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A Digital Visualization Approach for Bridge Structural Health Monitoring based on Building Information Modelling

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Abstract

Dealing with the unreadability of monitoring data poses a significant challenge in bridge structural health monitoring (SHM). This paper proposes a digital visualization approach of monitoring information based on building information modelling (BIM), which consists of establishing of the bridge information model (BRIM) and the dynamic visualization techniques. Multi-scale finite element models (FEMs) serve as the critical point for investigating the hidden information of the monitored data with the aid of big-data methods. Then the life-circle information is saved in the BRIM to realize information integration, which includes the structural designing data, operation data, monitoring system, load and environmental condition, damage information, FEM analysis results, etc. A customized four-dimensional (4D) visualization platform is subsequently developed via a secondary development interface to present heterogeneous information, reflecting the long-term state changes of infrastructures. Finally, the proposed digital visualization approach is applied to a three-span continuous model bridge case for verification.

Keywords: digital visualization approach, bridge structure health monitoring, building information modelling, bridge information model, four-dimensional visualization platform, life-circle information, heterogeneous data presentation

1 Introduction

The long-term serviceability of bridges depends not only on the quality of construction but also on the level of management and maintenance [1]. In this regard, intelligence and information techniques can improve the series life of bridges and address new challenges in bridge management. In recent years, structural health monitoring (SHM) has developed as a promising tool for intelligent management [2, 3], advanced by building information modelling (BIM), numerical modelling, internet of things (IoT), big data, and automatic technologies [4]. SHM is considered through the full life cycle of bridges, including the design, construction, management, and maintenance stages [5]. In particular, BIM is a revolutionary technology that significantly improves the performance and applicability of an SHM system from the following two aspects [6]. First, BIM provides an information integration and communication platform for bridge SHM. It serves as a repository to store massive data associated with SHM, such as those about objects, documents, inputs, outputs, IoT, management tools, etc. Second, BIM serves as a data visualization platform. The customized visualization interface can be developed based on the secondary development function of BIM software.

The IoT system can enhance and support a BIM because they are complementary. BIM represents physical entities with a high spatial resolution, while IoT collects real-time information with a high temporal resolution [7]. The BIM-IoT system provides a novel way for data collecting, storing, and exchanging. However, the BIM and IoT integration is in nascent stages and rarely applied to a real bridge [8]. A serious limitation of the BIM-IoT system is that BIM does not reflect the mechanical property of bridges, which is the essence of SHM. Besides, massive data collected via IoT should be processed and analysed to mine valuable information. The hybrid monitoring methodology developed in the past five years can overcome these limitations [9]. Hybrid indicates the integration of data and model, where a finite element model (FEM) is used to analyse the measured data to find hidden features and identify potential risks. By the proposal of BIM-based bridge SHM visualization approach, the in-field bridge, FEM, and BIM can be connected via IoT in a unified framework. Moreover, data and information flow between a real bridge and virtual models in dual directions, and thus, the physical and cyber spaces are able to interact in a real-time manner.

In this paper, the bridge information model (BRIM) is established based on BIM and a customized four-dimensional (4D) visualization platform is developed via a secondary development interface. Subsequently, an in-field bridge model subjected to ambient and vehicular loads is studied.

2 Methods

Bridges are subjected to ambient, traffic, and corrosion effects, and thus, its health state degenerate at a slow rate over a long period. Except for the natural aging process, the bridge can also be suddenly damaged after extreme events, including the earthquake, typhoon, over-weighted vehicles, etc. These continuous and sudden degenerating effects are investigated in SHM by measuring the loads and structural responses via IoT. Whereas, the measured data is spatially discrete and insufficient given the huge volume of a bridge. Besides, IoT could be affected by magnetic environments, making the measured data contaminated.

The FEM is used to process the collected data to simulate and analyse the mechanical behaviour of the real bridge. Moreover, the FEM is used to calculate the full-field bridge responses to different loads, which is an essential step to realize the holographic virtual sensing of a real bridge. In this regard, the hybrid monitoring methods proposed in recent years have provided substantial theoretical support for the exploration of monitoring data. The quasi-static hybrid monitoring methods have been proposed in [10,11], while the dynamic hybrid monitoring methods have been stated in [12].

The establishment of BRIM after data exploration serves as the kernel of digital visualization approach for bridge SHM. BRIM is a data integration modulus fusing multi-source and multi-structure data, including the sensor attribute, structural response, load distribution, damage condition, and periodical inspection text or pictures. Heterogeneous data are first analysed by data-driven approaches. Subsequently, they can be visualized and managed in a unified framework re-developed in BIM software. The temporal evolution and spatial features of a bridge can be analysed in the BRIM modulus in a 4D manner given the data accumulated over a long period. Moreover, the integration of heterogeneous data can help to make reasonable management decisions, for example, the optimal chance of the closure or repair of a bridge.

First, the static BRIM is established by utilizing the BIM core modelling software Revit, with modelling objects including the SHM sensor system, structural damage information, strain-related information, and deflection-related information.

(1) Regarding the SHM sensor system, various sensor-families are created by defining the corresponding family parameters for specific sensors, as shown in Figure 1. These sensor-families are then inserted into the overall bridge virtual model to realize the sensor arrangement for bridge SHM. Additionally, based on the discrepancy between family-type parameters and family-instance parameters in Revit, the parameters requiring annotation are categorized accordingly. Common parameters shared by sensors are categorized as family-type parameters, while individual parameters specific to each sensor are categorized as family-instance parameters. The specific categorization results are shown in Figure 2.

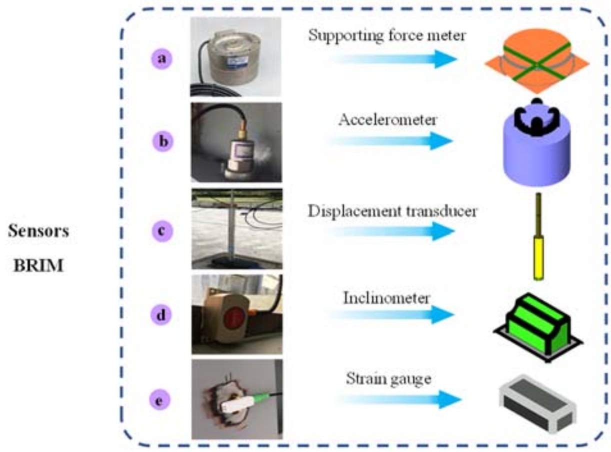


Figure 1: Creation of the BRIM of sensors.

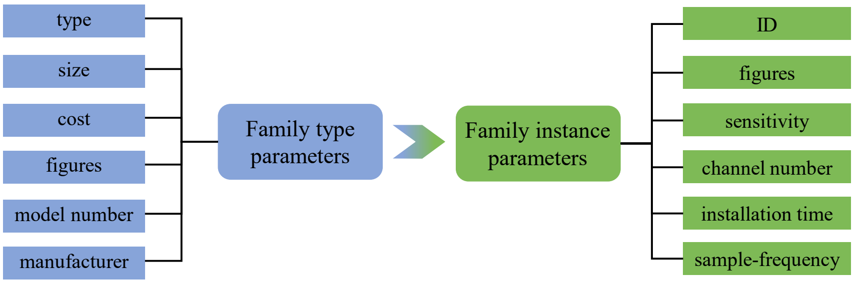


Figure 2: Classification of sensor parameters.

(2) Deflection-related information refers to the displacement response of the bridge, including vertical, lateral, and longitudinal displacements. For illustrative purposes, this paper focuses on the vertical displacement as an example. The specific steps to build the deflection-related information model involve creating a deflection-family using Revit software, where the approximate external shape of the structure is drawn based on an adaptive metric template from Revit. The deflection response is then visualized by adjusting the distance between the control section and the reference plane. Moreover, to enhance the visual representation of deflection, it is necessary to evaluate the relationship between sectional deflection values and allowable limits while displaying the bending shape of the bridge. A parametric family of coloured cylinders is employed to depict the magnitude of deflection, where the height of the cylinder is proportional to the deflection value and the colour represents different ranges: negligible range, normal range, cautionary range, and critical cautionary range. The specific cylinder design is shown in Table 1. The combination of the main beam deflection profile and the coloured cylinders constitutes the deflection family, which can be inserted into the overall bridge virtual model to present deflection-related information, as shown in Figure 3.

Model	Height	Color	Judgment	Condition
	u_i		$\lvert u_i \rvert \leqslant y_1$	negligible range
			$y_1 < \lvert u_i \rvert \leqslant y_2$	normal range
			$y_2 < \lvert u_i \rvert \leqslant y_3$	cautionary range
			$\lvert u_i \rvert > y_4$	critical cautionary range

Table 1: Cylindrical design to characterize the degree of deflection.

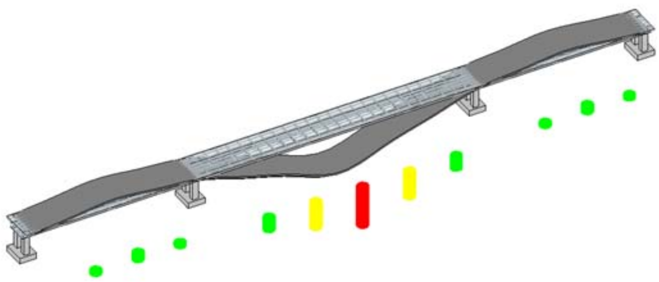
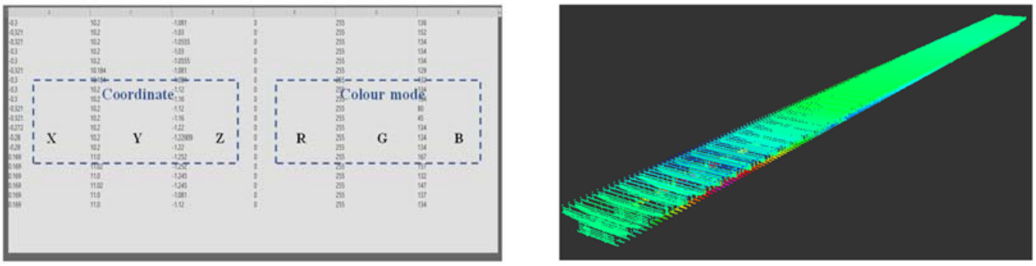


Figure 3: Creation of the BRIM of deflection-related information.

(3) Strain-related information refers to the strain and stress responses in various directions of the bridge, including but not limited to normal strain, shear strain, normal stress, and shear stress. For illustrative purposes, this section focuses on normal strain in the longitudinal direction of the bridge. The display of strain-related information utilizes the point cloud functionality supported by the Revit software. The conversion from strain values to RGB values is also involved, and the point cloud file can be imported into Revit after exporting it from Recap software. The interface of Recap software is displayed in Figure 4, while the strain display in Revit is illustrated in Figure 5.



(a) Data reading in Recap. (b) Point cloud in Recap.

Figure 4: The interface of Recap software.

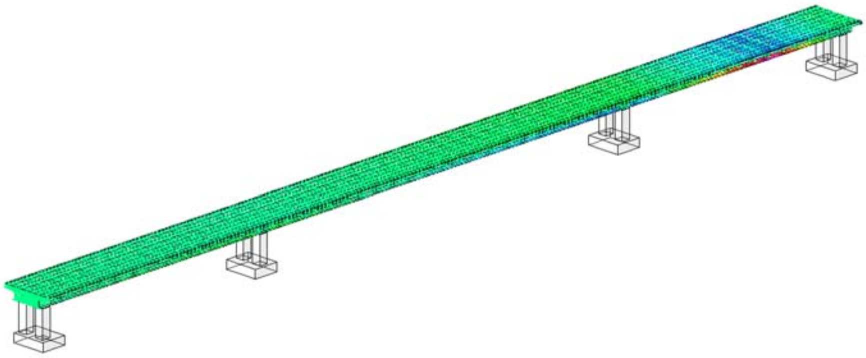


Figure 5: Creation of the BRIM of strain-related information.

(4) Damage information refers to the information of localized damage identified during the management and operation of the bridge, including the type of damage, occurrence time, severity of damage, the cause of damage, dimensions of the damage, and on-site photographs obtained through manual inspections. By incorporating the damage information into the overall bridge virtual model, it can be more intuitively considered in future analysis and handling processes. The establishment of the BRIM of damage information begins with creating a damage family in the Revit software. All the mentioned detailed damage information, except for the severity of damage, is categorized as family instance parameters. The severity of damage is represented by colour, where red, yellow, and green respectively indicate severe, moderate, and minor levels of damage.

Second, we achieve dynamic visualization based on the static BRIM, incorporating strain-related information, deflection-related information, and traffic information as dynamic visualization objects. The unified approach for dynamic visualization is as follows: Based on the multi-type created family files from static BRIM, the dynamic presentation can be realized by programming to automate the importation and modification of family parameters and re-displaying of family instances. APDL programming language provided by ANSYS can be used to get real-time family parameters, C# programming language can be used to handle the family parameters in Revit, and Python programming language can be employed to facilitate the interaction between these two languages. Therefore, the entire process is unified within the Visual Studio programming platform. The secondary development tools discussed in this paper mainly include Visual Studio 2022 development software, Revit SDK 2021 development toolkit, Revit Lookup 2021 plugin, and AddIn-Manager 2021 plugin.

Nowadays, traffic information is widely monitored by using video systems. The video data can be used to position the vehicles on the bridge deck based on computer vision techniques, which can be transformed to the BRIM of traffic information by the unified approach for dynamic visualization.

3 Results

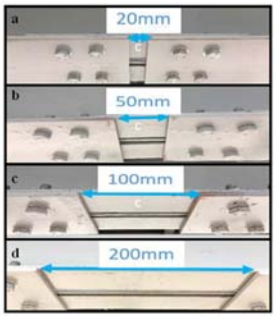
The proposed digital visualization approach in Section 2 is performed in a three-span bridge model to verify its effectiveness. The bridge model and BRIM are introduced in this section.

The bridge model was made of 6 mm thick steel plates. The span configuration was 6 + 10 + 6 = 22 m. The girder cross-section is π-shape with the width and height of 1200 mm and 262 mm. The transverse beams or diaphragms were welded to the main girder every 0.4 m in the longitudinal direction to increase its torsional stiffness. The model was placed outdoors and subjected to different types of environmental loads, as shown in Figure 6a. Four recovery damages were preset, as shown in Figure 6b. The lower flanges of the girder at the damage positions were connected using steel plates and friction bolts. The connecting plates were removed and the lower flanges became broken to simulate the damages.

The bridge model was equipped with a monitoring system consisting of sensors, a transmission system, and a data acquisition instrument. A total of 74 sensors were installed, including three displacement transducers, 11 inclinometers, 32 strain gauges, 11 accelerometers, eight reaction force meters, and nine thermometers. These sensors were installed at 21 longitudinal positions, and the sensor positions along the bridge are illustrated in Figure 7. Besides, a weather station, a weighbridge, and a video camera were installed. All these sensors have composed the IoT system for sensing the real-time structural responses to complex loads.

A BRIM was adopted to integrate heterogeneous data of the studied model bridge. Above all, the geometric model should be built in the Revit software by assembling the bridge components of a customized family. The detailed components of the bridge girder were first established in the SketchUp software, as shown in Figure 8, including the top plate (a), web plate (b), transverse beam (c), diaphragm (d), and stiffeners, etc.

These components were subsequently imported to Revit as a volume family with assigned material properties. The 3D geometric model of the bridge was subsequently built by assembling the customized components with a sufficient level of detail, as shown in Figure 9.



(a) Photo of the bridge model. (b) In-field photos of all damages.

Figure 6: the in-field bridge model.

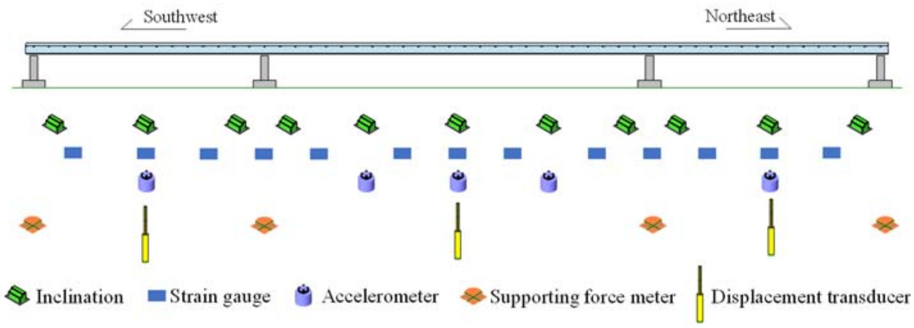


Figure 7: Placement of sensors along the bridge.

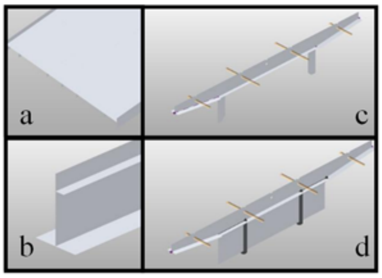


Figure 8: Model details in SketchUp.

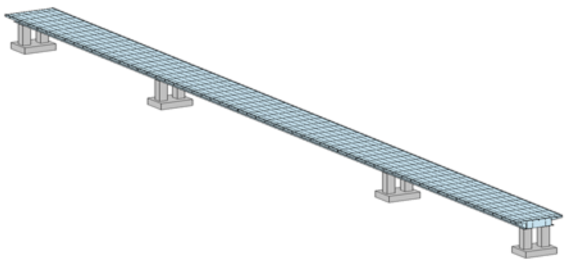


Figure 9: Overview of the geometric model in BRIM.

The IoT system was then virtually digitalized in cyberspace. Different types of sensors were modelled in the customized sensor-families. The real sensors were digitalized in Revit as instances, as illustrated in Section 2. The cyber sensors were then added to the digital geometric model as another family. The family-type and family-instance parameters were assigned to each sensor. In this way, massive information associated with the IoT system is stored and managed in an easy-access file. The bridge model and installed sensors were integrated and visualized in cyberspace to improve the data management efficiency, as illustrated in Figure 10.

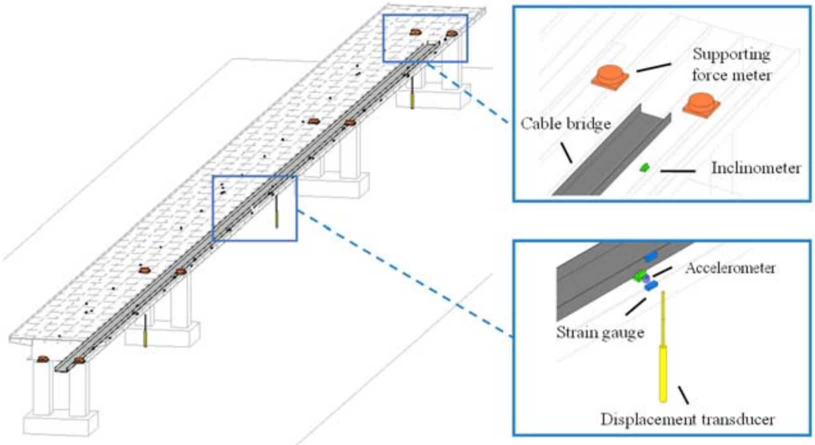


Figure 10: Integrated BRIM.

After the bridge model is established in cyberspace, the monitored heterogeneous data, including the video, environment, identified load, and response data, are fused and visualized on the interface of Revit based on its secondary development function. The model bridge was equipped with an SHM system. The measured data are processed, analysed, and then transformed into a data cloud format and mapped to the geometric model in BRIM. Finally, the strain field, vertical deflection curve, and traffic load are integrated into one interface to achieve multi-data fusion and visualization, as shown in Figure 11.

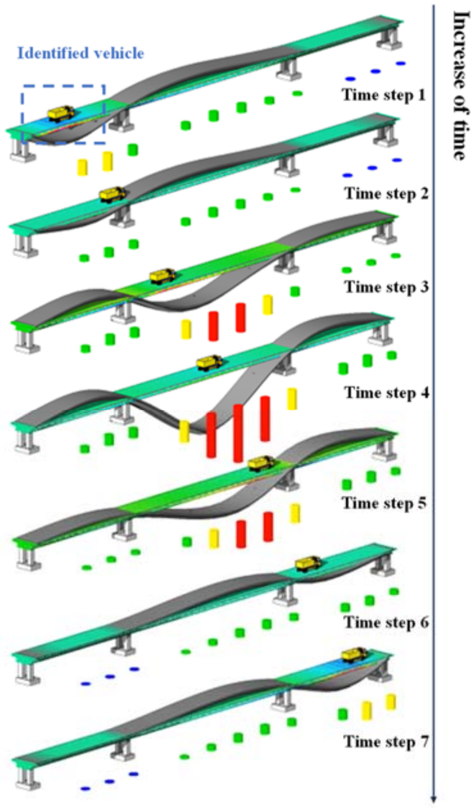


Figure 11: Dynamic visualization of structural response.

The damage information is saved in the BRIM when a defect is identified. It would also be updated if the damage condition changed. Each damage instance includes individual instance parameters, such as the size, detection time, photo, and type of damage, as shown in Figure 12. After a long period, the records of damages can be retrieved and analysed for bridge management.

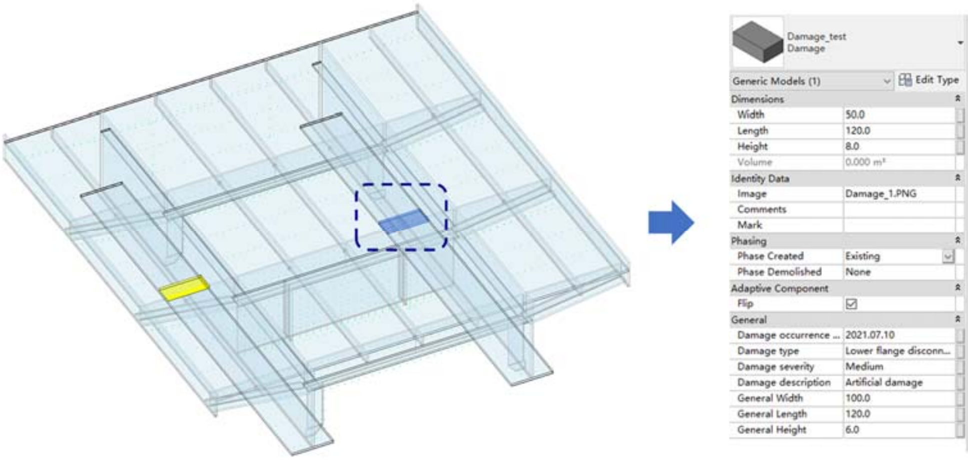


Figure 12: Damage information recording.

4 Conclusions and Contributions

The proposed digital visualization approach for bridge SHM is developed in this study to virtually sense the structural state. Meanwhile, it was successfully applied to a large-scale bridge model. The bridge structure and its IoT system are completely digitalized in a BRIM to manage massive heterogeneous data. Aided by dynamic visualization techniques, the FEM analysis results and in-field monitoring data are finally integrated and visualized in an interface that is secondarily developed in the BRIM, realizing the multi-source, multi-structure, and multi-dimension data fusion. The 4D visualization platform presenting the temporal evolution and spatial features of a bridge enriches visualization paradigms for bridge SHM. Moreover, data and information flow between a real bridge and virtual models in dual directions, which can help to make reasonable management decisions and maintenance feedback.

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