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Outrigger Systems for Tall Buildings in Korea

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Abstract

Outrigger systems are highly efficient since they utilize the perimeter zone to resist lateral forces, similar to tubular systems. The entire structural weight can be reduced due to the system's significant lateral strength. Therefore, it is the most commonly selected structural system for tall and supertall buildings built in recent years. In this paper, issues regarding the differential shortening effect during construction of the outrigger system and the special joints used to solve these issues will be addressed. Additionally, the characteristics of wind and seismic loads in Korea will be briefly discussed. Lastly, buildings in Korea using an outrigger as their major structural system will be introduced and the structural role of the system will be analyzed.

Keywords: Tall building, Outrigger system, Column shortening, Delay joint, Adjustment joint

1. Introduction

Since efficiency of the structural system occupies a large portion of the planning of super-tall buildings, the usage of the mega columns around the outer edge of the central core is commonly used to minimize torsion caused by plan irregularities. Various systems to support this kind of building have been developed, and recently the outrigger system has become popular.

According to research by the Council on Tall Buildings and Urban Habitat on the structural systems of 75 Tall buildings from 1961 to 2010, all buildings built before 1990 used framed-tube systems, while 73% of the buildings after 2000 used the outrigger system (Fig. 1).

In South Korea, the outrigger system has been applied in many tall buildings including Hyperion I (254 m, 69 stories, Seoul) and the Northeast Asia Trade Tower (305 m, 68 stories, Incheon).

The improvements in computing systems has allowed the industry to maximize the performance of structural systems with outriggers to be more applicable through the use of advanced construction and design technologies.

2. Outrigger System

2.1. Basic principles of outrigger systems

The outrigger system is one type of structural system which is formed from a cantilever-shaped horizontal member connected to a structure's inner core and outer columns. Through the connection, the moment arm of the core will be increased which leads to higher lateral stiffness of the system.

Examples of the outrigger system can be readily found around the world; they are used in many ocean going vessels in the South Pacific Ocean and are the structural system of mobile cranes.

According to Fazlur Rahman Khan's classification of structural systems based on height, the outrigger system is the optimal system for structures around 60 stories high (Khan, 1969) (Fig. 3). However, in the recent trend, the system can also be applied to super-tall buildings more than 100 stories high.

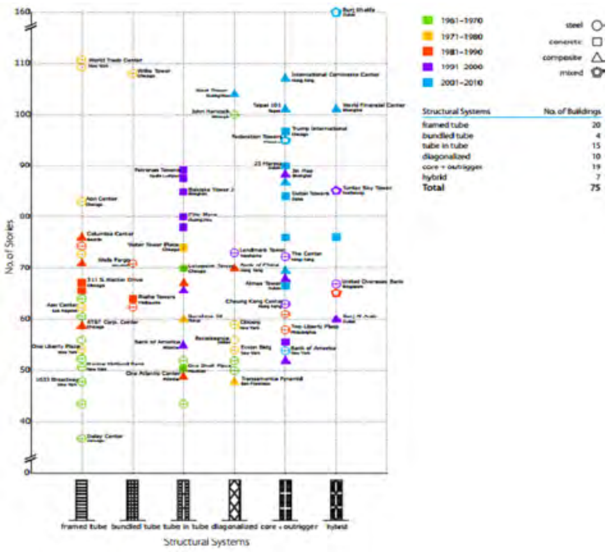

Figure 1. Classification of tall buildings by structural system (CTBUH, 2010).

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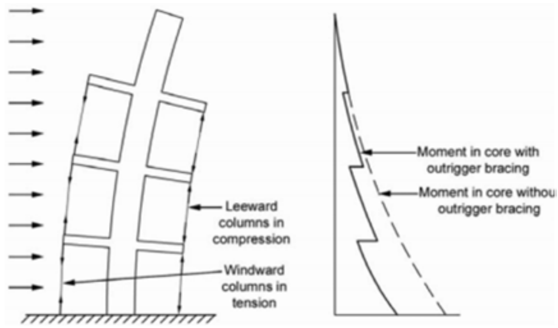

Figure 2. Structural principle of outrigger system.

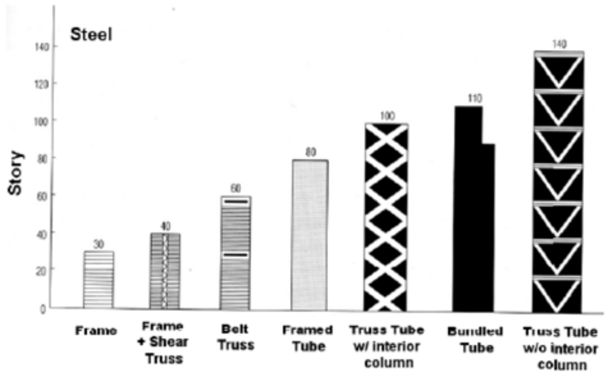

Figure 3. Optimal structural system for different height buildings (Recent Structural Systems in Steel for High-Rise Buildings, 1969).

2.2. Structural considerations in outrigger systems

Since an outrigger is a system that horizontally connects the core and outer columns, vertical differential column shortening should be verified carefully.

Amidst the trend of rapidly increasing height of structures, the loads applied to the vertical members are also increasing, which leads to high compression stresses and shortening in columns.

Table 1. Difference between delay joint and adjustment joint

	Delay joint	Adjustment joint
After construction	Truss system resists the 100-year return period for wind loads	
	Core + Outrigger resist	Core + Outrigger resist
During construction	Truss system resists the 10-year return period for wind loads	
	Only core resists	Core + Outrigger resist

In reinforced concrete or composite columns, not only deformation due to compressive stress, but also additional deformation from inelastic influences such as shrinkage and creep are major concerns. Each vertical member shows a different amount of vertical shortening, and their differential shortening significantly affects the stability and serviceability of the structural members.

Especially for super-tall buildings containing outrigger systems, in the case of immediate connection of outrigger trusses to the perimeter system, a concentration of stresses in the outrigger truss due to the differential shortening effect between the core and columns becomes a significant issue, as shown in Fig. 4. Optimization of the timing and methods for the connection of the outrigger to vertical members minimizes the effect of the additional stress.

As described above, applying special details in connections of the outrigger and columns to minimize the differential column shortening effect are very popular. These can be classified into two different methods: one is a delay joint, and the other is an adjustment joint.

Delay joints are a method which delays the connection of columns and the outrigger system until a certain amount of shortening occurs and then a permanent connection is made afterwards.

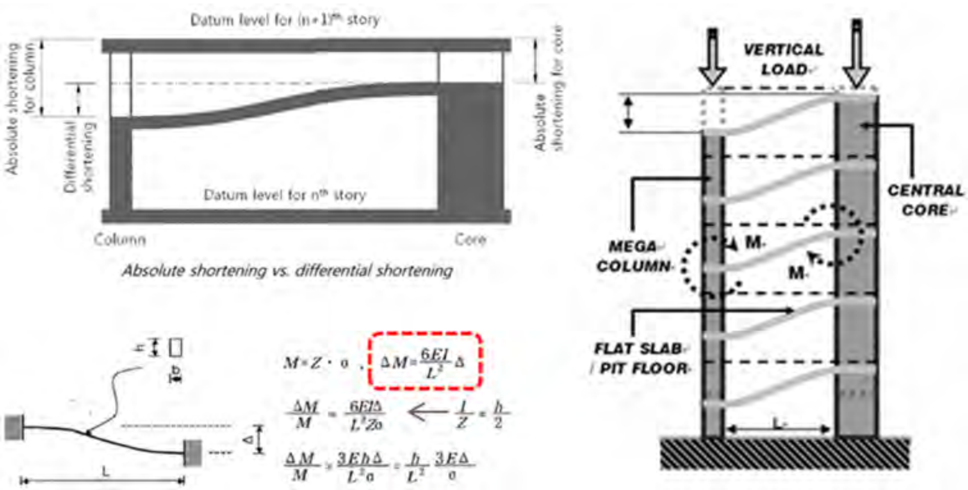

Figure 4. Effect of differential column shortening.

Figure 5. Delay joint (Hyperion I).

Figure 6. Adjustment joint (Hyperion I).

This method makes the structural design and construction process relatively simple. However, since all lateral loads, including the possible effects of a typhoon, must be resisted only by the core wallduring construction, the cost of the structure can increase (Table 1).

In contrast, adjustment joints can resolve the issues regarding the differential shortening effect while also resisting lateral loads during the construction phase of the outrigger system.

In order to do so, a shim plate needs to be placed in-between the outrigger and the outer columns. In this case, maintaining 1~2 mm of spacing is necessary.

2.3. Types of outrigger systems

Starting from the first applications of outrigger systems in buildings like Stock Exchange Tower in Montreal, Canada (48 stories, 1964), and First Wisconsin Center in Wisconsin, USA (42 stories, 1973, now known as U.S. Bank Center), the system has been applied to various construction projects in different forms and with variety of materials. In the beginning, the system was formed using a basic shape by connecting a steel truss core to the outer columns. Recently, due to improvements in concrete technologies, connecting reinforced concrete core walls to the outer columns has become the preferred method for the system (Lee et al., 2011).

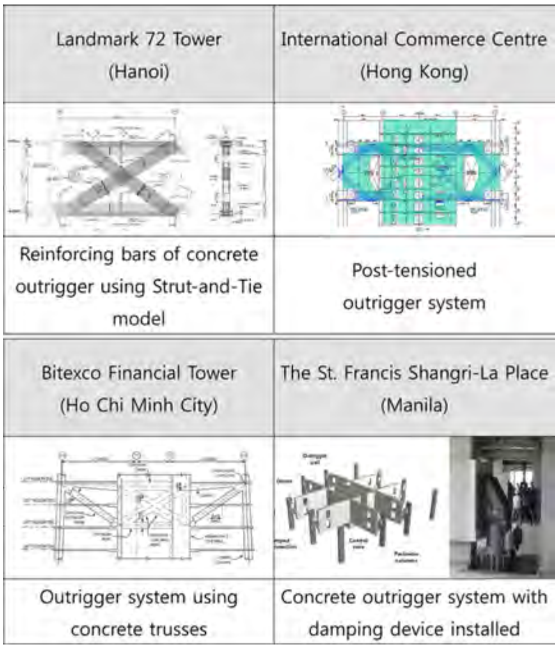

Figure 7. Various materials and forms of outrigger systems.

Columns connected to an outrigger system can be composed of various materials such as reinforced concrete, steel truss core, or composite columns according to construction efficiencies and structural plans.

In contrast, steel truss were traditionally the predominant material for outrigger systems. However, in order to minimize interference between the steel work and the concrete work, outrigger systems composed primarily of concrete have been frequently used, such as in Trump International Hotel & Tower (423 m, 98 stories, Chicago), and Landmark 72 Tower (336 m, 72 stories, Hanoi).

In order to improve performance and reliability of the concrete walls resisting the tensile force, a post-tensioned outrigger system was introduced in International Commerce Centre (484 m, 108 stories, Hong Kong) and World Tower (230 m, 75 stories, Sydney). For other cases, Bitexco Financial Tower (263 m, 68 stories, Ho Chi Minh City) is a building in which the concrete truss outrigger was used (Lee et al., 2011).

Also, The St. Francis Shangri-La Place (213 m, 60 stories, Manila) designed by Arup, is a structure in which the structural performance of the outrigger system has been utilized. In order to reduce the structure's response to wind forces, damping devices were installed in the connecting sections between the outrigger walls and column.

As shown in previous examples, various types of outrigger systems have been widely applied in the structural industry (Lee et al., 2011).

Figure 8. Ring of Fire (sites.google.com/site/volcanoesandtheringoffireurja).

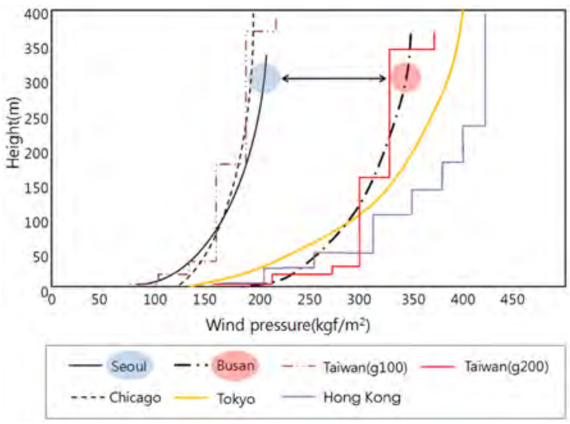

Figure 9. Design wind pressure in different regions.

3. Outrigger Systems in South Korea

3.1. Topographical characteristics of South Korea

Fortunately, since South Korea is located at the edge of the Eurasian plate, the land is not directly affected by the area near the Pacific Ocean where volcanic activity and earthquakes are very frequent, known as the "Ring of Fire". Recently, however, the frequency of earthquakes is on the rise.

Also, since 2~3 different typhoons tend to pass through the Korean peninsula each year between summer and autumn, the influence of wind forces is considered to be very significant.

3.2. Lateral load of South Korea

Since South Korea is a peninsula, surrounded by the ocean on three sides, the region is classified with a significantly large wind load. Is is especially recommended that the effect of serious wind loads be considered for regions near the coast and to prepare a solution for it. In Fig. 9, various wind pressures based on different altitudes are plotted according to the structural design code of several region. As can be seen, the level of wind pressure of Busan is in a similar range as the high-wind regions of Japan and Taiwan. The design wind load is significantly different depending on the buidling's location in South Korea (Sunwoo et al., 2004).

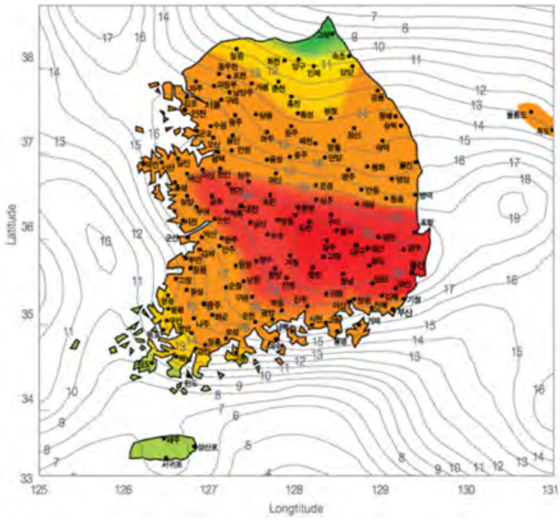

Figure 10. Effective ground acceleration of the 2400 year return period for the maximum predicted earthquake (midasarchi.com).

Based on the 2400-year return period seismic load for structural design in South Korea, 0.14 g is determined for the northern region of Gangwon Province, the southwest region of South Jeolla Province, and Jeju Island off the south coast of the peninsula, and 0.22 g is determined for the remainder of the country. Seismic forces can be reduced by using effective ground acceleration (Fig. 10) and, according to KBC 2009 (Korean Building Code), the effective ground acceleration coefficient cannot be lower than 80% of the region coefficient.

3.3. Tall buildings in South Korea

From the beginning of the 21st century, the number of tall buildings of different scales and for different uses have been designed and constructed.

Most tall buildings in South Korea are located in Seoul, Busan and Incheon. For the structures in coastal regions like Busan and Incheon which experience significant wind load effects, a great deal of research and discussion has been carried out in order to select the best lateral resisting system for each structure.

In South Korea, ever since the market for the super-tall buildings began to expand at the end of the 20th century, when the necessary concrete technologies were developed, most buildings have chosen an RC core system, all except for a few of the early ones.

Table 2. Tall buildings in South Korea

	LOTTE WORLD TOWER LOCATION: SEOUL STORIES: 123 TYPE: RC CORE, OUTRIGGER BELT TRUSS, STATUS: UNDER CONSTRUCTION YEAR: 2016
	FKI TOWER LOCATION: SEOUL STORIES: 50 TYPE: RC CORE, OUTRIGGER BELT TRUSS, STATUS: COMPLETE YEAR: 2013
	HYPERION I LOCATION: SEOUL STORIES: 69 TYPE: RC CORE, OUTRIGGER BELT TRUSS, STATUS: COMPLETE YEAR: 2003
	TRAPALACE LOCATION: SEOUL STORIES: 69 TYPE: RC CORE, BELT WALL, STATUS: COMPLETE YEAR: 2004
	HAEUNDAE I'PARK LOCATION: BUSAN STORIES: 72 TYPE: RC CORE, OUTRIGGER BELT TRUSS, STATUS: COMPLETE YEAR: 2011
	THE # CENTUM STAR LOCATION: BUSAN STORIES: 60 TYPE: RC CORE, BELT WALL, STATUS: COMPLETE YEAR: 2008

Figure 11. Northeast Asia Trade Tower.

4. Design Examples

4.1. Northeast Asia Trade Tower

The Northeast Asia Trade Tower (NEATT) is a 68-story super-tall building, of which the 2nd to 33rd floors are used for office space, which is a landmark of South Korea. The design overview is described below:

- Location: Incheon, Korea
- GFA: 138,316m^2
- Usage: office / hotel
- Scale: 68 Stories (305 m) - Above ground
  3 Stories - Basement
- Story Height: office 4.3 m
  Hotel 3.7 m
- Structural System: Core + Outrigger + Column
- Material: RC, SRC, Steel
- Foundation: RCD Pile

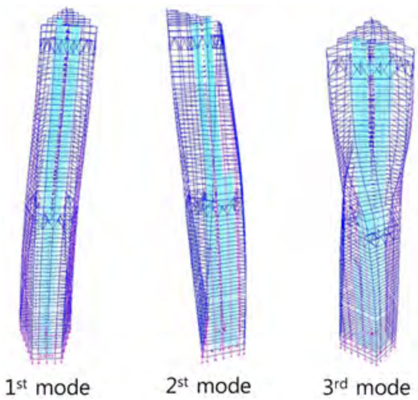

Figure 12. Mode shape of NEATT.

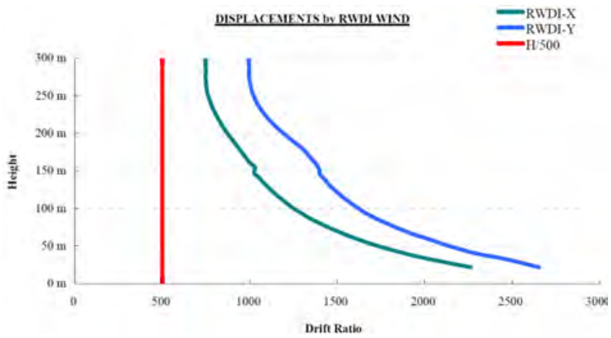

Figure 13. Displacement of structure due to wind Load.

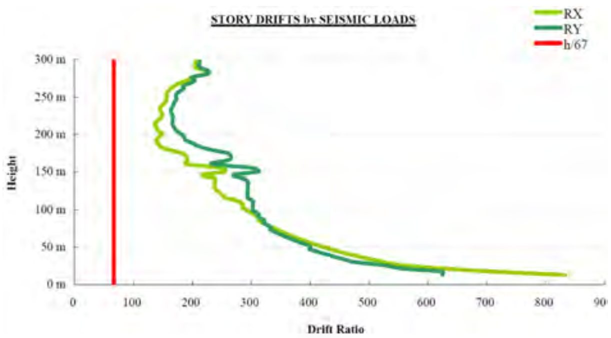

Figure 14. Drift of structure due to earthquake.

- Architect: KPF, Heerim
- Structural Design: Arup, DONGYANG
- Status: Complete

The main structural system of NEATT consists of 27 perimeter columns, 6 mega columns, core walls, and an outrigger/belt truss system. From the results of 3D analysis, the dynamic fundamental periods of NEATT were determined as 5.8 seconds for the 1st mode, 5.5 seconds for the 2nd mode, and 2.9 seconds for the 3rd mode.

Fig. 13 represents the ratio between height and displacement due to the wind load. For the top floor, the ratio is H/755 in the X-axis and H/988 in the Y-axis. Therefore, it satisfies all the design criteria of H/500.

Fig. 14 represents the story drift of the structure, and it appears that the maximum story drift satisfies 0.015 h (h/66.7) criteria in all stories (Jeon et al., 2008).

Similar to other super-tall buildings, the core wall takes the main role in resisting the gravity load and lateral loads. For NEATT, by varying the thickness and the form of the core wall, the optimization of the core wall proceeded as shown in Fig. 15 (Jeon et al., 2008).

The core wall takes 65% of the gravity load and around 70% of the overturning moment due to the wind load.

The outrigger/belt system was designed to take 30% of the overturning moment occurring in the structure. Also, the structural system was designed to support the axial force from the overturning moment distribution of the outrigger (Jeon et al., 2008).

Figure 15. Different thicknesses and forms of core wall for different story levels.

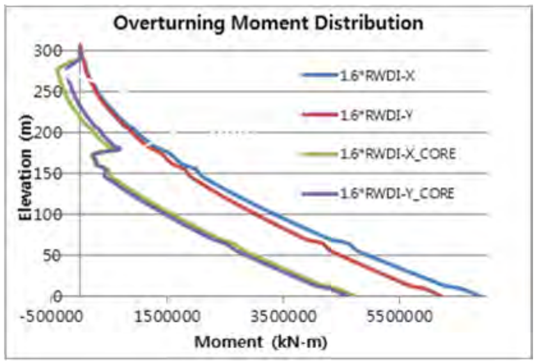

Figure 16. Effect of overturning moment distribution by outrigger.

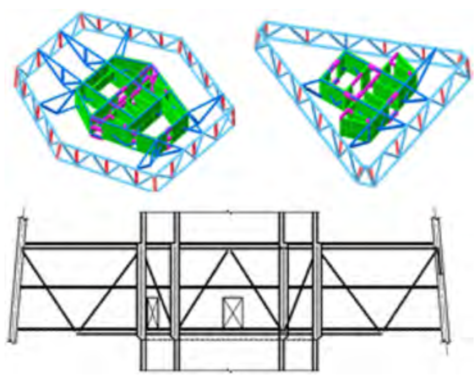

Figure 17. Outrigger modeling of NEATT.

For the outrigger, since each member has to meet in the diagonal direction and three or four members have to meet

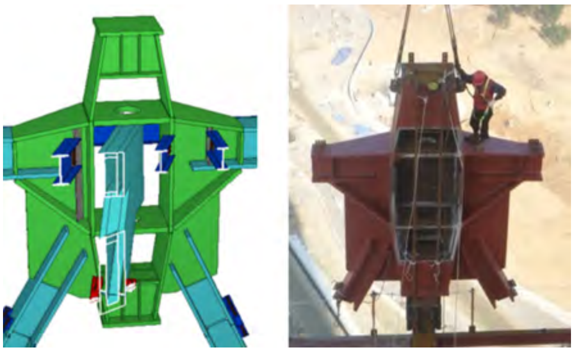

Figure 18. Outrigger connection of NEATT.

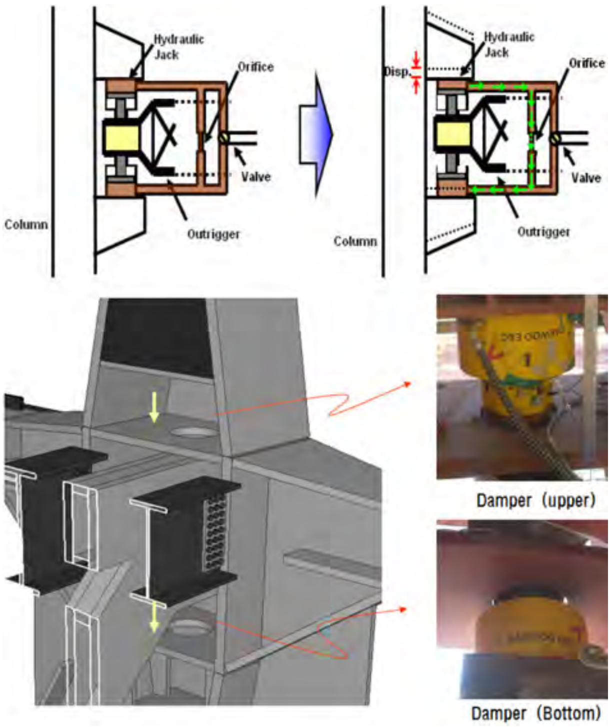

Figure 19. Automated adjustment joint outrigger system.

at the single point, a gusset plate was applied at the node point so that constructional efficiency could be achieved.

During the construction of NEATT, in order to ensure the safety and reliability of the structure under wind loads, an adjustment joint was applied so that the core wall and outrigger could work together in special circumstances.

In Fig. 19, the detail of the adjustment joint between outrigger and belt truss is illustrated. By using a hydraulic jack with an orifice, the outrigger was designed to resist the lateral forces. Also, an automated controlling system using a damper was domestically redesigned (by Daewoo) and applied so that the adjusting procedure using a shim plate could be omitted (Jeon et al., 2008).

Figure 20. Haeundae Resort.

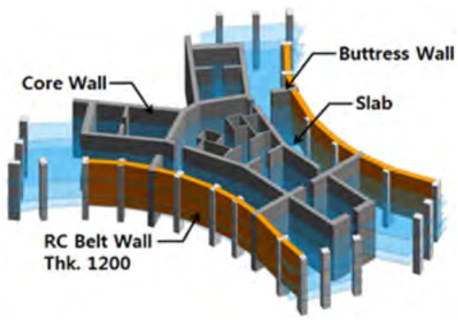

Figure 21. Structural modeling of outrigger and belt.

4.2. Haeundae Resort

- Location: Busan, Korea
- GFA: 473,426 m^2
- Usage: office / hotel
- Scale: 101 Stories (423.6 m) - Above ground
  5 Stories - Basement
- Structural System: core + outrigger + column
- Material: RC, SRC
- Foundation: Raft
- Architect: SOM, Samoo
- Structural Design: DONGYANG, Chungrim, SOM
- Status: Under Construction

Haeundae Resort consists of Landmark Tower and residential towers.

Landmark Tower is a mixed-use office/hotel building with 101 stories above ground and 5 basement floors. The structure is made of reinforced concrete containing high strength concrete and reinforced steel bars. Horizontal loads are resisted by the core, buttress walls and outrigger/belt systems located at the 22nd, 50th, and 78th floors. Gravity loads are designed to be resisted by flat plates, outer columns and core walls.

The 9.6 m height outrigger systems are connected to the outer columns. They resist moment and shear with the core

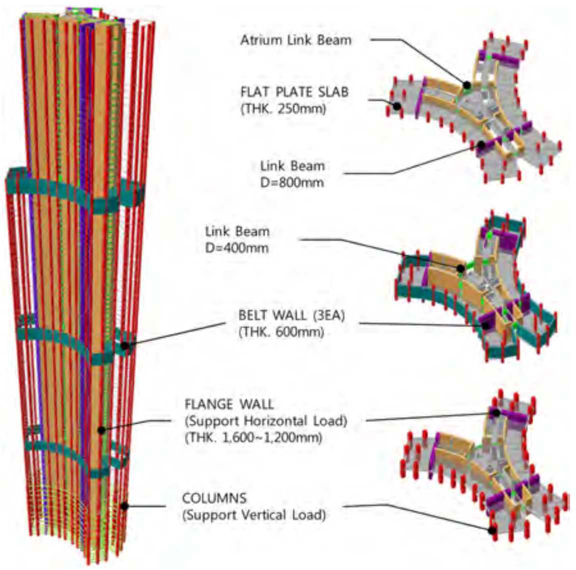

Figure 22. Lateral resisting system of Haeundae Resort.

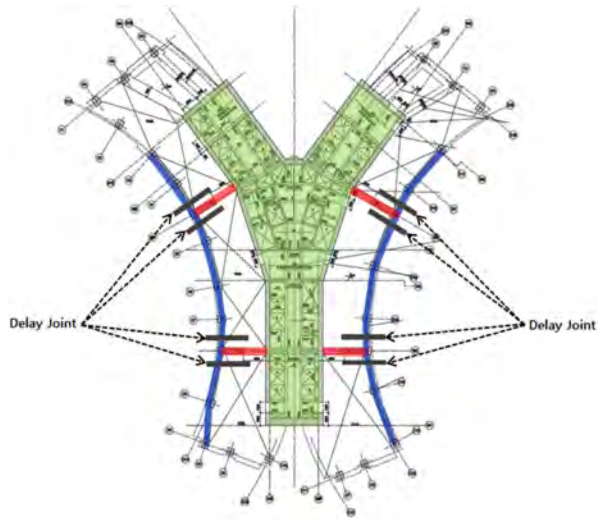

Figure 24. Delay joint locations.

and belt walls. The strength of the concrete applied to the outriggers are fck=80 MPa for the 22nd floor, fck=70 MPa for the 50th floor, and fck=60 MPa for the 78th floor.

The research to determine displacement of the structure by the wind loads was examined by RWDI by collecting the data from 24 load combinations of 100-year return period.

Generally, considering the special circumstances of reinforced concrete construction, settlement occurring before the concrete formwork is completed at each story is compensated for during the construction phase. Thus, it is recommended that buildings 30 stories or higher be verified with the output data so that analysis during the construction phase can be included. Therefore, if differential column shortening due to a dead load can be minimized, then the member force of the outrigger is expected to be lower and eventually will reduce the size of section/rebar used in the design.

As shown in Fig. 24, differential shortening of columns nearby buttress walls is predicted to take place after compensation during the construction phase. Therefore, in order to reduce the differential shortening effect of columns, delay joints were installed to the belt/outriggers nearby the columns.

Structural designs which contain large diameter rebar and compact installments of reinforcements such as an outrigger/belt tend to have a complicated construction which leads to difficulties in maintaining a high quality. Also,

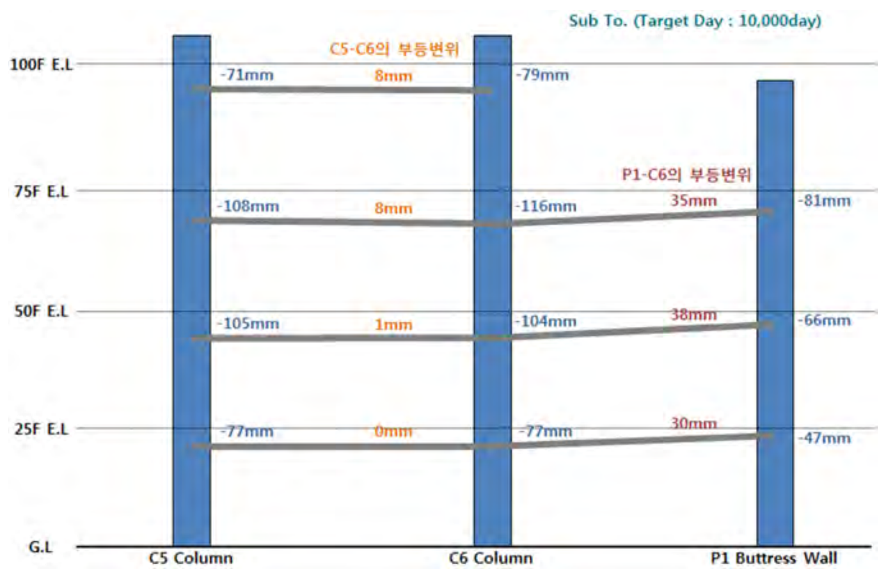

Figure 23. Sub To. column shortening prediction.

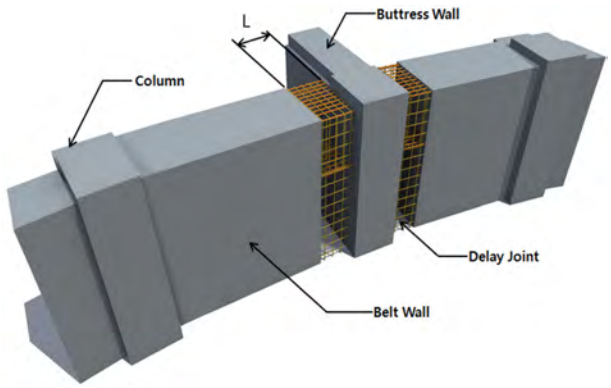

Figure 25. Delay joint detail.

complicated details like this can either delay or disturb the concrete formwork schedule.

Therefore, the use of pre-fab manufacturing is encouraged in order to increase the efficiency of the rebar of outrigger/belt systems, as well as maintaining of a high quality of work.

5. Conclusion

The outrigger system has earned a preferred status for the structural design of Tall and Supertall buildings around the world. Also, it is considered to be the most efficient lateral resisting system for tall buildings in South Korea. In the early stages, issues regarding differential shortening of columns, low construction efficiency, and delays in the construction schedule caused reluctance for the usage of the system. However, due to improvements in designing, materials, and construction technologies, these issues have gradually been resolved. After considering the improvements and advantages of the system regarding several issues from observing the case studies in South Korea, the outrigger system is expected to be developed as the primary lateral resisting system for the tall buildings in South Korea.

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