



## INVESTIGATION ON THE POTENTIAL OF BUILDING INFORMATION MODELING IN STRUCTURAL HEALTH MONITORING OF BUILDINGS

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**Abstract:** This paper investigates the feasibility of utilizing building information modeling (BIM) in structural health monitoring (SHM) of buildings and infrastructure. A building was modeled in Autodesk Revit Structure and then exported to ETABS for structural analysis purposes, as well as to identify the ideal locations for installing SHM sensors, such as strain sensors. The model was then returned to Autodesk Revit to update the existing BIM model. Strain sensor was modeled and placed in its designated locations in the BIM model. Some data were assigned to the virtual strain sensor —using the IFC file format of the BIM model. An external visualization tool verified and validated the sensor modeling and its associated data. A possible consequence of this research is that these integrated environments could be used as the basis for the integration of BIM and SHM into an effective real-time monitoring system for a smart environment.

**Keywords:** Building information modeling; structural health monitoring; IFC; SHM sensors; smart environment.

### 1 Introduction

Structures such as bridges, buildings, dams, pipelines, and aircraft are complex engineered systems that need to be monitored for various deterioration factors, such as load, during their lifetime to ensure that they are kept in good condition (Lynch and Loh, 2006). Although public funds are generally not available for the replacement of existing infrastructures, investment in their health assessment and maintenance is increasing considerably because the construction of new structures is much more expensive than extending the service life of the existing ones.

Structural health monitoring (SHM) has emerged as an effective structural evaluation technique to monitor the health of structures. SHM refers to an ongoing structural performance assessment using different kinds of sensors to evaluate the integrity and safety of the structures and help engineers decide on rehabilitation measures when a structure experiences unexpected changes, such as excessive deformation, deflection, and strains. Identifying the critical points of a building by doing an accurate structural analysis would lead to a reduction in the number of sensors installed for SHM purposes, which would ultimately decrease the overall cost of the SHM process. The main tasks in an SHM system include capturing and storing the sensor data for future retrieval. One of the inherent challenges in SHM is the high-volume data management. Management of all original raw data, and all post-processed data, during the entire lifecycle of the structure with a possible sum of hundreds of gigabytes, can become a problem if all the original data are to be kept for future processing (Rio et al. 2012). Efficient storage of SHM data facilitates easy examination and

backup. It is necessary to take the SHM data files saved in DAQ system and loaded into the database (Karbhari and Ansari 2009). Koo et al. (2011) presented an SHM data management system (SDMS) based on MySQL database management system (DBMS) for efficient data storage, retrieval and sharing large measurement data sets acquired continuously from SHM systems. However, to solve SHM data management issues, *there is a great need for more efficient tools and integrated systems.*

Building information modeling (BIM) has emerged as an effective data management tool (coBuilder, 2017). It can be utilized as a visual model as well as a repository for all data captured or made during the facility's life cycle. Combining BIM with real-time monitoring of structural health with simulation methods will provide a robust and intelligent system for managing modern buildings (Seam et al. 2013). There exist some challenges in integrating SHM into BIM environment. The study run by Rio et al. (2012) reveals that the process of accomplishing dynamic monitoring system of the structural behavior of a building to provide sensor data to BIM is not part of BIM functionality and is still a challenging issue. They concluded that BIM standards need to be extended to allow them to represent monitoring-related information. The study run by Wang et al. (2017) found that the applying BIM in SHM process can improve the effectiveness of monitoring processes and decision making in construction informatics applications.

The objective of this study is to investigate how an effective integrated data source such as BIM can be used for a consistent, digital representation of monitoring-related information to provide an integrated digital methodology that supports SHM.

## **2 Structural Health Monitoring (SHM)**

Because of inadequate inspection and insufficient visual monitoring of sensitive infrastructures such as tall buildings and long-span bridges, as well as prevalent structural issues, such as the corrosion of reinforcing bar and steel components, certain internal defects may be overlooked. SHM uses various types of sensors installed in the structure to help engineers identify and mitigate damage in a structure before it becomes critical.

According to ISIS Canada (2004), SHM refers to the broad concept of assessing the ongoing, in-service performance of structures using a variety of measurement techniques. All structures made by human beings have defined life spans, and they begin to degrade as soon as they are built and put into service. Therefore, examining and monitoring critical structural assets, on a periodic or continuous schedule to do the remedial action whenever it is needed, is important for maintaining the structure in good condition and extending its service life. SHM is applied in various civil engineering structures such as buildings, bridges, and highways (Doebling et al., 1996; Worden and Duijue-Barton, 2004).

Although there are other assessment techniques for a structure, such as non-destructive testing (NDT) and non-destructive evaluation (NDE), they all refer to a one-time structural condition evaluation, whereas SHM is implemented as a real-time and ongoing structural assessment technique. Although some owners of civil infrastructures may still be reluctant to use SHM because of the cost, the SHM system has proved that it can help optimize the life cycle of a structure by reducing the maintenance when possible, continuous inspection costs, downtime costs, etc. The recent and ongoing advancements of sensors, as well as the need for verification of the integrity of innovative designs and new materials, have led to an increase in the application of SHM in the construction industry. Monitoring significant factors such as load, deformation, strain, crack initiation, etc. in key structural elements can guarantee the extension of structures' service life by keeping them in good condition.

Therefore, making SHM intelligent by using advanced sensors and appropriate data interpretation and analysis will allow engineers to examine and evaluate structural damage-related factors, send them alarms when remedial actions are required, and archive the analyzed data in a database for future retrieval (Teng et al., 2012).

## **3 Building Information Modeling (BIM)**

The architecture, engineering, and construction (AEC) industry has been seeking an effective tool for reducing the cost and completion time of projects and increasing their productivity and quality (Azhar et al.,

2008). Typically, there are hundreds to thousands of documents for each project, and human interpretations are required to tie them together. Effective coordination between design disciplines and communication of the design to the field is a constant challenge. BIM has significantly altered the way that the AEC industry manages building information. BIM incorporates digital modeling software to design and manage a project more efficiently (Nassar, 2010). It provides powerful new value to construction firms. BIM breaks down the barriers between disciplines by encouraging the sharing of knowledge throughout the project's lifecycle. BIM improves constructability and shortens the project's completion time. In a BIM project, multiple documents are not used in the traditional ways (Australian Construction Industry Forum, 2014); instead, they are digitized and added to a database in BIM software. All information is built into an intelligent BIM model instead of looking at separate drawings, schedules, and specifications for the information on a particular element.

BIM is an organized collection of building data. When it comes to BIM, everything begins with a 3-D building model. This model is more than just a simple geometry added to it for visualization. A true BIM model consists of the virtual equivalent of the actual building sections (Graphisoft, 2015). These intelligent elements are the digital prototype of the physical elements, including walls, columns, windows, doors, and stairs. The model allows us to simulate the building and understand its behavior before the actual construction begins. Of course, the most basic BIM model is used to create realistic visualizations of the planned building. The BIM model helps the design decisions by comparing various design configurations. BIM models contain not only architectural data but also information about different engineering fields and sustainability, and other characteristics can be easily simulated in advance of actual construction. As mentioned earlier, the data in a BIM model is not only used during the design and construction phases of the building project but also throughout the building's lifecycle. The building-related data can be easily archived in the BIM model for such things as future usage, analysis, retrieval, and maintenance.

#### **4 Research Methodology**

The BIM model of a five-story concrete building was developed in Autodesk Revit Structure software. After defining load combinations and applying load on the building's BIM model, the model was exported to ETABS software for structural analysis. The building's model was analyzed in ETABS to determine its various structural responses, such as maximum bending moment, and to identify the ideal locations for installing strain sensors in the building. After identifying the critical points of the frame for placing strain sensors, the model was imported again to Autodesk Revit environment to update the existing BIM model. Virtual Strain sensors with all their essential parameters were modeled and placed in their designated locations in the BIM model. After adding the strain sensors to their location, the BIM model was converted to its IFC model that is interoperable with external tools. Relevant user-defined IFC property sets were created for strain sensors. Some sensor data was assigned to the strain sensor parameters using IFC text file. The building IFC file was then opened in the solibri Model Viewer, a visualization tool used to open IFC files, to verify and validate the virtual sensor and its parameters created in the BIM model.

#### **5 Building Simulation and Analysis**

The building was first modeled in Autodesk Revit Structure with all its specifications and structural analysis parameters. Then, the model was exported to ETABS, as shown in Figure 1, for doing structural analysis.

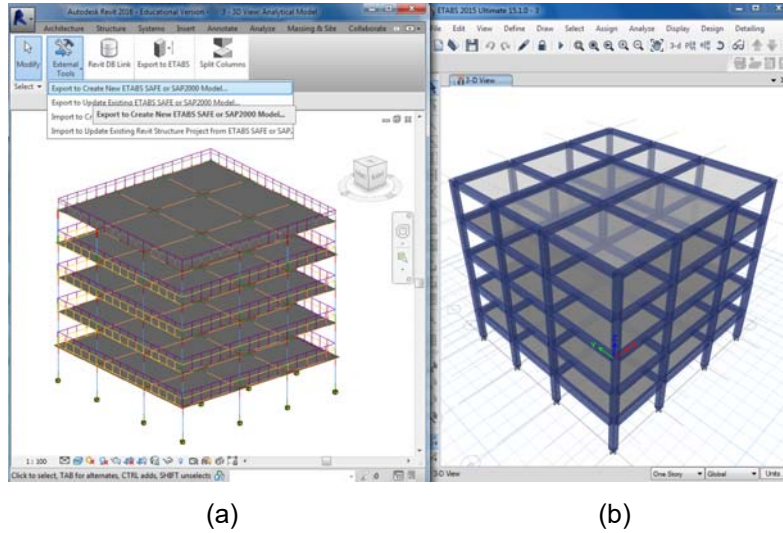


Figure 1: Exporting the building model from Autodesk Revit (a) to ETABS (b)

After doing structural analysis in ETABS, the analysis outputs were captured from the software. Outputs can be used to identify the location of various SHM sensors. For example, mode shapes and floor acceleration can be used to identify the locations of accelerometers, or maximum bending moment diagram can be used to find the ideal location of strain sensors. Strain sensors should be installed on parts of a building that have maximum bending moment because the maximum bending moment can lead to maximum stress and subsequently maximum strain. The only sensor used in this study was strain sensors. The maximum bending moment of all elements (beams and columns) in a building frame, shown in Figure 2, under each load combination was considered to identify the critical points of beams and columns.

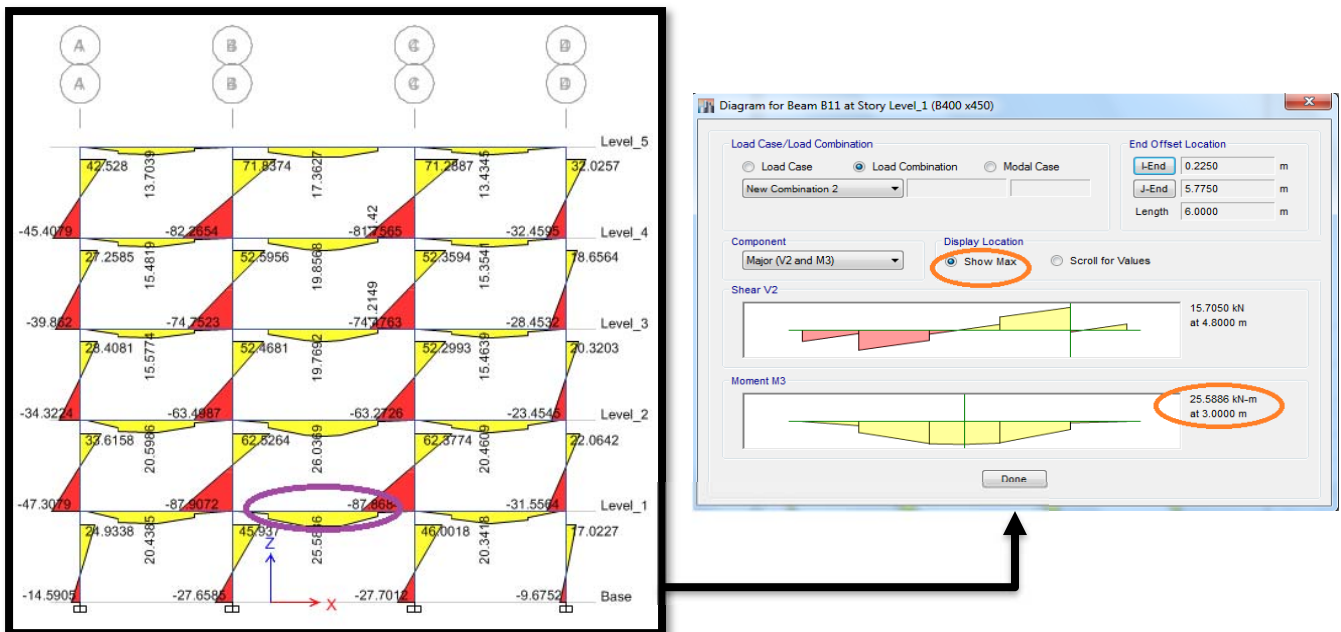


Figure 2: Bending moment diagram of the building frame

## 6 Modeling and Placing Strain Sensors in the BIM Model

After analyzing the building in ETABS and identifying the locations of the strain sensors, the model was returned to Autodesk Revit environment to update the existing BIM model. In this step, strain sensors must be modeled so that they can be attached to their specified locations. There are many different categories in Revit, such as a column, beam, floor, roof, door, window, etc. One of these categories of objects is specialty equipment. Each category has its own IFC class name; for example, the column has *IfcColumn* and roof has *IfcRoof*. For sensors, *IfcSensor* and *IfcSensorType* class names are categorized under the specialty equipment category. Therefore, the virtual sensors should be modeled under the specialty equipment category and exported as *IfcSensorType* to be interoperable with external tools that enable the manipulation of their data.

Different parameters were defined for the strain sensors during the sensor modeling, such as IFC parameters (IFC Export Type and IFCExportAs), identity data (manufacturer, label, mark, model, cost, etc.), phasing, scope, and station. Regarding the parameters, as mentioned earlier, IFC parameters were defined to enable sensors to be recognized by external tools, which is very helpful when their data must be manipulated by external software such as structural analysis software. The station parameter was defined to show the exact location of the sensors in the model. The mark parameter was defined to link the physical sensors in the field to virtual sensors in the BIM model. It is the sensors' specific ID in the field that must be assigned manually to each sensor to link the collected data from each physical sensor stored in the data acquisition system with virtual sensors in the BIM model. Figure 3 shows a strain sensor created in the BIM model, along with some of its defined parameters.

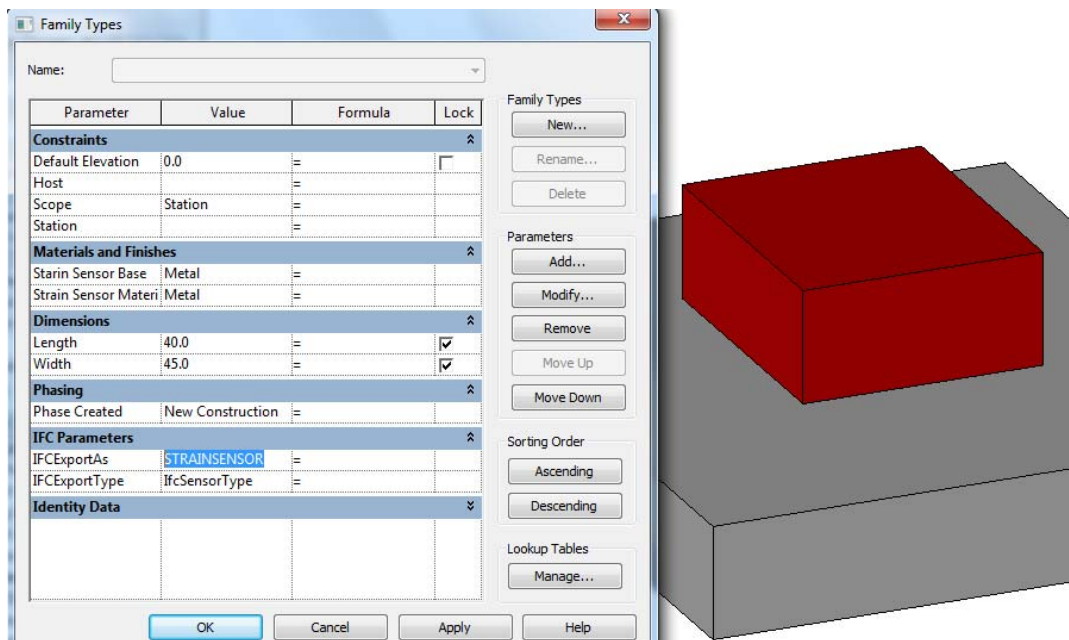


Figure 3: Strain sensor modeled in the BIM model

The strain sensors were then attached to their designated locations inside the corresponding member in the BIM model, as shown in Figure 4.

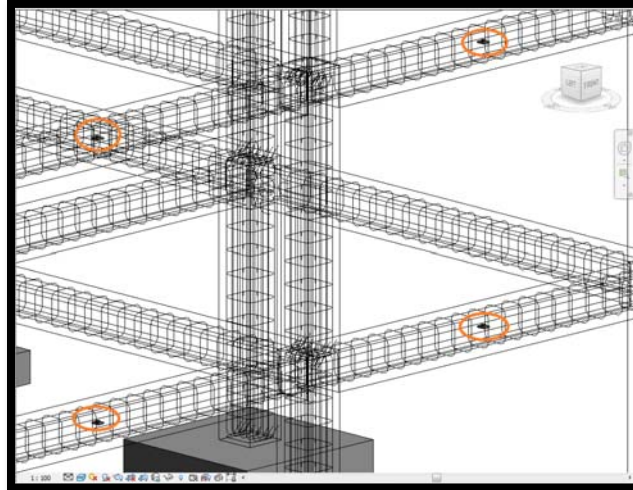


Figure 4: Strain-sensors visualization in the BIM model

## 7 Scheduling of Virtual Sensors Used in the Model

After all the strain sensors have been placed in their locations, their information can be sorted and managed. As illustrated in Figure 5, parameters such as name, model, level, manufacturer, mark, scope, station, phase created, and image were considered in the strain sensor schedule table. As mentioned earlier, the physical sensors' specific ID must be provided and assigned manually to each sensor in the model using the mark parameter. The station parameter is used to indicate the location of each sensor in the BIM model. Each element has its specific ID. By using the elements' ID, the exact position of each sensor can be understood in the model and is used when information about a sensor is required in case of the sensors failure.

<Strain Sensor Schedule>								
A	B	C	D	E	F	G	H	I
Name	Model	Level	Manufacturer	Mark	Scope	Station	Phase Created	Image
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 1	OMEGA Inc	100240-700	Station	Beam (ID 385315)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 1	OMEGA Inc	100240-720	Station	Beam (ID 385313)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 1	OMEGA Inc	100240-750	Station	Beam (ID 385317)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 2	OMEGA Inc	100240-736	Station	Beam (ID 408501)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 2	OMEGA Inc	100240-740	Station	Beam (ID 408499)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 2	OMEGA Inc	100240-756	Station	Beam (ID 408503)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 3	OMEGA Inc	100240-733	Station	Beam (ID 385493)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 4	OMEGA Inc	100240-744	Station	Beam (ID 385587)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 5	OMEGA Inc	100240-754	Station	Beam (ID 385667)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 3	OMEGA Inc	100240-737	Station	Column (ID 403956)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 4	OMEGA Inc	100240-748	Station	Column (ID 403904)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 5	OMEGA Inc	100240-746	Station	Column (ID 403904)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 4	OMEGA Inc	100240-763	Station	Column (ID 403932)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 5	OMEGA Inc	100240-758	Station	Column (ID 403932)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 4	OMEGA Inc	100240-760	Station	Column (ID 403916)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 5	OMEGA Inc	100240-709	Station	Column (ID 403916)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 4	OMEGA Inc	100240-725	Station	Column (ID 403884)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 5	OMEGA Inc	100240-738	Station	Column (ID 403884)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 3	OMEGA Inc	100240-767	Station	Column (ID 403940)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 4	OMEGA Inc	100240-772	Station	Column (ID 403940)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 3	OMEGA Inc	100240-776	Station	Column (ID 403924)	New Construction	SGK_2-ELEME
Strain Sensor	SGK-B3A-K350U-PC11-E	Level 4	OMEGA Inc	100240-778	Station	Column (ID 403924)	New Construction	SGK_2-ELEME

Figure 5: Strain sensor schedule table created in the BIM model

## 8 Verifying and Validating the Created Virtual Sensors

The main purpose of sensors modeling and simulation is to allow the interoperability of their data with external tools that manipulate their data. Without the ability to manipulate the sensors' data, sensors modeling is only conducted for visualization and data-storage purposes in the BIM model. For data manipulation, the sensor's object must be identified as an IFC file, which is why IFC parameters were used

to define the sensors. To examine whether the strain sensors in the BIM model are recognized as IFC files and visualized in an external visualization tool, the BIM model was saved as an IFC file and then opened in the Solibri Model Viewer visualization tool. IFC defines multiple file formats such as text format. One of the interesting features of IFC files is that they can be extended using their text format files. For example, the parameters required for real-time capturing of strain sensors' data, such as strain, date, time, etc., can be defined with their IFC class name, and then, by using the IFC text file, the values can be added to each of those parameters. The scenario can be automated using Application Programming Interface (API) to capture real-time data efficiently and quickly from the data acquisition (DAQ) center. Figure 6 shows that the strain sensor was appropriately exported as an element with an IFC class name.

```
#375206= IFCRECTANGLEPROFILEDEF(. AREA. , 'Strain' , #375205, 38.1, 38.1000000000002);
#375207= IFCCARTESIANPOINT((0. , 0. , 14.2135820688642));
#375209= IFCAXIS2PLACEMENT3D(#375207, #20, #16);
#375210= IFCEXTRUDEDAREASOLID(#375206, #375209, #20, 12.7);
#375211= IFCcolourRGB($, 0. , 0. , 1.);
#375212= IFCsurfacestyleRendering(#375211, 0.25, $, $, $, $, IFCnormalisedRatioMeasure(0.5), IFCspecularExponent(64.), .NOTDEFINED.);
#375213= IFCsurfacestyle('NetworkedSensorMoisture', .BOTH., (#375212));
#375215= IFCpresentationstyleAssignment((#375213));
#375217= IFCstyleItem(#375202, (#375215), $);
#375220= IFCstyleItem(#375210, (#375047), $);
#375223= IFCshaperRepresentation(#100, 'Body', 'sweptSolid', (#375202, #375210));
#375225= IFCAXIS2PLACEMENT3D(#6, $, $);
#375226= IFCRepresentationMap(#375225, #375223);
#375228= IFCsensorType('2wRQ0Y8V05BwUqVEE'Ypq, #42, 'Strain', $, $, $, (#375226), 411590', $.STRAINSENSOR.);
#375230= IFCmaterial('NetworkedSensorMoisture', $, $);
#375231= IFCpresentationstyleAssignment((#375213));
#375233= IFCstyleItem($, (#375231), $);
#375235= IFCstyleDrePresentation(#95, 'style', 'Material', (#375233));
#375237= IFCmaterialDefinitionRepresentation($, $, (#375235), #375230);
#375241= IFCmaterialList((#375230, #375081));
#375243= IFCmappedItem(#375226, #221);
#375245= IFCshaperRepresentation(#100, 'Body', 'MappedRepresentation', (#375243));
#375247= IFCproductDefinitionShape($, $, (#375245));
```

Figure 6: IFC text file of the BIM model

## 9 Inputting Sensor Data into the IFC Model

Two main purposes of using strain gauges are measuring strain some other quantities such as force, displacement, frequency, etc. For this purpose, five project parameters including *DisplacementSetPoint*, *ForceSetPoint*, *FrequencySetPoint*, *StrainSetPoint*, and *DateTime* were defined and assigned to each sensor in Revit model. IFC is the open data format for openBIM used to exchange data between applications. Before exporting the Revit model as an IFC file, a user-defined PropertySet called *Pset\_SensorTypeStrainGauge* was created for pre-defined strain sensors according to the IFC schema as shown in Figure 7 to convert the defined project parameters into IFC parameters.

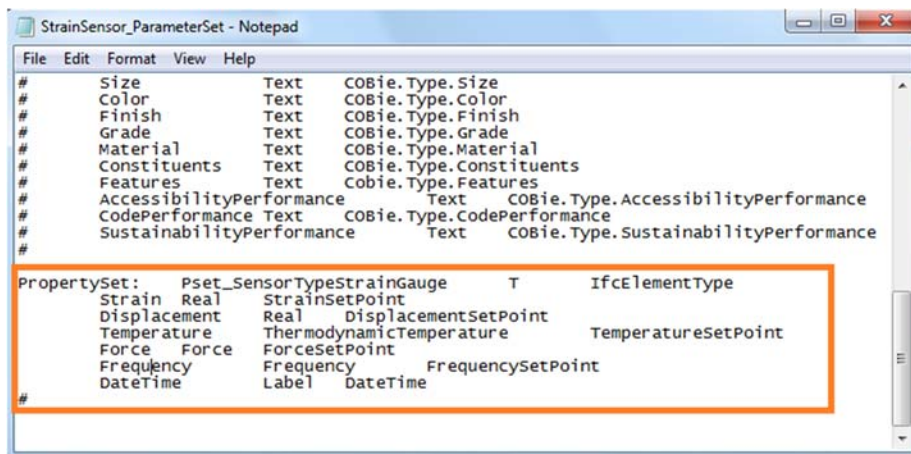


Figure 7: Defining an IFC property set for strain sensors

According to Figure 7, the following format must be used to define a new IFC property set.

```
PropertySet: <Pset Name> [/[instance]/T/type] <element list separated by ','>
# <Property Name 1> <Data type> <[opt] Revit parameter name, if different from IFC>
```

For creating *Pset\_SensorTypeStrainGaug* property set, *Real* data type was used for *Strain* and *Displacement* IFC parameters, *ThermodynamicTemperature* was used for *Temperature* IFC parameter, *Force* was used for *Force* IFC parameter, *Frequency* was used for *Frequency* IFC parameter, and *Label* was used for *DateTime* IFC parameter. The values can be added to each of parameters using the IFC text file. To validate this process, some values were assigned to each related parameter. As mentioned earlier, *Station* parameter was defined to show the exact location of the sensors in the model. Figure 8 shows the values assigned to the strain sensor which was attached to the column with 403904 ID number.

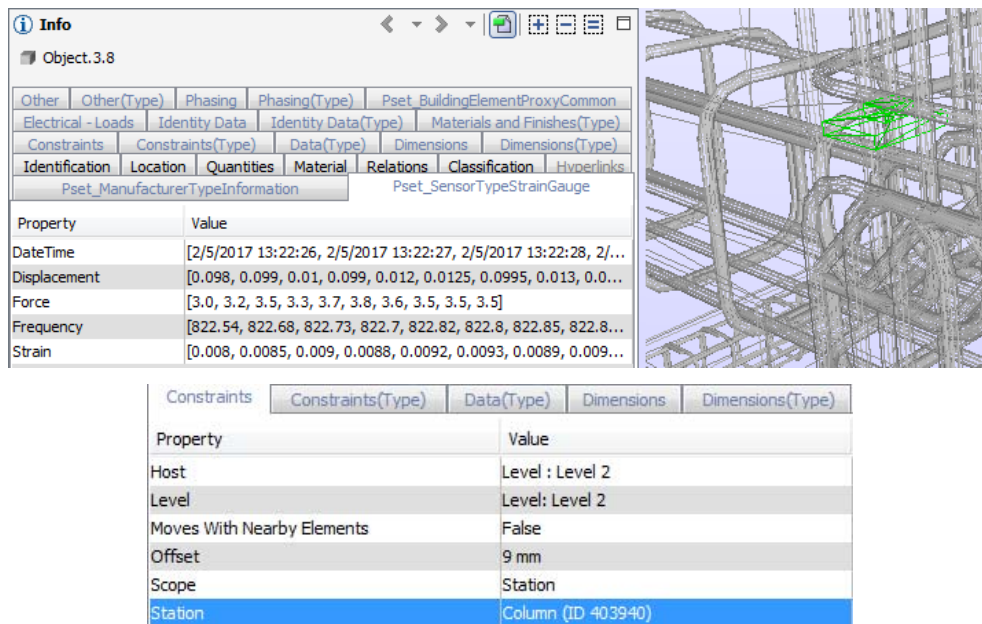


Figure 8: Visualizing the strain sensor data

The IFC model now can be exported into structural analysis tools such as Robot structural analysis for building structural condition assessment. A web-based server can be designed to facilitate the communication and data sharing between the SHM engineer and structural engineer. First, the structural engineer sends *IfcStructuralAnalysisModel* to a real-time open source database server like MySQL. By using *IfcGUID* of each virtual sensor in the BIM model, a practical link between database and virtual sensors in BIM can be made. Globally Unique Identifier (GUID) is created automatically in BIM software when objects are defined. It can be used to link the building IFC model with the SHM system. IfcGUID numbers can be captured using a programming tool like *Dynamo*. *Dynamo* is a visual programming and computational design tool which extends BIM with the data and logic environment of a graphical algorithm editor, and it is completely linked with Revit environment. Figure 9 shows the IfcGUID numbers extracted by *Dynamo* corresponding to each strain sensor in the BIM model. SHM engineers will have access to the IFC-based model and are able to insert all sensor data captured from DAQ center into the IFC model to update the model and send it back to the database server. The structural engineers will have access to the IFC model which includes sensor data. Therefore they can open it in a structural analysis software for structural condition assessment. Figure 10 demonstrates the conceptual data exchange process for sensor-based structural condition assessment of buildings using IFC-based BIM model.



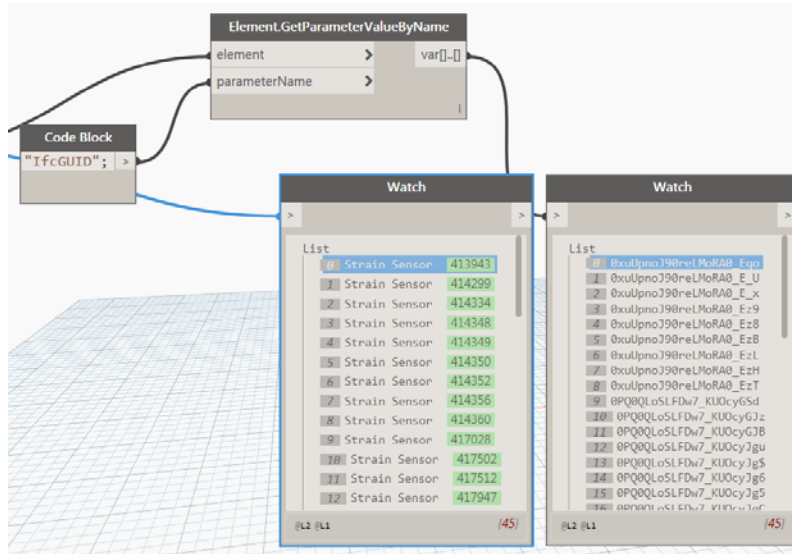


Figure 9: Extracting the IfcGUID of strain sensors from the BIM model

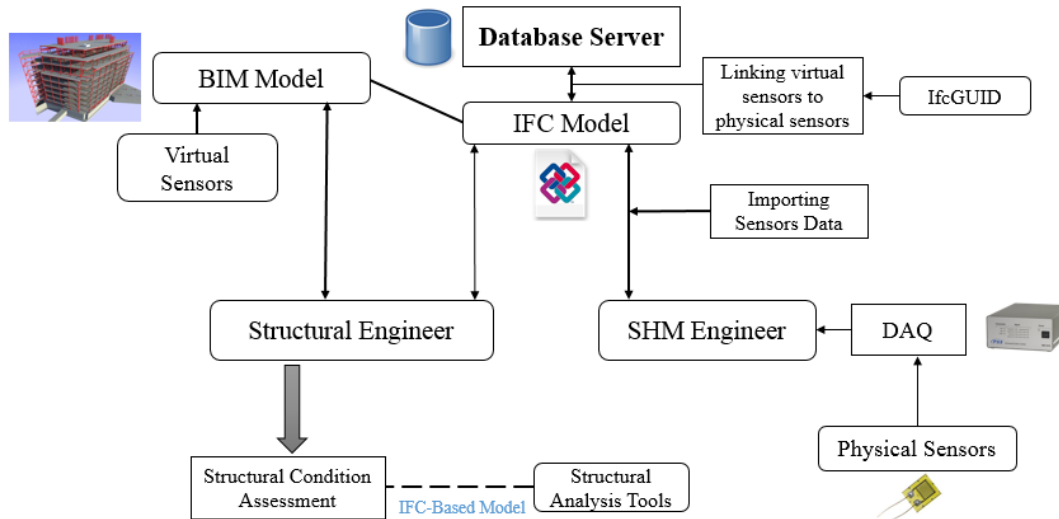


Figure 10: Data exchange model for sensor-based structural condition assessment

## 10 Conclusions

The research described herein has highlighted the potential of BIM in modeling SHM system elements, such as SHM sensors, and their optimal placement in a building to demonstrate how BIM software technology can be utilized to innovate and increase the opportunities for structural health monitoring. To achieve the objectives of this study, a sample five-story concrete building was first modeled in Revit Structure 2016 and then exported to ETABS for structural analysis purposes and to identify the ideal locations for the strain sensors. The model was then imported to Revit to update the existing BIM model. After updating the BIM model, a strain sensor family was modeled with all its essential parameters, such as its IFC parameters. The simulated sensors were then attached to their specified locations in a frame of the building. Finally, the BIM model was saved as an IFC file to investigate whether the sensors were recognized as IFC elements in an external visualization tool such as the Solibri Model Viewer. Extending a BIM model by linking the sensory data to simulated sensors will effectively allow engineers and facility managers to interpret and assess the ongoing performance of a building by providing and managing updated monitoring data. The benefits of utilizing BIM in SHM process include visualizing simulated sensors with their data, sorting, and scheduling of sensors data, on time emergency reaction, more effective

monitoring planning, better SHM data control, and management, linking monitoring data to simulated sensors for better interpretation and providing a useful database for future projects. It is obvious that effective handling of the SHM data is a demanding task. Integrating the collected data in an effective information management tool such as BIM can resolve this issue by creating a single digital model that can be effectively used whenever needed. Therefore, an effective visual model and database system such as BIM, which can be utilized as a repository of all data captured or made during the building's life cycle, should be part of the structural health monitoring process.

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