Structure and Infrastructure Engineering
Vol. 8, No. 7, July 2012, 687–703

Bridge information models for construction of a concrete box-girder bridge

K.M. Lee[a], Y.B. Lee[a], C.S. Shim[b]* and K.L. Park[c]

[a]*Department of Civil & Environmental Engineering, Sungkyunkwan University, 300 CheonCheon-Dong, Jangan-Gu, Suwon, Korea;* [b]*Department of Civil & Environmental Engineering, Chung-Ang University, 221 HeukSeok-Dong, Dongjak-Gu, Seoul, Korea;* [c]*Samsung C&T Corporation Co, 1321-20 Seocho 2-Dong, Seoul, Korea*

(*Received 16 September 2009; final version received 21 January 2010; accepted 20 February 2010; published online 27 April 2010*)

Large construction projects involve collaboration among a large number of participants with different specialised knowledge from various construction processes. A readily accessible bridge information model is needed to enable engineers to innovate prefabricated bridge construction. Three-dimensional (3D) information models can include multi-layered information for different users such as designer, contractor and owner. A construction project life-cycle management system was suggested to integrate and to accumulate valuable information. In this paper, 3D bridge information models for an international concrete bridge construction project were built to integrate design and construction processes. The 3D bridge models were realised by considering work breakdown structure and product breakdown structure to enable digital mock-up and design enhancement and to shorten the learning time of construction engineers. The models were also utilised for the fabrication of precast box segments and for the geometry control during construction. Assessment from the construction director was discussed and additional usage of the bridge information models was suggested.

Keywords: bridges; concrete structures; construction; engineering system; information technology; precast systems

Introduction

Integrated design and construction of bridge structures through well-established three-dimensional (3D) information models will be an innovation of the conventional two-dimensional (2D) methodology in 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 improvement of quality as a result of implementing 3D CAD-based integrated design and manufacturing processes along with accompanying interoperability standards (Verheij and Augenbroe 2006, Leeuwen and Zee 2005, Plume and Mitchell 2007, Whyte *et al.* 2000, Maher *et al.* 2005, Robinson 2008). Building information modelling (BIM) is a new technology in the construction industry.

Although the evolution and deployment of information technologies will undoubtedly play an important role in the current construction industry, many engineers are still unsure of 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 decisions between various established and innovative design alternatives. Prefabrication of concrete bridges can be enhanced by building the 3D models for specific construction methods.

The adequate interoperability of 3D objects from any CAD system is essential for the collaboration. The design of bridge structures is generally based on 2D drawings and design specifications also 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 performance of this collaboration. For information transfer, a mediator is needed between engineers. Object-based 3D models are useful for communication and for owners who need to maintain the information related to infrastructures in its entirety. Owners, contractors and design consultants were considered as users of 3D objects (Thomas *et al.* 2001, Shim *et al.* 2008). The National Institute of Standards and Technology (NIST) conducted research on the cost analysis of the inadequate interoperability in the US capital services industry and reported a waste in cost due to the lack of interoperability of systems utilised in the engineering lifecycle (Gallaher *et al.* 2004).

*Corresponding author. Email: csshim@cau.ac.kr

ISSN 1573-2479 print/ISSN 1744-8980 online

http://dx.doi.org/10.1080/15732471003727977
http://www.tandfonline.com

BIM is the process of generating and managing building data during its life cycle (Lee *et al.* 2005). The term BIM was popularised as a common name for these capabilities offered by several technology providers such as Autodesk, Bentley Systems, Graphisoft and others – a digital representation of the building process to facilitate exchange and interoperability of the information in a digital format. BIM covers geometry, spatial relationships, geographic information, quantities and properties of the building components (for example, manufacturers' details). Quantities and shared properties of materials can easily be extracted. BIM is able to achieve such improvements by modelling representations of actual parts and pieces composed 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.

The computer-based information technologies include computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), enterprise resource planning (ERP), digital mock-up (DMU) and product data management (PDM). Among them, DMU technology enables its users to pre-examine and reflect design errors or problems that might potentially happen during construction works by modelling or assembling a structure under a 3D virtual environment (Lee *et al.* 2005).

In this paper, a new concept of construction project lifecycle management was introduced and 3D bridge information models for precast concrete box girder bridges were constructed. The models were practically utilised for an international bridge construction project by a general contractor. All the components of a concrete segment were modelled and assembled considering the contractor's main purposes, and then some errors were found and revised appropriately so as to optimise constructability. Consequently, the DMU technology would improve the quality of the concrete segment and reduce time and cost for construction. With the development of design technologies, the massive scale and sophistication of structures has accelerated. In particular, the massive scale of reinforced concrete structures is generating a higher level of sophistication for the placing of reinforcing bars. Updated 3D information models could also be utilised for the manufacturing and construction processes, even for the training of inexperienced workers.

3D information modelling

Bridge information modelling

The construction project life-cycle management (CPLM) system was proposed from a research group to develop a virtual construction system (Shim *et al.* 2008). The system focuses on developing several

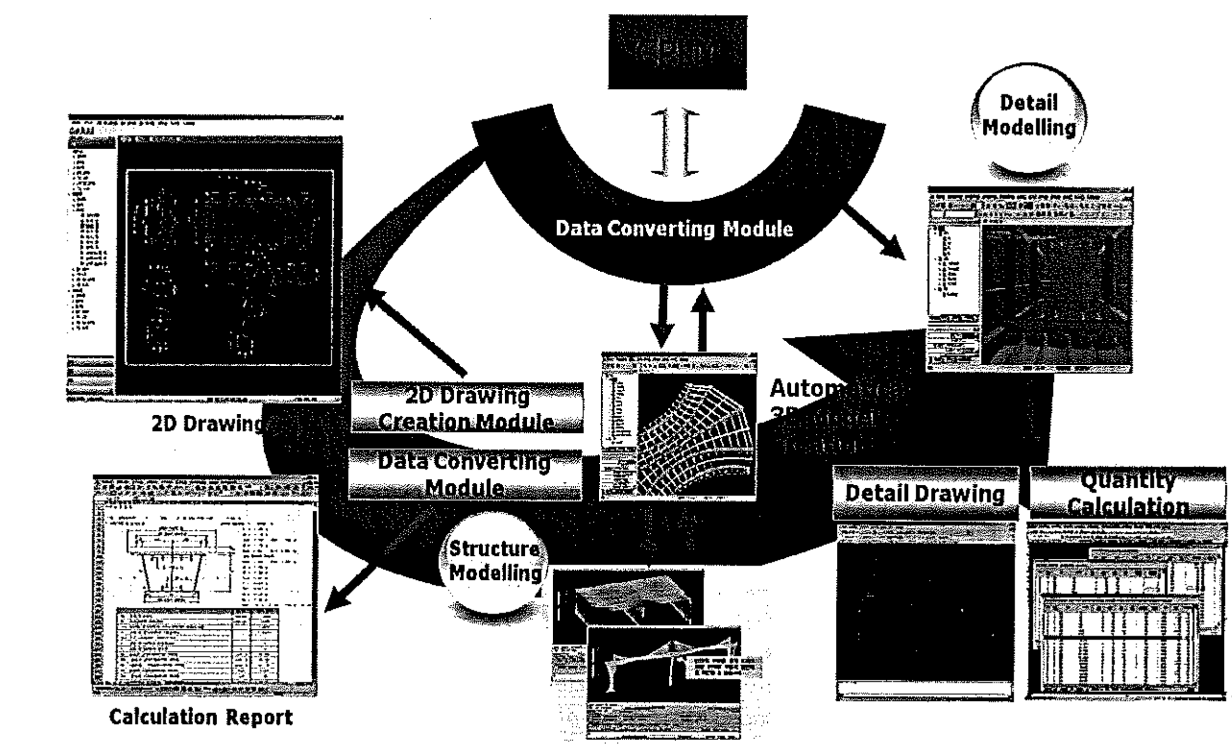


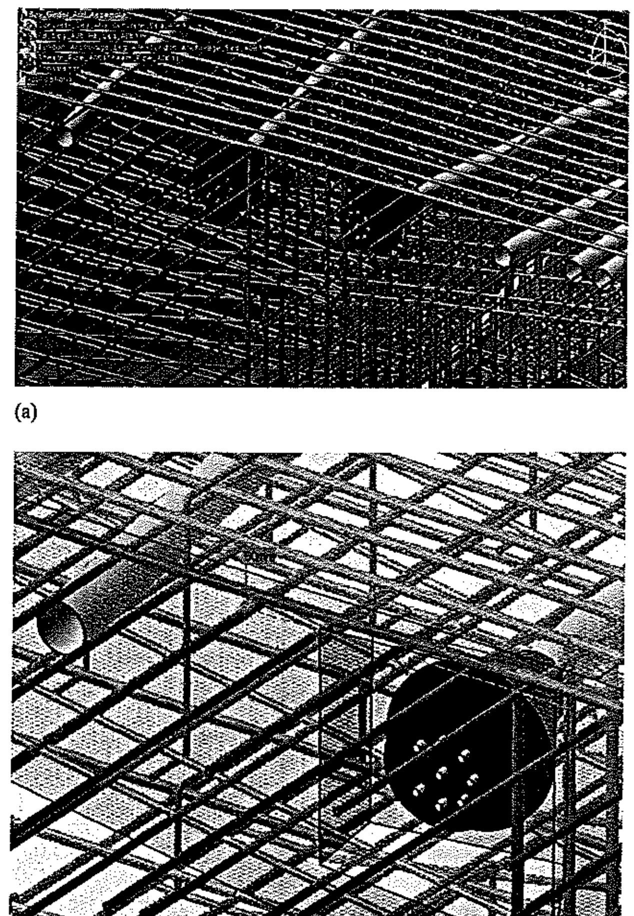
Figure 1. Examples of the integrated design process.

solutions and interface programs. The system mainly integrates these five systems: pre-planning, structural engineering, mechanical electrical and plumbing (MEP), and 3D-based estimation system; simulation system for the construction process, planning and feasibility study with help of the virtual reality technologies; the data managing system for managing construction project data, and the decision support system that constructs the collaboration between the project participants based on 3D technologies and information; the Standard Data Access Interface (SDAI), the localised guideline for 3D design, and a training program.

There are many obstacles to the realisation and application of these systems in practice. The first 3D models, called mother BIM, are crucial for successful process innovation. They should consider essential requirements from different construction processes. The standard classification codes for construction project and naming for geometry models should be agreed between participants. Models are refined during design and construction stages in terms of geometry and information. Most of the CAD engines allow several ways to export the model for other solutions. However, transferring the information architecture with its geometry from one CAD engine to another is still difficult. Therefore, it is necessary to develop interface programs to achieve the interoperability between various software systems in a construction project. Figure 1 shows examples of the integrated design process using different solutions. The data converting module is an essential part of the CPLM.

Recently, bridge information modelling (BrIM) was proposed for the innovation of bridge construction processes from planning to operation. BrIM is the organisation of all component data that is required to support the bridge asset throughout its lifecycle (Janjic *et al.* 2008). The concept is the same as BIM but it is closely related with an axis for road or railway design (Katz 2008). For each construction process from planning to maintenance, the model needs to be revised and needs to have different architecture of geometry and information for all parts of the bridge. In lieu of a complete industry-wide modelling of bridge information in a standardised format, attaining a competitive advantage can be expected by integrating information and communication technologies that will result in rapid and better quality project delivery and subsequent cost-effective life-cycle management (Chen *et al.* 2003). Tah *et al.* (1999) presented a conceptual project data infrastructure. 3D models can be easily utilised for manufacturing the structural components for construction (Verma *et al.* 2001). Several IFC-bridge models were proposed to enable the interoperability between different solutions and processes (Yabuki and Shitani 2003). However, there is lack of 3D bridge information models for an actual construction project.

Among several CAD engines to support 3D geometry models and their metadata, CATIA-V5 was utilised in this paper. Models from the CAD engine can be managed by the product data management (PDM) systems. Bill of materials (BOM) can be described as the information concerning what parts a specific product consists of. BOM entails a definition of not only information on all parts of a product but also correlation with other parts. The relation defined in this way can then be expressed as the relationship between parent and child. Since BOM includes information about a product constitution, it is basic information that can be applied for diverse uses such as calculation of the quantity of materials and costs as well as for the assembling of parts of a product, which is the most important information to DMU realisation. BOM could be



(a) (b)

Figure 2. 3D detail model for the constructability check. (a) Detail model for reinforcing bars and prestressing tendons. (b) Concrete cover constraint.

created from diverse viewpoints according to a person or the purpose of the division involved in a product, which means that there are a large variety of BOM, such as engineering BOM (E-BOM) and manufacturing BOM (M-BOM).

In order to embody DMU, a 3D shape is modelled for engineering purposes at a level as similar as possible to the real-life model using the 3D CAD tool. Simultaneously, the lowest parts of the product based on the previously constituted BOM are modelled

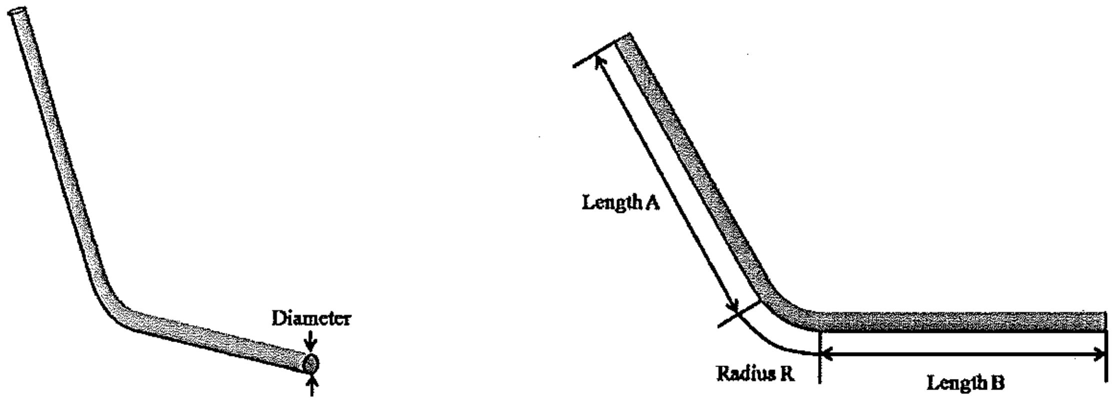


Figure 3. Parameteric modeling of reinforcing bar.

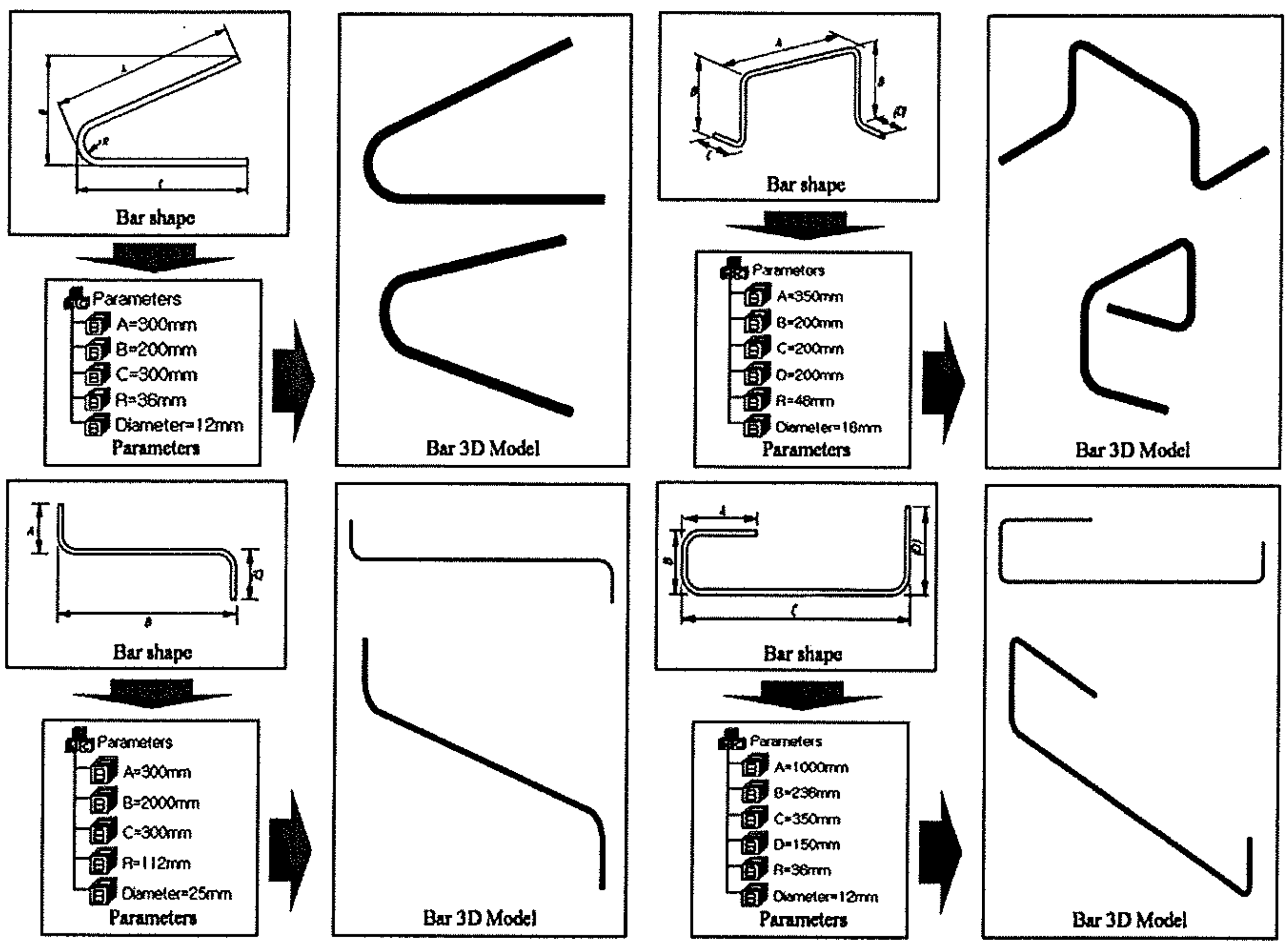


Figure 4. 3D models of reinforcing bars.

into 3D-shape models. The product can then be modelled by using the parametric technique allowing for the shape variables that constitute each part of the product. Parametric modelling can flexibly cope with shape changes and design changes and can also assist modelling of a 3D-shape model (Katz 2008). A 3D model displays a more remarkable visual effect than a 2D drawing and it can be handled easily in a similar way to an actual part in virtual space.

The lowest parts of the product modelled into a 3D shape model are then assembled as a real product by BOM. DMU incorporated in BOM includes information about each part of the product and the relationship between these constituting parts, making DMU available for diversified purposes. It is possible to verify part interference and constructability and to extract a variety of attributes and information on quantity through the visual examination by using DMU of the finally assembled product (Shim *et al.* 2008, Duxbury and Nader 2008). Considering the nature of the construction industry, the fabrication of a physical prototype is by no means practical. Therefore, the application of DMU may constitute an advantageous approach and this research intends to verify its efficiency.

BrIM should be made to fit the road planning and needs to allow structural analysis of the bridge by using a shell-mid-plane-model or one-dimensional elements. All the specific entities need to be placed relative to the road axis along the reference line for the section definitions at each point. Among geometry parameters, the constraints for reinforcement detail requirements are very important for concrete bridges to accommodate design checks of constructability. The concrete cover depth can easily be defined by parameters between 3D concrete box geometry and reinforcing bars, as shown in Figure 2.

Parametric modelling

For the efficient revision and reuse of design data, it is essential to utilise parametric modelling in the building of bridge information models. While the parametric modelling technique is common practice in CAE, it is not as common in the construction industry. Before modelling the 3D bridge models, main design parameters and their relationships need to be defined. The dimensions for one model have dependent parameters and their constraints so that revision of one dimension can be automatically followed by the change of the other dimensions according to the definition. Firstly, the base feature of the model is built and other features will then be added. 3D models have parent-child constraints in terms of location or dimension. When the 3D model has a significant amount of details and dimensions, the constraints can be very complex and result in less efficiency for the design and construction. Therefore, the parameters need to be carefully defined by design engineers.

In this application, the parameter modelling technique is mainly applied to generate reinforcing bars. The concrete box girders have complicated details of reinforcements, pre-stressing tendons, anchorages and ducts. Various shapes and details of reinforcing bars need to be generated to build 3D bridge models. As defined in design codes on reinforcement details (BS8666, 2005), the length and radius of the reinforcing bars are defined in Figure 3.

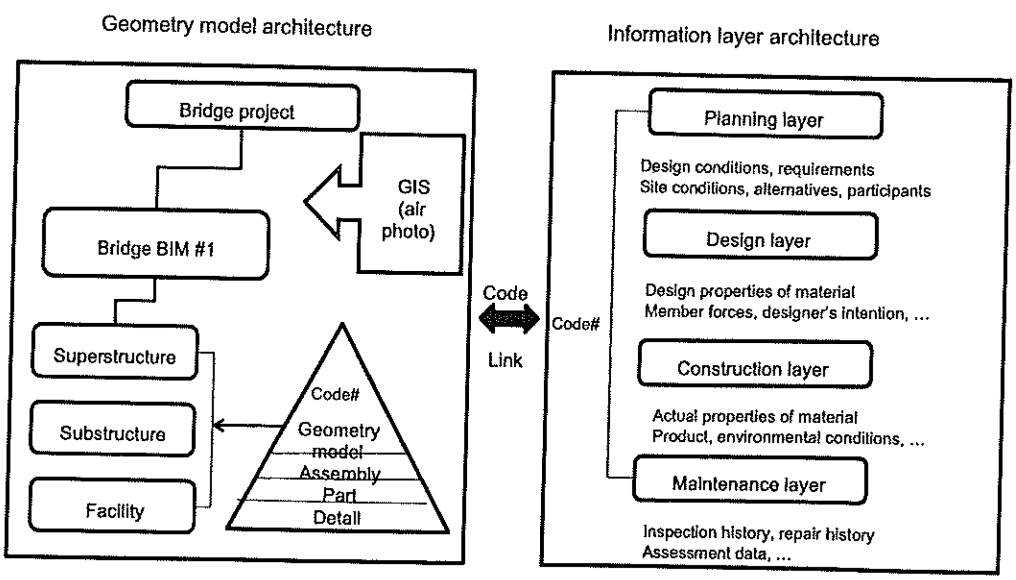
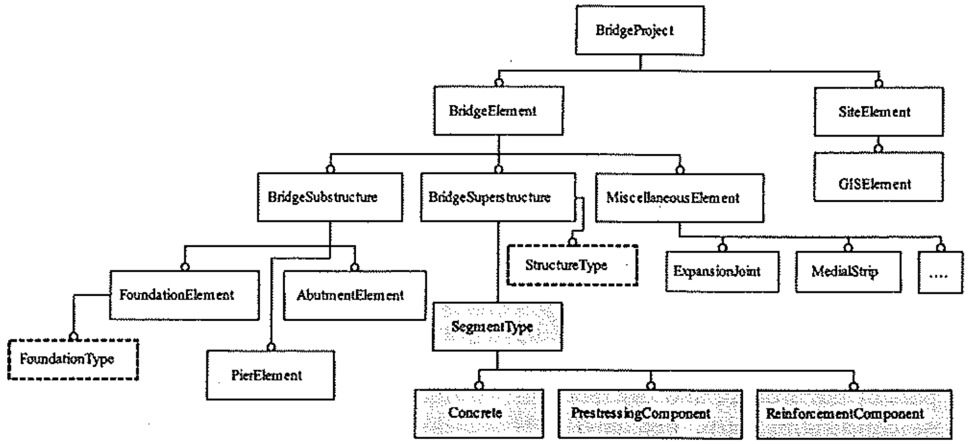
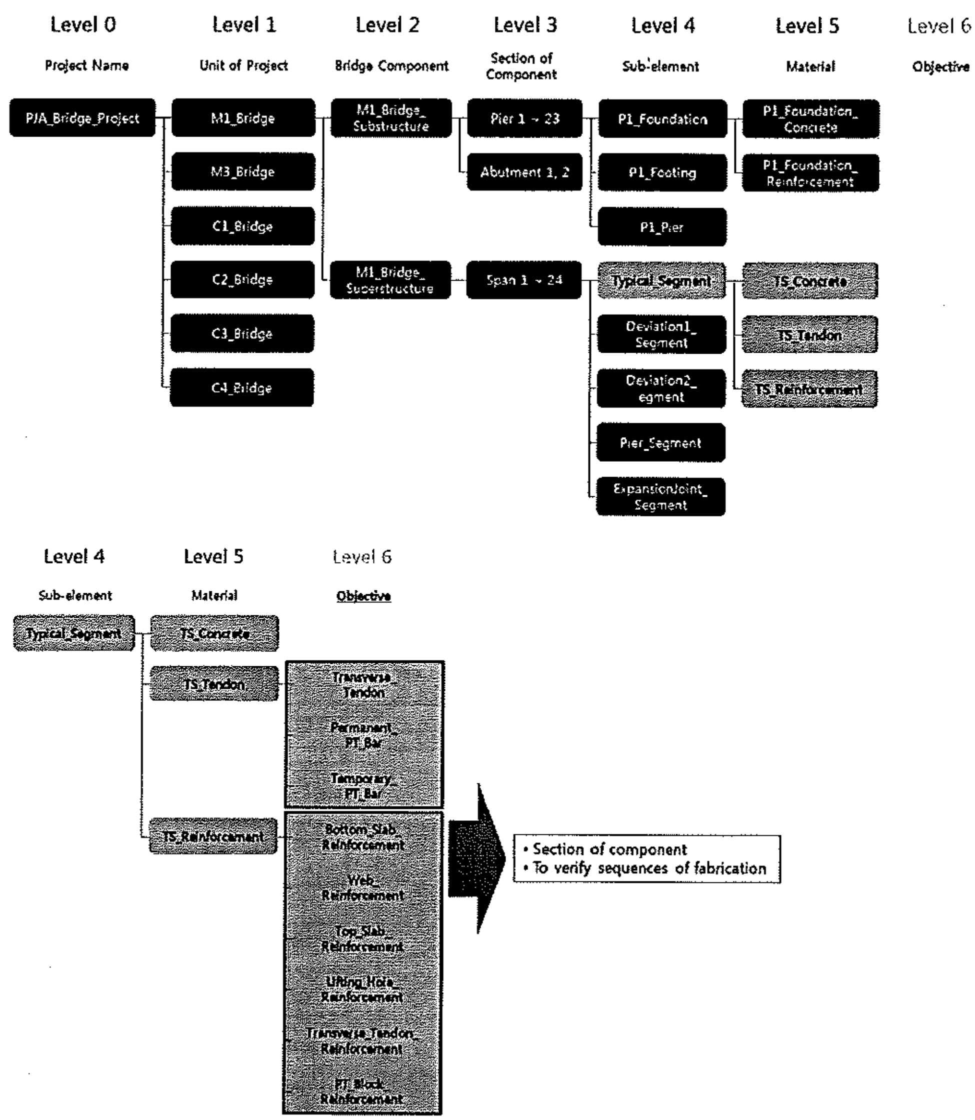


Figure 5. Architecture of the 3D bridge information model.



(a)



(b)

Figure 6. Tree structure of the BOM for typical segments. (a) Framework of bridge project. (b) Architecture of segment BOM.

According to the definition of the parameters, various 3D reinforcing bar models can be built easily as presented in Figure 4. Reinforcement models including design code requirements were built as a library for fast drawing of 3D details.

Model architecture and classification

Currently, a standard format of the bridge information model such as IFC-BRIDGE (Yabuki and Shitani 2003) is not available for practical application. Classification and naming are important for re-usability of the models. Basic geometry framework considered OmniClass™, which is provided from ISO 12006-2 (NIST 2007). Basic naming of the objects in the model considered dictionaries of ISO 12006-3. Descriptive metadata for phase and material was followed by ISO 12006-2. Relationship between objects was defined by feature model concept of parent-child.

3D models can include multi-layered information for the different users such as designer, contractor and owner. As shown in Figure 5, each part or component is first built as a 3D model and then assembled to build a system or a module. The product breakdown structure (PBS) is normally used for the architecture of the geometry model. Each part is directly related to design checks or design calculations. The work process is considered in the building of the work breakdown structure (WBS). Based on the customised information architecture and requirements, the information models are constructed. Essential contents in the information are for the delivery of design results between project participants because this application was started after delivery of design results to a contractor. Additional information can be included for the individual needs of engineers who want to re-use the particular information.

The 3D model's main object was being used in manufacturing and erection of the precast segments. For the fabrication, more detailed framework including every detail is essential. Through the interview with construction engineers in the construction sites, detailed architecture of the 3D objects was decided. Geometry control, estimation and shop drawings are main requirements for the models. Figure 6 shows a framework of the project and a tree structure of the BOM for typical segments. In the construction site, the models were delivered or shared between engineers after short training. The models were also utilised for particular solution developers such as design checks and analysis.

In addition, concrete structures are prefabricated in order to shorten construction time and for efficient quality control. A precast structure is structurally complicated and is characterised by high complexity in the arrangement of reinforcing bars and equipment for tendons. Moreover, there are many cases where construction work on placing reinforcing bars is impossible as a consequence of the drawing not allowing for constructional efficiency in its design stage. As the production of a prototype is impossible in the construction industry, DMU technology can be used to identify design problems in advance and to check constructability.

Application to concrete box-girder bridge construction

General description of the bridge project

Developed 3D information models were suggested for the connection bridge construction site of Palm Jebel Ali Island in Dubai, Arab Emirates. Two main bridges (M1, M3) and four crescent bridge portions (C1, C2, C3, C4) are to be built by a general contractor at Palm Jebel Ali Island as listed in Table 1. The M1 bridge was selected as a target bridge, as presented in Figure 7. The M1 bridge will be constructed by the precast segment method (PSM) as a round-trip eight-lane bridge with a total developed length of 1.25 km comprising a total of 750 segments. For the sake of constructional characteristics of the PSM, the fabrication and installation of segments constitute a major

Table 1. Summary of the Palm Jebel Ali Bridge Project.

Bridge	Length (metres)	Traffic lane	Pre-stressed concrete box girder
M1-bridge	1250	4 lane both	PSM (precast segmental method)
M3-bridge	1500		
C1-bridge	340	3 lane both	FSM (full staging method)
C4-bridge			
C2-bridge	360	2 lane both	
C3-bridge			

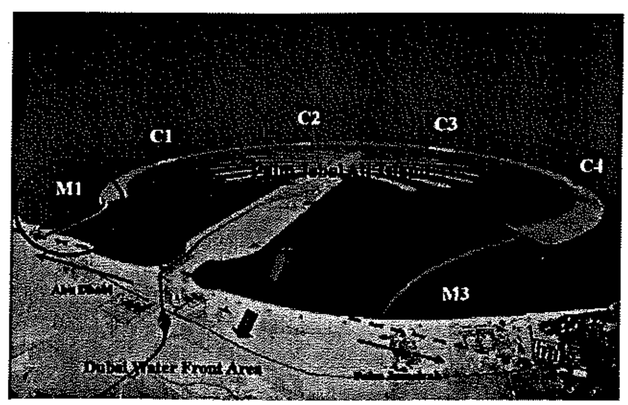


Figure 7. The Palm Jebel Ali Island and target M1 bridge.

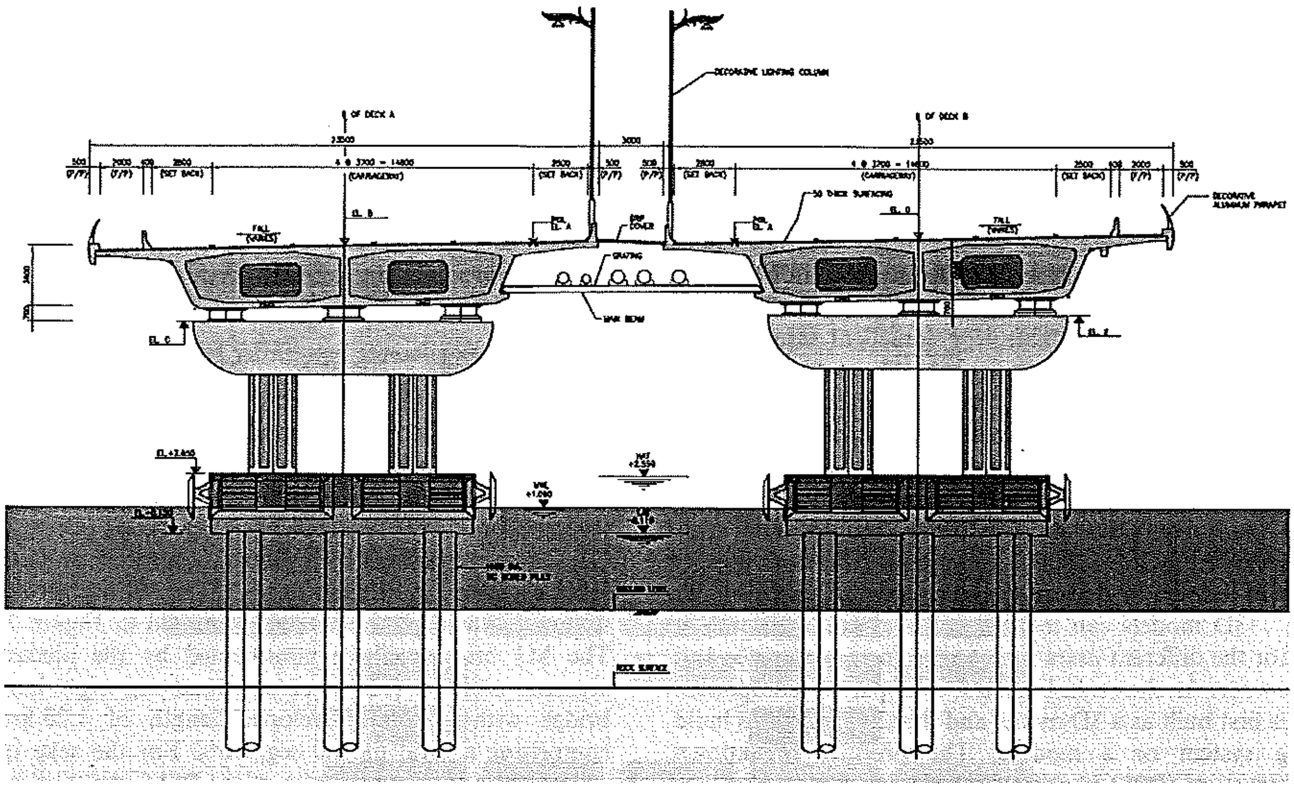


Figure 8. Section of the M1 bridge.

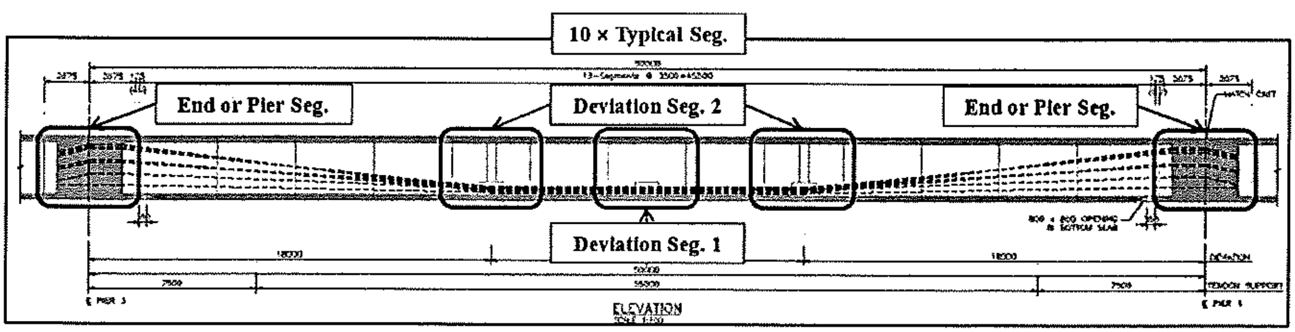


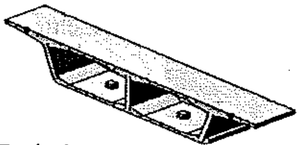
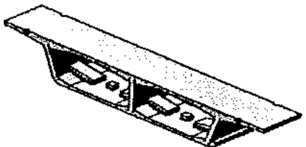
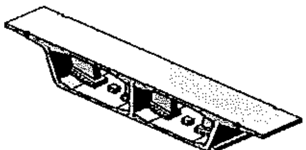
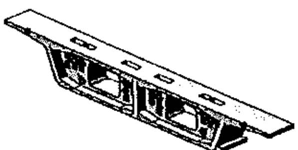
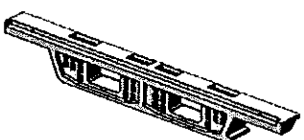
Figure 9. Layout of the M1 bridge.

part in the construction process, which requires the establishment of close planning for the construction of quality structures.

Due to the complication in placing reinforcing bars of the PSM segment and tendons to be installed, a series of problems can be predicted for construction work, such as a difficulty in the placement of ducts and fixing installations, and the interference between major materials at the time of initial fabrication due to the complicated block-out part. To solve these problems, existing construction sites draw up a detailed plan for construction and prepare a physical mock-up. This allows for fabrication to be implemented while actually placing reinforcing bars based on the drawn plan. This process is extremely complicated and time consuming, sometimes taking up to a few months to complete the mock-up per segment.

The aim of this pilot approach was to reduce the fabrication time of the segments and to accelerate the initial fabrication time of each segment by verifying risk factors that could occur during construction by applying DMU technology. The 3D bridge information models were delivered to the engineers on the construction sites and were also utilised for the construction processes.

Table 2. Five types of precast segments in M1 bridge.

Segment types	Length (mm)	Number	Properties
 Typical segment	3500	550	• No longitudinal tendon • 10 per span
 Deviation segment 1	3500	50	• Located at centre of span • No longitudinal tendon inflection • 1 per span
 Deviation segment 2	3500	100	• Located at longitudinal tendon • Inflection point • 2 per span
 Pier segment	2075	80	• Located above pier • Exist longitudinal tendon anchorage • 1 or 2 per span
 End segment	1825	20	• Expansion joint segment • Exist longitudinal tendon anchorage • 0 or 1 per each span

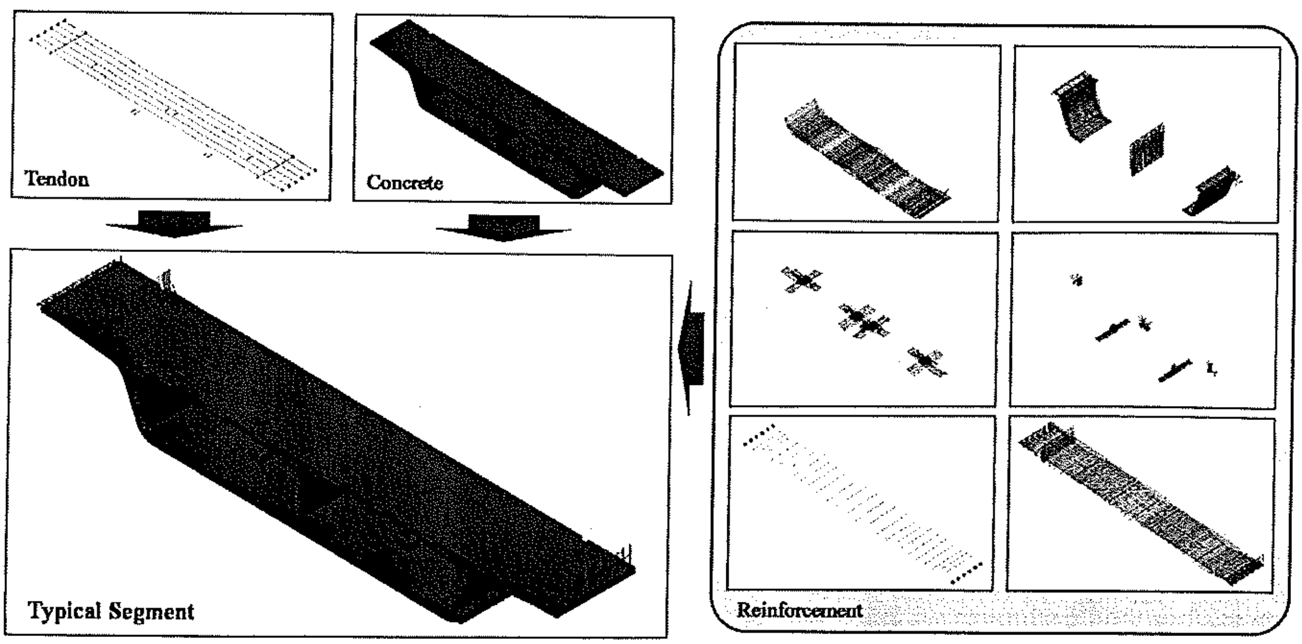


Figure 10. 3D typical concrete box segment.

M1 bridge consists of five types of segments as shown in Figures 8 and 9. Table 1 shows the length and required number of pieces of segments composing M1 bridge. Each of the segments should be designed differently considering horizontal and vertical alignment and super-elevation, and there were diverse shapes of segments even in the same type. However, it was verified by experts that five typical segments are

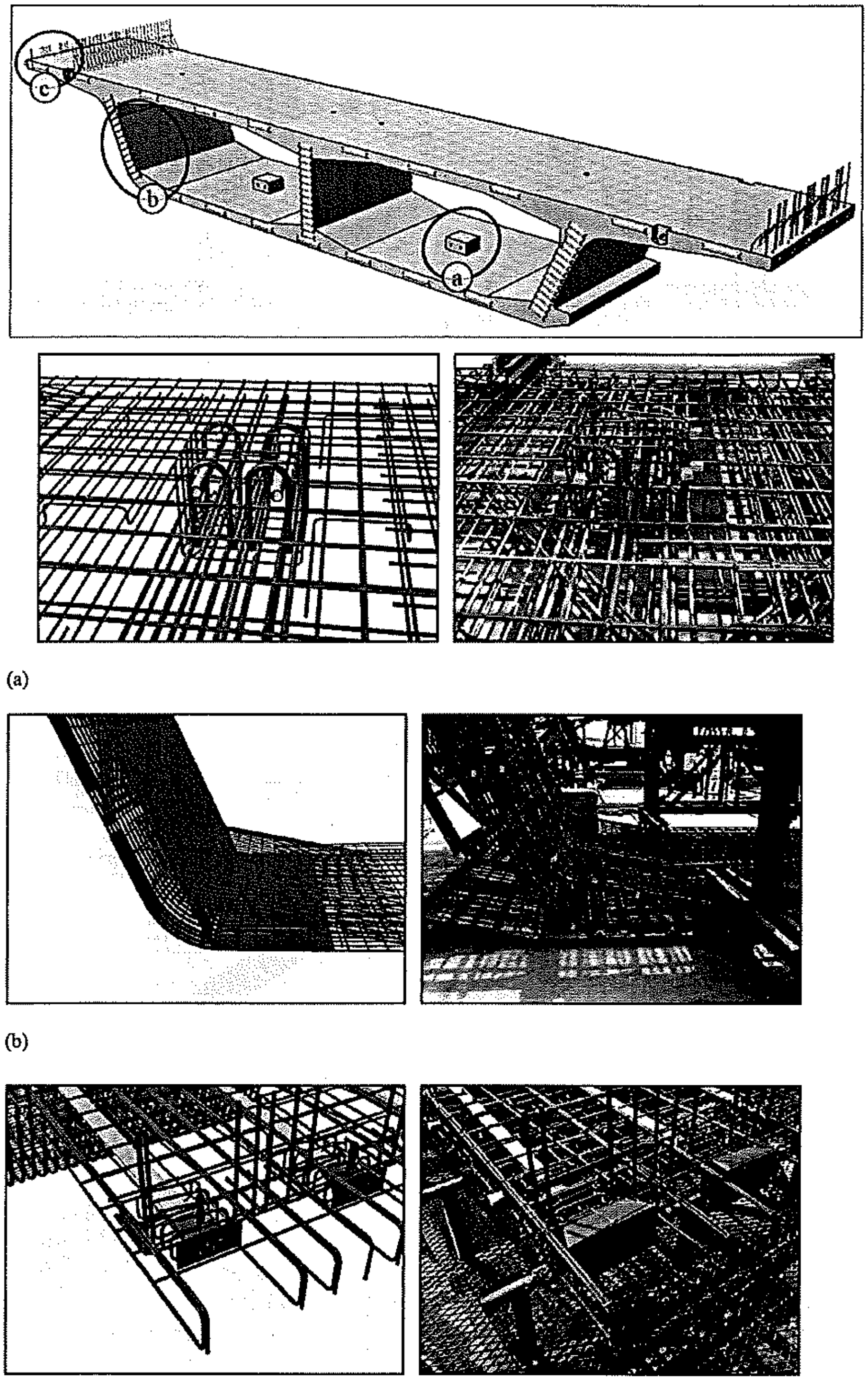
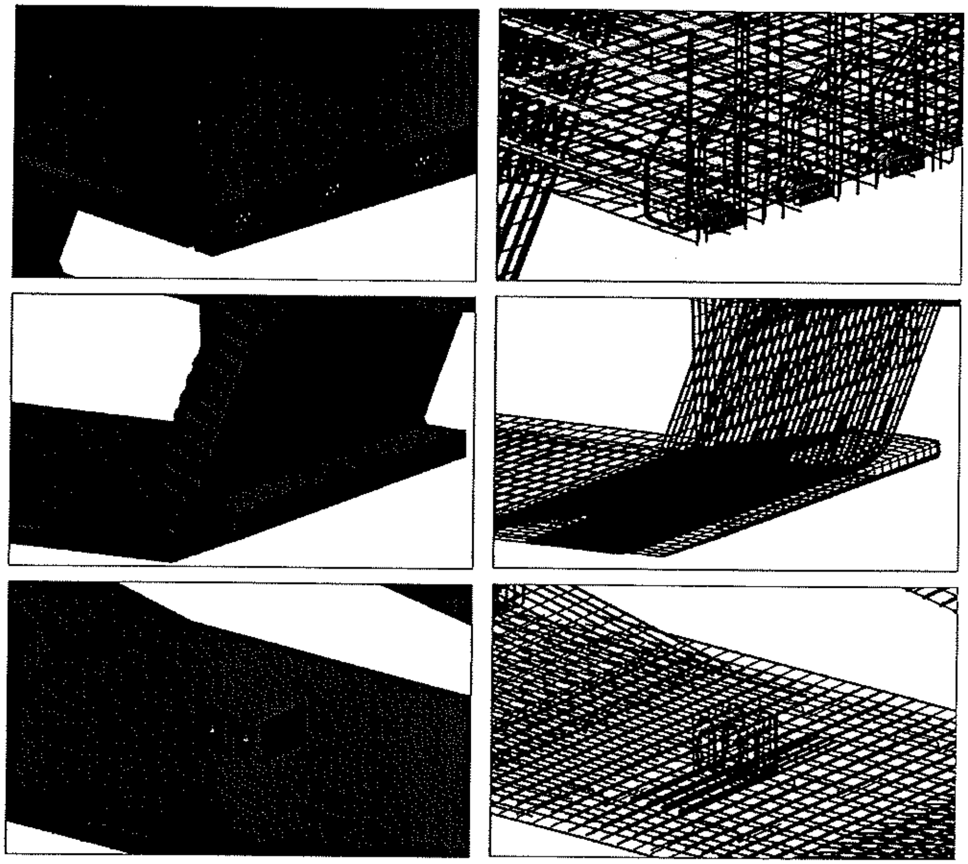


Figure 11. Close view of the typical segment. (a) Deviation block. (b) Web. (c) Transverse tendon anchorage. (d) 3D models and reinforcing bars.



(d)

Figure 11. (*Continued*).

able to represent all segments in DMU. Therefore, in this research, defining and applying DMU have been conducted only in five types of segments.

As mentioned previously, the BOM could be created in diverse forms according to the intended purpose. The BOM for fabrication segments was organised in this application. Accordingly, placing reinforcing bars was classified by section, which requires the most manpower and materials. The BOM was then constituted, considering the sequence of placing reinforcing bars from the lower part to the upper one, which is shown in Figure 6 for typical segments. The areas highlighted in green represent a sub-assembly forming a segment and the yellow areas represent the most subordinate individual parts. Table 2 summarises five 3D segment models.

The bridge construction for six bridges should be finished in 34 months and the fabrication cycle for a typical segment, a deviation segment and a pier segment was planned to be 1.5, 2 and 3 days, respectively. In addition, it was expected to take 3 months for the preparation and 5 months for learning time. It was very important to reduce these periods by utilising 3D bridge information models. Preliminary risk assessment was another issue for the fast construction of bridges. 3D models were also used for the construction drawings as in the case of the San Francisco Oakland Bay Bridge (Duxbury and Nader 2008).

3D bridge modelling

As a second stage for application of 3D models, 3D modelling of the most subordinate individual parts was carried out based on the BOM of segment defined at the previous stage, and the parametric modelling technique was applied considering the variables of shape of the composing parts. The parametric modelling was performed accounting for shape variables of a reinforcing bar. It offers very powerful and complete modelling capability and is able to directly model large complex assemblies for controlling both surfaces and assemblies (Eastman *et al.* 2008). A configuration of reinforcing bars obtained by parametric modelling was

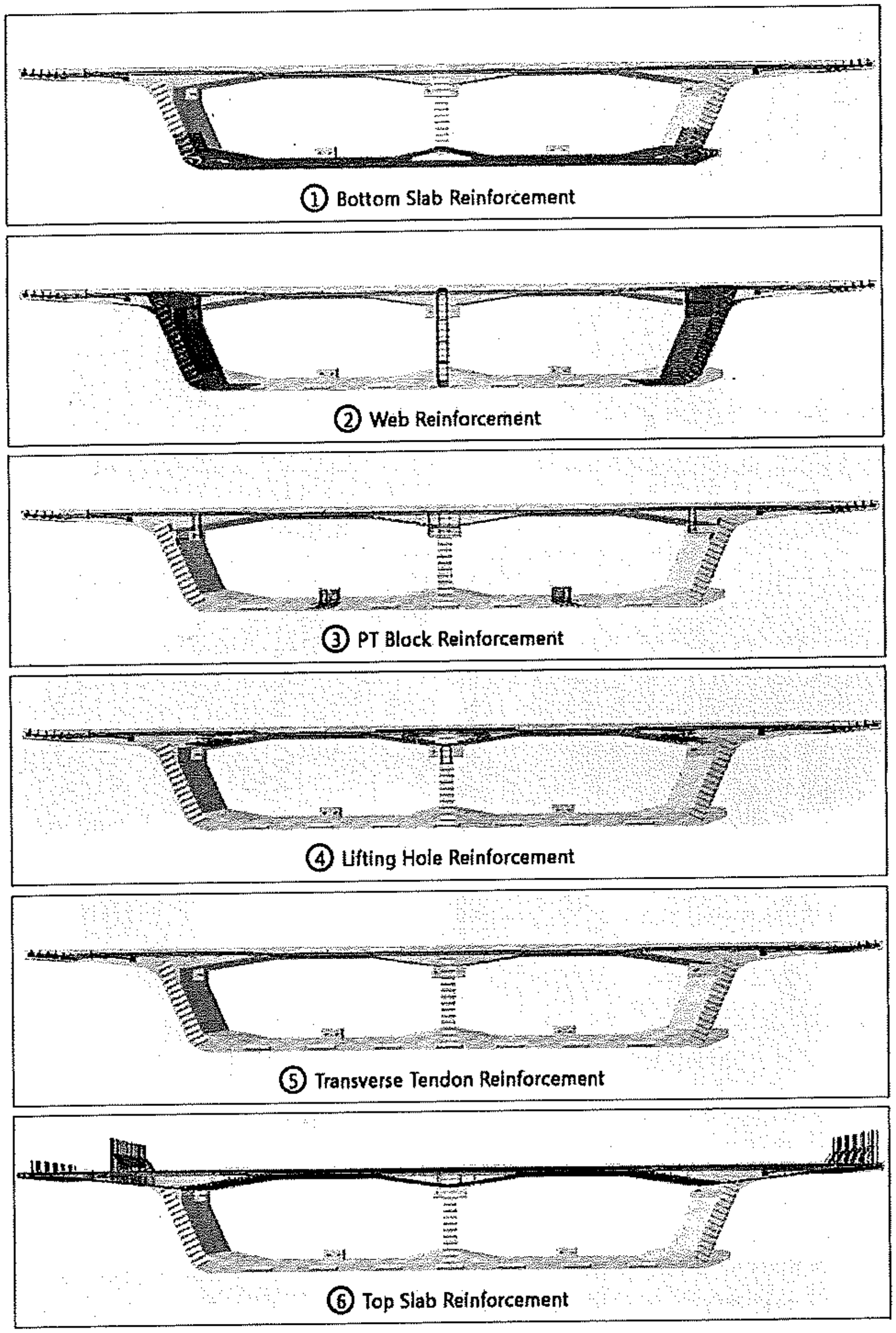


Figure 12. Classification of reinforcements of the typical segment.

illustrated in Figure 4. The 3D model created by considering such variables made it possible to flexibly cope with shape changes and design changes and to offer information on configuration for manufacturing of reinforcing bars. Figure 10 shows parts composed of a typical segment embodied into a 3D configuration. Figure 11 presents several close views of 3D models and their actual details for the typical segment.

The well-organised bridge information model can dramatically enhance the design revision process and communication with workers on the construction site. The 3D model for typical segments consists of three components: concrete, reinforcements (group of reinforcing bars) and tendons. It also sub-categorises for tendons as permanent PT-bars, temporary PT-bars, and transverse tendons. Reinforcements are divided

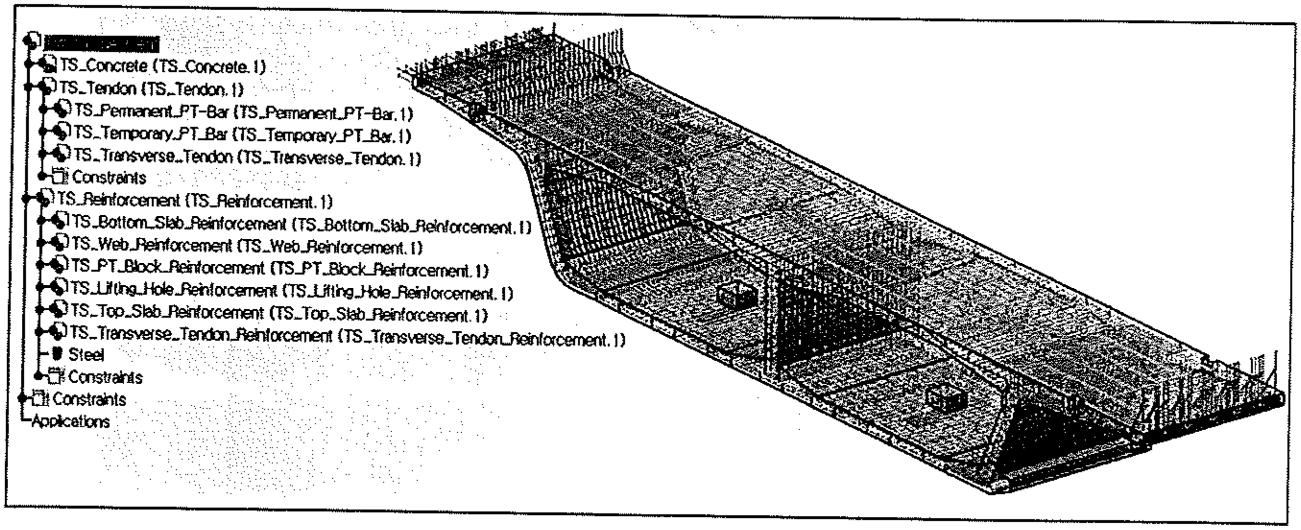


Figure 13. Architecture of the 3D bridge segment.

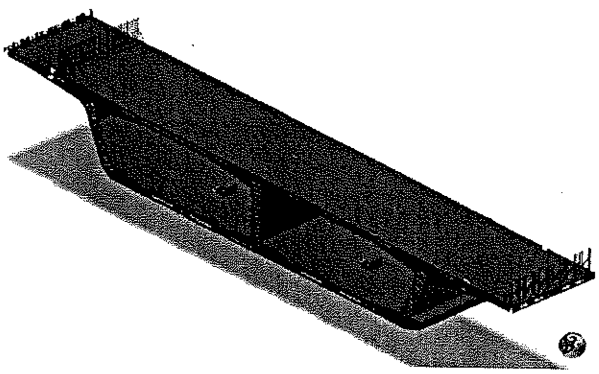


Figure 14. 3D-XML view of the 3D bridge model.

into six groups as bottom slab reinforcement, web reinforcement, PT block reinforcement, lifting hole reinforcement, transverse tendon reinforcement, and top slab reinforcement. Figure 12 shows the classification of the reinforcements of a concrete box segment and the architecture of the 3D model is presented in Figure 13. These models were delivered to practitioners and utilised for design revisions, approval process, shop drawings and training workers.

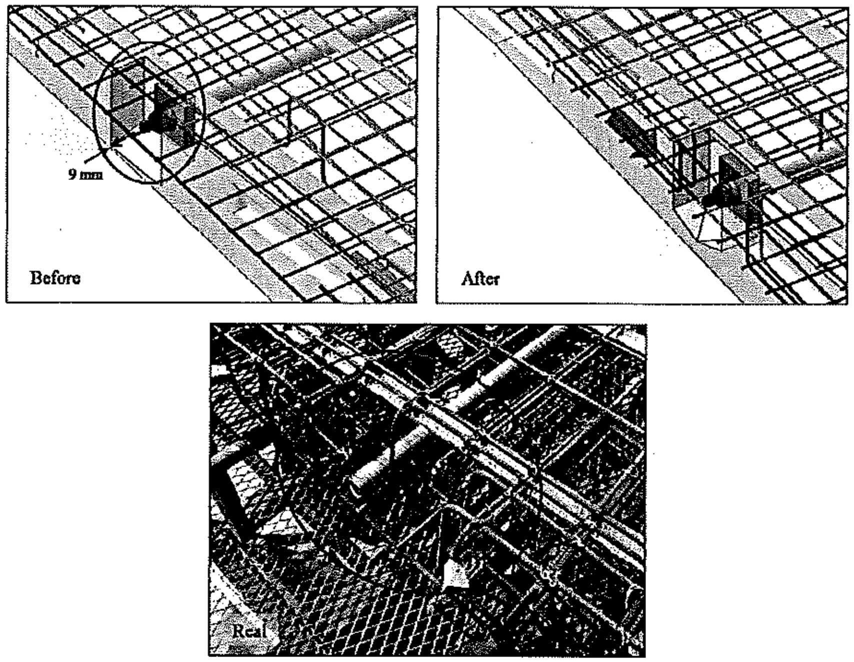
Verification and utilisation of the 3D bridge modelling

As suggested in the guideline for information quality (NIST 2007), the 3D bridge models can be verified considering clarity/consistency, accessibility, usability, completeness, timeliness, accuracy, and cost. Due to the incomplete design drawings, the initial version of the model was not complete. However, through the collaboration between modellers and engineers the errors were corrected and physical mock-up process was eliminated. Structured format of the model enabled easy access to each part by specialists.

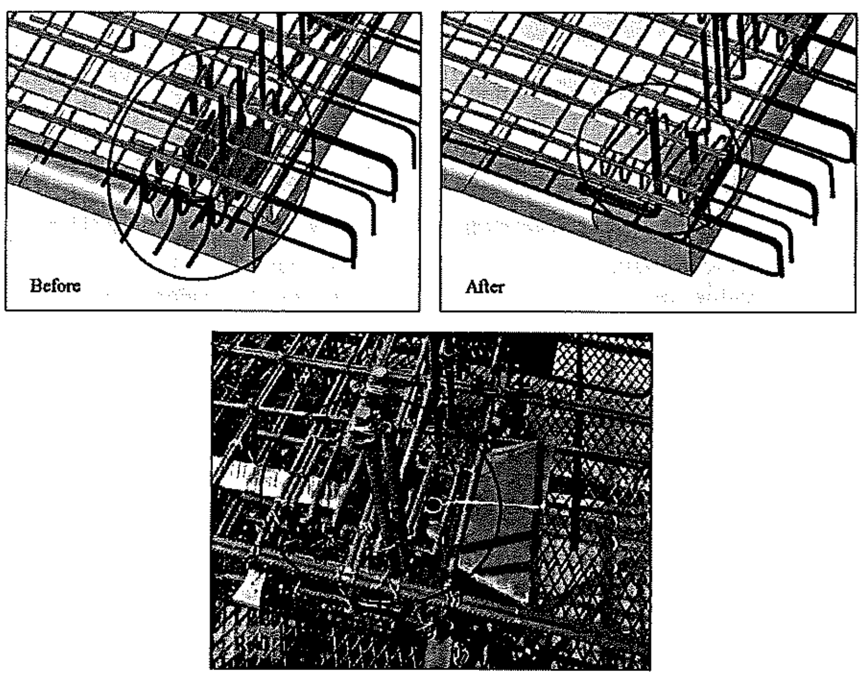
This research optimised constructability and minimised interference between parts and design errors by assembling the segment in 3D virtual space based on 2D fabrication drawings. At the stage of creating and applying the DMU model, individual parts modelled at the previous stage are to be assembled based on parent–child relations between parts of the BOM. Figure 14 shows the finally assembled typical segment which was provided for the construction engineers. 3D-XML models for the bridges were excellent tools for communication. By assembling parts in a 3D virtual space, interference between parts and errors in the design can be detected, and the assembly order and path of parts can also be optimised in advance.

During the so-conducted virtual assembling, it was found that the basic drawings made in two-dimensions included many errors and did not consider constructional efficiency. Figure 15 shows the discovered points at the issue of typical segment and its modified appearance through the embodiment of DMU. For the practical application of DMU in a concrete bridge construction, close collaboration is required between the 3D modeller and engineers for design checks and construction practices. Even though the CAD solution can automatically show the interferences between each part, the engineering judgment based on the engineer's experience is essential. During the DMU process, the engineers also had a clear view of the target objects and created various alternatives for the effective construction including process and equipment. It took about 4 weeks to complete the initial DMU. By using the initial DMU, design errors and interferences between parts were found realistically and revised easily.

The 3D configuration model and DMU can enhance the understanding of a structure's configuration in comparison with the typical 2D drawing information, especially effective in the case of complicated structures. Even experienced experts mentioned that it took them a considerable time to understand 2D drawings. A simulation that shows the sequence of reinforcement placing for efficient segment fabrication was produced. Accordingly, it is planned to



(a)



(b)

Figure 15. Examples of DMU. (a) Transverse pre-stressing anchor area; (b) Flat duct anchor area.

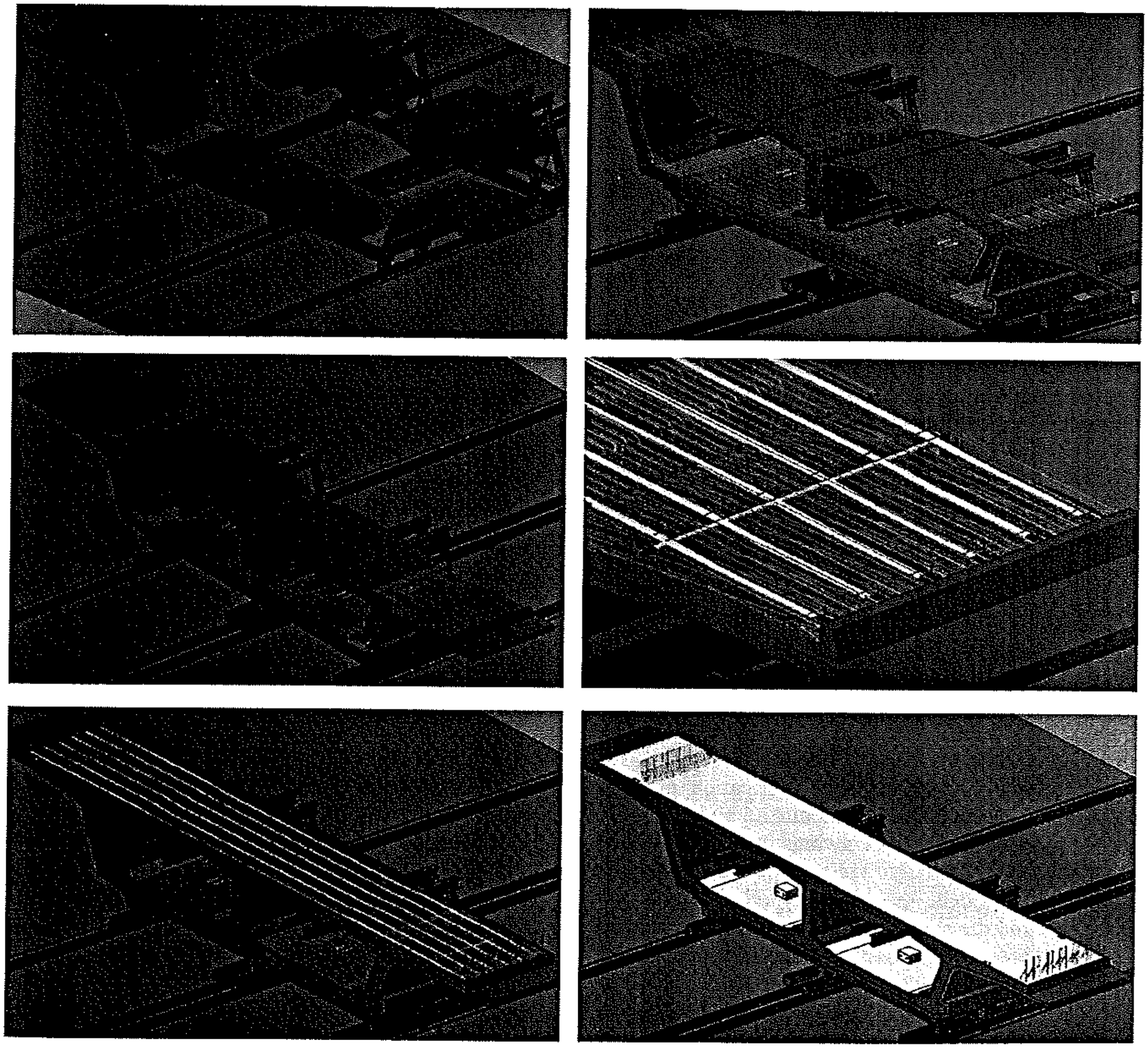


Figure 16. Simulation of the manufacturing process.

Table 3. Evaluation of the effects of 3D bridge information models from the contractor.

Classification	Description	Saving	Total
Time	Reduce time from the preparation of segment fabrication to the fabrication of initial segment	1.5 months	4.5 months
	Learning time 5 month → 2 month	3 months	
Cost	Reduce workers due to improve efficiency of operation	\$1.2 million	\$2 million
	Reduce indirect cost due to reduce workers	\$0.3 million	
	Loss of reinforcing bars about 5% per segment	\$0.5 million	

be used as instructional materials for those who are involved in the manufacturing segments. It is highly expected that this simulation would increase the efficiency in the making of a segment. Figure 16 shows images of the simulation for fabricating a typical segment.

Evaluation of the application of 3D bridge information models

During the pilot application of 3D bridge information models for an international project, engineers of the general contractor were required to evaluate the effects of the 3D models. As summarised in Table 3, several direct effects on the construction period and cost were observed. At the construction site, eight mould systems were installed, two sets for pier segments and six sets for normal type (typical and deviation) segments. One span of bridge M1 has been fabricated continuously at each mould system. For the most effective usage of the precast mould systems, it was scheduled that seven spans (105 segments) would be fabricated per month. Including the learning time, the period of the segment fabrication was planned to be about 7.5 months. The total quantities of reinforcing bars for the whole segment are 8400 tons and the cost related to reinforcing bars including materials, manufacturing, and assembly cost is $1200 per ton.

Since the construction period of the bridge is the crucial aspect for the successful project delivery, the contractor showed a remarkably positive attitude for the continuous application of the integrated 3D models. Firstly, it was expected that the construction period would be reduced to about 4.5 months. The initial setting time of segment fabrication and the learning time were reduced to about 1.5 and 3 months, respectively. Secondly, cost savings from several parts were expected. Through the use of the 3D bridge information models, the efficiency of operation was improved and the number of workers could be reduced by about 6%. Due to reduced workers, labour and indirect costs could be cut down by about $1.5 million. The effects of the reduced time on the other costs were not considered. In this pilot application, five types of segments including complicated reinforcements were prefabricated by 3D application to verify and optimise the shape of reinforcing bars and their manufacturing and assembly. From the verification process, problems that might eventuate during practical work were identified and solutions were derived. Consequently, quantities of reinforcing bars were reduced by about 5% and a cost of about $500,000 was saved.

More important values from the application were indirect effects. The risk management in an international construction project is the key factor. Previous virtual manufacturing and construction can reduce the possible risk during construction significantly. The models are used for the training of inexperienced workers and for the 4D simulation of the construction process. A few engineers on the construction site were trained to deal with 3D models and will modify the models for their own purposes. 3D bridge information models of precast concrete box-girder bridges had visible and invisible effects on the project in terms of construction time, cost, understanding and workability of workers and the client's confidence about technical expertise. After completion of the project, the contractor could own well organised bridge information models for concrete box girder bridges that can be re-used for similar international bridge projects.

Conclusions

The construction industry has made a rapid shift from a 2D-based environment to 3D information modelling, a new challenge in the construction industry. Even though the model seems to be excellent for the innovation of the current process, significant effort is needed to build well-organised models in the actual application of 3D models to practise needs.

In this paper, 3D bridge information models for an international concrete bridge construction project were built to integrate design and construction processes. Three-dimensional bridge models were realised by considering WBS and PBS to enable digital mock-up and design enhancement and to shorten the learning time of the construction engineers.

DMU technology was applied to the bridge construction site and verified the benefits brought by its application. BOM for the fabrication of five types of segments constituting the superstructure of the target bridge was defined. This BOM was exploited to create a 3D solid model and DMU by using the parametric modelling technique. By creating and applying DMU, the fabrication of the segment was optimised. Eventual problems that might happen during practical work were identified and solutions were derived. Such application is expected to shorten the construction time and reduce cost by minimising trial and error. Moreover, the order of placing reinforcing bars of the segment was optimised and a video was produced to enhance the understanding of the segment fabrication.

Three-dimensional information modelling and DMU technology are judged to have significant application value in fabricating segments and also in other aspects of bridge delivery. However, there are still many restrictions on the efficient application of these technologies. In this pilot application, it was judged that the understanding of these technologies and assurance of positive effects of their application have been insufficient. In addition, there were very few experienced engineers. Through this case study, effects of the application of these technologies for precast concrete segmental bridges were quantitatively estimated and they are expected to be a guideline and reference for similar international projects.

Acknowledgements

This research was supported by the Virtual Construction Research Center sponsored by the Ministry of Land, Transport and Maritime Affairs of Korea. This support is gratefully acknowledged.

References

British Standards Institution, BS 8666, 2005. Scheduling, dimensioning, bending and cutting of steel reinforcement for concrete – Specification.

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.

Duxbury, J. and Nader, M., 2008. Use of integrated shop drawings for the San Francisco Oakland Bay Bridge. *In*: *IABSE conference on information and communication technology for bridges, buildings and construction practice*, 4–6 June, Helsinki, Finland: IABSE, 94, 10–17.

Eastman, C.M., Teicholz, P., Sacks, R., and Liston, K., 2008. *BIM handbook: A guide to building information modeling for owner, managers, architects, engineers, contractors, and fabricators*. Hoboken, NJ: John Wiley and Sons.

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.

Janjic, D., Bokan, H., and Love, R.A., 2008. The evolution of bridge information modelling. *In*: *11th East Asia-Pacific conference on structural engineering and construction (EASEC-11)*, Taipei, Taiwan: National Taiwan University, 146–147.

Katz, C., 2008. Parametric description of bridge structures. *In*: *IABSE conference on information and communication technology for bridges, buildings and construction practice*, 4–6 June, Helsinki, Finland: IABSE, 94, 18–28.

Lee, G., Sacks, R., and Eastman, C.M., 2006. Specifying parametric building behavior (BOB) for a building information modeling system. *Automation in Construction*, 15 (6), 758–776.

Lee, Y.B., Lee, K.M., Park, Y.H., Park, M.S., Yoon, M.G., Shin, H.Y., and Park, K.L., 2006. Application of digital mock-up technology to design and construction of concrete bridges. *In*: *2nd ACF international conference*, 20–21 November, Bali, Indonesia: HAKI, 43–49.

Leeuwen, J.P. van and Zee, A.van der, 2005. Distributed object models for collaboration in the construction industry. *Automation in Construction*, 14 (4), 491–499.

Maher, M.L., Liew, P., Gu, N., and Ding, L., 2005. An agent approach to supporting collaborative design in 3D virtual worlds. *Automation in Construction*, 14 (2), 189–195.

National Institute of Standards and Technology, 2007. General buildings information handover guide: Principles, methodology and case studies, NISTIR 7417.

Plume, J. and Mitchell, J., 2007. Collaborative design using a shared IFC building model – Learning from experience. *Automation in Construction*, 16 (1), 28–36.

Robinson, C., 2008. Structural building information modeling in use. *In*: *IABSE conference on information and communication technology for bridges, buildings and construction practice*, 4–6 June, Helsinki, Finland: IABSE, 94, 30–31.

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. *In*: *IABSE conference on information and communication technology for bridges, buildings and construction practice*, 4–6 June, Helsinki, Finland: IABSE, 94, 112–113.

Tah, J.H.M., Carr, V., and Howes, R., 1999. Information modelling for case-based construction planning of highway bridge projects. *Advances in Engineering Software*, 30 (7), 495–509.

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. *Automation in Construction*, 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. Available from: http://www.international.fhwa.dot.gov/Pdfs/SteelBridge1.pdf [Accessed 5 July 2009].

Whyte, J., Bouchlaghem, N., Thorpe, A., and McCaffer, R., 2000. From CAD to virtual reality: modelling approaches, data exchange and interactive 3D building design tools. *Automation in Construction*, 10 (1), 43–55.

Yabuki, N. and Shitani, T., 2003. An IFC-based product model for RC or PC slab bridges. *In*: *Proceedings of the CIB W78's 20th international conference on information technology for construction*, 23–25 April, Waiheke Island, New Zealand, CIB, 463–471.