Towards BIM-based model integration and safety analysis for bridge construction

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Abstract:

Construction projects are challenging because of significant investment from various investors. The completion of construction work also requires the collaboration among experts from several disciplines. However, previous works on the integration of information available in the design, construction, and maintenance phases are insufficient. In this study, we initially reviewed the previous studies in this area and then discussed the possible challenges and demands. Afterward, we presented a thorough comparison of different models (i.e., *Tekla* model as architectural model and *Midas Civil* model as structural analysis model) and software applications. Then, we proposed a novel approach in which a unified information model and a region-based feature point matching algorithm (RFPMA) were employed to enhance the integration of information available in different phases of a construction project. Furthermore it has been achieved to dynamically integrate the monitoring data and analysis results into the unified information model. Finally, we proposed the method and the overall workflow that show how the available information in different phases is integrated. The proposed approach was implemented in a Client Server (C/S) platform and applied in a large real project located at Jinan, Shandong Province, China, which is called Jinan Yellow River Bridge. The application involved several scenarios, including information sharing between *Tekla* model and *Midas Civil* model, synchronous model updating and data visualization, and collaborative analysis of the safety level during the construction process. This research has made a breakthrough in the theory, technology, and application of model integration and has established the foundation for safety management.

Keywords: BIM, Data Model, Model Integration, Integrated Application

1. INTRODUCTION

Building Information Modeling/Model (BIM) has been the focus of considerable attention in the Architecture, Engineering, and Construction (AEC) industry because of its advantages in information integration and sharing (Yuan & Zhang, 2015). However, AEC projects are very challenging in terms of collaboration and sharing of information because of the involvement of many stakeholders and various technologies (Zhang et al., 2014). Interoperability is considered a key factor in streamlining information flows among different disciplines and influencing the value proposition of BIM in industry (Young et al., 2009). Over the past decade, research and development activities aimed at enhancing interoperability have been the focus of significant interest from the industry and academia (Serror et al., 2008; Ricardo & Antonio 2010).

The use of BIM has become increasingly common in effectively collaborating among construction project participants because of its benefits to various stages of a building's life cycle. Since the early 2000s, BIM has been used throughout the entire project life cycle to facilitate effective project collaboration and integration of data to support project activities (Karan & Irizarry, 2015). Numerous design firms and contractors reported the benefits of utilizing BIM in their projects (Luth et al., 2014). However, various problems have occurred because of the use of different BIM-based software among collaborators during the design and construction phases (Oh et al., 2015). Ding et al. (2015) determined that the compatibility and integration between BIM and other widely available software in the industry should also be improved. As BIM adoption continues to improve, various stakeholding practices involved in developing projects through integrated systems require process models to help them simplify issues relating to multidisciplinary integration (Alfred, 2011).

This study aims to address the integration challenge between the architectural model (including linked actual monitoring data) and the structural analysis model (including linked theoretical computation results). First, we discuss the differences between the architectural model and the structural analysis model. Second, we present our BIM-based approach and its components, which include the BIM-based unified information model, a region-based feature point matching algorithm (RFPMA) to achieve model integration, and the mechanism for the dynamic integration of actual monitoring data and theoretical computation results. Third, we illustrate the implementation of the proposed approach, including a Client Server (C/S) platform and the workflow of integration application. Finally, we demonstrate the application in a complex and large real project to show the integration value.

2. COMPARISON BETWEEN ARCHITECTURAL MODEL AND STRUCTURAL ANALYSIS MODEL

An architectural model is used to mainly describe the geometry and appearance representation of the building, whereas a structural analysis model consists of structural elements that are specified for vertical and lateral load transferring, adding different load cases and geometric boundary conditions by structural engineers (Zhang et al, 2014). For example, Figure 1 shows that the *Tekla* model mainly contains geometry and part information, difficult to extract axis, and section information, whereas the *Midas Civil* model mainly contains structural information, including joint, element, material, section, load, restraint and so on, which is mostly abstracted from the architectural model and defined by structural engineers manually. The file formats mainly supported are *.ifc and *.mct, respectively. The *Tekla* model is meaningful to construction simulation, quantity calculation, and automatic drawing, whereas the *Midas Civil* model is important to ensure construction safety. Thus, combining these two models to create significant values is the key problem discussed in the following sections.

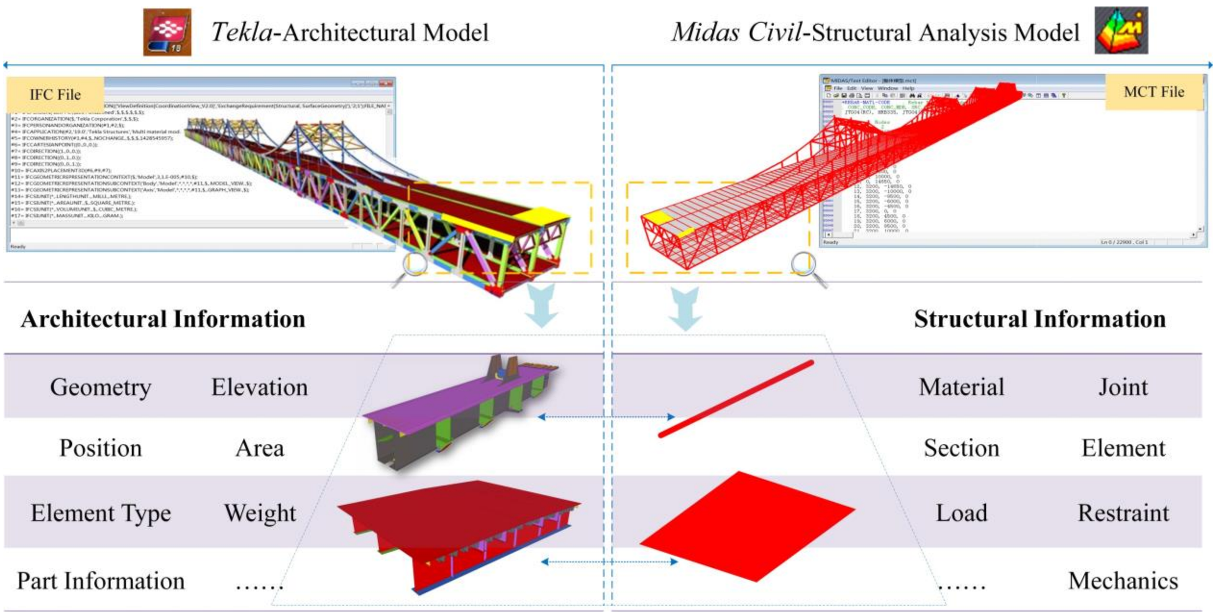

Figure 1. Comparison of architectural model and structural analysis model

3. APPROACH FOR INFORMATION MODELING AND DATA INTEGRATION

3.1 BIM-based unified information model

The BIM-based unified information model is a data model that is utilized to bridge the gap between architectural model and structural analysis model and to integrate the data collected by the strain meter and total station during construction. The model organizes data elements and standardizes how the data elements are represented and how they relate to one another (see Figure 2).

Each architectural component is a '*BuildingElement*'. The mesh representation of each architectural component is divided into several triangles to improve display efficiency. The extended properties of the component are also stored in the unified information model. The structural element includes basic node information and its attributes, such as material and section information. The structural element also contains mechanism computation results calculated by structural analysis software, which is associated with different construction cases. The structural element is associated with the architectural component via '*BEID*' (the ID of '*BuildingElement*'), which can be obtained through the following algorithm. During a construction period, the monitoring data, such as stress of the component, and the measured data, such as settlement and deformation, are integrated dynamically into the unified information model. These data are assigned to the monitoring point, which is linked to the architectural component via '*BEID*', obtained by the precise location of monitoring point on the components. The model overcomes semantic and information representation between architectural and structural analysis models and integrated project data dynamically, which lay the foundation for the following applications.

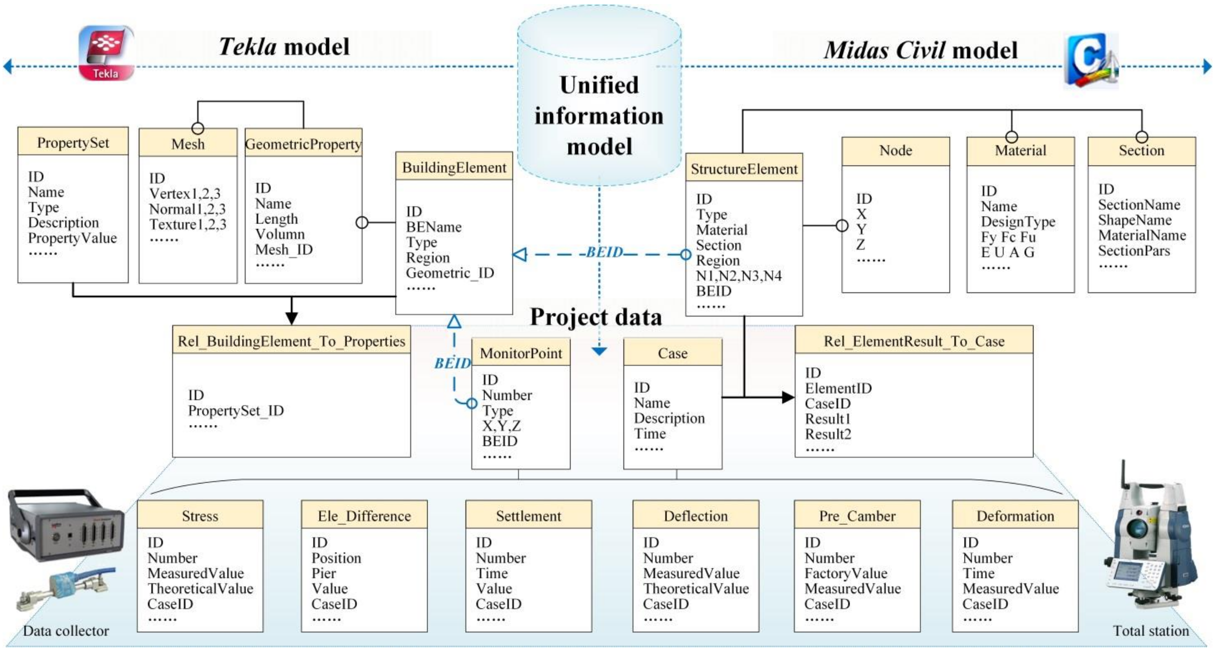

Figure 2. Framework of the BIM-based unified information model

3.2 Region-based feature point matching algorithm

RFPMA was proposed (as shown in Figure 3) to achieve the integration of the architectural and structural analysis models by combining heterogeneous models (*Tekl*a model and *Midas Civil* model).

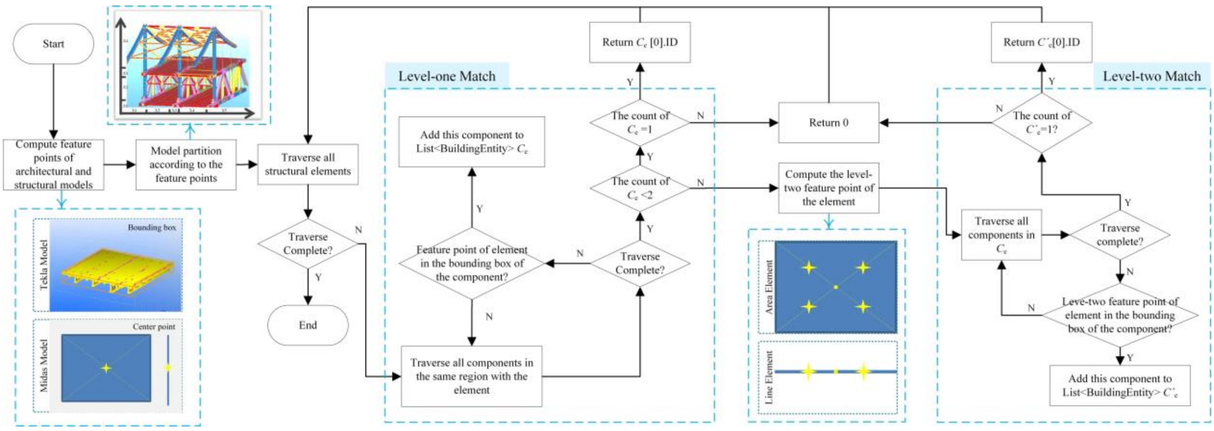

Figure 3. Workflow of RFPMA

First, the feature points for model partitioning must be calculated. Considering the complexity of the architectural model, we adopt the center point of the bounding box as the feature points of a building component. Given that the structural analysis model mainly contains three kinds of elements (i.e., beam, truss, and slab), we can define different levels of feature points for them to achieve matching accurately (the center point of the element as level-one feature point, one-fourth and three-fourth points of the element as level-two feature points). Given that the direction of the bridge is along the *y*-axis, the models can be divided into different regions based on the feature points, namely, five parts along the *x*-axis and four parts along *z*-axis, which is a total of twenty regions (see the upper left of Figure 3), to combine the component (unit of the architectural model) with the element (unit of the structural analysis model) within the same region. Thus the component or element has its own region number calculated by the the location of feature point within the region, which is a great help to improve the matching accuracy and operation speed. For each element, first, we need to search all eligible components containing the level-one feature point of the element and add to the eligible collection C_e. Then, the count of C_e is determined to obtain different results, as follows: (1) one, which indicates that the matching is successful and the ID of the component is retrieved; (2) zero, which indicates that the matching is failed; (3)

more than one, which indicates that level-two matching must be executed to eliminate distractions, thereby updating level-two feature points for these elements and executing a similar workflow within C_e to obtain the eligible component for this element. Also we proposed the manually matching way for processing two rare cases including failed matching due to unknown reason or each structural element is bounded by two or more architectural components. Thus, two heterogeneous models can be integrated accurately and the detailed applications are demonstrated in depth in the following sections.

3.3 Dynamic integration of actual monitoring data and theoretical computation results

A large number of monitoring and theoretical data were produced during construction. These data must be utilized properly and integrated into the proposed BIM-based unified information model. For monitoring data, they were dynamically integrated into the monitoring points associated with the *Tekla* model via '*BEID*', which can be obtained by determining the spatial relationship between the coordinate of the monitoring point and the bounding box of the *Tekla* component. The theoretical data, particularly for element stress results, were integrated into the *Midas Civil* model via '*ElementID*'. We can import the computation results from different cases, which were associated with the corresponding elements with the same '*ElementID*'. Based on the previously presented model integration, data integration and transformation can be achieved (see Figure 4). Thus, the following advantages could be provided: (a) the actual data can be compared with the theoretical data easily, thereby helping with decision making via contrastive analysis; (b) a convenient way to collect, manage, and view complex construction data was provided; (c) synchronous model updating and data visualization were enabled in accordance with the construction cases through the relationship between the *Tekla* model and the schedule; and (d) data transformation between actual monitoring and theoretical analysis was achieved, thereby adding the monitoring data to the structural analysis automatically, which is described in detail in the following section.

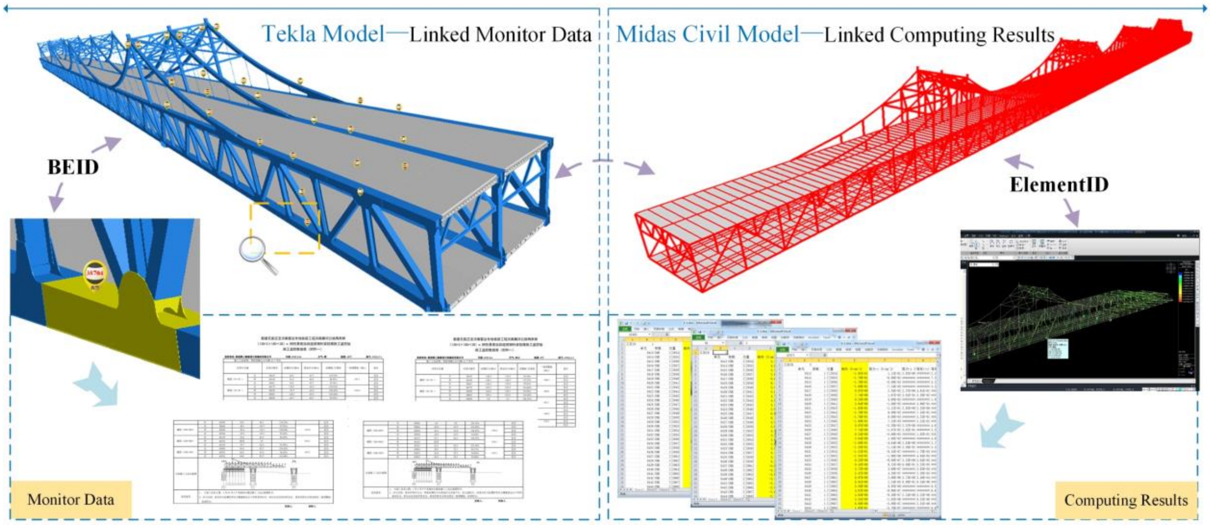

Figure 4. Dynamic integration of monitoring data and computation results

4. THE PROPOSED INTEGRATION SYSTEM

On the basis of the previously presented approach and algorithms, we developed a novel platform called '4D-BIM Information Integrated System' for model and linked data integration. The BIM-based unified information model was implemented as a central data server. The workflow of integrated application is described in Figure 5. In this research, we adopted the *Tekla* software to create the architectural design model and the *Midas Civi*l software to create the structural analysis model. These models were integrated into our platform through the appropriate interface (*.ifc and *.mct file formats) and the proposed algorithm. The monitoring data were collected by the strain meter or total station during construction. These construction data were dynamically integrated into our platform and then connected to the monitoring points of the *Tekla* model. Given that the *Tekla* model has been associated with the schedule, we can derive the appropriate *Tekla* model according to the case time. The corresponding structural analysis models can be derived from different construction cases because of the integration of the *Tekla* model and *Midas Civil* model. Furthermore, the monitoring data associated with the *Tekla* model can also be transformed into the load or restraint information of the structural analysis model, thereby automatically generating modified case models for structural engineers to analyze and evaluate. Thus, model integration and information transformation can be achieved, thereby eliminating rework and improving efficiency notably.

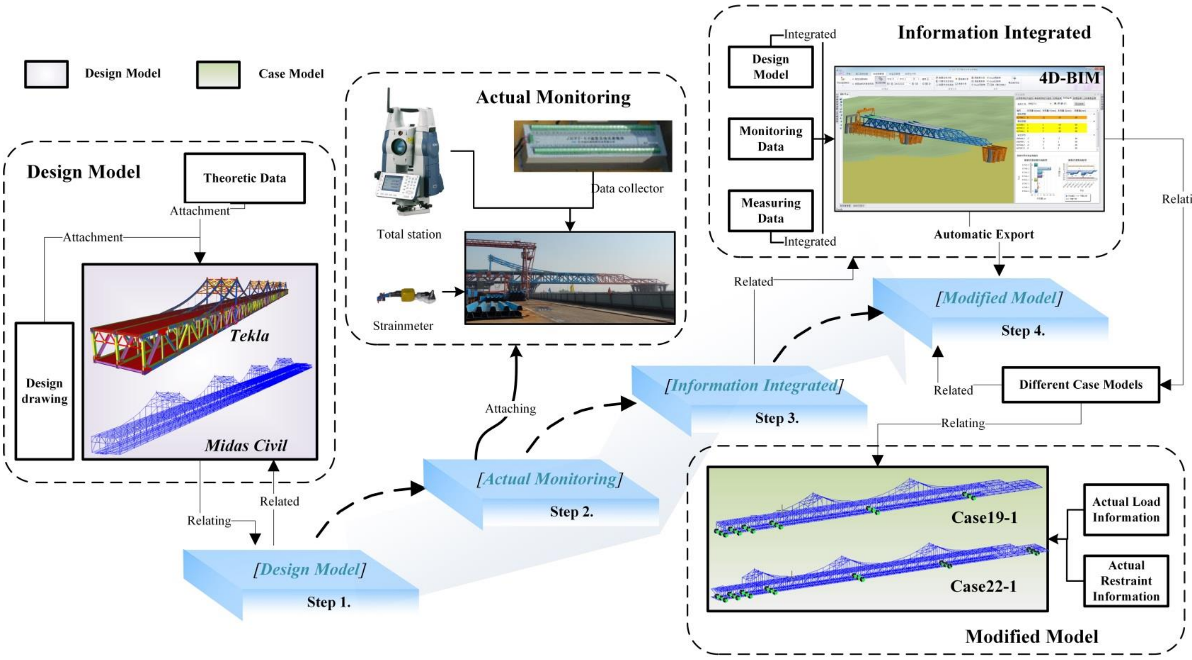

Figure 5. Workflow of integrated application

5. CASE STUDY

This research has been tested in a real project called Jinan Yellow River Bridge in Jinan, Shandong Province, China. This project is co-developed recently with Steel Structure Engineering Co. Ltd. of China Tiesiju Civil Engineering Group. This project is a large-span rail-road steel bridge that first applied the three main trusses stiffened with rigid suspension cables in China (six-lane highway and double-line railway bridge). The overall length of the bridge is 798.3 m, and it weighs up to 36,249 t. This bridge adopts three steel trusses girder structure; its architectural design model is created by the *Tekla* software, whereas its structural analysis model is created by the *Midas Civil* software. Based on the proposed approach and platform, two different kinds of models can be integrated successfully and applied in various aspects, thereby resulting in evident profit to the project.

The first scenario is information integration. Based on the integrated model (as shown in Figure 6), we can not only view the key information, such as geometry, part, and progress information, from the *Tekla* model, but also obtain the corresponding structural information, such as node, material, section, and stress in the same window, from the *Midas Civil* model. The stress results for the elements of different case models are also successfully imported, and the corresponding stress nephogram can be displayed in the developed platform (see the upper left part of Figure 6). Thus, information integration is also supported in tracing the historical stress of the element to aid the engineers in making decisions.

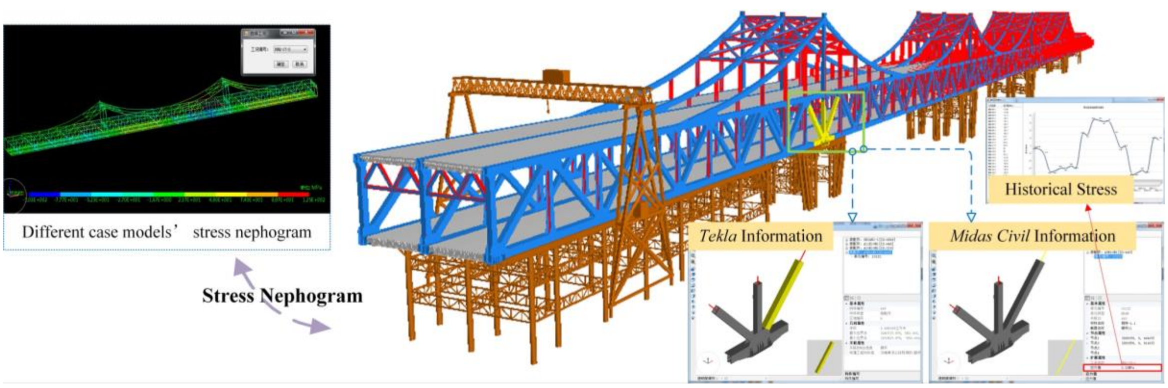

Figure 6. Application of information integration

The second scenario is synchronous model updating and data visualization. Given that the *Tekla* model is associated with the schedule, it is constantly updated along with time. Based on the model integration and linked data, updating and visualizing the integrated model along with the construction cases are supported, including the *Tekla* model, related monitoring points, and corresponding *Midas Civil* model (see Figure 7). Thus, the case model and case data can be conveniently viewed and analyzed, thereby establishing the foundation for the following application of case management.

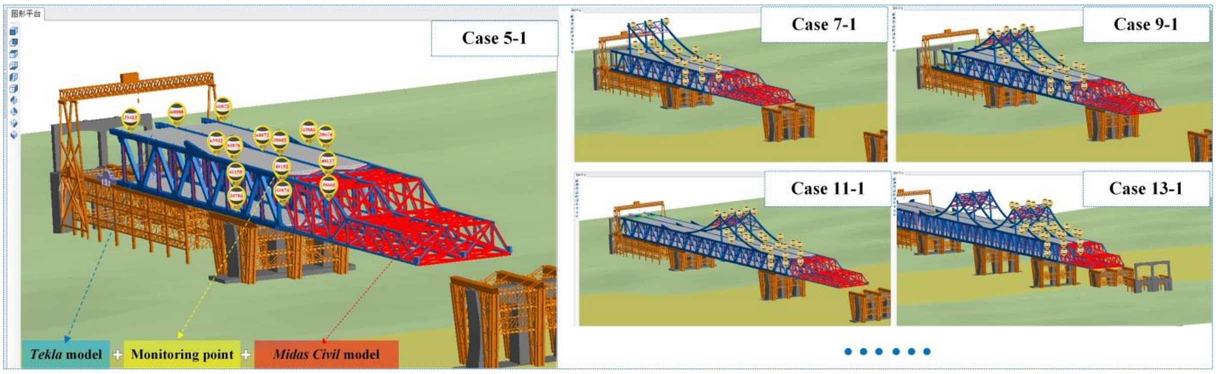

Figure 7. Synchronous updating of integrated model and data information

The third scenario is case management. The structural engineers must conduct model analysis of different construction cases with repeated modeling work and by adding restraint information manually. Based on the preceding workflow of integrated application, different case models can be generated automatically (e.g., case 19-1 in Figure 8). For a specific construction case, we can obtain the appropriate *Tekla* model based on the construction simulation. The corresponding related elements can be obtained, thereby generating basic geometry, material, and section information for the analysis model. Then, the elevation difference of the three main trusses measured during different cases, which are connected to the monitoring points of the Tekla model, can be transformed into the restraint and enforced displacement information, thereby adding to the structural analysis model automatically. Thus, the engineers can obtain the corresponding structural analysis model according to the construction case to save a significant amount of time and manpower.

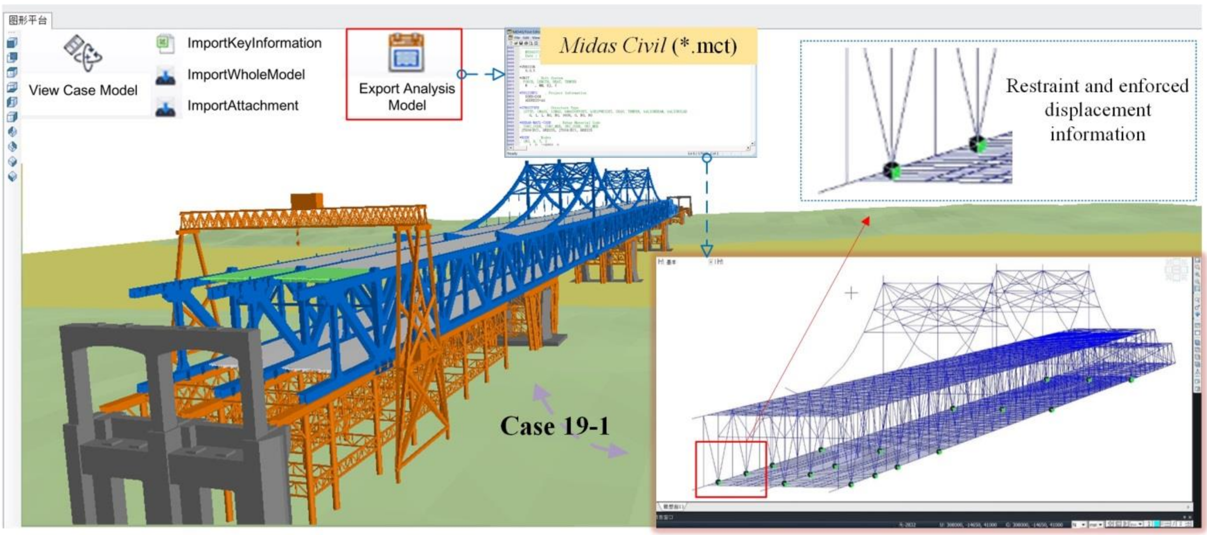

Figure 8. Application of exporting analysis model automatically

6. CONCLUSIONS

As BIM adoption continues to improve, various stakeholding practices are involved in construction projects through various systems, which require the appropriate approach and platform, to help simplify issues related to multidisciplinary integration. This study addressed the challenges of model integration and information transformation, which results in notable benefits for construction management and evaluation.

This study initially compared the differences between architectural model and structural analysis model to accomplish the integration challenge. Then, a BIM-based unified information model, which formed a central information layer for model and data integration, was proposed. The proposed model standardized the model entities and relationships required for such an integration. Then, the RFPMA and the mechanism for the dynamic integration of actual monitoring data and theoretical computation results were presented to help achieve model integration between *Tekla* model and *Midas Civil* model, including the linked data information. The proposed solution was prototyped in our own platform to achieve integration application.

Testing of the proposed approach and platform was conducted in a real project called Jinan Yellow River Bridge. The tested scenarios were successfully executed despite the significant size and complexity of the real project. On one hand, different kinds of information, including *Tekla* information, *Midas Civil* information, and stress nephogram information, etc., can be viewed based on the integrated model. On the other hand, the integrated model can be updated along with the schedule, and it has been achieved to export the structural analysis model according to different construction cases automatically, thereby reducing repetitive modeling work and improving efficiency.

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REFERENCES

Alfred, O. (2011). Modelling organizations' structural adjustment to BIM adoption: a pilot study on estimating organizations, *Electronic Journal of Information Technology in Construction*, 16, 653-668.

Ding, Z., Zuo, J., Wu, J., and Wang, J. (2015). Key factors for the BIM adoption by architects: a China study, *Engineering, Construction and Architectural Management*, 22 (6), 732-748.

Karan, E. P. and Irizarry, J. (2015). Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services, *Automation in Construction*, 53, 1-12.

Luth, G. P., Schorer, A., and Turkan, Y. (2014). Lessons from Using BIM to Increase Design-construction Integration, *Practice Periodical on Structural Design and Construction*, 19 (1), 103-110.

Oh, M., Lee, J., Hong, S. W., and Jeong, Y. (2015). Integrated system for BIM-based collaborative design, *Automation in Construction*, 58, 196-206.

Ricardo, J. and Antonio, G. (2010). Building information modeling and interoperability, *Automation in Construction*, 19 (4SI), 387.

Serror, M. H., Inoue, J., Adachi, Y., and Fujino, Y. (2008). Shared computer-aided structural design model for construction industry (infrastructure), *Computer-Aided Design*, 40 (7SI), 778-788.

Young, N. W., Jones, S. A., Bernstein, H. M., and Gudgel, J. (2009). *The business value of BIM-Getting building information modeling to the bottom line*. Retrieved from McGraw-Hill Construction: http://www.buildingsmart.pl/123/2009BIMreport.pdf, accessed on December 8, 2015.

Yuan, Y. and Zhang, Y. L. (2015). Research on BIM-based collaboration platform to integrate digital technology for building design, assessment and simulation: A case study on residential building, *2nd International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SMTA)*, Paris, France, pp.378-383.

Zhang, X., Hu, Z., Wang, H., and Kassem, M. (2014). An industry foundation classes web-based approach and platform for bidirectional conversion of structural analysis models, *Proceedings of 15th ICCCBE*, Orlando, U.S., pp.390-397.