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Effects of Perimeter to Core Connectivity on Tall Building Behavior

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Abstract

The Pertamina Energy Tower (PET) and Manhattan West North Tower (MWNT) are two supertall towers recently designed and engineered by Skidmore, Owings & Merrill (SOM). The structural system for both buildings consists of an interior reinforced concrete core and a perimeter moment frame system, which is primarily structural steel. As is typical for tall towers with both concrete and steel elements, staged construction analysis was performed in order to account for the long term effects of creep and shrinkage, which result in differential shortening between the interior concrete core and steel perimeter frame. The particular design of each tower represents two extremes of behavior; PET has a robust connection between the perimeter and core in the form of three sets of outriggers, while the perimeter columns of MWNT do not reach the ground, but are transferred to the core above the base. This paper will present a comparison of the techniques used during the analysis and construction stages of the design process with the goal of understanding the differences in structural behavior of these two building systems in response to the long term effects of creep and shrinkage. This paper will also discuss the design and construction techniques implemented in order to minimize the differential shortening between the interior and exterior over the lifespan of these towers.

Keywords: Skyscraper, Supertall, Construction sequence, Creep, Shrinkage, Differential shortening, Outrigger system, Moment frame

1. Introduction

Mathematical models for the analysis of creep and shrinkage in concrete structures and their application to tall buildings have been in development for over three decades and are well documented (Bazant, 1982). Since the completion of the Jin Mao Tower in Shanghai (Korista et al., 1997), composite steel and concrete structural systems for super tall towers have become increasingly popular throughout the world (Ali; 2001, Ali & Moon; 2007). A typical composite system consists of a reinforced concrete central core and a steel or composite perimeter structure. The success of these systems depends on an understanding of the effects of the distinct long-term behavior of the two materials. Composite super tall towers experience continuous differential shortening between the interior and exterior which must be accounted for in analysis, design, and construction, to minimize its effects on the structure as well as to ensure occupant comfort.

This paper will describe the structural systems of two composite super tall towers recently designed and engineered by Skidmore, Owings and Merrill (SOM), and



Figure 1. Architectural rendering of Pertamina Energy Tower (PET).

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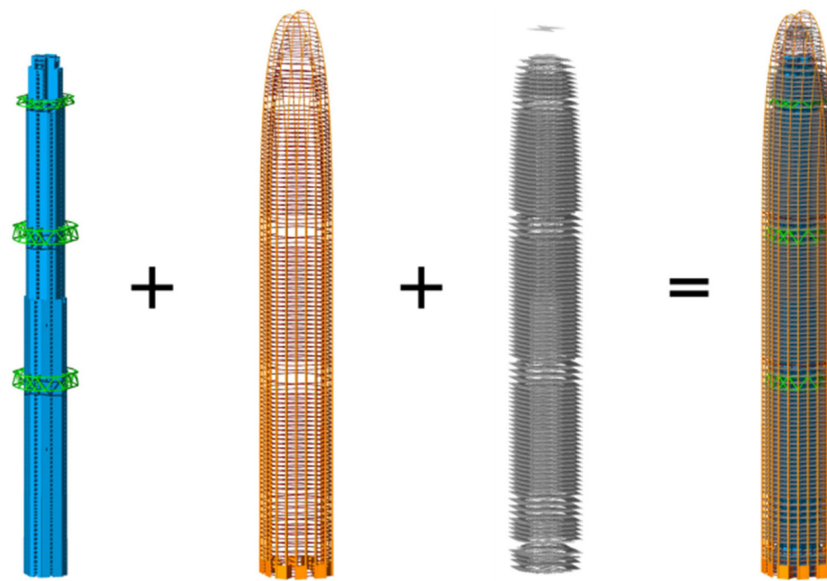


Figure 2. Pertamina Tower Structural System: (a) Reinforced concrete core with steel outriggers and belt truss, (b) Composite columns & steel beams moment frame, (c) Composite gravity framing system, (d) Overall structural system.

compare how these systems behave in response to the effects of creep and shrinkage and how their distinct characteristics affected the design and construction techniques implemented to minimize the differential shortening between the interior and exterior.

1.1. Pertamina Energy Tower

The Pertamina Energy Tower (PET) will be a 530 m tall, 99 story office tower located in Jakarta, Indonesia (Fig. 1). Part of a larger development that includes a performing arts and exhibition pavilion, a mosque, and a central energy plant, the tower will be the first super tall building in Indonesia (Besjak et al., 2015).

1.1.1. Structural System Description

The structural system is comprised of a ductile reinforced concrete core and a structural steel exterior moment frame with composite perimeter columns and steel beams. The two systems are coupled with three sets of structural steel outriggers and belt trusses located every 30 floors. The gravity system consists of a concrete slab on metal deck supported by composite steel beams acting as a diaphragm to transfer loads to the core and columns. Fig. 2 shows how these three parts come together to create a unified structural system.

1.2. Manhattan West North Tower

The Manhattan West North Tower (MWNT) is a 320 meter tall, 67 story office tower, which is currently under construction as part of the Manhattan West Development on the corner of 33rd Street and 9th Avenue in Manhattan, New York (Besjak et al. 2014) (Fig. 3). MWNT is located on a challenging site a portion of which is above the



Figure 3. Architectural rendering of Manhattan West North Tower (MWNT).

below ground rail tracks leading into Penn Station (Dunlap 2016). The potential area for a foundation is limited to approximately 25% of the total enclosure footprint of the building and none of the perimeter columns on the south side could come to the ground between the tracks. These constraints were addressed by transferring the perimeter columns to the concrete core

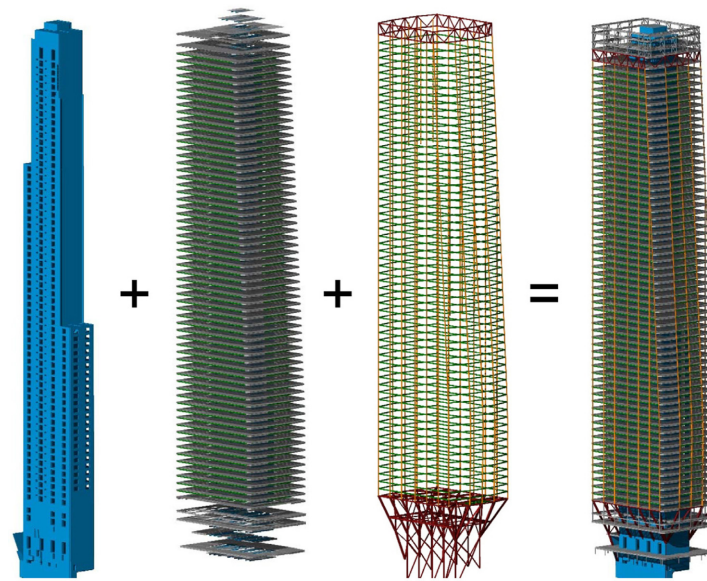


Figure 4. North Tower Structural System: (a) Reinforced concrete core walls, (b) Steel columns, ‘Kicker’ & belt truss, (c) Composite deck & steel floor framing, (d) Overall structural system.

between levels 2 and 6, making the concrete core the primary lateral force resisting system below the transfer and establishing MWNT as one of the most slender towers in New York City.

1.2.1. Structural System Description

The lateral system is a central reinforced concrete core and perimeter moment frame with structural steel columns and beams. The gravity system is a concrete slab on composite metal deck supported by structural steel floor beams and girders that span between the core and perimeter. The exterior columns along the north, east and south “kick back” to the concrete core below level 6. To enhance structural resilience, and reduce lateral drift, a perimeter belt truss is located at the top of the tower, however there are no outriggers.

2. Creep and Shrinkage Analysis

For both the Manhattan West North Tower and the Pertamina Energy Tower, a finite element model was created in E-Tabs 2013, a Structural Finite Element analysis software (CSI, 2015) using shell elements to model walls and floors and beam and brace elements to model columns and beams. Each model was analyzed using non-linear staged construction analysis, which combines the theoretical construction sequence and time-dependent material properties, to investigate the effects of creep and shrinkage on building behavior over the life span of the building.

2.1. Analysis Methods

E-tabs estimates the effects of creep and shrinkage

using the CEB-FIP 90 method (Comité Européen du Béton - Fédération Internationale du Béton). One drawback of this method is that it does not account for steel reinforcement in concrete elements, which can significantly reduce the creep and shrinkage (Altoubat et al., 2001). The Gardner-Lochman method (ACI 209.2R-08) takes account of the effects of reinforcement by utilizing a reinforcement reduction factor. This method has also been utilized previously by SOM (Baker et al; 2008) and is recommended by “Guide for Modeling & Calculating Shrinkage & Creep in Hardened Concrete” (ACI 209.2R-10). Fig. 5 compares the compliance of both methods to the RILEM databank, which is a comprehensive database on Concrete Creep and Shrinkage (ACI 209.2R-10). The Gardner-Lochman (GL2000) provides better correlation to the experimental data compared to the CEB FIP 90 method.

To achieve similar curves to the Gardner-Lochman method, a technique of varying the parameters f_c' and B_{sc} was used to achieve the most accurate possible estimation of the creep and shrinkage in E-Tabs. It was assumed that Relative Humidity is constant at 50% throughout the lifetime of the building. Fig. 6 shows an example of the curves utilized in E-tabs and how they correlate to the separate models. It should be noted that since this study was completed CSI have integrated additional creep and shrinkage models into E-Tabs that allow the user further control the time-dependent material properties.

3. Results and Discussion

For both MWNT and PET, the differential vertical

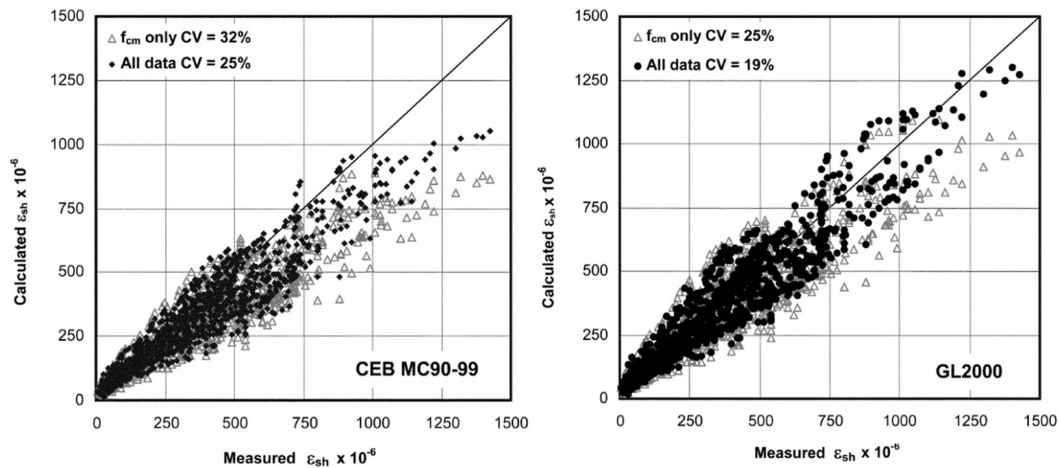


Figure 5. Comparison of CEB-FIP 90 and GL2000 method (ACI 209.2R-10).

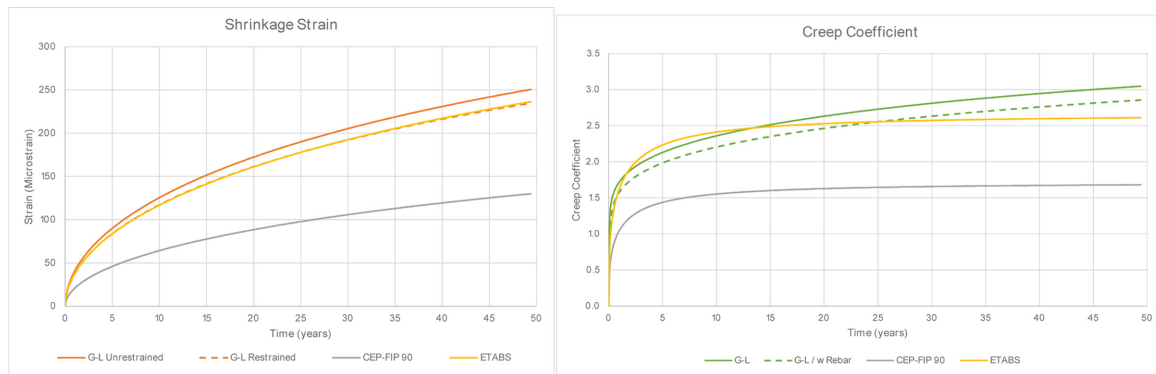


Figure 6. Creep & shrinkage curves for MWNT.

deflections between the interior and perimeter were analyzed for the entire core and all perimeter columns. Fig. 7 shows the key plans for PET and MWNT respectively.

3.1. Analysis - Relative Vertical Displacements

The effects of creep and shrinkage occur over the life span of the building. For this reason, it is necessary to compare analysis results from both towers over an extended period time, typically up to 50 years after the building's completion.

3.1.1. Pertamina Energy Tower

Fig. 8 shows the vertical displacement of the core and perimeter of PET vs elevation at three different stages of the building's lifespan; at the time of building completion, 1 year after completion and 50 years after completion. The dotted lines indicate the location of the outriggers. From the figure it is evident that core deforms non-linearly more than the perimeter columns. This is occurs due to the high percentage of embedded steel (8%

on average) in the perimeter columns. This trend continues from the time of the building's completion to 50 years after completion. The steps evident in the perimeter curve occur above outrigger levels and are due to the rigid connection created by the outrigger from the core and the perimeter. The steps evident on the core curve occur due to changes in core geometry.

3.1.2. Manhattan West North Tower

The plots below (Fig. 9) are vertical displacement plots comparing interior core displacement with perimeter column displacement for the northern portion of MWNT. Fig. 9 illustrates that during construction, the steel perimeter columns shorten more than the interior. This is caused by the relatively high stiffness of the core compared to the perimeter which does not rest on the ground. This limits the amount of initial elastic shortening experienced by the interior of the tower relative to the perimeter. Figs. 9(b) and 9(c) then show how, over the life span of the building, there is a gradual reversal of this trend.

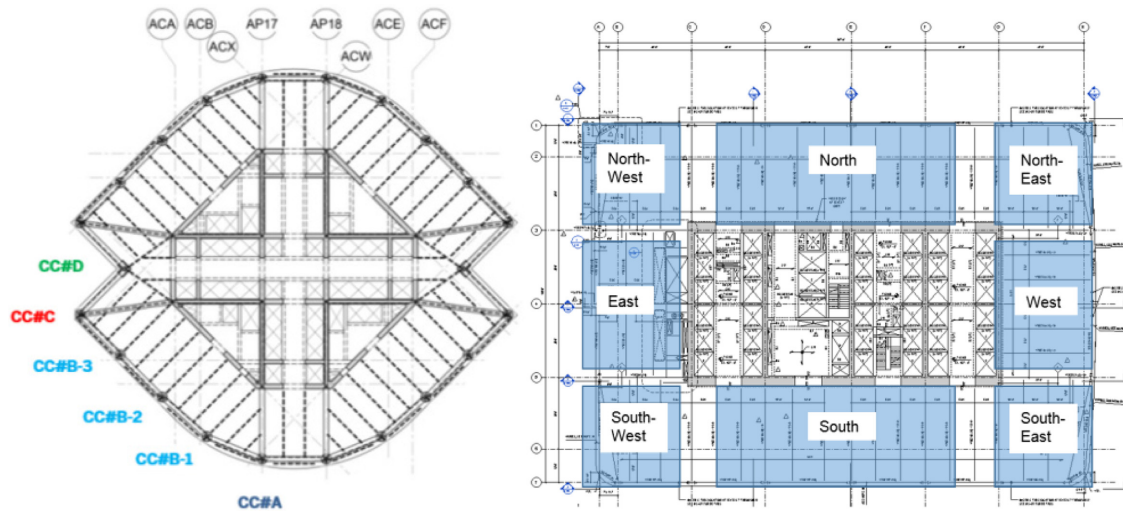


Figure 7. Key plan of PET and MWNT.

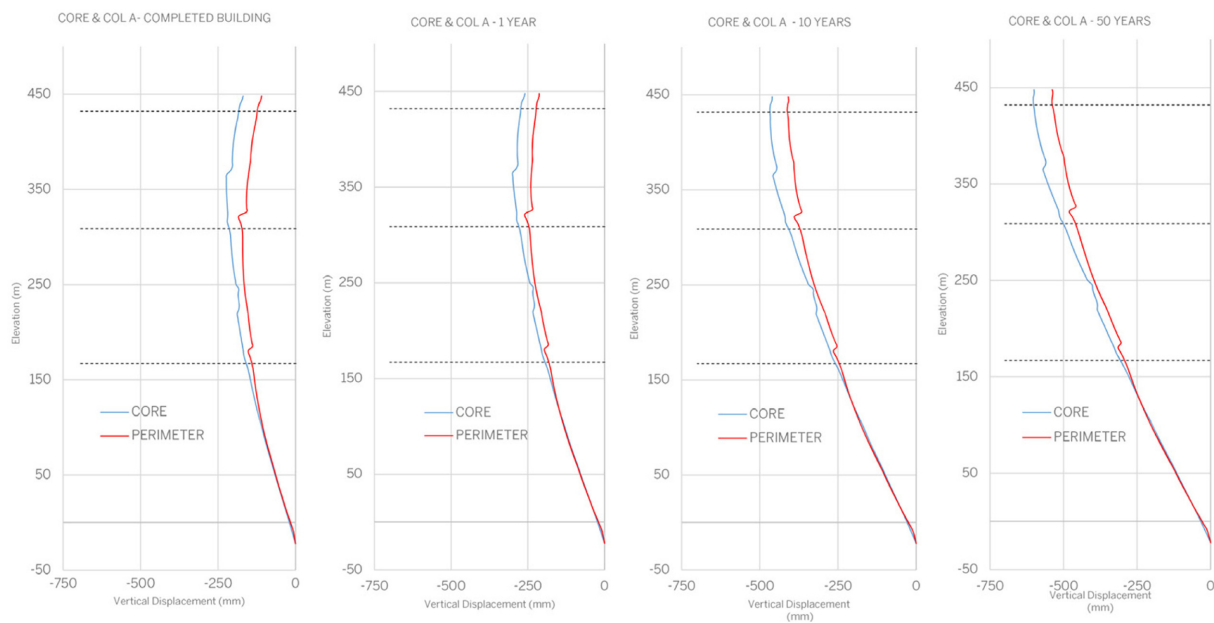


Figure 8. Vertical displacement for the core and perimeter of PET vs Elevation at (a) Building completion, (b) 1 year after completion, (c) 10 year after completion and (d) 50 years after completion.

This reversal is explained by the inherent difference in material behavior of the reinforced concrete core compared to the steel columns. Over time, the creep and shrinkage cause additional shortening of the interior core. These effects are not experienced by the steel perimeter columns, resulting in a more consistent deflection curve over time.

Figs. 9(a), 9(b), and 9(c) also share a spike in the relative displacements between the core and perimeter at the lowest level. This relative displacement at the base of the columns is a result of MWNT's structural system

where the perimeter columns rest on steel kickers. The kickers act as a spring support, translating their elastic deflection to the columns above.

3.2. Design & Construction - Limiting Effects of Creep & Shrinkage

Design and construction methods must be implemented to mitigate the effects of creep and shrinkage to ensure the building remains within the standards specified for strength and serviceability. These methods of mitigation depend directly on the structural system of a particular

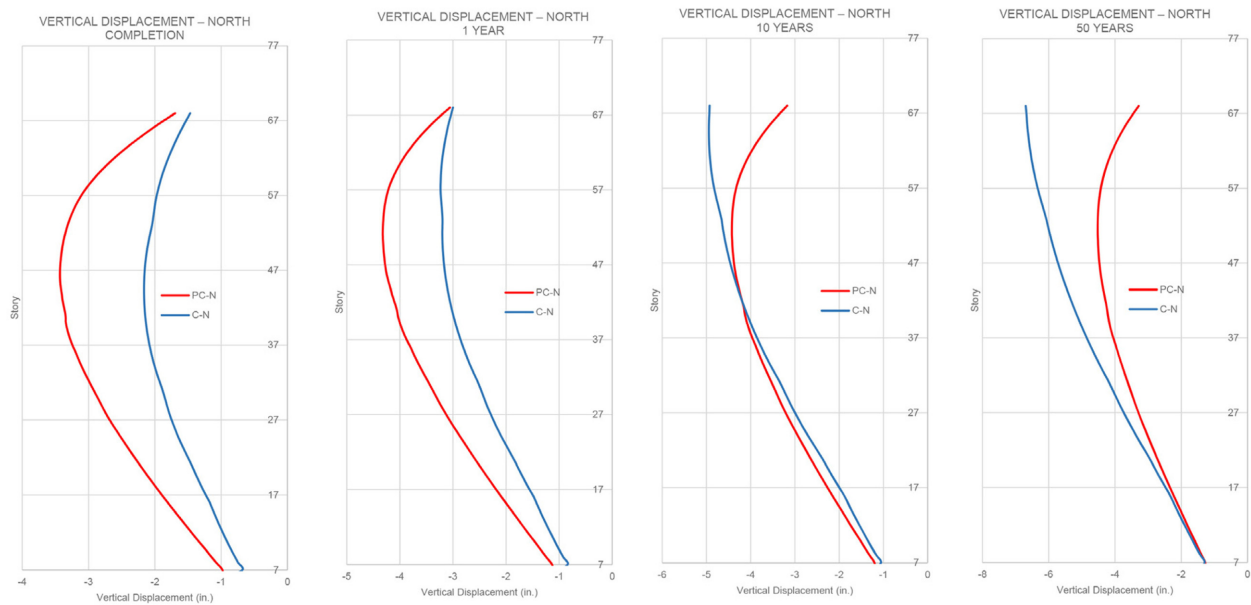


Figure 9. Vertical displacement for the core and perimeter of MWNT vs Elevation at (a) Building Completion, (b) 1 year after Completion, (c) 10 year after completion and (d) 50 years after completion.

tower.

3.2.1. Pertamina Energy Tower

The lateral system of PET is a dual system of three outriggers and a perimeter moment frame. Connecting the core to the perimeter frame at multiple levels results in significant axial forces in the outrigger trusses due to the large differences in vertical displacements between the core and perimeter, as can be seen in Fig. 8. To minimize the effect of this vertical displacement and to reduce axial stresses in the outrigger trusses, delaying the full connection of the diagonal members in the outrigger trusses to the perimeter frame until the tower is complete was investigated as well. Following this procedure allows the core to settle during the construction phase

independent of the perimeter columns. Fig. 10 illustrates the benefits of delayed connection of Outriggers.

It should be noted that the outriggers in PET were required for wind and seismic loads and serviceability, therefore the trusses would be installed as pinned with bolts left untightened to maintain the required stability and strength under wind and seismic forces during construction. It is estimated that delaying the connection of the outriggers until the building is complete reduces the axial force in the outrigger truss members by an average of 35%, Table 1 lists the percentage difference between axial forces in outrigger trusses if the truss connection is delayed or not. An example of a similar delayed outrigger construction in the constructed Zifeng Tower (formerly Nanjing Greenland Tower) is shown in

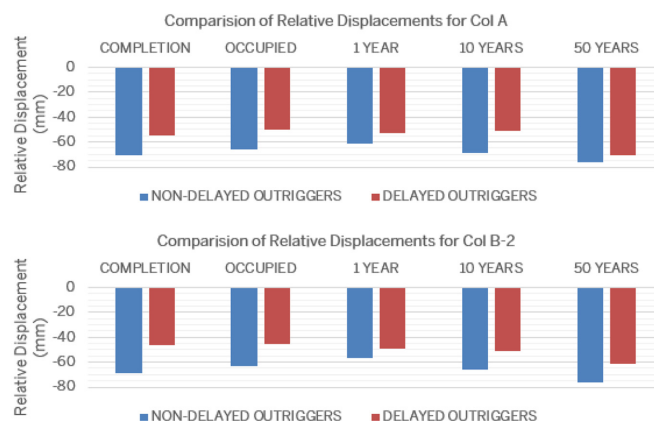


Figure 10. Relative displacement comparison for PET.

Table 1. Average percentage difference in outrigger members between non-delayed and delayed construction sequences

LEVEL	Percent Difference	
	Max (%)	Min (%)
Outrigger 1	-3%	-58%
Outrigger 2	40%	-37%
Outrigger 3	-17%	-53%

Fig. 11 (Besjak et al., 2010). Fig. 12 illustrates the proposed construction sequence for the outrigger trusses.

In addition to minimizing the axial forces in the outrigger trusses, the difference in vertical displacement between the core and perimeter required compensation during construction. This is achieved by prescribing over length values to the core, which are derived from the anticipated differential displacement at a time defined by designer, usually at the time of building occupation, such that at the time of complete floor deflection tolerances are within the required limits.

3.2.2. Manhattan West North Tower

To address the differential displacement highlighted in the non-linear staged construction analysis, vertical compensation is implemented. The vertical length of building elements are adjusted from their theoretical lengths to compensate for the combined effects of immediate elastic deflection and long-term shortening. During construction, both the concrete core and perimeter columns will experience elastic vertical deflection. Recall that, during and immediately after construction, the steel perimeter columns will experience greater elastic



Figure 11. Zifeng Tower (formerly Nanjing Greenland Tower) - Outrigger truss with bolts not tightened yet (Besjak et al., 2010).

deflection than the interior core due to the relatively low stiffness of the column transfer kickers. It is important to note that the concrete core has a level of vertical compensation inherently built in through its means of construction. Each story the core is typically poured to its theoretical elevation, compensating for any elastic shortening that occurs below. This method of construction means that the differential displacement must be addressed using vertical compensation of the steel perimeter via a schedule of column over-lengths. Since in the long run the concrete core will shorten more

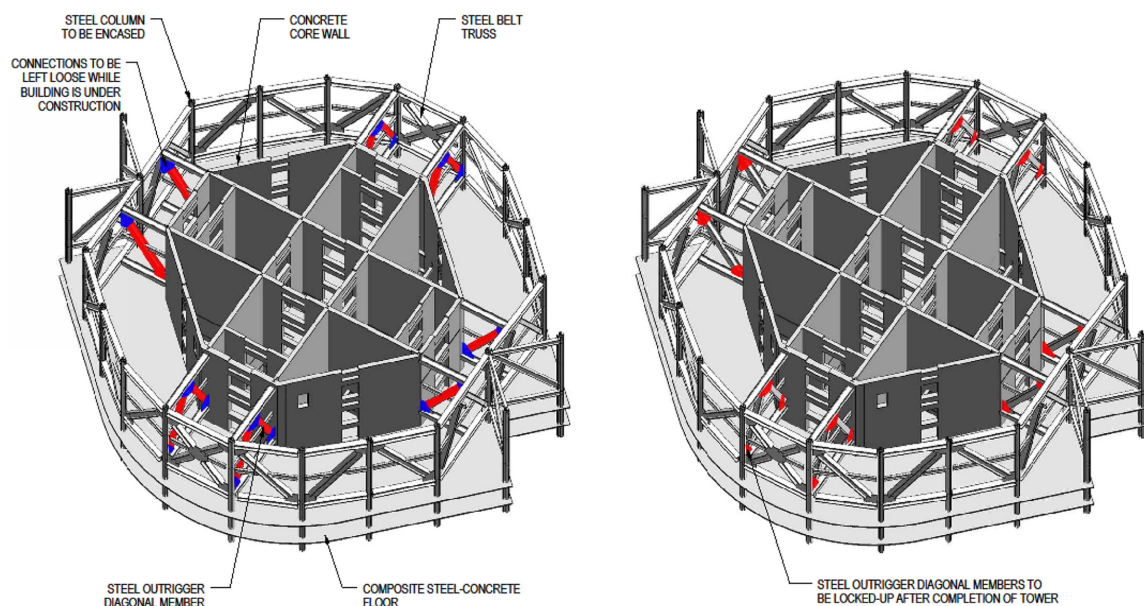


Figure 12. PET construction sequence for delayed outriggers.

than the steel perimeter columns, it is not accurate to derive the column over-lengths based only on their elastic shortening. If over-length values are defined based on elastic shortening only, a high differential displacement exists at the end of the creep and shrinkage cycle, skewed towards a higher perimeter. A result of this differential is a reduction in slab thickness towards the perimeter. This occurs because not all loads responsible for the columns elastic shortening are applied at the time the slab is poured. Similarly, it is not accurate to derive over-lengths based only on the differential displacements at the end of the building life-span. This approach results in the perimeter being lower than the core during construction and the early stages of the building life-span, resulting in an increase in slab thickness towards the perimeter. For these reasons MWNT implements a combination of the two approaches. Over-lengths are defined by establishing the elastic displacement and adjusting this value based on the long term shortening of the core. It is beneficial to round these values down in order to bias any necessary adjustments in the field towards shimming of perimeter columns as opposed to grinding, in the event of deviations from the theoretical results.

The elastic shortening of the kickers is addressed by overbuilding the kickers during erection above their theoretical elevation; Fig. 13 shows the construction in progress on MWNT. This causes some variations in slab thickness between the core and perimeter at the lowest level, since the vertical load responsible for the elastic shortening of the kickers is not present at the time this slab is poured. Another impact of the kicker shortening necessary to consider is the impact on the glass curtain wall façade spanning from the ground level up to level 4.

It is crucial to ensure that vertical stresses are not transferred from the kickers to the façade system. This is accomplished by using a vertically slotted connection (vertical roller) between the façade and the steel framing. Again, the staged construction analysis is used to establish the kicker displacement at the time of façade installation, as well as over the life-span of the tower in order to ensure that no vertical stresses are transferred.

4. Comparison of Building Results

The Creep and shrinkage behavior of two differing structural systems has been presented, the results of which highlight that long-term phenomena need to be carefully considered during all stages the of design and construction of tall buildings. The two buildings exhibit significantly different behavior. The displacements of PET exhibit distinct spikes for the perimeter columns, whilst the plots for MWNT are smooth curves. These spikes were due to the rigid connection of the outriggers to the core and significant transitions of the geometry of the core. Another clear distinction is how the behaviors of the systems change over time; the relative displacements between the core and perimeter for PET remain relatively static over time due to the outrigger connection.

Additionally, both towers required some form of compensation during construction to account for differential displacement between the core and the perimeter. This was achieved by constructing certain elements high: the core in the case of PET and the perimeter steel columns in the case of MWNT.

For both MWNT and PET, vertical compensation is established by first defining a target date at which

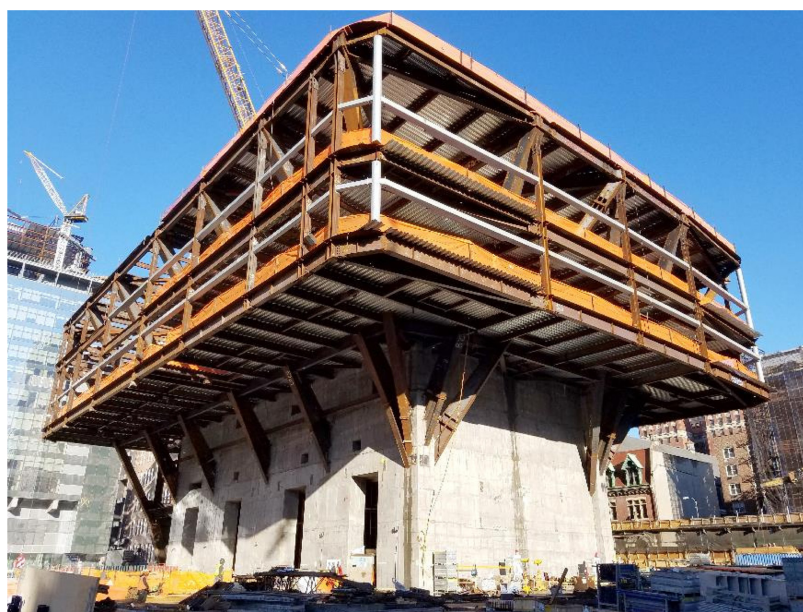


Figure 13. MWNT Construction in progress.

levelness is to be achieved. This decision must be informed by the creep coefficient and shrinkage strain curves. These curves, along with the analysis techniques described, establish the duration over which creep & shrinkage influence tower behavior. However, these curves historically have been based on empirical data taken from long term testing on a 1 ft³ sample of concrete. Recent studies have indicated that larger samples of concrete have longer durations of shrinkage, meaning the traditional equations overestimate the speed at which large concrete elements shrink. Therefore in supertall towers with relatively thick concrete elements, the theoretical shrinkage established from traditional analysis techniques overestimates the long-term vertical displacement. For this reason, the target time of levelness for MWNT was taken to be 5 years, as the majority of displacement due to creep occurs within this period.

In addition to floor levelness, these long-term analysis inform the design of the building façade systems. In the case of MWNT, these results highlight the need for and defined the magnitude of a vertical slotted connection at the top of the lobby glass curtain wall. This detail ensures that no stresses are transferred to the lobby glass façade system at any point during the life-span of the building. Similarly, these analysis techniques established that PET required a uniform stack joint at each floor of the tower.

5. Conclusion

This paper investigates the effects of creep and shrinkage on two different structural systems with differing heights. By analyzing the behavior of these supertall towers, and applying the results to the design decisions and construction sequencing, it is possible to minimize the impact of differential displacement between the core and perimeter. The investigation offers a compelling insight into how the effects of creep and shrinkage can differ significantly depending on the structural system and material utilized, as well as the height of the tower, and presented practical and cost-effective solutions.

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