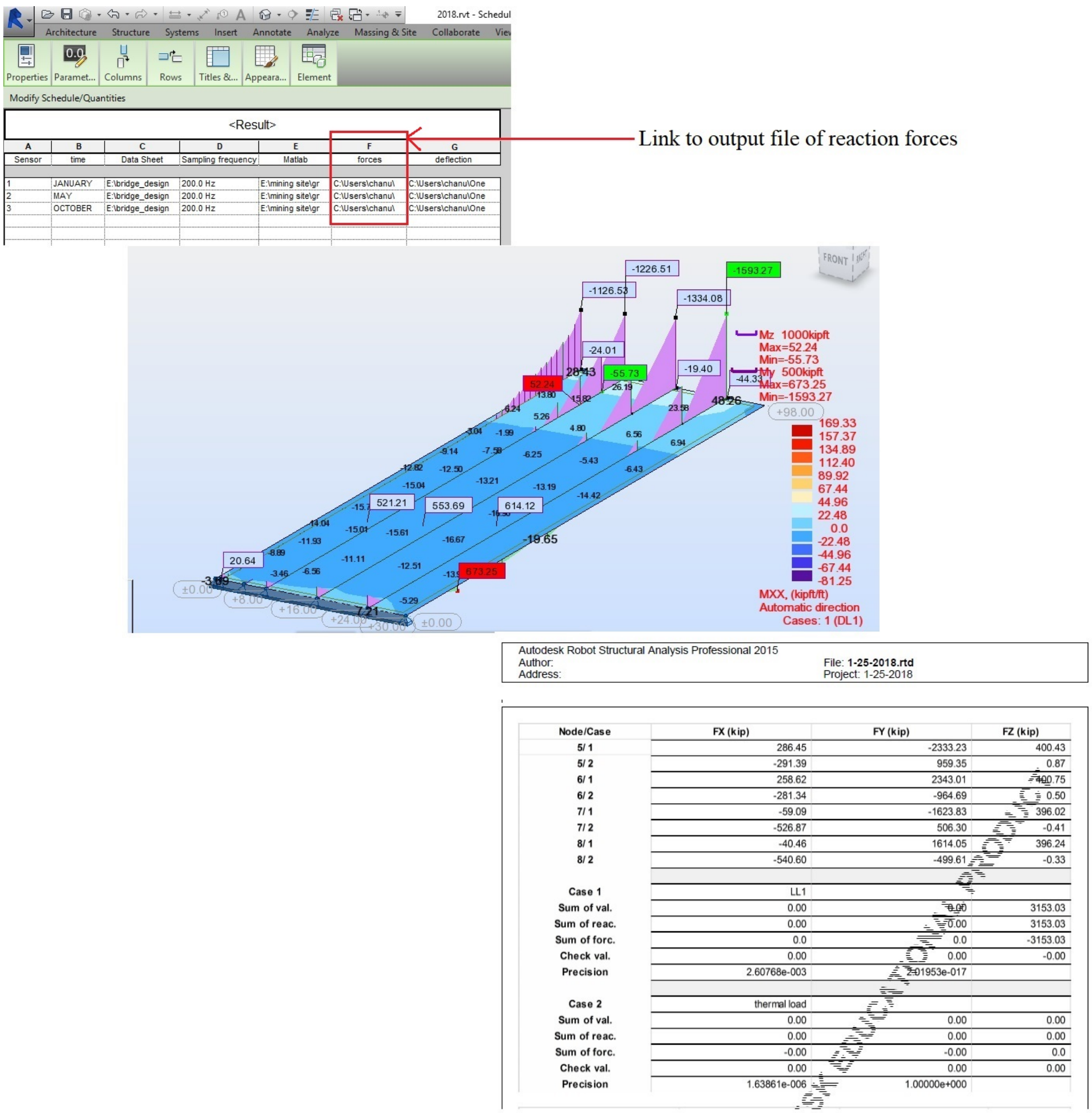


Figure 3.21: Report of the reaction forces obtained from the RSA®.

Chapter 4

Case Study: Short-span Bridge

In this chapter, the strategy of the proposed methodology is implemented in a short-span pedestrian bridge. The following sections elaborate the designed approach by integrating the vibration data of a pedestrian bridge into the BIM model. The results obtained from RSA® are used to evaluate the evolution of structural behavior for a long period of time, and the results are compared with the FE model.

4.1 Bridge description and Instrumentation

Figure 4.1: Pedestrian bridge on the campus of Lakehead University.

The bridge used in this case study is a footbridge on the campus of Lakehead University. The bridge was constructed in 1967 and is composed of two steel girders fixed on both ends with steel struts spaced evenly along the length of the bridge. The bridge is relatively short (approx. 20 meters) compared to the previous bridge and its location is protected against heavy winds that would have caused potential vibration.

However, due to aging, vibration performance could be a significant concern to the daily commuters such as students and staff members.

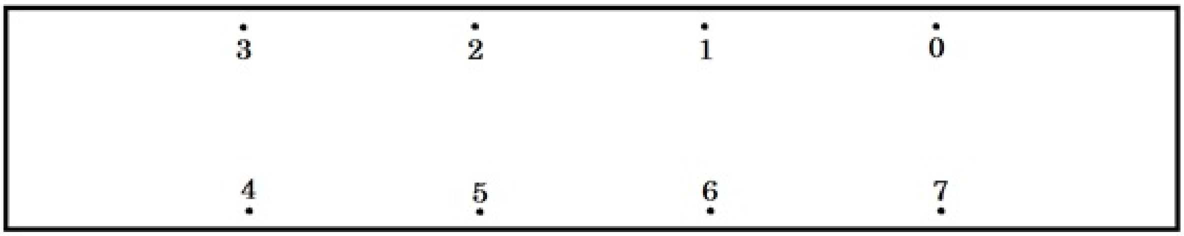


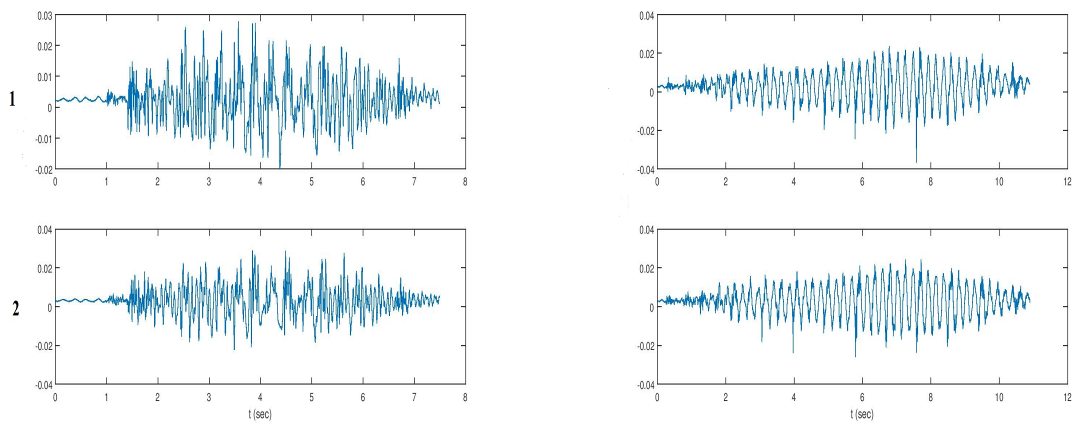
Figure 4.2: Sensor locations on the pedestrian bridge.

Figure 4.3: Typical sensor attached on bridge deck.

The bridge was subjected to a series of pedestrian excitation in 2016 and 2017 [69]. The footbridge was subjected to continuous excitation through a variety of activities such as walking, running, and cycling while monitoring using a series of accelerometers. As shown in Fig. 4.2, a total of 8 accelerometers were used to instrument the bridge that was evenly distributed on each side of the bridge. As shown in Fig. 4.3, the sensors were mounted to measure the vertical acceleration of the bridge. The data from the sensors was transmitted to the computer using QuickDAQ software. The sampling frequency was set to 200 Hz. The tests were performed during the single walk, group walk, single run, group run, single jump, group jump, and single bike.

4.2 Data Processing and System Identification

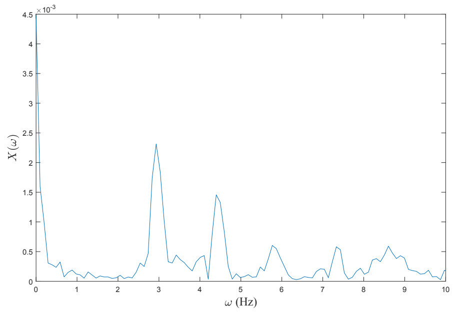
The data for different tests were recorded, and accelerated data was plotted in the time-domain. The data was recorded in time-domain and transferred into the frequency domain using FFT algorithm through MATLAB®. From the frequency domain plots, the natural frequencies of the bridge are determined by picking the frequencies corresponding to the most typical peaks, where energy is highest. The peak frequencies from these plots are investigated by visual inspection and recorded alongside the frequencies from other plots.



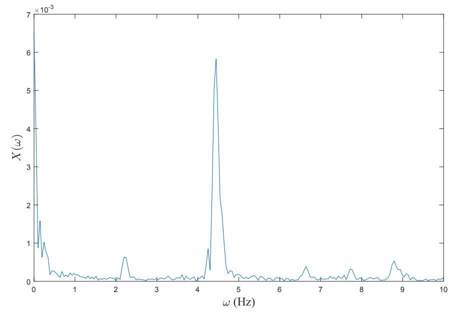
(a) running (b) walking

Figure 4.4: Typical vibration data of sensor 1 and sensor 2 during running and walking.

Fig. 4.4 shows two of the eight accelerometer readings for that test during running and walking and Fig. 4.5 represents the Fourier spectra of sensor 1 and sensor 2 during running and walking from measured data. The SOBI method involves constructing covariance matrices for the responses to extract the modal information through diagonalization of these matrices. For the current case study, it decomposes mixture of signals into a set of components that remain consistent with modal responses as shown in Fig. 4.6. The estimated frequencies are compared with the identified frequencies of the FE model in Table. 4.1.



(a) running



(b) walking

Figure 4.5: Fourier spectra of measured data during running and walking.

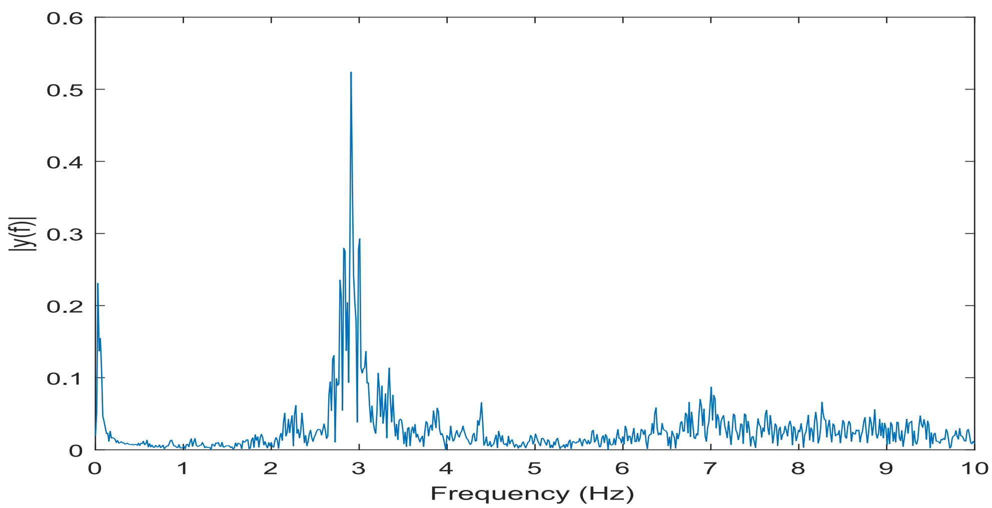


Figure 4.6: Sample modal response of pedestrian bridge.

Table 4.1: Comparison of the FE model with the identified frequencies of the pedestrian bridge.

FE	**2016**	**2017**
2.7	2.87	2.76
11.7	11.65	11.66
30.8	31.2	30.6

4.3 Development of BIM Model

To visualize the SHM system, a BIM model of the footbridge is developed. As mentioned in the earlier case study, the drawings are converted to a 3D BIM model.

Using the old 2D drawings of the model, the main structural elements of the structure are replicated into the main BIM system (Revit®). The bridge was assumed to consist of two girders fixed on both ends, and thirteen cross bracing beams between them. The steel connections of Revit® add-in provides access to a variety of parametric steel connections enabling in a higher level of detail. For the current design, as shown in Fig. 4.7, two main girders are designed each of 253.00 mm width and 835.00 mm height and placed at a spacing of 4 feet along the length of the bridge.

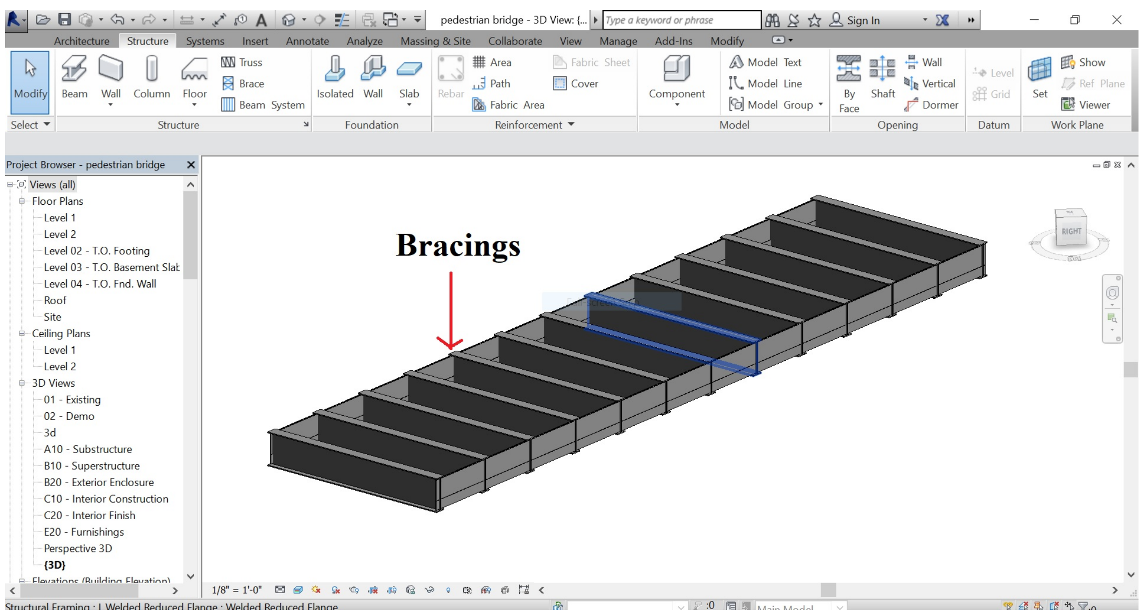


Figure 4.7: Design of bracing in BIM.

As shown in Fig. 4.7, 13 cross bracings are designed along the length of the span. To generate the family of bracings, "*Structure*" tab is selected in the "*Structure panel*" and bracings are selected. On the properties panel, the customized bracing is selected and edit the properties of the brace like material, dimensions and offset before adding it to the model. Along with the girders and bracing, to justify the BIM model with the real-life structure, the railings were placed along both the sides of the bridge. The railings were assigned through "*Architecture*" panel and select the railing panel. The model pop-up the property panel to modify properties, edit the family type of the railing and select *OK* to see the finalized BIM model as shown in Fig. 4.8.

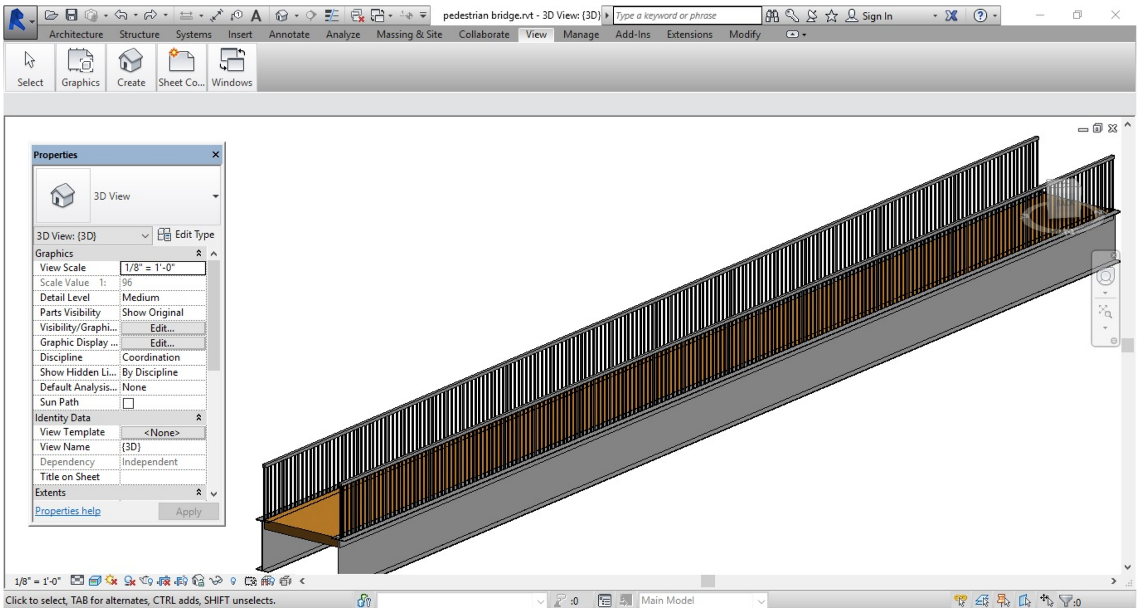


Figure 4.8: BIM model of the pedestrian bridge.

4.4 Robot Structural Analysis

In order to execute the currently proposed approach the model is exported from Revit® to RSA® and the load variations are amplified to study the performance of the structure. Due to the inaccessibility of the current platform, RSA® provides a key platform to perform static analysis of the current BIM model. Since RSA® and Revit® belong to the same family of BIM, the model is exported to RSA®, and the loads are applied on the structure using the design code to analyze the structure. Using the CHDBC, the designed structured is analyzed using different load combinations.

To perform the analysis, design loads are considered from CHBDC code. A total of live load, dead load, and thermal load combinations are applied to the model to extract the maximum deflection under different seasons. The design live load is collected from *clause 3.8.9* using the equation given below. The pedestrian load should not be less than 1.6 kpa and not greater than 4.0 kpa.

$$p = 5.0 - \frac{S}{30}$$

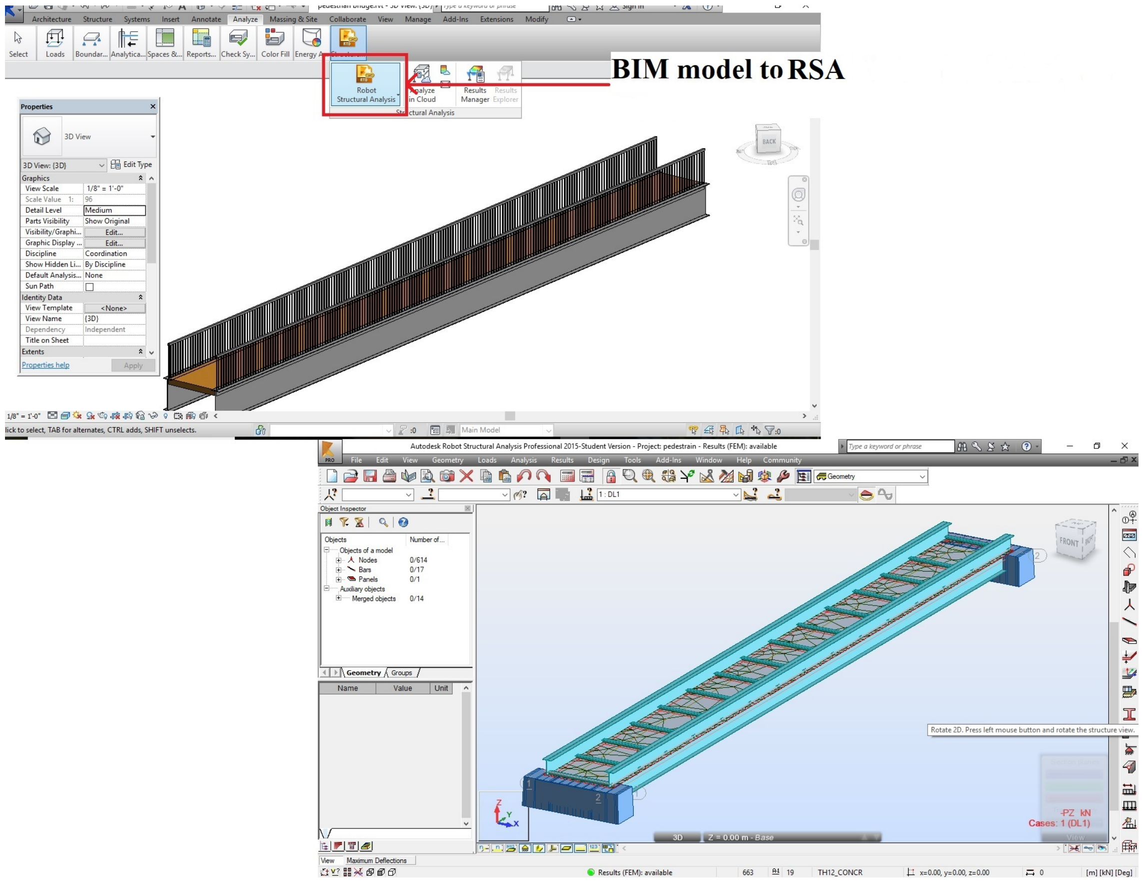


Figure 4.9: Integrated analysis in RSA®.

On further analysis, the software generated the graphical information which includes the forces, stresses, displacements, reactions and moments. The graphical representation of results and tables allows viewing of the specific nodes, bars, and members. For the current research, the maximum deflection from the applied load combination is identified for each panel of the footbridge to compare the results with the identified frequencies from SHM. As seen in the above table, the maximum deflection is observed at the panel 4 and panel 5 due to their larger span length and applied load combinations.

4.5 BIM-Integrated Visualization Tool

To integrate the SHM information into BIM model, the sensor properties are defined through "*Shared Parameter*". It helps in creating a schedule that displays various structural categories. The parameters are set by defining a group name, data type and family. Moreover "*Shared Parameter*" offers the greatest flexibility and maintains a spreadsheet in which project documents are perfectly organized and maintained.

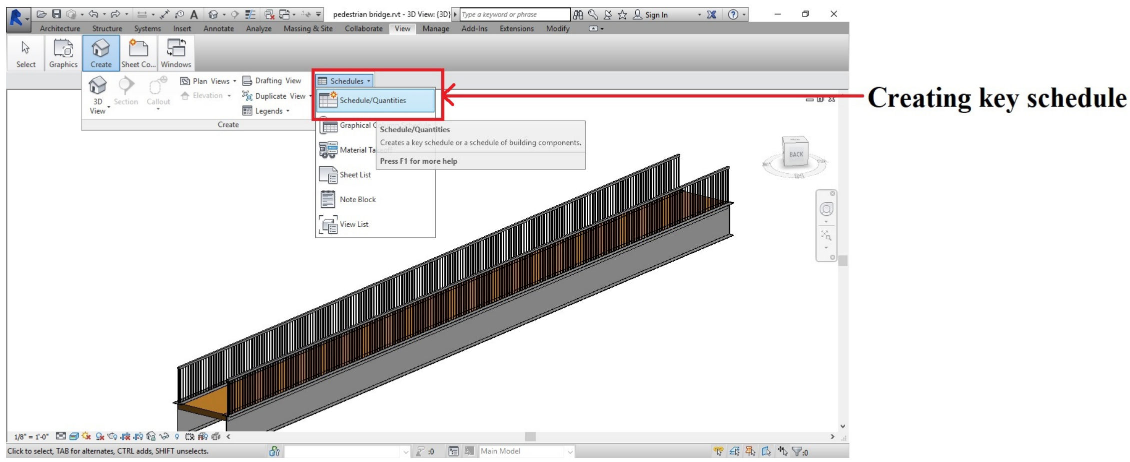


Figure 4.10: Creating schedule table to the model.

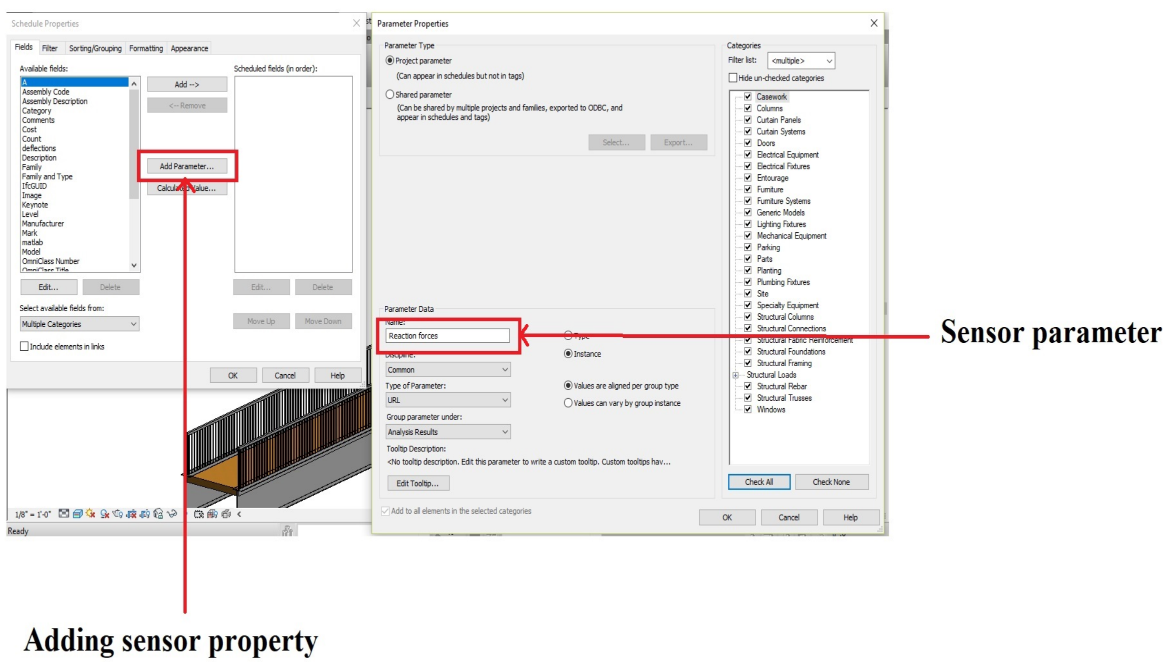


Figure 4.11: Sensor parameters assigned to the model.

In order to check the accuracy of the approach, the combined elements of simulations and analysis are integrated into the visualization tool. The sensor properties are created by generating a scheduled parameter table as shown in Fig. 4.10. Once the key schedule is created, the sensor parameters are specified that are driven by the key schedule. As shown in Fig. 4.11, the name of the parameter, type, group are assigned. The "*Family type*" is selected which opens a category dialog to assign the "*Family type*". The time-history responses of the bridge measured from the SHM system are exported as jpeg images, and the data sets are converted to excel sheets. The Robot Structural Analysis® results are exported as pdf and image files to provide a better understanding of the behavior of the system. To check the consistency of the BIM platform and its softwares, the results are reflected in the next sections.

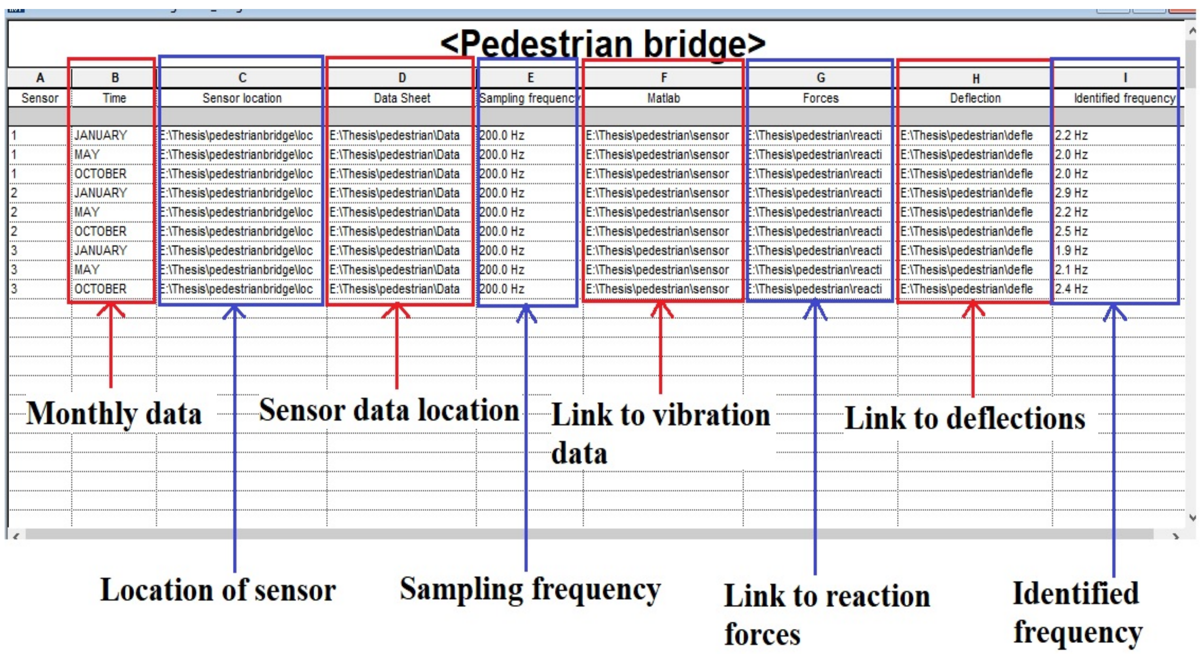
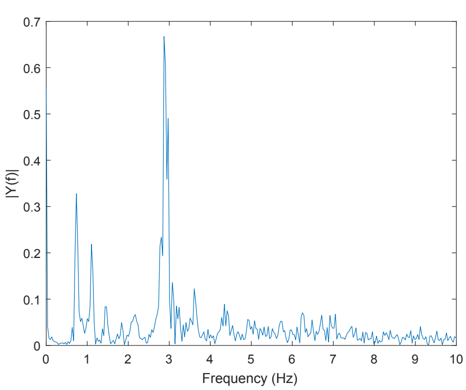


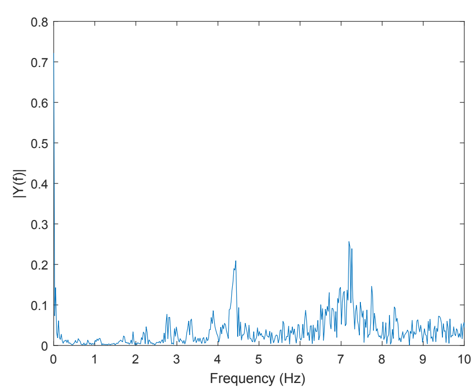
Figure 4.12: Integrated visualization tool for a pedestrian bridge.

To enhance the effectiveness of the present approach, the BIM model of the pedestrian bridge is created by utilizing the 2D drawings. With the assistance of the current platform, all the geometrical, structural and sensor properties of the structure are assigned by utilizing the current advancements in the software. To coordinate the 3D BIM model with SHM, the sensor locations and their properties are relegated to have the better comprehension towards the execution of the structure in a 3D situated view. With the created model, the model permits to explore the proposed sensor areas and check their execution amid their service period. Alongside the functional properties, SHM coordinated properties like time, MATLAB® data, dynamic analysis results such as deflections, reactions, forces are linked to the model. The FFT plots are changed over to jpeg images for better understanding and are connected to the BIM model. Sensors are implemented by using BIM shared parameter object and are characterized by the data measured over time. Hence, a link between the sensors contained in the BIM is established by providing database access using IFC as shown in Fig. 4.12. This step is a one-time manual process within the proposed method by which a link between the database and sensors is established. All required information about the sensors such as *type*, *image*, *date*, *frequency*, *reaction forces* are therefore inserted into the properties of the bridge model.

The output file of the vibration data is exported into jpeg files and linked with the sensor properties in the scheduled parameter table. The collected vibration data (.txt files) are assigned to the BIM model through scheduled parameter table as shown in Fig. 4.13. The collected sensor data during the test is exported from .txt files to excel files that provides better organization and understanding. The simulated vibration data from MATLAB linked to the scheduled table either as .eps file or jpeg. The peak amplitudes of the FFT plots from the vibration data are used to identify the highest peaks to provide an indication of natural frequency. As mentioned in the earlier case-study, the FFT's are visualized by clicking on the cells and monitor the behavior of the structure.



(a) running



(b) walking

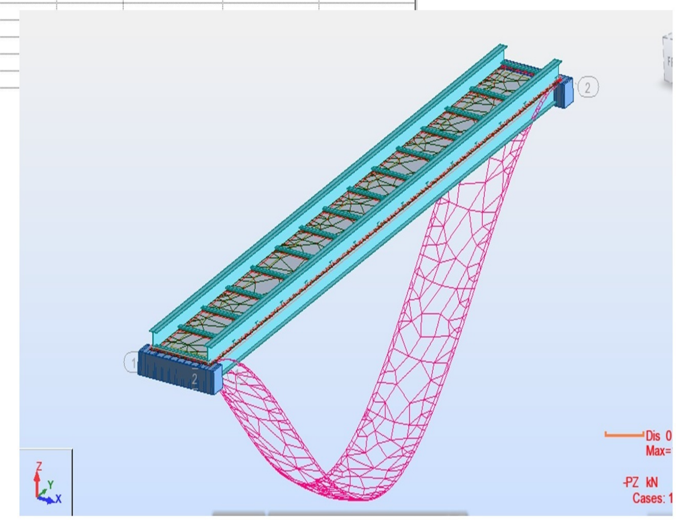
Figure 4.13: Modal responses of foot bridge during running and walking.

Modify Schedule/Quantities

<Pedestrian bridge>

A	B	C	D	E	F	G	H
Sensor	Time	Sensor location	Data Sheet	Sampling frequency	Matlab	Forces	Deflection
1	JANUARY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
1	MAY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
1	OCTOBER	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
2	JANUARY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
2	MAY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
2	OCTOBER	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
3	JANUARY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
3	MAY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
3	OCTOBER	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle

Source to deflection results



Bar/Case	UX (mm)	UY (mm)	UZ (mm)
2/ 1	0.0180	0.0125	-0.9860
3/ 1	-0.0180	-0.0127	-0.9860
4/ 1	0.0001	-0.0008	-0.0010
5/ 1	-0.0003	-0.0043	-0.0142
6/ 1	0.0003	-0.0035	-0.0181
7/ 1	0.0004	-0.0028	-0.0189
8/ 1	-0.0003	-0.0023	-0.0195
9/ 1	-0.0003	-0.0015	-0.0191
10/ 1	0.0003	-0.0008	-0.0189
11/ 1	-0.0003	-0.0002	-0.0191
12/ 1	0.0003	0.0006	-0.0198
13/ 1	-0.0003	0.0013	-0.0193
14/ 1	0.0004	0.0020	-0.0193
15/ 1	-0.0003	0.0027	-0.0193
16/ 1	-0.0003	0.0033	-0.0190
17/ 1	-0.0003	0.0043	-0.0175

Figure 4.14: Deflection reports through scheduled parameter table.

4.6 RSA-enhanced Comparison

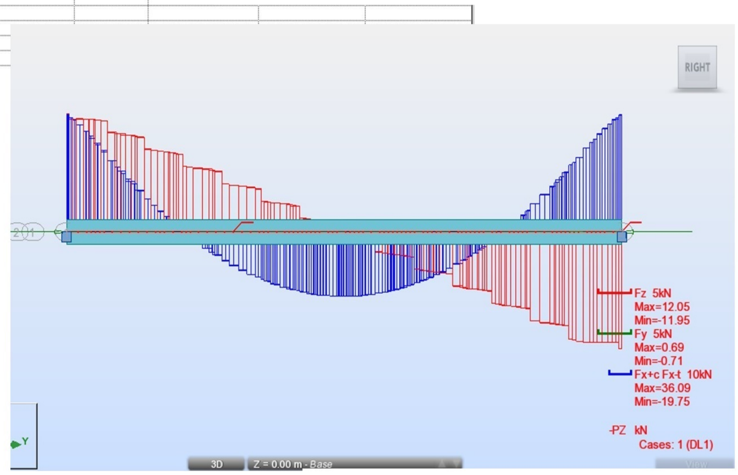
In Revit® software, the physical model, and the associated analytical model are linked to RSA to perform the analysis. Once the analysis is completed, the information is transferred back to Revit®. Based on the analysis outcomes, it allows to make decisions and develop updates to the analytical model and alerts the design. Based on the assumptions and load combinations form CHBDC, structural analysis is performed, and the generated output is exported to Revit® scheduled parameter table. The collected deflections of Fig. 4.14 and reaction forces of Fig. 4.15 are saved separately and exported as pdf files. The converted pdf format of the RSA® file is linked to the sensor entity as performed for the long-span bridge to categorize the performance of the structure. The graphs developed help in identifying the point of failure and facilitate in accessing the data with SHM data alert the failure in structure. The RSA® enhanced results are generated on the BIM model by clicking the cells from the scheduled parameter table.

Modify Schedule/Quantities

<Pedestrian bridge>

A	B	C	D	E	F	G	H
Sensor	Time	Sensor location	Data Sheet	Sampling frequency	Matlab	Forces	Deflection
1	JANUARY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
1	MAY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
1	OCTOBER	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
2	JANUARY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
2	MAY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
2	OCTOBER	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
3	JANUARY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
3	MAY	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle
3	OCTOBER	E:\Thesis\pedestrianbridge\loc	E:\Thesis\pedestrian\Data	200.0 Hz	E:\Thesis\pedestrian\sensor	E:\Thesis\pedestrian\reacti	E:\Thesis\pedestrian\defle

Link to reaction results from RSA



Bar/Node/Case	FX (kN)	FY (kN)	FZ (kN)	MX (kNm)	MY (kNm)	MZ (kNm)
2/ 4/ 1	36.09	-0.69	12.05	0.00	-27.07	-0.17
2/ 5/ 1	35.99	0.60	-11.95	-0.00	-27.07	-0.13
3/ 9/ 1	36.08	0.67	12.04	-0.00	-27.10	0.16
3/ 10/ 1	35.85	-0.58	-11.94	0.00	-27.09	0.12
4/ 13/ 1	0.26	0.46	0.44	-0.00	-0.05	0.06
4/ 14/ 1	0.27	-0.47	-0.44	0.00	-0.05	0.06
5/ 15/ 1	-0.48	0.32	0.82	0.00	-0.10	0.08
5/ 16/ 1	-0.50	-0.32	-0.78	-0.00	-0.08	0.08
6/ 17/ 1	-0.56	0.16	0.85	-0.00	-0.09	0.04
6/ 18/ 1	-0.43	-0.28	-0.88	0.00	-0.09	0.06
7/ 19/ 1	-0.24	0.44	0.99	-0.00	-0.08	0.06
7/ 20/ 1	-0.18	-0.42	-1.01	0.00	-0.09	0.06
8/ 21/ 1	-0.63	0.13	0.89	-0.00	-0.09	0.03
8/ 22/ 1	-0.68	-0.11	-0.92	0.00	-0.09	0.03
9/ 25/ 1	-0.31	0.19	0.96	-0.00	-0.08	0.03
9/ 26/ 1	-0.26	-0.22	-1.01	0.00	-0.08	0.03
10/ 27/ 1	-0.32	0.15	0.95	-0.00	-0.08	0.02

Figure 4.15: Reaction reports through scheduled parameter table.

Chapter 5

Conclusions and Future Work

This chapter summarizes the key outcomes, contributions and future work of the proposed research. In this thesis, primary attempt has been made to develop a user-friendly visualization tool using BIM and facilitate decision making on maintenance and rehabilitation of large-scale structures using long-term SHM data. The proposed tool is implemented and validated using two real-life bridges through SHM data collected on annual basis.

5.1 Conclusions

1. In the proposed approach, the sensor system and building information model are integrated to improve data management and visualization of big data of SHM.

2. The developed semantic rich BIM models enable a valuable digital representation of structural health monitoring information about the structural systems throughout their whole life cycle of the infrastructure, thus enhancing the quality and assessment of the infrastructure.

3. To demonstrate the integrated visualization tool, the modal frequencies from the sensor data are compared with identified frequencies of the FE model.

4. Two real-life structures, a highway bridge, and a pedestrian bridge are used for the validation. The results depicted the usefulness of the proposed approach in detecting and visualizing the potential hazards during its service period.

5.2 Major Contributions

The proposed research in this thesis has resulted in one conference paper publication. The research will be also considered for a possible journal publication soon.

1. **Boddupalli, C.**, Sadhu, A., and Rezazadeh Azar, E.(2018). "An Integrated Structural Health Monitoring tool using Building Information Modelling", **CSCE Structures Speciality Conference**, Fredericton, Ontario, Canada.

5.3 Future work

Most of the efforts in this thesis are made to develop the tool. However, there are several potential areas that can be improved further to contribute and develop better automated system.

1. The BIM models do not provide all the required information from the structural analysis, for example, the connection between girders and deck may not be well established while exporting the model to RSA. This may prevent identifying the risk of damage to large-span structures. Such safety-related design standards are needed to be formalized in the BIM model.

2. It would be worth to define sensors as the building objects in the integrated tool to visualize structural health without requiring the scheduled parameter table.

3. Additional case studies like complex structures with large sensor data are required to be tested for the proposed approach.

4. Some of the methods which are part of the established framework can also be automated by developing an API code for Revit to link with other analysis and simulation software which will enhance the results of system identification during its course of time.

5. By facilitating the system identification tool to the Revit, it will improve the structural health monitoring of the structure over an extended period of time.

6. It is necessary to create interface programs to improve the automation.

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