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Simulation of Hoisting Bottom Pool of Nuclear Power Plant by Open-Top Construction Method

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***Abstract*—The traditional construction method of a nuclear power plant is to build a factory building and a containment, and then put the key structure into the containment. From the AP1000 project, the open-top construction scheme is adopted. The open-top method can quickly hoist key structure, but the construction process, tooling and other equipment need to be changed. It is challenging for units that have no open top construction experience. This paper simulates the overall assembly and hoisting construction of the bottom pool for a nuclear power project. For the overall assembled tooling, the design scheme is verified; for the overall lifting of the pool, the problem of the construction plan is discovered in advance, and the hoisting construction plan is improved.**

Keywords—nuclear power plant; pool; open-top construction; hoisting

I. INTRODUCTION

In the construction of traditional nuclear power plants, the reactor building and the containment are all completed first, and then large equipment such as pressure vessels and evaporators are transported into the plant in a horizontal state, and finally inverted in the plant, and then hoisted in place by the ring crane.

Open-top construction refers to prior to the capping of the plant, heavy equipment such as pressure vessels, steam generators, pressure regulators, bottom tanks, and main pumps are assembled or externally hoisted in the factory by heavy lifting equipment, and directly suspended from the top of the plant. In the history of nuclear power construction in China, the Qinshan Phase III heavy water reactor nuclear power plant successfully used the open-top method for the first time, with a total construction period of 52 months.

Foreign engineering practice proves that modular design and construction technology is one of the effective measures to save resources (relative to traditional production methods), reduce nuclear power plant cost and shorten construction period. Open-top construction technology, which is the premise of modular technology application, has become a routine construction technology in foreign countries, especially in the construction of Japanese boiling water reactor nuclear power plants. According to the floor area of the plant, more than 80% of the areas are constructed using open-top construction methods. The application of the open-top construction method in the construction of nuclear power plants in China has been relatively small in the past few years and needs to be further promoted and applied. Up to now, AP1000, Shidao Bay high-temperature gas-cooled reactor demonstration power station project and Hualong No. 1 have adopted the open-top construction scheme[1,2].

Our simulation construction uses DELMIA software from Dassault Systèmes, and the 3D modeling uses CATIA software from Dassault Systèmes, which can be seamlessly combined. DELMIA (Digital Enterprise Lean Manufacturing Interactive Application) is an interactive manufacturing application for digital enterprises. DELMIA provides complete digital solutions to on-demand and just-in-time manufacturing processes, enabling manufacturers to reduce time-to-market while reducing production costs and promoting innovation. DELMIA digital manufacturing solutions help manufacturing departments simulate the entire production process of digital products, virtual demonstrations before deploying any physical materials and machines [3].

II. OVERALL ASSEMBLY SIMULATION OF THE REACTOR TANK STAINLESS STEEL LINING

The reactor tank stainless steel lining is installed at the bottom of the reactor and is the preferred equipment for installation prior to installation of the reactor pressure vessel. The traditional pool installation method is: after the bottom cement is solidified, the side plates constituting the pool are installed one by one, and each board is separately transported into the reactor building, the volume is not large, and there is no problem in transportation, which is basically an ordinary installation. Different from the traditional method, if the open-top method is used, the reactor tank stainless steel lining can be directly assembled outside the containment, and then directly hoisted to the installation position through the reactor building and the top of the containment, and installed as a whole. The installation sequence is very obvious: the cement structure of the outer surface of the pool (see Fig. 1) can be constructed while the reactor tank stainless steel lining can be assembled as a whole (see Fig.2), which saves construction time of the bottom pool and shortens the construction period. If the open-top method is not used, only each board of the pool casing in Fig.2 can be installed separately after the

construction of the building structure of Fig.1 is completed.

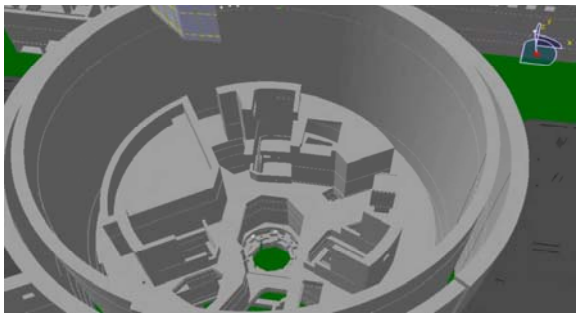

Fig. 1. Concrete Structure Shape outside the Reactor Bottom Pool

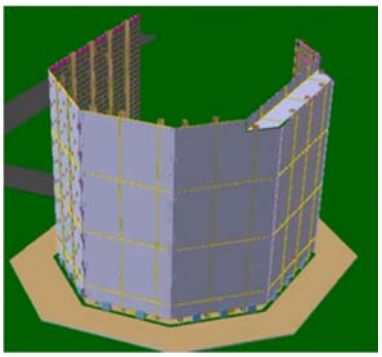

Fig. 2. Integrated Assembled Reactor Pool Stainless Steel Lining

Obviously, the assembly of the reactor tank stainless steel lining outside the reactor building is a new process for the construction unit, which has not been encountered before. The required tooling type, installation sequence, cranes, spreaders, etc. are all new. The construction unit needs to ensure that the designed tooling, the established procedures, the selected cranes and spreaders meet the construction requirements and avoid temporary changes. Simulations have shown that in order to ensure a side subassembly of the reactor tank stainless steel lining, two cranes are required for hoisting (see Fig.3). In order to ensure the rigidity of the pool shell assembly during lifting, it is necessary to add auxiliary tooling on the inner surface and the outer surface of the sub-assembly, and the function is to prevent buckling when hoisting in the reactor tank stainless steel lining. As can be seen from Fig.4, we added two layers of steel structure to the outer surface of the reactor tank stainless steel lining. The structure near the reactor tank stainless steel lining is channel steel, which is small in size but high in density, while the outer layer is increased by I-beam. The size is large, but there are only 3 I-beams. The channel steel is placed at right angles to the I-beam.

At the end of the I-beam, two circular holes are opened symmetrically, and the pin is inserted. The pin connects the upper channel steel and the lower channel steel together, and then welds to fix the structure, as shown in Fig. 5.

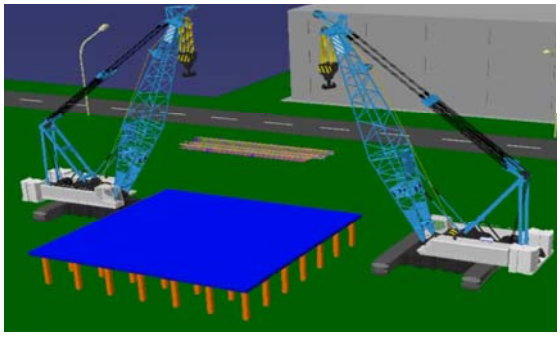

Fig. 3. The Entire Pool is Equipped with Two Cranes

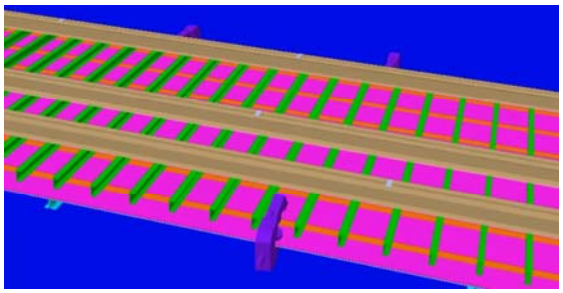

Fig. 4. Adding I-beams to the Surface of the Reactor Pool Stainless Steel Lining Sub-assembly

In the overall assembly reactor pool stainless steel lining station, tooling is also built to ensure the stability of the overall structure. Auxiliary tooling includes: laying the steel plate at the bottom; adding a C-shaped support structure to the steel plate according to the contour of the pool outer casing; six channel steel support columns are added to the side wall of the reactor tank stainless steel lining, and the bottom of the channel steel is welded with a thick steel plate block, and the steel plate is welded with the bottommost laying steel plate; on the C-shaped support structure, 18 support blocks are also welded, the support block is slotted in the middle, and the bottom of the reactor tank stainless steel lining falls in the groove; at the top of the vertical channel steel support column, a cylindrical positioning block is installed to position the reactor tank stainless steel lining, as shown in Fig. 6. After the sub-assembly of the reactor pool stainless steel lining is in place, the outer auxiliary tooling is removed. After the tooling of the overall assembly of the reactor pool stainless steel lining is completed, each subassembly can be transferred to the tooling for positioning and welding construction. That is, in this tooling, the reactor pool stainless steel lining is completely assembled, as shown in Fig. 7. In the simulation process, the tooling plan proposed by the construction party is corrected many times, mainly because of the interference of the tooling and the reactor pool stainless steel lining during assembly. The specific problems are summarized in Table 1, and specific problem solutions are given. Table 1 only gives some typical problems, and some of the interferences that can be detected by the simple modeling process or the unreasonable structure are not listed in the table. After many modifications and optimizations, the reactor pool stainless steel lining and the tooling is successfully installed.

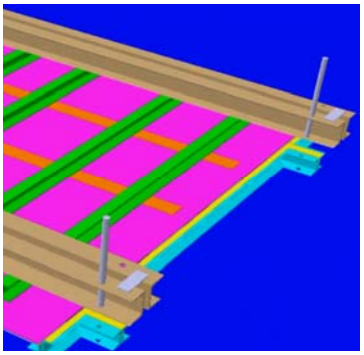

Fig. 5. I-beam Ends have Welded Joints

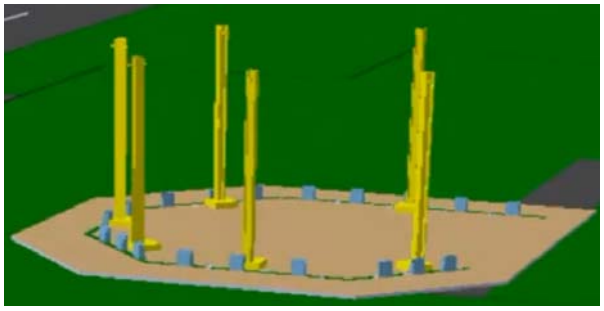

Fig. 6. Reactor Tank Stainless Steel Lining Overall Assembly Tooling

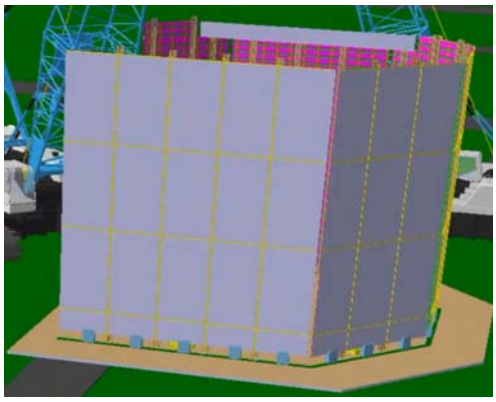

Fig. 7. Overall Assembled Reactor Pool Stainless Steel Lining

Table 1. Summary of Problems Found in Lining Reactor Pool Stainless Steel Lining Simulation

Number	Problem Description	Solutions and Measures
1	The stainless steel lining of the pool is not rigid enough.	(1) Increase auxiliary channel steel and I-beam on upper and lower surface; (2) After the sub-assembly is hoisted and erected, the auxiliary channel steel and I-beam outside shall be withdrawn.
2	Originally planned to use a car crane erecting the assembly structure, the simulation found that it could not be achieved. The subassembly will touch the ground and cause deformation.	Add one truck crane and two truck cranes to work together. After lifting to a certain height, one is responsible for lifting, and the other is responsible for slowly sending to the ground.
3	After the sub-assembly structure is erected, there is not enough fixing.	(1) Add 6 channel steel support columns to provide fixation; (2) Add the positioning pin on the top of the support column to directly position the sub-assembly.
4	The increased auxiliary channel and I-beam interfere with the channel support column.	Cut off the additional auxiliary channel steel and I-beam at the interference position.
5	18 support blocks interfere with the channel and I-beam.	Cut off the additional auxiliary channel steel and I-beam at the interference position.
6	The stainless steel lining of the pool is not a regular geometric shape, and its center position is not in a vertical line with the position of the hook.	Through calculation, the auxiliary counterweight is added on the stainless steel lining of the pool, so that the center of gravity of the structure is in a vertical line with the hook, which prevents the structure from shaking when hoisting.
7	After the weight is increased, the weight increases, which affects the strength of the welded lugs on the structure, and the strength of the selected lugs is insufficient.	Through finite element analysis, the lifting lug strength is directly calculated and checked, which proves that it can meet the requirements.
8	Track crane weight and building interference	Re-select the assembly location of the stainless steel lining of the pool to reposition the crawler crane.
9	The stainless steel lining of the pool does not coincide with the direction of the opening of the building when it is dropped.	Combined with the position of the crane, detailed calculations are made to determine the precise assembly direction of the stainless steel lining of the pool at the beginning of assembly.
10	Crawler crane lifting weight has the potential problems to damage the pavement of the factory area.	The steel plate is laid during the pavement lifting of the plant, and the grounding specific pressure is calculated to ensure that the grounding specific pressure meets the requirements.

III. Overall Hoisting Simulation of the Reactor Tank Stainless Steel Lining

After the overall assembly of the reactor tank stainless steel lining is completed, the hoisting work is started, and the reactor tank stainless steel lining is hoisted to the installation station. The crane used is a 750T crawler crane. Due to the relatively high elevation of the reactor building, the height of the crane's boom is also relatively long, which increases the jib and the total length exceeds 100m. For the longer boom, after the overall lifting, the stability of the system including the crane, has not been verified by simulation, directly check the manual of the crane to ensure that the lifting weight, boom length, angle, etc. meet the requirements of the manual. In the project, the strength of the lifting lugs in the reactor tank stainless steel lining is checked. We use the finite element analysis method, combined with the overall weight of the structure and configuration, to check the calculation to ensure that the strength of the lifting lugs meets the requirements.

Fig.8 is a simulation scenario before the overall hoisting of the pool stainless steel lining: the reactor tank stainless steel lining is at the bottom left of the figure, with a crawler crane in the middle and a reactor building with uncapped roof on the right. The hoisting is to use the middle crawler to hoist the reactor tank stainless steel lining in the lower left corner into the reactor building. It should be noted that although the

crawler crane can be moved by the crawler, the relevant hoisting construction regulations stipulate that after the crane lifts the heavy object, the overall movement of the crane is prohibited, that is, after the crane is positioned, the reactor tank stainless steel lining can no longer be moved.

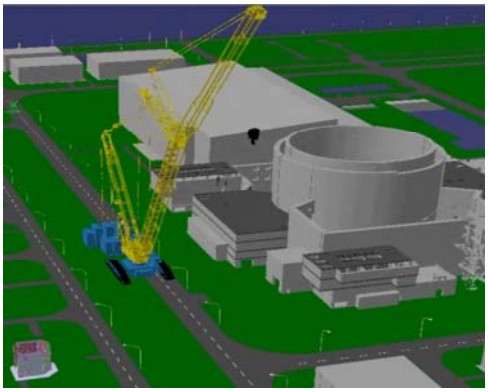

Fig. 8. Plant Layout before the Overall Lifting of the Stainless Steel Lining of the Reactor Pool

In the overall hoisting construction simulation, we find many problems in the construction scheme. Now take two examples to illustrate, both of which are issues that everyone didn't pay attention to before starting the simulation. (1) The position of the crawler crane interferes with the reactor building during the lifting process; (2) The stainless steel lining of the reactor pool interferes with the basic structure after entering the plant.

The position of the crawler crane is determined by the radius of rotation of the boom, the location of the stainless steel lining of the reactor pool and the centerline of the reactor building. After the radius of the boom rotation, the distance between the stainless steel lining of the reactor pool and the centerline of the reactor building are determined, the position of the crane is determined. As can be seen from Figure 8, there is no interference between the determined crawler crane position and the reactor building before the lifting begins. However, during the hoisting simulation, it is found that after the crane was rotated, the weight of the tail interfered with the reactor building, as shown in Fig.9. We define the distance parameter between the apex of the upper left corner of the crane counterweight and the outermost surface of the reactor building. During the simulation movement, the distance parameter is dynamically displayed in real time, so that the observer can clearly see that the weight interferes with the building. For the definition of the distance parameter, see the reference [4]. When the crane has not been rotated to the specified lifting angle, it collides with the reactor building. That is, using the current construction scheme, the crane cannot rotate the hook directly above the stainless steel lining of the reactor pool. The overall assembly position of the stainless steel lining of the reactor pool must be re-adjusted, and then the crane station should be adjusted to achieve hoisting construction.

Fig. 9. Dynamic Display of Crawler Crane Counterweight and Reactor Building Distance

After the reactor liner stainless steel lining is completely hoisted into the reactor building, it can be seen that the opening position of the reactor liner stainless steel lining does not correspond to the station to be installed at the bottom, as shown in Fig.10. The upper part is the reactor liner stainless steel lining that is being lowered, and the lower part is the concrete structure of the reactor liner stainless steel lining installation station. If it is the correct construction, it should be that the opening position of the reactor liner stainless steel lining is consistent with the opening position of the concrete structure, and the reactor liner stainless steel lining can be directly lowered. The two angles are inconsistent and the smooth installation of the pool cannot be achieved. In order to ensure the correct angle, the calculation must be carried out first. When the reactor liner stainless steel lining is assembled outside the reactor building, the correct opening direction and angle should be determined, not in any direction. After the simulation found the problem, we determine the precise position and orientation of the reactor liner stainless steel lining after detailed calculation and analysis.

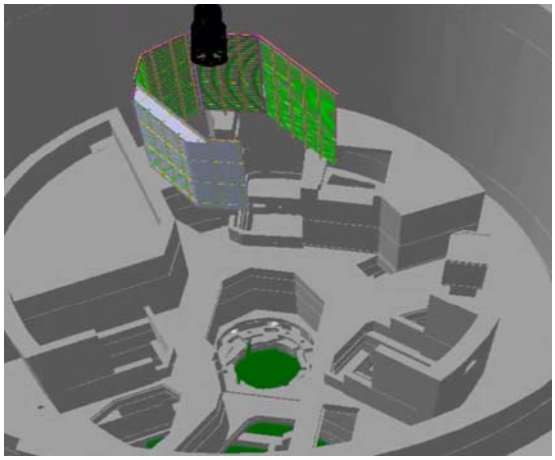

Fig. 10. The Angle of the Pool Stainless Steel Lining is not Consistent With the Angle of the Building

IV. Conclusions

The three-dimensional motion simulation software is used to simulate the open-top construction process of the reactor liner stainless steel lining in a nuclear power plant. The simulation includes the overall assembly of the reactor liner stainless steel lining and the overall hoisting of the reactor

liner stainless steel lining. For the assembly process of the bottom pool, the rationality and installation process of the auxiliary tooling are verified through simulation, and it is confirmed that the construction party's solution can successfully complete the overall assembly of the reactor liner stainless steel lining after many corrections.

For the overall hoisting simulation of the pool, it is found that the position of the crane cannot be placed casually. It is necessary to calculate and determine the position in detail to ensure that there is no interference with the surrounding buildings during the rotation of the crane. The simulation also find that when the pool is installed in the whole, the position and opening direction of the pool need to be determined in advance, so as to ensure the smooth progress of the overall lifting. Otherwise, when hoisting into the reactor building, it will interfere with the concrete wall that has been completed. Through the hoisting simulation of the reactor liner stainless steel lining, it is also proved that the importance of simulation for the new construction process, which can avoid detours, make fewer mistakes, and ensure that the newly formulated process can meet the construction requirements of the site.

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