NATIONAL STADIUM (BIRD'S NEST) DIGITAL CONSTRUCTION TECHNOLOGY

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ABSTRACT

As the main venue for the 2008 Olympic, National Stadium (Bird's Nest) is a construction project with a large scale, a complex construction process, a novel and unique design, and there existed many technical problems on member processing and manufacturing, steel structure installation and construction management. The researchers built the three-dimensional steel structure models adopting the technology of CATIA (Computer-graphics Aided Three-dimensional Interactive Application), developed the distorted thin-walled box member geometric configuration method and deepening design software, also developed a set of distorted plate CNC multi-point non-molded flexible manufacturing equipment and supporting software, so that ensured the accurate processing of the steel members. Combining the whole-process simulation analysis of the steel structures installation, they provide the control basis for the installation of spatial heterotypic steel structures, and applying the precision spatial lofting and setting-out technology, three-dimensional laser scanning technology, fourth-generation wireless sensor network technology, they solved problems such as structure installation lofting, deviation control, deformation and strain monitoring. The researchers developed a 4D construction management information system and a multi-stakeholder collaborative work platform system to achieve the 4D construction schedule management, 4D resource management, 4D site management, and 4D visual simulation of the project construction process, ensuring the progress and quality, reducing the costs of the project. These technologies not only ensured the construction quality and safety of Nest’s large and complex steel structure, but also have been applied in a number of major projects in China.

Keywords: national stadium, Bird's Nest, digitalization, construction technology

As the Olympic Stadium, National Stadium (Bird's Nest) undertook the opening and closing ceremonies as well as track and field competitions of the 2008 Beijing Olympic Games, which can accommodate 91,000 spectators, is one of the world's large-span sports buildings. Its structure system and architectural style jointly form an integral whole, and the peripheral large-span steel structure is woven with 42,000 tons of distorted steel members, and the internal grandstand is of a heterotypic frame structure which is composed of concrete columns with different angles, and the roof adopted Ethylenetetrafluoroethylene (ETFE) and Poly tetrafluoroethylene (PTFE) membrane structures, and without domestic and international precedents as well as relevant technical standards and specifications, the project construction faced a series of major technical problems.

(1) In order to achieve the unique shape of the "Bird’s Nest", the 14,000 tons of non-fixed-line space box-shaped distorted members were adopted as the shoulder steel members. All of the development of the geometry configuration method, 3D modeling and flattening lofting software, as well as the processing and production technology of large cross-section (1200mm × 1200mm) box-shaped distorted members were unprecedented at home and abroad.

(2) Because of the large-span structures, complex shape, the difficult selection and optimization of the overall installation program, the huge sizes of lifting members (the maximum one is 35m × 25m × 20m, the heaviest one is 360t), as well as the full adoption of box-shaped sections and the on-site installation interfaces up to 4000, especially the installation of top and shoulder sub-structures after unloading the main structure, and the spatial butt joint welding difficulty increased by configuration change, steel structure installation faced many major problems.

(3) The final closure of steel structure had a high quality requirement and implementation difficulty. Since Bird's Nest adopts a spatial "weaved" structure, all the installation errors, welding and temperature deformations were accumulated to the four closure lines of 128 closure junctions, and the use of welding has strict requirements for the gap and unfitness of closure junctions; the design required the closure temperature to be maintained at 19 ℃± 4 ℃, and the real-time monitoring of the structure temperature during the closure; Meanwhile, the completion of the closure welding needs at least 14 hours, while in a day of August in Beijing area, the time meeting the requirement of closure temperature is less than 3 hours.

(4) The support uninstalling of the steel roof with an area of 60,000 m2 and a weight of 14,000 t is unprecedented, and with 78 uninstalling points, the maximum end reaction of 300t and the synchronization accuracy of 3mm, the overall step synchronization uninstalling requires a very high technology.

(5) To ensure the mounting accuracy and architectural effect of the complex-shape, large-size and spatially-weaved “Nest” steel structure with the construction errors which are accumulated and passed easily, it is necessary to establish a high-precision measurement and control network to measure and control the high-precision assembly and installation of the members, especially to obtain the real-time junction configuration data of the installed members to guide the assembly on ground and high-altitude installation of steel members, and to timely digest and save various errors can significantly guarantee the quality and progress of the installation, so the appropriate control technology is needed to be developed

(6) The construction period is very limited – the effective construction period is of only four years; the construction management is very complex -- more than 100 international and domestic subcontractors, the coordination, management and control are very difficult, and the managed objects are very complex -- the concrete structures have no standard layer and standard segment, and thousands steel members only contain two identical members; and the management requirement is very high -- the general contractor must manage every piece of steel, each one seam, and even every welder’s dynamic changes.

1. THREE-DIMENSIONAL MODEL DESIGN BASED ON CATIA

Both the architectural space and shape of China National Stadium are very complex, and the unique "nest" structure consists of a large number of irregular spatial distorted members "weaved” together, therefore, the traditional methods of two-dimensional geometric design, positioning and corresponding drawings expression is almost impossible to complete the design task, and in the design process, the CATIA V5 R13 software which can achieve precise design and positioning in three-dimensional spatial model was introduced in the domestic construction industry for the first time, to solve the spatial modeling problems of complex buildings. The modeling work of the project was jointly completed by the architects and structural engineers with high-configuration computers. The architects used this accurate model to consider spatial effects, functions and detailed designs; the structural engineers used this model to conduct computation, and the precise positioning of all segments of the columns and beams, and then drew construction drawings with the spatial coordinate notation; the equipment engineers carried out the accurate analysis and positioning of the key equipment using this model.

2. DESIGN AND PROCESSING TECHNOLOGY OF LARGE-SCALE SPATIAL DISTORTED BOX MEMBERS

2.1 Geometric configuration and deepening design methods of distorted members

Proposing the geometric projection generation method of discretional curved surface distorted thin-wall box member which can control accuracies through distorted box member ridge feature points, using cubic B-spline curves, the designers and engineers of the project achieved the fitting of the continuous smooth contour lines of distorted members, developed a distorted box member deepening design software which can help to achieve the virtual construction of multi-way intersection space distorted members and automatically generate the Computer Aided Manufacturing (CAM) data files of distorted member siding lofting maps and the CNC cutting and pressing of various parts, as well as control data file of factory assemblage and on-site assembly and lifting, so as to greatly reduce the difficulty of member manufacture, and accurately complete the processing and production as well as the on-site installation and positioning of members, perfectly realizing the architectural style of "Bird's Nest".

2.2 Distorted panel forming technology

According to the characteristics of distorted box members, the researchers developed a non-molded forming technology and three-roll bending forming technology. Based on multi-point press forming theory and multi-point fitting curved surface theory, they developed the PC-controlled large-tonnage and large-size multi-point non-molded forming flexible manufacturing equipment and supporting software. And based on the traditional three-roll plate bending technology, integrating the processing and production technologies of shipbuilding, machinery manufacturing and construction steel structure processing industries, the researchers developed the control software supporting three-roll rolling machine, determined the forming control process parameters, and formed a complete set of three-roll forming technology of box member distorted panels using hydraulic machine locally finishing and forming technology.

Figure 1: Distorted panel multi-point non-molded forming equipment

2.3 Distorted member inspection technology

In the project, a set of special quality acceptance criteria was studied and formulated focusing on the characteristics of distorted panels and box-shaped distorted members, and two forming quality inspection methods were developed and applied: one is sample box method, the other method is to develop a three-dimensional coordinate measuring system for the forming quality inspection of distorted panels and box-shaped distorted members by introducing Metro In industrial three-dimensional measurement system into construction steel structure processing quality inspection technology,.

Using the above technologies, only in four months, the processing and manufacture of 14,000 tons of steel structural distorted members were completed, and the maximum curve deviation was only 2mm, of which the fabrication and installation accuracy of the 500-meter hyperbolic spatial track for torch ignition even reached 0.75mm / m.

3. WHOLE-PROCESS SIMULATION ANALYSIS TECHNOLOGY OF COMPLEX STEEL STRUCTURE INSTALLATION

3.1 Comparison and selection of steel structure overall installation program

The commonly-used programs of large span steel structure installation include overall lifting, slipping, separately lifting and high-altitude assembly program (KD method by short), local overall lifting and other methods. Focusing on the steel structure subproject of the National Stadium as well as the time and spatial relationships between the subproject and other subprojects, the above four methods were taken into comparison and consideration in selection process of the steel structure installation program, and subject to the constraints of time and space, the overall lifting and slipping methods were difficult to implement, so only the KD method and local lifting method mainly underwent the comparison and selection.

Making a simulation analysis of the three conditions of the local overall lifting, the results showed that: the junctions between the overall lifting blocks of the inner ring and the main truss of the outer ring saw relatively big deformations, namely about 50% of the junction misalignment deviations exceeded the allowable tolerances of Chinese national standards.

In the analysis of KD program, based on the project characteristics, the researchers carried out the simulation analysis of the two programs respectively with 50 and 78 anchors, and found that there were large difference of needed lifting equipment and member lifting deformation between the two programs, and the member lifting deformation emerging in the former is too large, exceeding the norms of the relevant national standards.

Taking all factors into account, the 78-anchor high-altitude KD program was finally adopted for the National Stadium steel structure project.

Based on the simulation analysis of different installation orders of steel structure, the engineers proposed the construction method -- install the top surface secondary steel structure after unloading the temporary support tower of the primary steel structure, significantly reducing the inner force of the top surface secondary structure, saving 1,350 tons of steel, resulting in a clear distinction between the primary structure and the secondary structure, and improving the seismic performance.

3.2 Installation of steel structures

The primary steel structure (including pedestals) is divided into 256 lifting units. The installation methods such as sliding, lifting, single-crane hoisting, dual-crane lifting and three-crane lifting were comprehensively applied. Before the construction, some typical lifting units were selected to undergo the simulation analysis of the member centroid and lug designs, the stress and deformation generated in member turning and lifting, member installation provisional fixing measures, and member installation sequences and so on.

About 4000 steel structure junctions were involved in the on-site installation, including 1440 primary structure junctions and 2560 secondary structure junctions. Through the simulation analysis of interface types, the R &D of interface bias adjustment methods, and the integrated application of on-ground overall pre-assembly and three-dimensional laser scanning technologies, the problems of mounting 4000 interfaces in precise directions have been successfully resolved.

3.3 Final closure of steel structure

The installation of the main steel structure from the start to the overall closure lasted nearly eight months, and there was a big difference between the temperatures of the initial installation and the final closure of the steel structure, which had a great influence on the smooth closure, so it is necessary to consider the variety of temperature changes and calculate the rod temperature deformation values at the closure section based on the determined closure sectional position, to determine the specific closure manner as well as the reserved gap size and approach of the closure interface.

The temperature effect simulation analysis of the whole steel structure installation process showed that the final closure gap constantly changed with temperature changes, and the maximum change value would not exceed 32mm, so taking into account the various factors, the post- installed-segment method was not adopted as the closure method, while the reserved weld gaps were taken as the final closure interfaces.

3.4 Unloading of steel structure support

After the principle of "phased overall hierarchic synchronous unloading" is determined, the simulation analysis of unloading was very important, in fact, the work had been preliminary completed before the construction of the entire project was officially started. The unloading simulation analysis is to solve the following problems:

(1) The comparison and selection between different unloading programs. To simulate the changes of structure internal force, deformation, support reaction and total reaction under different unloading programs, to complete the comparison and selection;

(2) To provide design basis for the support system and foundation. While the pile foundation construction of the official construction of the Bird’s Nest, the construction of the temporary tower foundation pile had been completed as well;

(3) To provide basis for the selection of unloading equipment system. To calculate the maximum reaction and the maximum unloading deformation value of each anchor to determine the selection of unloading equipment;

(4) To provide basis for the unloading monitoring. To make comparative analysis between the unloading measured value and the theoretically calculated value, to guide the unloading process and ensure the safety;

(5) To provide criteria to judge whether the unloading success or not. To compare the final unloading results (structural stress, deformation, etc.) with the calculated design values, to determine the unloading results.

Based on the unloading simulation analysis results, the whole unloading process of National Stadium steel structure works was divided into 7 major steps and 35 sub-steps, which were completed inward. The computer-controlled hydraulic jack cluster synchronic unloading system was used to accurately achieve the overall hierarchic synchronous unloading of nest 60,000m2 and 14,000-ton large-span saddle-shaped steel roof at 78 temporary anchors, effectively ensuring the safety of the construction process. The theoretically calculated maximum deformation for the Bird’s Nest steel structure unloading is 286mm, and the measured deformation is 271mm, so the error is only 5.2%.

4. PRECISION CONSTRUCTION MEASUREMENT TECHNOLOGY OF LARGE-SCALE HETEROTYPIC COMPLEX SPATIAL STEEL STRUCTURE

In the complex construction environment, using advanced measurement equipment such as intelligent total station, Global Positioning System (GPS) and electronic balance level, the high-precision control network better than 3mm was established to provide a reliable basis for the measurement of spatial heterotypic steel structure installation. The precision spatial lofting and setting-out technology was developed based on total Station and MetroIn three-dimensional measurement system to achieve the quick and accurate spatial lofting and setting out of the large and complex steel structure construction. Using laser scanning technology, the engineers conducted dynamic monitoring of the primary structure configuration changes during the installation of the secondary structure, so as to effectively control the processing and assembly of the secondary structure members, and provide information-based construction support for steel structure processing, on-site assembly and spatial taking place, improving construction efficiency and ensuring the installation quality.

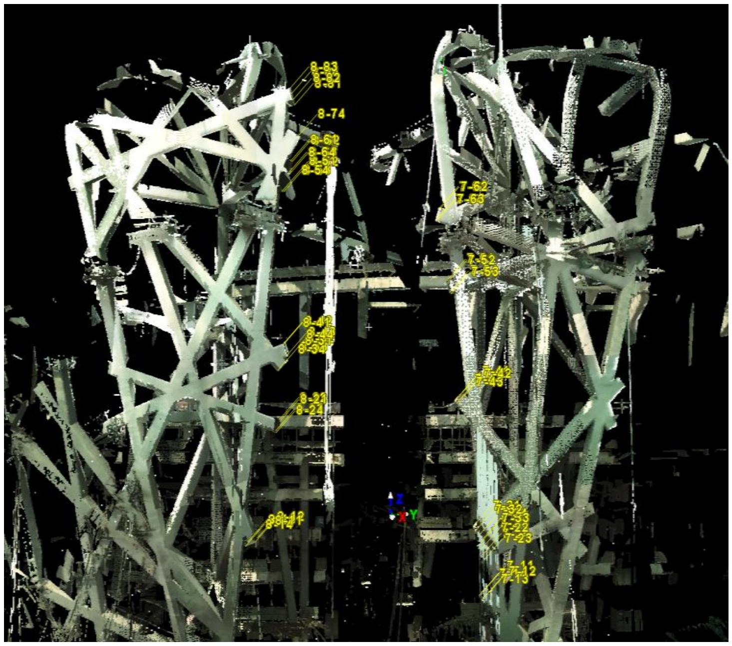

Figure 2: A three-dimensional laser scanning of typical corbels between columns

5. STRUCTURE SAFETY MONITORING AND INFORMATION-BASED CONSTRUCTION TECHNOLOGY

The monitoring technology application in construction process is a necessary means for the construction of such large and complex projects as Bird's Nest. The structural monitoring contents of National Stadium project included large-span steel structure temperature change, deformation, stress at key parts, foundation settlement and dynamic characteristics of facade major staircases, of which the typical applications included the monitoring of closure construction steel structure body temperature, as well as the monitoring of the steel structure temperature, stress, deformation and jack reaction, and temporary support tower stress during the support unloading.

The final closure of Bird's Nest including four closure line and 128 closure interfaces is a systematic project, which was conducted at the temperature (monitored by the monitoring system) meeting the requirements of design conditions, and the designed steel structure closure temperature of 19 ℃± 4 ℃ refers to the temperature of the whole steel structure, therefore, to accurately grasp the temperature distribution of steel roof, 60 temperature measurement points were set on the top surface and facade of the steel structure, and the measurement points were controlled by the wireless automatic temperature measurement system including the sensor subsystem, data collection and transmission subsystem, data management and analysis subsystem. The closure construction preparation work was carried out according to the weather forecast, and therefore, the relationship between the weather conditions and steel structure body temperature was studied in advance, and the professional observatory was employed to establish a meteorological observation point at the construction site, and the closure construction preparation was made according to the real-time and on-site weather data. The final closure of Bird's Nest steel structure was successfully completed at the design temperature on 26, 29, 31, August, 2006, respectively.

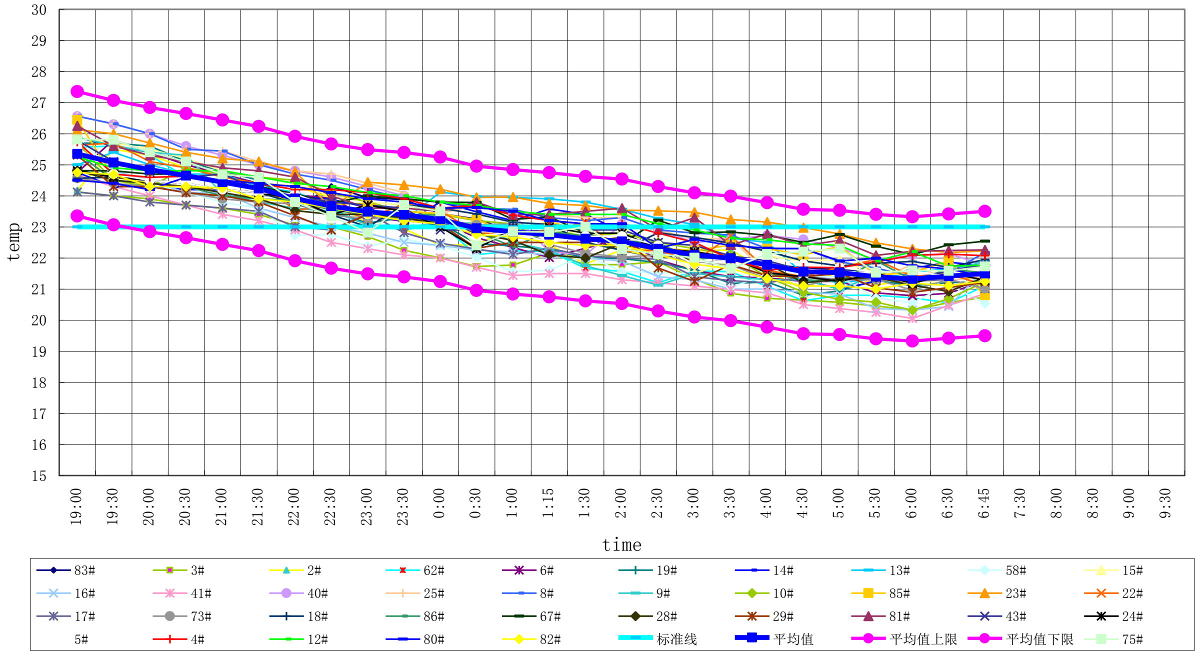

Figure 3: Steel structure temperature curve of the second closure of top surface

The construction monitoring of Bird's Nest steel structure support unloading includes the objects of five aspects: (1) The reaction force of the 156 jacks, to monitor the transfers of the roof steel structure loads from the support towers to the structures themselves in the unloading process; (2) The subsidence of the 16 monitoring points on the roof inner ring, to monitor the roof deformation in unloading process; (3) The four main trusses and two truss columns of the steel roof representing the 232 stress and strain measurement points, to monitor the actual stress and strain of the structure itself during the unloading to ensure structural safety; (4) 12 stress measurement points on three selected typical support towers, to monitor the stress state of the support towers during the unloading; (5) 60 temperature measurement points on the steel roof, to monitor the temperature effects during the unloading. In accordance with the unloading steps including 7 major steps and 35 sub-steps, to complete a comprehensive observation after the completion of each sub-step and take the results as the basis for the next step of unloading. The steel structure unloading of Bird's Nest lasted four days from 13 to 17 September 2006, and all the monitoring data met the design requirements.

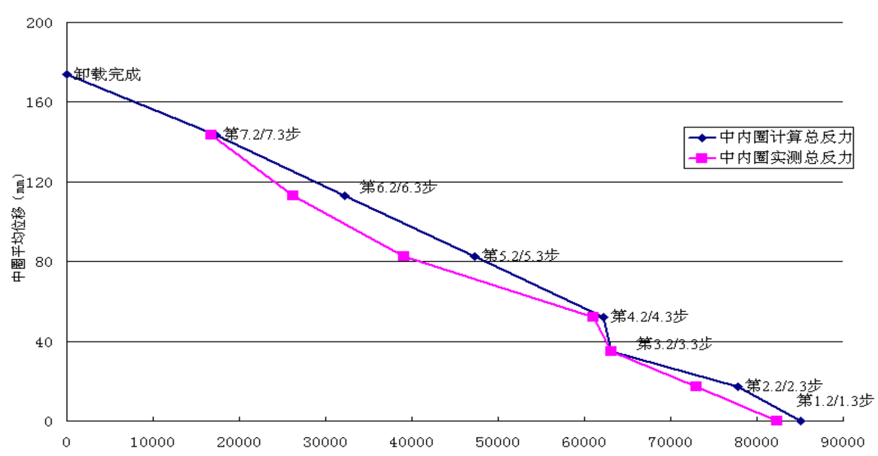

Figure 4: Comparison between measured and calculated reaction forces of jacks in inner ring unloading

6. INFORMATION-BASED MANAGEMENT TECHNOLOGY

Focusing on the construction management complexity and high-standard requirements of the National Stadium, a comprehensive information-based management technology research and application was completed. An information network combining wired and wireless sub-networks covering the entire construction area and the major subcontractors was established. A management information platform was developed and applied to achieve the office automation within the company of the general contractor and between the subcontractors; 13 video camera systems were established and integrated with the general contracting department LAN, to achieve the real-time monitoring of on-site working faces and main exits and entrances through desktop systems; An infrared security system was installed in the migrant workers living area to ensure the safety; A construction multi-party teamwork network platform system (ePIMS) was developed and applied to provide an efficient tool for the owners, general contractors, subcontractors, supervisors and other multi-stakeholder project management personnel to share the project information including documents, drawings and videos, conduct collaboration and make scientific decisions; A 4D construction management information system based on Industry Foundation Classes (IFC) standard was developed and applied to achieve the 4D construction management of the National Stadium, including schedule management, resource management, site management, and the visual simulation of construction process; The Internet-based National Stadium steel structure project management information system was developed and applied, to achieve the cooperative work between the factory processing, transportation, on-site assembly and installation of steel structures, as well as the 100% traceability of welding seams, welders and welding records.

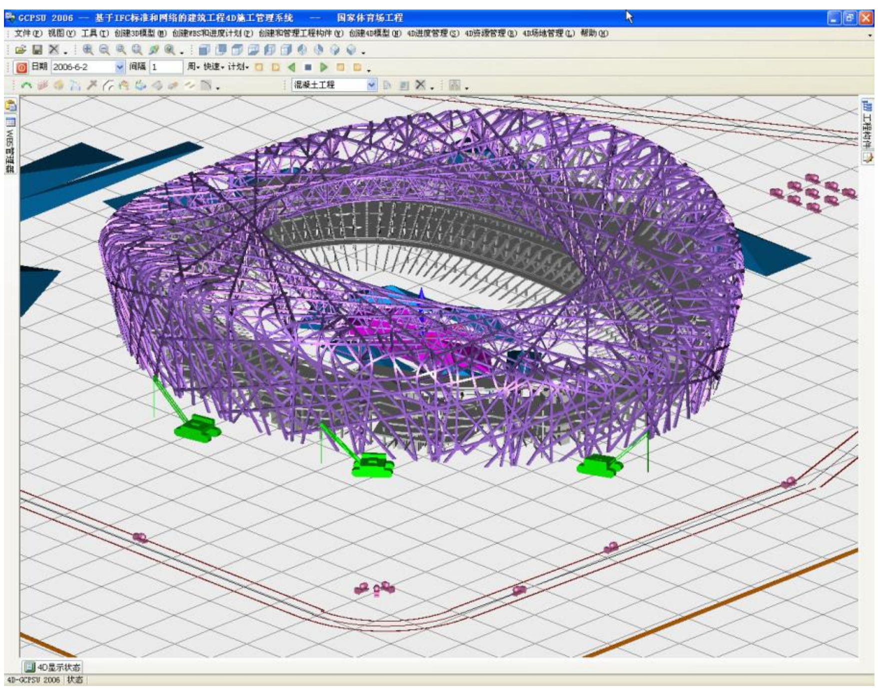

Figure 5: 4D construction site management

As the main venue for the 2008 Olympic, the National Stadium (Bird's Nest) has a novel and unique appearance, and a complex structure, as well as a remarkable and enormous construction difficulty. Through the research and comprehensive application of a variety of digital construction technologies, the key problems on engineering and construction have been solved, so that the structural safety, quality and architectural effect have been ensured, and in just four years the Bird’s Nest become a real building from a drawing, undertaking an exceptional Games and the history's greatest Paralympic Games. The relevant technologies have been applied in other domestic projects, promoting the improvement of China's building technology level. However, the existing information systems that mainly run on desktop computers cannot work efficiently for the material management on construction sites. It is because, in most cases, the materials on construction sites are stored far away from desktop computers in the office. As a result, warehouse keepers have to record management data in notebooks on site and then manually input the data into information systems after they return to office, which makes the material management on construction sites both inefficient and error-prone.

REFERENCES

Beijing Urban Construction Group Co., Ltd., CITIC Construction Co., Ltd. Weaving Dreams of the Bird's Nest, National Stadium – Part on Engineering Beijing: *China Building Industry Press*, 2009.

China Architecture Design & Research Group. Weaving Dreams of the Bird's Nest, National Stadium – Part on Design Beijing: *China Building Industry Press*, 2011.