International Journal of Steel Structures
December 2010, Vol 10, No 4, 317-324

International Journal of STEEL STRUCTURES
www.ijoss.org

# A Comparison Study of Conventional Construction Methods and Outrigger Damper System for the Compensation of Differential Column Shortening in High-rise Buildings

**Kidong Park[1], Daeyoung Kim[1,*], Donghyun Yang[1], Daeki Joung[1], Inho Ha[2], and Sangdae Kim[3]**

[1]*Daewoo Institute of Construction Technology, Daewoo E&C, 60, Songjuk-dong, Jangan-gu, Suwon-si, Gyeonggi-do, Korea*
[2]*Daewoo E&C, Kumho Asiana First Tower, 57, Sinmunno 1-ga, Jongno-gu, Seoul, Korea*
[3]*Korea University, Anam-dong, Seongbuk-gu, Seoul, Korea*

**Abstract**

The outrigger and belt truss system is commonly used as one of the structural systems to effectively control the excessive drift due to lateral load and minimize the risk of structural and non-structural damage. However, this prominent structural system has a demerit of excessive stressing to structural and nonstructural members during construction due to differential column shortening. In this paper, several potential construction methods managing the outrigger to perimeter column joints experiencing differential column shortening are discussed. These methods include fixed joint without any adjustment, delayed joint, delayed joint with shim plate adjustment, and outrigger damper (or lock-up-device) installed joint. Based on our research through computer analysis, large scale laboratory test, shake table test and real installation of the apparatus to a high-rise project, the building with outrigger damper or lock-up-device system has many advantages in terms of building performance, construction convenience, quality control and cost reduction.

**Keywords:** outrigger, column shortening, delayed joint, damper, lock-up-device

## 1. Introduction

As cities continue to grow and land values continue to rise, the buildings are getting taller and slimmer to maximize rentable space. To make possible for this slender structure, many structural systems for high-rise building have been conceived and designed. Among them, the outrigger structural system has proven to be an efficient lateral stiffness system for high-rise building in reducing lateral drift under wind or seismic loading. However, this magnificent structural system has a demerit of excessive stressing to structural and nonstructural members during construction due to differential column shortening. Columns under various magnitudes of load are not uncommon in tall buildings. Resulting from differential loads, uneven shortening of two adjacent vertical members will induce moment, shear and crack in the connecting slab or beams. The magnitude of this induced moment, shear and crack will increase with time due to the effects of creep and shrinkage. As the creep strain depends on the magnitude of the load, the higher is the load applied to the column, the more is the shortening.

There have been some efforts and studies regarding this issue including delayed joints and adjustable joint method through shim plate adjustment. In this paper, a more sophisticated and engineered method to handle this issue using damper or lock-up device as well as other conventionally available constructional methods will be discussed.

## 2. Outrigger Structural System

For medium high-rise buildings, the concrete core is usually the only main structural element resisting lateral loading as is often the case. Sometimes this core system involves moment-connected frames or trussed bracing at the core to enhance the lateral resisting capacity. However, the braced core system alone cannot provide enough lateral stiffness for the building to keep the wind drift within the acceptable limit when the building is taller than approximately 150 m.

Outrigger structural system is one of the efficient structural systems for high-rise buildings in resisting

Note.-Discussion open until May 1, 2011. This manuscript for this paper was submitted for review and possible publication on August 21, 2009; approved on December 13, 2010.

*Corresponding author
Tel: +82-31-250-1162; Fax: +82-31-250-1131
E-mail: kimdy@dwconst.co.kr

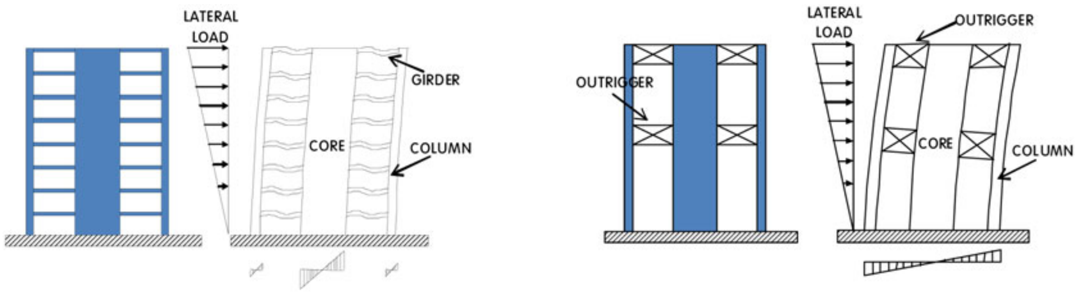



**Figure 1.** Comparison of building performance with or w/o outrigger system.

lateral loading, and it consists of a central core and horizontal cantilever outrigger trusses or girders attaching the core to the perimeter columns. It effectively reduces the lateral deflections and moments in the core compared to the core system described above by increasing the effective depth of the building due to the induced tension in the windward columns and compression in the leeward columns (Smith, 1991). Therefore, outrigger structural system can couple the core and perimeter columns enabling buildings to utilize its entire building width as shown in Fig. 1.

With the outrigger structural system the lateral loading is mainly resisted by the core and significant portion of the loading is transferred to the perimeter columns as a form of axial loads – compression and tension in the columns. Previous studies have indicated that the outrigger and belt truss system can provide additional lateral stiffness up to 25 to 30 percents (Taranath, 1988) or lateral drift decrease about 25 to 32 percent (Iyengar, 1995).

Belt truss is often used to tie all peripheral columns around the structure since every peripheral columns cannot be directly connected to outriggers. By doing that, it helps other columns to take part in restraining the outriggers.

Other benefits of the outrigger and belt truss system besides the reduction of core moment and roof drift are listed as below (Gamaliel, 2008).

- Equalize the differential shortening of exterior columns resulting from temperature and imbalanced axial loading.
- Reduce net tension and uplift force at the foundation level.
- Eliminate the need for moment-connected frames at the façade.

Even though the outrigger and belt truss system has many structural advantages as described above, this system has a significant defect due to differential column shortening such as elastic axial deformation, creep and shrinkage which is hard to be correctly estimated. The differential column shortening induces additional forces in the horizontal members such as outriggers, thus, causing structural and non-structural problems such as deformation of exterior cladding and pipe lines, and cracks in partition walls and slabs. The adverse effects of differential column shortening increase as the height of building is increased. To compensate for the adverse effects of differential column shortening in high-rise buildings, construction methods have been developed.

## 3. Conventional Construction Methods Managing the Issues from Differential Column Shortening

To deal with issues from the outrigger to perimeter column joints experiencing differential column shortening, three methods including fixed joint without any adjustment, delayed joint, delayed joint with shim plate adjustment are conventionally used.

### 3.1. Fixed joint without adjustment

Fixing the outrigger to perimeter column joints in the construction stage can be efficient for some cases since the outrigger system shares the overturning moment from the beginning without other remedies to the joint.

A representative project employed this method is Burj Dubai. In the Burj Dubai project, the wall thicknesses and column sizes were determined to minimize the effects of long-term differential shortenings such as creep and shrinkage on the individual elements which compose the structure (Baker, 2008). For example, for the case of creep the perimeter columns were sized carefully such that the self-weight gravity stress on the perimeter columns matched the stress on the interior corridor walls. Five sets of outriggers, distributed up the building, tie all the vertical load carrying elements together, further ensuring uniform gravity stresses; hence, reducing differential creep movements. For the case of the shrinkage, the ratios of volume to surface were considered to ensure the columns and walls will generally shorten at the same rate due to concrete shrinkage. This method can be reasonable for the concrete structure with the development of technology in the field of concrete material and differential column shortening estimation. However, the possibility of failure always exists and it depends chiefly on the structural ability of structural engineers.

But it cannot be reasonable for the concrete and steel (or SRC) combined structural system. For the concrete

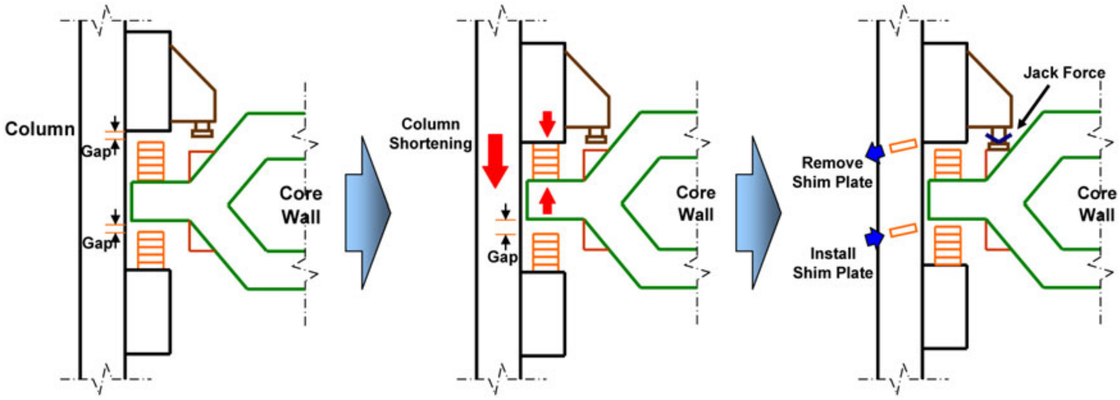



**Figure 2.** Typical construction sequence of outrigger connection by Shim Plate Correction Method.

and steel combined structural system, minimizing the creep and shrinkage is essentially impossible due to the inheriting difference in the material properties; therefore, the structure should be designed larger and stronger to withstand the elastic and non-elastic differential shortening. Even though the technology in the field of estimating differential column shortening has been greatly enhanced, it still is not good enough to be in the great accuracy, therefore, the structural members will be over-designed with great redundancy. It is the countermarch to the social demand which reducing the structural material with engineering technology for green environment and saving cost.

### 3.2. Delayed joint (Chung, 2002)

Delayed joint methods are widely used in the field of civil and architectural engineering as well as high-rise building with outrigger system. With this method, the outrigger and perimeter columns are not coupled in the construction stage and the connections will be fixed after the completion of the construction. Since the building is designed to resist lateral loading solely by the core, the design is less risky with comparatively simple engineering, however, the climbing of the construction cost due to increased structural materials is not avoidable.

### 3.3. Adjustable joint (Shim Plate Adjustment Method) (Chung, 2002)

Figure 2 shows the design philosophy of the typical adjustable connection links between an outrigger and perimeter steel members. This method will hereafter be referred to as the Shim Plate Adjustment Method.

As shown in Fig. 2, the bearing surfaces of the outrigger and the perimeter truss/column system will be separated by a nominal gap (<1 mm or 2 mm). The gap shall be monitored during construction. When the gap has decreased, shims shall be relocated such that the separation between bearing surfaces should be kept in a specified range during the course of construction. In the event that the gap has closed under calm wind, an oil jack shall be inserted at the locations shown in the Fig. 2 to induce a vertical separation between the outrigger tip and the column to relocate shims.

Shim Plate Correction Method is often used for adjustable joints for many civil and architectural structures as well as high-rise buildings with outriggers. However, this method also has several issues to be solved. These issues are listed as shown below.

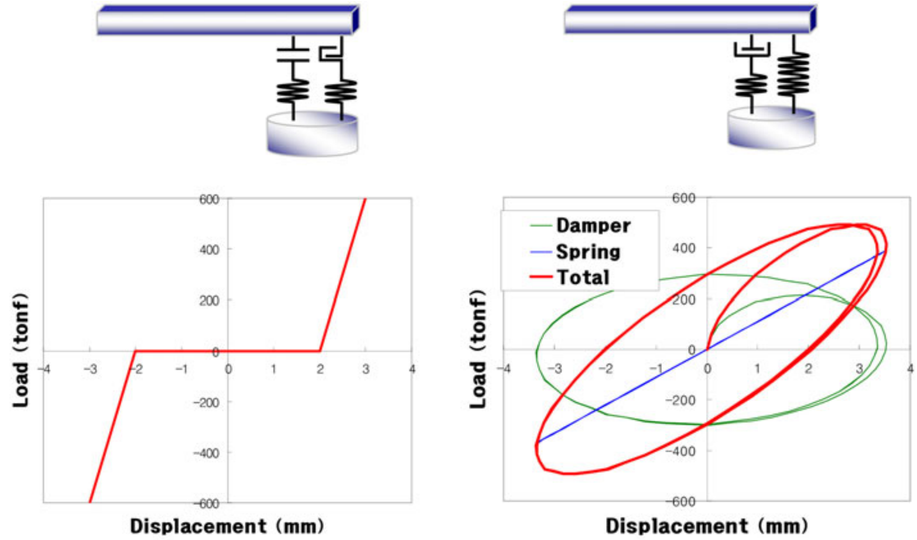
Direct Disadvantages

- If controlling the gap fails, additional stresses in the structural members may develop.
- Keeping the joint gap in a specified range such as 1~2 mm via shim plate replacements is essentially impossible.

- For the Shim Plate Adjustment Method, tens of steel shim plates with different thickness are required. These shims are required to be machined flat and in true bearing with adjacent shims. However, machining the steel shim plates with thickness of less than 10 mm to true fit is really difficult. Therefore, it is estimated that the accumulated gaps in between the shim plates itself could be greater than 5mm. Constructional tolerance due to structural welding also make irregular steel surface and this results in adding additional compressive displacement of piled shim plates. The contractor also needs to prepare an assortment of tapered shims to accommodate the tolerance of construction and fabrication (such as nonparallel bearing surface). The tapered shim is not only hard to be manufactured but also negative to keep uniform gap along the entire bearing surface.

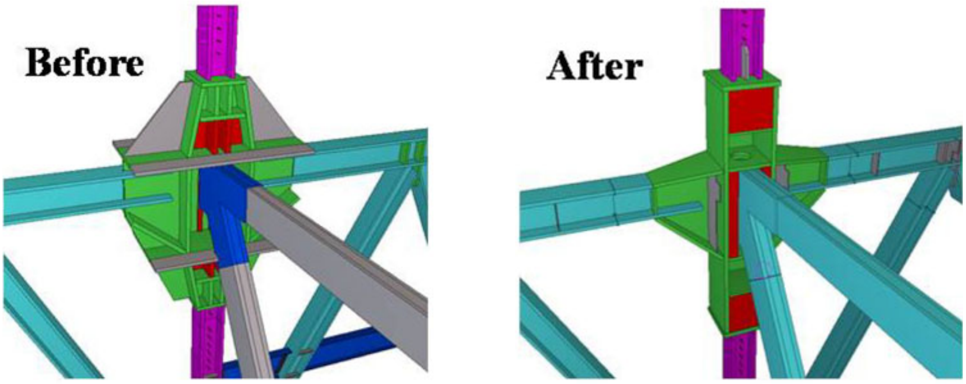
- Extra man power and devices are required during the construction for continuous measuring and monitoring process and shim plate replacements.

- Due to the uncertainty of the shortening amount it is usually required to monitor either the shim gaps or the induced forces every day. Therefore, the measuring and monitoring system shall be installed and relevant technician and workers need to be arranged at the construction site. These people will also perform the shim plate revision task. As mentioned earlier, the 1~2 mm gaps are easily




(a) Shim plate link (b) Outrigger damper link

**Figure 3.** Displacement-load curve comparison between shim-plated link and outrigger dampened link.




(a) Shim plate link (b) Outrigger damper link

**Figure 4.** Design change at the outrigger to perimeter column/belt truss joints.

closed during the construction due to differential shortenings. In the event that the gap has closed, the contractor shall insert oil jack(s) to induce a vertical separation between the outrigger tip and the column such that shims can be removed and the nominal gap can be restored at the upper and lower point. If oil jacks cannot be easily inserted and removed due to its joint detail, the oils jacks are required to be installed temporarily during the construction.

- The response of the building with adjustable joints should be obviously different with that of the final staged building after construction with fixed joint condition.

- Based on our preliminary analysis using SAP2000 Nonlinear computer model (CSI, 2001), the high-rise building with shim-plated outrigger joint is not expected to couple the core and perimeter columns. If there are outrigger systems at the multiple floors, this shim plated joints may spoil the integrated response of the building due to the difference of joint gap condition. This may lead to excessive cracks on the concrete core. The shim plated joints can be modeled as hook and gap nonlinear link elements in SAP2000 as shown in Fig. 3, however, there is uncertainty about the effective stiffness of the hook & gap links. This uncertainty will be studied further through shake table test with manufactured shim plate link model. The difference in structural properties between the shim plate link and outrigger damper link is clearly illustrated by the displacement-load curve in Fig. 3.

Indirect Disadvantages

- The size of outrigger to perimeter column joint structure become larger.

- As discussed in direct disadvantage part, oil jack(s) are required to be installed or inserted to the joint structure. This procedure causes the necessity of brackets at the both side of outrigger tip. It even leads to wider and larger joint structure compared to the joint structure with outrigger damper as shown in Fig. 4.

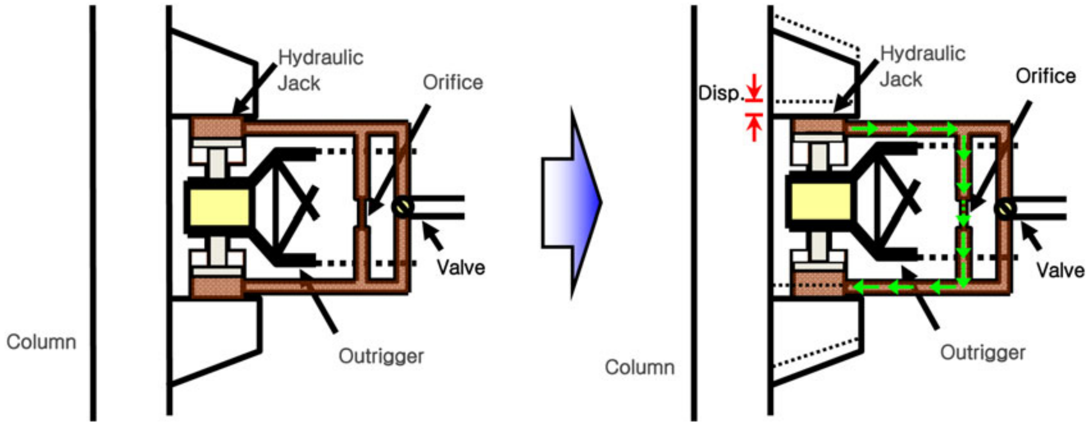



**Figure 5.** Theoretical functioning mechanism of outrigger damper.

- Cost-up due to increased on-site welding and greater crane capacity.

- The outrigger to perimeter column/belt truss joint structure is one of the largest assembled members in the building. It weighs easily over 10 tons and controls the lifting capacity of cranes. Considering the rental cost of the crane, contractors might decide to break up the joint structure to several pieces and perform on-site welding. But on-site welding of this giant structure is excessively time consuming and the quality cannot be guaranteed compared to the factory welding. Ultimately this may result in the delay of construction completion.

## 4. Outrigger Damper/Lock-Up-Device Installed Joint

### 4.1. Functioning mechanism

This new proposed method was conceived to overcome the difficulty of keeping such a small gaps at the outrigger connections. This method also should successfully transfer dynamic loads generated from winds and earthquakes. The theoretical functioning mechanism of this new method is shown schematically in Fig. 5. The schematic view of the proposed Outrigger Damper System at the outrigger tip is also shown in Fig. 6.

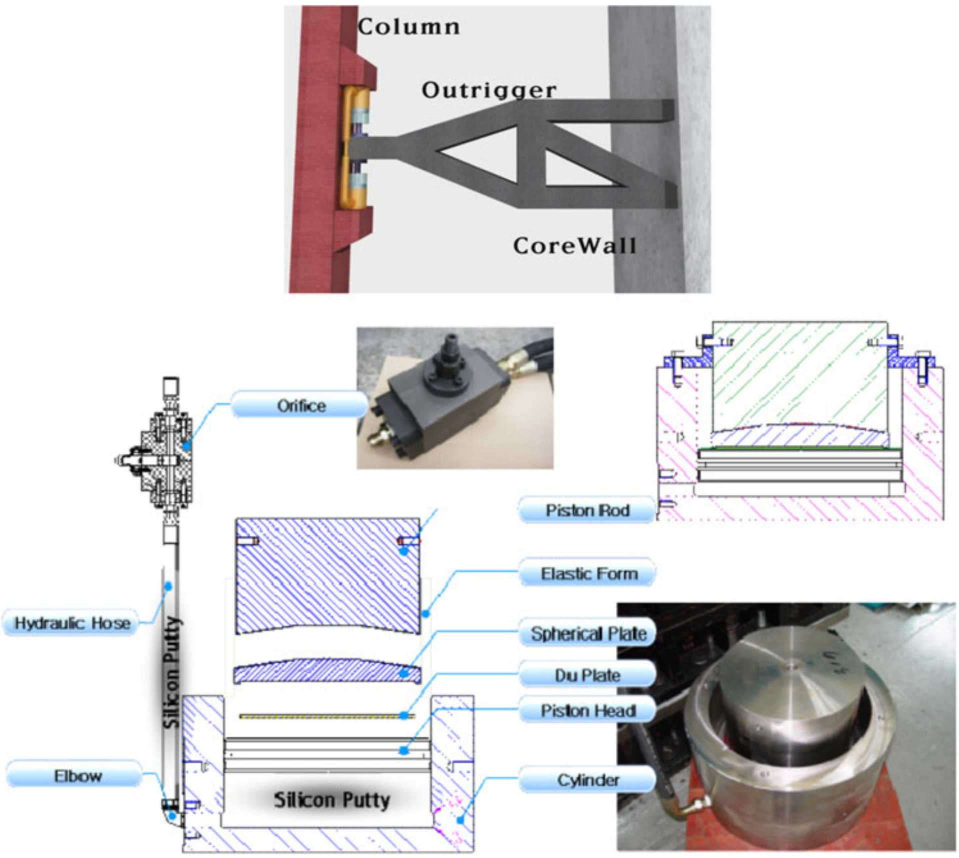



**Figure 6.** Schematic view and components of outrigger damper.

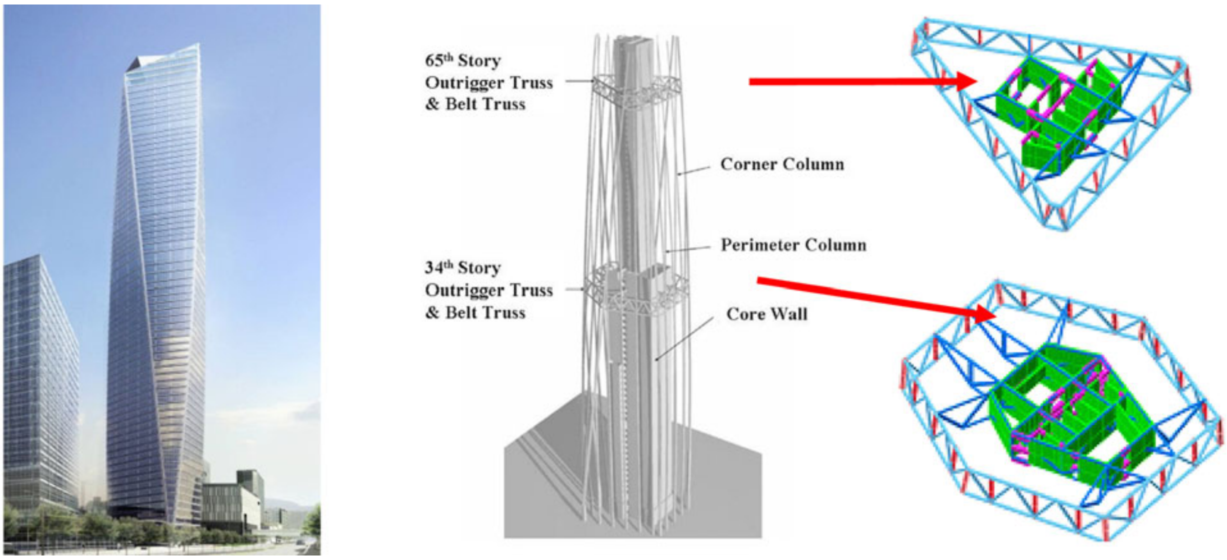



**Figure 7.** Structural system of NEATT.

This bi-directionally interlocking hydraulic system is composed of two hydraulic jacks and pipes with an orifice. The part and components of hydraulic jacks are illustrated in Fig. 6. The joint between outrigger damper and outrigger truss can be assumed as roller support due to the spherical plate (moment free) and due plate (horizontal force free) between piston head and ram. With this structural end condition the rotation and horizontal movement at the joint can be allowed during the installation to accommodate the construction tolerance and in the event of outrigger truss movement by lateral load.

For quasi-static vertical displacement, oil (or equivalent material such as silicon putty) flows slowly through the pipes and orifice. Therefore, the quasi-static vertical displacement due to column shortening will not cause considerable pressure to the hydraulic jacks and accordingly additional stresses in structural members. However, in the event of vertical displacement by dynamic lateral loads such as winds or earthquakes, oil (or equivalent material such as silicon putty) movement is resisted by the orifice. Through this mechanism the hydraulic jacks sustain pressures and the pressure is eventually transferred to the perimeter columns as a form of axial (vertical) loads.

### 4.2. Expected advantage of outrigger oil jack system

With this proposed Outrigger Damper System, the differential column shortening during the course of construction will be automatically handled without any extra stress to the structural members. Therefore, there is no need of shim plate revision and consequently construction cost declines by removing additional construction process. Additionally the building planed with the Outrigger Damper system is expected to show better performance than the same building with Shim Plate Adjustment Method since the oil jacks has some damping property as well as very high stiffness (Park, 2008). Potential of outrigger damper as a damping devices to reduce the amount of structural materials is also studied by Smith *et al.* (2007). The better performance is also resulted from the successful functioning of outrigger damper link for the interacting response between core and perimeter column/belt truss system through outriggers as intended.

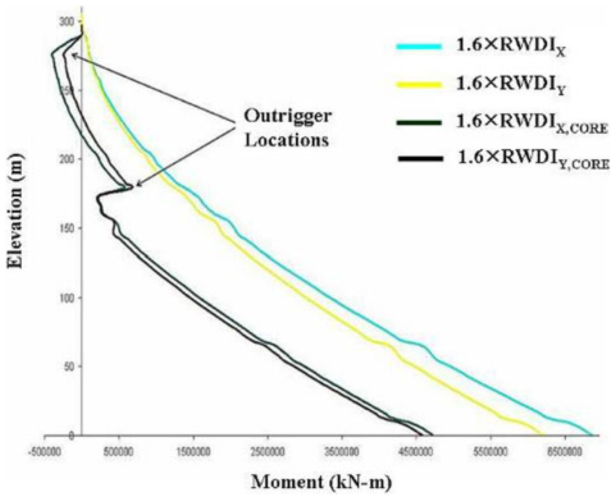



**Figure 8.** Effect of the outrigger's sharing of overturning moment (Source: Dongyang).

## 5. Application of Outrigger Damper to Songdo NEATT

### 5.1. Building description

A newly developing Songdo international city in South Korea will have area of 53 million square meters with quarter million population. Songdo NEATT, Northeast Asia Trade Tower, in the center of Songdo international city is expected to be a hub of northeastern Asian economy in the near future.

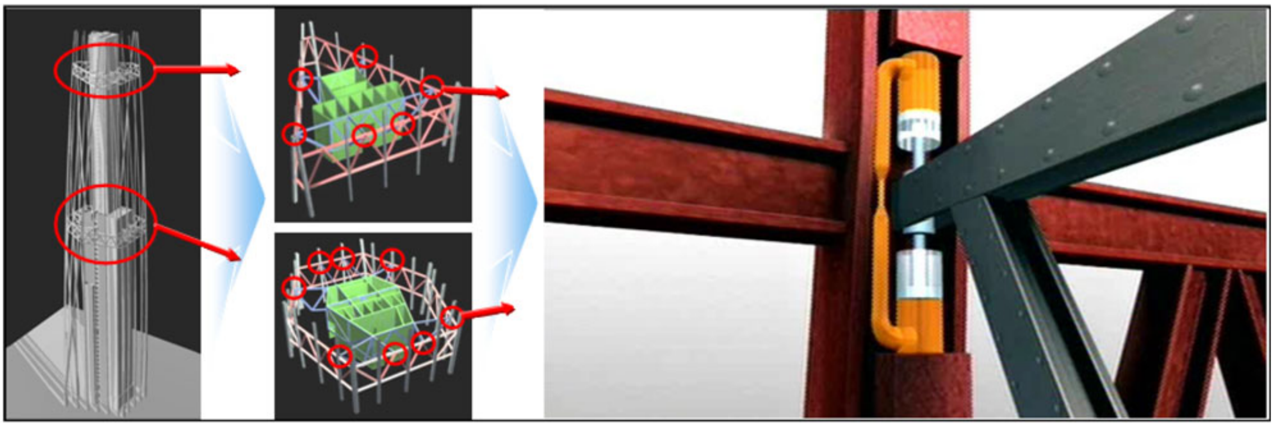


**Figure 9.** Illustration of installed outrigger damper.

Songdo NEATT comprises of 68 stories with a height of +305 m from level to the top of the roof and is currently under construction. The structural system is composed of the perimeter column, corner mega column, core wall, outrigger and belt truss system as illustrated in Fig. 7 (Chung, 2008).

As with other high-rise buildings, NEATT's core wall functions as a major structural element that resists gravity and lateral load. To resist lateral load efficiently, NEATT uses core walls with the outrigger and belt truss system. The 3-D frame and elevation of the outrigger and belt truss are shown in Fig. 7. It is calculated that the outrigger and belt system takes 30% of the total overturning moment applied to the building as shown in Fig. 8. It is clearly indicated that the overturning moment resisted by the core is significantly reduced at the locations of the outrigger floors at $34^{th}$ and $65^{th}$ floor.

Song-do Northeast Asia Trade Tower (NEATT) has total of 14 joints connecting outriggers to perimeter trusses and columns. Like typical other high-rise building, the Songdo NEATT is expected to sustains a large amount of differential column shortening between the core walls and perimeter columns/belt trusses, and consequently, additional stress is induced in the outrigger. A typical solution to this problem is the application of a delayed joint to the outrigger. However, if the delayed joint is applied, the core wall will be the only element that resists lateral loads such as wind and earthquake during construction.

Therefore, the adjustment joint was originally designed to NEATT's outrigger connections so that both the core walls and the outrigger could resist wind load during construction, successfully securing the building's structural stability against wind or earthquake load during construction. However, due to the pre-described problems in Section 3.3, Daewoo Outrigger Damper System is proposed to be installed to the outrigger to perimeter column/belt truss joints to automatically adjust differential column shortening during construction and resist vertical axial loading at the outrigger joints induced by severe wind load such as typhoons (Fig. 9).

### 5.2. Application of outrigger dampers to songdo NEATT

The outrigger dampers to Songdo NEATT were designed to withstand design wind and seismic load specified in Korean Building Code. Considering the temporary life span of the apparatus which is less than 2 years, the safety factor of the apparatus is approximately two. For the design of the outrigger dampers, Songdo NEATT was tested in a Boundary Layer Wind Tunnel at the Daewoo E&C's wind tunnel laboratory in Suwon, South Korea.

After manufacturing the apparatus, the performance test was carried out in the factory of Unison, Inc located in Cheon-an with 30 mega Newton LRB (Lead-Rubber-Bearing) tester and 2 mega Newton fatigue tester as


(a) 30 m·N Lead-Rubber Bearing Tester (b) 2 m·N Fatigue Tester

**Figure 10.** Performance tests of manufactured outrigger damper.


**Figure 11.** Installation of manufactured outrigger dampers.

shown in Fig. 10. The performance tests can be categorized as 1) Dynamic Displacement-Load Test, 2) Pseudo-static Displacement-Load Test, and 3) Endurance Test. The purpose of Dynamic Displacement-Load Test is to verify if the damper system successfully resists dynamic loading such as typhoon and earthquake with limited hydraulic jack ram displacement (2 mm).

The purpose of the Pseudo-Static loading test was to verify if excessive loading is applied to the system or not by the simulated static ram displacement with moving speed of 0.001 mm/sec which is equivalent to design displacement of 100 mm per 28 hours. With assumption of differential column shortening during the construction as 100 mm/18 months, realistic moving speed of the rams due to differential column shortening will be less than 0.00000214 mm/sec, therefore, the moving speed of rams for the tests are basically 467 times faster. Finally fatigue test of the damper system as an endurance check-up was also performed. The purpose of this Endurance Test is to secure the proper working of the damper systems during the construction without any damage such as leakage and broken seal ring to the system.

Eight sets of outrigger dampers have been installed to the 34th floor of Songdo NEATT as shown in Fig. 11. Monitoring system of the outrigger dampers during the construction will be set up as a part of Structural Health Monitoring (SHM) System of Songdo NEATT. To evaluate the performance of the proposed outrigger damper system, the applied load to the outrigger damper and relative displacement of the outrigger tip against the perimeter column/belt truss joint is planned to be measured during construction.

## 6. Conclusion

In this paper, a new proposed method as well as several conventional methods to settle the issue of differential columns shortening at the outrigger to perimeter column joints during the construction was studied. Conventional methods including fixed joints, delayed joints and delayed joints with shim plate adjustment have significant problems in the aspect of construction cost and period, quality control and construction convenience. However, with this proposed Outrigger Damper System, the differential column shortening during the course of construction will be automatically handled without any extra stress to the structural members and the building with the Outrigger Damper system is expected to show better performance than the same building with Shim Plate Adjustment Method. Furthermore, this outrigger damper can be designed as damping devices to reduce the amount of structural materials.

## References

Baker, W. F., Korista, D. S., and Novak, L. C. (2008). "Engineering the World's Tallest." *Proc. 8th World Congress on Tall Building*, Council of Tall Building and Urban Habitat, Dubai, UAE.

Chung, K. R., Kim, I. K., and Kim, M. H. (2002). "Structural Design of Hyundai-Hyperion Project, Seoul, Korea." *SEWC2002*, Yokohama, Japan.

Chung, K., Scott, D., Kim, D., Ha, I., and Park, K. (2008). "Structural System of North East Asia Trade Tower in South Korea." *Proc. 8th World Congress on Tall Building*, Council of Tall Building and Urban Habitat, Dubai, UAE.

CSI (2001). SAP *2000 Structural Analysis Program Non Linear, Version 10.0.7.* Computer and Structures, Inc, Berkeley, California.

Gamaliel, R. (2008). "Frequency-Based Response of Damped Outrigger Systems for Tall Buildings." Master's Thesis, Dept. of Civil and Environmental Engineering, Massachusetts Institute of Technology.

Iyengar, H. (1995). "Composite and Steel High Rise System, Habitat and the High-Rise, Tradition & Innovation." *Proc. 5th World Congress*, Council of Tall Building and Urban Habitat, Bethlehem, The Netherlands.

Park, K., Joung, D., and Kim, D. (2008). "Application of Outrigger Dampers as a New Construction Method for the Outrigger Connection." *Proc. Conference on Wind Engineering Institute of Korea*, Korea.

Smith, R. J. and Willford, M. R. (2007). "The Damped Outrigger Concept for Tall Buildings." *The Structural Design of Tall and Special Buildings*, pp. 501-517.

Smith, B. S. and Coull, A. (1991). *Tall Building Structures: Analysis and Design*. John Wiley & Sons, Inc., New York, N.Y., U.S.A.

Taranath, B. S. (1998). *Structural Analysis & Design of Tall Buildings.* McGraw-Hill Book Co., Inc., New York, N.Y., USA.