Smart Structures Systems, *Vol. 20, No. 6 (2017) 697-708*
DOI: https://doi.org/10.12989/sss.2017.20.6.697

Development of BIM-based bridge maintenance system for cable-stayed bridges

Chang-su Shim*[1], Hwirang Kang[1], Ngoc Son Dang[1] and Deokkeun Lee[2]

[1]Department of Civil Engineering, Chung-Ang University,
310 - 434, 84 Heukseok-ro, Dongjak-gu, Seoul, Republic of Korea
[2]Long Span Bridge Management Center, Korea Infrastructure Safety & Technology Corporation
131, Sadeul-ro, Jinju-si, Gyeongsangnam-do, Republic of Korea

(Received March 6, 2017, Revised October 28, 2017, Accepted November 12, 2017)

Abstract. Maintenance plays a critical role in the bridge industry, but actual practices show many limitations because of traditional, 2D-based information systems. It is necessary to develop a new generation of maintenance information management systems for more reliable decision making in bridge maintenance. Enhancing current work processes requires a BIM-based 3D digital model that can use information from the whole lifecycle of a project (design, construction, operation, and maintenance) through continuous exchanges and updates from each stakeholder. This study describes the development of a data scheme for maintenance of cable-stayed bridges. We implemented the proposed system for a cable-stayed bridge and discussed its effectiveness.

Keywords: bridge maintenance; BIM; 3D digital model; data schema; cable-stayed bridge

1. Introduction

The integrated design and construction of bridge structures through well-established 3D information models will be an innovation from the conventional 2D methodology for designing, constructing, and maintaining bridges. In the past, the construction industry has relied on 2D paper drawings as the primary representation of construction documents. Other manufacturing industries have already obtained excellent results, such as reduction of costs, faster delivery, and improved quality, as a result of implementing 3D object-based integrated design and manufacturing processes and accompanying interoperability standards (Marzouk *et al.* 2014, Verheij and Augenbroe 2006, Leeuwen and Zee 2005, Plume and Mitchell 2007, Whyte *et al.* 2000, Maher *et al*. 2005, Robinson 2008). Building information modeling (BIM) is bringing that trend to the construction industry.

Although the evolution and deployment of information technologies will undoubtedly play an important role in the construction industry, many engineers are still unsure about the economic value of using these technologies. Most engineers rely on limited private experiences when they create solutions or design alternatives. A detailed, authoritative, and readily accessible information model is needed to enable engineers to make cost-effective choices from among various established and innovative design alternatives. In the practice of bridge maintenance, reliable records about past and current bridge conditions are crucial for engineers to prescribe preventive maintenance actions. Current project-based maintenance systems need to be improved and connected with one another into network-based systems.

Adequate interoperability of 3D objects from any CAD system is essential for collaboration. The design of bridge structures is generally based on 2D drawings, and design specifications specify the limit states using member-based equations. Because drawings are normally done after design checks by different engineers, insufficient information delivery causes additional effort to correct constructability problems. Information technologies can dramatically enhance the efficiency of this collaboration. Information transfer requires a mediator between engineers. Object-based 3D models are useful for communication and for owners who need to maintain information about entire infrastructures. Owners, contractors, and design consultants can all use 3D objects (Thomas et al. 2001, Shim et al. 2008). The U.S. National Institute of Standards and Technology (NIST) conducted a cost analysis and reported waste in costs in the U.S. capital services industry due to the lack of interoperability among systems used throughout the engineering lifecycle (Gallaher *et al.* 2004). A computational framework was proposed by Denysiuk et al. (2016) for the asset maintenance scheduling.

BIM is the process of generating and managing data during a building's lifecycle (Lee *et al*. 2006). The term BIM was popularized as a common name for the capabilities offered by several technology providers (Autodesk, Bentley Systems, Graphisoft, and others): a digital representation of the building process to facilitate the exchange and interoperability of information in a digital format. BIM covers geometry, spatial relationships, geographic information, quantities, and the properties of

*Corresponding author, Professor
E-mail: csshim@cau.ac.kr

ISSN: 1738-1584 (Print), 1738-1991 (Online)

structural components. BIM can achieve improvements by modeling representations of actual parts and pieces of the structure. This is a substantial shift from the traditional computer-aided drafting method of drawing with vector-file-based lines that combine to represent objects.

Recently, bridge information modeling (BrIM) has been proposed to improve bridge construction processes from planning to operation (Chipman *et al.* 2016). BrIM is the organization of all component data required to support a bridge throughout its lifecycle (Janjic *et al.* 2008). The concept is the same as BIM, but it is closely related to an axis for road or railway design (Katz 2008). For each construction process from planning to maintenance, the model needs to be revised and contain the entire architecture of the geometry and information for all bridge parts. In lieu of a complete industry-wide modeling of bridge information in a standardized format, integrating information and communication technologies will result in more rapid and better quality project delivery and subsequent cost-effective lifecycle management, ultimately providing a competitive advantage (Chen *et al.* 2003). 3D models can be easily used to manufacture structural components for construction (Verma *et al.* 2001). Several IFC-bridge models have been proposed to enable interoperability between different solutions and processes (Yabuki and Shitani 2003). Recently, the OpenBrIM concept using a standard XML data format was developed (Bartholomew *et al*. 2015). However, there is a lack of 3D bridge information models for actual construction projects.

During the past few decades, bridge maintenance systems (BMSs) have received special attention. In developed countries that face aging infrastructure, various BMSs have been adopted, leading to a demand for a national bridge inventory (Hammad *et al.* 2007). To clarify the difference between repairs and strengthening for existing bridges, estimating the progressive deterioration of performance in bridge members needs to be considered, along with a rehabilitation strategy that combines maintenance-cost minimization and quality maximization (Miyamoto *et al*. 2001).

Designing and manufacturing via 3D CAD greatly improves quality and productivity (Lee *et al.* 2010, Bien 2011, Shimizu *et al.* 2013). Maintaining bridge structures appropriately requires that various data be managed. This work requires many resources; in particular, large construction projects involve collaboration among many participants with different specialized knowledge about various construction processes. A BMS that uses 3D models can ease collaboration and adequately integrate design and construction processes. Several of the available advanced geometry models require selection of the most rational solutions for specific applications, taking into account both increasing model accuracy and the increasing complexity of the representation of bridge structures in the computer systems (Bien 2011). On the other hand, 2D drawings (extended elevations) can be easily generated in chronological order and shared mutually. Photo positioning for tracing damage also needs to be enhanced (Shimizu *et al*. 2013).

Lifecycle information management is the main issue for BMS to perform adequately from the conceptual stage to the end of a bridge's useful life. Currently, various approaches and integrated studies have been proposed (Shim *et al.* 2011, 2012, 2016). Mobile model-based lifecycle management systems were the first attempt to integrate 4D bridge models with BMS and make the resulting information accessible to onsite workers with suitable interaction methods for navigation, picking, and level of detail (LOD) (Hammad *et al.* 2006). A database management system using object-oriented programming and client/server architecture can contain basic information about the bridge, inspection record, etc. Moreover, it can answer a variety of information queries, and recorded data can automatically generate the documentation needed for a comprehensive bridge evaluation, as well as meet the need for information sharing and regional management required by modern bridge maintenance and management (Yin *et al.* 2011). Combining bridge management on the building level and the optimization of maintenance schedules on a network level can thus be achieved. Structuring the model using an LOD approach can produce a fine granular prognosis, identifying the parts where and the time when maintenance should be performed. An ideal schedule considers not only the safety of all bridges but also the budget, traffic impacts, etc. (Lukas and Borrmann 2012).

In this paper, we propose a new data scheme for 3D digital information models in a new maintenance system for a cable-stayed bridge, along with its flow of information exchange throughout the entire lifecycle. Furthermore, based on that data scheme, we introduce an application to establish the data well; it shows good time-saving potential for maintenance work. We installed our proposed new BMS as a pilot application.

2. Employer's Information Requirements (EIR) for a bridge maintenance system

2.1 Main objectives for maintenance work

Previously, the maintenance/repair of bridges was often a "reactive activity" initiated only when deterioration threatened the safety or tolerance of the public. Now, influenced by BMSs, owners are beginning to emphasize cost-effective proactive strategies from the start, when the bridge is new, so-called *preventive maintenance*. Currently, many developed countries have made efforts to define the state-of-the-art in bridge maintenance and management and look ahead to the challenges that this field will face in the next century. In this regard, the Transportation Research Board (one of six major divisions of the National Research Council in the USA) has defined the following criteria as the main issues (Hearn *et al*. 2000): spalling, scaling, and cracking for concrete members; damage by corrosion, fatigue, and impact for steel members and cables; and scour, undermining, and settlement for substructure supports.

The standard procedure for repair activities is the iterative work of inspecting/monitoring, performing the needed repairs, and updating the database. Information is assessed based on a closed inspection and monitoring

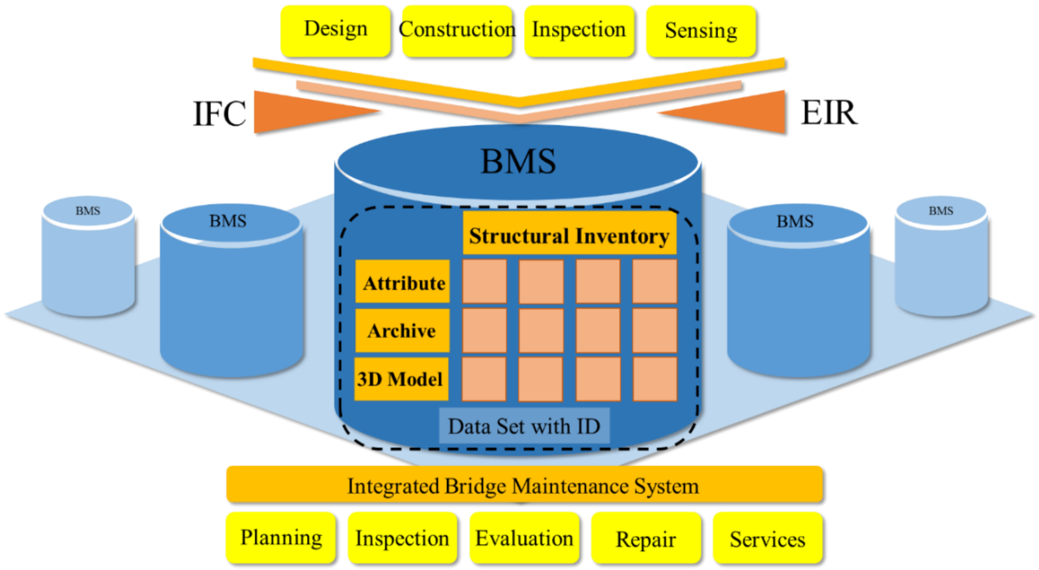


Fig. 1 Configuration of system proposed for BIM maintenance standard

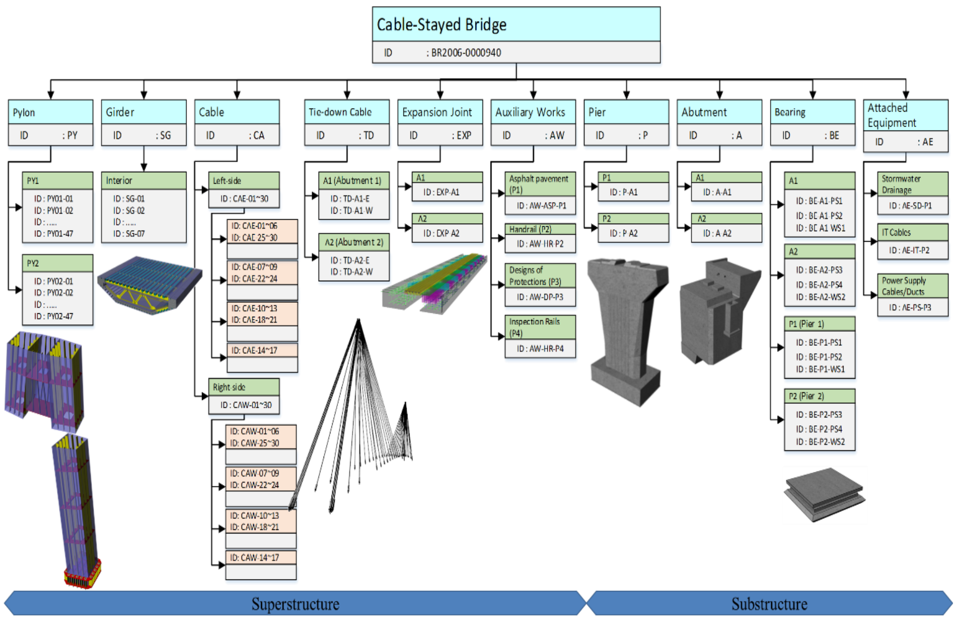


Fig. 2 Inventory system and ID definition of a cable-stayed bridge

system. Thereafter, workers use inspection/monitoring requirement forms to file evaluation reports about the current conditions of individual structures. Maintenance or repair needs are diagnosed and proposed if necessary, and the best repair method is chosen and performed. Finally, all related information, including inspection/monitoring data, date and method of repair work, and the structural condition after repair work, is updated in the database. This work is continually repeated throughout the whole bridge lifecycle. In fact, maintenance needs for older bridges have far outpaced available resources. This situation indicates the need for a comprehensive but minimalist approach to bridge management.

2.2 Information requirements for bridge maintenance

Depending on the purpose of maintenance, the EIR should be defined first. The information requirement orients the model and creates premises for the development of a maintenance system. In other words, logical and systematic information is required. The database stores all information about the bridge related to its physical features, conditions, etc., from the design team; all instructions and as-built models from the contractor; and also all indispensable records from the inspection and maintenance team.

The orientation of BIM-standards that we propose for a maintenance system is based on the principle of 3D-model-

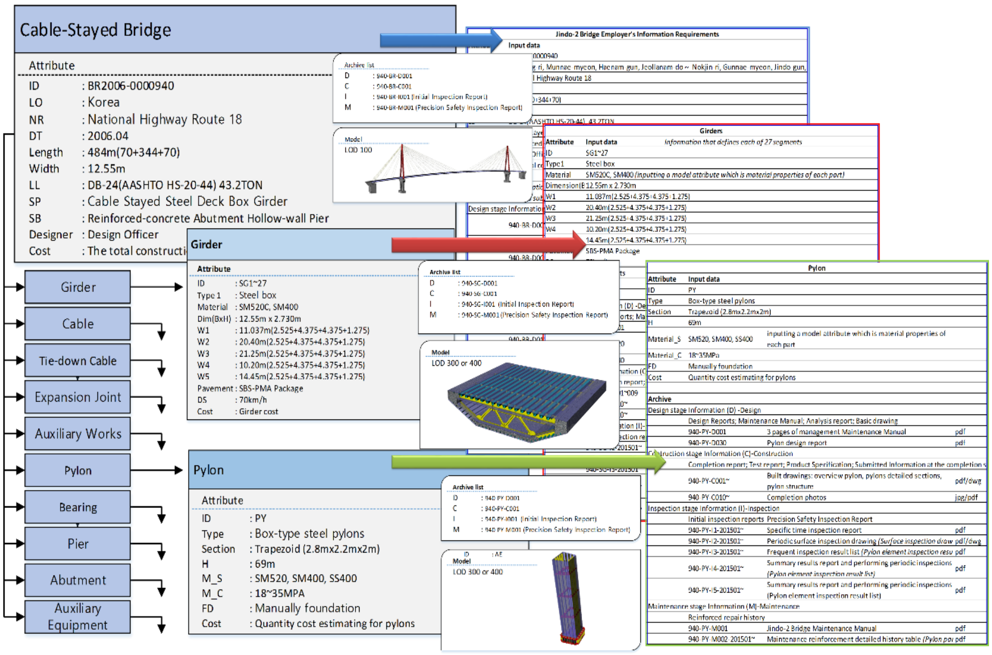


Fig. 3 Example of schematic information system for a cable-stayed bridge

based information (Fig. 1). The existing documentation system from the design and construction stage is reflected in the flow of information. Workers must be able to easily interact with the inspection/monitoring system or another maintenance system. Information must be strictly interoperable, traceable, scalable, and flexible.

2.3 Inventory system and object ID definition

Each structural element of the cable-stayed bridge must be inventoried into a category system according to its role in the service of the bridge, such as the superstructure (e.g., girder, cable, tie-down cable, expansion joint, auxiliary work) or substructure (e.g., pylon, pier, abutment, bridge bearing). In each category, structural elements should have similar characteristics and properties or be further classified into a more detailed category; otherwise, it is difficult to define the features of each category.

The category system makes it possible to identify each structural element using a specific identification (hereafter, ID). In this work, we create a systematic database in which the target model is defined element by element following the concept of a creative object-based program. The target information model will be produced by assembling the entire structure using each element's ID with its coordinates and constraint information. Fig. 3 shows an example of an inventory system and its developed object-ID definition for a common cable-stayed bridge.

2.4 Schematic information system for a new BMS

We formed the BIM-based 3D digital model by adding the corresponding information requirements to the specified object IDs in the inventory system. All information related to each object’s shape, size, physical property, coordinates, constraints, etc., is included, but only the information needed for the LOD of any particular job is provided. A parametric model will be created based on this information system. With the advantages of parametric modeling technology, the input information will be preserved, updated, and stored throughout the project lifecycle, with access permitted to rational stakeholders at each stage. Fig. 3 shows an example of the schematic information system for a cable-stayed bridge that can be considered as a standard adoption. The information added for each element should be imported as a spreadsheet or in some given format (Extensible Markup Language in this paper) so that information can be easily imported into the different applications used by each partner.

Each component, including the entire bridge, has two main characteristics: “attributes” and an “archive list.” Corresponding to the component ID, individual attribute features consist of all general information in terms of the location and role of the component: physical properties such as the type, shape, size, or material property; behavior of the component in the bridge system; and quantity/cost estimating. The attributes are essential for the extension of the new BMS to network-level maintenance. Each component also has its own archive list, which contains all the detailed information required by the EIR. During the lifecycle of the bridge, from design and construction through inspection, maintenance, and monitoring, the archive data are obtained using the corresponding document ID and specified in a list. In addition, any related information can be added to the archive list, such as an inspection plan, inspection manual, or damage history and repair record. Note that the archive files allow only a report form that can be recognized by a computer, which means it should be stored in a primitive file format such as .jpg for photo checking reports, .avi for video checking reports, and .pdf/.txt for document reports.

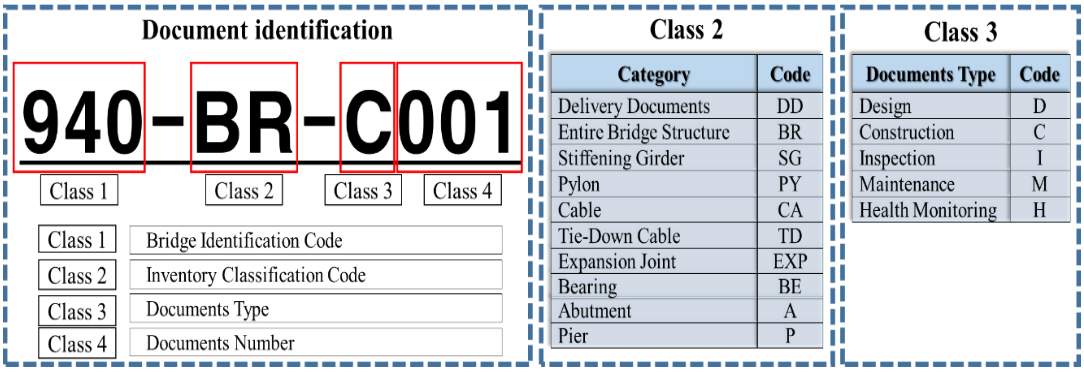


Fig. 4 Document ID convention for a bridge information system

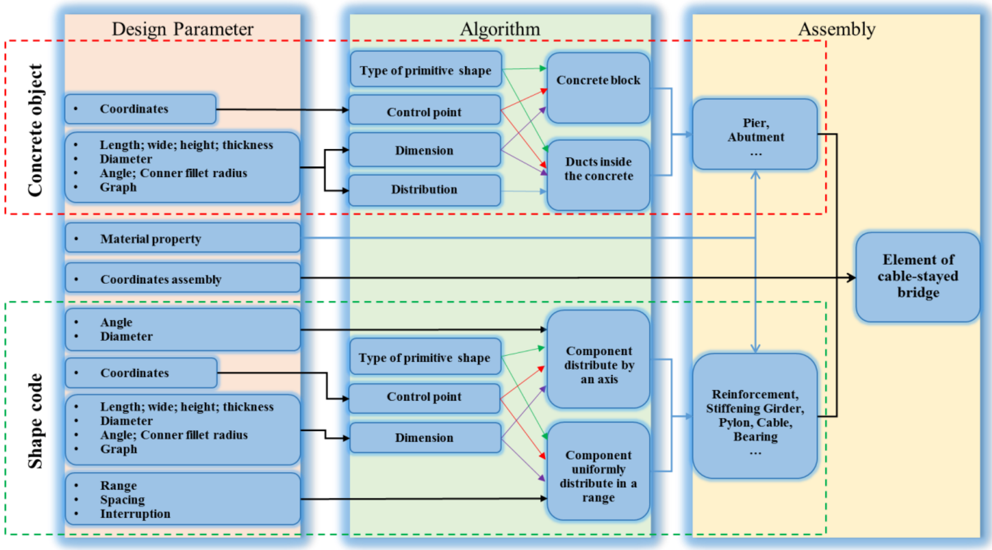


Fig. 5 Flowchart for parametric modeling of an element of a cable-stayed bridge

The naming convention for archive documents needs to be considered to ensure strict links between the attributes and archive for each bridge component. Figure 4 shows an example of the naming convention for a general bridge information system. Class 1 is the bridge ID, class 2 follows the inventory system, and classes 3 and 4 are the types or individual profiles of documents. All the general information about the bridge (class 1), as well as the member-specific information (classes 2, 3, 4), is stored using one document ID to fully manage the information in the BMS. Moreover, that naming convention could be used in a standard information system for various kinds of bridges. If documents from different bridges contain a shared category, such as materials lists, they would have the same document ID except for the bridge identification code.

3. Application to a cable-stayed bridge

3.1 General description of the bridge

Cable-stayed bridges debuted around fifty years ago and have undergone many improvements and optimizations in term of technology. Today, cable-stayed bridge technology is increasingly becoming civil engineers' common choice for long-span bridges. Cable-stayed bridges have good stability, optimum use of structural materials, good aesthetics, relatively low design and maintenance costs, and efficient structural characteristics. Cable-stayed bridges can be seen as an adaptation of the suspension bridge principle. The difference lies in how the cables are connected to the pylons. A cable-stayed bridge consists of one or more towers with cables supporting the bridge deck.

3.2 BIM authoring for 3D bridge model

The original CAD-models cannot be used as a maintenance system because they lack interoperability in terms of linking the metadata, including all attributes and archives. Most bridges are in the operation stage, so 3D bridge models need to be created from the existing 2D drawings. Model authoring is a challenging task in system

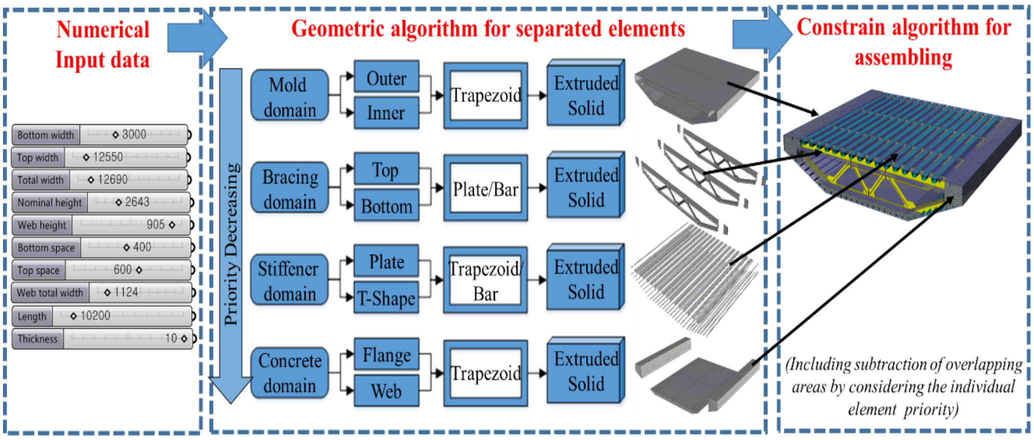


Fig. 6 Parametric modeling design for a stiffening girder using an algorithmic tool

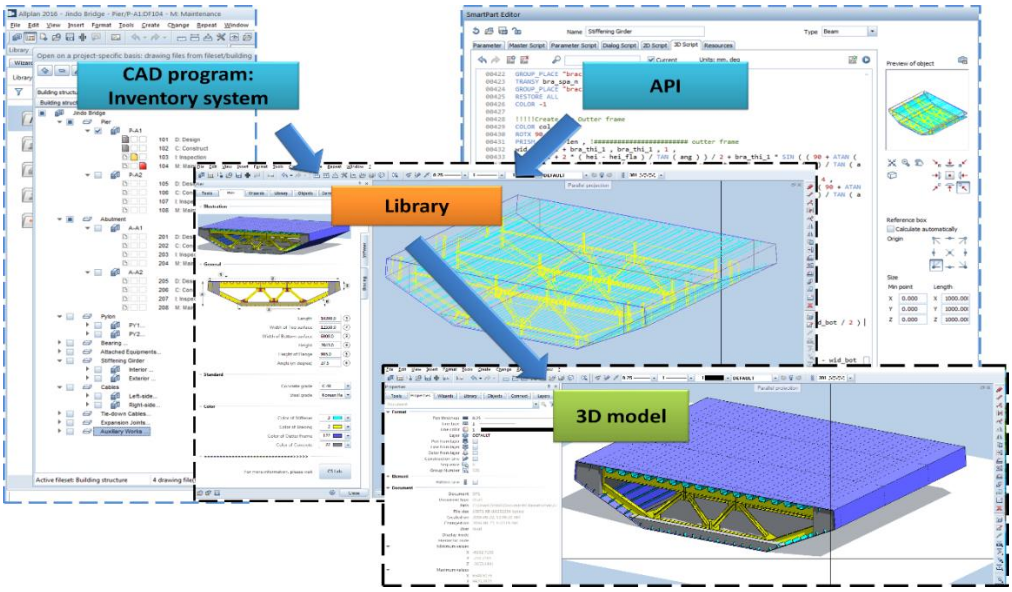


Fig. 7 Concept for digital mock-up by application programing interface

development, and we adopted 3D parametric modeling based on BIM technology for this application. Parametric modeling is the current paradigm for modern and innovative designs because it moves computer-aided design technology into the next generation. With its flexibility of design variables, all optimization and revision procedures can be automated and easily controlled. During the design process, geometric or even conceptual definitions can be varied at any time. The advantages of the parametric model are the parametric features, which match ever better with actual design and manufacturing processes. Automatic updating is a key refinement of parametric modeling technology that allows all associated aspects to be incorporated into a unified model and simultaneously changed whenever input data are updated.

Fig. 5 presents a flowchart for the concept of parametric modeling for the standard elements of a cable-stayed bridge. We divided the elements in the model into two parts, the main design parameters and their properties. First, we defined the information requirements for the parametric modeling. Then, the proposed algorithm built the concrete objects (pier, abutment) and shape code objects (girder, pylon, cable, bearing). The final design model was authored by combining those parts using predefined coordinates or constraints and adding the material properties.

As explained above, parametric modeling uses a combination of numerical input data and algorithms. Therefore, exploiting all the advantages of parametric modeling requires minimizing the number of input parameters and using an optimized algorithm. A parametric model can be interpreted by an algorithm using the general mathematical operations of geometric objects. Two types of parameters can be distinguished: one describes the shape and the other describes the position, orientation, or constraint of the geometric object. The chain of the algorithm will vary to determine the type of each parameter.

A geometric object is usually built from points, lines, and planes, and the parameters of only one type of those

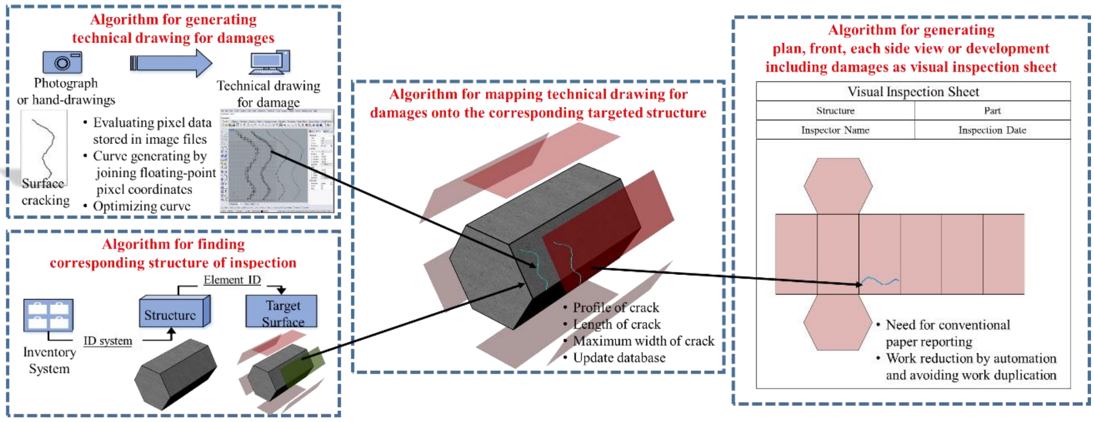


Fig. 8 Process to link 2D hand-drawing/photograph to 3D model surface using the algorithmic program

object features are used to specify the geometry. The algorithm to create the geometry of an object is based on linear equations of curves and surfaces in Euclidean three-dimensional space, whereas most exterior orientation parameters are based on matrix operations.

To enhance the design performance, 3D information models created by smart algorithms should be reusable for all construction practices, such as analysis, estimation, multi-dimensional simulation, and maintenance. In this regard, we launched integrative work between a CAD program and a programing language using an application programming interface (API). By accessing a database system, an API can ease the work of programming graphical user interface components. It also can facilitate the integration of new features into existing applications (a so-called plug-in API). Moreover, an API can help otherwise distinct applications share data, which can help to integrate and enhance the functionalities of all the applications.

Currently, APIs are increasingly popular, but they still have some limitations in terms of the geometric concepts for steel object and clash detection, the complications of matrix operations, etc. Therefore, it is necessary to use an open-source programming language strong and fundamental enough to handle integrated APIs. Libraries can now be easily created through APIs, and they contribute significantly to the infrastructure material market. However, the range of functions for every API still needs to be enhanced and optimized. Achieving the perfect result for future work will require practice and interactive plug-in APIs.

3.3 Inspection system using 3D models

Inspection work is commonly based on visual observation, and the main activity is describing damage to the structure in a technical format. The process of visual observations and hand-drawn descriptions or photographs can generate some inconsistencies. 3D parametric modeling shows good potential to enhance the productivity of this work.

Fig. 8 shows an example of surface-crack inspection work using digital information in the whole inspection process. The inspection engineers check the structure's conditions. When damage such as cracking is found, they describe it using hand-drawings or photographs that can be transferred into technical format by the geometric algorithm. Because this kind of digital technical information is created in the vector format, it is easy to calculate both the length and maximum width of the cracks. The surface in which the crack occurred can be found from the initial 3D model using its specified object ID. Finally, the technical drawing of the crack will be mapped onto that target surface, and the inspection information will be updated in the initial 3D model in digital format. The model can thus automatically generate inspection reports for bridge elements in 2D drawings.

3.4 Data management system

The database system for a cable-stayed bridge stores all information related to the physical features of the bridge, which can be gathered from the design and construction phase and updated from inspection and repair records. Following the requirements in an EIR, the database system is classified using structural elements and their constraints or coordinates, as represented by the element IDs.

The database system can be distinguished into three parts: the asset database, inspection database, and repair database. At this point, the BIM-based parametric model can demonstrate its outstanding features in term of archiving, exchanging, and delivering information while absolutely preserving its accuracy. The inspection database can be collected from regular or major inspections through an inspection contractor and synthesized into the bridge condition evaluation reports used to propose a plan for maintenance work. After repairs, information from the repair database, including dates and repaired as-built models, will be updated in the initial asset information.

A key component of a data management system is the data retrieval function, which must efficiently retrieve information through various functions for searching or collecting. Depending on the purposes of users, it is possible to extract information for individual structures using the element IDs or multiple-keyword retrieval. The

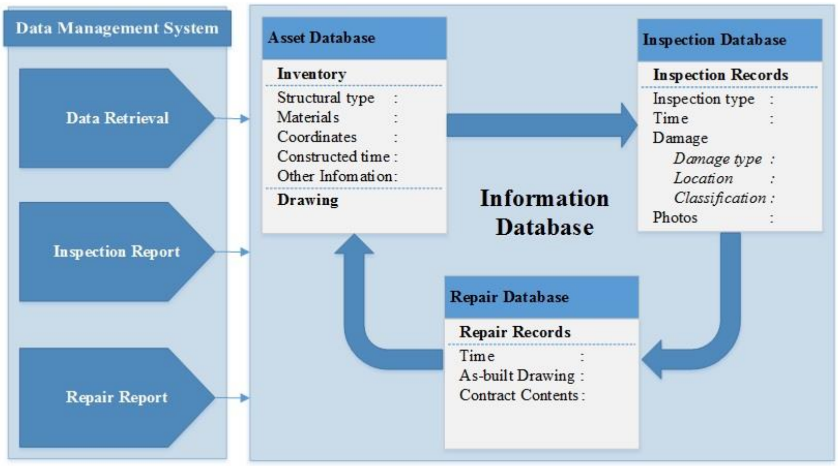


Fig. 9 Configuration for a maintenance information management system

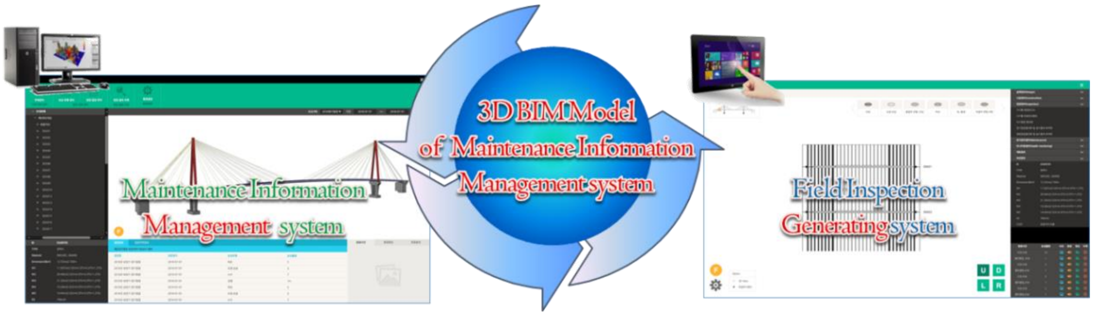


Fig. 10 Established BIM-based maintenance information management system prototype

"inspection/repair report" function can increase the efficiency of collaborative work between inspection/repair contractors and the client; all the required procedures for the contractor can be promptly performed, including delivering the inspection and repair results, instructions for repair work, and confirmation and sanction formalities with the client. The most rational instructions for repair can be found using the timely and precise flow of information in the system. Thus, the system will provide good resource management and cost reduction. This enhanced procedure will give the client a framework for network-based BMS.

As explained above, repair activities are iterative work; the process of inspection/monitoring, performing repairs, and updating the database is continual during the service of the bridge. To be open to further breakthroughs in the future, data management must maintain data compatibility with other bridge maintenance systems. Already, computer technology has reached goals for enhancing digital bridge maintenance; a system that not only enables fast database referencing and continuous updates but also supports decision-making for inspection and repairs is not too far away.

4. Layout of the new bridge maintenance system

Our research to develop a layout for a BIM-based BMS is ongoing. We need to cover the full range of maintenance information management systems for the inspection EIR and current conditions. The new BMS consists of two modules: a maintenance information management module and a field inspection operating module.

4.1 Module-1: Maintenance information management module

Based on our data scheme and established data management system, we created the maintenance information management module using the BIM authoring procedure. As explained above, it needed to convert the data scheme, with its inventory system, ID system, attributes, archive list, etc.. into the digital technical data format. To do that, we propose a sub-module for both 3D conversion and uploading data onto the server. This sub-module converts the information from our data scheme into a PC-readable 3D model that conserves the .dxf spreadsheetXML member file format for easy data exchange.

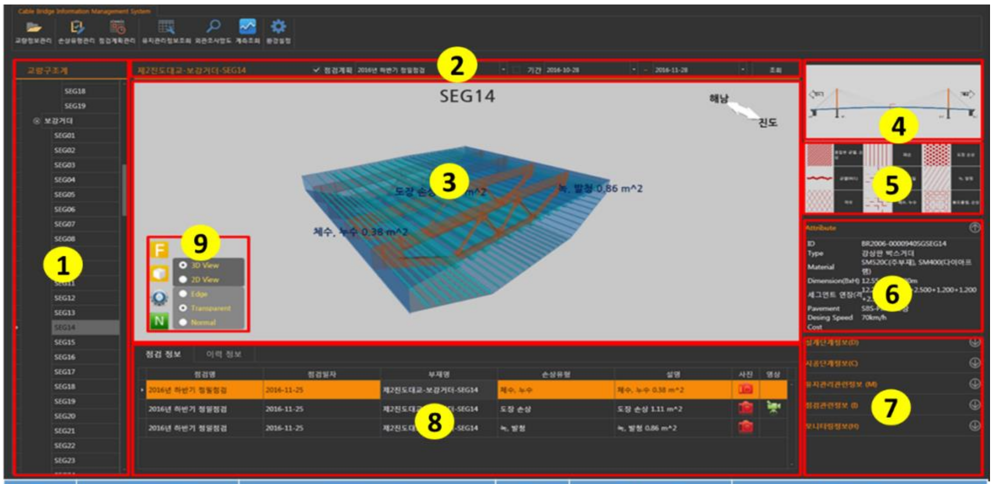
The main functions of this module are run by five sub-modules: basic information, inspection data, inspection plan, inspection report, monitoring data, and configuration.

Fig. 11 shows the software interface for the BIM-based maintenance information management system design and realization.

In our proposed design, the function of the "member category," including the entire inventory and member ID systems, is the key refinement of module-1. The whole

Section	Element	Description	Section	Element	Description
1	Hierarchy	Entire structure system	4	Basic Information	Structure attribute
2	Inspection Browsing	Selecting inspection case	5	Archive Information	Attached archive lists
3	3D Viewer	3D model display	6	Inspection Detail	Inspection history with damages

Fig. 11 BIM-based maintenance information management system design and realization — Software interface



Section	Element	Description	Section	Element	Description
1	Structure	Structure segments viewer	6	Basic Information	Structure attribute
2	Inspection Browsing	Selecting inspection case	7	Archive Information	Attached archive lists
3	3D Viewer	3D model display	8	Inspection Detail	Inspection history with damages
4	Key-Map	Approximate location of segment	9	Viewer Tool	View type option
5	Damage Remarks	Damage to apply			

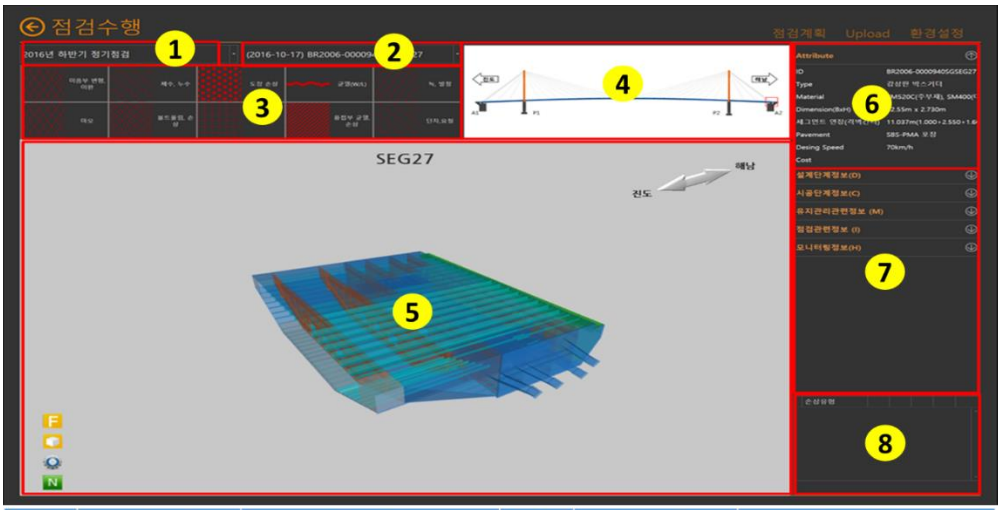
Fig. 12 Damage records for 3D objects

model is the assembly of a huge number of members, and each member has its own complex metadata. However, with one click on any ID component in the “section 2” area, the corresponding member can be easily found and accessed. The member sub-interface appears in Fig. 12.

The sub-interface covers all display tasks for the BMS data, including the intuitive location of each member and individual detail information, such as damage records and current condition. The advantage of this module is that the member data can be easily found and accessed and then updated in real time, leading to good time-savings for each activity in BMS work. In addition, the archive data in PDF format can be reached from the 3D model display.

4.2 Module-2: Field inspection operating module

The second module of this proposed BMS focuses on real-time data generation and utilization. The field inspection data generating module is adopted for each member as a mobile tool. The inspection data are separately



Section	Element	Description	Section	Element	Description
1	Inspection Browsing	Selecting inspection case	5	3D Viewer	3D model display
2	Segment Browsing	Selecting inspection parts	6	Basic Information	Structure attribute
3	Damage Remarks	Damage to apply	7	Archive Information	Attached archive lists
4	Key-Map	Approximate location of segment	8	Input Data Screen	Inputting data viewer

Fig. 13 Field inspection system design and realization— Software interface

updated and immediately reflected in the entire bridge model. Thus, this system permits real-time collaboration between field engineers and office engineers. We also considered future robotic or drone-based inspections when allowing real-time sharing of inspection images.

The main functions of this module are also run by five sub-modules: basic information, inspection plan, inspection record browsing, uploading, and configuration. Note that the 3D detailed member is identical to the visual inspection report through the use of a 2D-based visual inspection report form. In this regard, for a more intuitive look, the proposed software interface can change the observation angle, with some optimal angles suggested (up, down, left, right angle, etc.).

4.3 Information exchange using VPN

Following the above process for information exchange, the proposed BMS uses a network-based system with an authority VPN backbone network. As explained above, the BMS converts our data scheme, with its inventory system, ID system, attributes, archive lists, etc., into a digital technical data format. Indispensably converted data need to upload onto the client-server, and then the BMS can access, download, update, and exchange all information. With the aid of a portable device, inspection data can be easily generated and immediately uploaded onto the server. To manage data more efficiently, the proposed BMS separates the server into two peer functions: a file server and a database server. The database server stores all information. including member data, inspection data, and the entire bridge's structural condition. Meanwhile, the file server stores only the 3D model and inspection data, including photos, videos, and document reports. Fig. 15 shows the network-based information exchange system.

5. Conclusions

In this paper, we've proposed a new framework for a BIM-based BMS. The system is based on a data scheme that considers all aspects of maintenance work. Furthermore, we have introduced an application system that shows good potential for improving current maintenance work. Through a schematic information system and using the proposed BIM authoring, we generated a bridge data management system without any limitations. Also, it can be adapted for various bridges or types of bridge, significantly helping engineers to save time and money. Through this attempt to build a new BMS based on BIM technologies, we derived the following conclusions.

- Information requirements for the system need to be defined by stakeholders: the owner, designer, contractors, and maintenance manager. To achieve lifecycle operation for a bridge, information about its design, construction, and measurements is needed, and that constitutes the main part of the EIR. Once information is defined, the maintenance manager and other stakeholders can access all the information within the BMS through 3D objects.
- A unified format is adopted for proper data exchange. In BMS, 3D model data, attributes, and archives are stored as specific file types: database as an .xml spreadsheet, 3D model data as .dxf, archives as .pdf, images as .jpg, etc. These formats are common types in normal use. Gradually, the IFC format, including attributes and 3D models, will become a standard for data exchange.
- In bridge design, parametric modeling allows designers to get instant 3D models using the bridge type and a few fundamental parameters, such as longitudinal alignment, span length, and clearance. With our

algorithm, designers can get 3D models from just those parameters. Composing a parametric modeling algorithm takes longer than object modeling or manual 3D modeling. However, once the algorithm is composed, it can decrease the time needed for model authoring by half because a BMS operator requires hundreds of 3D bridge models.

- Our BMS has an algorithm to make an additional layer with damage on a 3D model and automatically generate field inspection reports whenever an inspector draws or records any type of damage with an inspection device. The system contains 3D models identical to the physical bridge structures. Inspectors can access specific members by browsing with the ID or scanning marks, such as QR codes, attached to member surfaces. The BMS in this research provides image-based damage recording, which is more efficient than conventional systems.
- The development of communications technology allows engineers to browse data wherever they have access to the BMS. The BMS consists of two modules, the main management module and the inspection module, that can simultaneously share and exchange inspection and stored data. They can handle their own work and make decisions, even if they are not in same place. Moreover, their compatibility prevents work duplication and loss of data.

The developed BMS is being installed on the 2nd Jindo bridge in Korea. All the models and information have been linked together and will be used for future maintenance work.

Acknowledgments

This research was supported by a grant, ‘Research on Standard Development for BIM Based Special Bridge Maintenance,’ funded by the Korea Infrastructure Safety & Technology Corporation (KISTEC) and by a Chung-Ang University Graduate Research Scholarship in 2016.

References

Bartholomew, M., Blasen, B. and Koc, A. (2015), “Bridge Information Modeling (BrIM) Using Open Parameter Objects”, FHWA-HIF-16-00, U.S. Department of Transportation Federal Highway Administration.

Bien, J. (2011), “Modelling of structure geometry in Bridge Management Systems”, *Arch. Civil. Mech. Eng.*, 11

Chen, S.S., Kannan, N., Patil, R.B. and Potturi, K. (2003), “Evaluation of 3D Computer Modeling and Electronic Information Transfer for Efficient Design and Construction of Steel Bridges”, *National Cooperative Highway Research Program (NCHRP), Revised Draft Final Report on Project 20-7,* Task 149.

Chipman T., Eastman C., Liebich, T. and Yang, D. (2016), Bridge Information Modeling Standardization Report Volume I, II, III”, FHWA-HIE-16-011, U.S. Department of Transportation Federal Highway Administration.

Denysiuk, R., Fernandes, J., Matos, J.C., Neves L.C. and Berardinelli, U. (2016), “A computational framework for infrastructure asset maintenance scheduling”, *Struct. Eng. Int.*, **26**(2), 94-102.

Gallaher, M.P., O’Connor, A.C., Dettbarn, J.L. and Gilday, L.T. (2004), “Cost analysis of inadequate inoperability in the capital facilities industry”, *National Institute of Standards and Technology (NIST) Technical Report*, NIST GCR-04-867.

Hammad, A., Yan, J. and Mostofi, B. (2007), “Recent development of bridge management systems in Canada”, *Proceedings of the 2007 Annual Conference and Exhibition of the Transportation Association of Canada*.

Hammad, A., Zhang, C., Hu, Y.X. and Mozaffari, E. (2006), “Mobile model-based bridge lifecycle management system”, *Comput.-Aided Civil Infrastruct. Eng*., **21**, 530-547.

Janjic, D., Bokan, H. and Love, R.A. (2008), “The evolution of bridge information modeling”, *Proceedings of the 11th East Asia-Pacific conference on Structural engineering and Construction(EASEC-11)*, Taipei, Taiwan, National Taiwan University, November.

Katz, C. (2008), “Parametric description of bridge structures”, *Proceedings of the IABSE conference on information and communication technology for bridges, buildings and construction practice*, Helsinki, Finland, June, IABSE.

Lee, G., Sacks, R. and Eastman, C.M. (2006), “Specifying parametric building behavior (BOB) for a building information modeling system”, *Automat. Constr.*, **15**(6), 758-776.

Lee, K.M., Lee, Y.B., Shim, C.S. and Park, K.L. (2010), “Bridge information models for construction of a concrete box-girder bridge”, *Struct. Infrastruct. Eng.*

Leeuwen, J.P. van and van der Zee, A. (2005), “Distributed object models for collaboration in the construction industry”, *Automat. Constr.*, **14**(4), 491-499.

Lukas, K. and Borrmann, A. (2012), “Integrated Bridge Management from 3D-Model to Network Level”, *Proceedings of the 6th International IABMAS Conference*.

Maher, M.L., Liew, P., Gu, N. and Ding, L. (2005), “An agent approach to supporting collaborative design in 3D virtual worlds”, *Automat. Constr.*, **14**(2), 189- 195.

Marzouk, M.M., Hisham, M. and Al-Gahtani, K. (2014), “Applications of bridge information modeling in bridges life cycle”, *Smart Struct. Syst.*, **13**(3), 407-418.

Miyamoto, A., Kawamura, K. and Nakamura, H. (2001), “Development of a bridge management system for existing bridges”, *Adv. Eng. Softw.*, **32**(10-11), 821-833.

Plume, J. and Mitchell, J. (2007), “Collaborative design using a shared IFC building model - Learning from experience”, *Autom. Constr.*, **16**(1), 28-36.

Robinson, C. (2008), “Structural building information modeling in use”, *Proceedings of the IABSE conference on information and communication technology for bridges, buildings and construction practice*, Helsinki, Finland, June, IABSE.

Shim, C.S., Dang, N.S., Kang, H.R. and Kim, D.C. (2016), “3D Information Model Based Bridge maintenance”, *Proceedings of the 5th International Technical Conference*, Kota Kinabalu, Malaysia, November.

Shim, C.S., Kim, S.W., Song, H.H. and Yun N.R. (2011), “Development of BIM for a maintenance system of subway infrastructure”, *J. KIBIM*, **1**(1), 6-12.

Shim, C.S., Lee, K.M, Kang, L.S., Hwang, J. and Kim, Y.H. (2012), “Three-dimensional information model-based bridge engineering in Korea”, *Struct. Eng. Int.*, **22**(1), 8-13.

Shim, C.S., Lee, K.M., Son, W.S. and Moon, J.W. (2008), “Collaborative design of high-speed railway lines using 3D information models”, *Proceedings of the IABSE conference on information and communication technology for bridges, buildings and construction practice*, Helsinki, Finland, June, IABSE.

Shimizu, T., Yoshikawa, S., Takinami, I. and Nakayama, T.

(2013), “Development of bridge management system using three-dimensional model”, *J. Japan Soc. Civil Engineers, Ser. F3 (Civil Engineering Informatics)*, **69**(2), 45-53.
Thomas, S.R., Macken, C.L. and Lee, S.H. (2001), “Impacts of design/Information technology on building and industrial projects”, *National Institute of Standards and Technology (NIST) Technical Report*, NIST GCR 01-828.
Verheij, H. and Augenbroe, G. (2006), “Collaborative planning of AEC projects and partnerships”, *Automat. Constr.*, **15**(4), 428-437.
Verma, K., *et al.* (2001), “Steel bridge fabrication technologies in Europe and Japan [online]”, *US Department of Transportation, Federal Highway Administration, International Technical Exchange Program*, Report No. FHWA-PL-01-018.
Whyte, J., Bouchlaghem, N., Thorpe, A. and McCaffer, R. (2000), “From CAD to virtual reality: modeling approaches, data exchange and interactive 3D building design tools”, *Automat. Constr.*, **10**(1), 43-55.
Yabuki, N. and Shitani, T. (2003), “An IFC-based product model for RC or PC slab bridges”, *Proceedings of the CIB W78’s 20th international conference on information technology for construction*, Waiheke Island, New Zealand, April, CIB, 463-471.
Yin, Z.H., Li, Y.F., Guo, J. and Li, Y. (2011), “Integration research and design of the bridge maintenance management system”, *Procedia Eng.*, **15**, 5429-5434.

HJ