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LATERAL FORCE-RESISTING BEHAVIOR OF OUTRIGGER WALL WITH POST-TENSIONED SLABS

By

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This paper presents the results of research on high-rise reinforced concrete (RC) buildings using outrigger wall with post-tensioned slabs (OW+PTS) as part of the buildings' lateral force-resisting systems (LFRS) along with the core wall. The lateral force-resisting capability, constructibility, and long-term differential settlement mitigation are investigated and discussed in comparison with the structural steel-reinforced concrete belt wall (SRCBW). A typical 59-story high-rise RC residential building in Korea is used for comparison. The research reveals that while both systems provide comparable lateral force resistance, the OW+PTS system has the advantage of vertical distribution of the lateral resistance and cost-effectiveness over the SRCBW. Superior constructibility and smaller differential settlement are other core advantages of the OW+PTS system.

KEYWORDS

core wall; high-rise building; outrigger walls; post-tensioned concrete; slabs.

INTRODUCTION

The general purpose of the use of outrigger systems is to augment the building's lateral force resistance by reducing the overturning moment in the building core. This is accomplished by restraining the rotation of the core and by transferring a portion of the core bending moment to the perimeter column through the outrigger in the form of a vertical axial force couple. Due to this transfer of moment to the perimeter column, there is generally a net savings in core size and materials used. Thus, the combined outrigger and core system forms one of the most ideal lateral force-resisting systems (LFRS) for high-rise buildings. While there are many types of outrigger systems, in this study, a newly developed outrigger wall system with post-tensioned slabs (OW+PTS)—an I-shaped sectional element formed by slabs and an outrigger wall—is introduced.

The building considered in this study is a typical 59-story, high-rise reinforced concrete (RC) residential building in Korea (Fig. 1). The considered building was taken from a 33-story building project completed by Daelim Industrial Co., Ltd. The LFRS of the 33-story building comprises the concrete core only. To evaluate the feasibility of building with a similar functional layout but increased height, the building footprint was maintained and the building was expanded from 33 to 59 stories. To maintain floor plate and core size, the capacity of the core wall would need to be significantly increased or a new LFRS such as a belt wall or outrigger system would need to be introduced in the 59-story prototype model. Therefore, the use of the belt wall or outrigger system in addition to the core wall is considered in the midheight of the building between the 30th and 31st stories (Fig. 2 and 3).

LATERAL FORCE-RESISTING SYSTEMS

The lateral force design challenge is to effectively transfer the large force from the core to the perimeter column through bending and shear. To ensure proper transfer of the force, two types of LFRS are considered: 1) a structural steel-reinforced concrete belt wall (SRCBW) system; and 2) an outrigger wall with post-tensioned slabs (OW+PTS) system. Both systems, functioning in combination with the building core wall, provide comparable lateral force resistance. However, the OW+PTS system using only outrigger wall without a perimeter belt wall is more efficient in terms of material costs and constructibility.

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Structural steel-reinforced concrete belt wall (SRCBW)

The concept of an SRCBW is to use only the perimeter belt wall connected to perimeter columns (Fig. 4). In this case, the core moment is translated to a force couple between the top and bottom slab which carries the force in shear to the perimeter belt wall, which in turn translates the force in the axial component to the perimeter column.

The SRCBW has the drawback of inducing very large diaphragm forces in the top and bottom slabs. As such, serviceability issues (for example, cracking) are caused

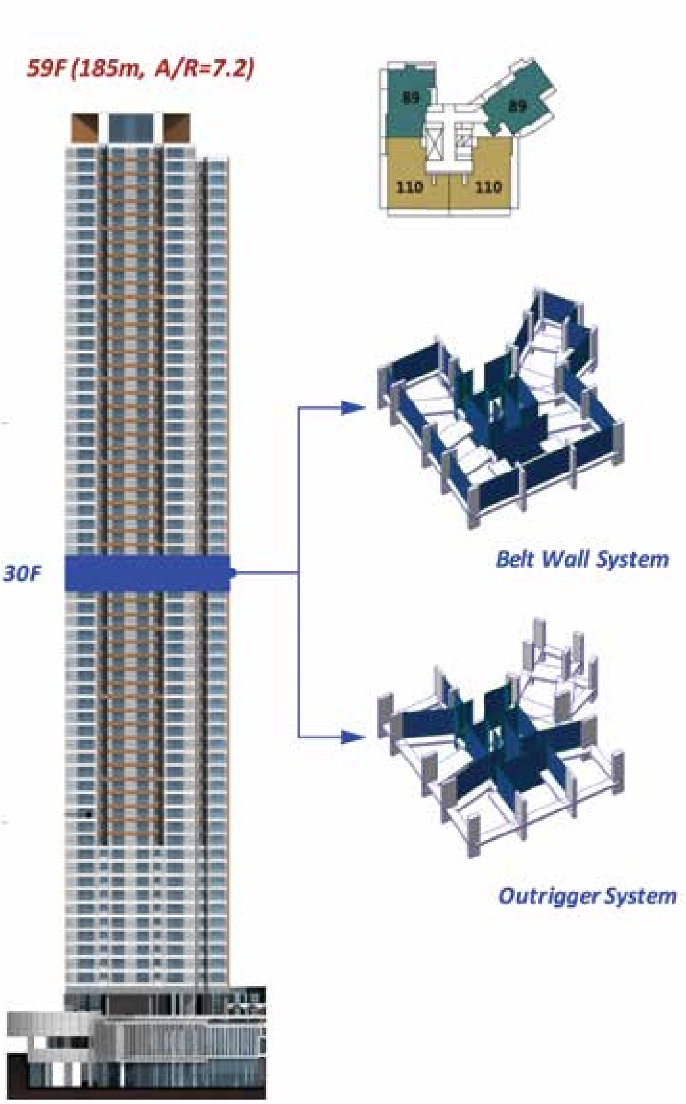
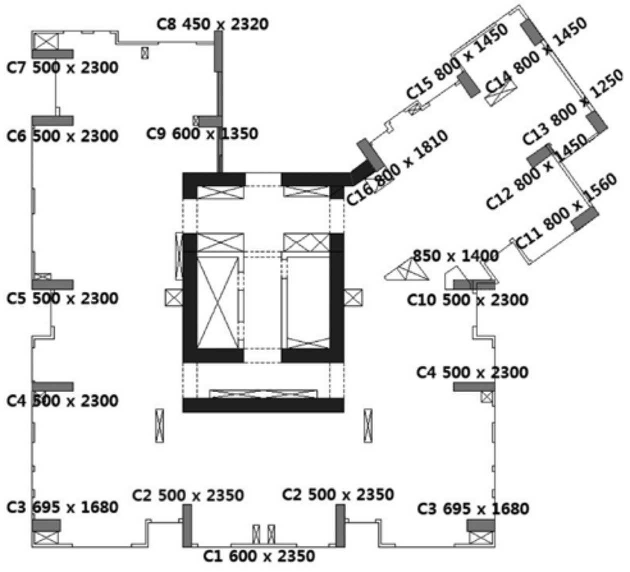
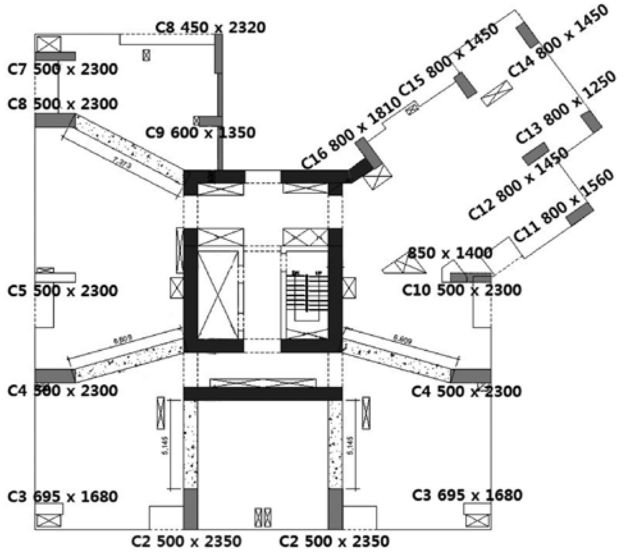


Fig. 1—59-story prototype RC residential building.



< Typical Floor Plan >



< 30F Outrigger Floor Plan >

Slab Thickness	mm	in.
Typical (PT Slab)	210	8.3
Typical Elevator Core	180	7.1
30F/31F	500	19.7
30F/31F Elevator Core	500	19.7
Link Beam Section		
LB1 ~ LB4	800 x 600	31.5 x 23.6
EB1 ~ EB4	300 x 600	11.8 x 23.7
Core Wall Thickness		
CW1 ~ CW7	800	31.5
EW1 ~ EW4	300	11.8
AW1	300	11.8
Outrigger Wall Thickness		
OT101 ~ OT105	800	31.5

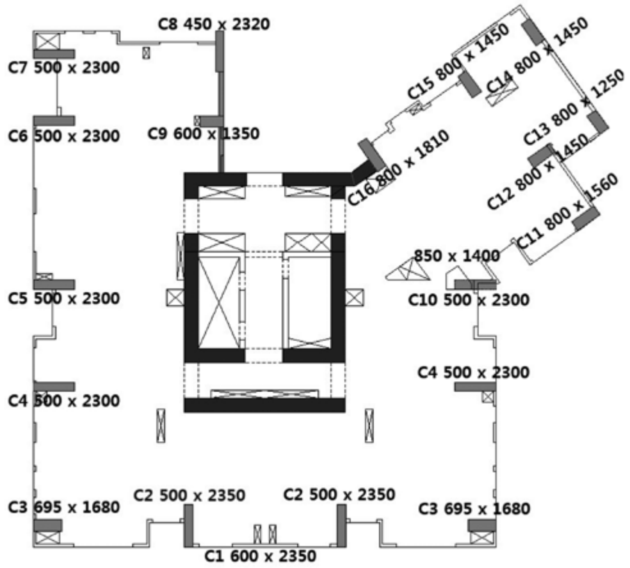
Fig. 2—Outrigger floor plan for OW+PTS.

from the outrigger action as well as from long-term differential settlements between the perimeter column and the core. Furthermore, the following challenges exist when using the SRCBW:

1. Introduction of another trade (structural steel workers);
2. Inherent slowdown when starting the steel erection;
3. Complicated reinforcing bar placement and detailing around the structural steel frame and perimeter column;
4. Challenging to meet tight structural steel tolerances;
5. Working on the edge of the building to erect the steel frame and reinforcing bar; and
6. Larger wall volume.

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

The concept of OW+PTS is to use outrigger wall along with the top and bottom slabs as an I-shaped outrigger connecting from the core wall to the perimeter column (Fig. 5 and 6). To ensure proper transfer of the outrigger force to and from the core wall, the outrigger wall is aligned toward the core wall and the post-tensioning (PT) is extended into the core wall.



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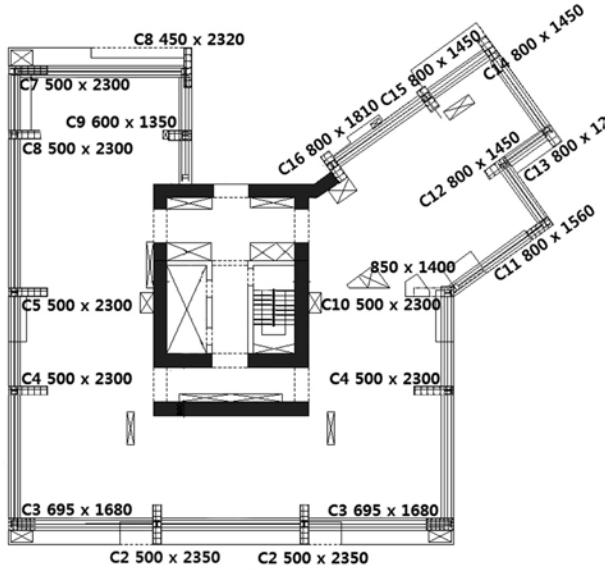


< 30F Belt Wall Floor Plan >

Slab Thickness	mm	in.
Typical (RC Slab)	250	9.8
Typical Elevator Core	180	7.1
30F/31F	500	19.7
30F/31F Elevator Core	500	19.7
Link Beam Section		
LB1 ~ LB4	800 x 600	31.5 x 23.6
EB1 ~ EB4	300 x 600	11.8 x 23.6
Core Wall Thickness		
CW1 ~ CW7	800	31.5
EW1 ~ EW4	300	11.8
AW1	300	11.8
SRC Belt Wall Thickness		
BW1 ~ BW18	700	27.6

Fig. 3—Outrigger floor plan for SRCBW.

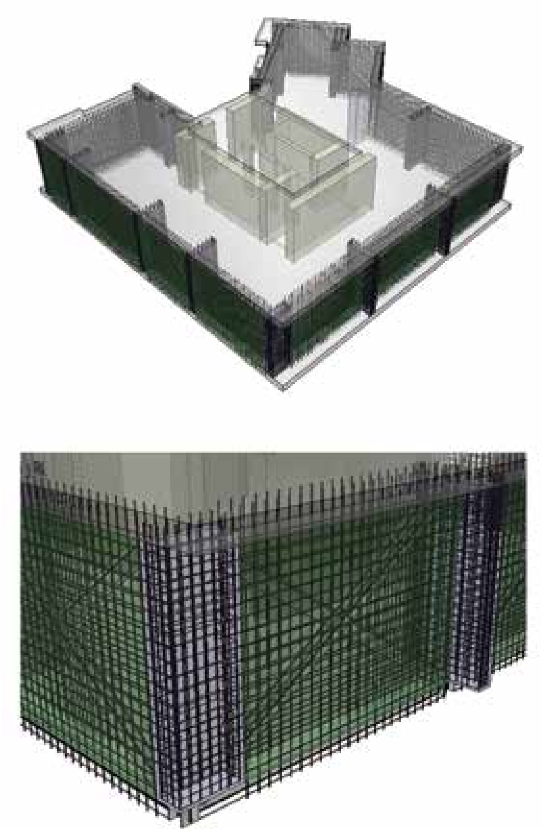


Fig. 4—Structural steel-reinforced concrete belt wall (SRCBW) system.

The OW+PTS has cumbersome tasks such as delay joint and stressing of tendons after casting of the delay joint. Nevertheless, it has many advantages over the SRCBW, as follows:

1. Inherent ease of construction, requiring only conventional reinforcing bar placement and detailing in the wall along with PT tendons that can be easily placed in the slab;
2. Considerably less slowdown in the construction cycle;
3. Working within the building area (not on the edge); and
4. Possible saleable and rentable space on the outrigger floor.

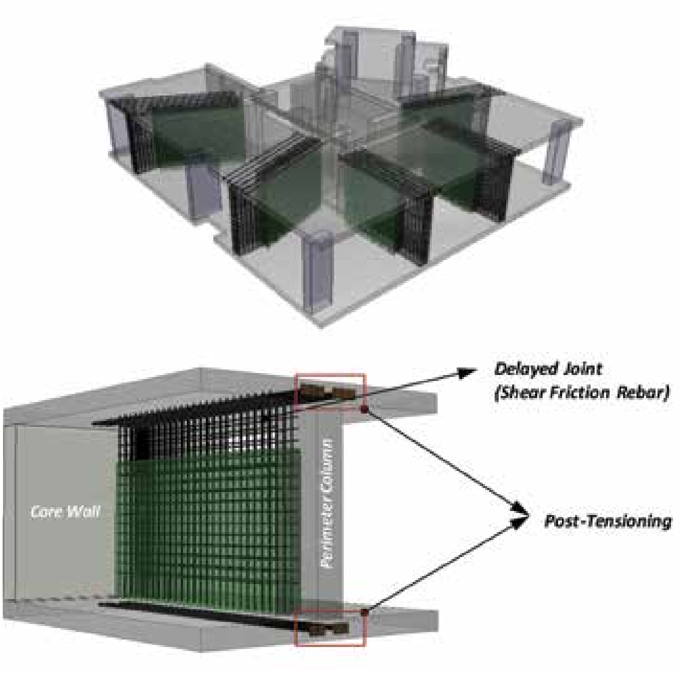


Fig. 5—Outrigger wall with post-tensioned slab (OW+PTS) system.

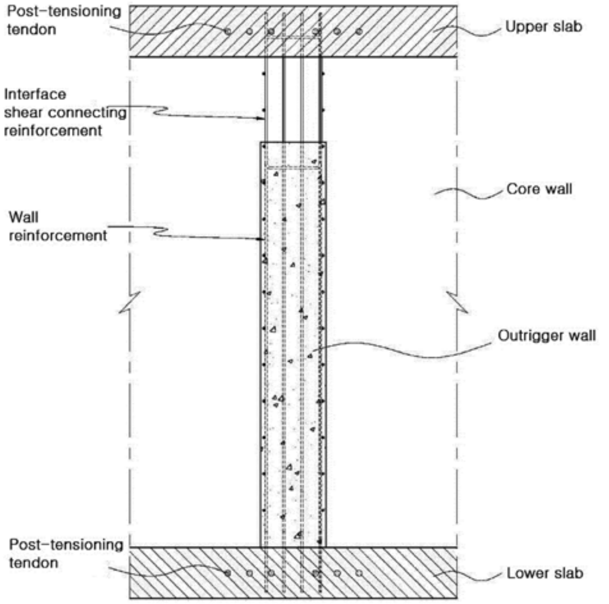


Fig. 6—I-shaped sectional element of OW+PTS.

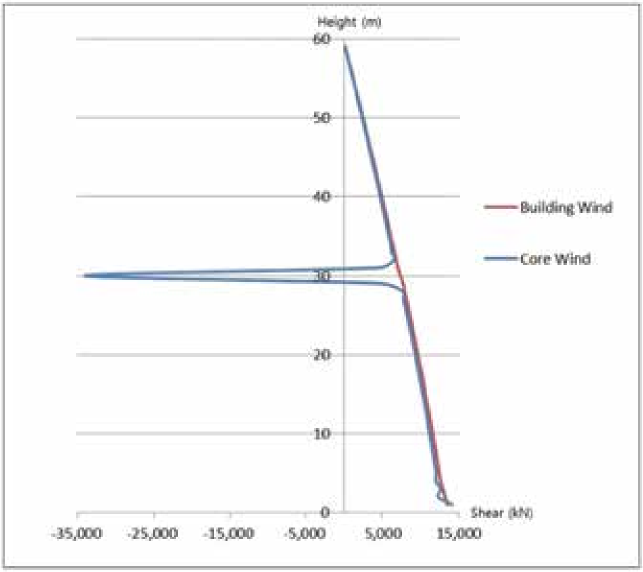


Fig. 7—Cumulative story shear for building frame and core wall of SRCBW. (Note: 1 m = 3.28 ft.)

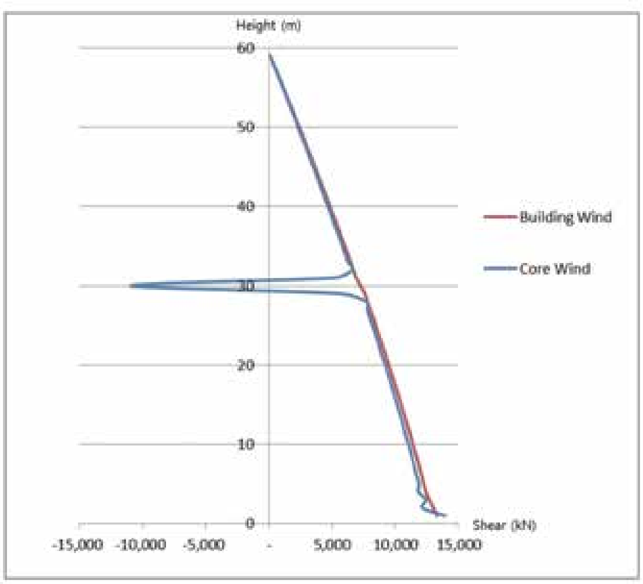


Fig. 8—Cumulative story shear for building frame and core wall of OW+PTS. (Note: 1 m = 3.28 ft.)

Comparison of effectiveness of LFRS

The effectiveness of the SRCBW and OW+PTS as part of the building's lateral-force-resisting systems is discussed in this section. As shown in Fig. 7 and 8, for both options, a shear reversal is noted at the belt wall level and outrigger location when the building is subjected to substantial lateral force. A significant decrease in the core wall overturning moment (OTM) is also observed below the belt wall or outrigger floor (Fig. 9 and 10). In both cases, the observed behavior corresponds to the behavior that would be expected in the belt wall and outrigger installed building and the results are consistent between both options.

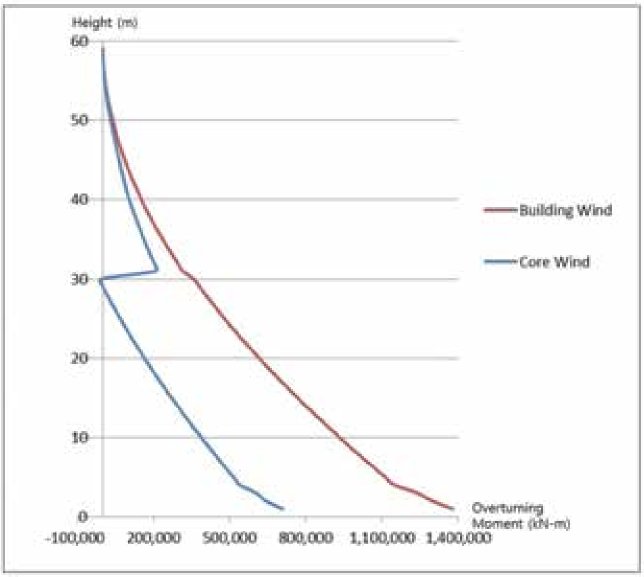


Fig. 9—Cumulative overturning moment for building frame and core wall of SRCBW. (Note: 1 m = 3.28 ft.)

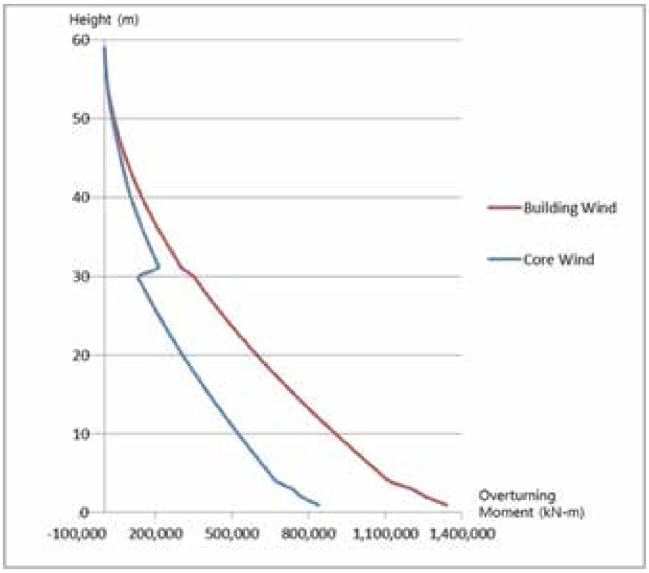


Fig. 10—Cumulative overturning moment for building frame and core wall of OW+PTS. (Note: 1 m = 3.28 ft.)

DESIGN METHODOLOGY FOR OUTRIGGER WALL WITH POST-TENSIONED SLABS

For the OW+PTS design, the following design and construction components are considered: 1) conventional shear wall reinforcement with slab PT; 2) PT layout and stressing sequence; 3) delayed outrigger connection; and 4) long-term differential settlement between the perimeter columns and the core.

Conventionally reinforced concrete outrigger wall with post-tensioned slabs

To resist the horizontal and vertical shear forces more effectively, the outrigger wall is designed to be in compression by the post-tensioning in the slab. The PT is expected to resist bending and horizontal shear in the outrigger wall. The ACI 318-11[1] shear capacity is described by Eq. (1)

$$V_n = V_c + V_s \tag{1}$$

where V_c is the concrete shear strength; and V_s is the additional shear capacity provided by reinforcing bars. According to ACI 318-11, Section R11.2.2.2, the concrete shear capacity is neglected or discounted when the element is subject to tension. Thus, when significant tension is present, V_c approaches zero.

Given that the outrigger wall is mostly in net compression, V_c and V_s are determined as follows

$$V_c = 0.17\lambda\sqrt{f_c'}b_w d \tag{2}$$

$$V_s = A_s f_y d / s \tag{3}$$

where λ is a modifier for lightweight concrete; f_c' is the specified concrete strength; b_w is the member width; d is the effective depth of the member; A_s is the reinforcing bar area; f_y is the reinforcing bar yield strength; and s is the spacing between shear reinforcing bars.

For the post-tensioned slab to truly act as a flange in the I-shaped outrigger section, horizontal shear should be transferred from the outrigger wall (acting as a web) to the top and bottom slab (acting as flange). This horizontal shear can be evaluated by Eq. (4) as beam horizontal shear stress.

$$\tau = \frac{VQ}{It} \tag{4}$$

where V is the total shear; Q is the static moment of area; I is the moment of inertia; and t is the wall thickness. To resist this horizontal shear across the length of the outrigger wall, the reinforcing bar crossing the joint between the outrigger wall and the post-tensioned slabs should be calculated by considering shear friction per Eq. (5)

$$V_n = A_{vf} f_y \mu\lambda \tag{5}$$

where A_{vf} is the cross-sectional area of the reinforcing bar crossing the joint; f_y is the yield strength of the reinforcing bar; μ is the coefficient of friction; and λ is the lightweight concrete factor.

PT layout and stressing sequence

Because the high-rise building moves laterally from one direction to the other, the outrigger wall is subject to tension-compression force reversals (Fig. 11). With the PT as designed, the axial force N_u may approach zero compression or little tension. Therefore, Eq. (2) and (3) are adopted to calculate shear strength V_c and V_s. The total bending in the outrigger wall, which is due to the tension-compression reversals, is resisted by the PT tendons in top and bottom slabs.

The gravity load effect and the long-term settlement effect of the concrete perimeter column create larger tension force at slabs above the outrigger wall (31st story). Thus, the greater PT force is required in the upper floor slab (Fig. 12). Additionally, to provide a direct load path of the outrigger force to and from the core, the outrigger wall is aligned toward the core wall and the PT anchorage is extended into the core wall to complete the load path. Some of the tendons are terminated in staggered sections to effectively distribute compressive stresses.[2] The bonded PT system using twelve 15.2 mm (0.6 in.) diameter strands in each 80 mm (3.1 in.) diameter duct is considered. The proposed construction sequence is as follows:

1. Cast outrigger wall with delay connection joint;
2. Continue building above the outrigger level;
3. Complete the top roof slabs;
4. Cast delay joint;
5. Stress lower-slab PT (30th story); and
6. Stress upper-slab PT (31st story).

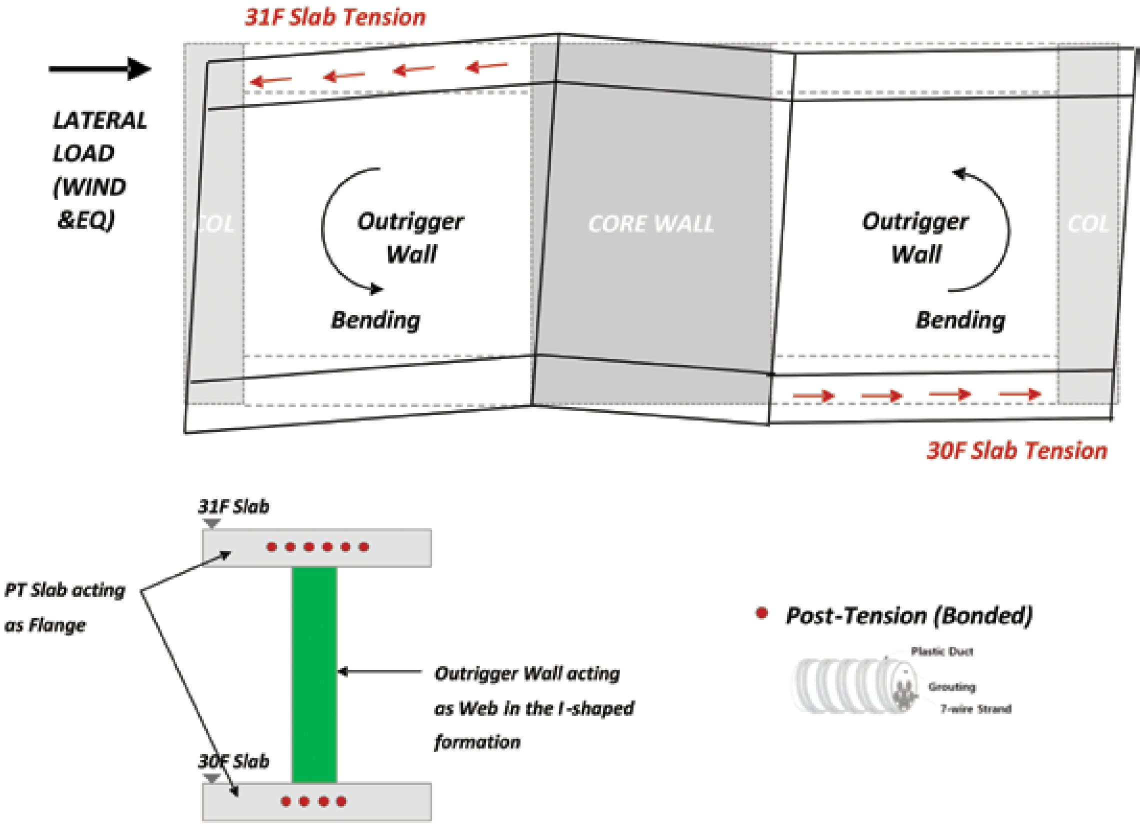
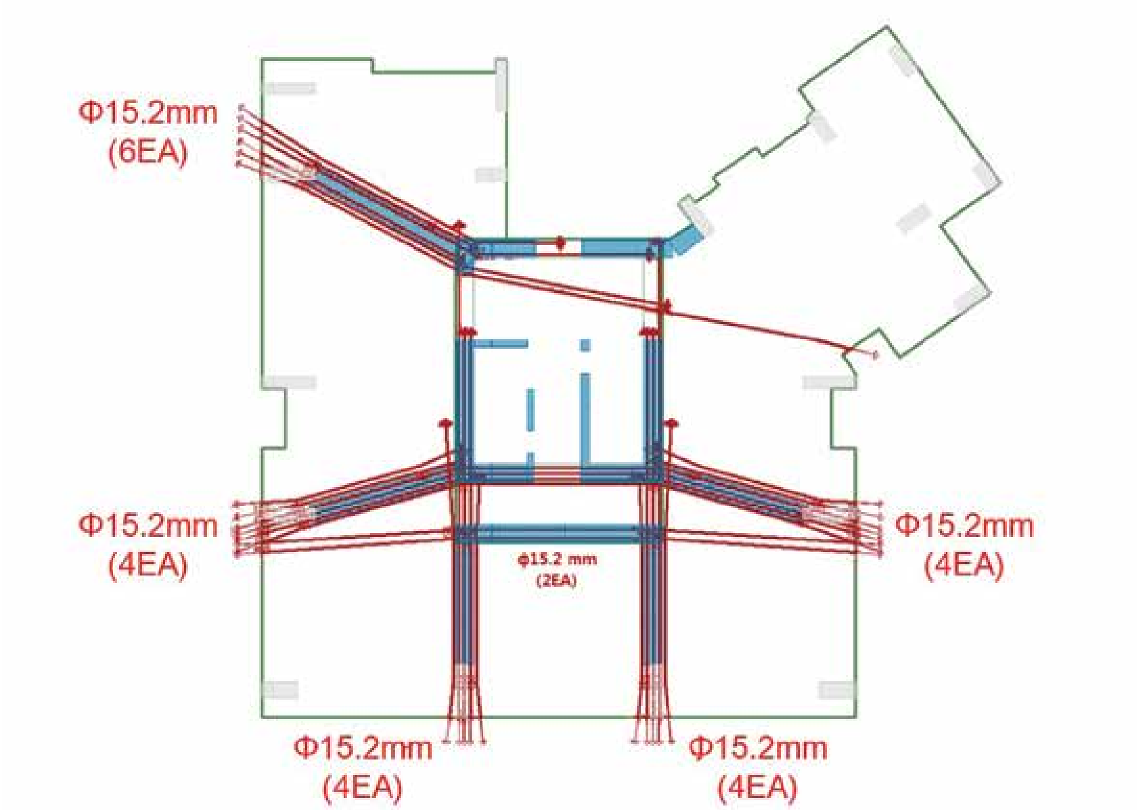
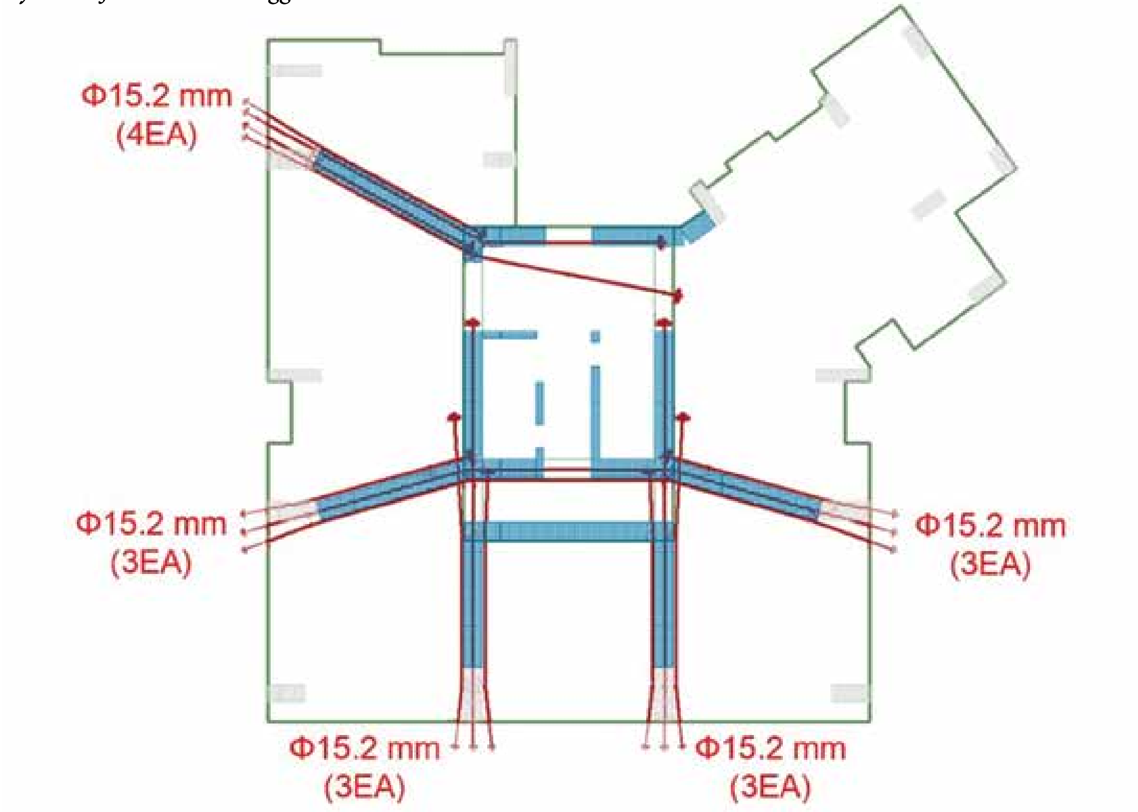


Fig. 11—OW+PTS sway mechanism.



(a) Tendon layout on floor above outrigger wall



(b) Tendon layout on floor below outrigger wall

Fig. 12—Tendon layouts on floors above and below outrigger wall. (Note: 15.2 mm = 0.6 in.)

Design outrigger connection

One of the primary challenges is to avoid carrying the perimeter column's gravity load into the outrigger wall. As the outrigger wall is a relatively stiff element connected to the relatively stiff core wall, the outrigger wall attracts the perimeter column's load into the core wall.

If outrigger walls are completely connected during the construction, the perimeter column's load from the floors above may be partially carried through the outrigger wall into the core wall. In this case, the outrigger vertical forces and bending forces are increased by more than 50% and approximately 30%, respectively. Figures 13 and 14 show the difference in column axial load distribution between the cases with and without the delayed connection. For the case without the delay joint, the outrigger vertical forces increase up to 30%.

Long-term differential settlement

RC high-rise buildings typically have the problem of long-term differential settlement between the perimeter column and core wall due to creep and shrinkage of the concrete. With the perimeter column generally settling more than the core, outrigger walls inherently carry some of the perimeter column loads. For that reason, conventional outrigger systems contain structural steel or composite steel-reinforced concrete (SRC). The steel allows for ease of delayed connection via a bolted connection that is not fully tensioned until after completion. However, as mentioned earlier, the disadvantage is that the introduction of the steel trade into an RC structure process often delays the project at the outrigger floor. Additionally, the challenge of meeting steel tolerance with a composite concrete construction may create difficulty. In this respect, the OW+PTS with delay joint would be a good alternative solution to absorb long-term differential settlement caused by creep and shrinkage.

The differential settlement is attributed to two factors: 1) elastic shortening from the perimeter column being more highly stressed than the core wall; and 2) long-term shortening due to creep and shrinkage of the concrete. The long-term effects occur more rapidly in the early stages of the building life and reduce gradually with time; however, when considering the duration of the building life, the post-completion effects can be significant.

These long-term effects could be considered for several scenarios including with and without the delayed outrigger joint and through various time-dependent analytical techniques. For this study, the construction procedures considering non-delayed and delayed pour joints in the outrigger ([ALT 1] and [ALT 2] in Table 1) are considered in the construction sequence analysis. In Table 1, DL is the dead load by self-weight; CLL is the construction live load of 2.5 kN/m² (52.2 lb/ft²); SDL

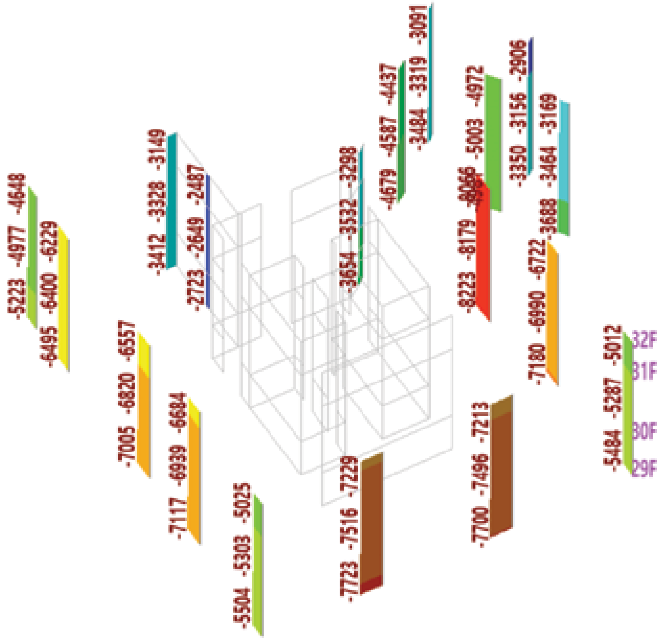


Fig. 13—Distribution of perimeter column axial loads with non-delay joint. (Note: Units are in kN; 1 kN = 224.82 lb.)

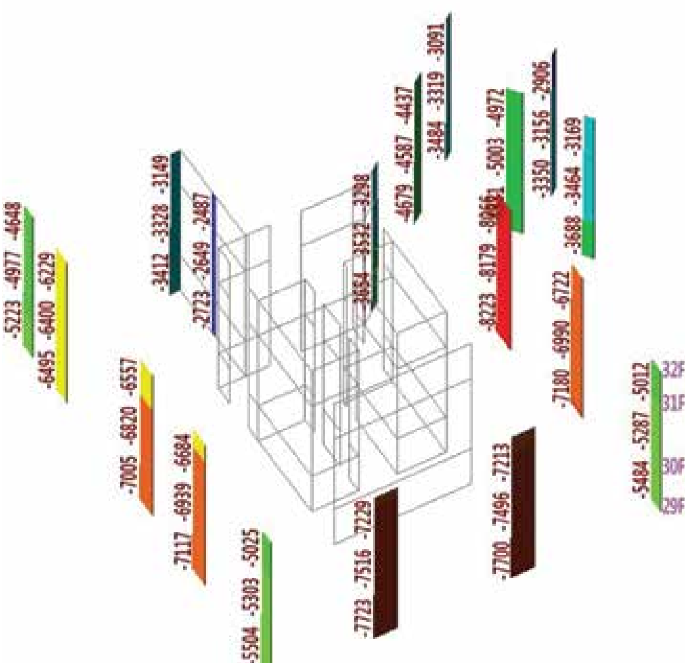


Fig. 14—Distribution of perimeter column axial loads with delay joint. (Note: Units are in kN; 1 kN = 224.82 lb.)

is the superimposed dead load, which includes finish or ceiling; and LL is the live load. For an evaluation of the building response and performance, three-dimensional finite element modeling was developed using MIDAS/GEN[3] and performed by grouping each construction step (Fig. 15).

The construction sequence analysis was carried out in accordance with Korean building code (KBC).[4] The details of the concrete material properties considered in the analysis are shown in Table 2. To account for the long-term effect of the differential settlement between the perimeter column and core wall, the concrete creep and shrinkage properties were also calculated according to KBC,[4] as shown in Table 3.

Table 1—Construction sequence analysis

Stage	Acc. Day	Load				Note
		Activation		Deactivation		
1	6	DL1	CLL1			
2	12	DL2	CLL2			
3	18	DL3	CLL3			
4	24	DL4	CLL4			
5	30	DL5	CLL5	SDL1	CLL1	
6	36	DL6	CLL6	SDL2	CLL2	
7	42	DL7	CLL7	SDL3	CLL3	
8	48	DL8	CLL8	SDL4	CLL4	
30	180	DL30	CLL30	SDL26	CLL26	[ALT 1] Outrigger Installation (Non delay joint)
54	324	DL54	CLL54	SDL50	CLL50	
55	330	DL55	CLL55	SDL51	CLL51	
56	336	DL56	CLL56	SDL52	CLL52	
57	342	DL57	CLL57	SDL53	CLL53	
58	348	DL58	CLL58	SDL54	CLL54	
59	354	DL59	CLL59	SDL55	CLL55	
60	360			SDL56	CLL56	[ALT 2] Outrigger Installation (Delay joint)
61	366			SDL57	CLL57	
62	372			SDL58	CLL58	
63	378			SDL59	CLL59	Frame Completion
64	408	LL1~59				30 days after Stage #63
65	11358					30 year after Stage #64
66	18658					50 year after Stage #64

The differential shortening was determined through the construction duration and post-completion building design life. The differential settlement values were taken at an age of 50 years (Stage No. 66), which is the building life cycle. The long-term differential settlements between the perimeter column and core wall in the non-delay joint model [ALT 1] varied from 2.93 to 12.07 mm (0.12 to 0.48 in.) (Fig. 16), whereas those in the non-delayed model [ALT 2] were varied from 1.12 to 5.46 mm (0.04 to 0.21 in.)(Fig. 17).

To accurately capture the forces resulting from the differential settlement, additional axial force P, horizontal shear V, and bending moment M resulted from creep and shrinkage were added to the short-term forces (Table 4). This increased the outrigger vertical forces on the order of 55%, shear forces by 8%, and bending forces by 17%.

SUMMARY AND CONCLUSIONS

A comprehensive study was conducted on two types of lateral force-resisting systems (LFRS) for a 59-story prototype high-rise RC residential building in Korea.

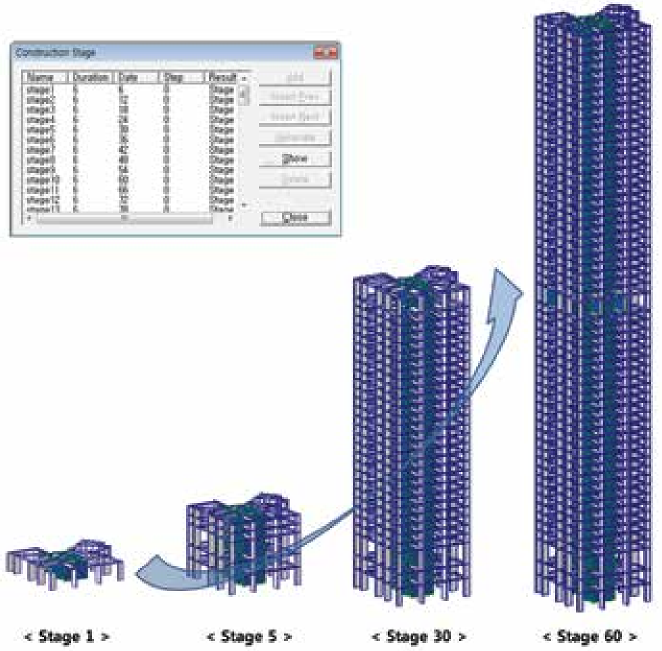


Fig. 15—Construction sequence analysis.

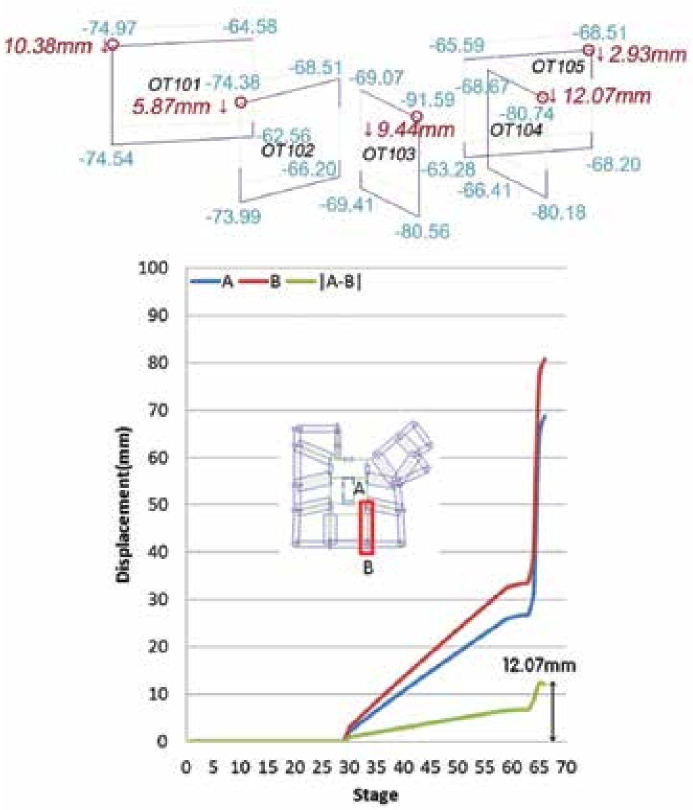


Fig. 16—Differential shortening with non-delay joint. (Note: 1 mm = 0.04 in.)

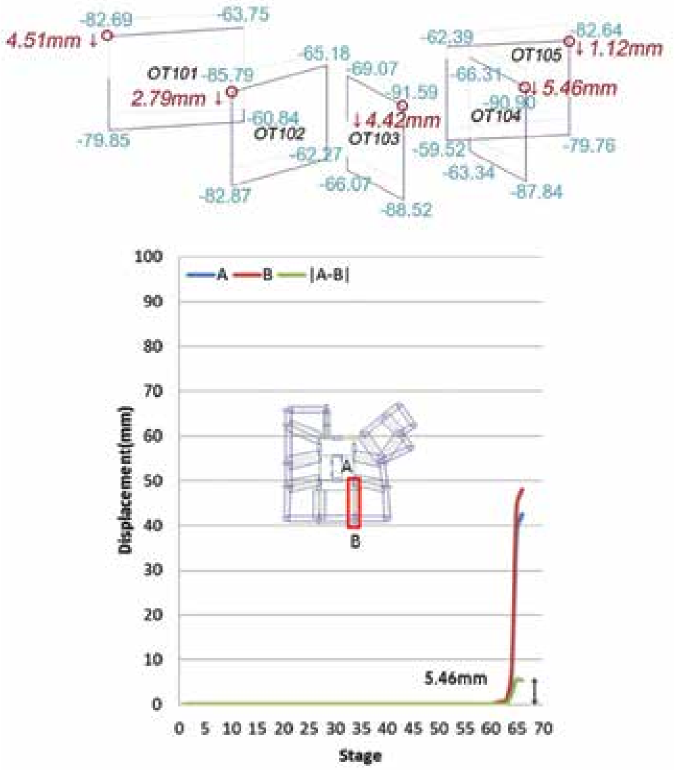


Fig. 17—Differential shortening with delay joint. (Note: 1 mm = 0.04 in.)

In addition to the lateral design for gravity, wind, and seismic forces, additional design factors were also considered. These include the construction sequence with and without delayed outrigger connections and the long-term differential settlement between the perimeter column and core wall. The two systems were structural steel-reinforced concrete belt wall (SRCBW) and the core and outrigger wall with post-tensioned slabs (OW+PTS), the latter of which was proposed by this study. While both systems, working in combination with the building core wall, provide comparable lateral force resistance, the proposed OW+PTS system has the advantage of cost-effectiveness over the SRCBW system that uses internal structural steel cross bracings. It is also worth noting that the time savings is greater with the OW+PTS option, as it does not mobilize an additional trade (steel workers). The combined materials savings and ease of installation make the OW+PTS a superior option, particularly when compared to the SRCBW.

Table 2—Concrete material properties

Level		Compressive strength	Modulus of elasticity
Outrigger	30F	60 MPa	34,700 MPa
Wall & column	1F ~ 10F	60 MPa	34,700 MPa
	11F ~ 10F	50 MPa	32,900 MPa
	21F ~ 30F	40 MPa	30,900 MPa
	31F ~ 59F	30 MPa	28,550 MPa
Link beam	1F ~ 11F	60 MPa	34,700 MPa
	1F ~ 21F	50 MPa	32,900 MPa
	22F ~ 31F	40 MPa	30,900 MPa
	30F ~ Roof	30 MPa	28,550 MPa
Slab	1F ~ Roof	21 MPa	26,100 MPa

Note: 1 MPa = 145 psi.

Table 3—Creep and shrinkage parameters

Parmeter	Values
Specified Compressive Strength of Concrete	21 MPa ~ 60 MPa
Relative Humidity of Ambient Environment	0.5
Type of Cement	Normal or Rapid Hardening Cement
Age of Concrete at the Beginning of Shrinkage	3 days

Note: 1 MPa = 145 psi.

Table 4—Outrigger wall forces with non-delay joint

Load combination		*P*, kN	*V*, kN	*M*, kN-m
LCB2	1.2D + 1.6L	3014	–2006	–6476
LCB3	1.2D + 1.3Wx + 1.0L	3237	2347	8966
LCB4	1.2D + 1.3Wy + 1.0L	–2977	–9502	–28,864
LCB5	1.2D – 1.3Wx + 1.0L	530	–4855	–17,062
LCB6	1.2D – 1.3Wy + 1.0L	6744	6994	20,769
LCB7	1.2D + EQ_1 + 1.0L	165	–242	279
LCB8	1.2D + EQ_2 + 1.0L	348	–176	54
LCB9	1.2D + EQ_3 + 1.0L	–74	1636	5021
LCB10	1.2D + EQ_4 + 1.0L	124	1711	4791
LCB11	1.2D + EQ_5 + 1.0L	3603	–2266	–8374
LCB12	1.2D + EQ_6 + 1.0L	3420	–2331	–8150
LCB13	1.2D + EQ_7 + 1.0L	3841	–4144	–13,116
LCB14	1.2D + EQ_8 + 1.0L	3643	–4219	–12,886
LCB15	0.9D + 1.3Wx	1354	3601	13,014
LCB16	0.9D + 1.3Wy	–4860	–8248	–24,816
LCB17	0.9D – 1.3Wx	–1354	–3601	–13,014
LCB18	0.9D – 1.3Wy	4860	8248	24,816
LCB19	0.9D + EQ_1	–1719	1012	4326
LCB20	0.9D + EQ_2	–1536	1078	4102
LCB21	0.9D + EQ_3	–1958	2890	9068
LCB22	0.9D + EQ_4	–1760	2965	8838
LCB23	0.9D + EQ_5	1719	–1012	–4326
LCB24	0.9D + EQ_6	1536	–1078	–4102
LCB25	0.9D + EQ_7	1958	–2890	–9068
LCB26	0.9D + EQ_8	1760	–2965	–8838
Short-term	Top slab tension	6744	8248	24,816
	Bottom slab tension		–9502	–28,864
Long-term	Creep (A)	3320	–145	–2023
	Shrinkage (B)	5283	–678	–3763
	Differential shorting (A + B)	8603	–823	–5786
Envelope	Top slab tension	15,347	7425	19,030
	Bottom slab tension		–10,325	–34,650
Increased ratio		56%	8%	17%

Notes: 1 kN = 224.82 lb; 1 kN-m = 0.738 k-ft.

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