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POST-TENSIONING INSTITUTE ®

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DESIGN AND ANALYSIS OF HIGH-RISE BUILDING WITH POST-TENSIONED OUTRIGGER WALLS AND SLABS

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INTRODUCTION

ACRO Seoul Forest is a high-rise residential and commercial complex located in Seoul, South Korea, constructed by DL E&C (formerly Daelim Industrial Co., Ltd.). The complex consists of two residential buildings and one office building (Fig. 1); this paper highlights the residential buildings in terms of their characteristic structural system and details. The two buildings were designed with the architectural concept of a "100-year-old house" that can safely be handed down across multiple generations. To obtain long-term structural performance befitting this concept, the structural system uses outrigger walls with post-tensioned slabs (OW+PTS) as part of the buildings' lateral force-resisting system (LFRS) along with the core wall (Yoon and Kang 2015). Furthermore, select outrigger walls and adjacent slab areas are additionally post-tensioned as a solution to structural challenges that arose in the design process. The design was finalized through a performance-based seismic evaluation using ETABS nonlinear dynamic analysis from Seoul National University and an extensive peer-review process from Magnusson Klemencic Associates (MKA).

Fig. 1—Building view from Seoul Forest Park (photo courtesy of KUNWON Architects Planners Engineers).

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PROJECT OVERVIEW

At a height of 656 ft, the 49-story residential buildings of ACRO Seoul Forest feature a T-shaped plan divided into three areas by the central core (Fig. 2). The left and right areas are each an individual residence, while the bottom area is either one whole residence or two residences divided at the center, depending on the floor. The windows in the bottom area are also placed at an angle to provide privacy between units. Being situated near landmarks such as Seoul Forest Park (after which this complex is named) and the Han River, the buildings boast excellent views unfettered by any nearby buildings.

The slabs at the residential floors are post-tensioned with unbonded single-strand tendons with a two-way layout. Tendons at the longer span are uniformly distributed at a spacing of 3.94 ft, and the fixed-end anchors are embedded within the core wall. Conversely, tendons for the shorter spans have a banded configuration layout, which passes through the column-slab intersections so that it enhances the structural integrity against progressive collapse, compared to a conventional reinforced concrete (RC) flat plate. Although the buildings have a flat-plate system, which does not rely on beams or girders to resist gravity loads, a wide shallow girder (band beam) is added at the perimeter of the bottom region. This girder acts as a fail-safe measure to control long-term deflection at the longest span, given that they are luxury homes. Slab thickness for residential floors is 9.84 in. but is decreased by 2.75 in. at bathroom areas, to accommodate wet bathrooms where the shower area is not segmented off by glass screens or shower trays. These types of bathrooms are preferred in Korean residences, where all floor and wall surfaces are waterproofed and floor inclination is required to allow for drainage.

The main LFRS of ACRO Seoul Forest consists of the RC core and perimeter columns, where the lateral load is distributed from the building core to the perimeter columns by I-shaped sectional elements formed by the outrigger walls at the 28th floor and post-tensioned slabs at the 28th and 29th floors. To bolster the shear and moment capacity of this collective element, four out of the 12 outrigger walls are post-tensioned diagonally, while the slab areas above and below these four walls have additional post-tensioning placed horizontally, along the wall directions. The columns up to the 29th floor are steel-reinforced concrete (SRC) to effectively resist axial force and minimize differential shortening, while those above this floor are conventional RC columns.

Outrigger wall with post-tensioned slab (OW+PTS)

Designing for lateral force is a substantial issue for high-rise buildings, where the cumulative story drift and overturning moments can reach considerable levels. Many LFRS have been devised to relieve forces at the building core, transferring them to the perimeter columns and thus reducing the overall size and material costs for the core. In this project, two types of LFRS were initially considered: 1) a structural SRC outrigger wall (SRCOW) system; and 2) an outrigger wall with post-tensioned slabs (OW+PTS) system. While both options provide considerable lateral force resistance, the OW+PTS system was selected due to its advantage of cost-effectiveness in terms of material cost and time savings due to streamlining of the construction process (Yoon and Kang 2015).

Outrigger walls transfer lateral forces from the core to the perimeter columns as a vertical axial force couple acting on each side of the wall; in this process, they are subject to both shear force and bending moment. The OW+PTS

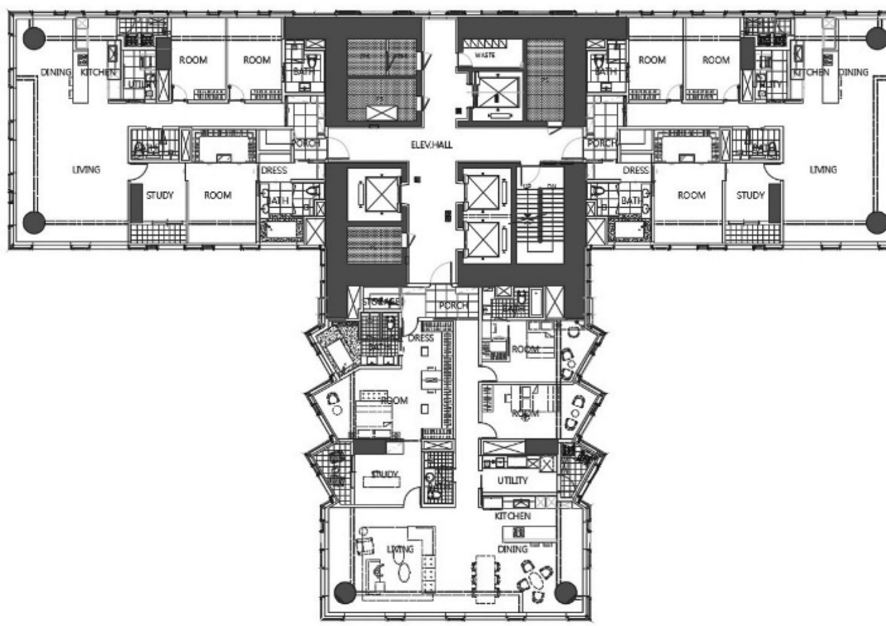


Fig. 2—Typical floor plan of ACRO Seoul Forest.

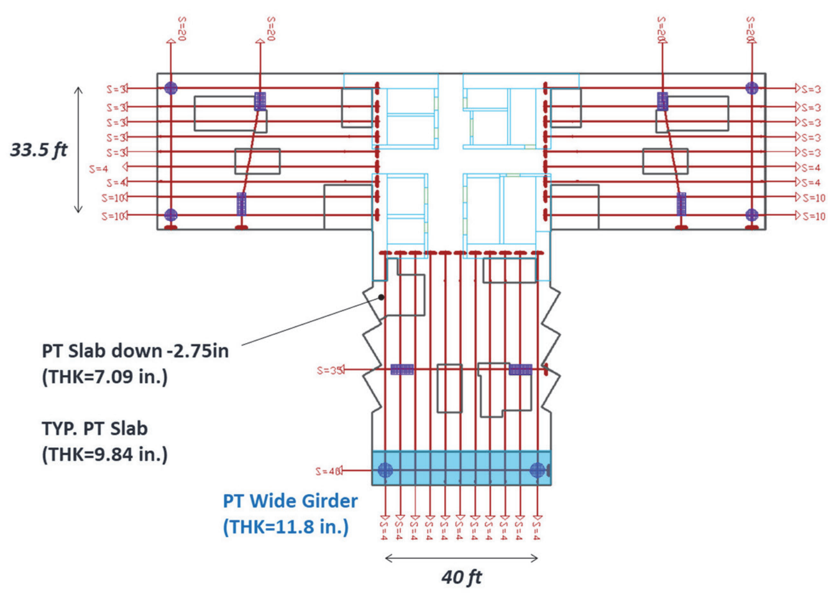


Fig. 3—Post-tensioned layout of typical floor.

system addresses this issue by having the outrigger wall and the post-tensioned slabs form I-shaped sectional elements where, as with the case of an I-beam, the shear is resisted by the wall, and moment (translated into flexural load) is resisted by the slab. This transfer mechanism is depicted in Fig. 4.

Figure 5 shows the configuration of the 12 outrigger walls, as well as where they are additionally post-tensioned. This post-tensioning to wall types ABW1 and ABW3 and their nearby slabs is applied primarily to improve shear and moment capacity at the walls with excessive structural demand. The number of added tendons was determined using newly developed equations (Eq. (13) through (15)) based on ACI 318 (ACI Committee 318 2011) provisions, whose derivation process will be detailed later in this paper.

Structural analysis and design

A performance-based design approach, by Chang Minwoo Structural Consultants, was undertaken for ACRO Seoul Forest, where linear analysis was initially performed to check for sectional forces and to perform structural design for each member. Thereafter, a nonlinear response-history analysis (NLRHA) was performed by Seoul National University to verify and improve the seismic

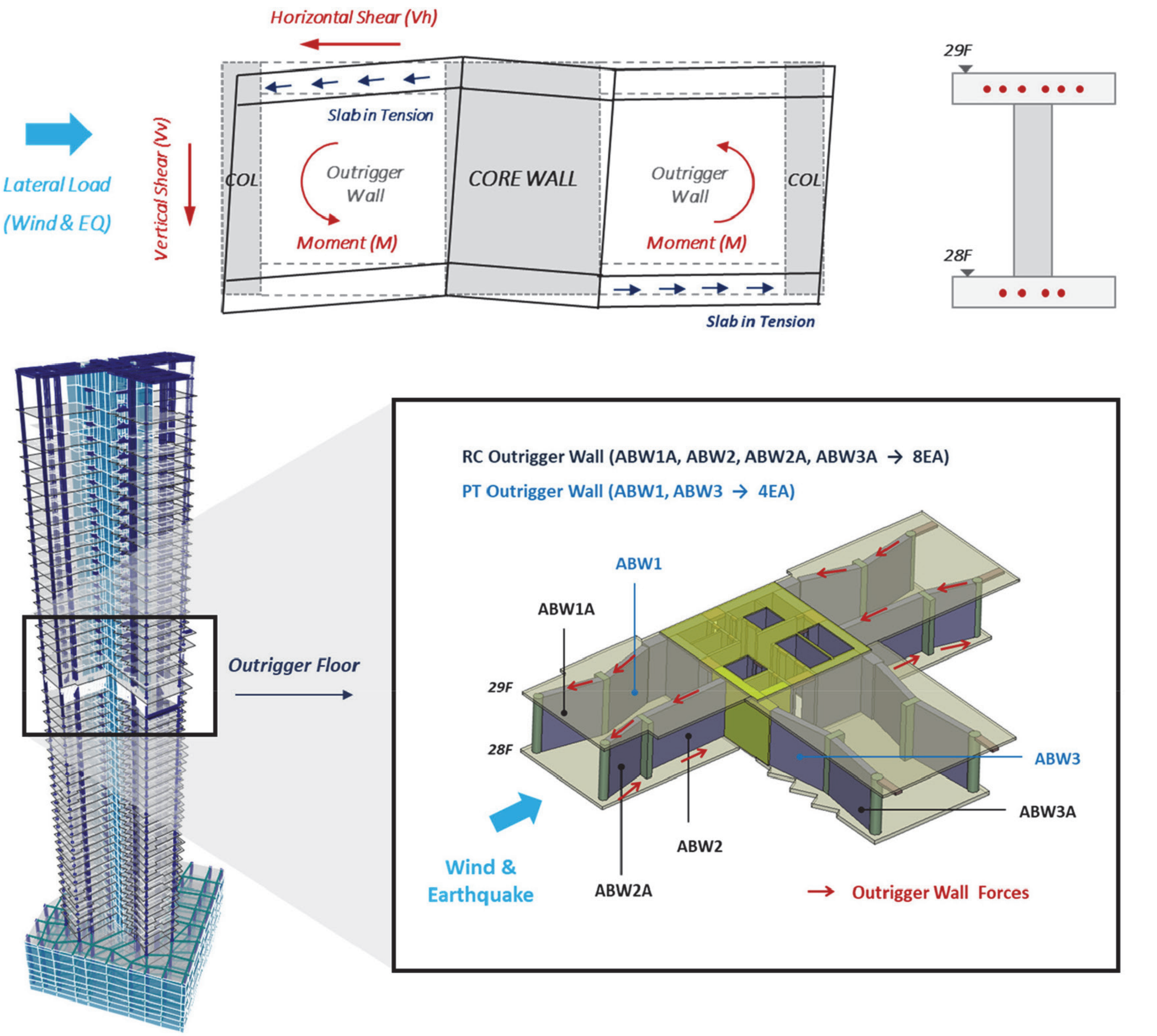


Fig. 4—OW+PTS load-transfer mechanism.

performance of walls, columns, and coupling beams at requisite performance levels. The linear analysis was carried out as a comparative study using two finite element method (FEM) software, MIDAS and ETABS. The building core, outrigger walls, and the slabs adjacent to the outrigger were modeled as meshes to accurately portray the structural response of the buildings' LFRS. Here, the outrigger walls were modeled in detail, including their openings, and the sectional stresses at each mesh were examined for code compliance.

The results of this comparative study were used in determining the buildings' initial design, but also presented a design challenge at the outrigger walls. Four of the outrigger walls (wall types ABW1 and ABW3) were found to have substantial forces under design wind load combinations. In particular, the shear demand was higher than the upper bound of shear capacity allowed by ACI 318-11, which could not be resolved by increasing the amount of reinforcing bar. The extra post-tensioning of the outrigger walls and slabs was implemented as a solution to this issue, where diagonal tendons at the walls and horizontal tendons at the slabs provide additional shear and moment capacity, respectively. Because the post-tensioning keeps concrete in compression, cracks will be kept to a minimum at this crucial part of the buildings' LFRS. With the added structural capacity from post-tensioning, member design was successfully carried out that conforms to the Korean Building Code (KBC) (Ministry of Land, Infrastructure and Transport 2016) and ACI 318-11 provisions, and its seismic performance was further evaluated through nonlinear dynamic analysis.

NLRHA was performed to evaluate the buildings' seismic performance under seven sets of ground motions for the maximum considered earthquake (MCE) and three sets for rare earthquakes (RE) larger than the MCE. This analysis was carried out using ETABS software and includes the nonlinear modeling of materials and structural members, effects of the underground structure, and the buildings' structural damping (Jeong et al. 2020).

The seismic performance objective of ACRO Seoul Forest was Seismic Use Group 1, defined by KBC (Ministry of Land, Infrastructure and Transport 2016) (Table 1) as life safety (LS) and collapse prevention (CP) for 1.2 times and 1.5 times the design spectral acceleration, respectively. Acceptance criteria at the system level were taken in terms of the interstory drift, while criteria at the individual member level were assigned according to the members' governing deformation- or force-controlled actions (Table 2). The overall NLRHA procedure and its results were reviewed by MKA. It was concluded that the seismic performance of the building design with added structural capacity at post-tensioned outrigger walls would satisfy the acceptance criteria under the MCE level and RE

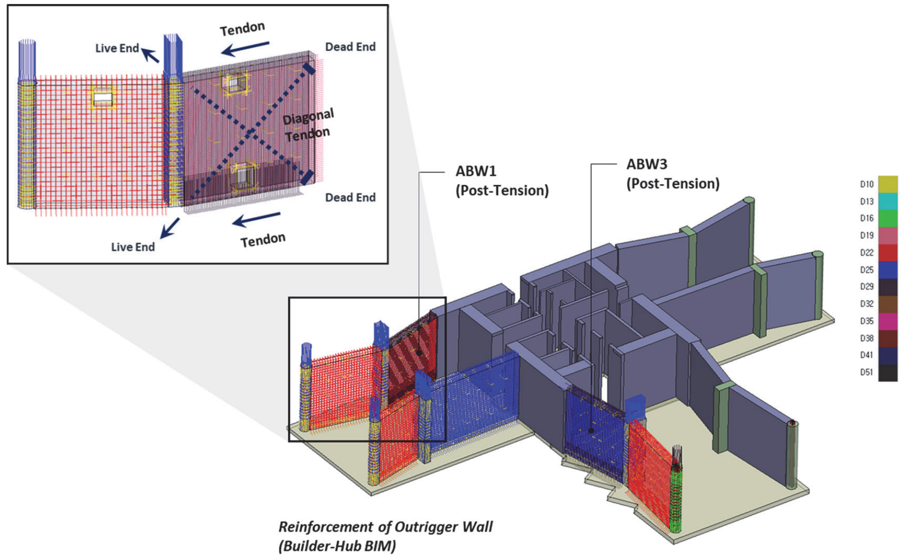


Fig. 5—Post-tensioned outrigger walls of 28th floor.

Table 1—Performance objectives in KBC 2016

Seismic Use Group	Performance objective	
	Performance level	Seismic hazard
Special	Operational (or immediate occupancy)	$1.0S_D$
	Life safety and collapse prevention	$1.5S_D$
1	Life safety	$1.2S_D$
	Collapse prevention	$1.5S_D$
2	Life safety	$1.0S_D$
	Collapse prevention	$1.5S_D$

Table 2—Deformation- and force-controlled actions

Component	Deformation-controlled	Force-controlled
Coupling beam	Moment	—
Core wall	Moment, axial force	Shear
Outrigger wall	—	Moment, axial force, shear
Column	Moment, axial force	Shear

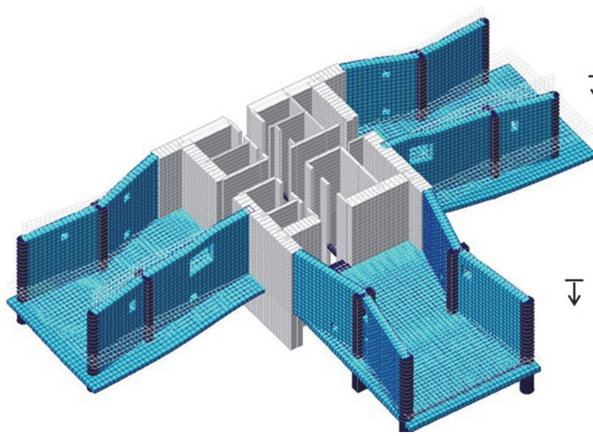


Fig. 6—Analysis results for differential shortening.

earthquakes. The shear forces of outrigger walls exceeding the upper-cap shear strength of RC walls can be resisted by unbonded post-tensioned tendons, as agreed by MKA.

Differential shortening analysis

Differential shortening between the building core and perimeter columns is a typical occurrence for RC high-rise buildings. This phenomenon can lead outrigger walls to carry part of the loads at perimeter columns where the settlement is greater than the core and initiate unwanted cracks, which would diminish the effectiveness of the LFRS. Delay joints are often used to mitigate this issue, where the outrigger walls are permanently connected to the core and columns only after a certain amount of shortening has occurred. Indeed, delay joints were initially considered for the buildings' outrigger wall construction, and a corresponding staged construction process was considered accordingly for structural analysis and design.

However, a separate analysis on the effects of differential shortening indicated that delay joints were unnecessary for the structural system. The analysis input differential shortening after 100 years of use as imposed displacements for the outrigger walls, which are shown in Fig. 6 for the three outrigger wall types connected to the peripheral columns. Results showed that the outriggers sufficiently resist the member forces introduced by the shortening even when modeled as conventional RC walls (that is, the additional capacity from post-tensioning is ignored). It was decided that the outrigger walls would be placed in their entirety along with the core walls and columns, but for safe measure, the extra diagonal and horizontal tendons at the outrigger walls and floors were tensioned 1 month after the outrigger wall concrete was placed.

Post-tensioning of outrigger walls

Post-tensioning at the outrigger walls is a characteristic feature of ACRO Seoul Forest which was implemented as a solution to large structural demands observed from structural analysis. ACI 318-11 and KBC (2016) define the nominal shear strength of RC structures as the sum of the concrete shear strength and the shear capacity provided by the reinforcing bars. For shear walls, equations are given in Sections 11.1.1, 11.9.6, and 11.9.9 of ACI 318-11 as follows

$$V_n = V_c + V_s \quad (1)$$

$$V_c = 3.3\lambda\sqrt{f_c'}hd + \frac{N_u d}{4l_w} \quad (2)$$

$$V_s = \frac{A_v f_y d}{s} \quad (3)$$

where V_n is the nominal shear strength; V_c is the concrete shear strength; V_s is the shear capacity provided by reinforcing steel; λ is a modifier for lightweight concrete; f_c' is the specified concrete strength; N_u is the factored axial force normal to the cross section; d is the effective depth of the member; l_w is the wall length; A_s is the reinforcing bar area; f_y is the reinforcing bar yield strength; and s is the spacing between shear reinforcing bars.

This calculation process is straightforward, but a problem occurs when considering the upper limit of nominal shear capacity, defined in Section 11.9.3 of ACI 318-11 and KBC (2016) provisions as

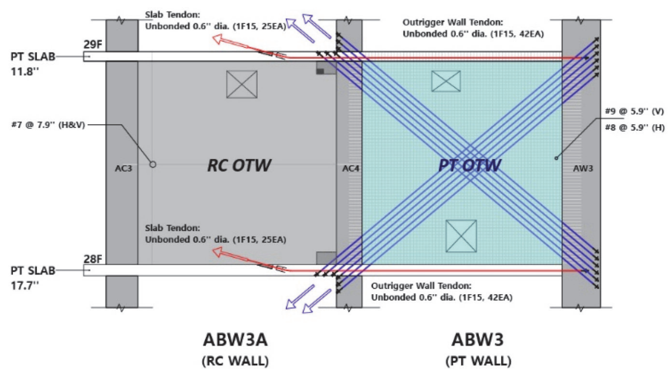
$$V_n \leq 10\sqrt{f_c'}hd \quad (4)$$

When the shear demand exceeds this threshold, as observed in linear analysis results for wall types ABW1 and ABW3, adding reinforcement steel to the outrigger walls cannot serve as a solution because this value is governed by the concrete compressive strength. To overcome this limitation of conventional RC walls, diagonal and horizontal post-tensioning was applied to the four outrigger walls and their adjacent slab areas, respectively (Fig. 7). The diagonal tendons supplement the deficient shear capacity at the outriggers, while the horizontal tendons offset excessive tension at the slab due to the bending moments.

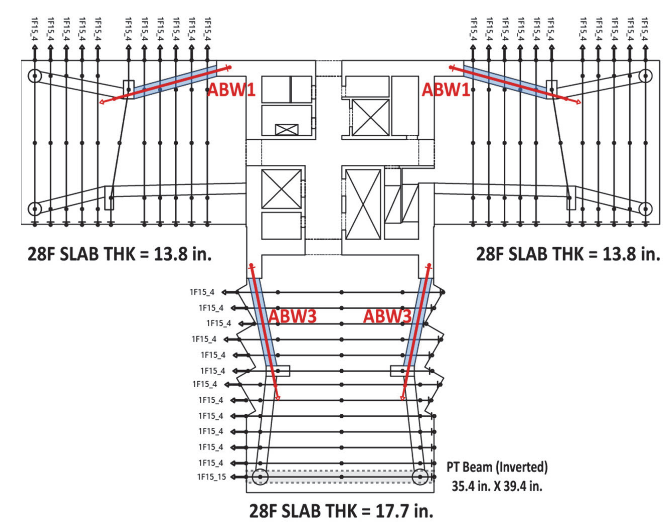
The numbers of tendons for the slab and outrigger layouts, denoted N_s and N_w, respectively, were determined using equations that were newly developed based on the ACI 318-11 strength design method. The variables used in the derivation process, as well as their notations, are depicted in Fig. 8. The basic concept is to obtain the deficient structural capacity and provide sufficient post-tensioning so that the additional capacity provided would offset this margin. The required structural capacity is obtained by subtracting the RC design strength from the structural demand, which can be expressed as Eq. (5) through (7). Equation (6), in particular, considers the contribution of both horizontal and diagonal tendons in supplementing horizontal shear capacity.

$$V_{PT,h} + P_{PT} \geq V_{req,h} = V_h/\phi - V_{n,h} \quad (5)$$

$$V_{PT,h} + P_{PT} \geq V_{req,h} = V_h/\phi - V_{n,h} \quad (6)$$



(a) Post-tensioned layout of ABW1

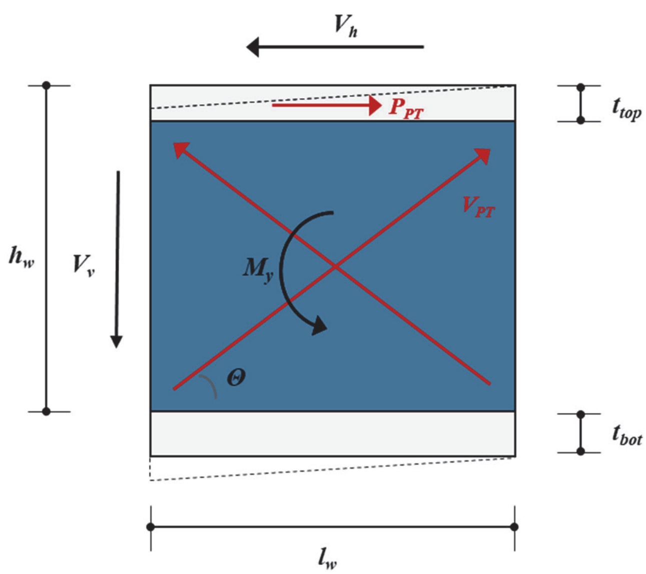


(b) Post-tensioned layout of 28th floor

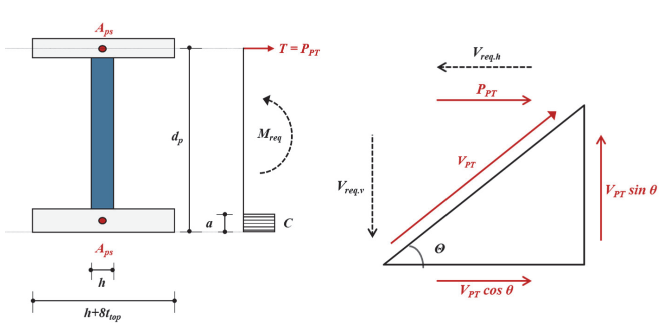
Fig. 7—Outrigger wall post-tensioned layout.

Table 3—Equations for calculation of number of tendons at post-tensioned OW+PTS

Tendon type	Equation	
Horizontal tendon	$N_s \geq \dfrac{M_y/\phi - M_n}{d_p f_{ps} A_{ps}}$	(14)
Diagonal tendon	$N_w \cos\theta \geq \dfrac{V_h/\phi - V_{n,h}}{f_{ps} A_{ps}} - N_s$	(15)
	$N_w \sin\theta \geq \dfrac{V_v/\phi - V}{f_{ps} A_{ps}}$	(16)



(a) Acting forces at post-tensioned OW+PTS system



(b) Sectional stress distribution for moment *(c) Force equilibrium for shear*

Fig. 8—Diagrams for calculation of required tendons.

$$V_{PT,v} \geq V_{req,v} = V_v/\phi - M_{n,v} \tag{7}$$

where M_{PT}, $V_{PT,h}$, $V_{PT,v}$ are the moment capacity, horizontal shear capacity, and vertical shear capacity provided by the post-tensioning, respectively; and ϕ is the strength reduction factor.

The additional structural capacities are then calculated. M_{PT} is obtained from the I-shaped sectional element of the OW+PTS system (Fig. 8(b)), where the post-tensioning force P_{PT} forms an axial force couple with the opposite flange's compressive strength, which is resisted by the concrete. The moment arm length is taken as the effective depth of the section to the centroid of the tendon layout, giving Eq. (8). The shear capacities $V_{PT,h}$ and $V_{PT,v}$ are obtained from the equilibrium relationship in Fig. 8(c), as Eq. (9) and (10).

$$P_{PT} = M_{PT}/d_p \tag{8}$$

$$V_{PT,h} = V_{PT}\cos\theta \tag{9}$$

$$V_{PT,h} = V_{PT}\cos\theta \tag{10}$$

The minimum post-tensioning forces obtained in this process can be converted to N_s and N_w using Eq. (11) and (12), respectively. By putting together Eq. (5) through (12), Table 3 shows the final equations for obtaining the number of tendons required for each layout. In this process, N_s is first determined by Eq. (14) and then inserted into Eq. (15), after which N_w is determined so that it satisfies both Eq. (15) and (16).

$$N_s = \frac{P_{PT}}{f_{ps} A_{ps}} \tag{11}$$

$$N_w = \frac{V_{PT}}{f_{ps} A_{ps}} \tag{12}$$

where f_{ps} is the stress in prestressing steel at nominal strength; and A_{ps} is the strand area.

For this project, Grade 270 unbonded single-strand tendons of 0.6 in. diameter were assumed, with 20% jacking loss and 20% long-term loss for the effective prestress. f_{ps} was defined in accordance with Section 18.7.2 of ACI 318-11, as no specific equation for this type of tendon is available. For flexural members with unbonded tendons and with a span-depth ratio of 35 or less, the following equation is given

$$f_{ps} = f_{se} + 10{,}000 + \frac{f_c'}{100\rho_p} < \min(f_{py}, f_{se} + 60{,}000) \qquad (13)$$

where f_{se} is the effective prestress; f_c' is the specified concrete compressive strength; ρ_p is the ratio of A_{ps} to bd_p; b is the width of the compression face; and f_{py} is the specified yield strength of the prestressing steel.

Using Eq. (12) through (15), $N_s = 30$ and $N_w = 42$ were determined for wall type ABW1, while $N_s = 25$ and $N_w = 42$ were determined for ABW3. These results were examined and approved by MKA during the peer-review process.

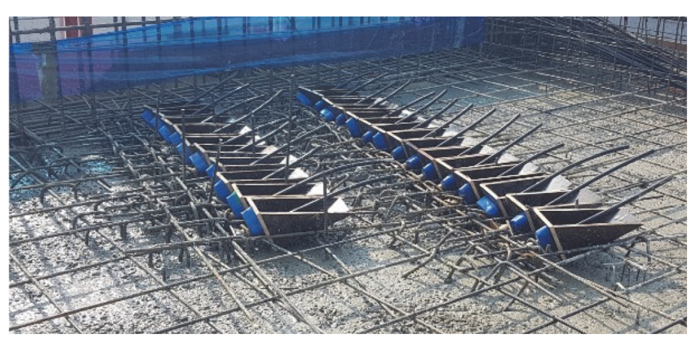
Here, P_{PT} and V_{PT} are the post-tensioning forces of the horizontal and vertical layouts, respectively; V_{PT} is the post-tensioning force at one diagonal layout; M_y is the bending moment; V_h and V_v are the horizontal and vertical shear forces, respectively; t_{top} and t_{bot} are the slab thickness at the top and bottom; h_w is the floor-to-floor height; l_w is the length of the outrigger; A_{ps} is the area of a single post-tensioning strand; h is the wall thickness; d_p is the effective depth of the OW+PTS element; M_{req} is the deficient moment capacity; θ is the slope angle of the diagonal tendons; and $V_{req.h}$ and $V_{req.v}$ are the deficient horizontal and vertical shear capacities, respectively.

Construction details for post-tensioned outrigger walls

Construction of ACRO Seoul Forest began in July 2017 and was completed in December 2020, during which the post-tensioning of the outrigger walls and slabs was successfully implemented by Freyssinet Korea. Having made use of the post-tensioning equipment and workforce readily available on site, additional construction costs were kept to a minimum. Both diagonal and horizontal tendons had their fixed ends embedded in the core wall, as with tendons at typical floor slabs. At the stressing ends, some distinctive construction details were used to accommodate

(a) Diagonal tendon anchorage, from beneath formwork

(b) Diagonal tendon anchorage installation

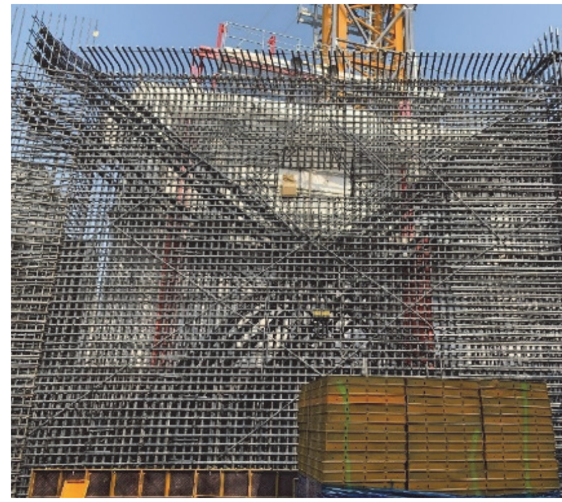


(c) Horizontal tendon anchorage

Fig. 9—Post-tensioned stressing-end anchorage at ABW3.

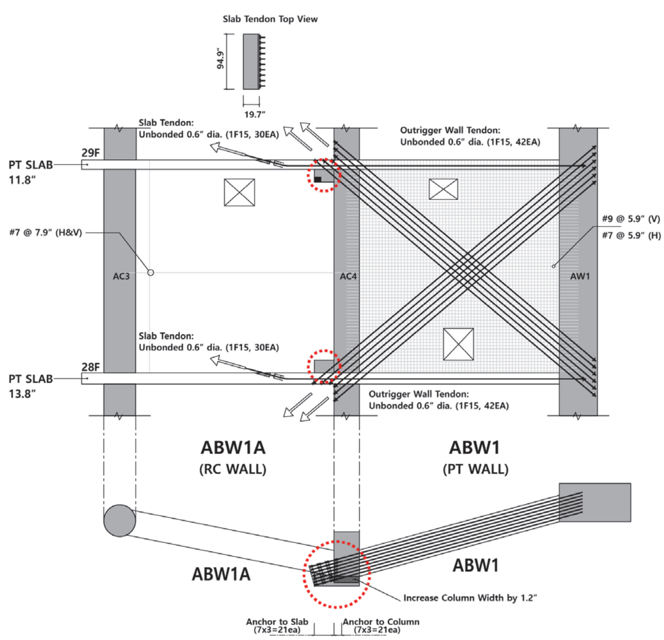
(a) Prefabricated reinforcing bar assembly

(b) Diagonal tendon installation



(c) Completed reinforcing bar and tendon layout

Fig. 10—Construction process of ABW3.



(a) Location on structural plan

(b) Location of tendon protrusion

Fig. 11—Additional concrete placement at column-slab intersection.

the tendon layouts into the final shop drawings, such as the additional concrete placed to fully embed the diagonal tendons, or the upward anchorages of horizontal tendons at the slab.

The diagonal tendons at each layout were arranged as six rows of seven tendons, and some alterations were made to the wall opening locations in consideration of this. For the stressing end, three rows were anchored at the slab and the other three were anchored at the column (Fig. 9(a)). The stressing-end anchorages were installed from above the formwork (Fig. 9(b)), while the tendons were placed after the prefabricated reinforcing bar assemblies were transferred and installed on site (Fig. 10). One issue with the diagonal configuration was that some tendons at the upper rows protruded outside the concrete, cutting off load transfer from the anchorage to the outriggers. To keep the entirety of the tendons embedded, pedestal-like concrete was placed at the column-slab intersections and the width of column type AC4 was increased by 1.2 in. at the outrigger floor (Fig. 11).

The horizontal tendons at ABW1 and ABW3 do not have their stressing ends anchored at the slab edges because they are used to bolster structural capacity only at areas near the designated outrigger walls. Instead, the stressing ends are anchored as two rows at the top of the slab, where they are fixed in place along with triangular formwork (Fig. 9(c)). The formwork creates pockets in the slab after concrete placement that provide enough space for post-tensioning equipment.

SUMMARY AND CONCLUSIONS

The two residential buildings of ACRO Seoul Forest feature a flat-plate system with post-tensioned slabs, and a lateral force-resisting system (LFRS) which consists of the building core and outrigger wall with post-tensioned slabs (OW+PTS). The outriggers in conjunction with the post-tensioned slabs form an I-shaped element that transfers lateral forces from the core to the perimeter columns.

Performance-based design was performed, where the initial structural design was carried out based on linear analyses results from two finite element software, MIDAS and ETABS. This design was verified through nonlinear response-history analysis (NLRHA), where the buildings' seismic performance was found to satisfy the acceptance criteria under the maximum considered earthquake (MCE) and rare earthquakes (RE). The process and results of NLRHA were reviewed and approved by Magnusson Klemencic Associates (MKA). The design process also made considerations for differential shortening, where delay joints were first considered but were deemed unnecessary after a separate analysis on the effects of this phenomenon.

A structural challenge arose in the design process, where the shear demand at certain outriggers exceeded the upper bound of shear capacity set by ACI 318-11. This issue was resolved by post-tensioning the outrigger walls in question and their adjacent slab areas, which would provide the required structural capacity. The number of required tendons for this method was calculated using equations based on ACI 318-11 design philosophy. Several construction details were added at the outrigger floors in consideration of these tendons, such as concrete pedestals at column-slab intersections and upward anchorages at slabs.

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