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3D/BIM Applications to Large-scale Complex Building Projects in Japan

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Abstract

This paper introduces recent applications of three-dimensional building/construction data modeling (3D) and building information modeling (BIM) to large-scale complex building construction projects in Japan. Recently, BIM has been utilized as a tool in construction process innovation through planning, design, engineering, procurement and construction to establish a front-loading-type design building system. Firstly, the background and introduction processes of 3D and BIM are described to clarify their purposes and scopes of applications. Secondly, 3D and BIM applications for typical large-scale complex building construction projects to improve planning and management efficiency in building construction are presented. Finally, future directions and further research issues with 3D and BIM applications are proposed.

Keywords: 3D, BIM, Modeling, Coordination, Structural analysis, Sequence simulation

1. Introduction

Recently, large-scale complex buildings, which have comparatively free-shaped building surfaces and structures, have been designed using 3D/BIM on three dimensional CAD (3-D CAD) systems. In general buildings, such specific building surfaces and structures have been partially introduced due to the limitation of building costs. However, in many design competition projects, proposals for completely novel designs are rapidly increasing, according to performance upgrades of 3-D CAD systems and rapid progress in applications of 3D/BIM. 3D/BIM is defined as a digital representation of the physical and functional characteristics of a facility. Also, 3D/BIM is viewed as a shared knowledge resource for information about a building forming a reliable basis for decisions during the building's life-cycle.

When constructors utilize a complex design and sophisticated engineering in a real building, 3D/BIM should be produced at an early project stage to feed back results of buildability/constructability investigations into design development, which covers coordination and product design of building components, and structural analysis based on construction process planning with project participants. Moreover, large-scale complex buildings require a high level of cooperation between manufacturers of mechanical equipment, electrical machinery, steel frames and exterior curtain walls depending on which 3D/BIM are relevant, due to requirements for detailed engineering and efficient exchange of building data at an early engineering stage.

Furthermore, when newly developed structural systems and construction systems are introduced to a large-scale complex building project, precise construction planning is usually required as-built simulations, including construction method planning, site layout planning, temporary equipment planning, and construction process planning, which are not defined in the drawings and specification of buildings.

Thus, because 3D/BIM associated with 3-D CAD is widely used in complex large-scale buildings, it is important to create integrated building data models as 3D/BIM, which are to be shared by designers, engineers, manufacturers and contractors to support cooperative decisions at an early stage of the project (Fig. 1).

2. Background and former research with 3D/BIM

In the late 1980s, many large construction firms started making huge investments to adapt innovative automation and information technologies to building construction based on the successful introduction of Computer Integrated Manufacturing (CIM) in the manufacturing industry. At first, many of the efforts were carried out in the context of Computer Integrated Construction (CIC). To

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Figure 1. An overview of current 3D/BIM applications in building construction projects.

implement CIC, a systematic approach for applying computerization and automation to building construction by illustrating a future vision of building construction was introduced (Miyatake et al., 1993).

In the field of automation in construction, automated construction systems were developed and implemented in actual building projects (Fig. 2). In the field of computerization, object-oriented CAD systems, product models and project databases were researched to establish integrated information models to be shared among different functions and processes. Among such efforts, research on frameworks and strategies of CIC focused on integration of product models, process models, information modes and project models with building construction and proposed future visions of sophisticated building construction brought about by the integration of data, information and knowledge, including BIM (Eastman, 1993; Luiten et al., 2003; Fisher et al., 1993; Yamazaki, 1995).

Figure 2. An example of automated construction system (SMART System at Yokohama Nisseki Building).

There are many ways to establish BIM. At first, several object-oriented approaches to add semantic attributes and relationship to graphics information of building components and parts produced by CAD were researched. For example, a wall, which is one object (thing), is expressed by encapsulation of CAD data and semantics such as the definition as a wall, relations among connected building components, size, weight, material used, and performance, to represent a building as a set of these building objects (Björk, 1989; Ito et al., 1990).

The approach is particularly useful when product models can be represented in well-established structures such as standardized housing systems and fully prefabricated building systems, in which interface rules among building components are clearly defined (Yamazaki, 1990; Björk, 1992).

However, such product models are insufficient since materials and parts data have to be determined for each stage of the design plan upon reflecting the feedback of production and construction for most architecture projects. BIM has been eagerly anticipated as well as advanced high performance design tools to control the BIM pro-

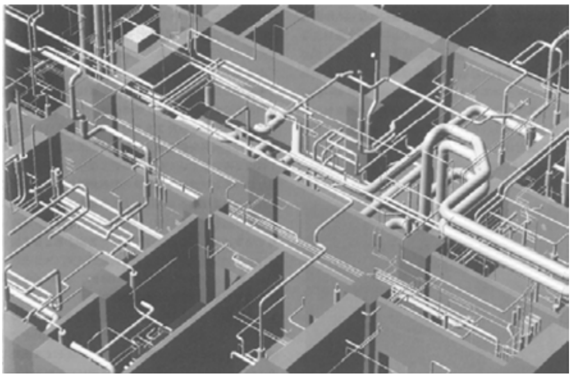


Figure 3. An example of product design by 3-D CAD at the beginning of 1990s.

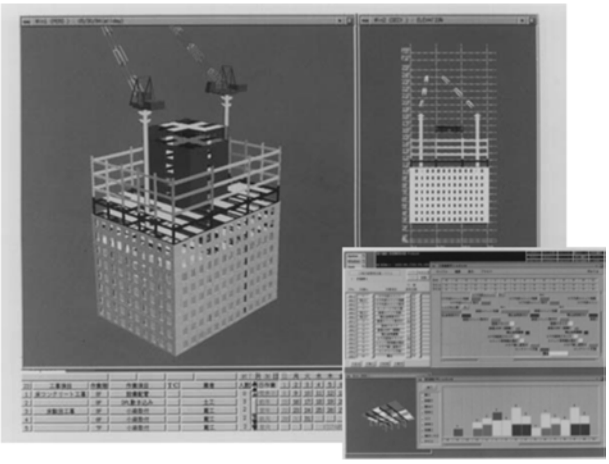


Figure 4. Integrated construction planning for hybrid structure building by 3-D CAD at the middle of 1990.

cess. Under such circumstances, graphics data using two dimensional CAD has been used for product modeling of architectural production so that the CAD data created in the upstream process was used in the downstream process in order to avoid duplication of data as well as to share such production data in the phases of design, structural design, and facility and construction planning data.

In the next stage, with the increase in size and complexity of architectural structures, it became difficult, in many cases, to achieve consistencies of production data only with two dimensional CAD. Consequently, a 3-D data model was created with an advanced model of 3-D CAD to simulate the design and construction plan (Figs. 3, 4). The simulation of 3-D CAD using 3-D model enables the designer to calculate numerical data for consistencies or coordination of interference of the structural members and facilities and simulation of the construction so that it makes it possible to coordinate various tasks regarding architectural design, structure and facilities based on the design and construction schedule in a precise and prompt manner (Yamazaki, 2000; Yamazaki et al., 2003).

In particular, there should be cases of trial and error to study the rationalities of the structural and construction systems for large-scale and specially designed structures. Therefore, it is important to create a large amount of 3-D data required for designing details, studying the construction method and production of structural members, in order to visualize and identify issues and construction procedures for the parties concerned to share.

For such a complicated and detailed construction plan and its validation, 3-D data models and BIM have been updated as an efficient simulation method using 3-D CAD, as the cost efficiencies are sufficient against costs to create 3-D data model, and its know-how to create, change and use the integrated model for architectural structures has been researched and developed (Kataoka, 2008; Kataoka, 2009). With the rapid advancement of CAD and BIM tools to use such data, 3D/BIM has been used more for construction planning phases, rather than the design phase. The following report is on a recent major case of 3D/BIM tools used for a large-scale architectural construction project.

3. Yokohama International Passenger Terminal: A Structure Designed to Continuously Change Shape

Yokohama International Passenger Terminal, completed in May 2002, has no columns or beams that are supposed to exist in such a structure, but it does have an extremely complex structure with roofs and floors combining triangular pyramid members between two beam-and-girder structures extending toward the north and south on both sides of the structure (Fig. 5).

The shape of the building was designed using 3-D CAD according to some geographical design rules by a non-Japanese designer who won an international design competition. The section on the long side of a rectangle continuously changes according to a certain rule, so that there is not only the complicated shape of the beam-girder

Figure 5. View of Yokohama International Passenger Terminal.

Figure 6. Construction by large steel blocks.

structure but there are also different materials used for its folded-plates that seem to be placed in series.

The building is designed to be a steel structure with steel materials and plates, as well as a complex of folded-plate structures and a series of substructures in order to achieve the image the designer intends. In order to secure a certain structural strength, the steels are welded for connection in principle. However, rivets are used connection between steel plates and steel beams to sufficiently integrate.

For construction, large-sized mobile cranes were used to build the structure in order with large-sized blocks for the beam-girders as the main structure, and the folded-plate units of the floor and roofs (Fig. 6).

3.1. Comprehensive coordination using 3-D data

Such a large-scale and specially designed building, due to its difficulties in construction, required a production design and production plan consistent with its architectural design, structure and facilities through comprehensive coordination using 3-D CAD, as well as a precise 3-D data model of the building information developed from the initial stage of the construction (Fig. 7).

The complicated shape of beam-girder construction is comprised of face plates, not using existing mold steel. In addition, the folded-plates are designed to have steel plates attached to H-shaped channel frames, though there is no same angle for the heads of the channels. Therefore, it was important to determine the shape and materials for such members during the steel production stage.

The construction method for this project is to apply large-size blocks of the beam-girder structure to realize construction efficiency. However, there is an issue in designing such large-sized steel blocks in that the PC steel bars attached to the base should not be interfered with by utility piping or the blocks. In particular, it was necessary to thoroughly coordinate the connecting parts and the reinforced parts of the steel members so as not to have the piping and members penetrate through them.

One of the major characteristics of the design of the building is the free-form surface deck at the top. Although the construction of such a design tends to be difficult with any kind of materials, wood decks were employed for this project. Construction onsite required many man-hours since the details needed to be done by hand, while 3-D data concerning the shape and sizes were effective to create a grid of the curved surface to design the

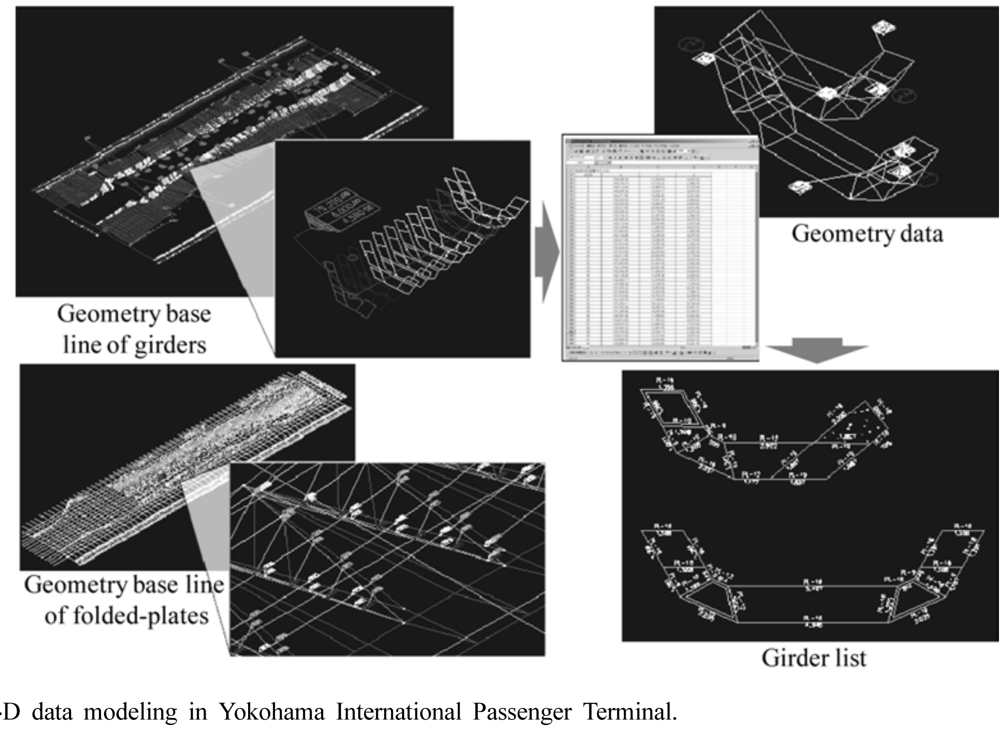


Figure 7. 3-D data modeling in Yokohama International Passenger Terminal.

layout of the wooden plates on the surface.

In this case, a data set was created for shapes, locations and thickness of steel plates of the beam-girder structure and folded-plates based on the geographical model determined by the architect to develop a 3-D data model of the structure as a basis of consideration. Then, another 3-D model was added containing PC steel bars for blocks to attach to the base, utility piping, external curtain wall and rooftop wood decks to create a comprehensive 3-D data model of the inconsistencies. It was further followed by different 3-D data for each block, which was used to develop 3-D data and the detailed working drawing for shop fabrication of the steel, curtain wall and wood decks, etc.

3.2. Utilization of structural analysis in construction process

In recent years, special structures and large-scale structures with a large space or hanging structure have been increasing. The analysis during construction is for analyzing the structure of a building reflecting the construction procedure, by studying an appropriate way of supporting the structure to secure structural safety during construction so as to develop the optimum construction plan. This facility required its large-sized blocks of the steel beam-girder structure and the folded-plate units of the floors and roofs to be supported by a temporary supporting pedestal. Thus, it was necessary to study methods for reinforcing and supporting the temporary facilities and their construction procedure to prevent deformation or collapse of the members during construction so as to confirm the proper location and precision during the stage.

For the reasons above, the 3-D data model is used for construction analysis on construction methods considering deformation and the numerical studies to secure the design quality based on the method through safety studies regarding the dead weight, wind and seismic loads of the facility during various phases of construction of the steel blocks and folded-plate units As for the result of the studies, a method was employed using setting beams to install the folded-plate units, not using the temporary supporting pedestal (Fig. 8).

3.3. Utilization of 3-D measurement system

For production and onsite installation of blocks in such a way so as not to have a vertical place on any structural members, it is essential to have a precise setting of the coordinates and 3-D measurement since even minor design errors in production and construction could affect the work to follow. This project applied the 3-D measurement system that combines a total station and personal computers using a program to combine data from CAD and measurement of survey works to facilitate the measurement of various structures in a complex shape (Fig. 9).

Accordingly, it can be said that the best mix of the skills of the designer, manufacturer and contractor made the project successful and the complicated structure was completed on schedule.

4. Mode Gakuen Cocoon Tower: A Structure with Curved Outline and Distinctive Cocoon Shape

Mode Gakuen Cocoon Tower is the tallest educational building in Japan. It is a 50-story, 203.65 m-high, super-

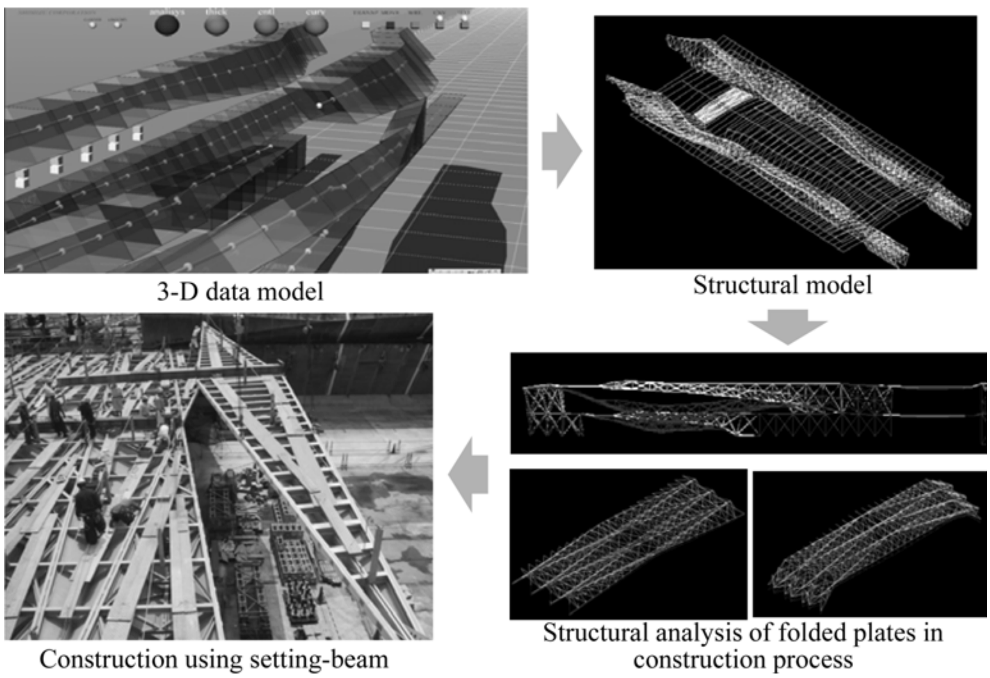


Figure. 8. Structural analysis reflecting construction procedure.

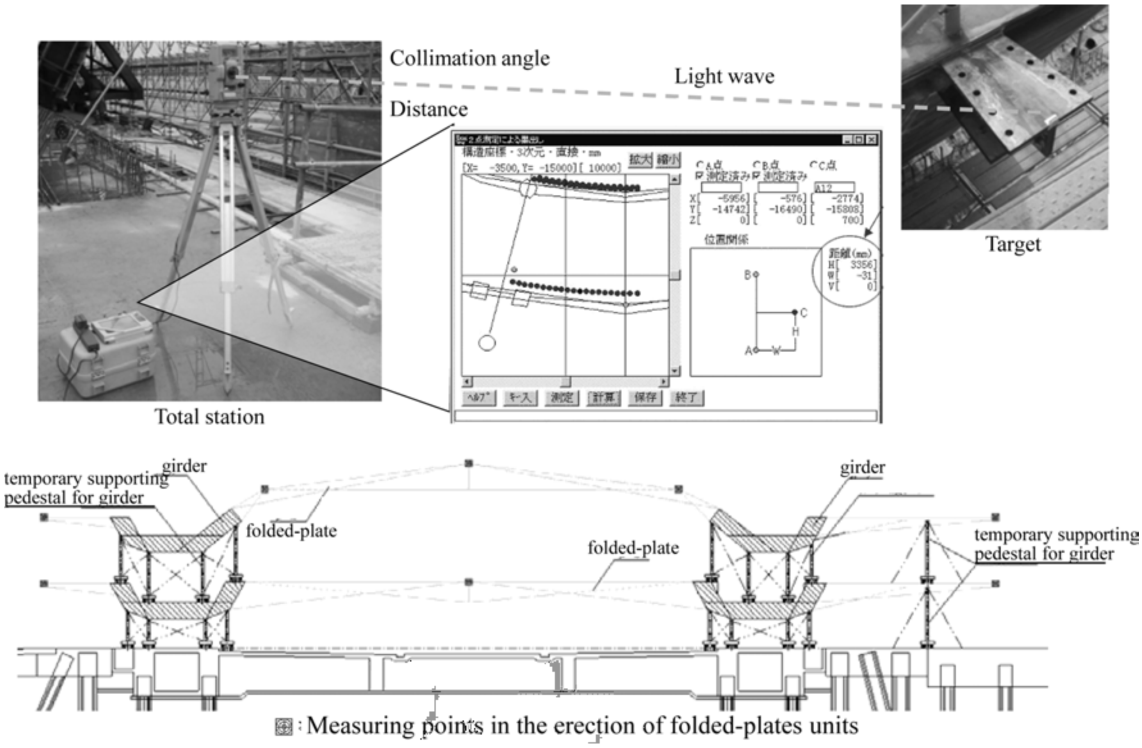


Figure 9. Application of 3-D Measurement System.

high-rise building, completed in October 2008. The tower's curved outline and distinctive cocoon shape required sophisticated technical solutions and innovative ideas for structural systems and construction methods.

The main structure consists of three elliptical diagonal structure frames of steel and an inner core frame with 12 rigid concrete-filled steel tubular columns. Because the three diagonal structure frames are rigidly connected with each other at the base and the top only, the building has relatively large shear deformations in the middle stories due to the bending of each diagonal structure frame. The inter-story displacement of the perimeter frame is largely through bending, while that of the inner core is by shear. Oil dampers are utilized to exploit the shear deformation of the inner core and to dissipate the associated seismic energy. On each floor from the 15th to the 39th, the inner core has six oil dampers, which reduce the seismic force that needs to be resisted by the structure (Fig. 11).

4.1. Utilization of visualized investigation and planning by 3D

In this project, importance was placed on utilization and coordination of knowledge and innovative ideas with project participants to solve problems caused by the distinctive cocoon shape and specific structure. Therefore, visualized investigation of design details and construction planning were aimed at to attain higher productivity using 3D, in spite of the various complexities in the project.

3D played an important role in checking areas for which two-dimensional identification was difficult such as the facade with its distinctive elliptical curved surface, points of interference between the building and equipment and a heliport with a retractable roof.

Figure 10. A view of Mode Gauken Cocoon Tower under construction.

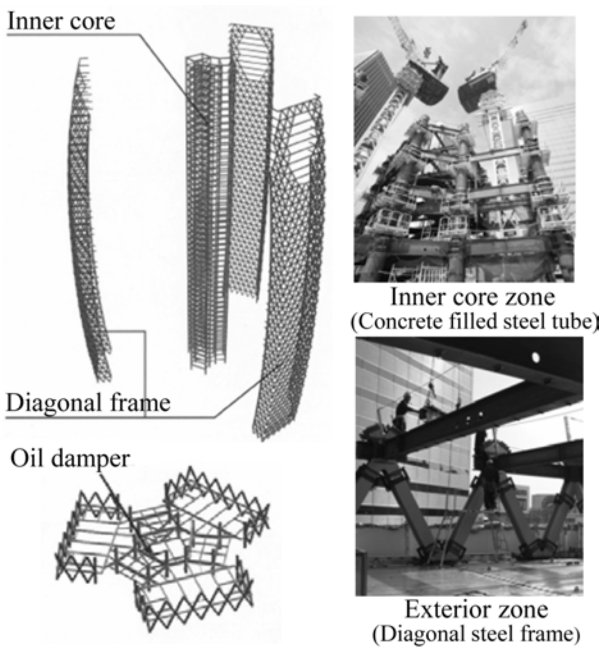


Figure 11. Outline of structure system.

With underground construction, structural analysis based on 3D was utilized to establish an efficient construction method for demolition of the existing underground building frame which was 20 m below ground. Consequently, an earth retaining structure of an RC ring beam using the existing underground building frame was developed, and underground construction work was safely completed in a short period (Fig. 12).

With superstructure construction, to complete the structural work of each floor in 5.5 days, the construction method and procedure are carefully examined using 3D. Systematized construction was introduced, namely, 3 floors of the inner core steel frame were erected to secure perpendicular accuracy, and then the diagonal steel frame of the perimeter was installed on every floor, and finally floor steel beams horizontally connecting the diagonal frames and the inner core were installed, to produce an elliptical curved surface as intended in the design. To secure the safety of welding work with perimeter diagonal steel frames, exterior hanging scaffolding units were adopted after examination of constructability and mobility using them depending on 3D (Fig. 13).

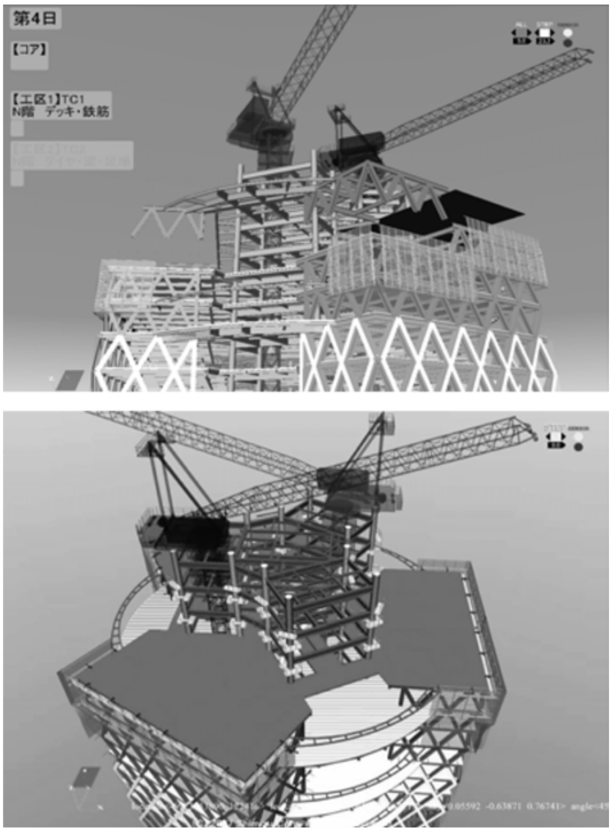
The three-dimensional measuring system using an electro-optical distance measuring instrument was also adopted with 3D to secure the accuracy of diagonal steel frames.

Furthermore, 3D was also used for verifying daily work so as to let those concerned have an effective common understanding of the plan.

Figure 12. Construction simulation for underground works using RC ring beam.

4.2. Examination of standardization of curtain wall units based on pre-assembling method

A pre-assembling method of three Z-type curtain wall units (2 m in width and 3.7 m in height) to a large curtain



Figrue 13. Construction simulation for erection works by 3D.

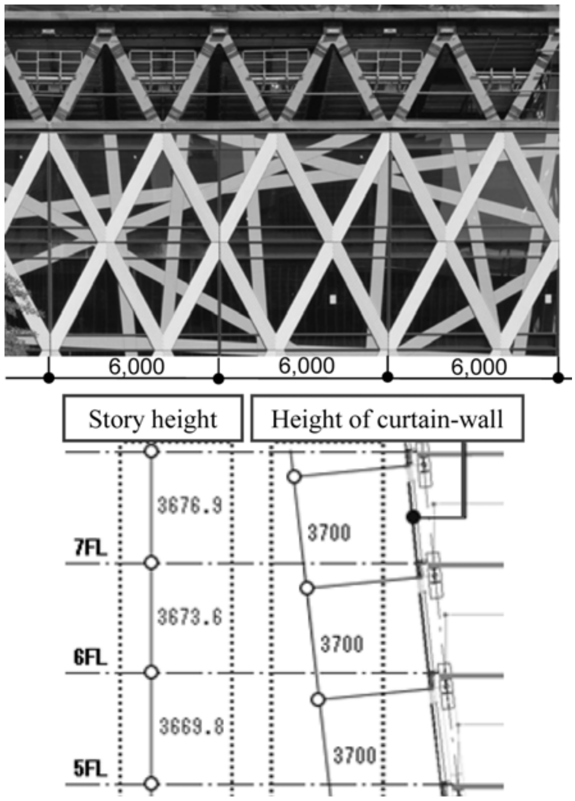


Figure 14. Standardization of curtain-wall units.

Figure 15. Pre-assembling of curtain-wall units at site factory.

wall unit (6 m in width and 3.7 m in height) at the construction site factory was selected through the examination of efficient methods to fabricate the units at a factory and to transport them by cantina, to help express the curtain wall cocoon pattern design and curved form. Story heights are such that the distance on the elliptical line is uniformly 3.7 m, allowing the diagonal structure members to intersect at the same angle on each floor. This shows that the external patterns smoothly and significantly simplified the fabrication of steel and exterior curtain wall units (Figs. 14, 15).

Pre-assembled curtain wall units are stocked in the lifting equipment installed in an elevator shaft, and are sequentially conveyed to the top construction floor with lifting equipment by a tower crane. Since a curtain wall is to be installed under an elliptical curved surface, balancing equipment is used to arrange its position under 3 floors of structural frame construction. The conveying and installation process is examined by construction simulation using 3D (Fig. 16).

While solving the wind problems associated with transportation of large exterior curtain walls in super-high-rise buildings, efficient pre-assembling and conveying methods for curtain wall units were realized.

5. Shimizu New Head Office: A Structure Comprises Reinforced-concrete Inner Core Wall and Hybrid Exterior PC Frame

The Head Office is Japan's first high-rise office over 100 meters to incorporate a reinforced-concrete seismic-isolation structure. The primary reasons for this choice were twofold: to create a building that has outstanding seismic performance that can serve as a disaster-relief facility, and to create column-less space that maximizes

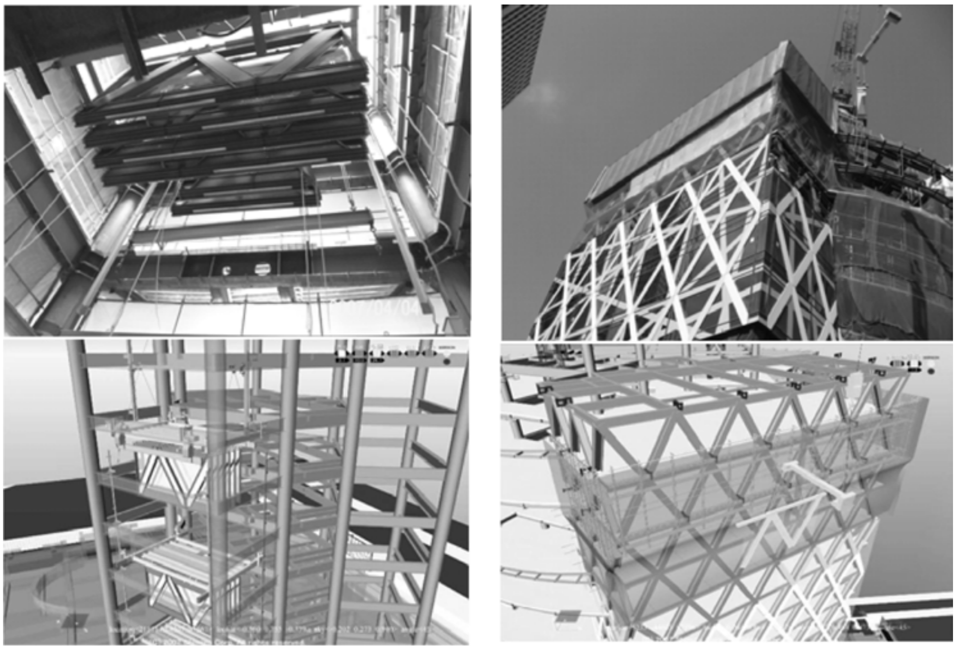


Figure 16. Transportation/Installation of unitized exterior curtain walls and construction process simulations using 3D.

Figure 17. A view of Shimizu Head office under construction.

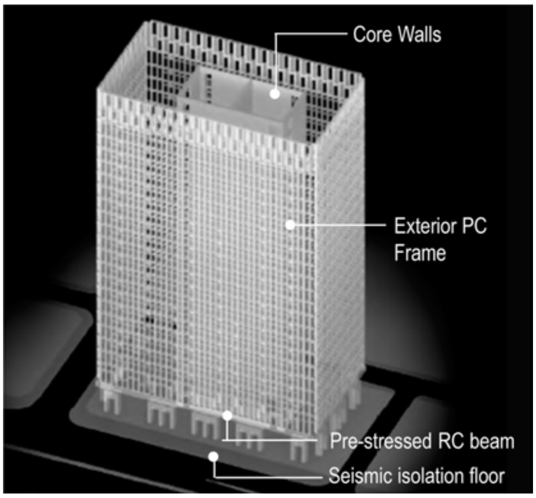


Figure 18. Structural system of Shimizu Head office.

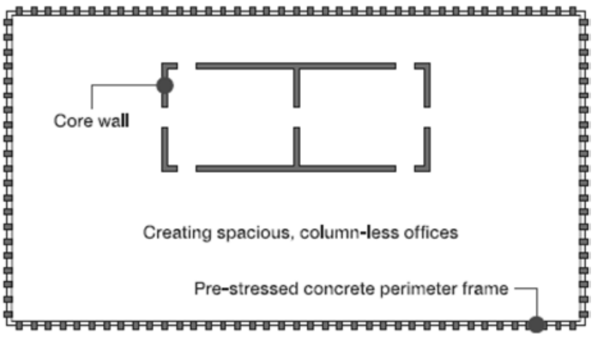


Figure 19. Standard floor area of Shimizu Head office.

office flexibility (Figs. 18, 19).

As for the plan of the building, it is a regular plane surface with a size of 34.2×63 m. The standard floor has reinforced concrete structure core walls with a thickness of 700 mm located around the center core. The peripheral PC frames integrated into the structure and external materials function to support the building from both the outside and inside. The floor slabs connecting the PC frames of the outer wall and the core wall are designed to have a thickness of 150 mm taking into consideration the transition of horizontal shear force when affected by earthquakes. The beams supporting the floor slabs are steel connected with pins for both sides, which should not be affected by seismic force.

Generally, peripheral PC frames are divided at the borders of the structural elements of a building such as columns, girders and connecting parts. However, the building referred to in this paper has a hybrid type of external wall PC panel with a size of 3.2×4.2 m, surrounding the windows and solar panels, that takes into consideration not only seismic performances but also various functions of the exterior wall including water sealing, water resistance and precision in construction.

The exterior PC panels are made of high strength concrete in the design standard strength $Fc = 80\ N/mm^2$ to minimize the sizes of structural members. With such a frame-shaped structure, there are risks in the structure such as thermal cracks caused by hydration-heat and cracks that are caused by autogenous shrinkage during production of the PC panels, and other types of cracks due to drying shrinkage or ambient temperature changes after erection. Therefore, limestone for concrete aggregate, which has minor shrinkage strains, is used for this building. Furthermore, AFR (Advanced Fire Resistant) high strength concrete containing polypropylene fibers (PP fibers), which prevent high strength concrete exploding in the case of fire, is used.

This project is for a building with a relatively simple design in shape. Therefore, an off-the-shelf BIM tool was introduced from the design phase, by taking advantage of the design-built concept. Accordingly, the design plan was developed not only striving to achieve consistencies of various elements of the design data such as its architectural design, structure and facilities from the preliminary design and basic design phase, but also making efforts to solve issues in the structural analysis and assessment of environmental efficiencies of the building in advance.

5.1. Investigation of details and construction process of hybrid exterior structure system by BIM

Since construction of a hybrid exterior structure system had many untried portions, the examination items were identified through as-built simulations using BIM and demonstration experiments in the design phase. Then the solutions were reflected in the building design, engineering, manufacturing and execution plan of building components.

Although adjacent PC panels are connected as an integral structure with cast-in-place concrete, the reinforcement of beams was required to be connected using mechanical joints in the limited space of 340 mm between PC panels. A mock-up of joint mechanisms was produced with real-scale PC panels to examine the allowance and quality of the panels, thus construction procedures are confirmed by BIM (Fig. 21).

Figure 20. A view of installation of exterior PC panels.

5.2. BIM-based material handling simulation

The building has typical site conditions of office buildings in the center of Tokyo that have cramped outside space. Therefore, the whole material handling process including transportation, horizontal and vertical conveying and installation should be carried out inside of the building. Hybrid PC panels were carried into the stockyard on the ground floor of the building at night. The PC panels were horizontally lifted and conveyed to an erection mount by a goliath crane. After raising a PC panel perpendicularly on an erection mount, it is vertically installed in a stock mount to be equipped with a column rebar unit, Low-E double-glazed glasses and photovoltaic units. The PC panels are transported from stock mounts to lifting equipment to be conveyed to the designated position by a tower crane. The entire material handling process with PC panels was carefully investigated using

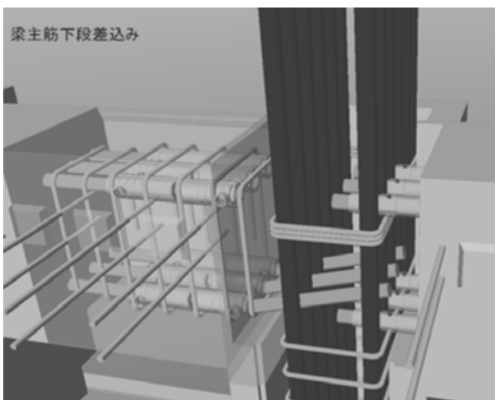


Figure 21. Investigation of details and construction process with mechanical joints.

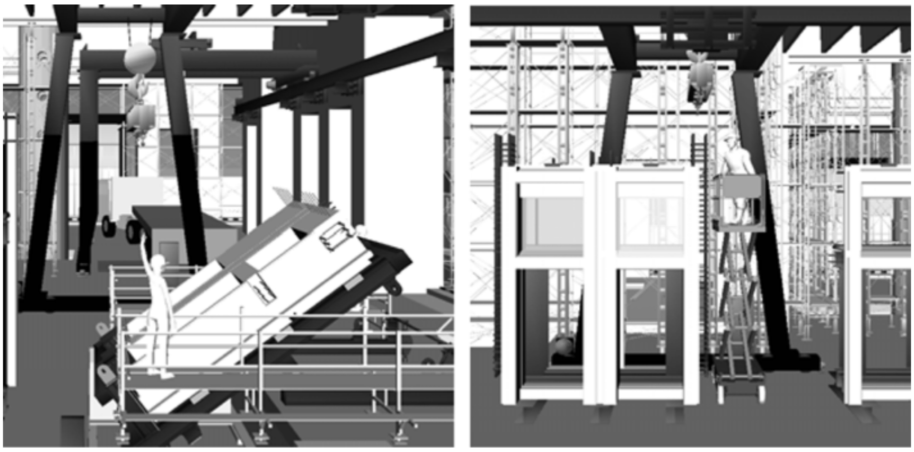


Figure 22. Transportation/Handling process simulation using BIM.

as-built simulations based on BIM, which covers the layout planning of material handling equipment on the ground floor and crash checking of PC panels, material handling equipment and building structure, resulting in efficient construction planning (Fig. 22).

5.3. BIM-based real-time construction sequence simulation

Construction of the superstructure for each floor should be performed in 6 days, which covers structural work with the RC core wall inside a building, installation and joint works of PC panels and installation and joint works of floor beams between the core wall and PC panels; real-time construction sequences were required to be investigated to optically utilize tower cranes, conveying equipment and stockyards. These precise examinations had to be performed under complex constraints; BIM-based as-build simulations are fully applied to early construction planning decisions. To efficiently perform as-built simulations, BIM should be attached with subdivided attributes of construction blocks, type of construction work and precise building components such as pre-assembled reinforcement units and mechanical reinforcement joints, according to work packages to enable efficient procurement for manufacturers and suppliers. Also, 3D temporary construction objects such as tower cranes, material handling equipment, formwork systems and scaffolding, which are usually delivered by software vendors, were attached to BIM with standard operating time data.

Using these semantically extended BIM, the real-time construction sequence for a standard floor is precisely analyzed and detailed construction procedures are examined and coordinated where problems or contradictions were identified (Fig. 23).

5.4. BIM applications to construction process monitoring

In the construction stage, problems in the construction process are rapidly understood and solved by comparing construction work processes produced by BIM based on real-time construction sequence simulation and actual progress gathered as monitoring image data using web came-

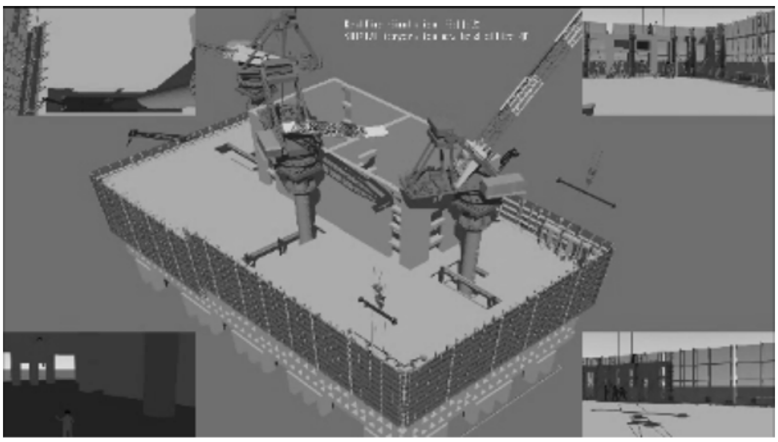


Figure 23. Real-time construction process simulation based on BIM.

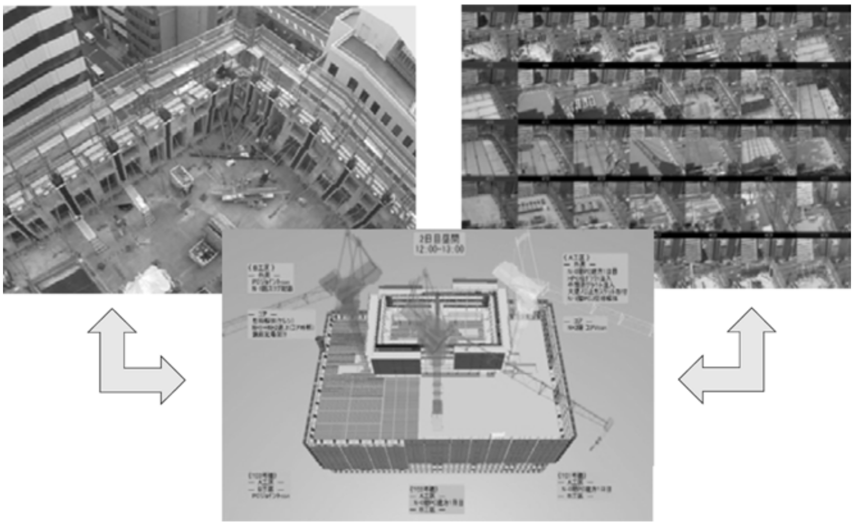


Figure 24. Comparison of sequence simulation and monitoring.

ras (Fig. 24). For example, to install PC panels in standard operation time, simultaneous construction work such as construction of the core wall structure, material handling at site factories and inspection of structural works should be controlled and coordinated in a harmonized operation time; in addition, quality and progress management systems utilizing mobile terminals were introduced to smoothly promote planned construction sequences.

Depending on the management systems, all the information regarding manufacturing of the PC panel and related components, delivery of them to the site, quality and accuracy in installation of the PC panels, and results of inspection with reinforcement at connecting parts of panels, were gathered and sent to the web server to be confirmed by designers, supervisors, manufacturers and constructors.

To improve productivity in such quality and progress management, the necessary information and data are displayed on the PC panel as a two-dimensional bar code to be read and checked with the mobile tool at the construction site. Such information and data regarding inspection results are also immediately delivered to workers at each construction stage to confirm permission for post-process work.

The structural work construction process of each floor including hybrid PC panel installation realized actual progress in six days, through the above investigations and improvements depending on BIM applications to construction process monitoring.

Thus, various examinations and verifications are performed using BIM in frontloading-type design building systems.

6. Conclusions

At present, 3D/BIM is widely adopted for complex large-scale building projects associated with innovative structural engineering and improved construction technologies. Among such innovative engineering and technologies, structural analysis in construction process, automated crash checking technology, real-time construction sequence simulation, and 3D measurement technology are keys to efficiently utilize 3D/BIM.

The following issues are proposed for 3D/BIM applications, to introduce advanced automation and information technologies such as algorithmic design of building facades and structures, automated production of building components, real-time inspection of building parts using 3D scanning, and ubiquitous communication systems depending on sensor networks:

– Sophistication of collaboration environment with AEC functions by improving production/delivery systems through investigations using 3D/BIM

– Promotion of technology and knowledge fusion toward higher level of automation and integration by reviewing 3D/BIM as a tool for fusion

– Continuity of research and technology development toward construction innovation by promoting basic research and organized experimentation with CIC based on 3D/BIM

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