Automating Closed-Loop Structural Safety Management for Bridge Construction through Multisource Data Integration

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Abstract: Structural safety during construction is vital to engineering success of large scale bridges. However, difficulties in time-dependent structural modeling and data fragmentation of different engineering and management systems remain unresolved, hindering the plan, do, check, and adjust (PDCA) loop for structural safety management during bridge construction. In this paper, an integrated framework for closed-loop management of structural safety based on multisource data integration is presented. The proposed framework consists of a bridge safety information model (BrSIM), algorithms for data integration and semi-automatic time-dependent structural model generation, and methods for structural safety warning and assessment. The proposed BrSIM and algorithms integrate data related to 3D products, schedule, structural simulation and monitoring from various engineering systems, which covers the main data for structural safety management during construction. Meanwhile, automatic calculation and generation of static loads and constraints of a structural model based on 3D product information and monitoring data are also considered. Demonstration in the construction of a long-span bridge shows that with the proposed framework, it is possible to visualize the construction process, generate time-dependent structural models and simulate, monitor and assess the structural safety dynamically. Thus, the structural safety management loop is automated and fully closed. Furthermore, by tracking and simulating the changes of structural performance over time, and comparing the difference between simulation results and monitoring data, earlier detection and better evaluation of potential structural risks are achieved. Moreover, efficiency of information modeling and sharing is improved and effective management and decision-making are achieved with the proposed approach.

Keywords: structural safety; closed-loop management; information modeling; data integration; time-dependent structure

1. Introduction

The construction industry is characterized by intensive labor input, large investment, and extensive involvement. Construction accidents greatly threaten worker health, project progress, and social stability. Therefore, construction safety has been extensively studied, and related studies can be generally divided into two topics, namely, structural safety and personal safety. The former refers to the deformation or destruction of on-going main or temporary structures in construction, whereas the latter refers to personal injuries caused by external forces or unsafe behaviors during construction. In recent years, comprehensive studies on personnel safety from the aspects of psychological stress and personal resilience[1, 2], protection design[3, 4], safety training and safety culture[5], to personnel position tracking[6] and construction planning[7] have been performed to avoid accidents prior to design and construction. In structural safety, existing studies focus on the analysis of different load states, structural monitoring and warning of possible risks. However, few studies have performed dynamic analysis during construction. Although the theory of time-dependent structure in construction was presented over a decade ago, it has not been widely applied because of the large modeling workload and the unmatched data between monitoring and simulation results. In structural safety monitoring and early warning systems, sensor selection, networking technology, sensing and monitoring programs, and warnings at different levels are included[8]. Nevertheless, the monitoring, project management, and structural analysis systems remain independent of one another. Effective mechanisms for information integration and sharing have yet to be implemented.

Under normal circumstances, the high risks and frequency of construction accidents and other issues are often caused by poorly educated workers with low safety awareness rather than the lack of bearing capacity of the engineering structure itself. Therefore, many studies have focused on how to ensure construction safety from the aspects of worker behavior, safety measure, and management method. However, for large-scale projects such as bridges, particularly jacking construction, the bearing capacity of local structures often reaches or approaches the ultimate bearing capacity, which results in a high risk of structural failure. Therefore, in addition to the aforementioned worker behavior and other factors, the analysis, monitoring, and control of the mechanical state of the structure itself is particularly important for the construction of bridges.

Generally, control and continual improvement of products and construction processes can be achieved through the plan, do, check, and adjust (PDCA) method[9]. Known as the Demining circle, PDCA is a management method executed iteratively in a project. Each iteration, or a PDCA loop consists of four steps[9]:

1) Plan: involves assessing a current process, and figuring out how to improve it.

2) Do: executes the plan from the previous step and the data is collected.
3) Check: evaluates the data and results gathered from the do phase to see any similarities and differences.
4) Adjust: involves making adjustments or corrective actions based on evaluations from the check phase.

Successful implementation of the PDCA method requires flexible data collection, integration and sharing from one step to another, and from one iteration to the next iteration, thereby enabling efficient decision-making and continual improvement. Without flexible data integration and sharing, though it is doable based on traditional methods, work efficiency is highly influenced, which may lead to overlooking of certain issues. More accurately, it is hard to say the PDCA loop is closed and practical if there lacks efficient data integration and sharing tools or environments.

Management of structural safety during bridge construction follows the same way as PDCA. That is, planning and simulation are implemented before a construction process starts, progress and structural performance are then monitored and measured, with comparison and evaluation of the gathered data, possible adjustments are made to ensure structural safety in the future, and finally a new loop starts. However, the structural analysis, monitoring, and construction management systems involved in the PDCA loop for structural safety management during bridge construction are independent of each other and lack effective mechanisms for information integration and sharing. The information sharing is primarily based on drawings, documents with bad interoperability and requires repeated modeling and conversion work, which is time-consuming and error-prone. Obviously, the structural simulation, planning and execution, monitoring, and safety assessment involved in construction safety management are not sufficiently integrated. As a result, the PDCA loop always suffers lack of enough data and is not fully closed. The situation will become worse when a decision must be made in limited time in scenarios like structural safety management. Moreover, current bridge construction projects lack advanced analytical approaches and practical management tools for multisystem information integration, time-dependent structural analysis, closed-loop management and decision making. Therefore, it is difficult to conduct a comprehensive and effective assessment of structural safety and adjust the construction plan dynamically, hindering the effective control of the safety risk during the construction of a bridge.

In this study, with the integrated application of information modeling, data integration, time-dependent structural analysis, and sensing and monitoring, a closed-loop management framework and structural safety model for bridge construction are proposed to enable a rapid and comprehensive assessment of the structural stress and safety risks. The remainder of this paper is as follows. Section 2 reviews the relevant research findings. Sections 3 and 4 introduce the methodological framework and implementation, respectively. Section 5 presents and verifies the application of the proposed methods. Finally, Section 6 discusses and concludes the research findings.

2. Literature Review

2.1 Structural Safety During Construction

During construction, structural safety analysis mainly focuses on the safety of the structure under construction. Based on corresponding theories and structural calculation software, the continuous time-dependent characteristics of buildings during construction are described and analyzed to evaluate the safety performance of an entire structural system[10]. Existing codes and standards are focused on the completed structure instead of different states during the course of construction. Hence, the lack of methods for dynamically simulating and tracking structural performance during construction leads to a higher risk level during construction than in the normal service life of the structure. This situation has drawn considerable attention since the 1960s when time-dependent structure analysis methods were proposed[11]. Liu and Fang et al. explored the models and methods of structural analysis during construction[12] and developed an analysis tool accordingly[13], and the aspects of the automatic layout of temporary structures[14], load distribution[15], safety management [16] and risk assessment [17] were studied to provide a theoretical basis for time-dependent structural safety analysis during construction.

Construction safety control and management involves safety inspection, monitoring, and safety analysis and evaluation. Safety inspection requires the safety manager to inspect the workers and the construction site based on the corresponding regulations in order to stop unsafe behaviors[18, 19]. Safety monitoring utilizes sensing technologies to tracking structural behaviors and identify possible risks based on user defined thresholds. Construction safety analysis involves a feasibility study that analyzes and predicts the source and extent of potential hazards of a project to proposes practical safeguards, which is also valuable for safety monitoring. Traditional methods for safety analysis and management are primarily based on the static analysis of structures, without considering the dynamic changes and timing of hazardous factors. Thus, time-dependent structural safety analysis was investigated by Zhang and Hu[10]. Although tests of their method show that it may not be effective for structures with geometrically complex components, the model represents a useful beginning for applying time-dependent structural analysis during construction. Safety evaluation is the assessment of potential risks including structure failures and injuries of workers by taking multiple factors into account.

As a flexible technology for construction monitoring, sensors have been widely used in the field of construction. In 2005, fiber Bragg grating (FBG) sensors were used in tracking the hydration and creep of bridge construction [20]. Omenzetter et al.[21] introduced the ARIMA model for the analysis of bridge health monitoring data, to identify the decrease in structural bearing capacity based on changes in model parameters. Chen et al. [22] developed a lightweight system for bridge inspection. With attractive characteristics as nonintrusivity, light weight, low cost, rapid response time, etc., piezoelectric transducers showed high flexibility in the monitoring of civil infrastructures[23]. In the Guangzhou West Tower project, stress development and low-frequency and low-amplitude environmental vibration during the construction of the project were monitored via wireless sensors[24, 25]. However, the integration of power supply and heterogeneous sensor data remains a key issue[8]. To address this need, based on ubiquitous sensor network technology, a holistic integration environment combining multiple information and communication technologies such as sensors, wireless networking, safety monitoring applications, and independent power supplies in the monitoring of the concrete structure formwork was proposed[26].

2.2 Information Modeling for Construction Safety

A construction project involves many stakeholders, professionals, diverse systems and tools. Related information including models, drawing, spreadsheets, documents, and videos is distributed in different files. The exchange of information among professional systems is poor, and the “information island” phenomenon is prominent.

As early as the 1990s, a 4-dimensional (4D) model linking 3-dimensional (3D) models and project schedule information was proposed, which effectively improved the project management[27]. With further integration with cost, resource, 4D, 5D[28] and even nD technology have become a developing trend in the construction area. Its potential has been explored in applications such as virtual construction[29], workflow re-engineering[30], conflict analysis[31], and construction safety management [10, 31, 32]. Tom et al.[33] thoroughly analyzed engineering applications in construction safety management. Benjaoran et al.[34] implemented automatic detection and early warning based on safety norms, providing protection for collaborating workers.

At the beginning of the 2000s, the concept of building information modeling (BIM) was put forward, beginning another revolution of information modeling in the construction field. At the core of BIM, a data model, called the building information model (BIM model), is proposed to integrate all relevant information of a building project based on 3D digital technology [35]. At present, BIM is widely adopted during construction [36]. Ding et al. [37] integrated a 3D model with progress, cost, and safety information and developed a BIM-based 6D project management system. Zhang et al. [38]

first proposed the overall solution framework for BIM automatic safety inspection, and automatically detected and evaluated the safety of a construction model based on rule sets and corresponding algorithms [39]. By contrast, information integration and sharing for collaboration in design [40, 41] and construction [42] are studied respectively. In safety monitoring and management, Collins et al.[17] thoroughly discussed the visualization of security risk and the safety factors of scaffolding systems, while Taneja et al. [43] reviewed various sensing technologies that may be utilized in construction. Jeong et al. [44] proposed an information modeling framework to incorporate sensing data in bridge monitoring. Hu et al. [45] also developed a unified information model of structural analysis to achieve information sharing among different structural analysis software.

In recent years, along with the increasing attention given to infrastructure, such as roads, bridges, and tunnels, bridge information modeling (BrIM)[46] and civil information modeling with reference to BIM theory and technology have been pursued. Essentially, all of these theoretical methods set up corresponding domain information models based on the object-oriented theory for specific domain problems, and improve the model information via data conversion and information fusion.

2.3 Review Summary

Structural safety and project progress during construction are often difficult to effectively coordinate and guarantee, which is particularly important for large-scale bridges. Although time-dependent structural analysis, and sensing technology are adopted in construction, there are still gaps to achieve a closed-loop management of structural safety for bridge construction. These gaps include the following:

1. Modeling of different construction states for time-dependent structural analysis is tedious and time-consuming, and the automatic generation of structural models cannot effectively incorporate geometrically-complex objects.
2. Heterogeneous data integration and monitoring of large structures to avoid conflicts and safety issues within the construction process remain a problem[47].
3. Most importantly, the engineering management, structural simulation, and monitoring systems remain independent of each other. Research on the integration of these systems and their information is rare. Hence, effectively conducting the entire process of safety management of construction is difficult.

Therefore, a unified information model and framework are needed to integrate 3D design data, structural simulation results, monitoring data, and construction planning from different systems. A closed-loop process for structural safety management can be achieved by dynamically simulating, monitoring, and assessing the structural performance during construction.

3. Framework and Methodology

3.1 Framework for Closed-Loop Management of Structural Safety

Generally, closed-loop management of structural safety can be divided into two levels: the workflow level and the data level. At the workflow level, tasks of a PDCA loop are completed by different stakeholders. That is, structural simulation, construction planning, structural monitoring and safety risk evaluation are conducted by designers, contractors, consultants, respectively. At the data level, work of different stakeholders uses different systems and could not share all the data easily, so the printed documents and drawings are widely used. Which means, the PDCA loop is achieved through manually inputting and interpreting data, thus taking a long time and leading to overlooking of safety hazards. In this situation, it is difficult to effectively account for the entire process of construction safety management when the systems of project management, structural simulation analysis, and structural monitoring are independent of each other. To solve this problem, a framework consisting five layers as shown in Figure 1, is proposed in this study.

(1) Model Layer

The bottom layer is the model layer, which describes the data models related to structural safety in construction. These data models include the 3D product model, schedule model, structural analysis model, sensing data model, etc. They should be incorporated into an integrated model. Analyzing the structures of the abovementioned data models and extracting the relationships among their components enables the overall structure of the integrated data model to be established for data conversion and sharing, data integration, and decision making, providing the foundation for the closed-loop management of structural safety in construction.

(2) Database/Cloud Layer

With the model defined in the model layer, a database schema can be developed to house all the data related to structural safety management. Schedules, 3D product data, structural analysis data, sensing data, and even inspection data are all kept in the database for further contributions to the decision-making process. Since massive data are collected in the construction phase, NoSQL (not only SQL) databases such as Cassandra, HBase, MongoDB may be utilized. Web services or application programming interfaces (APIs) are also provided in this layer for better data sharing capacity.

(3) Platform Layer

On top of the database or cloud layer, various engineering and management software can be integrated. When integrating these systems, different approaches are utilized. For example, direct data conversion is one of the simplest methods, but due to poor reusability, it is not widely used now. Conversely, middleware is flexible and is widely used for integration. To address domain-specific problems, algorithms are investigated and prototype tools are usually developed. With respect to structural safety management during construction, algorithms and tools to establish the relationship among various data model and convert them to the defined integrated model are needed. Additionally, tools and platform are required to simulate and visualize the construction process, assess the structural safety and control possible risks. These considerations are important to achieve closed-loop management of structural safety during the construction process.

(4) Workflow Layer

In this layer, each procedure of structural safety management in construction is described. First, the schedule is developed based on construction planning technologies such as discrete event simulation[48], which provides information for how the structure are constructed. When planning the construction process, simulation is usually conducted to identify possible risks. In addition, a monitoring plan is established based on the simulation and previous experience. Then, the structure will be constructed based on the schedule. Meanwhile, the status of the structure is monitored according the monitoring plan. As the construction progresses, the sensing data are continuously collected. By simulating the on-going structure, we can compare the sensing data and simulation results to identify differences and reveal possible safety risks. Finally, with deep investigation of the identified issues, the construction schedule and monitoring plan can be further improved. The improved schedule and monitoring will reduce the possible risks and increase the structural safety in construction. Implementing the plan, do (execute and monitoring), check (analyze and check), and adjust (improve plan) loop enables structural safety in construction. At the same time, knowledge related to structural safety management can be gained through this workflow, which is important to improving the construction industry.

(5) Stakeholder Layer

The final layer is the stakeholder layer in which different stakeholders are involved. Generally, the project manager, structural engineer, safety manager, monitoring engineer, and inspector are the main stakeholders involved in structural safety management. The project manager leads the overall project and consider progress, safety, and quality together to ensure the success of the project. The safety manager mainly focuses on the safety of the workers and the structure with help from the structural engineer, monitoring engineering and project manager. The structural engineer can help to simulate the on-going structure and identify the most dangerous parts of the structure. The monitoring engineer utilizes various sensors and the monitoring system to track the performance of the on-going structure. If any sensed data are out of predefined thresholds, a warning will be issued. Moreover, the safety inspector can check and identify possible on-site safety issues and help to fix them.

In the proposed framework, the upper layer depends on the lower layers as described above. From the top layer to the bottom layer of the framework, by identifying the key stakeholders, tracking corresponding workflows, and analyzing the involved systems and tools, one can develop an integrated model, related algorithms and the platform to ensure the closed-loop management of structural safety in construction.

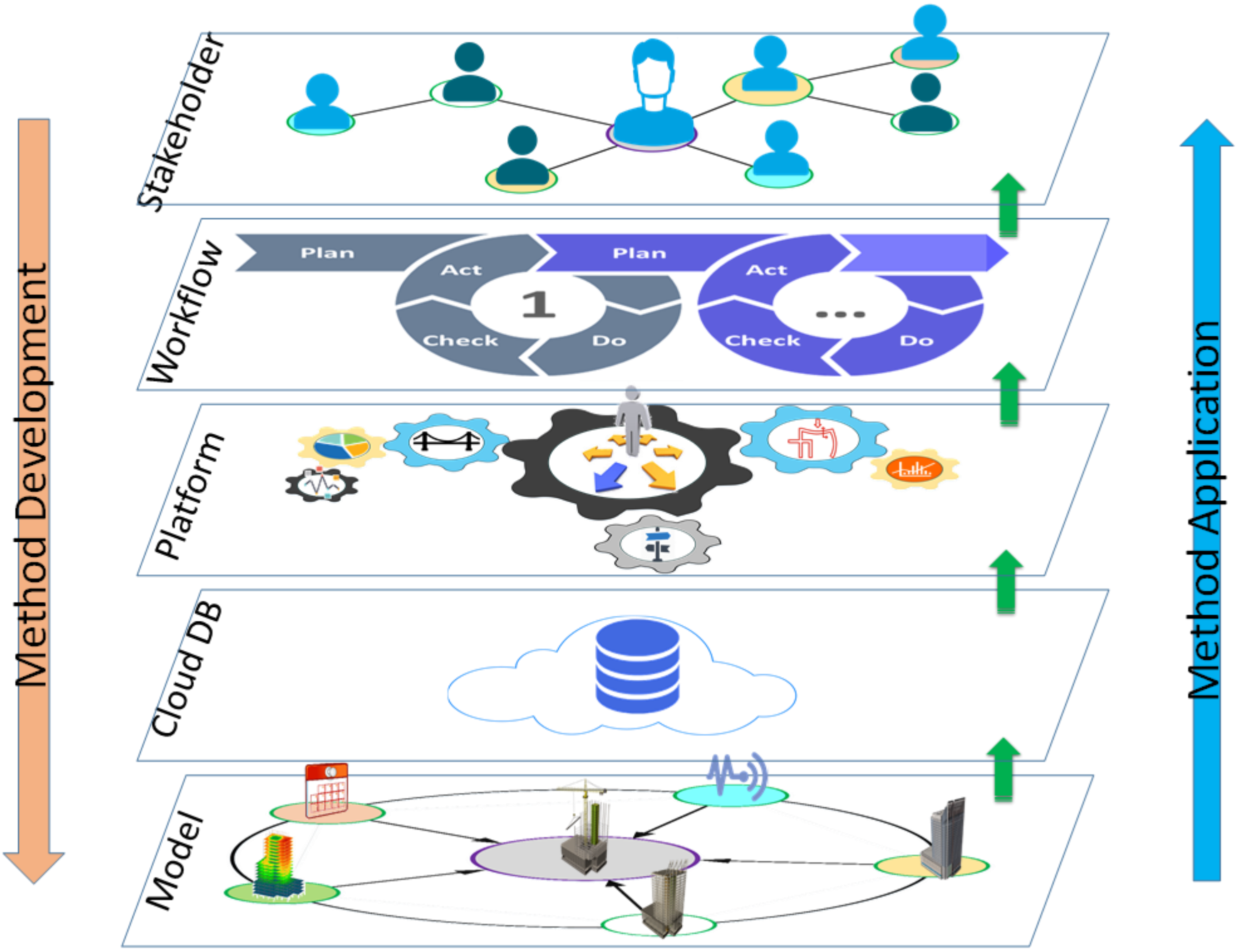


Figure 1 Framework for Closed-Loop Management of Structural Safety

3.2 Methodology

Multisystem integration and information sharing are prerequisites for the dynamic and closed-loop control of construction safety. A series of methods and means have been proposed in this field, such as direct data conversion, federated database, middleware, and enterprise service bus[49] Middleware integration was first proposed by Wiedehrold[50]. This approach can encapsulate the data source via the wrapper and convert its data model to a unified model with which the middleware can provide users with a consistent data access mechanism. Given the advantages of simple operation, strong autonomy, structured compatibility and unstructured data, data integration is widely applied.

Therefore, the middleware approach is applied to realize the integration of engineering management, structural analysis, and structure monitoring system to form the overall research method as shown in Figure 2.

Figure 2 Research Methodology

The first step is information modeling. Based on the reverse engineering method, the structure and content of the data models of existing project management, structure analysis, and structure monitoring systems are analyzed, and key objects such as beam, plate, pier, task are identified. The relationship between these objects can also be extracted from built-in data model of abovementioned systems. Then, relationship among objects of different systems and their mapping mechanism can be established together with domain experts. Finally, a unified model is created via the object-oriented modeling approach.

On the basis of the unified model, the second step is algorithm development. An algorithm for data model conversion is first developed to transform the different data models of engineering software related to structural safety in construction to the unified model. Then, a few algorithms are proposed to establish a relationship between the components of each part of the unified model. For example, linking the 3D product data to the schedule data and finding structural members related to a specific 3D product component are achieved with the proposed mapping algorithms.

The third step involves implementing the proposed information model and algorithms as a prototype are the third step. A relational database is adopted to house all the data related to structural safety management. Then, middleware and a prototype system are developed to encapsulate the proposed algorithms and provide functions for structural safety management. For example, construction process visualization, structural risk warning, and safety assessment can be included in the prototype system.

Finally, the proposed framework and approach is validated with a case study method. The prototype system is deployed and tested in the construction of a large bridge project. After testing of the implemented model, algorithms following the proposed workflow, statistics and feedback of engineers are collected. With the collected data and case analysis, the proposed framework can be verified and further improved.

3.3 Bridge Safety Information Modeling

Based on the aforementioned methods, and previous structure information modeling[45] and 4D modeling, we further analyzed the composition and relationship between the structure simulation results and bridge monitoring data to form the BrSIM, as shown in Figure 3. The entire model can be divided into several major parts, which describe the 3D product model, the construction process and schedule, the structural analysis model, the structural simulation result, and the sensing data.

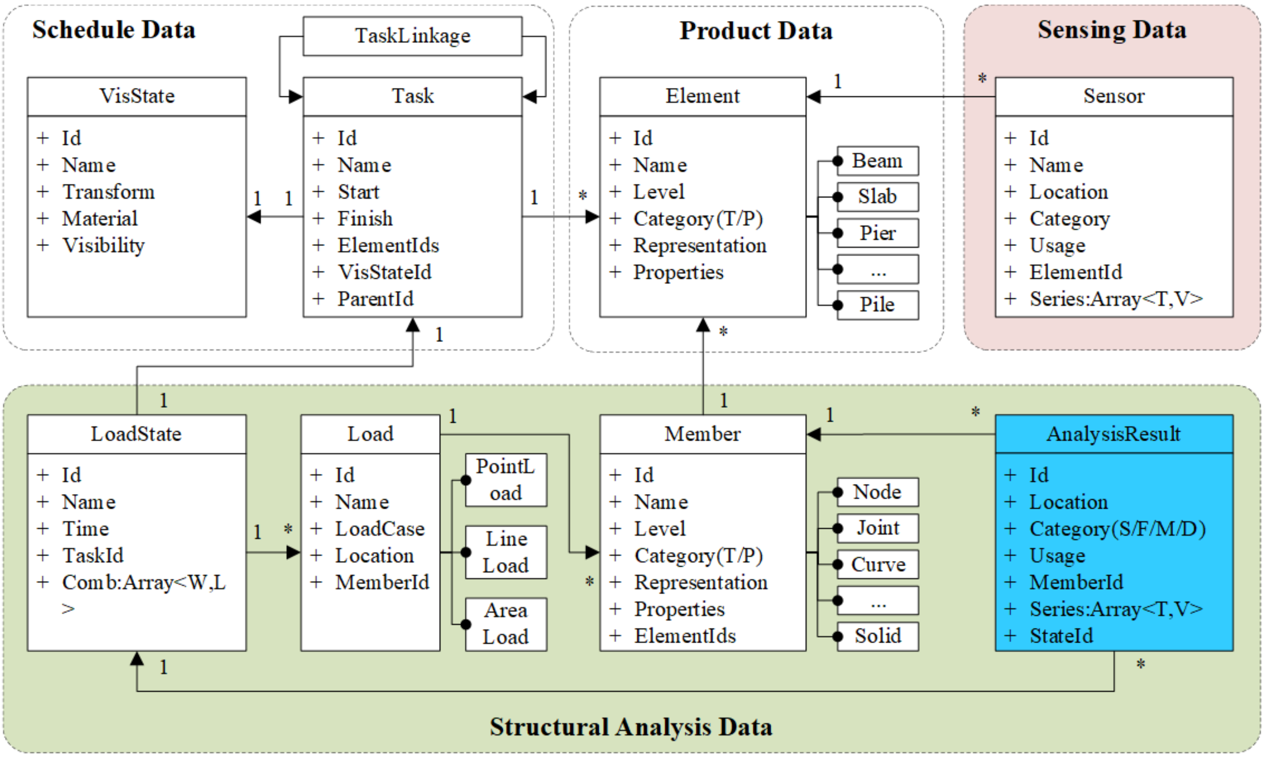


Figure 3 Bridge Safety Information Model

As shown in Figure 3, in view of the project management and visualization process, the appearance of the model is not usually modified or adjusted. Therefore, considering the information expression and visualization effect, we use the surface-based model to express the geometric information of the 3D engineering products and their components. The basic information includes the 3D shape, spatial location, material, and volume. On these bases, information on the time and construction process based on the construction progress is added to describe the construction status and spatial location of 3D products at different times during construction. The structural analysis information includes structural analysis model and simulation results. The structural analysis model includes the basic structural element, node, material, and section, as well as the load state, load, and constraint required for the structural analysis. The structural analysis results describe the strain, displacement, and stress at different locations of each structural unit. Finally, the monitoring data from sensors and manual measurements include information such as the number, location, data type, and usage and data series.

Given that time-dependent structural model requires relevant information of constructed 3D products or elements at a certain time, a 4D model is needed, which can be formed by combining the 3D product model with the construction schedule. To further simulate the jacking process of bridges, the information for describing spatial transformation can be further added[51]. Thus, the parts of the model related to the 3D product model and the schedule can be derived from the 4D model and will not be described in detail. A previously proposed method[45] defined a one-to-one relationship between the 3D elements and the structural members to directly generate the structural analysis model from a 3D product model. However, considering the abstraction of structural mechanical features during structural design, the relationships between these features are not simple one-to-one relationships; rather, a structural member may often correspond to multiple 3D product elements. In addition, different load cases should be considered for different construction stages.

Therefore, in this study, we further extend the previous model to reflect the actual situation of construction in the following aspects:

(1) Relationship between the 3D product model and the structural analysis model

Instead of one-to-one relationship, an one-to-many relationship between the 3D product model and the structural analysis model is considered. Generally, the 3D product model created in the design phase mainly describes the geometry and appearance of a bridge and is used for cost estimation, prefabrication, manufacturing, 4D visualization and other applications in construction. Thus, the elements of the 3D product model may consist of many parts or components. These kinds of elements are also called assembled elements and widely used to represent prefabricated elements. For example, a frame element of a steel structure is usually modeled as an assembled element consist of several steel plates, and each steel plate could be cut and manufactured in the factory. Other information, such as the geometry or shape, quantity, cost, and type, is also embedded in the 3D product model (left of Figure 4). Since few changes to the 3D product model are made during construction, the different parts of this element type can be taken as a whole. In the development of a structural analysis model of a building or bridge, the elements of the 3D product model can be abstracted as different structural members, such as lines, plate/shells, or solids. The sections, materials, constraints, and loads that are important for structural analysis are also included in the model(right of Figure 4). Different structural engineers may generate different models of the same building or bridge. That is, more than one element of the 3D product model may be taken as a single structural member. Therefore, a one-to-many relationship is more suitable in this situation. In a relational model, this relationship is implemented as the ElementIds property of a structural member.

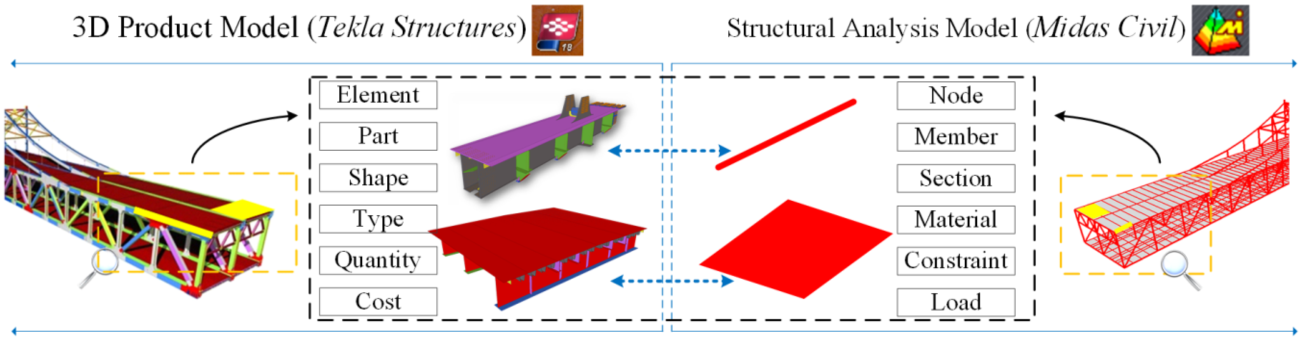


Figure 4 Comparison of 3D Product Model and Structural Analysis Model

(2) Time-dependent features of the structural analysis model

The construction stage is modeled to describe the change in loads, node connections and supports as the construction progresses. Under normal circumstances, as the construction progresses, the loads, connections and supports of the on-going structure will change accordingly. Therefore, we need to model the structural state of the on-going structure after every step is taken. Here, we abstract the structural state as a load state of the on-going structure. That is, as the construction progresses, a series of conditions will be formed and captured as load states, each of which includes the corresponding node connections, supports and loads as well as the combination coefficient of different loads. Since changes to the on-going structure are the results of different construction tasks, which are modeled as a schedule, a relationship between the load state and the task in a schedule is established. Considering this close relationship between the load state and construction process, we apply the TaskId to describe the relationship between the load state and construction task node during construction.

(3) Simulation results

Entities to capture the results of the structural simulation are also introduced, which provide the ability to compare the simulation result with the integrated sensing data. A set of structural analysis results will be generated when simulating each load state. The analytical results include the force, displacement, stress, strain and relative location of each member and node. Thus, a relational model with time series arrays (bottom of Figure 3) is proposed to represent simulation results and their relationship to structural members.

For large-scale buildings or bridges, the structure monitoring and measurement plans are designed prior to the construction process to determine the monitoring points, indexes, and frequencies. Then, with the monitoring system deployed, the stress and strain can be dynamically tracked, and a few time series are collected. Deformation of the structure is also collected as a time series based on the on-site measurements of personnel. Based on the drawings and information of the monitoring and measuring plan and the site layout, information such as the number, location, and monitoring data of the monitoring equipment that corresponds to each monitoring point is collected and analyzed. Integrating the corresponding elements of the 3D product model enables the connection between the monitoring data and 3D elements to be established. Finally, a data entity called sensor is introduced to persist basic properties and monitoring data (right top of Figure 3).

4. Implementation

4.1 Automated Data Integration for BrSIM Establishment

4.1.1Region-based Matching of the 3D Product Model and Structural Analysis Model

As described above, one-to-one mapping from a 3D product to a structural analysis model is not suitable to represent the relationship between the two. Instead, a one-to-many relationship may be more appropriate. In this paper, a region-based matching method is proposed to integrate the two type of models (Figure 5).

The first step of the proposed method is model alignment. Considering that different coordination systems may be adopted by different designers or engineers, this step can be simplified by choosing some points as references instead of move, rotate or scale the model manually.

Then, to accelerate the matching process, both the 3D product model and the structural analysis model are divided into different regions. Given that the models are aligned in the same coordination system, a simple model partition strategy is utilized, and the model can be split into a few parts by dividing the X, Y, and Z axis based on the axes grid used in the design. To locate different 3D elements or structural members in different regions quickly, the axis-aligned bounding box of the 3D elements and the center of the structural members are utilized. If more than 4 corners of the bounding box of a 3D element are in a pre-created region, then the 3D element will be placed in this region, and if the center of a structural member is in a given region, it should also be placed in this region. Although applying these geometric features does not provide a fully accurate alignment of the models, it provides a reasonable result. This strategy is suitable for 3D product model with complex geometries and structural analysis model without large solid members, and this situation is very common in buildings and bridges.

After the elements and members are split into different regions, they are matched by iterating each region. For each 3D element E and structural member M that form a pair P_{em}, the algorithm checks whether the center of M is enclosed by the bounding box of E in the first phase. If this is the case, then P_{em} will be added to the candidate collection. If there are two structural members related to the same 3D element, the algorithm proceeds to phase 2. Additional steps are conducted to check whether the 1/4 and 3/4 points (geometric features) of the structural member are also contained in the bounding box of the 3D element. If one of the two feature points is outside of the bounding box, then this 3D element and structural member pair should be remove from the candidate collection; otherwise, the pair will be reserved. Thus, the two heterogeneous models can be integrated and utilized in the subsequent applications.

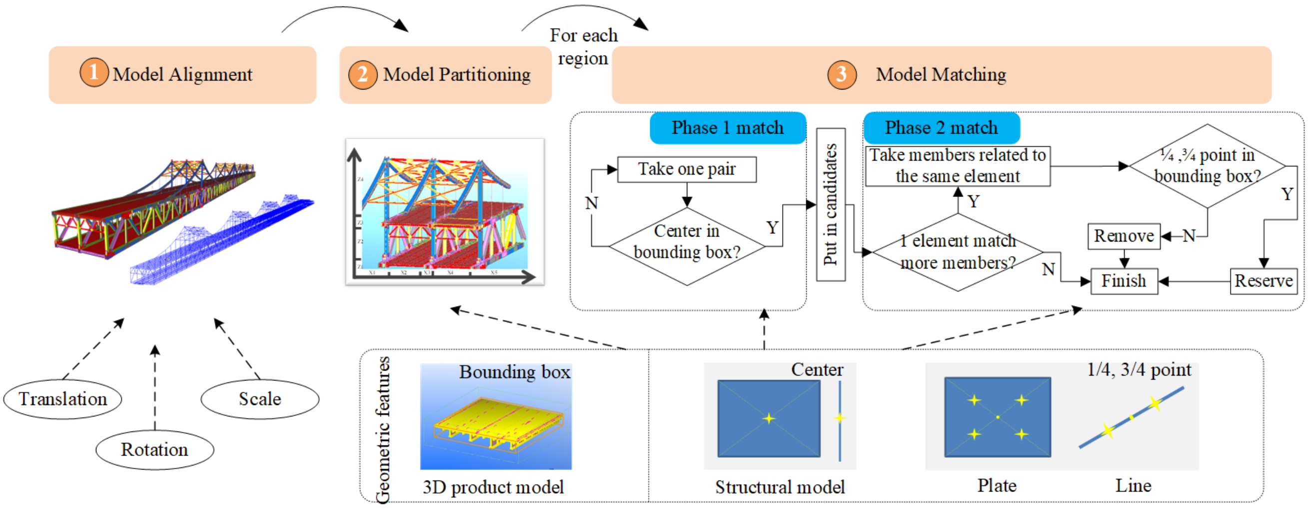


Figure 5 Region-based Matching of 3D Product Model and Structural Analysis Model

4.1.2Integration of Structural Analysis Results and Sensing Data

After the correspondence between the 3D product model and the structural analysis model is established, the structural analysis results and the sensing data during construction can be integrated. As such, the theoretical analysis results are analyzed and compared with the actual measurements.

As indicated in Figure 6, the structural analysis software enables export of the stress, strain, and displacement at different positions of every structural member in the text format . This software covers the member identity (ID), location, axial force, shear force, bending moment, stress, strain, and deformation. This information allows the direct establishment of the relationship between the above structural analysis results with structural members according to their IDs.

In terms of the structural safety during construction, the internal force, strain, deformation, and settlement of the main structure and temporary structures are usually tracked by combining the dynamic monitoring system and the manual measurements. In the actual operations, every monitoring or measuring point is numbered according to the monitoring plan, and the number of every point is indicated on the data interface of the monitoring system and in the manual monitoring form. To establish the relationship between the sensing data and the 3D product model, the two data sets are matched using the location of each monitoring point and the AABB bounding box of the 3D elements.

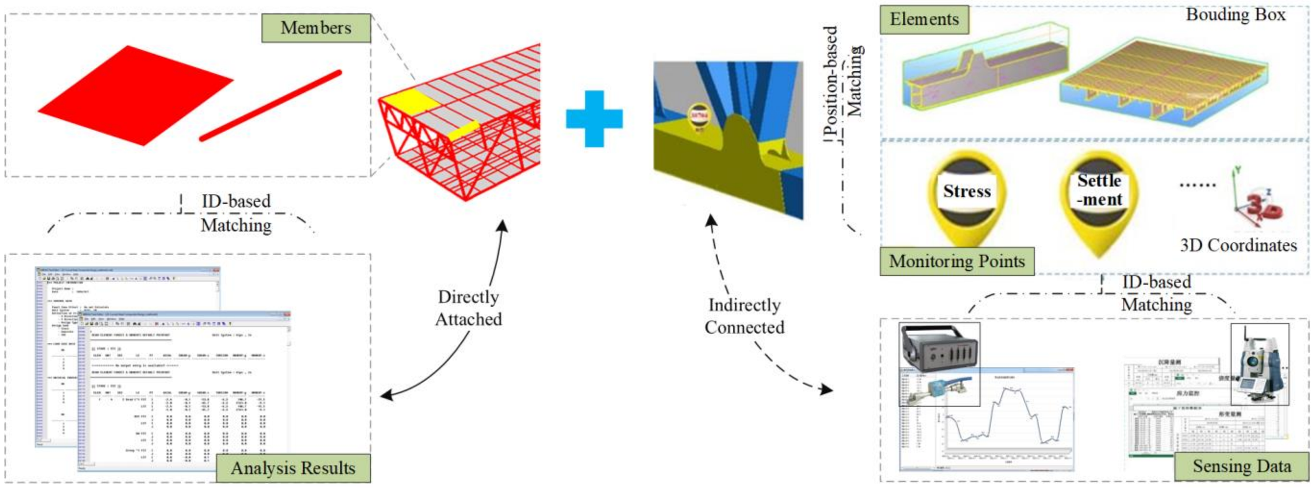


Figure 6 Integration of Simulation Results and Sensing Data

Combining the theoretical analysis results and the monitored data allows the sensing data to be further queried, analyzed and visualized. For example, historical retrieval of the sensing data may be implemented and the sensing data and theoretical simulation results of structural members under different conditions may be compared and analyzed, to help in risk identification, warning, and assessment.

4.2 Semi-Automated Structural Analysis Model Generation

4.2.1Frame Model Generation for Simulation of the Whole Structure

Frequent adjustment of the constraint type, node displacement, and other parameters due to heavy workload in updating the structural analysis model during construction severely hinder the efficiency and popularization of time-dependent structural analysis. Based on the temporal information in the 4D model, the structural state at a specific time may be quickly obtained, so that a model for the structural analysis during construction can be established. In view of the complicated process and assumptions of directly converting the 3D product model into the structural analysis model to address the complex shapes of elements and joints, the relationship between the 3D elements and the structural members of BrSIM proposed in the present study is used for the direct extraction of the structural analysis members corresponding to a specific time. Meanwhile, the measured displacement and deformation at the support point are exported as the constraints and initial conditions of the model, thereby realizing the rapid generation of the structural analysis model and the reuse of information (Figure 7) . The specific method is described as follows:

1) The current construction time is selected as the basis for the generation of the corresponding structural analysis model.

2) The completed task node is then extracted at this time point, thereby filtering out the completed 3D elements according to the relationship between the construction task node and the 3D elements.
3) Based on the relationship between the structural members and the 3D elements, information such as sections and materials about the corresponding structural members and nodes is extracted.
4) Then, the load and constraint information of the structural members and nodes, which is already defined in structural analysis model, can be extracted. The dead load of the structural members can also be calculated based on the information about the 3D elements.
5) Moreover, based on the relationship among the structural members of the 3D elements at the monitoring point, the structural analysis model is further updated and improved using the monitored information such as the displacement of the support.
6) Finally, the model is exported to the structural analysis software. After further review and adjustment by the user, the structural simulation is performed.

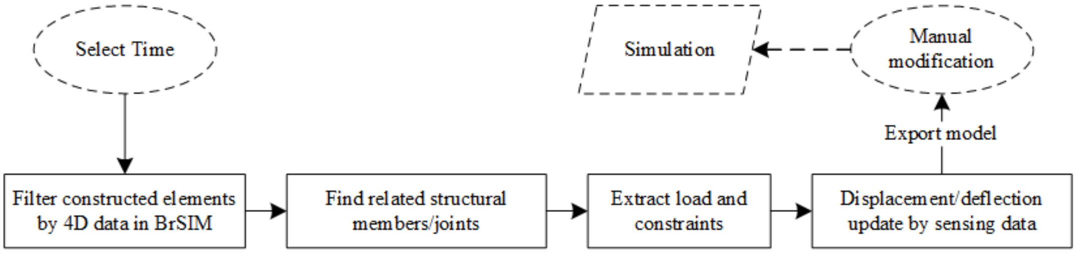


Figure 7 Process for Frame Model Generation based on BrSIM

4.2.2Detailed Model Generation for Simulation of Key Structural Members

Except for structural analysis of the whole structure based on a frame model in Midas Civil software, additional in-depth analysis of certain members or nodes is also necessary to ensure structural safety. Based on previous experience, structural members or nodes that are highly important during construction should be considered for further detailed simulation. Moreover, with real-time structural sensing data and multi-stage structural simulation results integrated in BrSIM, the following elements or nodes may be further analyzed to avoid potential safety issues:

1) Elements or nodes whose simulated stress, deflection or other factors exceed predefined thresholds;
2) Elements or nodes with their measured or monitored stress, deflection or other factors exceed predefined thresholds;
3) When there is a big difference between the simulated and monitored stress, deflection or other factors, in-depth analysis of corresponding elements or nodes should also be conducted.

The stress states of such members or nodes are often analyzed using the finite element modeling method, and their geometrical features may directly adopt the geometrical information of 3D elements.

The loads of such members or nodes can be extracted from the simulation results of the overall structural frame model based on Midas Civil software. Therefore, a method to establish a finite element model for key members or nodes based on BrSIM is adopted, thereby achieving the conversion of the BrSIM to the finite element model and simulating its mechanical behaviors with software such as ANSYS or ABAQUS. As Figure 8 shows, the finite element model can be exported through the following steps:

1) The 3D elements to be exported are selected by users.
2) Based on the previous method[45] , the 3D model for the selected elements is converted into the relevant information describing the 3D finite elements.
3) The structural members corresponding to the selected 3D elements are found, and their adjacent structural members are identified.
4) Based on the simulation results of structural frame model, the information about the load, deformation, etc. at the locations of the connections between the selected structural analysis members and their adjacent members is extracted and exported.
5) The exported model is imported into finite element simulation software such as ANSYS for the analysis.

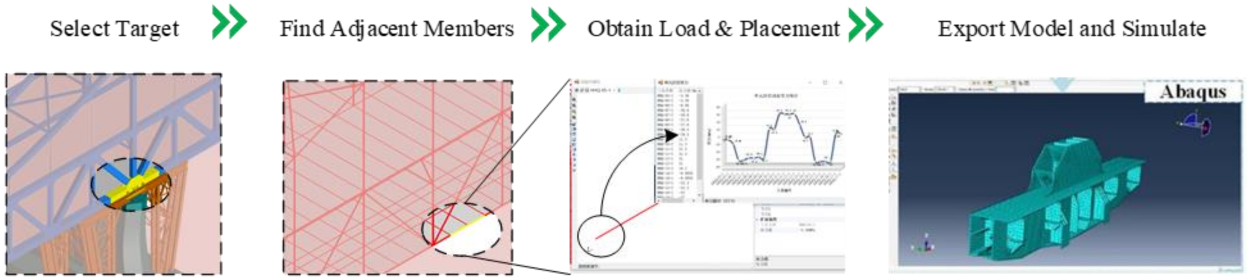


Figure 8 Detailed Model Generation for Key Members

Generating structural analysis model at a certain time saves quite a lot of time for repeated modeling work, making it possible to apply time-dependent structural analysis during construction. With structural analysis model of the whole structure and key components generated, safety assessment can be achieved at different scale, enabling a more comprehensive evaluation of the structural safety during bridge construction.

4.3 Structural Safety Warning and Assessment Based on BrSIM

4.3.1Risk Identification and Warning for Structural Safety

The structural safety risk identification and warning system is designed to detect and predict all hidden structural safety problems during construction, thereby reminding the relevant management staff of timely measures for improvement and pre-control. The warnings based on the monitored data is usually graded, as illustrated in the following formulas. For the monitoring indicator p, a series of limits L_i is set. When $L_i \leq p < L_{i+1}$, the corresponding risk level is R_i. For certain important indicators, the absolute value and the rate of change are often considered with a series of limits set. The risk level usually takes a higher value, and the overall risk level increases when both reach a certain level of risk at the same time. The final risk level $g(p)$ is calculated with the formula below where p and p' represent the absolute value and rate of change of the monitoring indicator, respectively, and $f(p)$ and $h(p')$ represent the corresponding risk rating functions.

$$f(p) = \begin{cases} R_2 \ , & |p| > L_2 \\ R_1 \ , & L_1 < |p| \leq L_2 \\ R_0 \ , & L_0 \leq |p| < L_1 \\ 0 \ , & |p| < L_0 \end{cases} \tag{1}$$

$$g(p) = \begin{cases} R_2 \ , & f(p) = R_2 \ or \ h(p') = R_2 \ or \ (f(p) = R_1 \ and \ h(p') = R_1) \\ R_1 \ , & f(p) = R_1 \ or \ h(p') = R_1 \ or \ (f(p) = R_0 \ and \ h(p') = R_0) \\ R_0 \ , & f(p) = R_0 \ or \ h(p') = R_0 \\ 0 \ , & f(p) = 0 \ and \ h(p') = 0 \end{cases} \tag{2}$$

In previous studies on risk identification and warning, the thresholds were determined according to the relevant standards and specifications. The thresholds were generally determined by the material strength and the engineering experience. In the present study, structural simulation results are introduced to support the comparison of the theoretical simulation result and the monitored data, enabling the comprehensive analysis of the traditional risk indicators and the differences between the simulation results and the monitored data. As a result, hidden risks may be found earlier.

Specifically, the corresponding risk rating and warning thresholds are established based on standards for construction safety and knowledge gained in previous projects. For stress and other indicators, risk warning thresholds based on the comparison between the simulation results and the monitored data are also introduced. Since less knowledge on the differences between the simulation results and the monitored data was obtained, the corresponding warning thresholds are discussed and specified by a group of engineering experts. The final statistics of certain thresholds are shown in Table 1 (for the cases with multiline criteria, the current level of risk may be determined by meeting any of the lines).

Table 1 Definition and Thresholds of Risk Levels

Data Type	**Thresholds**	**Risk Level**		
		High (Red)	**Medium (Orange)**	**Low (Yellow)**
Stress *s*	Maximum Stress *S* Simulated Stress θ of Element	$\frac{\lvert s\rvert}{S} \in [1, +\infty)$	$\frac{\lvert s\rvert}{S} \in [0.9, 1)$	$\frac{\lvert s\rvert}{S} \in [0.8, 0.9)$
		$\left\lvert\frac{s}{\theta}\right\rvert \in [1.3, +\infty)$	$\left\lvert\frac{s}{\theta}\right\rvert \in [1.2, 1.3)$	$\left\lvert\frac{s}{\theta}\right\rvert \in [1.1, 1.2)$
		$\frac{\lvert s\rvert}{S} \in [0.9, 1) \& \left\lvert\frac{s}{\theta}\right\rvert \in [1.2, 1.3)$	$\frac{\lvert s\rvert}{S} \in [0.8, 0.9) \& \left\lvert\frac{s}{\theta}\right\rvert \in [1.1, 1.2)$	
Total Settlement *st* and its Rate of Change *st'*	Maximum of Total Settlement *St* Maximum of Rate of Change *St'*	$\frac{\lvert st\rvert}{St} \in [1, +\infty)$	$\frac{\lvert st\rvert}{St} \in [0.9, 1)$	$\frac{\lvert st\rvert}{St} \in [0.8, 0.9)$
		$\frac{\lvert st'\rvert}{St'} \in [1, +\infty)$	$\frac{\lvert st'\rvert}{St'} \in [0.9, 1)$	$\frac{\lvert st'\rvert}{St'} \in [0.8, 0.9)$
		$\frac{\lvert st\rvert}{St} \in [0.9, 1) \& \frac{\lvert st'\rvert}{St'} \in [0.9, 1)$	$\frac{\lvert st\rvert}{St} \in [0.8, 0.9) \& \frac{\lvert st'\rvert}{St'} \in [0.8, 0.9)$	
Deformation *d*	Maximum of Deformation *D*	$\frac{\lvert d\rvert}{D} \in [1, +\infty)$	$\frac{\lvert d\rvert}{D} \in [0.9, 1)$	$\frac{\lvert d\rvert}{D} \in [0.8, 0.9)$
……		-	-	-

The relevant monitoring data are analyzed and processed based on the above thresholds, thereby obtaining the risk of different monitoring points under different conditions at different time. The data are visualized in the form of a chart with colors to reflect relevant risk levels.

4.3.2Overall Assessment of Structural Safety

Based on the above safety risk warning system, a variety of structural safety-related indicators are comprehensively considered. Since the indicators utilized in risk warnings reflects the safety status or possible risk only at a specific point or location, an approach to assessing the safety of the whole structure is needed. To consider a number of safety indicators, the analytic hierarchy process (AHP) is usually adopted, which provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions[52]. When the problem is modeled as a hierarchy, the weight of each node of the hierarchy can be evaluated through a series of pairwise comparisons. Then, with the safety-related indicators of each node defined, the overall structural safety can be assessed. In this research, a three-layer hierarchy is utilized (Figure 9), in which the overall structural safety is first divided into the main structure and the temporary structure. Then the safety of the main structure is further decomposed as the stress, the deflection, and the elevation difference of the supports, while the safety of the temporary structure is made up of the stress, the settlement and the deformation. When calculating the safety-related indicators or scores of the nodes of the lowest layer, the criteria in Table 2 are used. By utilizing the risk level defined above, the criteria can consider both the engineering experience reflected in related standards or specifications and the difference between the simulation results and the monitored data. Therefore, with weights of nodes derived from the AHP method, the overall safety of the structure can be successfully evaluated.

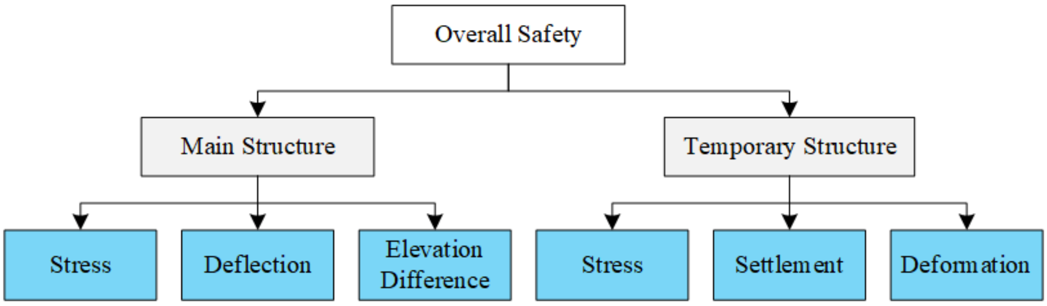


Figure 9 Hierarchy of Indictors for Structural Safety

Table 2 Safety Scores of Different Indicators

Level	Scores	Severity	Criterion

I	0~20	Very Dangerous	The monitoring points in the High risk level are more than 30%
II	20~40	Dangerous	The monitoring points in the High risk level are between 15-30%
III	40~60	Medium	The monitoring points in the High risk level are between 5-15%, or the monitoring points in the Medium risk level are more than 30%
IV	60~80	Safety	The monitoring points in the High risk level are less than 5%, and the monitoring points in the Medium risk level are less than 15%
V	80~100	Very Safety	The monitoring points in the Medium risk level are less than 5%, and no monitoring points are in the High risk level

5. Case Study

5.1 Case Introduction

The Shi-Ji Yellow River Bridge (YRB) in Jinan, the capital city of Shandong province in China, is a double-decked bridge; the lower level has a four-lane railway and the upper level is a two-way six-lane highway. The main bridge is 934 m and weights approximately 36, 249 t. It is currently the largest bridge across the Yellow River in Jinan. Considering the flood season, and surrounding environment of the Yellow River, the bridge construction adopts the incremental launching method, by which the assembly is completed on one side of the river and the bridge is further launched to the desired position incrementally. In view of the bridge's weight and the pier spacing, there are many cantilever situations in the jacking process, where the elements under very large stress are prone to failure and even demolition. In addition, the section of the bridge consists of three pieces of trusses, and three supports are used in the jacking process. The differences in elevation of the three supports may greatly affect the reaction force on the support, resulting in the failure or even demolition of the elements. BIM, sensing technology, and time-dependent structural analysis and risk management during construction are combined considering the characteristics of bridge construction. The relevant functional modules are developed and expanded on the previous 4D-BIM platform[51]. The software and hardware environment architecture are set up, and the proposed method and platform are tested with the construction progress. The surface steel strain gauge is used for strain measurement due to its high sensitivity, convenient readability, and good stability. The gauges are distributed on various parts of the bridge (Figure 10).

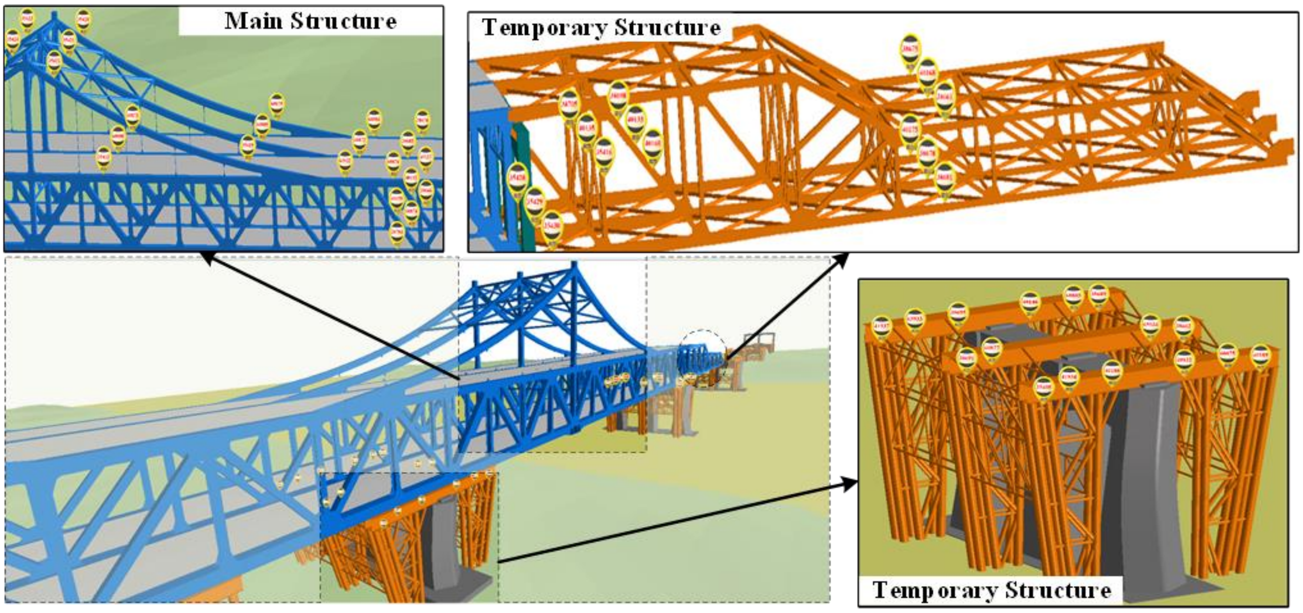


Figure 10 Monitoring Plan

Based on the proposed method and algorithm, the overall application process is established as shown in Figure 11. Information on the three-dimensional product model designed by Tekla and the structural analysis model by Midas, as well as the construction schedule, monitoring plans, and other information, is collected and imported into a unified platform by developing the corresponding data interface. Then, the 4D relationship is established with the schedule and the 3D product model, which is then linked to the structural analysis model and the distribution of monitoring points. Subsequently, combined with the actual progress of construction, the relevant monitoring and measuring data are continuously acquired with strain gauges, total stations, and other devices, and then integrated into the platform. Meanwhile, the structural analysis model of key construction stages is derived and analyzed, and the results are integrated into the platform, thereby achieving the hierarchical construction safety risk warning, visual analysis, historical data tracing, and safety evaluation. Finally, the results of safety evaluation and assessment can be utilized to identify potential elements and positions that safety hazards may happen, thus, further improving the planning, and safety management of the next construction stage.

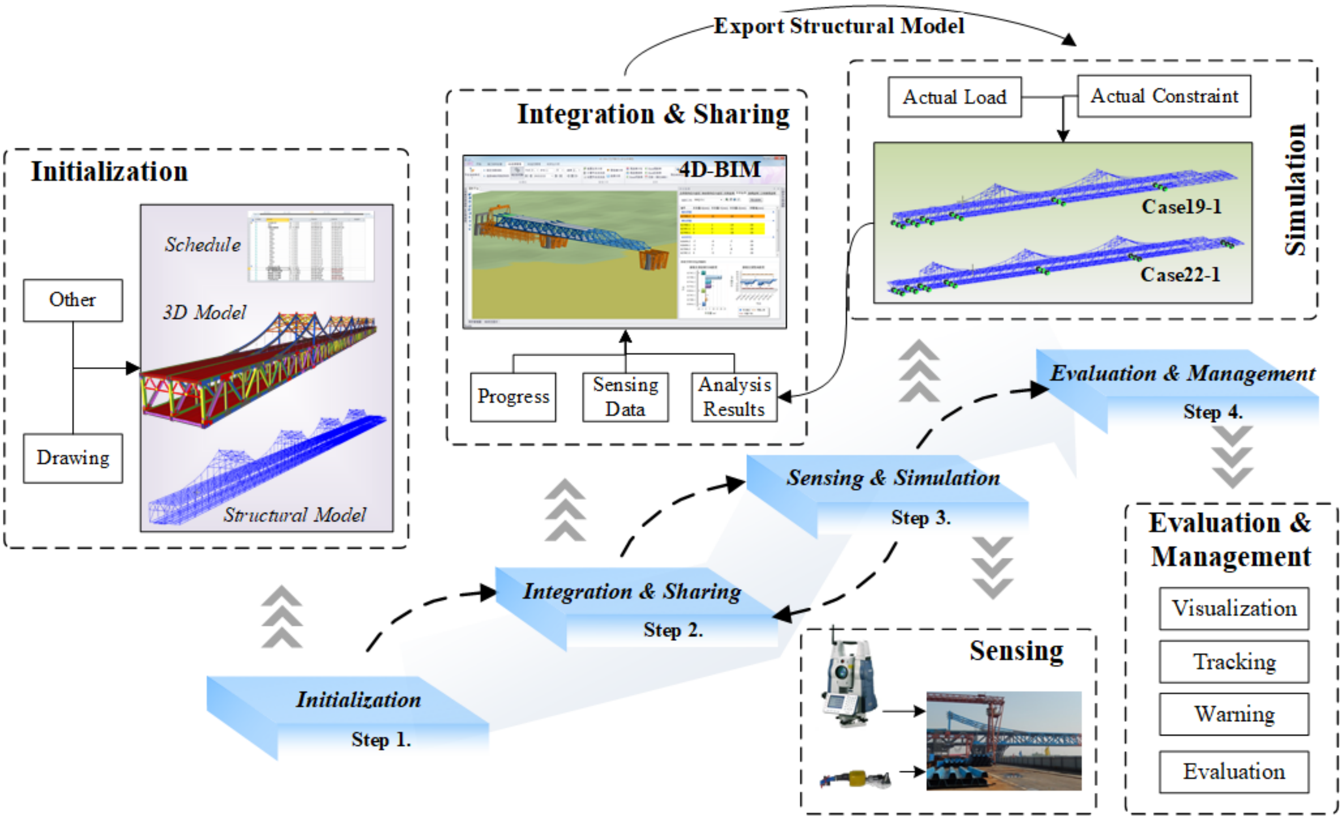


Figure 11 Process for Data Collection, Modeling and Application for Structural Safety Management

5.2 Data Integration and Modeling

The design team creates the 3D bridge model with Tekla software. To improve the efficiency of visualization and processing of the data imported in the platform via the IFC data interface, different parts of a single 3D element are combined in order to reduce the total number of elements. A total number of 14, 055 elements are available. The structural design team establishes a structural analysis model with Midas Civil, covering a total of 13, 842 members such as lines and plates, which is imported into the platform via the mct data interface. The schedule is compiled with Microsoft Project and 3D information about the monitoring points is also imported into the system.

Then, based on the previously proposed region-based matching algorithm, the axial direction of the bridge is defined as the y-axis direction, the vertical direction is defined as the z-axis direction, and the x-axis direction is determined by the right-hand coordinate system. According to the grid features, the centers of 3D elements and structural members are selected as the feature points to divide the x-axis into 5 segments and the z-axis into 4 segments, forming a total of 20 regions. Thus, the 3D product model is semi-automatically correlated with the structural analysis model. Based on the algorithm, 13,655 structural analysis units are linked, with a rate of autocorrelation up to 98.6%. Similarly, the relationship between the monitoring point and the 3D elements is established by calculating the point included in the axis-aligned bounding box. Finally, the relationship between the 3D elements and the schedule is established based on the original features of the 4D-BIM platform. Statistics of the BrSIM are summarized in Table 3.

Table 3 Statistics of BrSIM

Data	**Amount**	**Integration Method**	**Auto-Integration Rate**
3D Product Elements	14, 055	/	/
Structural Members	13, 842	Based on proposed in section 4.1.4	98.6%
Scheduled Tasks	554	Based on name of tasks and elements	84.5%
Sensing Data	367	Based on ID of sensors	100%

5.3 Closed-Loop Safety Management based BrSIM

5.3.1Model Visualization

4D simulation is widely used in design and construction. Based on the previously proposed incremental launching simulation of bridges[51] , the entire construction process of the bridge assembly and incremental launching is presented intuitively. The structural members and monitoring points associated with 3Delements are also visualized. With the construction process, the process of progressively highlighting the monitoring points and the process of change at different stages are displayed. (Figure 12)

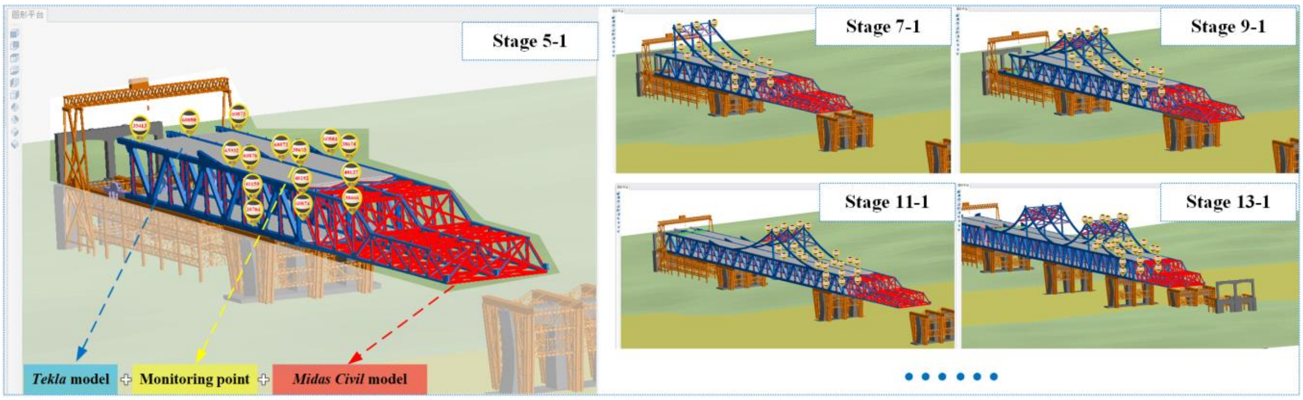


Figure 12 The Jacking Process for the Construction of the Bridge

Monitoring the deformation and deflection is important to the structural safety during construction and the final quality in this project. The control of such deformation and deflection mainly involves the monitoring of vertical deflection, pre-camber, and horizontal straightness. Based on the

BrSIM, the monitored and theoretical values are compared and analyzed, ensuring that the difference between them is under control. Thus, by fitting of the bridge deformation based on the Bezier curve, the monitored and theoretical values of the pre-camber and straightness of three trusses (in the west, middle, and east parts of the bridge) are visualized and the site control and management of the pre-camber and straightness are enhanced. At the same time, an intuitive query on the differences between the monitored and theoretical values and the corresponding dangerous components is enabled for assisting the site construction control. (Figure 13)

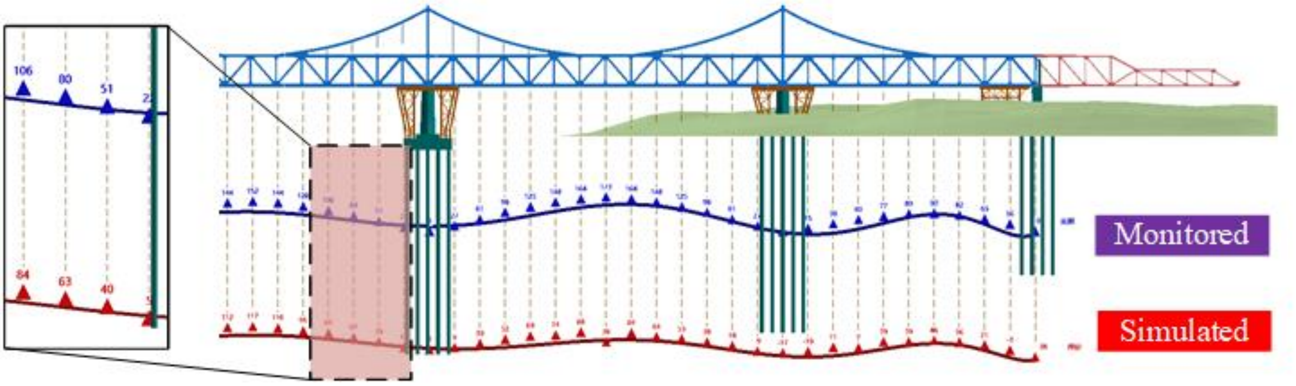
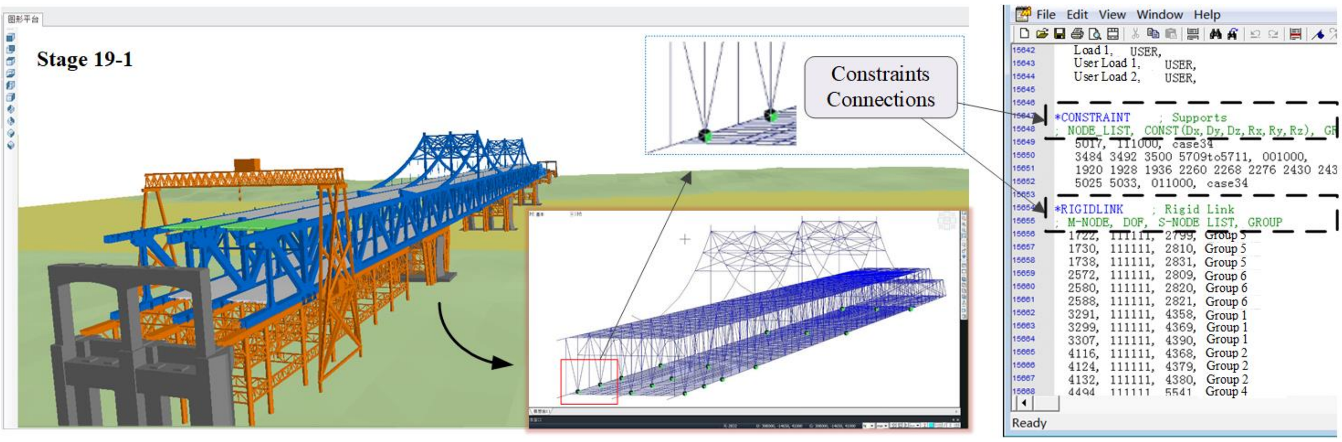


Figure 13 Visualization of Pre-Camber

5.3.2Structural Analysis Model Generation and Simulation

Based on the proposed method of establishing the structural model during construction, a construction stage is selected optionally to generate the corresponding structural analysis model. Taking Figure 14 as an example, stage 19-1 is selected to export the corresponding mct files, in which the added constraint and load information may be viewed, so that the analysis and computation can be directly completed using Midas Civil software.



```
   Load 1,    USER,
   User Load 1,     USER,
   User Load 2,     USER,

*CONSTRAINT    ; Supports
; NODE_LIST,  CONST(Dx, Dy, Dz, Rx, Ry, Rz),  G
   5017,  111000,  case34
   3484 3492 3500 5709to5711,  001000,
   1920 1928 1936 2260 2268 2276 2430 243
   5025 5033,  011000,  case34

*RIGIDLINK     ; Rigid Link
; M-NODE,  DOF,  S-NODE LIST,  GROUP
  1722,  111111,  2799,  Group 5
  1730,  111111,  2810,  Group 5
  1738,  111111,  2831,  Group 5
  2572,  111111,  2809,  Group 6
  2580,  111111,  2820,  Group 6
  2588,  111111,  2821,  Group 6
  3291,  111111,  4358,  Group 1
  3299,  111111,  4369,  Group 1
  3307,  111111,  4390,  Group 1
  4116,  111111,  4368,  Group 2
  4124,  111111,  4379,  Group 2
  4132,  111111,  4380,  Group 2
  4494,  111111,  5541,  Group 4
```

Figure 14 Structural Analysis Model Generated

The entire engineering process involves 62 different construction stages. Structural model of each stage was exported and simulated in Midas Civil software. Figure 15 shows the statistics of generated structural models of 5 typical stages. It is showed that as the construction goes from stage 5-1 to stage 29-1, more elements are constructed and corresponding constraints of the structural members are also finished. According to the discussion with the designers and engineers, 1 days is needed to create a typical stage like 19-1, on the contrary, the developed system can generate the structural model in seconds. As such, the time need for structural modeling and manually adding analysis information decreases from hours to minutes, thereby improving the efficiency.

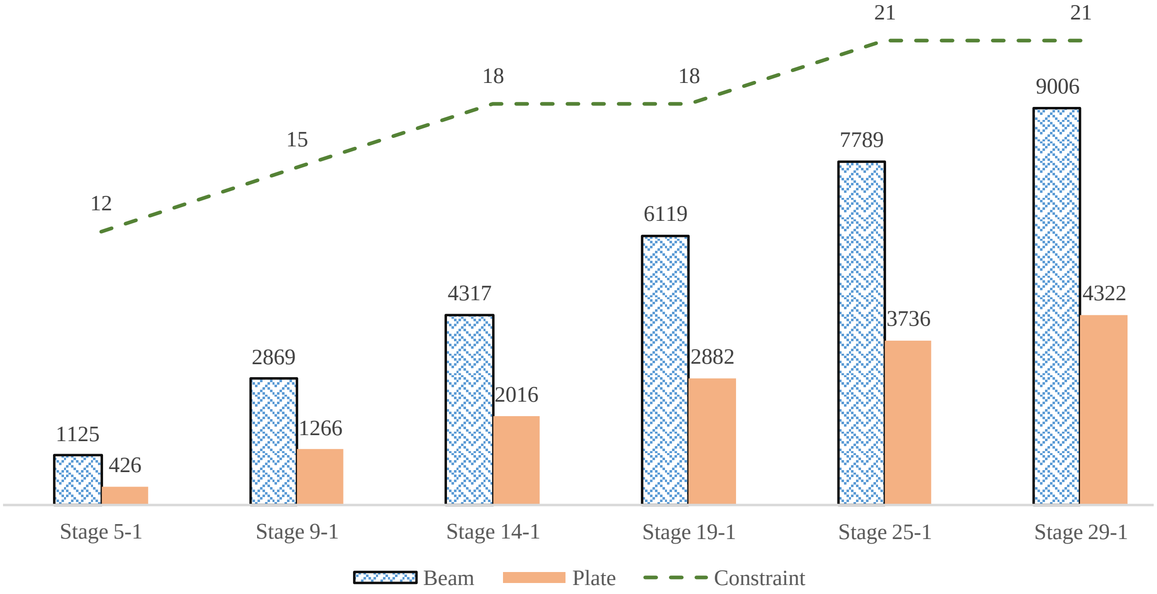


Figure 15 Statistics of Generated Structural Models

With proposed generating method of time-dependent structural model, two typical closure stages are selected for discussion as shown in Figure 16.

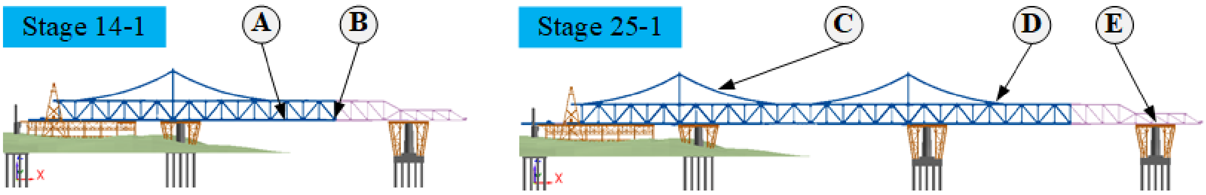


Figure 16 Typical Construction Stages of the Yellow River Bridge

The above model is exported for analysis and calculation, then the maximum displacement and stress at different construction stages are obtained, as shown in Table 4. The maximum displacement of the main truss appears at the closure of the first stiffening chord at closure stage 14-1 (Figure 17). At this moment, the maximum midspan displacement of the main truss is 357.0 mm, and the stiffness of the main truss and launching nose meets the specifications. The maximum stress of the launching nose appears at the closure of the first stiffening chord at closure stage 14-1, the stress on the lower chord of the launching nose linked to the main truss is 238.4 MPa, and the stiffness of the launching nose meets the specification requirements. That is, the bridge structure is theoretically safe at the stage of 14-1 and 25-1. However, the engineers should pay more attention to location A and B for stage 14-1, and location C, D and E for stage 25-1, respectively. Moreover, the simulation results can be further compared with the monitored data to evaluate the accuracy of the simulation. Moreover, the analysis results can be integrated into the system, laying a foundation for the subsequent structural safety risk warning and evaluation.

Table 4 Statistics of Maximum Stress and Deflection of Different Construction Stages

ID	Deflection		Stress of Main Truss		Stress of Landing Nose	
	Max (mm)	**Location**	**Max (MPa)**	**Location**	**Max (MPa)**	**Location**
14-1	357	A	134.2	B	238.4	B
25-1	325.4	C	175.7	D	123.7	E

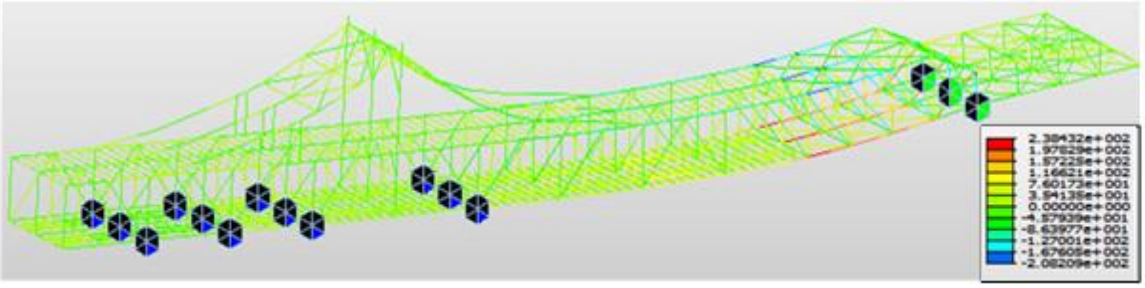
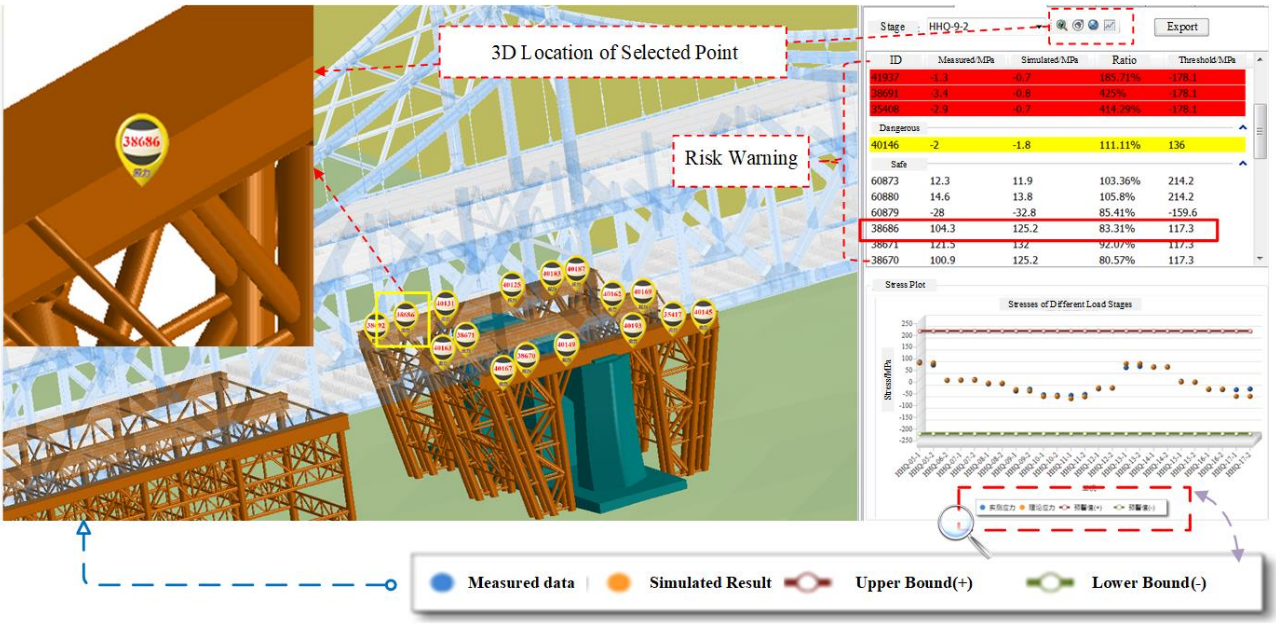


Figure 17 Stress of Construction Stage 14-1

5.3.3Risk Warning, Tracking and Assessment

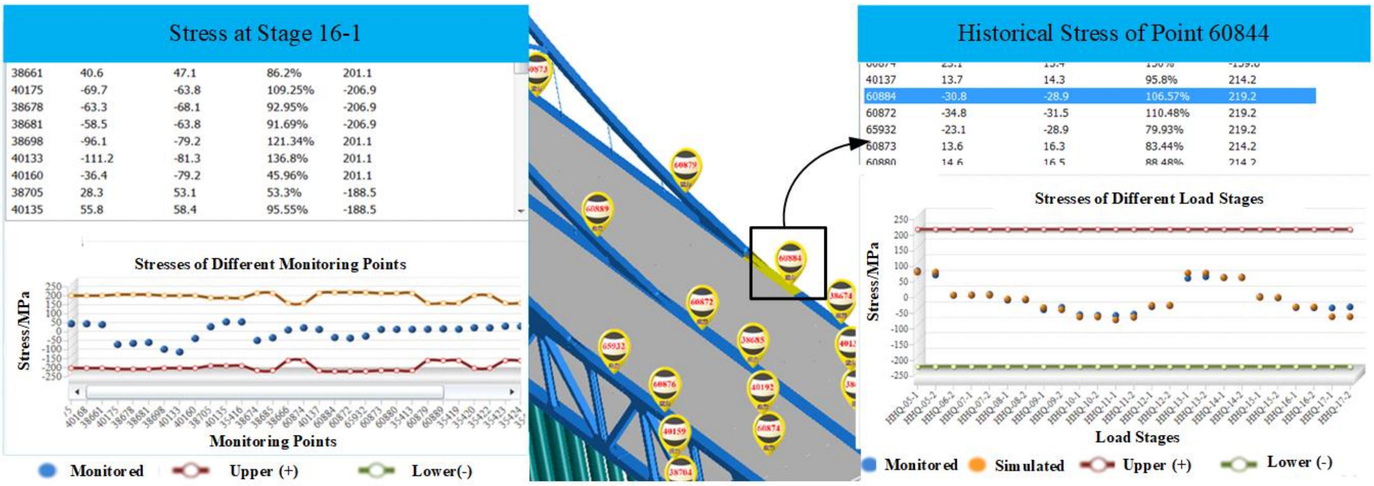
Given that different types of monitored data are dynamically integrated in the system platform, the monitored data at the monitoring point under condition can be quickly obtained and intuitively analyzed according to the hierarchical warning standards, as shown in Figure 18. The results of the risk warning also allow the highlighting and coloring of the risk level-based model according to the relationship between the relevant data and the 3D product model, thereby displaying the distribution of safety risks more intuitively.



ID	Measured/MPa	Simulated/MPa	Ratio	Threshold/MPa
41937	-1.3	-0.7	185.71%	-178.1
38691	-3.4	-0.8	425%	-178.1
35408	-2.9	-0.7	414.29%	-178.1
Dangerous				
40146	-2	-1.8	111.11%	136
Safe				
60873	12.3	11.9	103.36%	214.2
60880	14.6	13.8	105.8%	214.2
60879	-28	-32.8	85.41%	-159.6
38686	104.3	125.2	83.31%	117.3
38671	121.5	132	92.07%	117.3
38670	100.9	125.2	80.57%	117.3

Figure 18 Points in Different Risk Levels and Their Locations

The structural stress and deformation are queried from different aspects by integrating the structural analysis results and the monitored data at different construction stages. The differences between the analysis results and monitored data of a monitoring point or element can then be analyzed, and the history of the stress condition at a certain point or element can be queried, as shown in Figure 19. The monitored data of each point of the bridge at construction stage 16-1 are displayed on the left side. The stress at different monitoring points of the main structure at the stage is within the upper and lower warning lines. At the same time, based on the historical stress conditions of the monitoring point (ID: 60884), both the historical monitoring data and the simulation results are displayed, illustrating that the difference is within the warning scope. These findings illustrate that at construction stages 17-1 and 17-2, the differences between the monitored and theoretical simulation results become more evident and should be considered in the subsequent structural analysis and construction process. Thus, the automatic comparative analysis and historical data retrieval of the monitored and theoretical values are achieved.


Stress at Stage 16-1

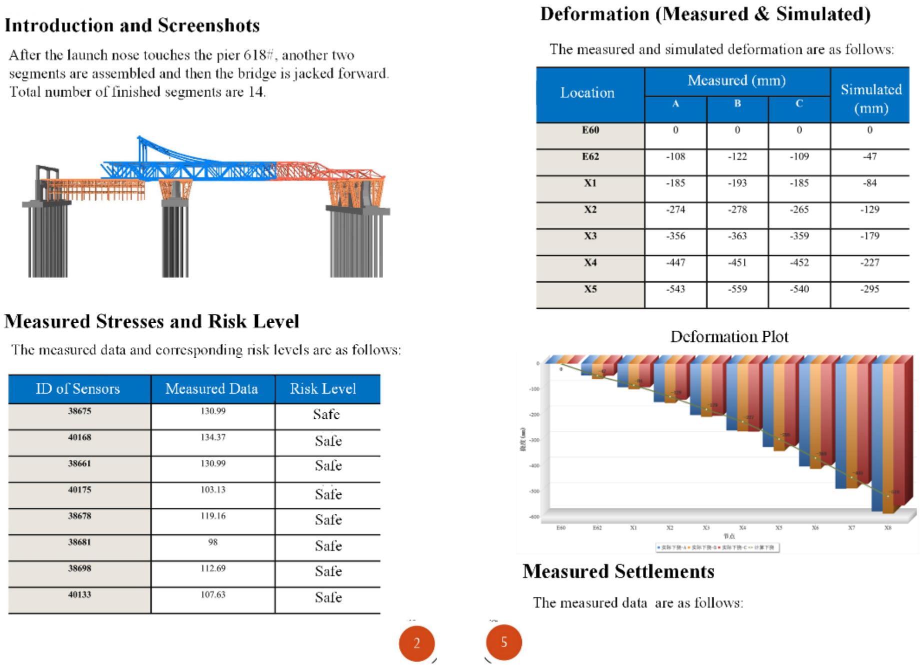
38661	40.6	47.1	86.2%	201.1
40175	-69.7	-63.8	109.25%	-206.9
38678	-63.3	-68.1	92.95%	-206.9
38681	-58.5	-63.8	91.69%	-206.9
38698	-96.1	-79.2	121.34%	201.1
40133	-111.2	-81.3	136.8%	201.1
40160	-36.4	-79.2	45.96%	201.1
38705	28.3	53.1	53.3%	-188.5
40135	55.8	58.4	95.55%	-188.5

Historical Stress of Point 60844

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
40137	13.7	14.3	95.8%	214.2
60884	-30.8	-28.9	106.57%	219.2
60872	-34.8	-31.5	110.48%	219.2
65932	-23.1	-28.9	79.93%	219.2
60873	13.6	16.3	83.44%	214.2
60880	14.6	16.5	88.48%	214.2

Figure 19 Comparison and Tracking of Simulated and Sensing Data

Based on the above model and algorithm, the system automatically compares the monitored data and theoretical simulation results under a certain condition or at a specific stage, thereby generating statistical charts. In addition, the system calculates the overall structural safety performance under a certain condition based on the proposed overall safety assessment method. As shown in Figure 20, with user-specified weights of different aspects, the overall safety performance of the main structure and temporary structures is assessed. This analysis includes the stress, deflection, settlement, etc., automatically generating safety assessment reports at a certain construction stage and assisting the project manager or safety engineer in decision making. Meanwhile, the system can also summarize and export the analysis results, monitored data, and safety status reports of different points, thereby facilitating information sharing, discussion, and exchange.



Introduction and Screenshots

After the launch nose touches the pier 618#, another two segments are assembled and then the bridge is jacked forward. Total number of finished segments are 14.

Measured Stresses and Risk Level

The measured data and corresponding risk levels are as follows:

ID of Sensors	Measured Data	Risk Level
38675	130.99	Safe
40168	134.37	Safe
38661	130.99	Safe
40175	103.13	Safe
38678	119.16	Safe
38681	98	Safe
38698	112.69	Safe
40133	107.63	Safe

Deformation (Measured & Simulated)

The measured and simulated deformation are as follows:

Location	Measured (mm)			Simulated (mm)
	A	B	C	
E60	0	0	0	0
E62	-108	-122	-109	-47
X1	-185	-193	-185	-84
X2	-274	-278	-265	-129
X3	-356	-363	-359	-179
X4	-447	-451	-452	-227
X5	-543	-559	-540	-295

Deformation Plot

Measured Settlements

The measured data are as follows:

Figure 20 Assessment and Reports of Structural Safety Performance

5.4 Discussion

Based on the practical applications, the relevant engineering staff have expressed positive opinions on the methods and tools established in this paper. These professionals believe that the heavy workload of structural analysis modeling during construction under different condition and difficulties in information integration and application can be effectively resolved. Based on the BrSIM, powerful platforms and tools are provided by continuously integrating the structural analysis results and the monitored data for the entire closed-loop management of construction safety planning, execution, as well as for safety monitoring, risk warning and assessment. As such, the structural safety during construction risk can be controlled and a structure-safe construction process is ensured.

The region-based matching algorithm is proposed to achieve the mapping between the 3D product model and the structural analysis model. The proposed algorithm avoids the pairwise comparison between the 3D product elements and the structural analysis members by the spatial division and feature point matching. The principle is based on the gridding of bridge elements or members, and the partitioning of such elements or members may also be achieved by an octree, binary tree, etc. While matching 3D product elements and structural analysis members, the calculation speed is also increased using the axis-aligned bounding box and the feature points of elements. If the axis-aligned bounding box has a problem matching certain elongated elements when applying the proposed method, then the oriented bounding box may be considered for use. Moreover, feature points may be flexibly chosen according to the 3D features of the structural members. In actual practice, the point at 1/4, 1/2 or 3/4 of the length of line member, as well as the center or the middle of the center-angle line of plate or shell members, can be selected as the feature point, thereby improving the computational efficiency and the matching accuracy. If none of these feature points provides a good result, then overlapping of 3D shapes can be considered as a final solution.

A method for generating the structural analysis model at a specific time based on a 4D model was presented previously by the authors. Based on a series of rules and assumptions, this method extracts and converts the 3D product model into the structural analysis model[45]. This method completely relies on computer-aided abstraction, which is often problematic in addressing a combination of complicated components and parts. However, this study adopts another means of introducing the structural analysis model that is generated at the design phase and establishing the relationship with the 3D product model, enabling the corresponding structural members to be indirectly extracted and exported based on the temporal information of the BrSIM. The method may better cope with different components and compositions, while maintaining the consistency and universality of the structural information exported under different conditions. In addition, actual monitoring data are introduced, and relevant data are converted into the constraints and displacements of nodes, thereby better reflecting the actual construction scenario and reducing the time for the manual adjustment of the relevant parameters. Meanwhile, considering the semantic information of the 3D product model, the structural analysis model for the main structure and temporary structures under typical construction condition can be derived with the proposed method, and used for the time-dependent structural safety analysis during construction. The results can be integrated according to the ID of the structural member/node, creating stress-related records of structural members and nodes under different conditions and facilitating the analysis of the structural performance. Adopting the proposed method in the construction progress makes it convenient to export the structural analysis model under different conditions and to dynamically analyze the stress condition, thereby effectively reducing the time and cost of repeated modeling.

Finally, a comparison of the theoretical simulation results and the actual monitoring data are highly important for recognizing the safety risk and accumulating engineering knowledge. On one hand, the dangerous conditions of the elements are intuitively evaluated and the safety analysis is assisted through data visualization. On the other hand, the trend of the stress is also valuable for the subsequent time-dependent structural analysis, thereby effectively simplifying the process of manual comparison, improving the efficiency of analysis, and laying the foundation for follow-up safety assessment and management. Moreover, the differences between the theoretical analysis and the actual monitoring data not only reveal all hidden engineering risks but also indicate imperfections of the theoretical model as well as errors or faults of sensor monitoring systems. Determining the differences between the two models in advance is highly useful for avoiding structural safety risks, improving the theoretical analysis model, and identifying sensor monitoring system errors or faults.

6. Conclusion

For large infrastructure projects, structural safety during construction is vital for engineering success. However, problems such as difficulties in structural modeling and simulation during construction and the fragmentation of software used in construction management and safety analysis of the monitoring system, which hinder closed-loop management of the structural safety during construction, should be addressed. In this paper, a closed-loop management framework for structural safety is presented based on multisource data integration. Then, a bridge safety information model (BrSIM) is established by analyzing the data objects related to the construction management, the structural simulation and the monitoring system. The BrSIM is composed of five parts, namely, 3D product information, schedule information, structural analysis information, structural simulation results and the monitoring data, which capture the main data related to structural safety management in construction. Meanwhile, a series of algorithm and methods are developed to establish relationships between the information of these parts and to form an integrated model. Finally, with the prototype system developed and deployed, the proposed framework, model, and algorithm are verified in the construction of the YRB. The results show that the proposed framework, model, and methods are flexible and effective. By integrating the 3D product model, the structural analysis model and the simulation results, as well as the monitoring data, it is possible to visualize the construction process and the corresponding structural performance during construction. A time-dependent structural analysis model and its loads and constraints under certain conditions can be generated dynamically, enabling rapid structural safety analysis. Then, by comparing the theoretical simulation results with the monitoring data collected, new methods are provided for the structural safety risk warning and assessment during construction. Thus, the PDCA loop for structural safety management is automated and closed, promoting safety and efficiency during bridge construction. Moreover, the relevant methods improve the efficiency of information modeling, sharing, communication and collaboration. This method avoids the need for considerable repeated modeling work, saves manpower and material resources, and provides effective solutions and management approaches for the closed-loop management of structural safety during construction.

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