

**BIM-BASED DATA MANAGEMENT SYSTEM FOR STRUCTURAL
HEALTH MONITORING**

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**A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Honours) Civil Engineering**

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May 2020

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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ABSTRACT

Structural Health Monitoring (SHM) is important to identify and quantify the damage or deterioration state of a structure that might occur over the service life. However, SHM involves enormous volume of raw data in real-time and the analysis and interpretation of the data is a challenging issue. Current SHM practices are limited due to the limitation of storing and retrieving data. Besides, SHM practices also lack of visualisation where processed data are displayed as images and graphs only. In the recent years, Building Information Modeling (BIM) is gaining popularity due to its abundant benefits. In this study, a research framework for integrating a BIM-based data management system into SHM was developed. The objectives of the study are to investigate traditional SHM and how BIM can be incorporated into it, to review the current BIM-based data management system and to investigate the suitability of the proposed BIM-based data management system for the SHM. A proposed was carried out using the BIM related software and visual programming platform Revit® 2021 by Autodesk and Dynamo. In this study, a 3D model of a four-story concrete model was constructed together with the SHM system in Revit. Then, five visual programming modules for linking SHM to BIM are constructed with Dynamo to automatically extract and manage processed data. The data and information of the structural elements are stored in Revit model to reduce the risk of data loss throughout the lifecycle of the project. Besides, the BIM-based SHM enable damage visualisation via colour-coding the damaged elements in the 3D model. The study proposed the framework for BIM-based SHM that enable real-time data storage, visualisation of the damaged elements, and manage real-time data within its dynamic BIM model, where both data and analysis can be viewed on the same platform.

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LIST OF SYMBOLS / ABBREVIATIONS

BIM	Building Information Modelling
SHM	Structural Health Monitoring

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Under the vast development of the country in recent years, the present-day societies are densely dependent on structural building on daily basis for example bridges for transportation, dam for water supply and flood control, etc. A large number of the existing structures are currently approaching their design life and some of them hold high importance and cannot be economically replaced such as bridges, dams, and historical buildings. This phenomenon paved the way for damage detection techniques to prolong the structure of life beyond the intended service life (Farrar and Worden, 2012). Owners and stakeholders show growing interest and demand for detecting damages of the structure at the earliest possible time to optimize the usage of the structures by extending its useful life as well as avoid catastrophic failures.

The term “damage” in the study of damage identification in a structural system can be interpreted as changes found in the system that will negatively affect its present or future performance (Farrar and Worden, 2010). Damages are correlated with stiffness reduction, exceeding allowable strength, the occurrence of deformation or instability of a component in the (Miskiewicz, Pyrzowski and Wilde, 2017; Farrar and Worden, 2012). Farrar and Worden (2012) presented that damage can build up over long periods in the form of fatigue or corrosion of steel reinforcements and can also progress instantly resulting in critical fracture. The time taken for the damage to alter the system’s performance depends heavily on the location and seriousness of the crack. Damage does not decisively imply that the system loses its functionality, but it can no longer operate in its optimal manner to execute the intended purpose. Where the damage influences the structure to the point it is no longer tolerable, the structure then is under a dangerous and failure state. Damage can occur to the structure by: (i) natural ageing of raw materials, (ii) actions of the environment and (iii) accidental events (Balageas, Fritzen and Güemes, 2010).

In several countries, guidelines related to monitoring and detect damages of civil infrastructure have been formulated. However, most of the regulations

promote conventional monitoring activities such as visual inspections and non-destructive evaluation (NDE) that are done periodically to a structure. Other than periodic monitoring, the present-day society also implements Structural Health Monitoring (SHM) which refers to continuous methods of carrying out damage detection over time. The concern in SHM is to deal with a huge volume of data and therefore an effective data management system is required to implement SHM (Valinejadshoubi, Bagchi and Moselhi,2016). In recent years, various methods have been suggested to enhance the effectiveness of SHM systems such as artificial intelligence, autonomous software, approaches inspired by biology, and agent-oriented concepts (Theiler, Dragos and Smarsly, 2017).

In recent years, flourishing interest in the construction sector by using Building Information Modelling (BIM) due to its abundant benefits and resource savings during the life-cycle of construction (Volk, Stengel and Schultmann, 2014). BIM is a software that put together 3D modelling with architectural engineering to construct a virtual model of the building. BIM can promote greater data management and the representation of sensory peripherals of the structural health monitoring system of the structure when integrated into SHM. BIM is also an excellent visualisation tool where damaged building components are highlighted in the BIM model where damage is detected through the real-time sensor data (Valinejadshoubi, Bagchi and Moselhi,2019).

1.2 Importance of the Study

In modern society, humans rely heavily on structures to provide a safer way to connect cities and to create livable homes. Many structures are coming to the end of their design life span where there are commonly designed for 50 to 100 years of operating life. Some structures that hold a high importance to society may be costly or impossible to be rebuilt for example historical buildings, dams, underwater tunnels, etc. Thus, prolonging the operation life of the structure to exceeds its initial design life becomes a noteworthy study to save the cost of constructing similar structures for identical objectives. The concern of prolonging the operating life of structures is none other than the safety and integrity of the structures. Structural failures can lead to catastrophic events in which millions of human lives and assets are at risk. To ensure the functionality

and reliability of the structure, damage detection methods are favoured by the construction industry and by stakeholders. Timely detection of threatening safety issues is crucial to prevent the health condition of the structure to deteriorate rapidly leading to possibilities of a disastrous result. In order to achieve timely detection of threatening safety issues without continuous monitoring, visual inspection needs to be done frequently.

Visual inspection is labour-intensive and time-consuming as field personnel needs to inspect the items listed on the checklist one-by-one and often required to disassemble secondary parts to gain access to load-bearing structural elements (Liu, Chen, Hu and Zhang, 2019; Balageas, Fritzen and Güemes, 2010). Visual-based observation also proved that this method has low efficacy, impractical, and not plausible due to this method does not offer detailed or quantitative information about the interior defects within the structure member. The problem with such techniques will lead to unpredictability and unreliability in appraising the structural health of a structure (Ghosh et al., 2020).

With SHM, continuous monitoring is applied to the structure to enable damage detection throughout the building lifetime. By adapting SHM, damage can be detected as soon as possible due to the real-time monitoring and analysis of SHM and issue warnings to the stakeholders of the building. With the condition of structural members and location of damages, stakeholders can make better decision to evacuate or call for maintenance service. Early detection of damages in the building will yield a lower maintenance cost due to the damages will be repaired at early stages before it worsens into a dangerous state. The building's operating life can also be prolonged by knowing the real-time building condition, unlike classic structures to abandon buildings that are past their design life in fearing of the building's safety. Other than that, in presence of natural disasters such as earthquakes, SHM can also be used for rapid screening to provide dependable knowledge about the condition of the structure during the event and its integrity of the structure. This can benefit from determining if the structures are safe for reoccupation and significantly alleviate economic losses after major seismic events (Farrar and Worden, 2012). To take full advantage of SHM, BIM data management, and processing method is studied to lay the foundation for better visualisation and better interaction between non-engineer stakeholders.

1.3 Problem Statement

In Structural Health Monitoring (SHM), it is required to manage and analyse data obtained from sensors and present the structure condition to the users for decision making. The problem of traditional ways of SHM is mainly caused by a series of factors such as it is challenging to store and retrieve huge volumes of data and lack of visualisation.

SHM involves an enormous volume of data which includes raw data from sensors and information about sensors or structural elements such as model, manufacturer, maintenance company contact number, etc. Unfortunately, the current SHM practices are limited to only storing data recorded by sensors. Its limitation is where users wish to retrieve information of certain structure members, they will need to refer to data stored in hardcopies such as 2D drawings or catalogue for information such as dimensions, materials, and locations of structure members. It is questionable to take an extra step before users are able to retrieve crucial data of structural members. By storing essential data in a separate location or folder will present a risk of loss of data during retrieval in the future.

A key problem in current SHM practices is its lack of visualisation in presenting processed data to users. Current SHM displays their monitoring data in numbers, figures, and charts in a web interface to the users (Furtner, Stöger and Schreyer, 2013). The images and graphs presented can only be understood by trained personnel such as engineers or technicians. The current SHM is lacking in interaction with non-engineers such as buildings owners and stakeholders because graphs and values cannot be understood by them. Other than that, the exact location of the damage cannot be visualised by users with the current practices of SHM. Users will need to refer back to drawings to determine the locations of the sensors in order to find out the damaged structural members. Lastly, at the moment there is not a preferred workflow to integrate BIM with SHM. The absence of a common validated framework for BIM-based SHM is the case for such a study (Del Grosso et al., 2017).

1.4 Aim and Objectives

The main aim of this study is to propose a framework to integrate a BIM-based data management system into Structural Health Monitoring. The objectives of the study are as below:

- (i) to investigate traditional structural health monitoring and how BIM can be incorporated into it.
- (ii) to review the current BIM-based data management system.
- (iii) to investigate the suitability of a BIM-based data management system for structural health monitoring using the proposed framework.

1.5 Scope and Limitation of the Study

The scope and limitations of the study are listed as follows. First, the BIM-based SHM developed in this study was tested only by interpreting data from only one type of sensor which is an accelerometer sensor. Second, the raw data obtained from the sensors are assumed to be reliable without noise and monitoring errors due to the faulty of the sensor. Furthermore, the BIM-based SHM conducted in this study is towards a four-story concrete structure. Lastly, the proposed framework was developed using Revit and Dynamo.

1.6 Contribution of the Study

The thesis' final product will serve as a guide and a reference for future research on incorporating BIM-based data management systems for structural health monitoring. This research aims to develop a framework for implementing a BIM-based data management system for SHM. Because of its generality and flexibility, the proposed framework can be used as a preferred workflow for integrating a BIM-based data management system into SHM using Revit and Dynamo. Furthermore, as compared to conventional SHM, the proposed framework enhances data management and damage visualisation, allowing stakeholders to make better decisions.

1.7 Outline of the Report

This thesis comprises a total of five chapters which are the introduction, literature review, methodology and work plan, results and discussion, and conclusion and recommendations. Chapter 1 is the introduction of this thesis,

by a briefing on damage identification, implementation of SHM and BIM in the construction sector. Chapter 1 concluded with the aims and objectives of the thesis together with the scope and limitation of the thesis. Chapter 2 reviews the studies of previous researchers on the current practice of SHM and the integration of BIM-based data management system on SHM. The frameworks of current BIM-based SHM are also studied in this chapter. Chapter 3 explains the methodology of proposing a framework integrating BIM into SHM using Revit and Dynamo. Moving on to Chapter 4, results and discussions on the proposed framework of BIM-based SHM are shown and interpreted clearly. Lastly, conclusions have been made in Chapter 5 with recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the current practice of Structural Health Monitoring (SHM), the problem faced by current SHM and BIM-based data management. Different challenges and advantages of integrating BIM into SHM were explained. Finally, various cases related to integrating BIM into SHM were reviewed.

2.2 Current Practice of SHM

Structural Health Monitoring (SHM) is a rising discipline that brings together different disciplines such as civil engineering, software engineering, and data management engineering to keep an eye on the safety of structures (Malik et al., 2019). It is a damaged identification mechanism that involved observing a structure over time and extracting damage-sensitive features to determine the structure well-being (Farrar and Worden, 2010). It is implemented in civil infrastructures, to ensure structural safety and declare impending warnings of structural damage prior to costly maintenance or failure of structure (Ghosh et al., 2020).

Detection of damage usually takes place during the maintenance work of the structure. The initial maintenance philosophies are a run-to-failure approach where the system is operated until some major components break down. It evolves into a time-based maintenance approach where the previous approach is unacceptable when life-safety is at concern. This approach is used broadly in this decade where important components are maintained and replaced at a planned time interval regardless of their condition. Due to the lack of data transfer possibilities, it began with picking up measurement data on-site visits and carrying them back to the office for necessary analysis (Furtner, Stöger and Schreyer, 2013). With the rise of wireless standards and the rapid development of the internet, the SHM system has evolved from intermittent data collection and limited data processing to obtain data with the deployment of sensors and setting up data acquisition, transmission processing, and control system for

structural health evaluation (Zhou et al., 2006). SHM is a valuable technique because it evolves the current time-based approach to evolve into condition-based maintenance philosophies where continuous monitoring is applied and will only notify the operator when the damage has been identified (Farrar and Worden, 2012).

The advantages of SHM systems are minimizing downtime of structure, reducing maintenance cost by human involvement, labour and replacing scheduled and periodic maintenance inspection with performance-based maintenance, decreasing number of inspection points leads to enhancing knowledge of structural behaviour and improve future design concepts and constant maintenance cost (Balageas, Fritzen and Güemes, 2010; Delgado et al., 2017).

McNeill (2019) laid out the four main steps of the SHM system. They are a direct measurement of structural properties using sensors, transportation of the collected data to a location that they will be analysed or processed, storage of the data in a suitable manner that ensures the data's efficient, reliable and robust access and analysis of the data to deliver the evaluation of the structure's health.

The development of sensor data management framework for SHM can be which is the database, data processing tools, and web interface as illustrated by Jeong et al. (2015) in Figure 2.1.

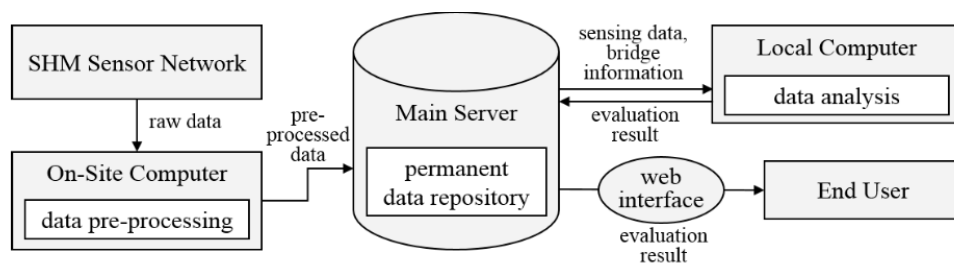


Figure 2.1: Sensor Data Management Framework for SHM (Jeong et al., 2015).

2.3 Problem Faced in Current SHM

In periodic monitoring, all data gathered during the monitoring process are mainly stored on-site with no accessibility for off-site personnel and no backup. Documentation of technical details such as placement of the sensors together

with manufacturer and models of sensors as well as data measured by sensors must be retained well for future reference. In periodic monitoring, there is no guarantee that the technical documents and records will be accessible after several years (McNeill, 2009). Periodic monitoring can also be costly when dealing with spatial areas or limited access locations such as underground and sea. SHM can reduce the cost of travelling and save time to dispatch technicians, where only when damage is detected maintenance is needed. Periodic monitoring is shifting to SHM unless damage locations are accurately identified beforehand due to its ability to store large amounts of sensor data and technical documentation in the database (Cawley, 2019).

SHM is a multi-discipline field that makes useful decisions based on the diagnosis of health assessment data collected by large numbers of sensors (Bao et al., 2019; Balageas, Fritzen and Güemes, 2010). The traditional ways of dynamic data monitoring are by finding key nodes of the structures through the 2D plan drawings for sensors installation. The sensor's data are obtained and calculated manually by comparing the values with the structure initial condition. This method causes the monitoring data to be relatively low and the amount of data obtained cannot fully represent the characteristics of the building (Xia, 2020). Malik et al. (2019) illustrated that SHM is carried out by analysing the input data from various sensors on a structure such as vibrations, strain, stress, displacement, acceleration, and shock sensors. The problem of SHM is that it requires more monitoring sensors to be deployed and requires more complicated data analysis procedures to process a large volume of data. As SHM practices continuous monitoring and the number of monitoring locations increase, the data stream becomes unmanageable (Cawley, 2019).

Valinejadshoubi et al. (2018) illustrated that the fundamental task in an SHM system is capturing and storing the sensor data for future retrieval. This can be true as long-term SHM systems have to deal with a massive amount of high-dimensional data with diverse and complex data types that are continuously collected from the system (Valinejadshoubi, Bagchi and Moselhi, 2016; Zhou et al., 2006; Jeong et al., 2017a; 2017c). The data must be collected and managed properly because SHM has to deal with a huge amount of both raw data as well as post-processed data during the entire lifecycle of the

structure (McNeill, 2009; Valinejadshoubi, Bagchi and Moselhi, 2016; Delgado et al., 2017).

The problem faced by the current practice of SHM is that it is challenging to store and organize a large amount of measurement data that might sum up to hundreds of gigabytes throughout the entire lifecycle of the structure for risk and hazard mitigation of the structures (Valinejadshoubi et al., 2018; Boddupalli, Sadhu and Rezazadeh Azar, 2018). Data management, processing, analysis, and interpretation are a huge threat especially in the case of permanent monitoring over the lifetime of the structure (Furtner, Stöger and Schreyer, 2013).

The current database for SHM which are Relational Database Management System (RDBMS) and the file-based system are not effective to manage large and complex data as a massive hike of data makes both file-based system and RDMS inadequate to cater for the huge volume and heterogeneity of sensor data (Jeong et al., 2017b; Riaz et al., 2017). Selecting a suitable database tool is crucial for the success of the data management system and can ensure low efforts in extracting data in the future. The database selected must also be obliged to be scalable and robust against node failures (Jeong et al., 2017b; Jeong et al., 2017c; Riaz et al., 2017). Furtner, Stöger and Schreyer (2013), listed out major requirements to be solved to have a satisfying data management system. (1) Reliability of monitoring system where operational interruptions and system malfunction have to be automatically recognized; (2) Huge amount of data have to be developed and stored in data library and allow easy access to the data; (3) Fully automatic detection, alert and action triggering when threshold values are surpassed; (4) User interfaces which are straightforward and intuitive to operate are required for data presentation; and (5) Support of system operators that are capable for the permanent day-to-day operation of the monitoring system.

The current SHM also lacks visualisation where they mostly present their monitoring data in different types of charts and images (Furtner, Stöger and Schreyer, 2013). The web interface set up provides images, scatter plots visualised by visualisation code using Google Chart Tools API (Koo, Battista and Brownjohn, 2011). These images and graphs do not show the exact locations of the damaged element and can only be understood by technicians.

The current SHM visualisation lacks engagement and interaction for structure stakeholders and non-engineers with the current structure condition.

2.4 Case Studies of Current Practice of SHM

These are the case studies done on the current practice of SHM that have been put into use in both the United Kingdom and Hong Kong.

2.4.1 Sheffield SHM Data Management System

Sheffield SHM data management system has been used to conduct SHM on Tamar Bridge, Humber Bridge, and Arts Tower in the United Kingdom. The three key components for the Sheffield SHM data management system are a MySQL database, a MATLAB interface, and a web interface (Koo, Battista and Brownjohn, 2011). Data are extracted from sensors and stored into a raw file in a remote PC before it is transferred to the server and stored into the MySQL database. MATLAB scripts run signal processing from time to time and analysis is done on the latest and past data obtained from the MySQL database. The processed data are saved back into the database for future reference. MATLAB is chosen in this system due to MATLAB being the most familiar signal processing platform due to its state-of-the-art toolboxes. The MATLAB database toolbox can provide access to a virtual database engine although it requires an additional license to obtain the toolbox. Sheffield SHM allows international researchers to collaborate over the Internet, with an Internet-enabled PC, researchers can access the data stored in the database and analyse it in the MATLAB workspace. A web interface is also set up to present structure data such as time-histories, images and scatter plots for any channels over a selected time frame as shown in Figure 2.3. The web interface also aims to provide instant visualisation of measurement data for its users (Koo, Battista and Brownjohn, 2011).

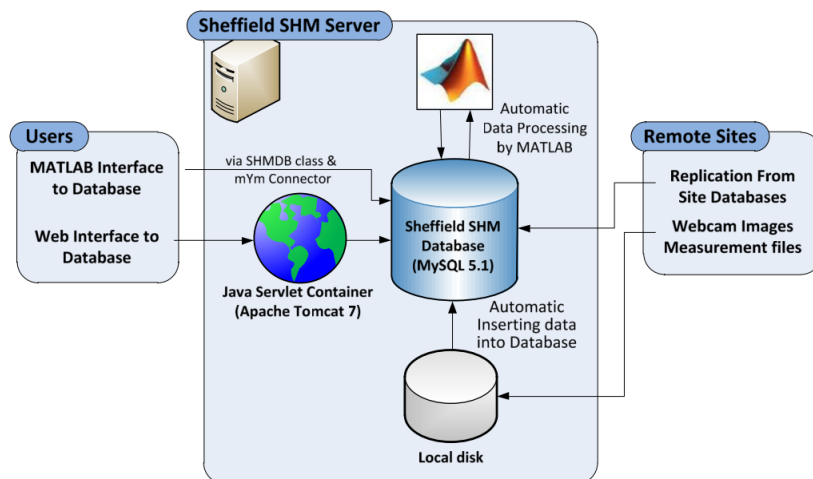


Figure 2.2: Organization of Sheffield SHM Data Management System (Koo, Battista and Brownjohn, 2011).



Figure 2.3: Screenshot of Web Interface of Sheffield SHM (Koo, Battista and Brownjohn, 2011).

2.4.2 Wind and Structural Health Monitoring System (WASHMS)

The WASHMS is a long-term SHM system developed by the Polytechnic University of Hong Kong and operated on cable-supported bridges such as Tsing Ma bridge, Kap Shui Mun bridge, and Ting Kau bridge in Hong Kong. The WASHMS consists of five key components which are: (i) Oracle database of 4D bridge model; (ii) MySQL database; (iii) MATLAB-based structural health evaluation software; (iv) web interface for communication between database and users by 3D bridge model; and (v) web interface for displaying

sensor information, querying data and results. The framework of the database system is shown in Figure 2.4.

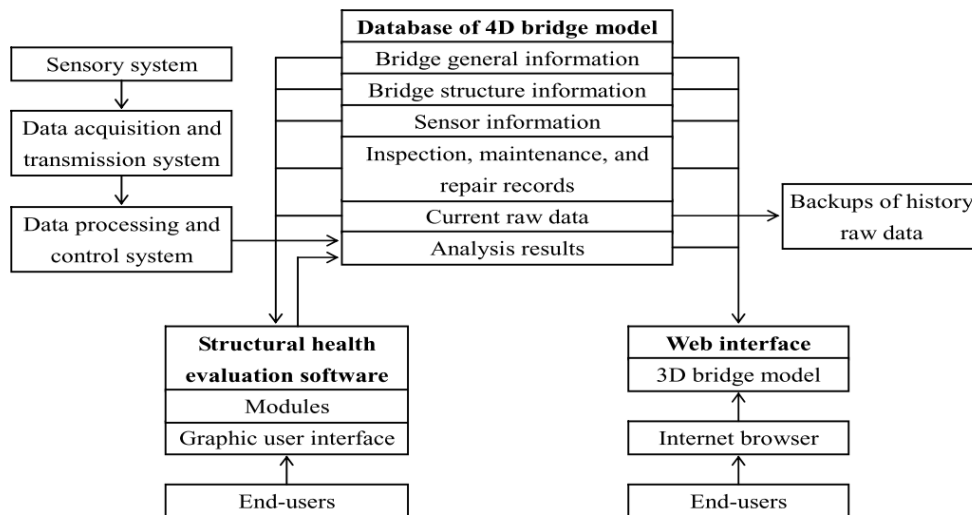


Figure 2.4: Framework of WASHSM (Zhou et al., 2006).

The database of the 4D bridge model is using Oracle one of the systems from RDBMS. The database is designed to hold both static and dynamic data from the bridges. The static information retained is bridge general information, structural information, and sensor information, while the dynamic data stored are recent raw data acquired from WASHMS, analysis results, and inspection and repair records. However, due to the limited storage capacity and increasing volume of data along the lifecycle, MySQL database software has been introduced to store history raw data. MATLAB Database Toolbox allows an automated data swap mechanism between MATLAB and the 4D bridge model database. By using the mechanism, MATLAB can access data in the database for advanced data analysis. There are two modes of data analysis provided in MATLAB which are single analysis and batch analysis. The main difference between the two is for a single analysis, end-users need to specify the time of the data to be analysed while in the batch analysis only requisite parameters need to be set and the rest is automatically carried on by the software. The single analysis allows end-users to get a closer insight into the raw data by selecting a specific time frame. Due to the single analysis being laborious, a combination

of both modes is suggested where only affected results are extracted from batch analysis and analysed individually.

A web interface is created for authorized users to access information regarding bridge structural health conditions. The 3D model of the bridge is created by converting CAD drawings into DXF and VRML files. By constructing the 3D model, users can engage with the database system and the selected element will be highlighted and relevant data about the element will be presented. Another web interface is also created to provide in-depth sensor information. The web interface also serves as a query where users can explore desired data by indicating sensor ID and time period. It is proven that WASHMS conquers the obstacle of limited storage capacity by introducing two databases which are the database of the 4D bridge model and MySQL database (Zhou et al., 2006).

2.5 BIM-based Data Management System

Building information modelling (BIM) is widely used during the architectural, engineering, and construction (AEC) phases, but its usage in SHM is still immature due to limited and slow adoption in the SHM community (Edirisinghe, London, Kalutara and Aranda-Mena, 2017). BIM has emerged as an efficient and capable data management tool by collecting, sorting, storing, sharing and retrieving data, and providing a digital environment. Other than that, BIM is also an object-oriented model that can simulate all structural elements to provide end-users to visualise the whole building and individual elements to aid in enhancing practical decision-making (Valinejadshoubi, Bagchi and Moselhi, 2016). The contribution of BIM in the SHM process is illustrated in Figure 2.5. The leading providers in the BIM market are software developers like Revit, Tekla, Bentley and ArchiCAD (Zhang and Bai, 2015).

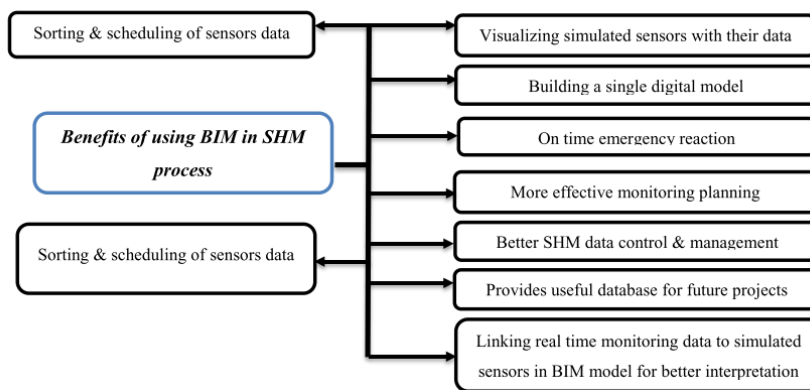


Figure 2.5: Benefits of Using BIM in SHM Process (Valinejadshoubi, Bagchi and Moselhi, 2016).

The major component of the BIM framework for SHM can be categorized into three steps which are developing an accurate model, collection of sensor information, storing of data, and linking data from the database to the BIM model as shown in figure 2.6. In BIM, everything is kickstarted by building a 3D digital model of the structure. BIM is a technology that fuses 3D modelling with architectural engineering to produce a virtual model of the building (Xia, 2020). The construction of the model requires a large amount of building data to convert them into semantic BIM objects (Volk, Stengel and Schultmann, 2014). The model must also include the virtual sensor’s location, its parameters to assists the engineers to visualise the location of the sensors and manage the sensor’s data easier. A legitimate BIM model must consist of all virtual elements equivalent to the actual structure and their properties (Valinejadshoubi, Bagchi and Moselhi, 2019; Boddupalli, Sadhu and Rezazadeh Azar, 2018). The overall BIM data framework is illustrated in Figure 2.7.

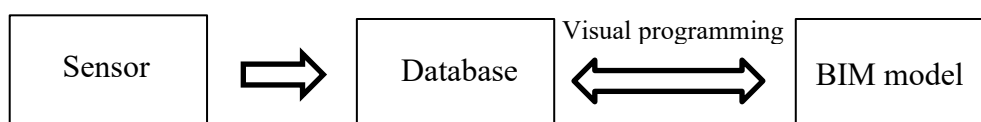


Figure 2.6: Major Components of Integrating BIM into SHM

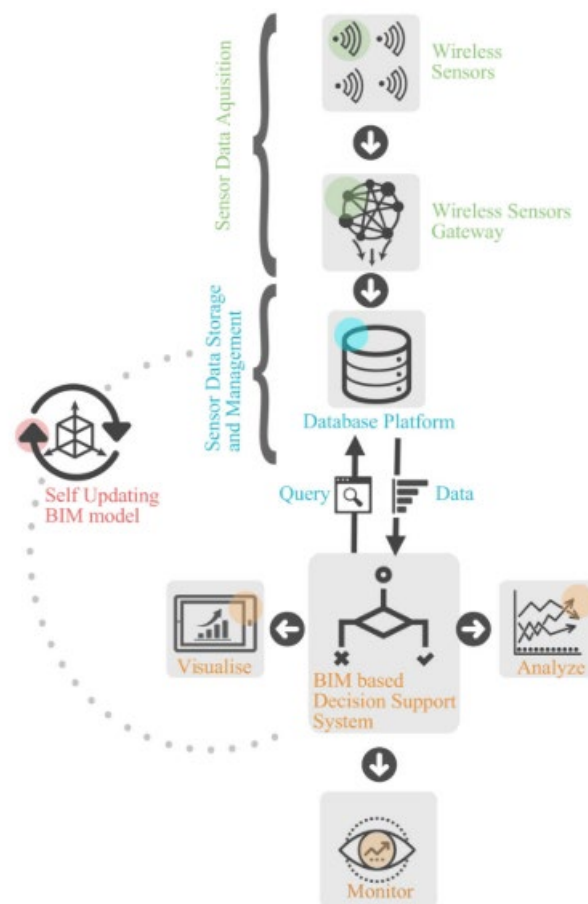


Figure 2.7: Data Framework of BIM (Riaz et al., 2017).

2.5.1 Industry Foundation Class (IFC)

The problem with the BIM approach is its lack of interoperability and data exchange with other software due to the lack of open standard data models that permit a robust swap of data (Delgado et al., 2017). Industry foundation class (IFC) emerges as a universal data format for inter-platform data exchange. BIM model must be converted into an IFC file before interacting with other software such as SHM and FE analytic software. IFC-based BIM enables sensors to be modelled into the model and import pieces of information from physical sensors. This can be done by mapping monitored sensor information into the IFC object model through the IFC scheme that connected sensor modules with the BIM. To import and manipulate the data from physical sensors into the model, each type of sensor must be assigned a predefined sensor type under `IfcSensor` that falls under the speciality equipment category (Valinejadshoubi, Bagchi and Moselhi, 2016). However, not all sensors are

predefined in the IFC object model, thus sensor information and identity are required to be modelled under the sensor type USER DEFINED manually.

Although it is noteworthy that IFC is by far the most promising standard to increase BIM interoperability drastically by uniting modelling languages, no single IFC adapter can connect to all software in the SHM system, therefore, the weakness of BIM to exchange data have not been solved completely. IFC versions may also be troublesome to keep up with where a newer version of BIM launched, data loss or incompatibility may occur when transferring to users of the previous version. At this moment, IFC standards are still evolving and improving causing earlier IFC data to be rendered useless and unreadable in the present IFC version. The drastic changes introduced by the new IFC version will cause engineers or technicians a laborious effort to update the model accordingly (Gu and London, 2010).

2.5.2 Database

After defining the sensors in the IFC object model, the sensors are loaded into the model and placed at the exact location of the physical sensors. With the IFC-based model, external data can now be linked from the database to the virtual sensors in the model. The database is chosen to store the dynamic data monitored due to its ability to store and manipulate complex data efficiently. NoSQL emerges as a more suitable database system when compared with MySQL and RDBMS in terms of reading and write speed, scalability, and flexibility of data schemas (Jeong et al., 2015; 2017b). Jeong (2015) also suggest that the NoSQL database can be categorized into 3 types of models which are: (i) key-value store; (ii) document-oriented stores; and (iii) column-oriented stores. The common NoSQL databases are MongoDB and Apache Cassandra.

MongoDB is a document database that provides high performance, automatic scaling, and the ability to write intensive applications. MongoDB's promising functions are its powerful query capability and its capability to handle huge data sets in real-time analysis. The serious drawback with MongoDB is it implements master-slave replication when scaling, this causes the failure of the entire database when the master node fails (Jeong et al., 2015; Riaz et al., 2017). Apache Cassandra, on the other hand, is a type of column-oriented NoSQL that enables different column sets and new columns to be added at each row without

modifying the other rows. This feature of Apache Cassandra is noteworthy in the fact that it gives a more flexible database in terms of a tabular structure. Unlike MongoDB, Cassandra stores its data over several machines as illustrated in Figure 2.8, leading to a decreasing in query performance due to distributed data storage. However, the Apache Cassandra database is more promising due to its decentralized system that would not fail where either point fails, unlike MongoDB. Moreover, Apache Cassandra has a significant advantage over document-oriented database such as MongoDB when encountering huge data sets of unstructured information. Cassandra's feature of availability, scalability, and schema flexibility let it deal with a huge volume of data transaction and storage effortlessly. As SHM is more likely to have a high transaction of read-write rates given the continuous monitoring process, Apache Cassandra gains more popularity in the SHM field because data retrieval from the database will be performed less frequently (Jeong et al., 2015; 2017b;).

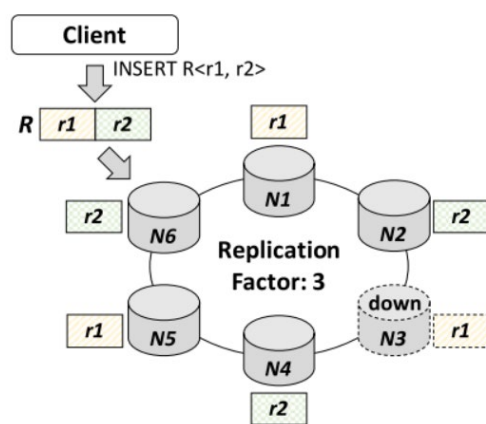


Figure 2.8: The Ring Architecture of the Cassandra Database (Jeong et al., 2017b).

2.5.3 Processing and Visualisation of Data

BIM is an effective data management tool however dynamic monitoring is not part of BIM functionality and transferring physical sensor data into BIM virtual sensor still pose a challenge (Valinejadshoubi et al., 2018). BIM are mostly static representations, in order to extend the BIM model for dynamic monitoring, real-time sensor data have to be linked for more effective decision making (Valinejadshoubi, Bagchi and Moselhi, 2016). The evidence from the literature

proves that it is possible to create a link between SHM and BIM to allow bi-directional data flow (Del Grosso et al., 2017). Visual scripting tool and Application Programming Interface (API) can be used to connect sensors to BIM overcoming the gap between physical sensors and virtual sensors in the BIM model (Kensek, 2014).

There are several ways to extract sensor data from the database which are program add-ins, scripts, and APIs into BIM software in this case Revit. The link between the BIM model and SHM data can be formed by Revit APIs using Dynamo, Keynote manager tool, etc. Keynote manager tool is a Revit add-in to integrate data into Revit by creating a keynote to define each sensor. Each sensor is defined with a numerical code known as keynote and is added to the main keynote list of Revit. After defining sensors with keynotes, external files can be linked to each virtual sensor to store data with different formats such as images, PDF, Excel spreadsheets, etc. (Valinejadshoubi, Bagchi and Moselhi, 2016).

Another way of extracting physical sensor data is with the Revit API plugin, Dynamo. Dynamo is a visual programming tool that can be used with no programming experience to perform automated repetitive tasks. Dynamo uses code blocks that contain small scripts written in a python programming language to create a workflow (Valinejadshoubi, Bagchi and Moselhi, 2019). In Dynamo, each node performs a specific task. Nodes will have output ports to communicate with other nodes. Node to node communication can only occur when the output data type matches the input of another node with wires as a connector as shown in Figure 2.9 (Kensek, 2014). Nodes can be classified as transactional and non-transactional depends on their function. A transactional node will open the database to update elements created during that phase while a non-transactional node will not change anything in the database. An example of transactional nodes will be extracting sensor data from the database and non-transactional nodes will be comparing the sensor data with the pre-defined threshold value. With the Dynamo tool, the sensor data in the database is converted into an excel spreadsheet and read into the Revit model to be displayed as key schedules. Users can choose for Dynamo to run automatically on each start-up of the model or manually to update the BIM (O'Shea and Murphy, 2020). After reading the sensor data into BIM, Dynamo can also compare the value with the threshold value to classify structural members as

damaged or undamaged. The damaged structural element will be filtered and highlighted in the BIM model (Valinejadshoubi, Bagchi and Moselhi, 2019).

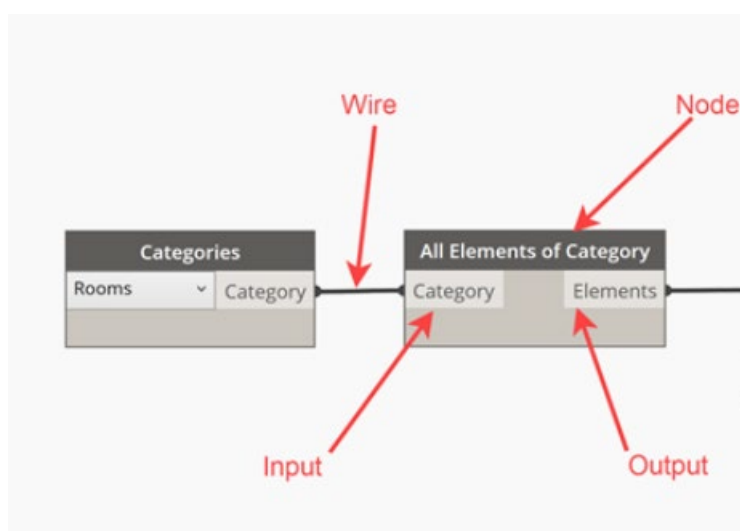


Figure 2.9: Dynamo Code Blocks

By transforming a static Revit model into a dynamic tool for structural health monitoring, data and analysis can be visualised on a single platform. With the aid of customized visual programming tools, SHM BIM has enhanced the integration of real-time data from the SHM sensor linked to virtual sensors in the model. By integrating BIM in SHM, the damage visualisation method is also developed such as colour-coding the model based on the data analysis done with the automatically updated sensor data through visual programming tools (O'Shea and Murphy, 2020). BIM is also efficient in managing data from the SHM system, where Revit can generate sensor schedules to include all sensors as well as their information as shown in Figure 2.10. By clicking on the sensor on the schedule, the location of the sensor will be highlighted in the model to prevent finding the location of sensors manually from drawings (Valinejadshoubi, Bagchi and Moselhi, 2016). Another advantage of BIM SHM is that all the information on a damaged member can be extracted easily from the model regardless of dimension, manufacturer, contact number, etc. Revit (Valinejadshoubi, Bagchi and Moselhi, 2019). All pieces of information of sensors and structural elements will also be retained in the BIM to guarantee lifetime access along without relying on documents and drawings.

The modelling and visualisation of the monitoring data were done using Autodesk Revit. The IFC-based structure model was developed with the help of engineering drawings using Revit while all the sensor's data are processed using MATLAB. The data extracted from each sensor were handled by MATLAB with the Fast Fourier Transform (FFT) algorithm and the FFT plots are exported as JPEG files for better visualisation of model parameters of the structures are to be stored in Revit. To enhance the accuracy of the model, Robot Structural Analysis (RSA) is adopted to compare the SHM result. RSA was chosen to perform structural analysis due to both Revit and RSA are compatible. The working space of RSA can also be reduced by exporting the Revit model into the software to start analysing. The results of RSA such as reaction, forces, and deflections are converted into PDF format and linked to the Revit model. The output from MATLAB together with RSA is compared to observe the structural health of the structure. All results of the analysis are transmitted into the BIM model for evaluation of damage and decision making.

2.6.2 Case 2

Valinejadshoubi, Bagchi and Moselhi (2019) proposed a framework as in Figure 2.12, that consists of two main modules to fuse BIM to ease the data management of SHM. The two major modules consist of: (i) an automated data procurement and storage module based on sensors; and (ii) an automated data and damage visualisation model.

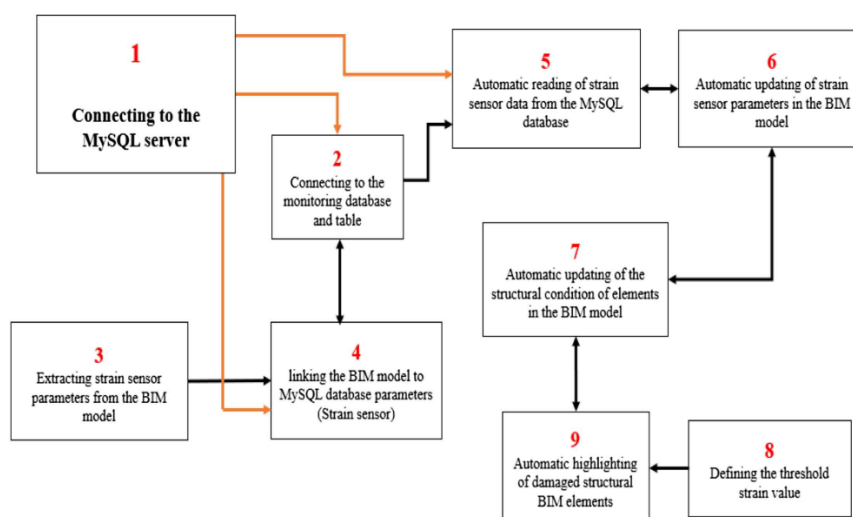


Figure 2.12: Proposed BIM Framework (Valinejadshoubi, Bagchi and Moselhi, 2019)

The BIM software chosen for structure modelling is Autodesk Revit where it is modelled using the Industry foundation class (IFC) standard. MySQL is used as a database to store and update the captured sensors data. However, in order to insert the data into MySQL a schema and a table must be defined along with all important parameters. Modules are created in a graphical programming interface installed as part of Revit called Dynamo. This is because Dynamo can produce the schema and table automatically and link the MySQL database to the BIM model. With the help of Dynamo, the connection between the BIM model and MySQL database is formed and the BIM model can now read the data stored in the MySQL database. The strain value obtains from the sensors are updated into the BIM model at the end of each time interval. Dynamo also applied a module to classify the virtual sensor as a damaged or undamaged condition where it compares the strain data from the entered with a predefined threshold strain value. Where in a case that the strain data exceeded the predefined threshold, the condition of the sensors will be updated to the BIM model. Through the colour-coding scheme, the structural elements where the strain values exceeded the threshold values will be highlighted in the model. It is proven that BIM as an effective data management system inefficient structural condition assessment and visualisation. However, there is a limitation in the study presented which is conducted with only one type of sensor which is the

strain sensor. The system has not been tested with multiple types of sensors; hence further tests should be held before the implementation of the proposed framework.

2.6.3 Case 3

Valinejadshoubi et al. (2018) also published on utilizing BIM in SHM of structure. Autodesk Revit is chosen as its modelling software to model the structure and the model is exported to ETABS for structural analysis. This step is to analyse and identify the critical points of the structure for sensor placements. By placing sensors accurately and effectively, the number of sensors can be reduced drastically together with the monitoring cost and incoming data. After identifying the ideal locations of the sensors, the model is imported to Revit again to update the model and place the sensor virtually. After modelling the sensors, the BIM model is converted to the IFC-based model in order to allow interactions with external software. In order to certify that the sensors in the BIM model are recognized in the IFC model, the IFC model is opened using a visualisation software called Solibri Model Viewer. IFC model is then linked with the MySQL database to obtain all sensor data from the database. The linking of the IFC model with the database is performed with a visual programming tool, Dynamo. With all the sensor data inserted into the IFC model, the IFC model can now be exported into another structural analysis tool, Robot Structural Analysis for condition assessment. Lastly, a web-based server is designed to enhance data exchange and communication between SHM engineers, structural engineers, and clients. The overall data management is illustrated in Figure 2.13.

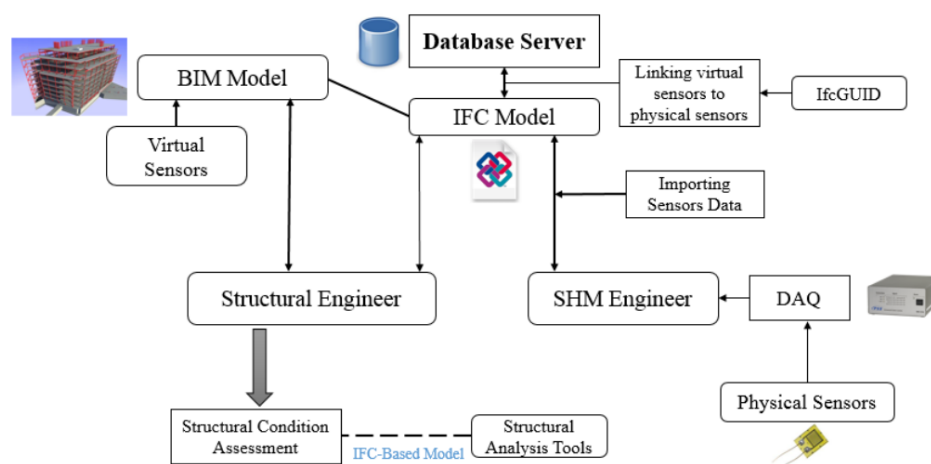


Figure 2.13: Data management model for SHM (Valinejadshoubi et al., 2018).

2.6.4 Case 4

Jeong et al. (2017c) also proposed a BIM framework for a bridge, and develop standards and frameworks for Bridge Information Modelling (BrIM). OpenBrIM standards were developed to enhance the interoperability between bridge monitoring and management applications. In this framework, OpenBrIM is used as the base schema and expand to include engineering entities for analysis modelling and sensor information. The model is then linked to the Apache Cassandra database and data are exchanged by pre-written data retrieval scripts. The bridge model modelled according to OpenBrIM standards is then analysed with a finite element software CSI Bridge. The overall bridge information management framework is illustrated in Figure 2.14. This framework proposed is flawed since current OpenBrIM standards still lack the data entities for representing the pertinent information to bridge monitoring applications. Thus, further development and improvement of OpenBrIM standards before BrIM is implemented.

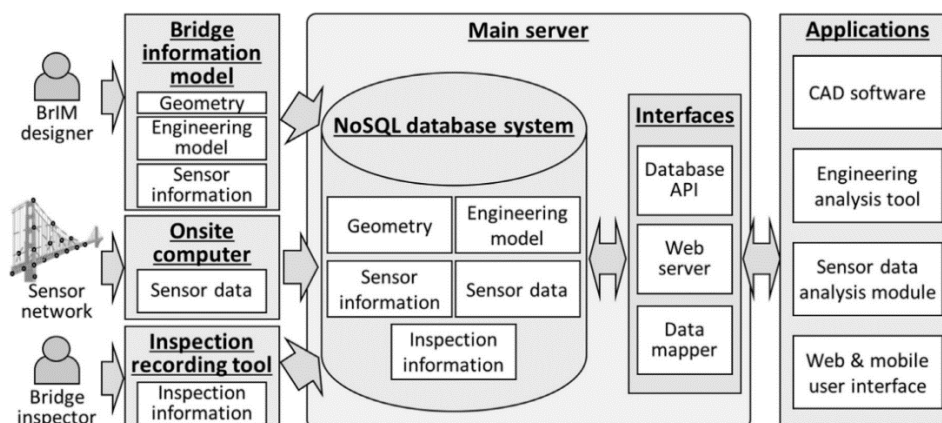


Figure 2.14: Bridge Information Management Framework (Jeong et al., 2017c).

2.7 Summary

This chapter briefly introduced the current practice of SHM, the problem faced in the current SHM and the BIM-based data management system. Furthermore, the details of implementing BIM-based data management into SHM are being outlined together with their challenges and benefits. Integrating BIM into SHM gives a more effective monitoring, better SHM data control and management, better interpretation and visualisation of sensor data, and providing a useful database for future projects. The importance of engaging and interacting between engineers and non-engineers can also be seen to enhance the damage identification process and maintenance of the structure. However, BIM-based data management is still immature and requires more studies and tests before actual implementation.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter describes the actions of integrating a Building Information Modelling (BIM) based data management system into a Structural Health Monitoring (SHM). The proposed framework consists of a few parts which are 3D modelling, extracting data from the sensor, analyse and sync sensor data to the visual sensor in BIM, and BIM model visualisation. The BIM software and visual programming platform were chosen to conduct this study are Revit® by Autodesk. Firstly, a 3D model of the four-story concrete structure was constructed in Revit structure together with virtual sensors and their information. Then Dynamo was used to read and analyse the mimicked sensor data generated in excel spreadsheet before integrate it with the BIM model and virtual sensors. The sensor value of amplitude data was then imported into the virtual sensor and conduct threshold analysis. If the virtual sensor value exceeds the threshold, the element will be flagged and colour-coded in the BIM model. Figure 3.1 illustrates the flowchart of the methodology to conduct this study.

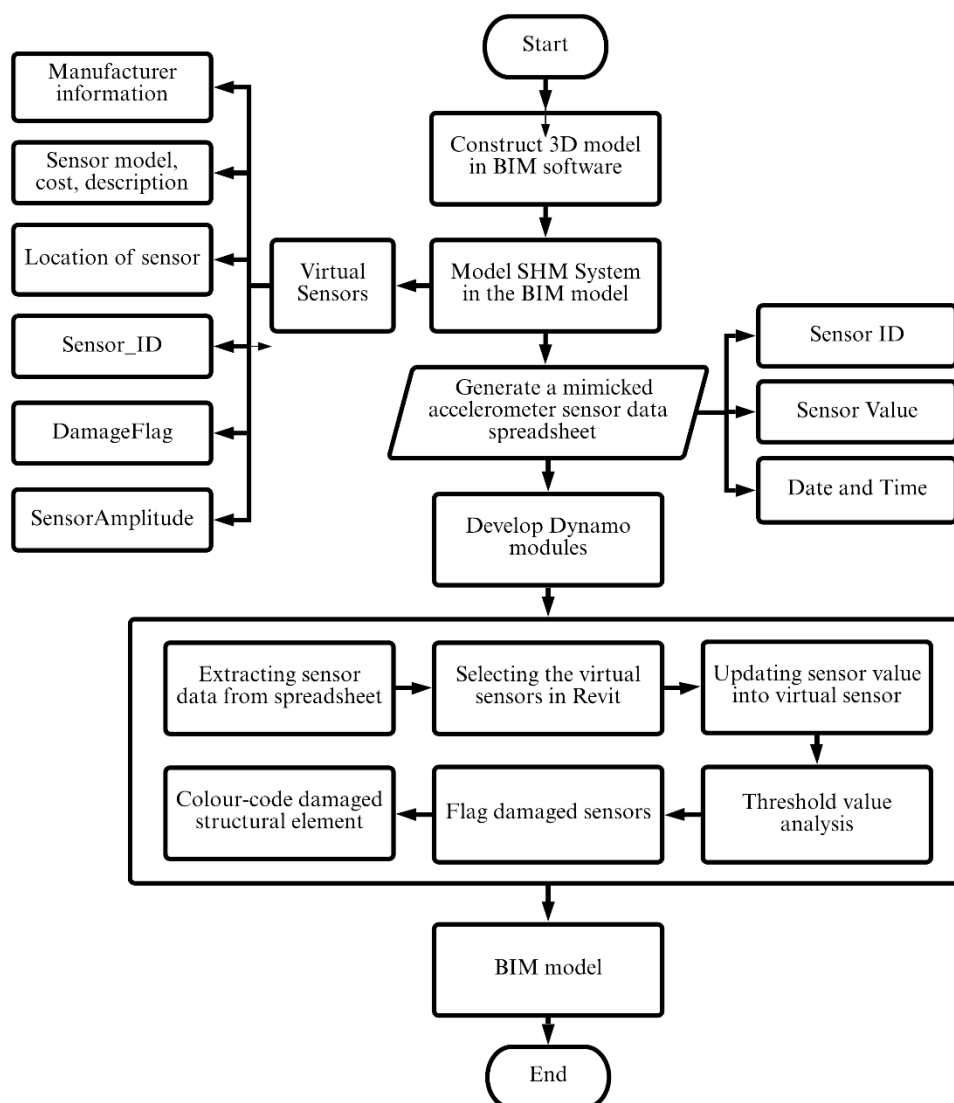


Figure 3.1: Flowchart of the Methodology of this Study.

3.2 Constructing 3D Structure Model

The first step was to model the structure in BIM software. The BIM software chosen here to construct the 3D model was Revit® 2021 by Autodesk. A simple four-story concrete structure was modelled with grade 30 concrete. The dimension of elements modelled was as follows concrete beam size 300×600 mm, concrete column size 300×450 mm, and slab thickness of 225 mm. Figures 3.2 and 3.3 illustrates the plan view of the structure and the building model.

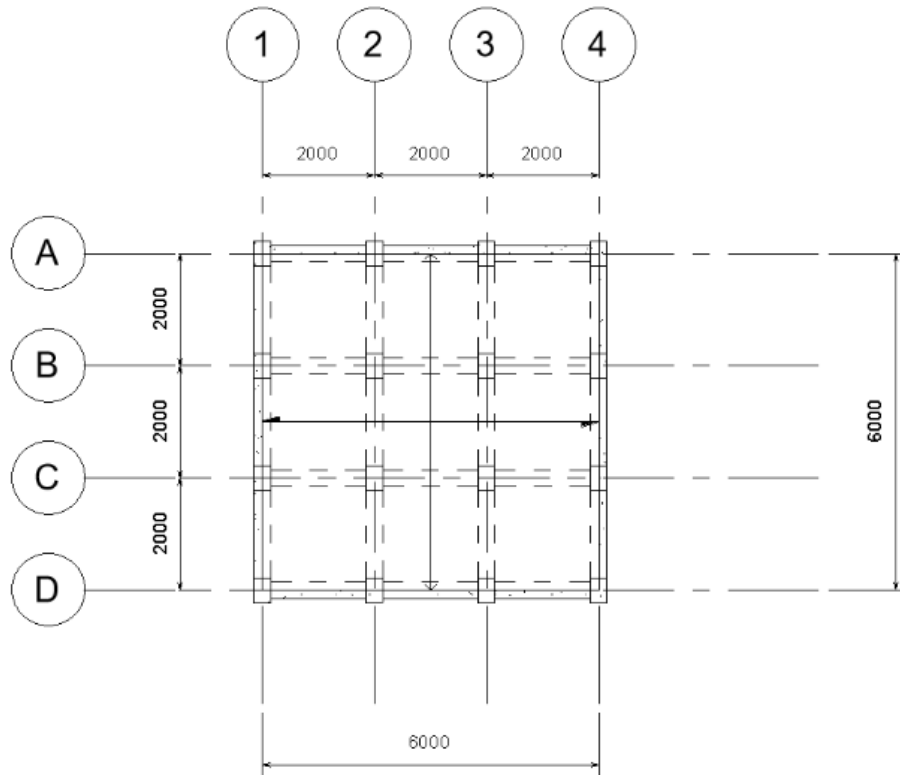


Figure 3.2: Plan view of the concrete structure.

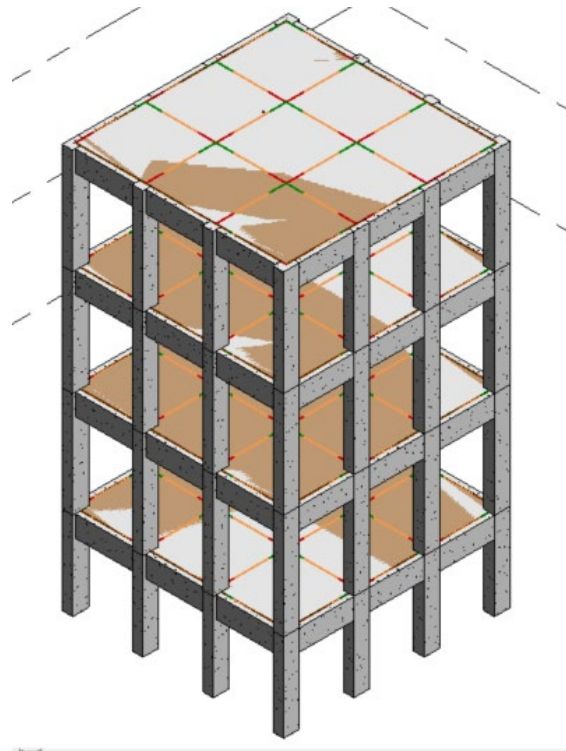


Figure 3.3: Concrete Structure 3D View in Revit.

3.3 Modelling SHM System in Revit

SHM sensors are modelled and be placed as physical sensors after developing the structure model in Revit. In this study, accelerometers are chosen to be placed on structural elements and monitor the structural condition. There are various categories in Revit, such as beam, column, slab, roof, etc. Accelerometers are modelled under the speciality equipment category as user-defined virtual sensors. After modelling the virtual accelerometer, other user-defined parameters and data can also be defined for the accelerometer such as manufacturer information, sensor model, cost, description, location of the sensor, Sensor_ID, DamageFlag, and SensorAmplitude. Sensor_ID of physical accelerometer must be allocated manually to each correlating virtual accelerometer to link the collected data from physical sensors and store it into virtual sensors in the BIM model. The DamageFlag parameter was created to represent structural elements conditions and can ease the colour-coding process during visualisation. Figure 3.4 illustrate the modelling of an accelerometer in Revit 2021 under speciality equipment and its parameters.

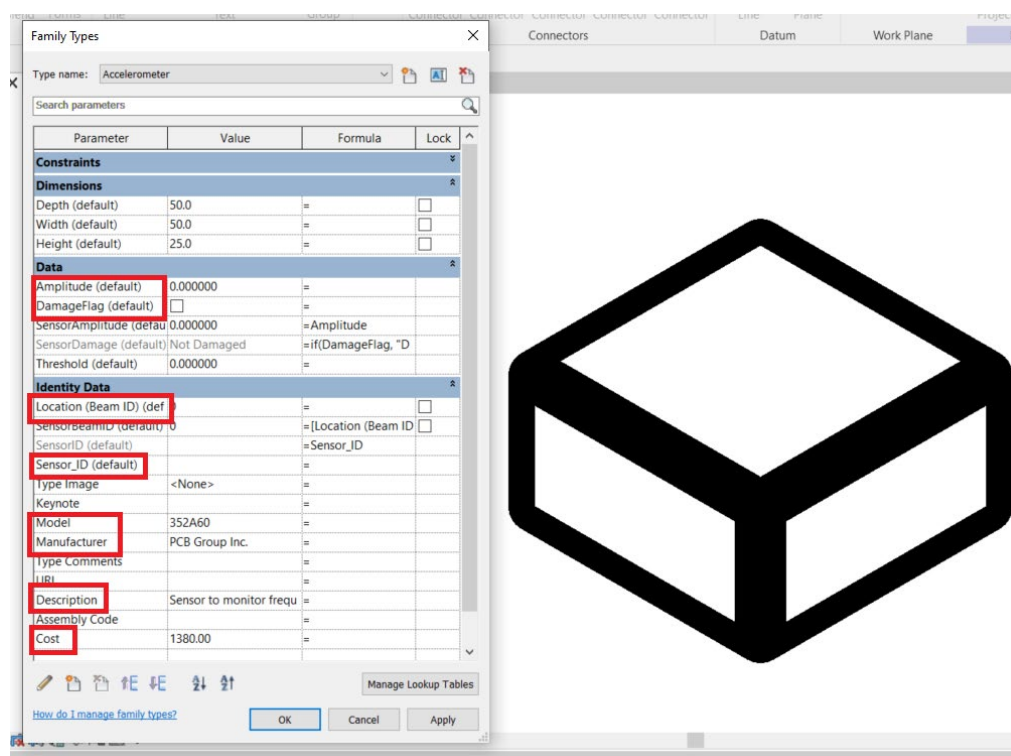


Figure 3.4: Accelerometer Modelled as Speciality Equipment Family in Revit.

The accelerometers were then attached to the designated locations below the structural beams. A total of 12 accelerometers were modelled and placed in the model. The accelerometers were attached below the level 1 beams at gridline D-1/2, D-2/3 and D-3/4 with 25 mm spacing apart. The accelerometers are placed near the midspan of the beam due to it being the most crack prone location as shown in Figures 3.5, 3.6 and 3.7.

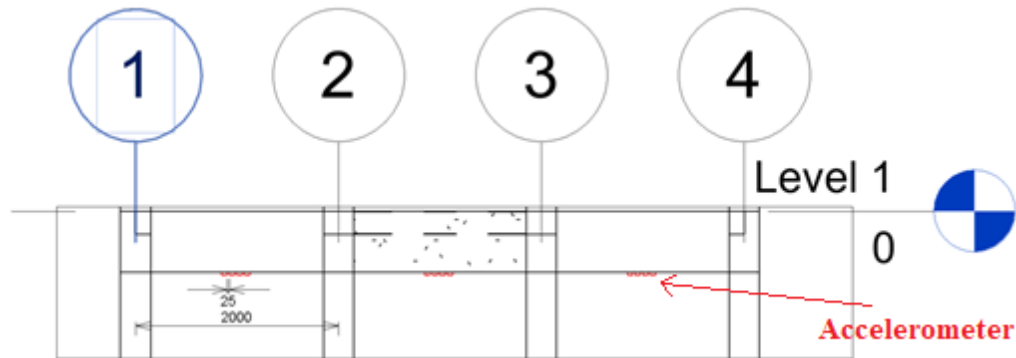


Figure 3.5: Level 1 Section View of the Structure.

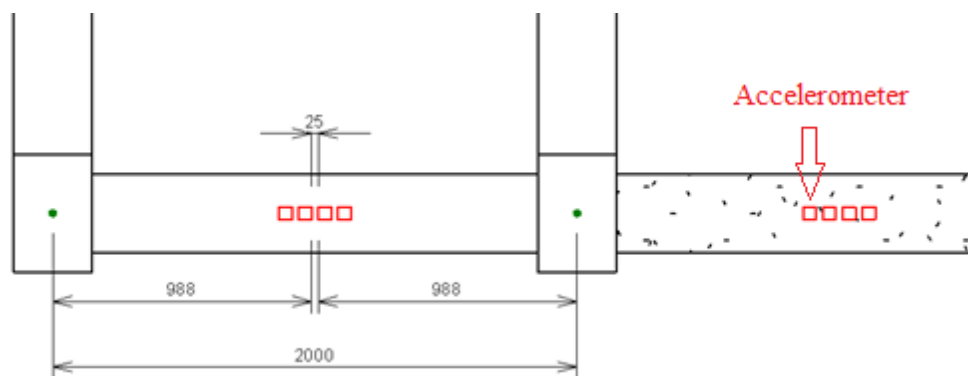


Figure 3.6: Bottom View of the Beam and the Placement of the Sensors.

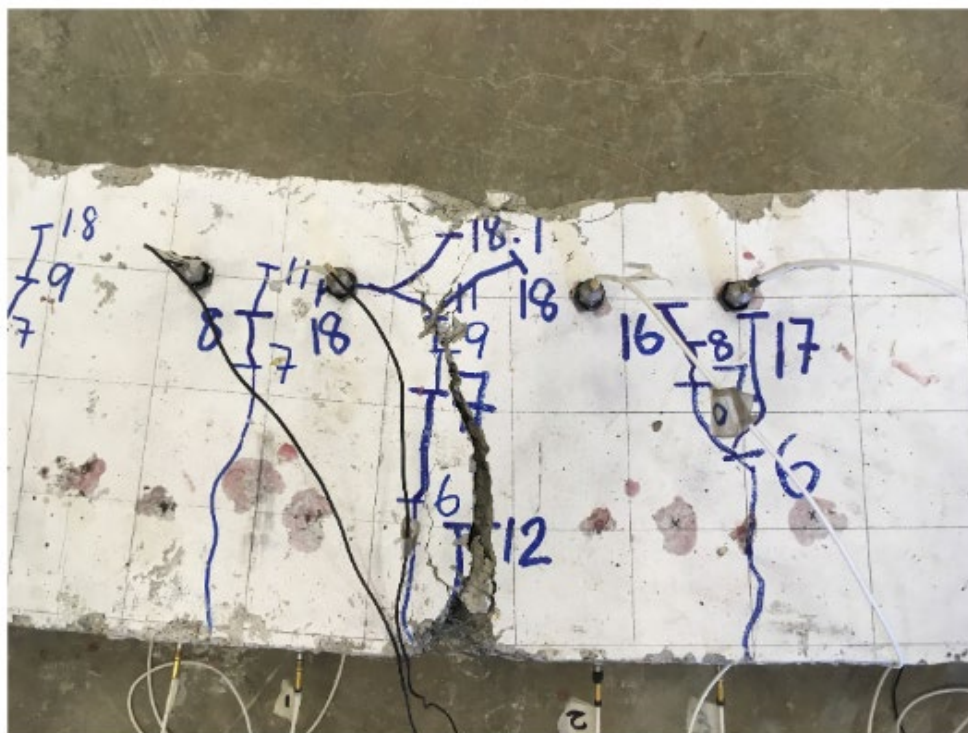


Figure 3.7: Placement of Sensors During Lab Test.

3.4 Generating Accelerometer Data

In this framework, a set of data was generated to mimic real data produced by an accelerometer as shown in Figure 3.8. The data used were obtained from a laboratory test where accelerometers were installed on a 2-meter grade 30 concrete beam. The set of data contain information generated by accelerometers such as amplitude, time and date. The mimicked accelerometer data was generated and stored in the form of a spreadsheet in Microsoft excel to ease data extraction in the next step.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Sensor	101	102	103	104	105	106	107	108	109	110	111	112	
2	1	-0.00379741	-0.00621021	-0.0163275	-0.00930846	-0.00729322	-0.00275552	-0.01517594	-0.01046002	-0.00509977	-0.00427723	-0.01664281	-0.00781417	
3	2	-0.00360548	-0.00693679	-0.01343489	-0.00806093	-0.00360548	-0.00324905	-0.01418889	-0.01258492	-0.00570297	-0.00386596	-0.01639605	-0.00715613	
4	3	-0.00747144	-0.00571668	-0.01492918	-0.00697792	-0.00355065	-0.00653923	-0.01126885	-0.01063824	-0.00419497	-0.00509977	-0.01113176	-0.00963748	
5	4	-0.00556588	-0.0052917	-0.0128454	-0.00784159	-0.00464737	-0.00564814	-0.01113176	-0.00716984	-0.00435948	-0.00515461	-0.01187205	-0.00797868	
6	5	-0.0046885	-0.00496268	-0.01343489	-0.00812948	0.001795888	-0.00296116	-0.01037776	-0.00928104	-0.00068545	-0.0025773	-0.01358569	-0.00782788	
7	6	-0.00470221	-0.00612795	-0.01443565	-0.00618279	-0.0057441	-0.00038385	-0.01298249	-0.00622392	-0.00593603	-0.00522316	-0.01418889	-0.00422239	
8	7	-0.00556588	-0.00756741	-0.01704037	-0.00700533	-0.00933588	-0.00409901	-0.01232445	-0.00520945	-0.00138462	-0.00631988	-0.01388729	-0.00777304	
9	8	-0.00855446	-0.0043869	-0.01631379	-0.00799239	-0.00490785	-0.00434577	-0.01200914	-0.00871897	-0.00701904	-0.00542879	-0.01524448	-0.00707388	
10	9	-0.00461996	-0.00552475	-0.01455903	-0.01059711	-0.00212491	-0.00261843	-0.01132369	-0.0117898	-0.00903428	-0.00870526	-0.01250267	-0.00538766	
11	10	-0.00758111	-0.00614166	-0.01719117	-0.00685453	-0.00437319	-0.00190556	-0.00944555	-0.0083214	-0.0046885	-0.00718355	-0.01444936	-0.00563443	
12	11	-0.01162529	-0.00943184	-0.01507998	-0.00616908	-0.00202894	-0.00485301	-0.01235187	-0.00745773	-0.00445545	-0.00394821	-0.01420259	-0.00854075	

Figure 3.8: Generated Accelerometer Data in a Spreadsheet.

3.5.2 Selecting the Virtual Sensors in Revit

In this module, the virtual accelerometers were selected in order to proceed with later modules. All element of the speciality equipment in the Revit model was selected and have their Sensor_ID parameter read by Dynamo. The dictionary by key values node from the Dynamo library was used to bind each accelerometer's element ID with their Sensor_ID parameter and stored in a dictionary. The dictionary was then sorted according to the order of sensor ID read from the spreadsheet from the previous module. The unique data value of each sensor is now paired to their respective sensor ID according to the order of columns in the spreadsheet.

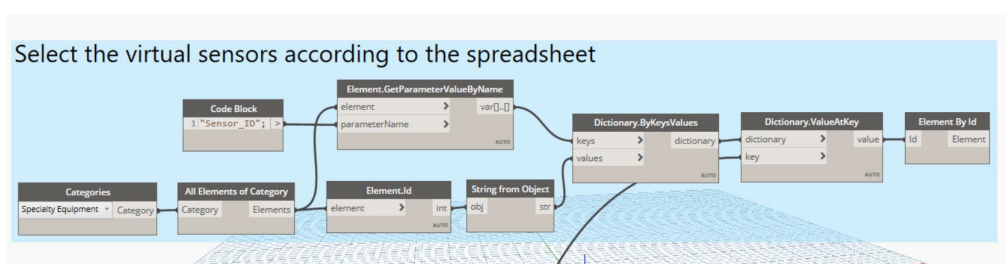


Figure 3.10: Selecting the Virtual Sensors in Revit Module.

3.5.3 Updating Sensor Value into Virtual Sensor

After reading and sorting the sensor value stored in the spreadsheet, a module was developed to update the BIM model. The amplitude parameter of virtual accelerometers in the model was updated with the maximum sensor value sorted by the first Dynamo module. Maximum sensor values of each time intervals were extracted from the spreadsheet by the first module and were updated to the amplitude parameter of virtual sensors respectively. This module was created to link the sensor data from a spreadsheet into the virtual sensors in the BIM model.

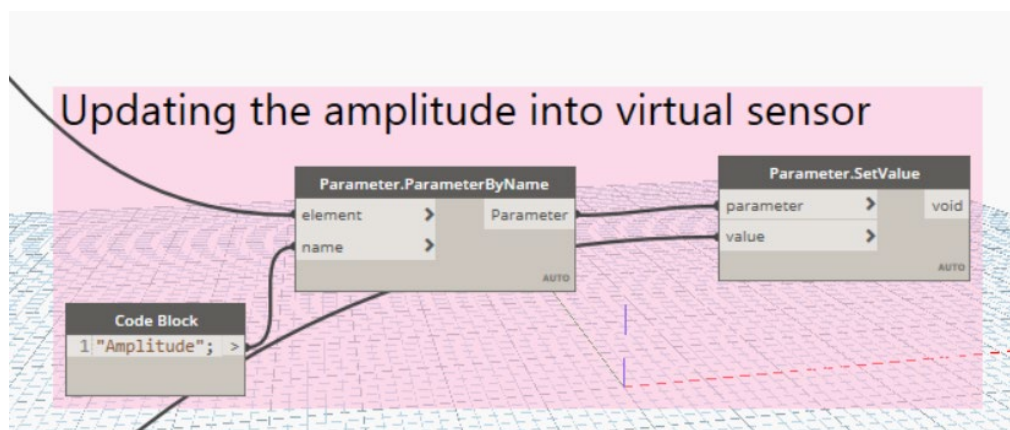


Figure 3.11: Updating Sensor Value into Virtual Sensor Module.

3.5.4 Threshold Value Analysis and Flag Damaged Sensors

Next, this Dynamo module was developed to conduct an analysis of the sensor data and flag the damaged sensors. A fitting threshold value was identified to monitor the structural health condition of critical structural elements. According to the mimicked accelerometer data, from the amplitude generated from the lab test, a threshold of 50 was set for the current case. The accelerometer's wave amplitude that travels below the amplitude of 50 were assumed to have cracks in its structural element that causes the decrease of amplitude and will be marked as damaged. By applying the amplitude threshold, accelerometers that fall below the predefined amplitude threshold value will be marked. The accelerometers were then categorized as damaged or undamaged in the DamageFlag parameter.

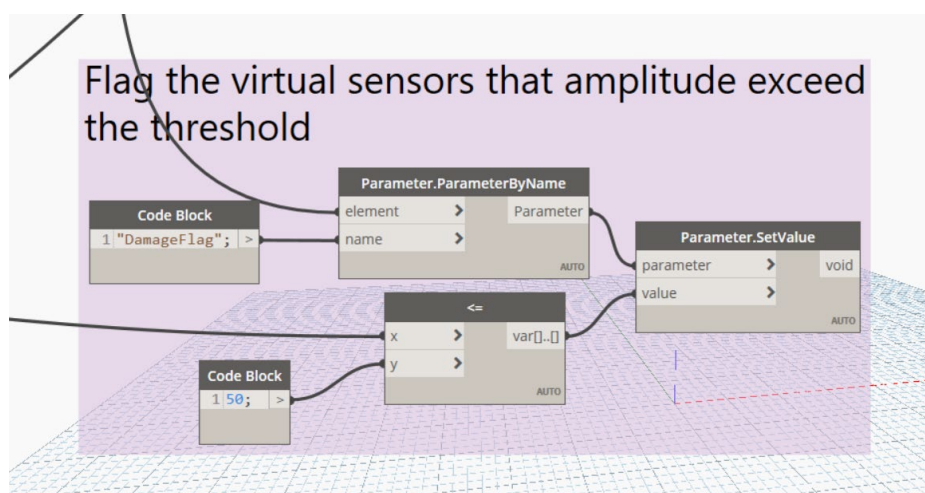


Figure 3.12: Threshold Value Analysis and Flag Damaged Sensors Module.

3.5.5 Display Warning and Colour-Code Damaged Structural Element in Revit Model

In the final module, the damaged structural element will be selected, and colour coded based on the DamageFlag parameter of the virtual sensors. The DamageFlag of all accelerometers modelled under speciality equipment will be read and sorted. The Location (Beam ID) parameter value was extracted from the accelerometers that DamageFlag parameter was marked as damaged from the previous module. Damaged structural elements were then selected by their element ID and colour coded. The colour red was chosen to highlight the damaged structural elements in the Revit model. A warning message popup was also set to appear if there were damaged structural elements in the BIM model to warn users.

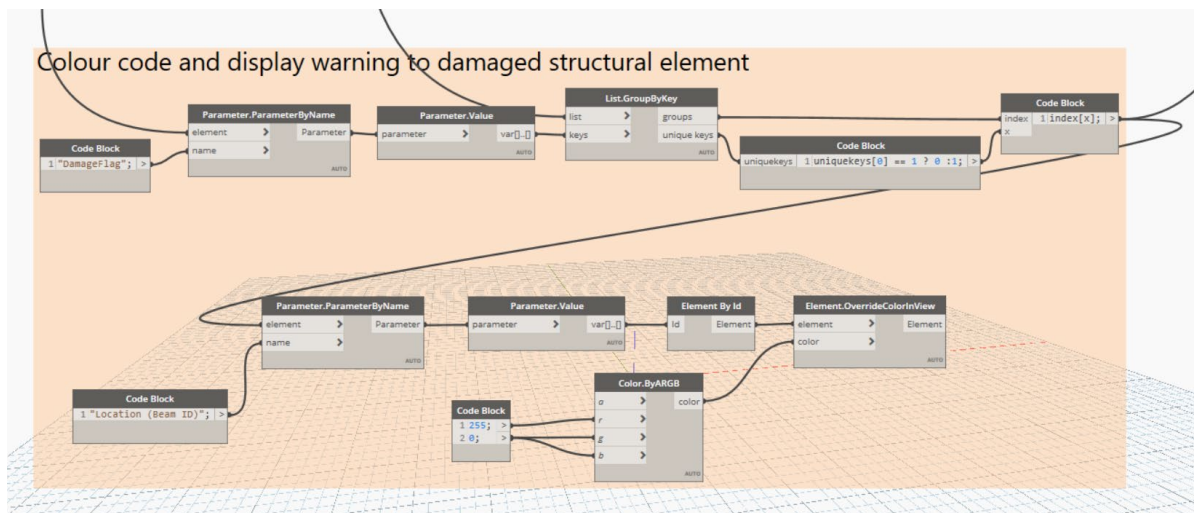


Figure 3.13: Colour Code Damaged Structural Element Module.

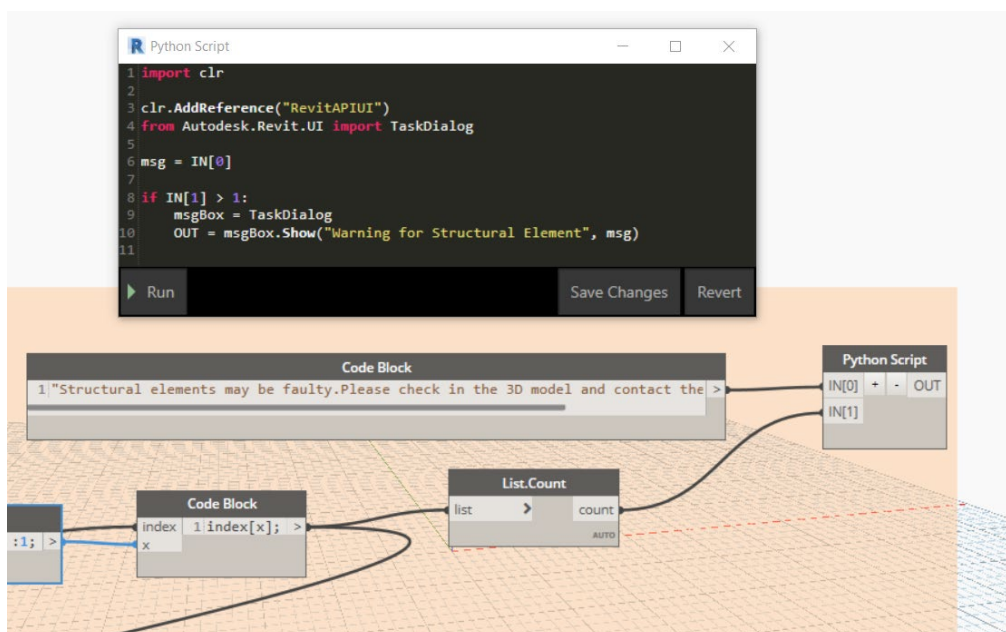


Figure 3.14: Warning Popup Display Module.

3.6 Summary

In a nutshell, this chapter layout the framework to integrate BIM into SHM. In this study, Revit and Dynamo were used to model and monitor the structural health of the four-story concrete structure. The 3D model of the structure was modelled in Revit together with accelerometers as user-defined virtual sensors. Next, five Dynamo modules were constructed to automatically manage, analyse and update the BIM model from the data obtained from physical sensors. Lastly, damaged structural elements were highlighted in the BIM model as a warning for users. With the proposed framework in integrating BIM into SHM, the damages on structural elements were identified and visualised dynamically.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter focusses on the results of integrating Building Information Modelling (BIM) data management system into Structural Health Monitoring (SHM) developed with the proposed framework in Chapter 3. The capability of BIM in data storage, damage visualisation and its feasibility are thoroughly discussed.

4.2 Data Management

Unlike traditional SHM, which has difficulty storing and retrieving large amounts of data, the BIM data management system stores all information from sensors and structural components in the BIM model using the framework established in Chapter 3. To prevent data loss and accessibility during the structure's operational lifetime, information and data are stored in a single location, as opposed to traditional SHM, which stores data in multiple folders.

Data of structural components are stored in Revit as parameters during the initial modelling phase of the 3D structure model. Figure 4.1 demonstrates how the structure component's data are inputted. Components' data such as materials, manufacturers, costs, model numbers, component types, maintenance company contact number, etc were stored in Revit. The data of structural elements can be accessed in the properties panel, as shown in Figure 4.2 by clicking on the element in the 3D model.

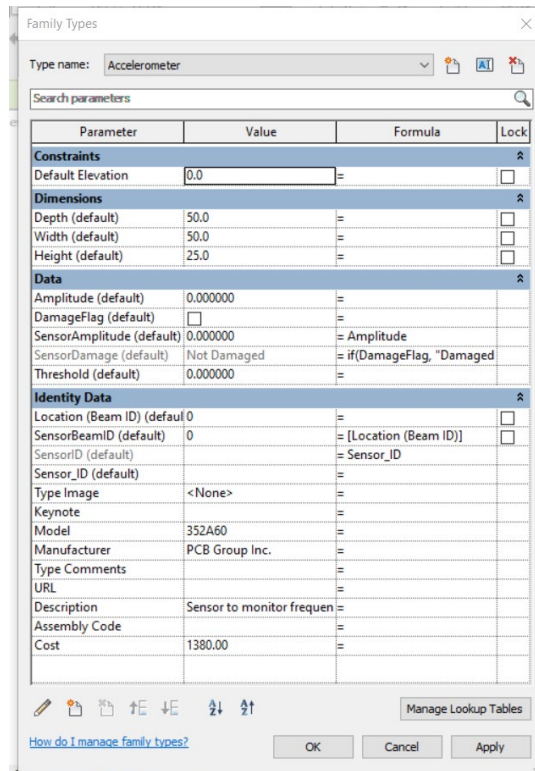


Figure 4.1: Accelerometer Parameters and Data.

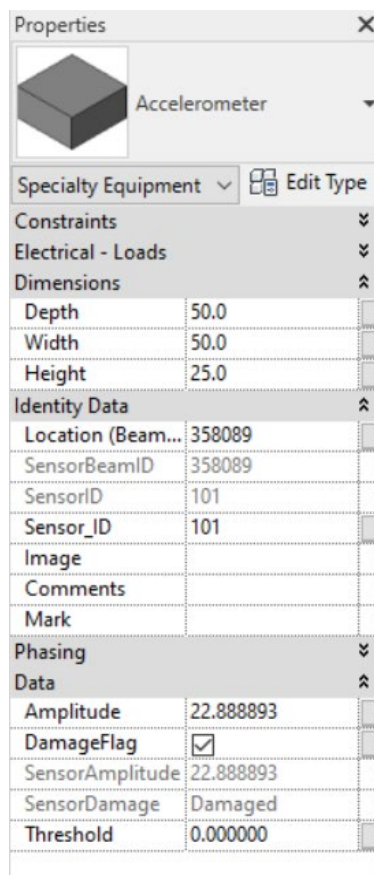


Figure 4.2: Properties Panel in Revit.

The virtual sensors are modelled in the 3D model to correspond to the physical sensor locations in the structure. SensorID shapes the physical-virtual sensor linkage by assigning physical sensor IDs to the SensorID parameter of their respective virtual sensors. By validating the physical accelerometer IDs on the first row of the spreadsheet shown in Figure 4.3 to the SensorID parameter of virtual accelerometers in Revit, the accelerometers' amplitudes are assigned to their respective sensors under the SensorAmplitude parameter with the dynamo modules constructed in Section 3.5.1, Section 3.5.2 and Section 3.5.3 as shown in Figure 4.4. The IDs and data of accelerometers from Microsoft Excel spreadsheets are retrieved by the first Dynamo module. The virtual sensors' ID in the SensorID parameter is compared with the sensors' ID from the spreadsheet with the second Dynamo module constructed in Section 3.5.2 to select the corresponding virtual sensors in Revit. With real-time data retrieved by the first Dynamo module constructed in Section 3.5.1, the amplitude parameters of the selected virtual accelerometers are updated using the third Dynamo module in Section 3.5.3 respectively. This implies that by linking physical and virtual sensors using Dynamo modules, the static Revit model was transformed into a dynamic model capable of retrieving and storing real-time sensor data. Utilising the speciality equipment schedule generation feature in Revit, all information on accelerometers, such as SensorID, model, description, manufacturer, and many more, can be presented in a single spreadsheet. Figure 4.5 indicate the speciality equipment schedule, which categorises accelerometers by parameters. Sensors' data could be accessed easily by Revit users to retrieve necessary data with a single click. The ability of Revit to present all sensor data in a single spreadsheet with a schedule generation feature differs significantly from traditional SHM which stores data in different folders and therefore is prone to data loss. The findings demonstrate the effectiveness of a BIM-based data management system in SHM for data storage and retrieval.

Sensor	101	102	103	104	105	106	107	108	109	110	111	112
1	-0.0038	-0.00621	-0.01633	-0.00931	-0.00729	-0.00276	-0.0051	-0.00428	-0.01518	-0.01046	-0.01664	-0.00781
2	-0.00361	-0.00694	-0.01343	-0.00806	-0.00361	-0.00325	-0.0057	-0.00387	-0.01419	-0.01258	-0.0164	-0.00716

Figure 4.3: Accelerometers' Amplitudes in Spreadsheet.

parameter of accelerometers and analysed by the threshold analysis module as displayed in Figure 4.7. Where the amplitude falls below the predefined threshold value, the DamageFlag parameter in the accelerometer was set to true by the module. The DamageFlag parameter in the accelerometer indicates if the structural components are damaged or in good condition.

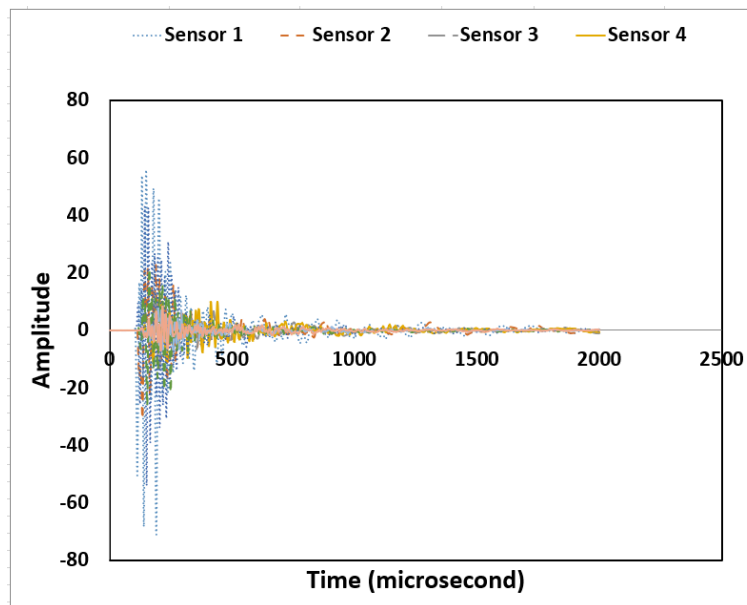


Figure 4.6: Graph Plotted from Raw Data Obtained from Laboratory.

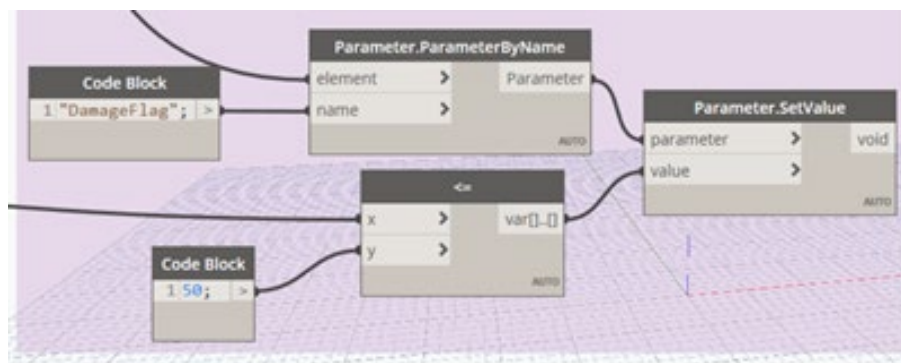


Figure 4.7: Threshold Analysis Module in Dynamo.

Furthermore, the DamageFlag parameter is evaluated by the final Dynamo module to determine the condition of the structural component. The colour red was selected to colour code the damaged structural components based on their element ID and DamageFlag parameter. The need to highlight and draw attention to the structure's critical condition to Revit users can be adequately

explained by colour coding damaged elements. Damages were presented in the form of graphs and figures in traditional SHM such that only trained personnel could comprehend. The presentations of the analysis for BIM-based SHM was significantly different such that damages were shown in the colour-coded 3D model where non-trained personnel such as stakeholders could visualise the location of the damaged elements by viewing the 3D BIM model as illustrated in Figure 4.9. The damage visualisation capabilities of BIM-based SHM indicate that stakeholder interactions and engagements were enhanced because data-driven decisions could be made when the structural condition was visualised in the BIM model.

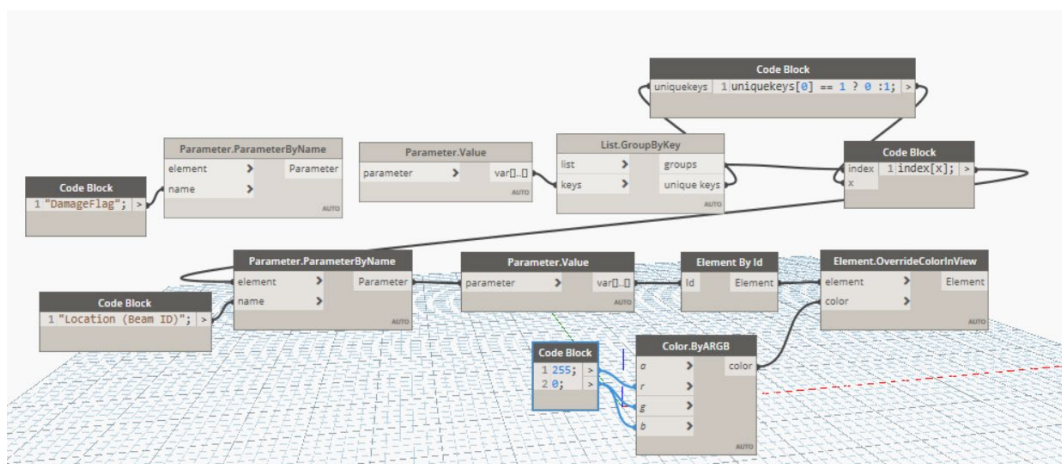


Figure 4.8: Color Coding Damaged Elements Module in Dynamo.

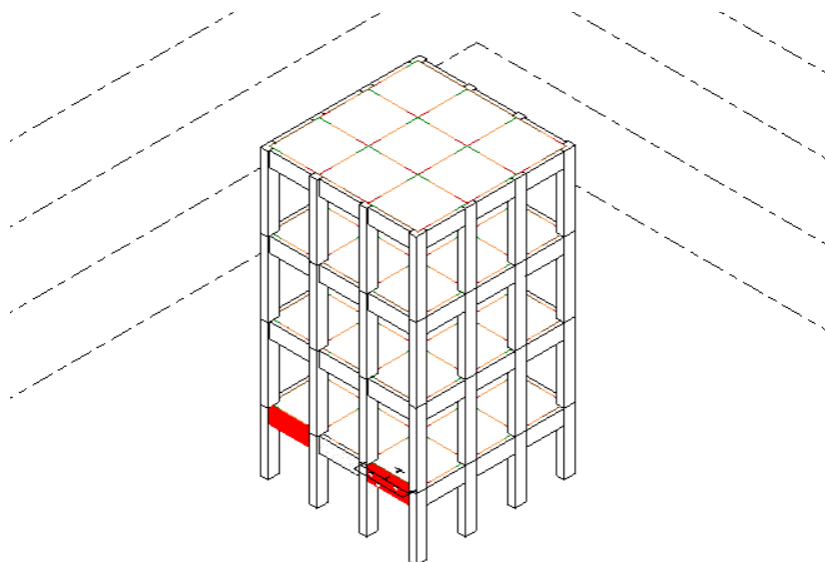
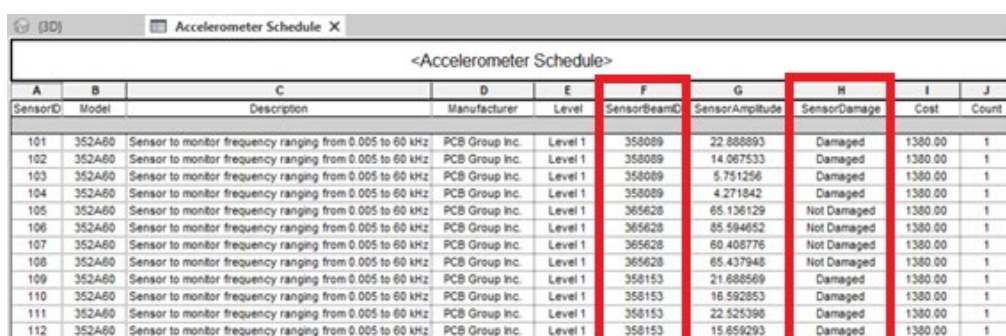


Figure 4.9: 3D Model of Colour Coded Damaged Structural Elements.

Aside from that, damaged structure elements that are small and positioned in the 3D model's blindspot can be viewed by Revit users at the Speciality Sensor Schedule under SensorDamage parameter to assess the condition. After obtaining the element's IDs of damaged structural from SensorBeamID parameter in the schedule as illustrated in Figure 4.10, Revit users can select the structural components with the Select by Element ID feature from the manage tab as shown in Figure 4.11 and Figure 4.12 to view and modify the information on the properties panel. This finding ensures that damaged elements that are small or located in the BIM model's blindspot are not overlooked.



<Accelerometer Schedule>									
A	B	C	D	E	F	G	H	I	J
SensorID	Model	Description	Manufacturer	Level	SensorBeamID	SensorAmplitude	SensorDamage	Cost	Count
101	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358089	22.888893	Damaged	1380.00	1
102	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358089	14.067533	Damaged	1380.00	1
103	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358089	5.751256	Damaged	1380.00	1
104	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358089	4.271842	Damaged	1380.00	1
105	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	365628	65.136129	Not Damaged	1380.00	1
106	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	365628	85.594652	Not Damaged	1380.00	1
107	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	365628	60.408776	Not Damaged	1380.00	1
108	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	365628	65.437948	Not Damaged	1380.00	1
109	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358153	21.688569	Damaged	1380.00	1
110	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358153	16.592853	Damaged	1380.00	1
111	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358153	22.525398	Damaged	1380.00	1
112	352A60	Sensor to monitor frequency ranging from 0.005 to 60 kHz	PCB Group Inc.	Level 1	358153	15.658293	Damaged	1380.00	1

Figure 4.10: Beam ID and Damage Parameter from Accelerometer Schedule.

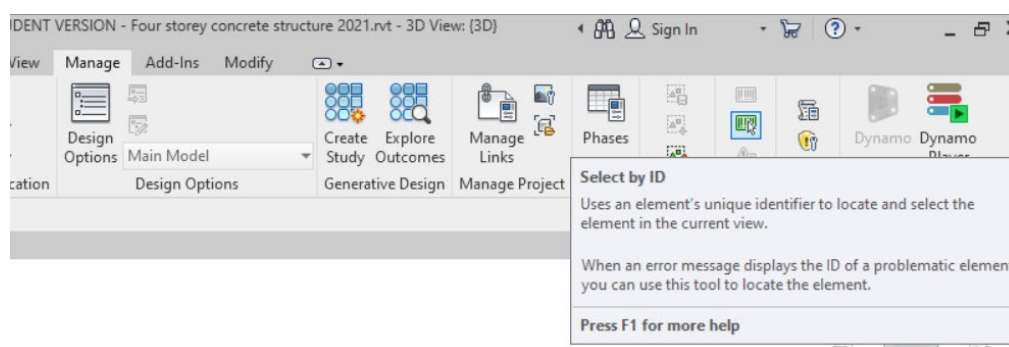


Figure 4.11: Select by Element ID from Manage Tab in Revit.

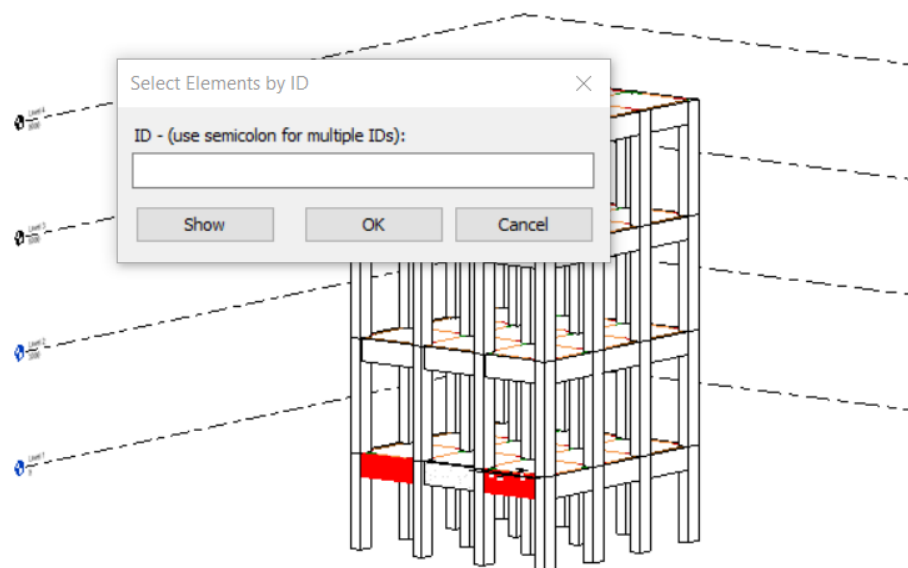


Figure 4.12: Select Elements by ID in Revit.

4.4 Feasibility of BIM-based SHM

The proposed framework for integrating a BIM-based data management system into SHM was implemented on a four-story concrete structure. The ability to be extended and used on other structures such as bridges, underground tunnels, stadiums, offshore structures, and so on can be attributed to BIM's adaptability in modelling different types of structures. Damaged structural elements were colour coded in this proposed framework after the amplitudes of the accelerometer were analysed by Dynamo modules using the threshold analysis approach. With the help of visual programming tools, other types of sensors can also be installed and linked to the BIM model. This is due to the highly customizable Dynamo, which can be programmed to perform not only threshold analysis for accelerometer but almost any type of analysis for various data obtained from diverse types of sensors. The proposed framework's Dynamo modules are flexible and can be programmed to analyse structural elements in accordance with structural design codes and standards to ensure structural components are in a safe condition. Another advantage of the customizable Dynamo tool in BIM-based SHM is the prompt generation of a warning popup

window, as shown in Figure 4.13, to alert and alarm the BIM user whenever a damaged structural component is detected. This provided clear evidence for the feasibility of BIM-based SHM, owing to its ability to be used on any types of structures and to perform various analyses on data obtained from various types of sensors.

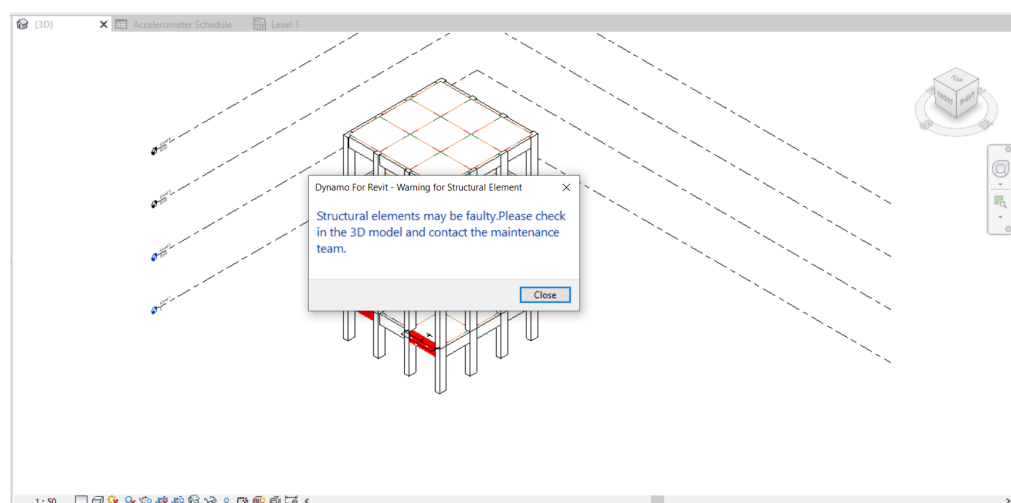


Figure 4.13: Warning Popup in Revit.

The proposed framework transformed the stationary BIM model into a dynamic model in this study, allowing BIM users to access and visualise both data and damaged structural components on the same platform. This result validates the feasibility of integrating BIM into SHM due to the significant difference where traditional SHM stores its data separately in different folders and lacks visualisation of analysed data for non-trained personnel. Furthermore, BIM-based SHM helps to improve the interaction and involvement of stakeholders in structure decision-making by allowing both data and damages could be accessed and visualised on a single platform. The BIM-based SHM alert system is manually clicked where data can be obtained from the properties panel by clicking on the colour coded damaged elements in the 3D BIM model. The information gathered about the damaged elements can be used to make quick decisions such as evacuating the structure or contacting the repair and maintenance team. According to the findings, it can be deduced that a BIM-based data management system is a highly customizable platform that offers data-driven decisions in the decision-making process by allowing stakeholders

to connect, visualise, monitor, control and implement proactive condition-based actions to reduce downtime of the structure and increase productivity.

4.5 Summary

In summary, this chapter demonstrates the capabilities of BIM-based SHM in data management and damage visualisation, as opposed to conventional SHM. Storage of data and information about the structural components were stored as parameters in the BIM model according to the proposed framework. In contrast to traditional SHM, which stores data and information in separate locations or folders that are susceptible to data loss throughout the structure's lifecycle, BIM-based SHM safeguards and ensures instant retrieval of data and information by clicking on the element in the 3D model. Furthermore, BIM-based SHM also improves damage visualisation, allowing non-trained personnel to visualise the location of structural damages. From the findings of this chapter, BIM is a highly flexible and customizable platform that provides data storage, real-time damage analysis and damage visualisation to its users for data-driven decisions to be made in the decision-making process by allowing stakeholders to connect, visualise, monitor, control and implement proactive condition-based actions.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this thesis, the main aim of this study had been fulfilled which was to propose a framework to integrate a BIM-based data management system into Structural Health Monitoring. All three objectives of this study were also met, which are to investigate traditional SHM and how BIM can be incorporated into it, to review the current BIM-based data management system and to investigate the suitability of the proposed framework of BIM-based data management system for SHM.

The first objective is to investigate traditional SHM and how BIM can be incorporated into it. Through investigation, traditional SHM poses two major flaws which are the possibility of data loss during future retrieval and lack of visualisation when displaying processed data to users. Since the BIM model can store data and information within the parameters of its elements, it can be integrated into SHM as a data management system. BIM's ability to store and retrieve all data in a single model reduces the risk of data loss, as opposed to traditional SHM where data are stored in different locations and folders. Unlike traditional SHM, which presents its damage analysis using graphs and images that can only be understood by trained personnel. BIM-based SHM has the ability to colour code damaged structural elements on the 3D model for better visualisation, BIM-based SHM can also improve the interaction of untrained users in structural decision making.

The second objective is to review the current BIM-based data management system. The objective is achieved where through reviewing, it shows that BIM-based data management system in SHM is not uncommon as many case studies have been conducted in the past. The majority of BIM-based SHM employs a variety of BIM software and database and lacks a standardised workflow and validated framework.

The last objective is to investigate the suitability of a BIM-based data management system for SHM using the proposed framework. From Chapter 4,

the proposed framework which uses Revit and Dynamo demonstrated conclusive evidence that BIM-based data management system for SHM is feasible. The main advantage of BIM-based SHM is that it is flexible and customizable, making it easy to modify for use with any structure and any type of sensor. The BIM-based SHM constructed using the proposed framework not only demonstrated its ability to store data and improve damage visualisation but also converts the stationary BIM model into a dynamic SHM tool in which both data and analysis can be visualised on the same platform. BIM is a highly flexible and customizable platform that provides data storage, real-time damage analysis and damage visualisation to its users for data-driven decisions to be made in the decision-making process by allowing stakeholders to connect, visualise, monitor, control and implement proactive condition-based actions.

5.2 Recommendations for future work

Based on the current study conducted, recommendations are identified while considering the limitations of this thesis. There are some recommendations for future research:

- i. Other types of sensors and threshold values can be adopted to achieve precise and detailed structural health monitoring of the structure.
- ii. Installing multiple sensors of the same kind on each structural member will be expensive and inefficient. Prior to sensor placement, the structure model should be analysed in structural software to identify critical locations to reduce the number of sensors.
- iii. Instead of spreadsheets, databases should be used to store data from sensors until it is retrieved by BIM.
- iv. Use of a cloud platform to allow anyone to access the data from anywhere in real-time, promoting data sharing and enhance coordination and communications among stakeholders.

- v. Error detections of architecture and MEP components can also be done by modelling respective sensors into the BIM model to enhance the interaction between stakeholders.
- vi. Using augmented reality or virtual reality to provide a clearer visualisation of the BIM structure model by allowing for a walkthrough of the visual structure.

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APPENDICES

APPENDIX A: Computer Programme

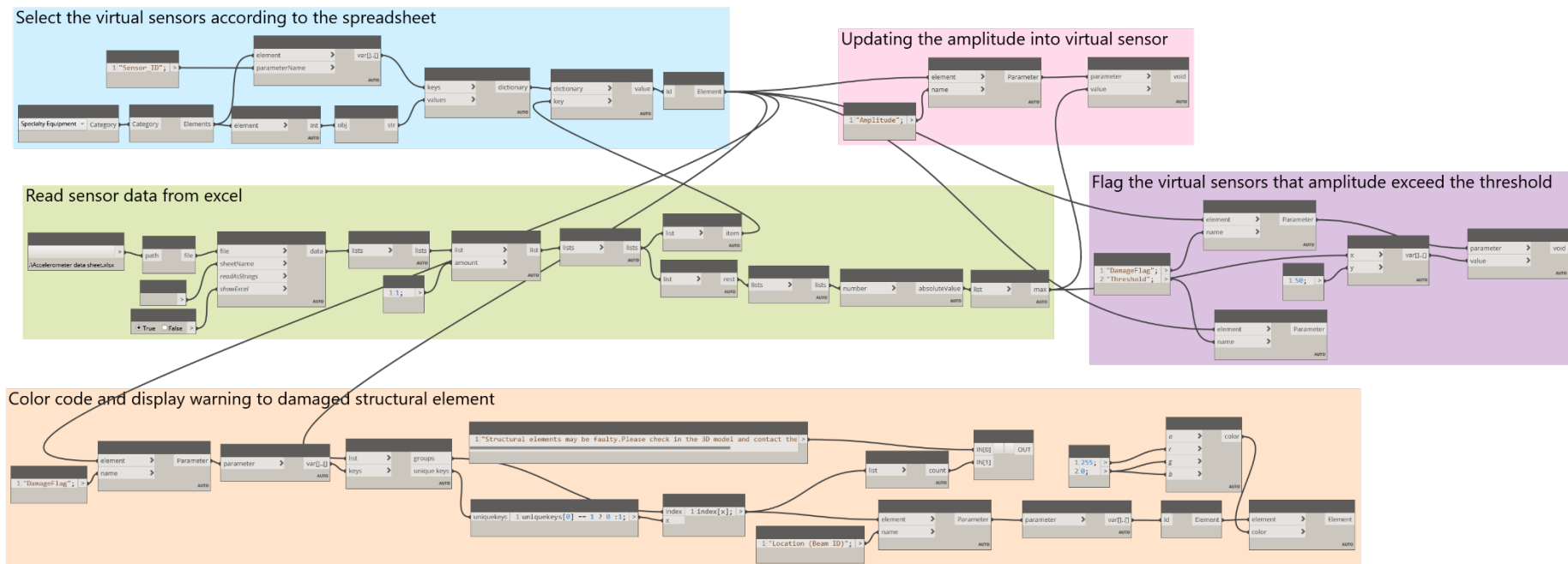


Figure A-1: Five Dynamo Modules Constructed in the Proposed Framework.