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A building information modelling framework for streamlining bridge construction and health monitoring

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ABSTRACT

Building information modeling (BIM) generally refers to the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions. It encompasses the facets of information management, collaborative working, graphical and data models, and asset data to automate life-cycle engineering asset management. In this paper, a BIM-based framework is developed to streamline the construction process and health monitoring of bridges. It integrates information from different phases of the full project life-cycle, and establishes a digitalized system supported by complete common data collaboration platform that features seamless connection with and dynamic visualization of the bridge health monitoring instrumentation data. The system has been successfully implemented in the construction and health monitoring of a large-scale cable-stayed highway bridge in practice.

1. INTRODUCTION

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After the turn of the 21st century, project management expert groups postulated the use of “enabling technology” to document, visualize, integrate, and coordinate project information, thereby leading to a more effective design, build, and management process (Construction Users Roundtable 2004). This set out the preliminary concept of BIM (Building information modeling), which was envisaged to empower full collaboration through information sharing early in the project process; shift the analysis, design, and decision-making earlier in the design process; maximize the ability to effect change and minimize the potential cost of design changes, achieve desirable outcomes of better efficiency, effectiveness and economy, among the plentiful advantages. With the advent of computational technologies and hardware and software capabilities, BIM has been widely popularized in the architecture, engineering and construction (AEC) industries worldwide (Sacks et al. 2018). It is not confined to the original virtual design and construction (VDC) workflows of a project, but holistically implemented throughout the project life-cycle comprising the planning, feasibility study, design, construction, commissioning, operation, maintenance, decommissioning and disposal (Institution of Civil Engineers 2020).

Generally speaking, BIM refers to the use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions (Barnes 2021). This gives the project collaborators maximum opportunity for good decisions. Technically, BIM encompasses the facets of information management, collaborative working, graphical and data models, and asset data to automate life-cycle engineering asset management. BIM can be broadly applied to building and civil works including by not limited to airports, bridges, piers, stadia, tunnels etc. Though some researchers use specific notions of Bridge information modelling (McKenna et al. 2017), Infrastructure information modelling (Esfahani 2018) and Civil information modelling (Bowmaster 2019), in consideration of the general applicability of BIM, the authors hereby adhere to adopt the terminology of BIM.

With regard to the conventional workflows of bridge construction and operation, there are often difficulties in coordination amongst project parties pertaining to data authenticity, change management, version control, etc. The problems are more acute when long-span bridges are concerned, which typically require input from expert design team and specialist construction team. For example, the designers have to estimate and allow for the movement and deformation during construction in their analyses, and formulate measures to cater for the beneficial and adverse effects of such movements and deformations. The contractors have to monitor and quantify the movement and deformation as the construction progresses, and adjust the geometries in order to ensure appropriate as-built project delivery, and at the same time communicate with the designer to fine-tune and update the analytical model. The above are crucial steps of construction control, which has been emphasized for cable-stayed bridges and suspension bridges (Han and Yan 2003).

As on health monitoring, manual recording of data read from instrumentation and automatic acquisition of sensor measurements by digital data-logger are the mainstream methods of data collection (Xu and Xia 2012). The former necessitates deployment of technician personnel to collect field data physically, which is inevitably restricted by working hours and inclement weather, and would be negatively affected by possible manual record and input errors. While the latter reduces the reliance on manual works by partial automation, the distinct protocols among sensor types arise compatibility issues in data logging and transmission. Losses in information fidelity and time during data acquisition, processing and uploading would result in delays in timely devising and executing corrective measures. The above adds to the difficulties in the coordination among operation team and maintenance team. Therefore, a robust system to facilitate the bridge construction and health monitoring is highly desirable.

In this research, a BIM-based framework is developed to integrate information from different phases of the full project life-cycle, and a digitalized system supported by complete common data collaboration platform is established. The details are explicated hereunder with reference to the realistic application to the construction and health monitoring of a large-scale cable-stayed highway bridge.

2. ESTABLISHMENT OF BUILDING INFORMATION MODEL

In consideration of the interoperability and prevalence of usage among AEC entities, Revit software was employed for establishing the information model of the bridges. The format of the 3D information model aligned with the Industry Foundation Classes (IFC), which is the standardized data schema prevailing in the construction industry (Eastman 2018). For the practical bridge project of the present research application, it is a highway bridge across Chaobai River connecting Beijing City and Langfang City, namely Chaobai River Bridge. The bridge is a prestressed concrete cable-stayed bridge with single tower and double cable planes, and has main spans of 165 m + 165 m. In each cable plane, there are 19 pairs of stay cables supporting the bridge deck. Fig. 1 depicts the schematic layout of Chaobai River Bridge.

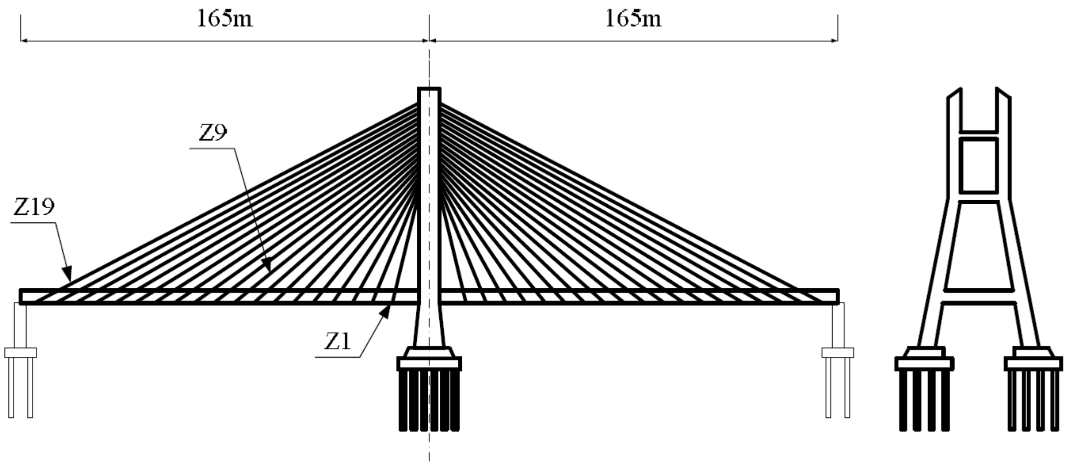


Fig. 1 Schematic layout of Chaobai River Bridge

To facilitate structural analysis, Midas Civil software was adopted, which allowed importing the 3D structural model via an IFC file converted from Revit software, then pre-processed the input to create the finite element model. Fig. 2 illustrates representative structural components of the 3D model, and Fig. 3 displays the BIM model geometry. The engineering properties and attributes of the structural components were defined in the BIM model, and were exported to the IFC file. On the other hand, the loading and restraints were defined in Midas Civil before conducting finite element analysis.

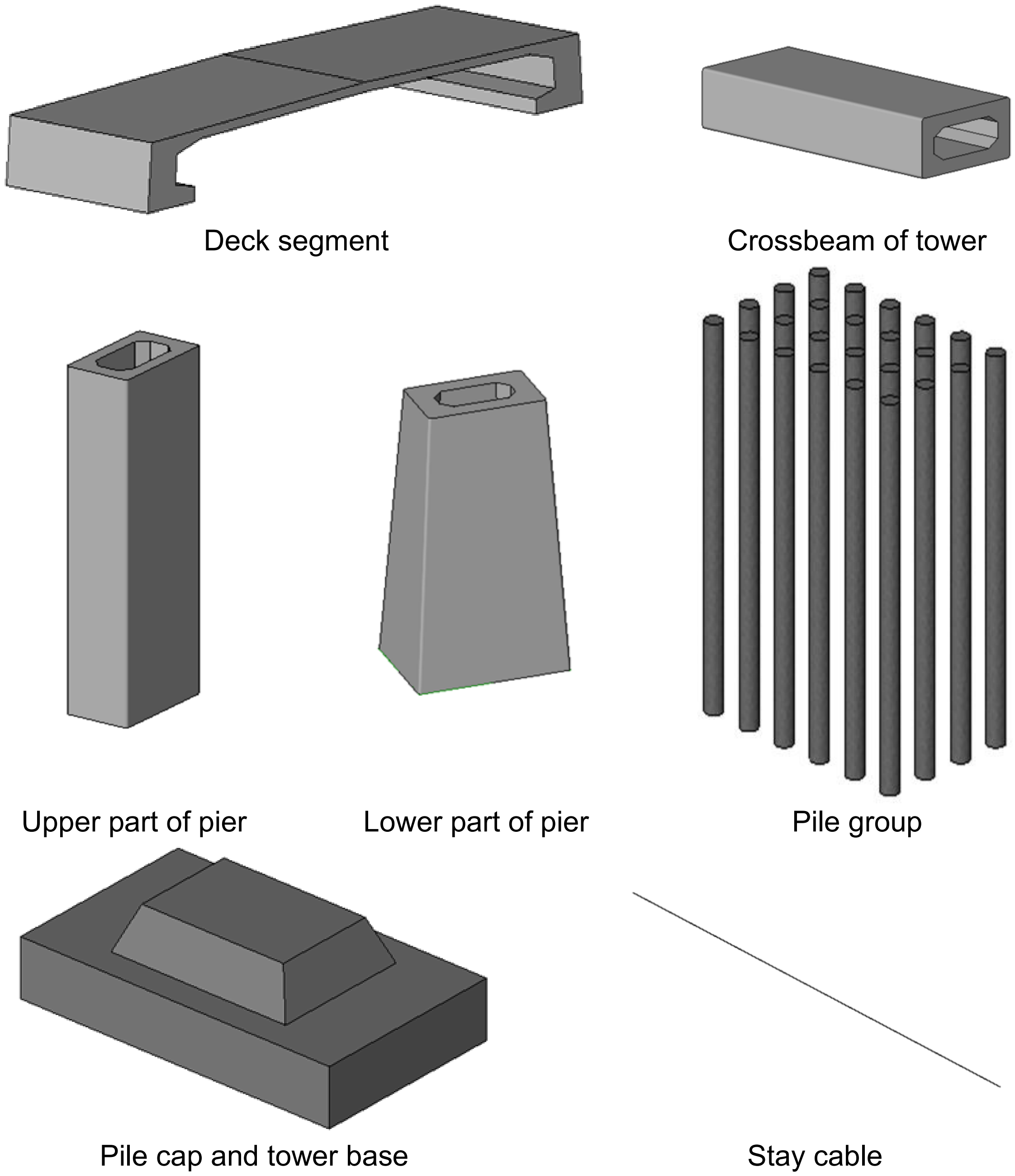


Fig. 2 Structural components of 3D model

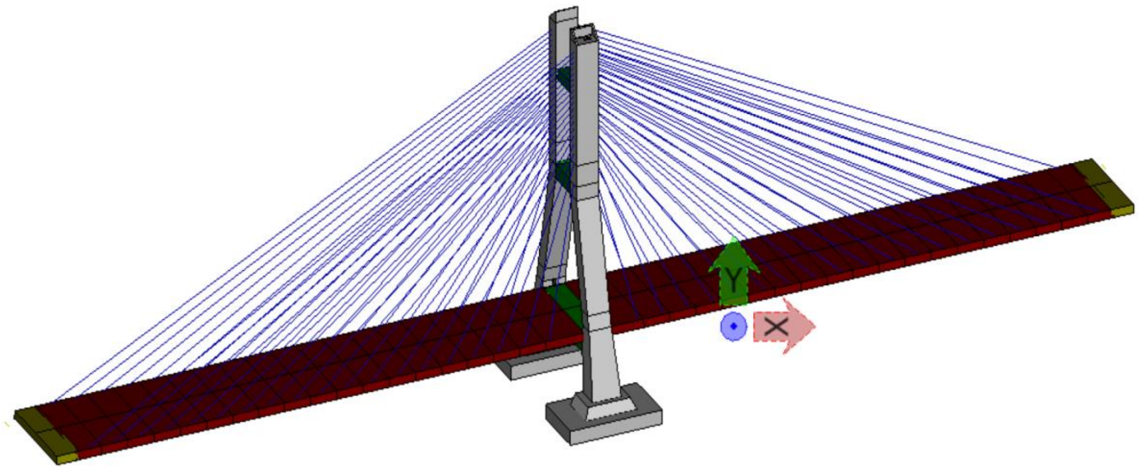


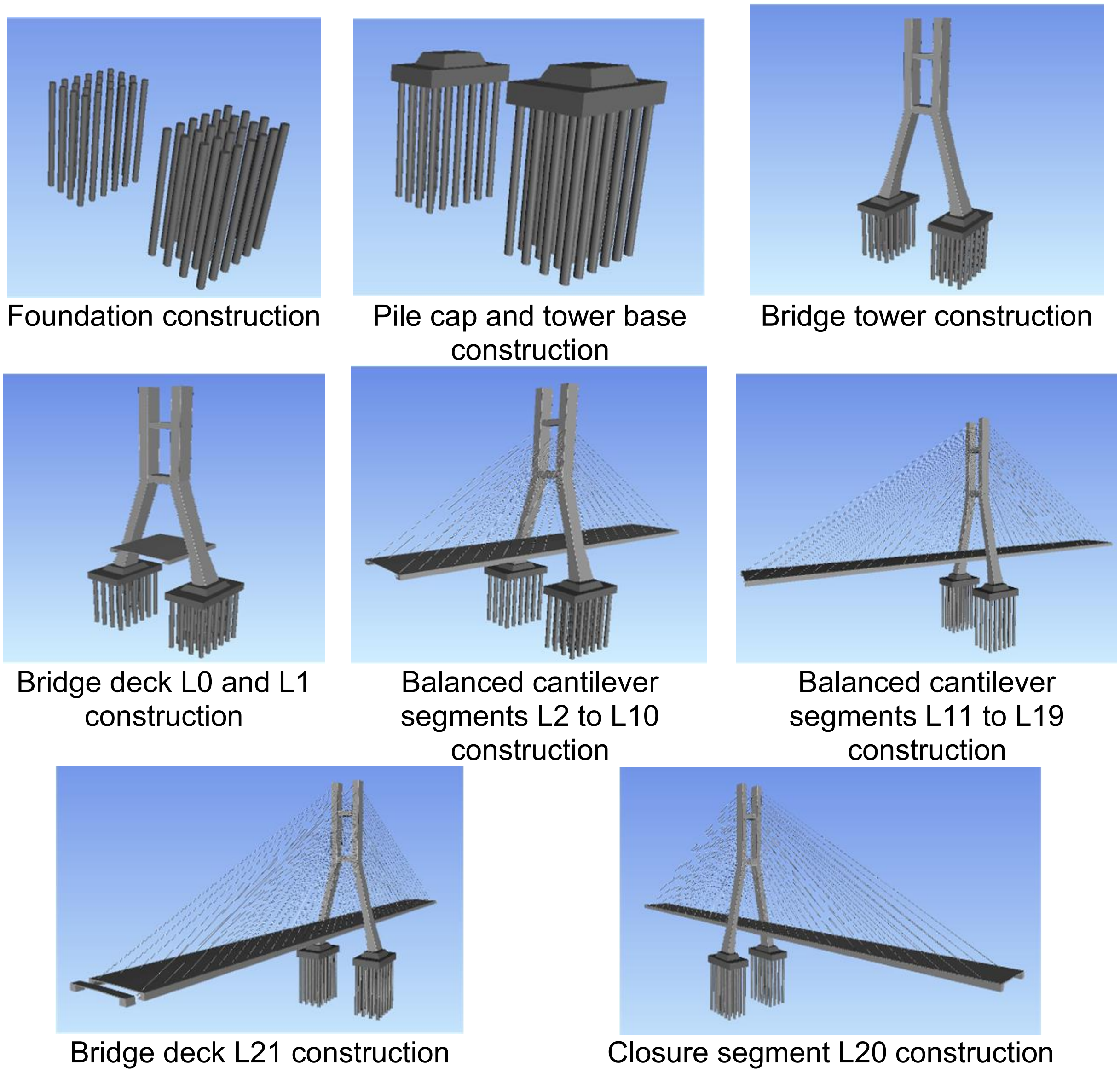
Fig. 3 BIM model of Chaobai River Bridge

3. FACILITATION OF CONSTRUCTION

3.1 Construction Simulation

To simulate the construction process, the Navisworks software was adopted, which imported the 3D model through linking a coordination model from Revit software. The time variable was introduced to describe the time dependence of the construction activities, and the works sequence was animated by using Navisworks software. Fig. 4 illustrates the overall construction sequence. For the substructure, bored piles were constructed for the foundation and the construction of pile cap was aided by temporary steel cofferdam. For the superstructure, the piers of bridge tower were divided into segments and cast in-situ using climbing formwork, and the crossbeams were cast in-situ with customized temporary supports derived from the piers. The bridge deck was divided into segments numbered L0 (at bridge tower location), L1 (adjacent to L0), L2 (adjacent to L1), and eventually up to L21 (at side support location). Basically, L0, L1 and L21 were cast in-situ deck supported on falsework, L2 to L19 were cast in-situ segments by means of balanced cantilever method, and L20 was cast in-situ closure segment supported on falsework. Following the construction progress of deck segments, the stressing of stay cables was executed in a balanced manner.

Moreover, the steps of key construction activities were simulated with the aid of families of temporary works provisions in the BIM library, such as falseworks, temporary platforms and formwork. As an example, Fig. 5 displays the steps of constructing the in-situ bridge deck at the bridge tower location. Other key construction activities were also simulated in a similar manner. The simulation and animation of construction process enabled visualization of site activities by the construction personnel prior to carrying out the physical works on site, thereby allowing thorough planning and identification of potential safety hazards in advance. This significantly enhanced the productivity and safety of construction works.

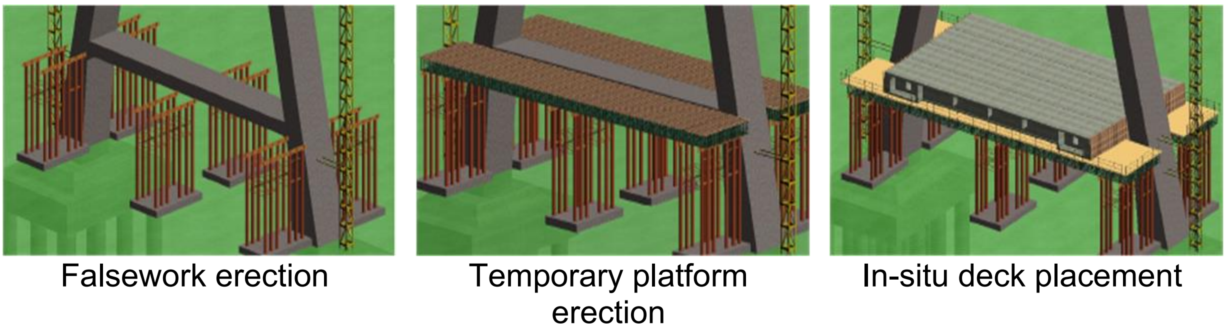


Foundation construction | Pile cap and tower base construction | Bridge tower construction

Bridge deck L0 and L1 construction | Balanced cantilever segments L2 to L10 construction | Balanced cantilever segments L11 to L19 construction

Bridge deck L21 construction | Closure segment L20 construction

Fig. 4 Simulation of overall construction sequence



Falsework erection | Temporary platform erection | In-situ deck placement

Fig. 5 Steps of in-situ deck construction at bridge tower location

3.2 Construction Response Monitoring

During construction, the structural responses including deformations, cable forces, and member stresses were monitored. To integrate the construction response monitoring into the BIM-based framework, the 3D model objects were purposely assigned coding parameters in Revit software for linkage to the monitoring results. For deformations monitoring, monitoring points were installed in the middle of width and close to two edges of top surface of each deck segment, and monitoring targets were installed at designated positions of the piers. The monitoring points/targets were surveyed to determine the elevation of various positions of the bridge deck and lateral deviations (mainly in the longitudinal direction due to stay cable stressing) of the piers. For cable forces monitoring, instrumentations including vibration frequency sensor and cable force dynamic tester were installed at the stay cables, and the monitored force in each cable was constantly compared with the analytical value as the baseline. Fig. 6 depicts the instruments for cable forces monitoring. For member stresses monitoring, vibrating wire strain sensors were embedded inside the webs of bridge deck at mid-span and quarter points, and inside the piers at deck level, mid-height and top level. The embedded vibrating wire strain sensors were utilized for the subsequent bridge health monitoring.

Vibration frequency sensor

Stress transducer

Cable force dynamic tester

Signal amplifier

Fig. 6 Instrumentation during construction

From static analysis of completed bridge, a set of analytical cable forces for attaining static equilibrium was obtained and is plotted in Fig. 7. Accompanying the deck segments construction and stressing of stay cables, the partially completed bridge manifested deformations. In the execution of construction control, the deviations were in part or in whole corrected by adjusting the cable forces. The BIM-based framework provided enhanced common data environment, herein referred to as common data collaboration platform, for the engineering team comprising specialist designers and contractor to retrieve the monitoring results, feedback to the analytical model, and devise suitable corrective adjustments. The adjusted design cable forces are also plotted in Fig. 7 for comparison. It can be seen that the analytical values and adjusted design values differed by no larger than 5%, which fell within the normal range of variation.

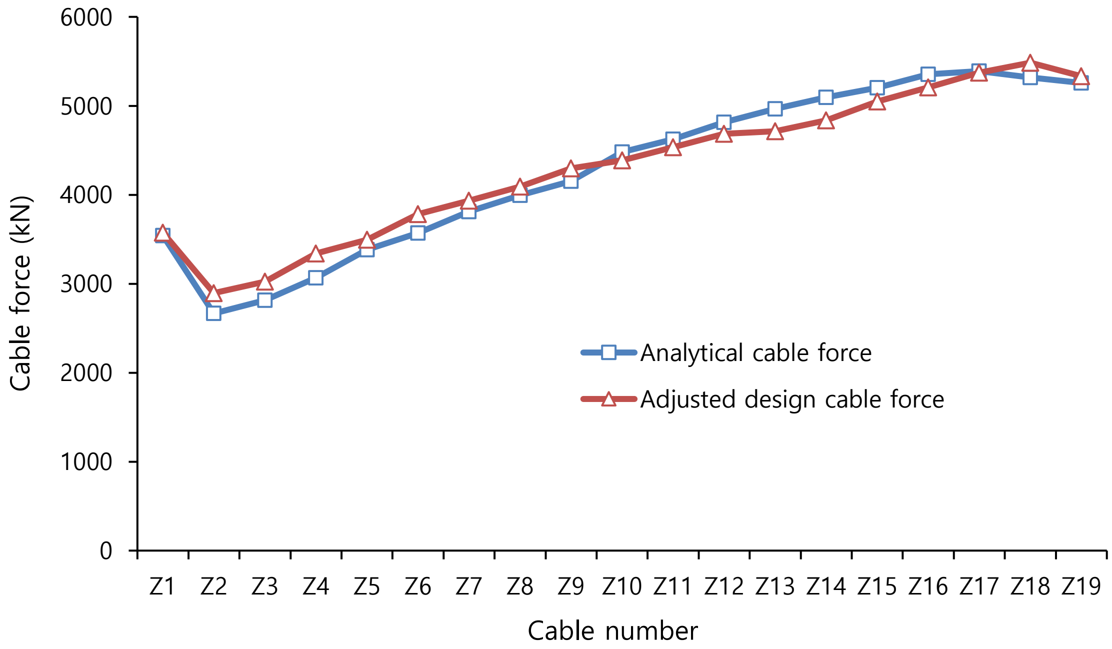


Fig. 7 Comparison of analytical cable force and adjusted design cable force

4. FACILITATION OF HEALTH MONITORING

A bridge health monitoring plan was formulated and agreed among the project parties. Accordingly, the BIM-based framework was tailored to cater for the integration with health monitoring. The instrumentations and configurations for bridge health monitoring are summarized in Table 1. In addition to the functionalities of BIM-based framework during construction phase, the health monitoring during operation phase posted more stringent requirements on the connectivity and compatibility of the common data collaboration platform with different instrumentations. The data structure of collaborative platform was customized to suit the needs of health monitoring. The digitalized system allowed instant retrieval, display and visualization of health monitoring data. Users could also view the instrumentation layout via the user interface.

Table 1 Instrumentation and configuration for bridge health monitoring

Instrument	Quantity	Measurement objective	Location
Sonic anemometer	1	Wind velocity	Top of bridge tower
Electronic thermohygrograph	1	Temperature and humidity	Crossbeam at mid-height of tower
Vibrating wire strain sensor	102	Concrete strain	Mid-span and quarter points of deck; deck level, mid-height and top of piers
Accelerometer	6	Cable vibration	Cables Z1, Z9, Z19 at both spans
Differential pressure liquid level meter	8	Bridge geometrical alignment	Mid-span of deck and top of piers
Obliquity sensor	2	Bridge piers deflection	Top of bridge tower

Fig. 8 illustrates the system architecture of BIM-based framework for bridge health monitoring. The system architecture constituted four layers, namely the data acquisition layer, interaction layer, business logic layer, and data access layer. Data from instrumentation is collected in the data acquisition layer. Users could input commands and obtain output from the system through the user interface of the interaction layer. Data processing and system functions were executed in the business logic layer. Accessing data from and editing of the database of common data collaboration platform were carried out in the data access layer.

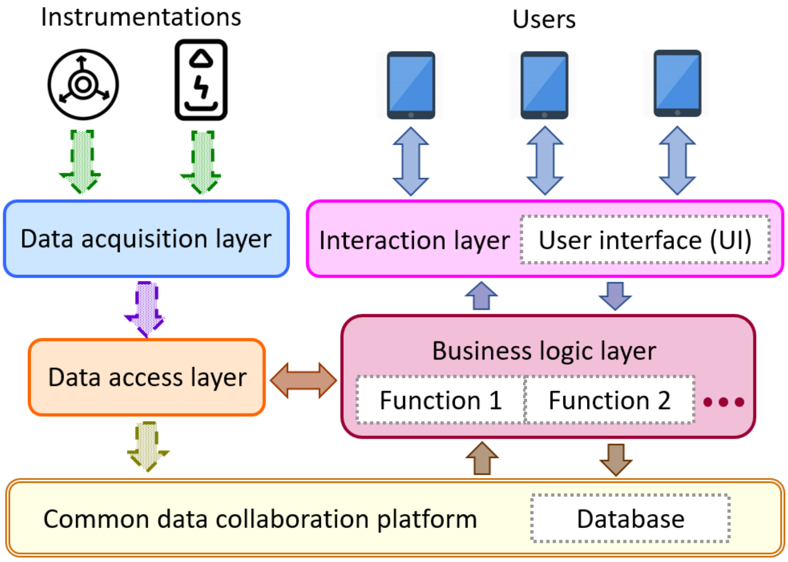


Fig. 8 System architecture for health monitoring

During the service life of the bridge, the gradual structural deterioration caused by steel corrosion and concrete degradation would take place slowly and can generally be dealt with by planned maintenance. However, there could be transient phenomena such as cable vibrations caused by aerodynamic and aeroelastic effects, and large deformations of the bridge structural components under strong wind. With the BIM-based digitalized system in place, any excessive cable vibration and deformation could be instantly detected and the relevant personnel are alerted for decision and execution of apposite immediate measures such as imposing traffic restrictions. The system substantially facilitated effective operation management of the highway bridge. Further research will be conducted for automated analysis of health monitoring data via machine learning to identify damages, characterize the health status, and categorize risks.

5. CONCLUSIONS

This paper has reported the development of BIM-based framework for streamlining the construction process and health monitoring of bridges. Information from different phases of the project life-cycle was integrated, and a digitalized system supported by common data collaboration platform has been launched. The aspects of BIM model establishment, construction simulation, construction response monitoring, and facilitation of bridge health monitoring have been explicated in detail. The digitalized system integrates various types of health monitoring instrumentation, and allows dynamic visualization of the monitoring data. Through instant alert of excessive bridge cable vibrations due to aerodynamic and aeroelastic effects, and excessively large deformations of structural components under strong wind, the system could effectively improve the operational safety of bridges. The real-life implementation in the construction and health monitoring of a cable-stayed highway bridge has been presented.

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