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Structural Stability for Construction of High-Rise Building

In-Hwan Song, and Jae-Myoung Lee†

Busan Lotte Tower Site, LOTTE E&C, South Korea

Abstract This paper introduces the structural engineering of permanent structures, scaffolding, and construction equipment for structural stability during the construction of Lotte World Tower, which was completed in 2017. Verifications at various construction stages were performed ahead to ensure the safety of the completed high-rise building. Then, Structural review items for mega structure members at each construction sequence were discussed. Additionally, a Structural Health Monitoring System that monitors the stability of the building after completion was introduced.

Keywords Structural Stability, High-rise building construction, Lotte World Tower, SHM

†Corresponding author:
Jae-Myoung Lee
E-mail:
jaemyung.lee@lotte.net

1. INTRODUCTION

Lotte World Tower is a 555-meter high, complex skyscraper located in Jamsil, Seoul, which was completed in 2017. It consists of offices, a hotel, an observatory, and retail facilities. The architectural designers of the tower are KPF (USA) and Baum Architects (Korea), and the structural designers are LERA (USA) and Changminwoo (Korea). Lotte was responsible not only for the construction of the tower but also for the design, construction, and operation of the building at all stages.

This paper introduces measures taken to ensure structural safety during the construction stages and the structural engineering of permanent structures, scaffolding, and construction equipment for structural stability during the construction of Lotte World Tower. Up to eight structural engineers, including skyscraper experts from overseas, were involved.



Fig. 1. Project Summary.

2. Structural Design of Tower

The structure of the tower consists of a concrete core, mega columns, and a steel outrigger/belt truss system.

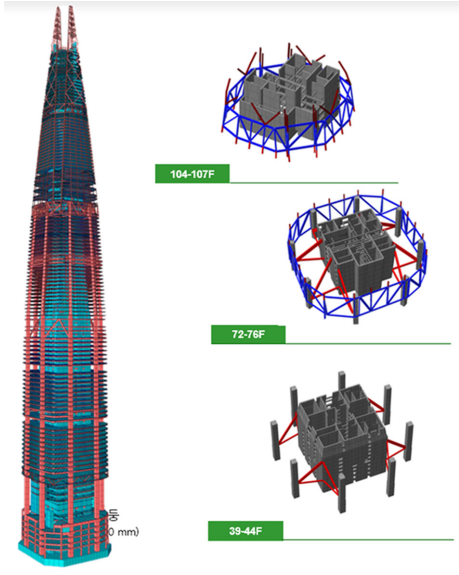


Fig. 2. Lateral Load Resisting System.

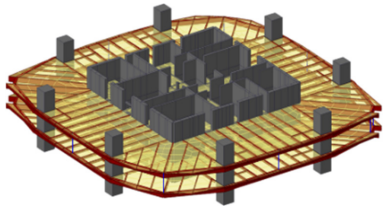


Fig. 3. Gravity Load Resisting System.

The mega columns and outrigger/belt truss are designed to resist lateral forces such as wind and earthquakes. It is the first high-rise structural system with mega columns in South Korea.

Gravity force resisting system consist of Deck slab + steel Beam + Mega column. The 50~120mm thick plate of TMCP steel was applied to the long span steel beam flange.

3. Performance Test

To verify the performance of the outrigger node and diagrid node, which are very large members, full-scale mock-up tests were performed before actual construction. The spandrel girder and belt truss were joined to the side of the mega column. To verify the performance of the connection, finite element computer analysis and performance tests were conducted at the design stage.

3.1. Outrigger Node

At the Design Development stage, node design concept was presented. Then, the shape of the node was determined through structural analysis of concentrated stress evaluation. By comparing casting production and built-up production, it was decided to use a built-up member, considering quality and economy. To confirm the manufacturability of the node member, the manufacturing sequence was established, and 3D Tekla models and full-scale models were made to check workability, such as reachability by hand and weldability. Based on that, a full-scale mock-up was conducted, and final verification was performed through manufacturability and welding quality tests.

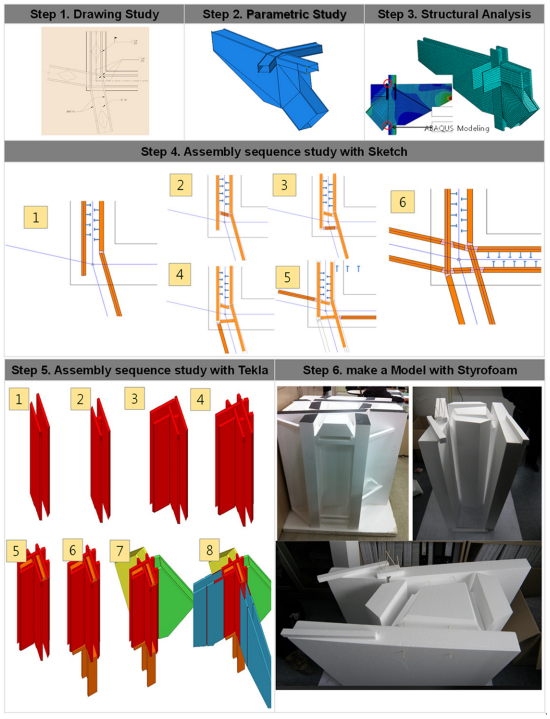


Fig. 4. Assembly study of Outrigger Node.

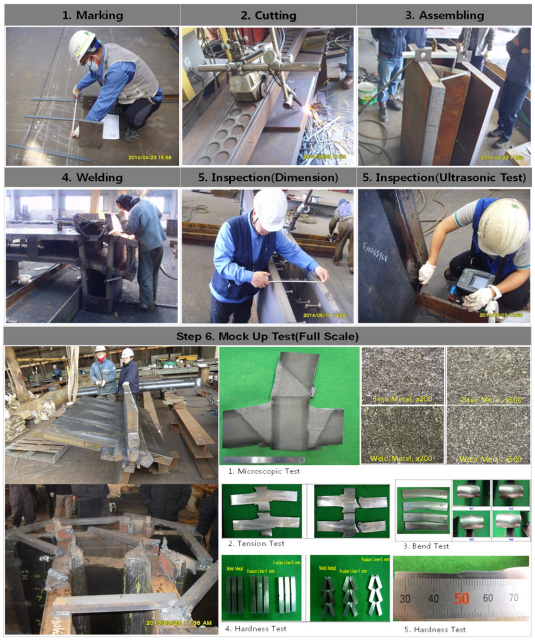


Fig. 5. Mock-up Test of Outrigger Node.

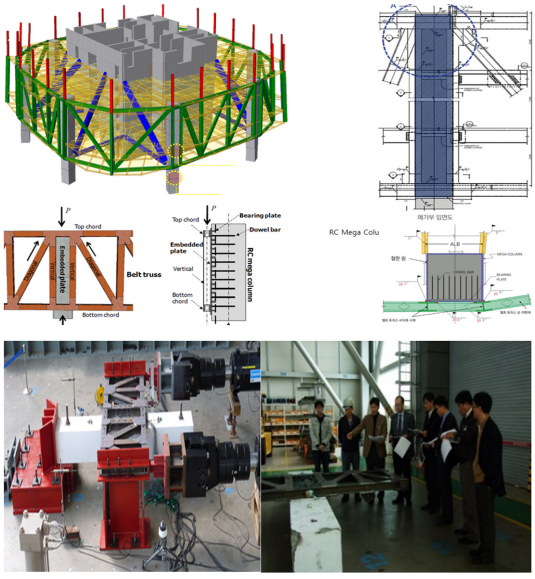


Fig. 6. Mega column+ Belt Truss connection Test.



Fig. 7. Diagrid Node Test.

3.2. Mega Column+ Belt Truss Connection

Considering the architectural design, it was decided that a belt truss would be joined to the side of the mega column. To make this connection, the embedded plate was installed with a shear key and a dowel bar. This configuration was verified through a structural verification experiment at the design stage and subsequently incorporated into the design.

3.3. Diagrid Node

In order to verify the manufacturing details, weldability, and quality of the Diagrid Node composed of circular steel pipes, a full-scale member was manufactured and weldability was confirmed, and a scale model was manufactured and verification experiments were performed.

4. Structural Stability During Construction

4.1. Superstructure

4.1.1. Core Wall

The core plan is approximately a 35 m × 35 m square shape. The wall thickness is up to 2 meters at the base and gradually becomes thinner towards the upper floors. Thus, a sloped wall core was applied to the middle floors and less core walls were placed in high floor zone.

Therefore, initially, the lower core walls were pre-constructed using the Jump Up Form system before the rest of the floor slabs and columns were constructed.

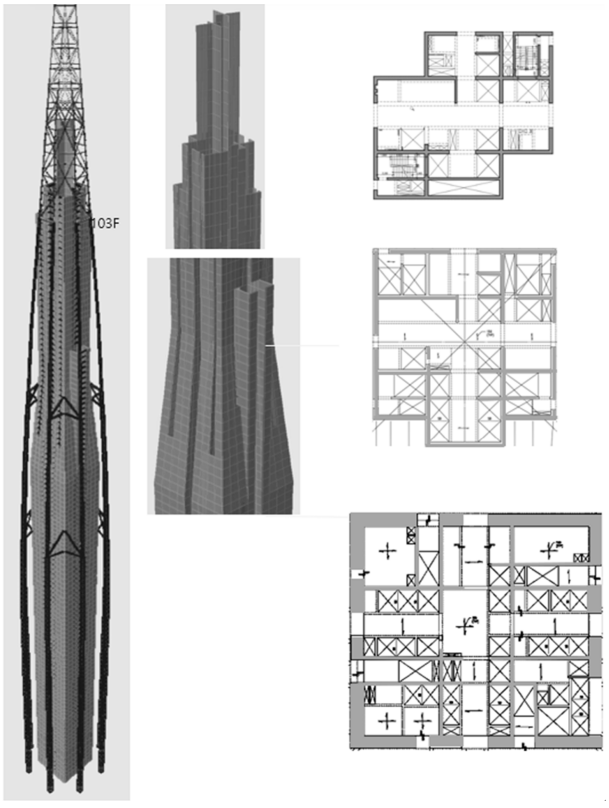


Fig. 8. Core wall geometry.

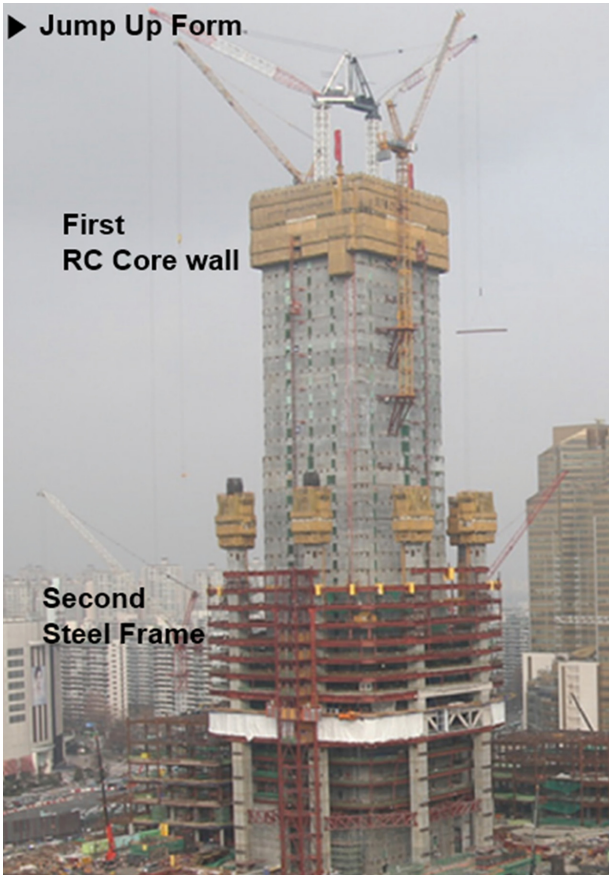


Fig. 9. Construction photo of Core wall.

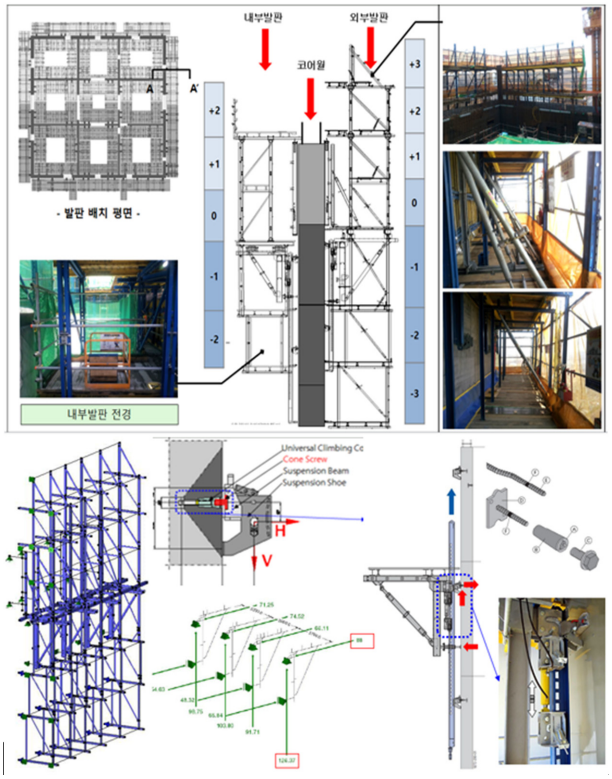


Fig. 10. Structural Review of Jump up Form.

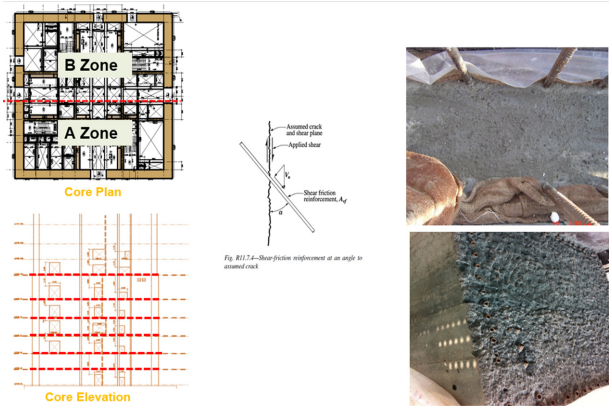


Fig. 11. Structural Review of Construction Joint.

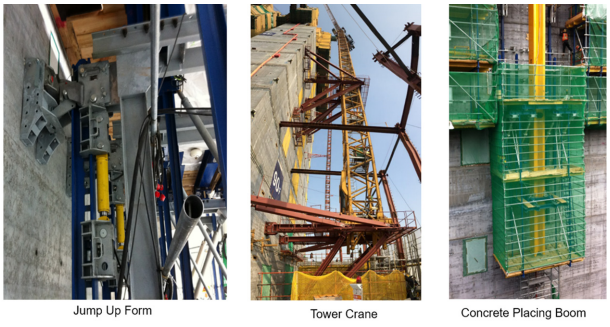


Fig. 12. Heavy temporary structure.

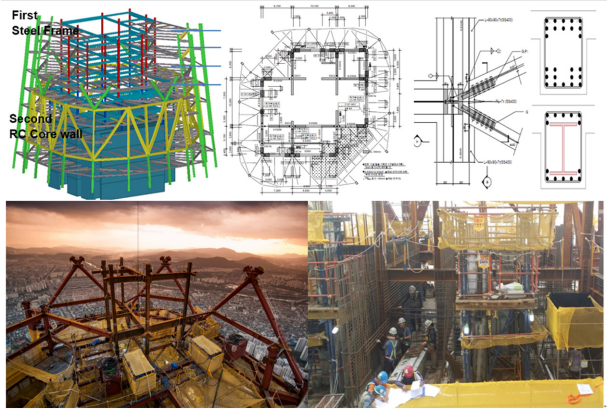


Fig. 13. Construction photo of High-zone core wall.

When only a partial core wall of the upper floor remained, a temporary steel column was installed inside the wall, and the steel frame of the outer periphery parts were pre-constructed. The post-construction method was then applied to construct the core wall.

The Jump up Form system was applied to construct core walls. To ensure the stability of the temporary structure, safety checks were evaluated included conducting structural calculations to account for various conditions such as construction work, typhoon conditions, and lifting operations.

The core was constructed in two parts due to limitations on the amount of concrete poured per time, resulting in horizontal and vertical construction joints on each floor. To ensure the structural integrity of these joints, laitance was removed, and the necessity for chipping was assessed through structural review to ensure safety and constructability simultaneously.

A heavy temporary structure (Jump Up Form, tower crane, CPB) was installed on the core wall, and safety was ensured by calculating the required concrete strength through structural review and installing equipment after confirming the concrete strength on-site.

Since only a portion of the core wall was present in the high-rise area, temporary steel columns were installed inside the core wall, and construction of the core wall proceeded after the steel frame of the outer periphery. Safety of the temporary steel frame was reviewed, and any interference between the temporary steel frame and the core wall reinforcement was resolved through engineering.

4.1.2. Mega Column

Mega columns were planned from the 6th basement floor to the 76th floor with outriggers, and 8 were placed on the floor plan. The size of the cross section changed for each floor from a maximum square of 3.5 m to 2 m. In order to determine the construction method of the column, various abroad cases were studied, and mega column was decided to be used. It was the first time mega column used in Korea. There was a disadvantage in having to absorb the construction tolerance of the steel beams that had to be installed between the core wall and the mega column before them. In order to absorb construction tolerance, it was necessary to make actual measurements before installing the steel beam and to manufacture and install the gusset plate, which wasted a lot of time. To overcome this, a temporary steel column was installed inside the mega column to construct an outer steel frame, which was changed to a general method. For this, engineering was performed to change the installation sequence to a long slot for structural safety and tolerance absorption.



Fig. 14. Construction photo of Mega Column.

4.1.3. Outrigger Truss

Outrigger trusses were planned in two zones: the 39th to 44th floors and the 72nd to 76th floors. They were designed with triangular-shaped lower chords and diagonals, with steel members embedded inside the concrete walls and mega columns. The outrigger, being a large member, was segmented to fit within the tower crane lifting capacity, and a construction plan was established with temporary posts.

Based on the this, the construction plan was decided through structural review.

Due to the embedding of steel members inside the core and mega column, interference occurs with rebar, steel embed plate, jump up form, etc., so we performed interference review using BIM and detailed review of interference resolution three months before shop drawings, and performed Shop DWG.

Delay joints were applied to resolved additional stress caused by unequal vertical shortening and were fastened after completion of structure construction. Because a level difference was expected at the connection when differential settlement occurred, the part buried in the core was manufactured with the member depth increased by 50 mm.

4.1.4. Belt Truss

Belt trusses were planned in two zones, on the 72nd to 76th floors and the 103rd to 107th floors. Temporary posts were placed for assembly during construction, and

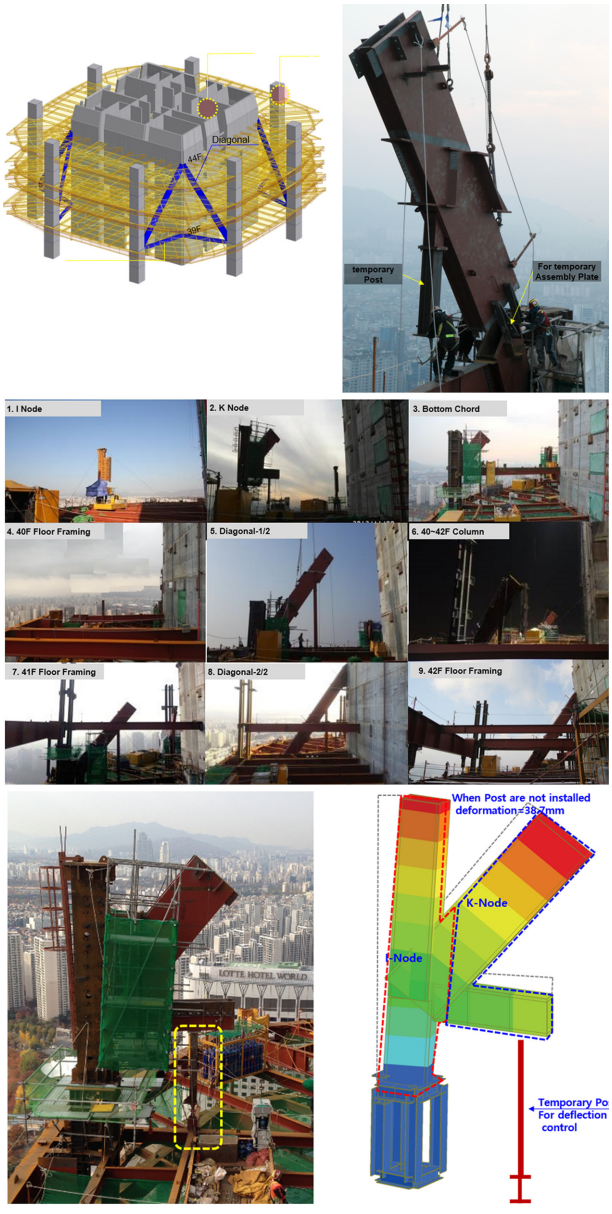


Fig. 15. Constructing Sequence of Outrigger truss.

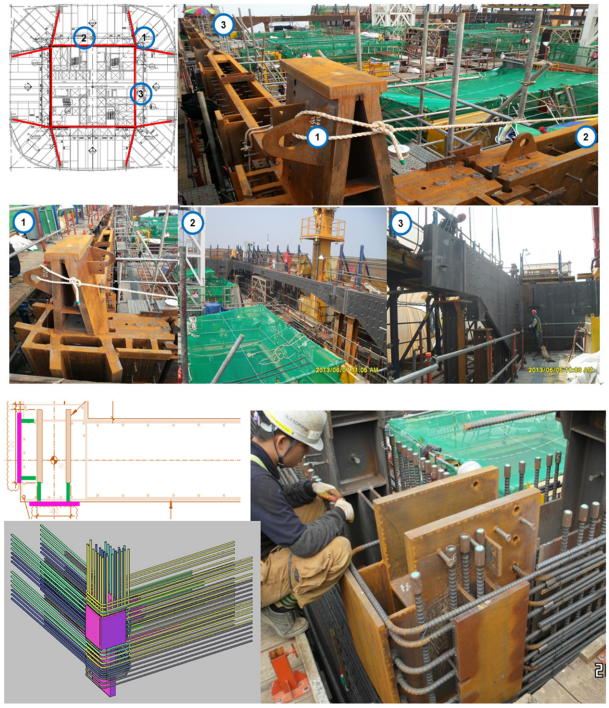


Fig. 16. Engineering of embedded steel on core wall.

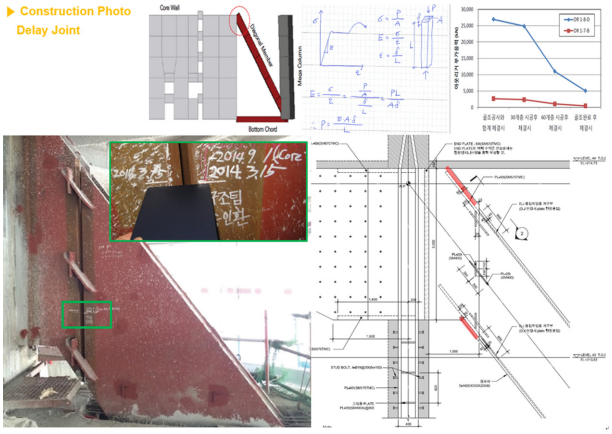


Fig. 17. Delay Joint of Outrigger truss.

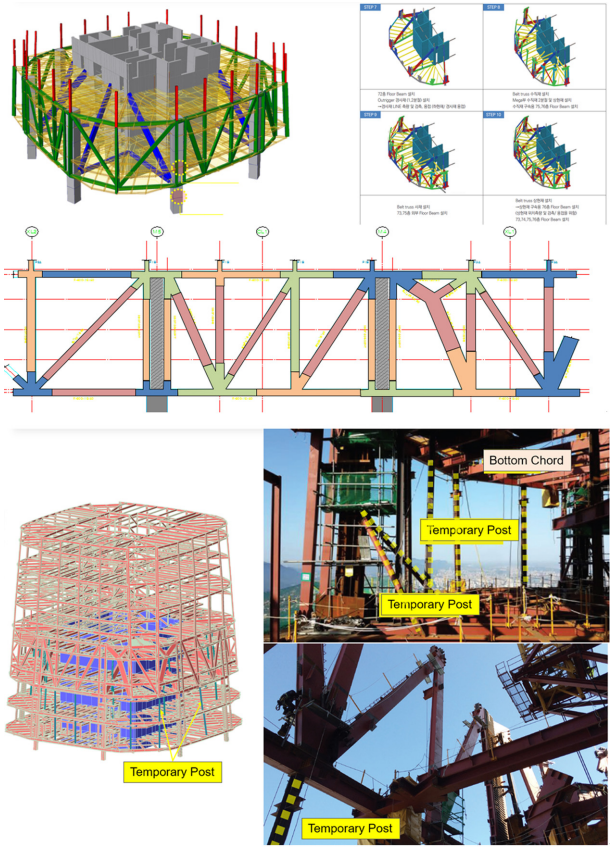


Fig. 18. Constructing Sequence of Belt truss.

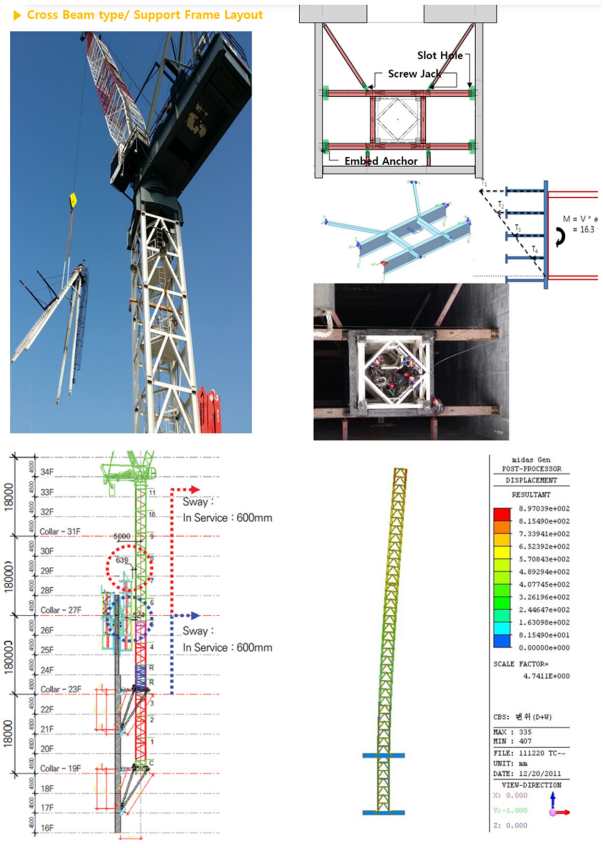


Fig. 20. Support Frame of Cross Beam type.

safety was ensured through structural review for each stage of the construction plan.

4.2. Temporary Work

For high-rise construction, numerous tower cranes are required for lifting materials, lifts for transporting personnel, and temporary structures. In addition, steel structures became necessary for the safety of low-rise buildings in operation during high-rise construction.

4.2.1. Tower Crane

Two tower cranes were installed as Cross Beam Type,

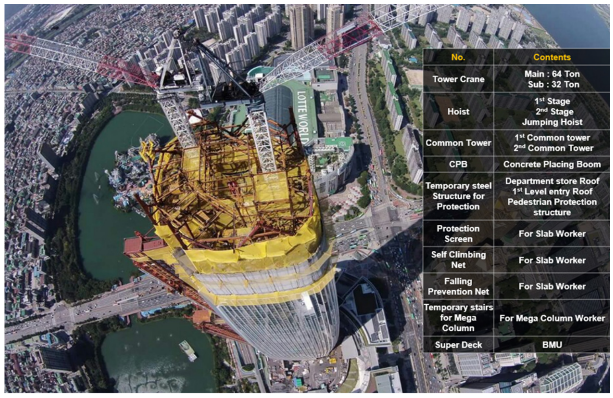


Fig. 19. Temporary Equipment.

and two were utilized as Bracket Type. After calculating the reaction force, taking into account typhoon and construction conditions, and reviewing the steel frame supporting them along with the safety of the core wall,

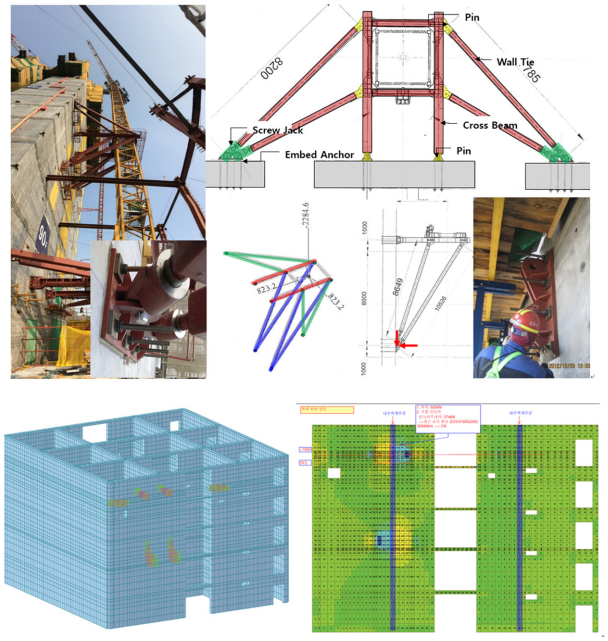


Fig. 21. Support Frame of Bracket type.

some walls were reinforced by adding reinforcing bars. Additionally, to prevent collisions, a separation distance from the jump-up form was secured, considering the deformation of the mast.

After completing the structural work, the method for dismantling the tower crane was determined through a comprehensive simulation. Safety checks were conducted for additional cranes and temporary structures installed at each stage before dismantling.

4.2.2. Common Tower

A common tower was planned to centrally deploy lifts for personnel transportation. Considering the shape of the

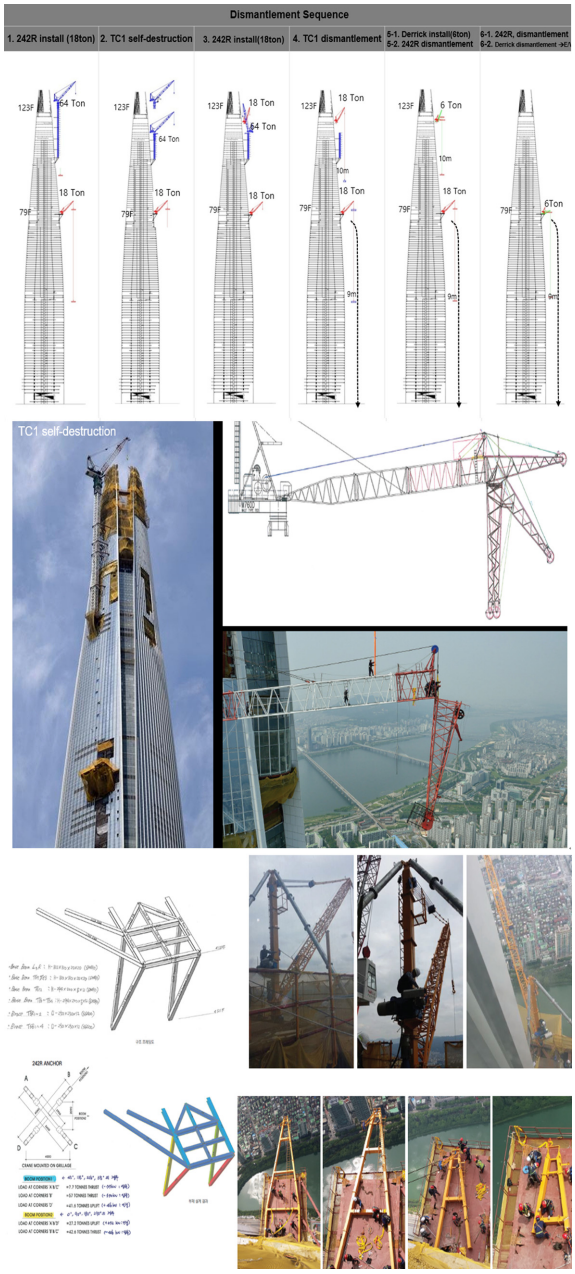


Fig. 22. Dismantling the Tower Crane.

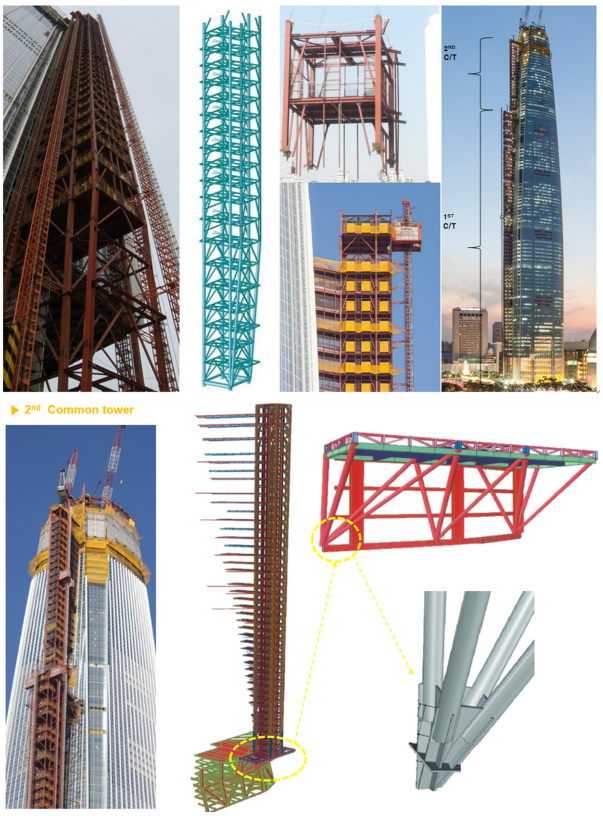


Fig. 23. Structural System of Common Tower.

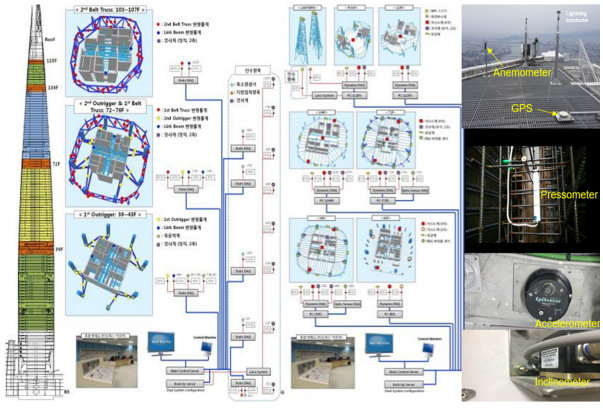


Fig. 24. Sensors Plan of SHM.

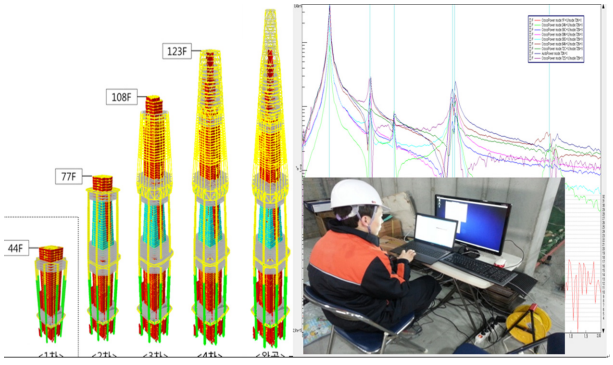


Fig. 25. Dynamic test under Construction.

building, it was installed in two stages, and in the second, a cantilever truss was installed on the belt truss of the 72nd to 76th floors, and a common tower was planned on top. To monitor the safety of this truss, a stress gauge was installed and monitored in real time.

5. Structural Health Monitoring

Structural Health Monitoring (SHM), capable of real-time structural safety monitoring, has been established with over 500 sensors and monitoring programs, including GPS. With this system, sudden accidents or disasters can be prevented in advance.

During construction, the dynamic characteristics of the actual building were measured at each of the five stages and incorporated into the analysis modeling. These characteristics were then reflected in the final system. The earthquake and typhoon monitoring results during construction and after completion show similar results to the predictions.

Upon completion of the building, the SHM operation manual was drafted, and a handover meeting was conducted with Lotte C&T, which is the operating company. Currently, the system is under continuous monitoring and maintenance by professional structural engineers to ensure optimal operation.

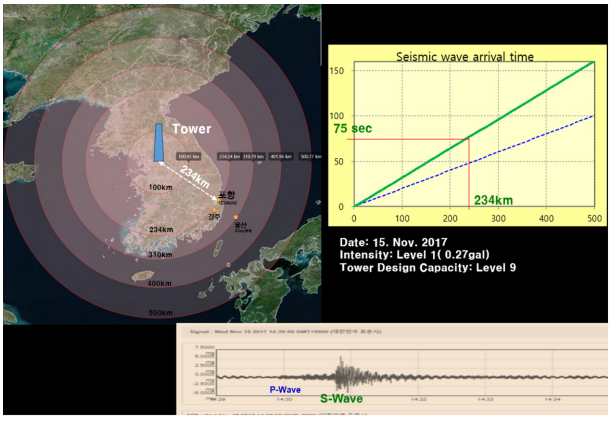


Fig. 26. Measure results of Seismic.

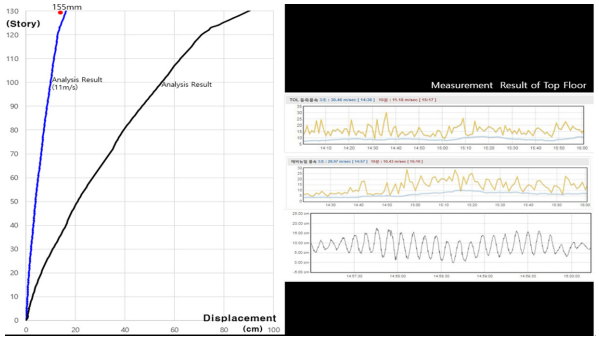


Fig. 27. Measure results of Typhoon(2019).

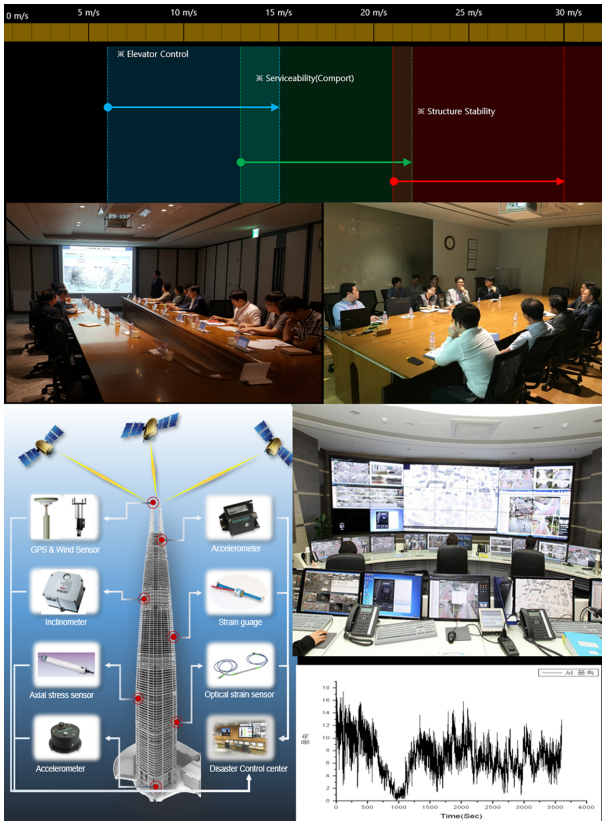


Fig. 28. SHM Operation System

6. Discussion

6.1. Lessons Learned

As a structural engineer, I have been involved in the design, construction, and operation phases of high-rise buildings for the past 10 years. The application of special structural systems and large cross-sectional members, which are requires precise construction, making it a significant challenge to overcome construction tolerances.

A representative example of this is the process of first constructing the RC structure's core walls and mega columns, and then installing the steel beams in between.

This process posed considerable difficulties in overcoming construction tolerances that occurred during the initial construction phase. By changing the construction method to one that could overcome these issue. Generally, designers assume that there are no construction tolerances when designing structures, but in practice, construction errors within the tolerances allowed by standard specifications are inevitable.

Therefore, I realized that it is essential to anticipate how deformations and construction tolerances will occur at each stage of construction when planning the construction process, and to confirm whether these can be overcome before finalizing the construction plan.

6.2. Thoughts for the future improvements

In high-rise building design, the vertical member

shortening and wind-induced serviceability are the most important parameter. These are still being studied, and various predictive formulas based on research data. The Structural Health Monitoring (SHM) of the Lotte World Tower has been continuously monitored and managed since its completion in 2017. Based on this data, comparisons between predicted and actual vertical member shortening, evaluations of lateral stiffness during typhoons, and Damping Ratio values are invaluable data. these actual building measurement values are expected to greatly contribute to the advancement of high-rise building technology.

7. Conclusion

From the design stage, safety was ensured through third-party reviews and verification experiments. Structural reviews were conducted not only for the framing work during construction but also for the curtain walls, interior stone, ceiling frames, glass structures, railings, and artwork to build a safe skyscraper. Creating a single skyscraper building from the design stage to the construction phase requires significant manpower. It is the result of hard work and dedication. It is hoped that Lotte World Tower will be remembered as a landmark of Korea and loved by its citizens.