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Application of Post-Tension Technology on Tall Buildings

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Abstract

It's been a decade since post-tension system began to be applied in earnest to buildings in Korea. In the meantime, post-tension system has been used in various buildings as main structural system including tall buildings. And post-tension system plays a role to overcome architectural limit of regular RC tall buildings particularly in the realization of long span with shallower depth than other structural system. The post-tensioned building market of Korea has been steadily grown in recent years with such advantage. Recently, post-tension technology is adapted for special structural members like belt walls. In this paper, the authors would like to explain design and construction of tall buildings in Korea using post-tension technology.

Keywords: Prestressed concrete, Post-tension, Floor structure, Belt wall

1. Introduction

Prestressed concrete has been used as alternative of reinforced concrete all over the world for decades. Now, prestressed technology provides efficient solutions for various structural members and situations; floor structure, vertical element, lateral load resisting system, etc. However, in Korea, prestressed concrete, especially post-tension system, has been used as the major floor system starting from around 2005. Post-tension system is in the process of going to be a mainstream in the Korean building market.

This paper introduces state of the art technology and prospects of prestress concrete technology; especially post-tension in Korea through introducing tall buildings where post-tension technology was applied.

2. Tall Buildings with Post-tension Technology

2.1. Landmark 72

Landmark 72 consists of one 72-story mixed-use tower with the height of 350m and two 48-story residential twin towers. It was completed by Korean general contractor in 2011.

Because of the size of typical floor (about 90×50 m), structural system, especially floor system, was a matter of interest to the people involved.

Initial plan had interior columns with 7~8 m span, and nonprestressed RC was proposed as floor structure (Fig. 2). In this case, interior columns bear much larger loads than the exterior columns and the column size had to be about 1.5×1.5 m at lower levels which decreased usable space.

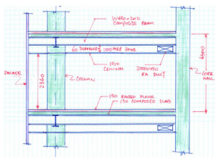
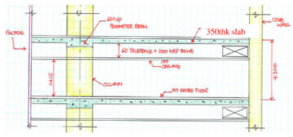
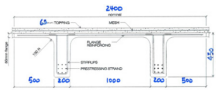
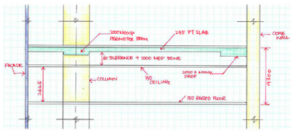


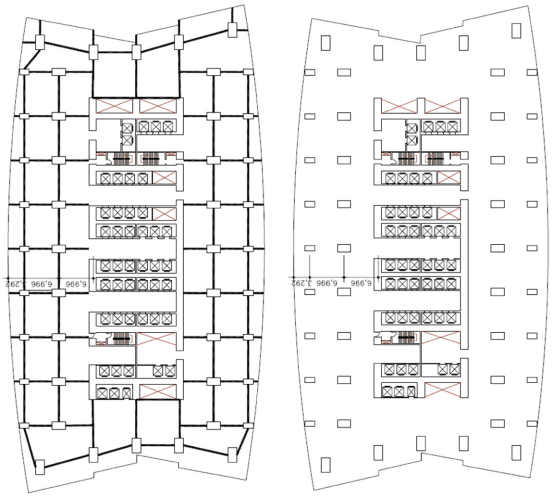
Figure 1. Street view of Landmark 72 (Source: Heerim Architecture).

Then, the design was changed to have 13 m spans without interior columns. At this time, choosing a structure system to handle long span became major concern. Sev-

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Table 1. Floor structural system comparison (Source: Arup Hong Kong)

	Steel Frame	RC Flat Slab	PC Frame	PT Flat Slab
				
Member size	W450×200 Composite Beam	THK 350 RC Flat Slab 650 depth Perimeter Beam	1800×515 Beam 200×450 PC	THK 275 PT Slab 600 depth Perimeter Beam
Self-weight	▼	▲	▼	▼
Story height	▲	▼	▲	▼



(a) RC frame (b) RC flat slab

Figure 2. Initial plan of Landmark 72.

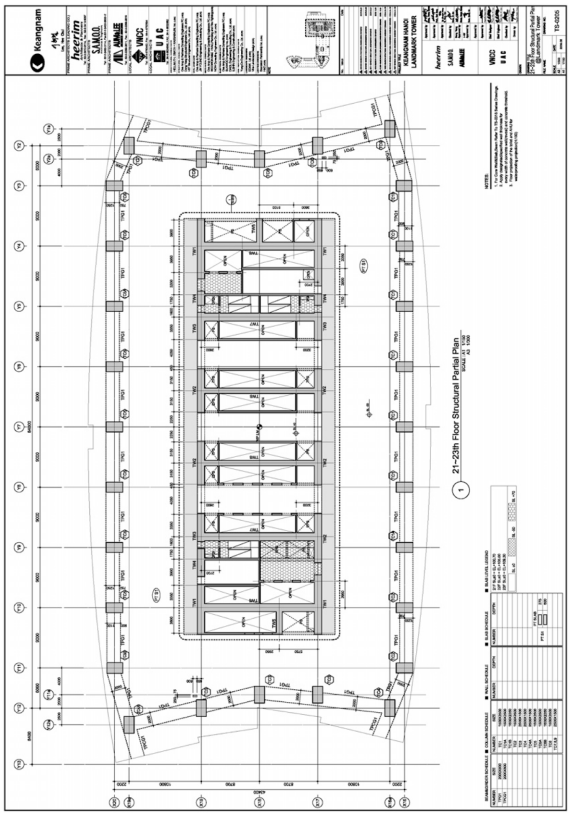


Figure 3. Structural plan of Landmark 72.

eral floor structural systems were compared and post-tension flat slab system was selected (Table 1). It consist of 275 mm slab with perimeter beam of 600mm depth and wall drop to reduce slab thickness (Fig. 3). At the time of construction, the contractor was concerned about constructability and construction period of post-tension system because they had no experience with PT flat slab in a tall building. As there were numerous cases where post-tension flat slabs in overseas tall buildings were built with 4~5 day cycle, we persuaded the general contractor to accept the structural concept. Table form system was used for floor construction considering regular and repeated plans to achieve the planned construction schedule and, the system provides the space for tendon stressing.

Bonded type post-tension system was applied considering the local characteristic. Perimeter beams were designed as general RC beams to eliminate the possibility of interference between construction joint and tendon, except for some cantilever members.

Minimum strength of 35 MPa concrete was used for post-tension slab. Allowable tensile stress of $0.62\sqrt{f_{ck}}$ (Class U of ACI) was applied and stress check result of typical module is shown in Fig. 4. Cantilever acts to reduce the slab thickness and the deflection of interior spans.

2.2. Parnas Tower

Parnas Tower is an office building located in the downtown Seoul and was completed in 2016. It has 40 stories above ground and 8 basement floors. Originally, it was designed as mixed-use (office and hotel) building then, the usage was revised to office only.

The architect wanted 12 m spans without interior columns, which most of office buildings in steel use in Korea because of the span and construction period. Thus the initial main structural system was steel frame. However, the system could not satisfy the ceiling height (2.8~3.0 m) the client required due to the building height limit (about

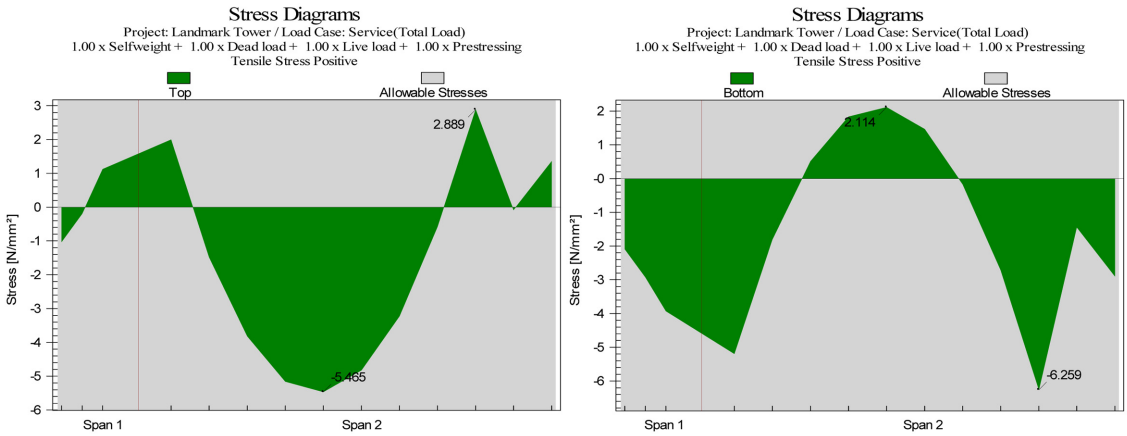


Figure 4. Stress check of typical module.

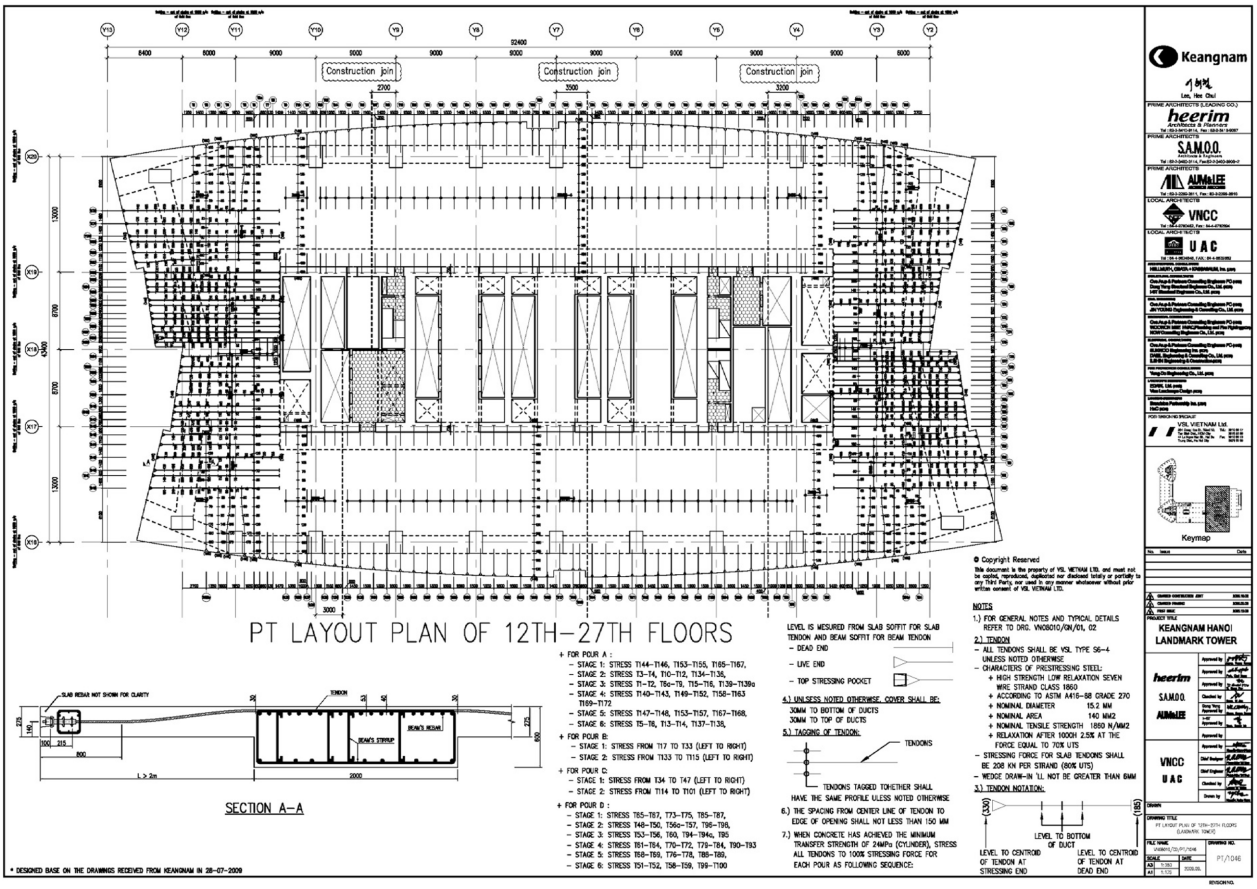


Figure 5. Tendon shop drawing of typical floor.

180 m).

Therefore, post-tension flat slab system was proposed based on the experience of Landmark 72. As a result, 250 mm slab with perimeter beam of 400 mm depth and wall drop was adopted as floor structural system.

Because the depths of perimeter beams are shallow compared to the Landmark 72, tendons were placed on perimeter beams as banded type for serviceability and structural safety. The perimeter beams were designed as slab bands with open stirrups, not a beam for easy construction due to relative stiffness difference of each floor structural members. For this reason, the perimeter beams



Figure 6. Birds eye view of Parnas Tower.

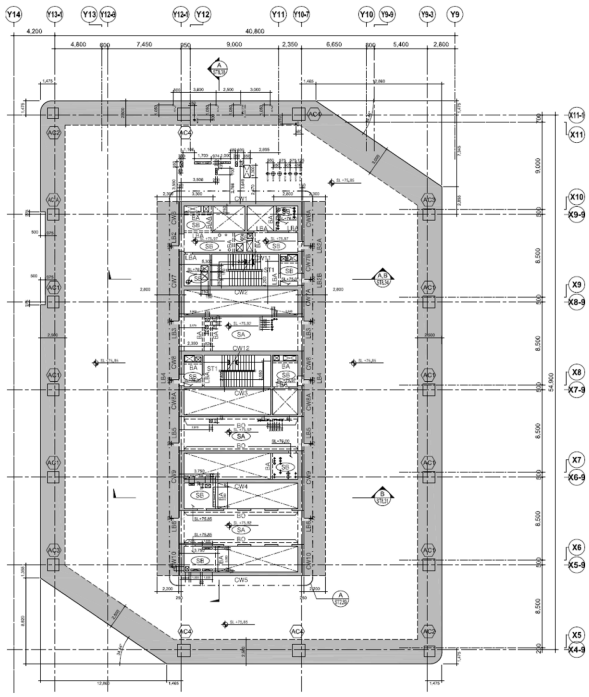


Figure 7. Structural plan of Parnas Tower.

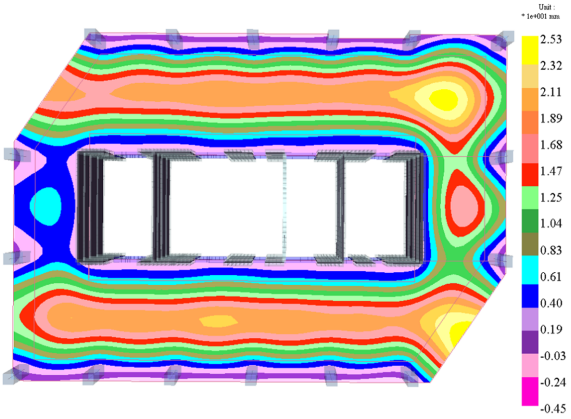


Figure 8. Long-term deflection.

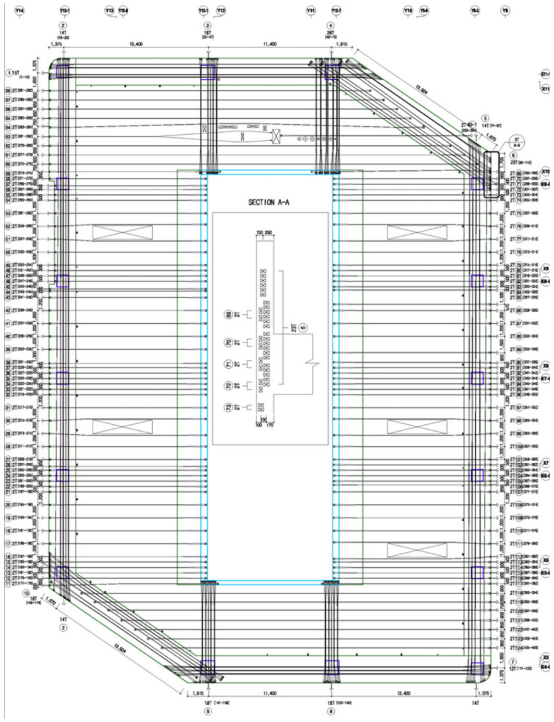


Figure 9. Tendon shop drawing.

were checked if close stirrup reinforcement was required. Performance based design was conducted and it was confirmed that lateral loads could be sustained by core wall only. As a result, seismic details for slab bands were eliminated.

Dia. 15.2 mm strand (unbonded type) was used to minimize the number of anchorages. At the inclined slab edge, banded tendon intersects another banded tendon, therefore carefully designed shop drawings were made considering actual site condition for such areas (Fig. 9). At the time of the construction, Korean general contractors had no experience with post-tension flat slab in office building. Moreover, a table form was not applied because of a safety problems. To meet targeted construction schedule, the general contractor decided to divide the plan to two pouring zones. Finally, the building was constructed successfully within 4.5~5 day cycle for each zone.

However, like general domestic projects, a hole on the gang form was required to penetrate a tendon tails. This

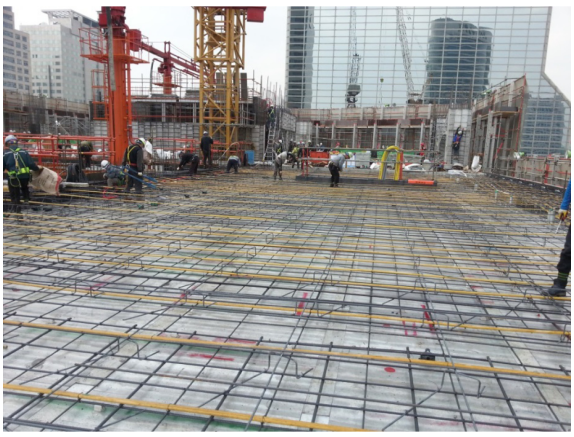


Figure 10. Construction of typical floor structure.



Figure 11. Site view from a street.

acts as a disadvantage for post-tension system when general contractor consider an application of post-tension system.

2.3. Raemian Yong-San

Raemian Yong-san is a residential tall building with 40 stories above ground and 9 basement floors built at the front of Yong-san station in Seoul. The architect planed higher ceiling height than that of general Korean residential building to gain competitiveness in the residential building market. The ceiling height of general Korean residential building is 2.3 m. However, 2.5~2.7 m was applied for this project. And the span was decided to be over 10 m to increase space efficiency.

Long span and high ceiling height within limited story height was the main issue of this project. Generally, steel structure is not selected as floor structure system for residential buildings in Korea because of floor vibration and noise issues. However, general RC also had the difficulties with story height and self-weight when constructing long span.

For these reasons, post-tensioned slab was selected as



Figure 12. Street view of Raemian Yong-san.

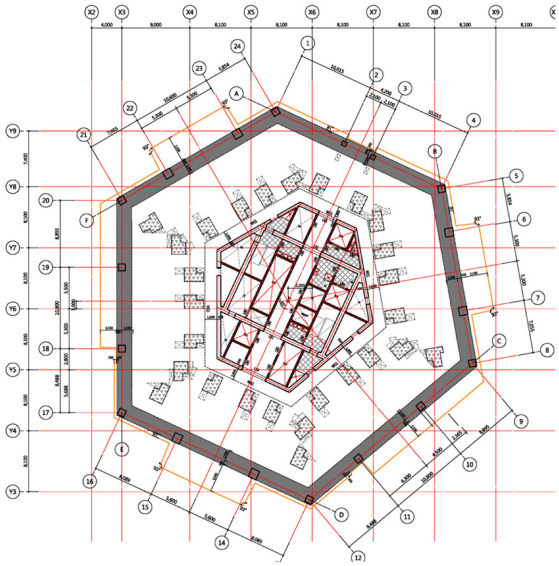
an alternative. The slab thickness using post-tensioned flat plate was still thick due to the long span of 10~12 m (Fig. 13), therefore post-tensioned slab with wall drop and slab band was used to reduce slab thickness to 230 mm.

Considering the slab band size (2,000×450 mm) the slab behaves more like a two-way slab than one-way slab, the width was wider than the depth and thickness difference was little, therefore open stirrup was used instead of general RC beam's stirrup. It prevents constructability degradation of tendon placement by interference with beam's rebar.

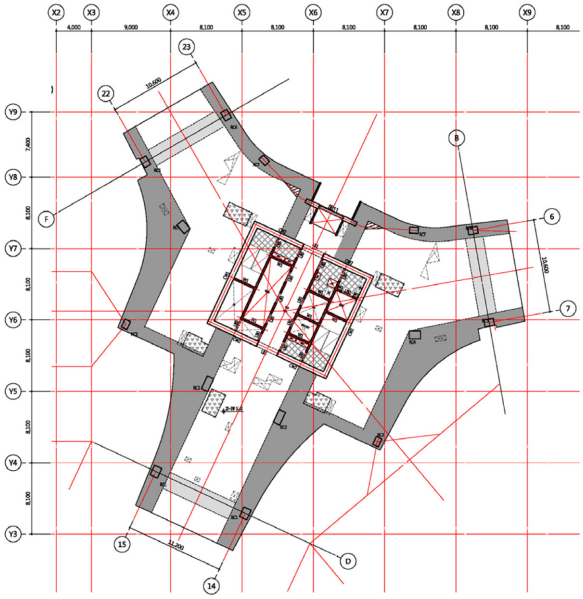
Dia. 12.7 mm strand is usually used for a slab because of its low self-weight and flexibility. However, dia. 15.2 mm was used to minimize the number of anchorages considering inclined slab edge and interference with curtain wall anchorage (Fig. 14).

Shoring and reshoring plan is important for RC multi story building. Generally, gang form (Fig. 15, exterior, vertical) and drop head system (horizontal) are used for form system in Korean construction sites. Table form is rarely used in tall building site in Korea therefore, stressing is performed at gang form's scaffold. But, in most cases it interferes with gang form's frame and with stressing conducted at the bottom level of gang form. The problem in this case is that formwork 1~2 floors above are stripped without prestressing therefore placing basic bottom rebar is preferred in Korea.

Korean general contractor prefers to use 'drop head'



(a) Lower typical floor



(b) Upper typical floor

Figure 13. Structural plan of typical floor.



Figure 14. Live end of inclined slab edge.

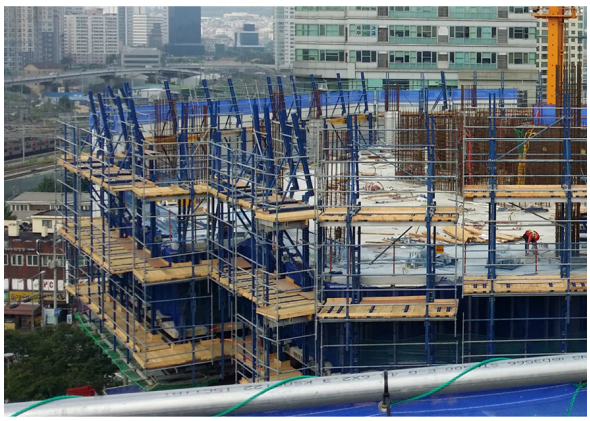


Figure 15. Construction using gang form.

Table 2. Construction stage analysis

Story (Concrete strength when N's pouring, MPa)		Case 1*	Case 2**
		Max. deflection	Max. deflection
N(-)	Poured	-	-
N-1(-)	Nonprestressed	-	-
N-2(21)	Prestressed	14.5mm	10.2mm
N-3(24)	Prestressed	13.6mm	9.56mm
N-4(27)	Prestressed	-	9.01mm

Note: *Case of 2 floors carry upper floor's loads, **Case of 3 floors carry upper floor's loads

type for floor form system, for most cases. This system does not require reshoring, and weight of wet concrete and construction load are transferred to the lower level, then at the lowest level where there is no shoring beneath the slab bearing the largest load. Occasionally, this causes too much deflection and causes a problem to maintain proper ceiling height and to prevent cracks. The load distribution ratio of each floors depend on the stiffness of concrete and support and it is very hard to predict (Park et al., 2011; Hwang et al., 2016).

Construction stage analysis was performed considering various shoring condition for constructing the building without reshoring and the number of prestressed floors needed to sustain upper floor's loads was checked. As previously mentioned, because of interference problem with gang form frame, when N floor's concrete is poured, N-1 floor is not prestressed yet, and N-2 floor is prestressed. We found that 2 floors (N-2 and N-3) can sustain the loads from 2 floors above (N-1 and N-2) through detailed analysis when short-term effect of construction loads is considered. In this case, 3-set of support are required at maximum. At this analysis, we assumed a upper floor's load distributed according to their own modulus of elasticity of each prestressed slab. During the actual construction phase, 4-sets of supports were provided considering unexpected situation.

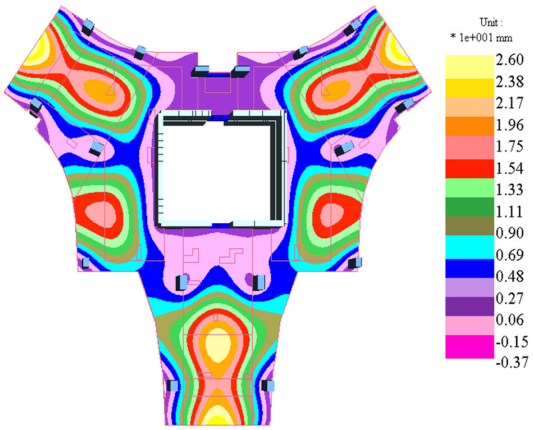


Figure 16. Long-term deflection of typical floor.



Figure 17. Street view of Twin Tree.

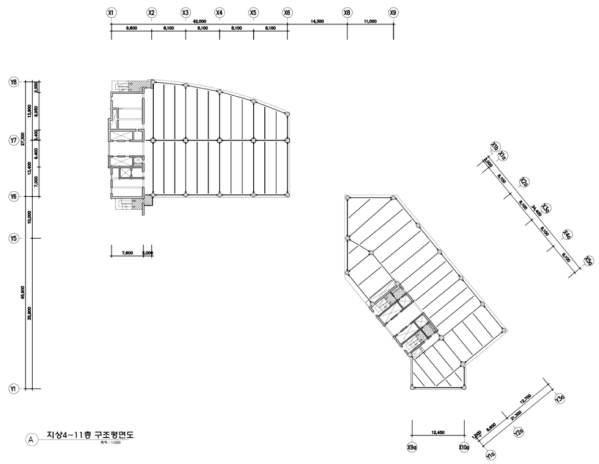
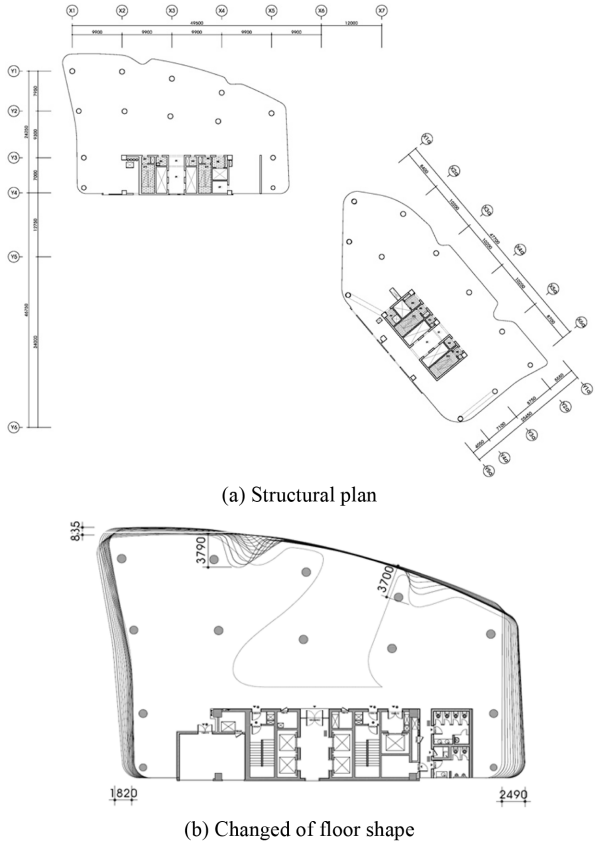


Figure 18. Structural plan (initial design).

2.4. Twin Tree

Twin Tree tower is a RC office building with 17 stories above ground and 8 basement floors. It is not a high-rise, but is a landmark of local area because of its unique shape.



(a) Structural plan

(b) Changed of floor shape

Figure 19. Structural plan (revised design).

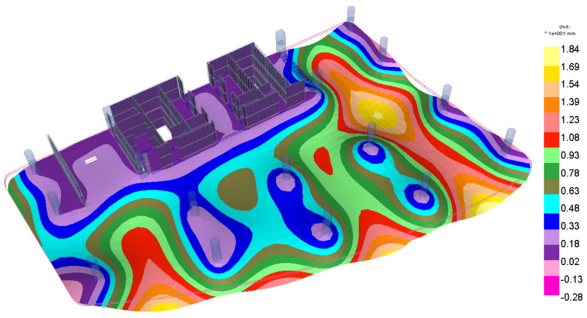


Figure 20. Long-term deflection.

The building is located near cultural heritage protection area, therefore the building height was limited to a certain level and the story height was reduced from 4.0m to less than 3.6 m at the permit phase.

In the beginning of the design phase, it was planned as steel frame building (Fig. 18), but the ceiling height (2.3~2.4 m) was too low for an office building.

Two ideas were issued to resolve floor height problem. First was to reduce internal span using cantilever at the edge. The architect redesigned the building's shape like the bottom of a tree using cantilever. Modified plans show different shapes at each floor with cantilever of 3.0 m

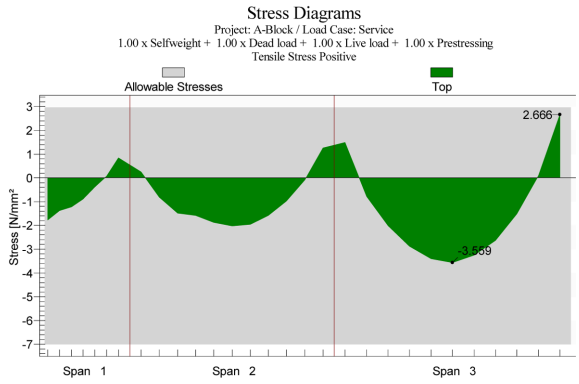


Figure 21. Stress check at service stage.



Figure 22. Reshoring of a cantilever.

(Fig. 19). Second was application of post-tensioned flat slab. Post-tension system was issued because of the long cantilever. The architect wants to minimize the thickness of slab edge to emphasize the horizontal line at the elevation. After the comparison of structural systems, post-tensioned flat slab (250 mm, unbonded type) was decided as major floor structure.

Regarding the facade, 3D steel frame curtain wall system was used because of its irregular shape. Thus the minimization of the deflection and the tensile stress at a cantilever was very important to prevent failure of the curtain wall. Long-term deflection and tensile stress were controlled below 20 mm and 1.5 MPa (approximately $0.25\sqrt{f_{ck}}$), respectively. At most of regions, tensile stresses at top surface of a cantilever slab (span 1 at Fig. 21) was designed to be below 1.0 MPa. 35 MPa concrete was applied to increase structural performance even though 30 MPa was enough for structural safety.

2.5. LCT

LCT is the tallest RC building in Korea located at Busan Haeundae. The project is composed of two 84-story towers (A & B), the 101-story Landmark Tower, a podium,



Figure 23. Birds eye view of LCT.

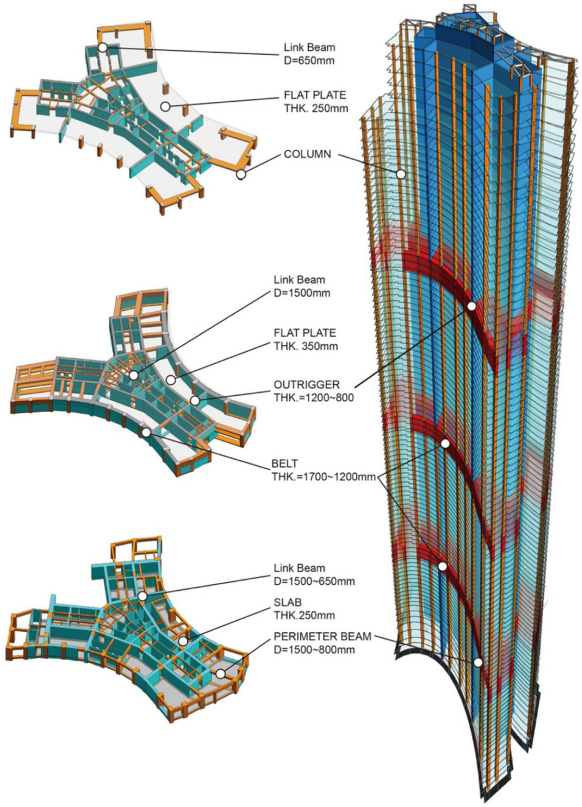


Figure 24. Structural system of Landmark tower.

and an underground parking garage will be completed in 2019.

The Landmark Tower's structural system is designed such that the gravity loads are supported by the core, perimeter beams, buttress walls as well as the columns, while

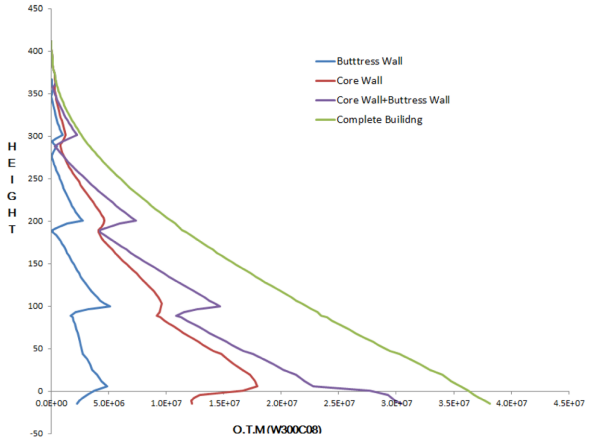


Figure 25. Overturning moment comparison.

the lateral loads are supported by the core, buttress walls, and the belt walls located on L76~L78, L48~L50, and L20~L22. Perimeter beams are used only for long-span, and the flat plate was used for the rest of the structure. Belt Walls connects buttress walls and the outer walls to effectively provide lateral stiffness, and accordingly, very high forces are produced.

The strengths of concrete (f_{ck}) used for the Landmark Tower's columns, link beams and walls are 80 MPa for the underground 5th floor to the 49th floor, 70 MPa for the 50th to the 77th floor, and 60 MPa for the 78th to the topmost floor. 35 MPa concrete was used for slabs and edge beams.

The contribution percentages of the members were analyzed, and the results were plotted on a graph. About 70 percent of the lateral load is resisted by the core, while the buttress and belt walls contribute about 15 percent each (Fig. 25).

Originally the belt wall design used D51 rebars and required large amounts of reinforecements. Consequently, the

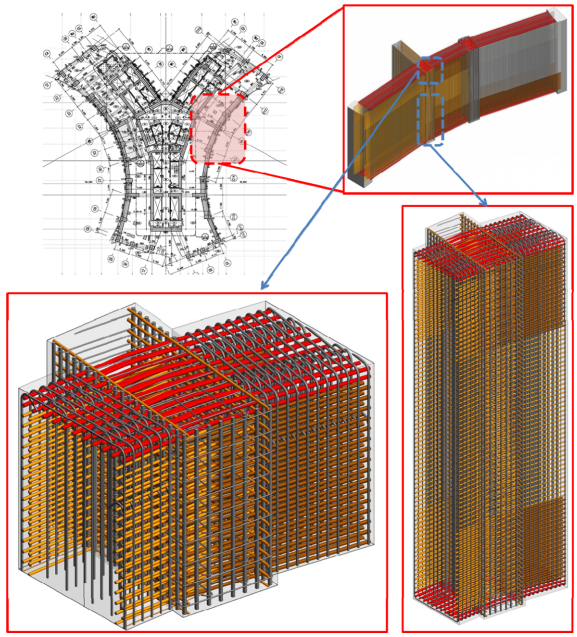
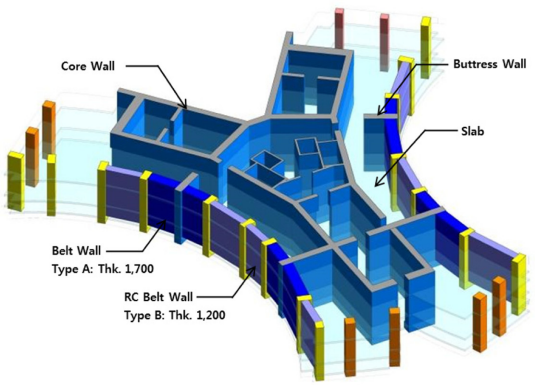


Figure 26. Layout of the belt wall rebars (before).

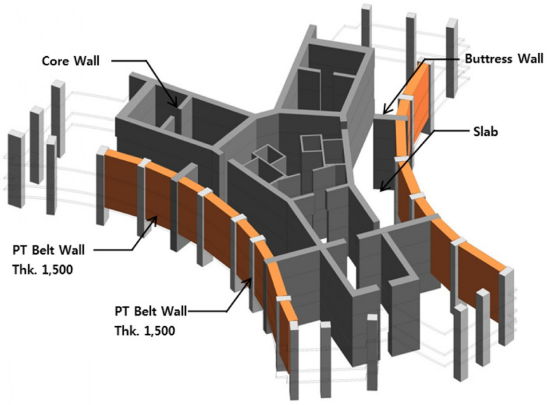
positioning of rebars and interferences caused numerous problems, and construction delay was evident (Fig. 26). And, the RC belt wall thicknesses were 1200 mm and 1700 mm. Difference of wall thickness caused anchorage problem of D51 and D41 rebars at the curvature of belt walls.

In order to solve these problems, the post-tension system was utilized, and as a result the thickness was reduced and modified to have uniform thickness of 1500 mm. In addition, rebar quantity was reduced and the integrity of the structure was improved.

The first consideration when applying PT belt wall for a structure is choosing which system to use between bonded or unbonded system. Usually, the unbonded type is app-



(a) Before the change of the thickness



(b) After the change of the thickness

Figure 27. Belt wall thickness change.

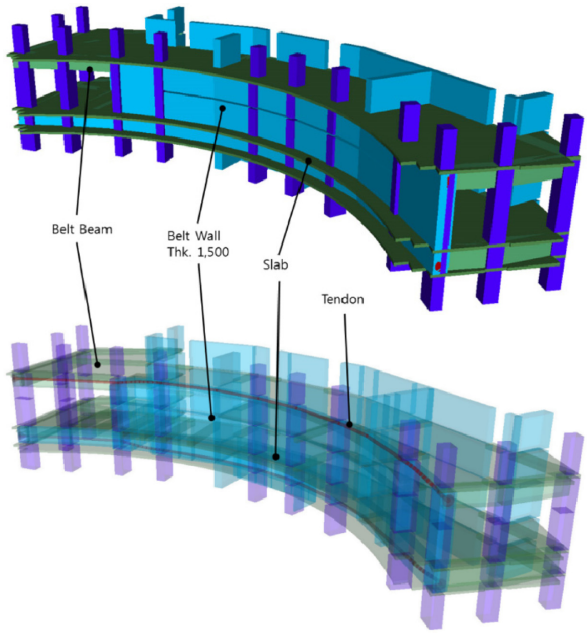
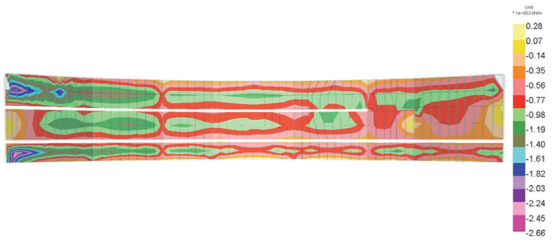


Figure 28. PT belt wall analysis modeling.



(a) Axial stress of belt wall



(b) Slab stress by service loads

Figure 29. Stress check for prestressing force.

lied to most buildings in Korea. However, if unbonded type is applied for this tower, the height of the tendons must be set individually, which may result in a longer construction period and aggravate constructability. On the other hand, the bonded type requires the ducts to be placed before inserting the strands, so it is easy to install the tendons. Furthermore, the bonded type shows better structural performance than the unbonded type. After evaluating all of these considerations, the bonded type was applied

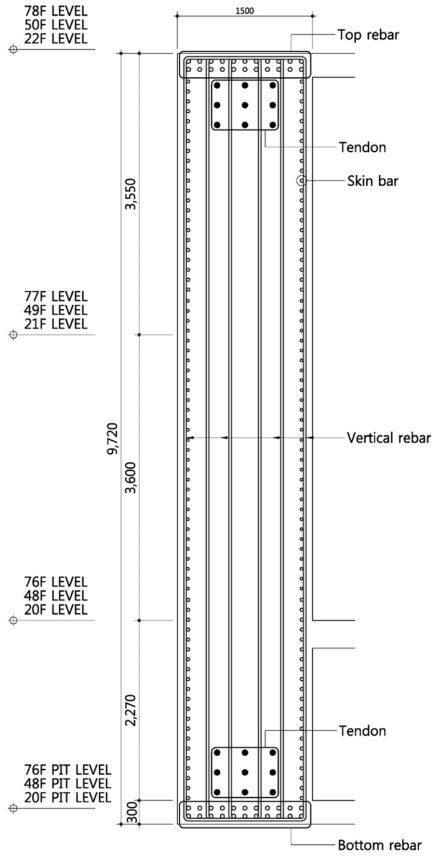


Figure 30. Section of post-tensioned belt wall.

in the design.

Even after PT belt walls were applied, the behavior of the structural system did not change significantly; therefore, PT belt walls were considered as flexural members. The tendons are placed near the tension side along the building profile in order to increase the tendon's contribution to the flexural strength. Tendons are about 70 m in length. Slabs connected to the belt walls extend up to four slabs. For this reason, a review was needed to examine the effect of prestressing force on the surrounding members and partial analysis was performed using post-tension analysis program (Figs. 28, 29).

The belt walls were treated and designed as flexural members. If $f_{se} \geq 0.5f_{pu}$ is not satisfied, f_{ps} should be calculated by strain compatibility. It is assumed that the tendons are prestressed at the one-side considering the site condition. $0.7f_{pu}$ is used as the prestressing force. The result considering short-term and long-term loses is f_{se} = 907 MPa at live end and f_{se} = 526 MPa at dead end. Since these values are less than $0.5f_{pu}$ = 930 MPa, there is a difference at each member, but f_{ps} is calculated to be 1,650~1,790 MPa by strain compatibility. For conservative design, 1,600 MPa was decided as f_{ps} to estimate the flexural forces. Since top and bottom main reinforcements and column reinforcement can interfere each other, the number of rein-

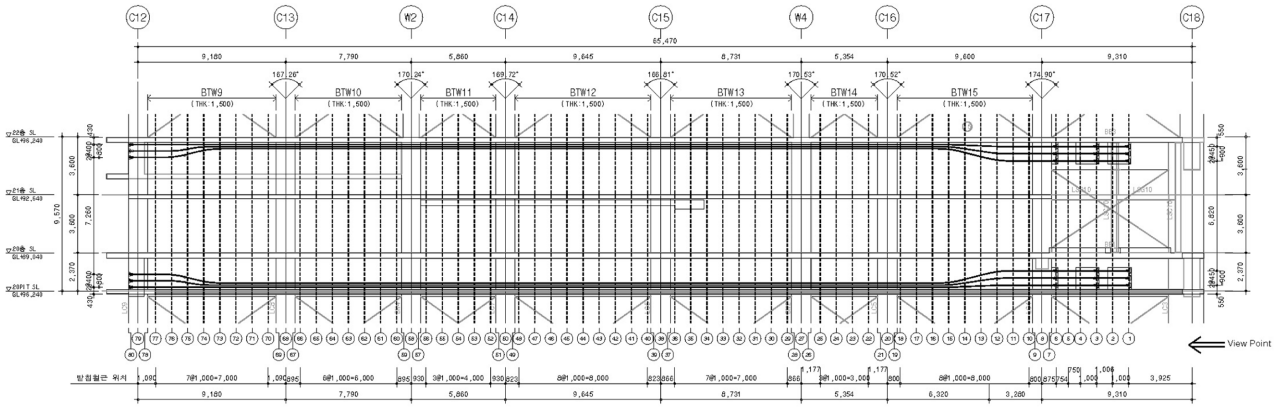


Figure 31. Tendon layout on elevation.

forcing bars was limited to 9 pieces which were placed in a row. In this case, since the reinforcement places max. three layers, the tendon cgs is also influenced. Since the accurate cgs will be determined in the process of shop-drawing for tendon and reinforcements, 500 mm was assumed in design stage. Because it is advantageous to use the same tendon strand size for the construction, Ø15.2-63EA was applied for all of the strands. Additional flexural strengths required by the structure are achieved by adjusting the amount of the non-prestressed rebars.

Based on the calculated amount of tendons and tendon profile, prestressing force influence to belt walls and nearby slabs was reviewed. The f_{ci} of belt walls and slabs were assumed to be 40 MPa and 30 MPa respectively. Depending on the members, higher concrete strength may occur. However, the assumed strengths were used to identify the effect of prestressing force as well as for consideration of uncertain construction process. When the prestressing forces are applied to the members which the centroid axis is changed, the tendons are arranged along the centroid axis. If the prestressing forces are acted vertically to the members at the end of member, the balanced moments would not theoretically occur. On the floor plan, if the strands are arranged along the centroid axis of belt walls which have a regular thickness, the horizontal force should not basically occur. However, since the shape of building is not identical, the horizontal force or vertical force should occur. Therefore, the effect of prestressing force to structural member is reviewed through the finite element analysis.

The applied allowed tensile stress is 1.37 MPa (for f_{ck} = 30 MPa) and 1.58 MPa (for f_{ck} = 40 MPa). The applied allowable compressive stress is $0.6f_{ci}$ = 18 MPa (for f_{ck} = 30 MPa) and 24 MPa (for f_{ck} = 40 MPa). These are the concrete allowable stresses to apply prestressing force to prestressed concrete based on ACI 318.

Firstly, stress check is carried out with only prestressing force and gravity loads. As a result of the review, the precompression of belt walls is 0.5~1.0 MPa at most areas, except near the anchorage because it is identified that the precompression (about 1.0 MPa) is uniformly distributed to overall area of belt walls by prestressing force. Also, for slabs, the tensile stress at the adjacent area to the belt walls is very little which is less than 0.5 MPa so that the reinforcement for horizontal force is not necessary. Consequently, if the reinforcement for anchorage is performed, the concrete crack by prestressing force only would not occur and the special reinforcement for this is not necessary. At the review considering the effects of floor loads and effective prestressing force at the same time, the tensile stress more than 1~3 MPa occurs at the connection between belt wall and slab. The stress is bigger than the stress by prestressing force only, but it is not a problem in the structure as the slab is designed as general RC slab.

Considering the sizes of the anchorages and ducts, the interference with column rebars is inevitable. The largest interference occurs in columns with anchorages. Considering the size of block out and duct, the position of the column rebars were modified.

3. Conclusion

The post-tension technology of Korea has developed gradually reflecting the characteristics of Korean construction site over the last decade. And, it is expanding its application. In the near future, a post-tension technology will be one of the most competitive solution for certain limited circumstances in Korea. This paper could promote exchange of ideas for sustainable development of post-tension technology in Korea.

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