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Authors:	John Peronto, Thornton Tomasetti Robert Sinn, Thornton Tomasetti Matthew Huizinga, Thornton Tomasetti
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Vertical Shortening Considerations in the 1 km Tall Jeddah Tower

John Peronto†, Robert Sinn, and Matthew Huizinga

Thornton Tomasetti, Inc., 330 N. Wabash Avenue, Suite 1500, Chicago, IL 60611

Abstract

Jeddah Tower will be the first man-made structure to reach a kilometer in height upon its completion in 2019. From conception, it was clear that an all-concrete superstructure would present many advantages for a building of such unprecedented height and slenderness. An all-concrete structure, however, did present many challenges that needed to be addressed in the system arrangement and through comprehensive analysis and design, among them vertical shortening effects due to the time-dependent creep and shrinkage of concrete. This paper outlines and presents the engineering solutions developed by the authors regarding this complex concrete material phenomenon, while addressing the construction and regional challenges associated with realizing a concrete tower of this unprecedented scale.

Keywords: Ultratall, High-rise, Creep and shrinkage, Vertical shortening

1. Introduction

The origin of the Jeddah Tower project was the aspiration of HRH Prince Alwaleed bin Talal to construct the tallest building in the world, which would serve as a symbol for the country and for the world in Jeddah, Saudi Arabia. Jeddah Tower is a catalyst and also the anchor to future regional development in the northern portion of Jeddah. Thornton Tomasetti (TT) was a partner in the Adrian Smith + Gordon Gill Architecture team during the project's competition phase, who were awarded the project in 2009 (Sinn, 2016).

2. Structural System Overview

The reinforced concrete bearing wall system of Jeddah Tower was developed to maximize concrete material efficiency for the resistance of the large lateral load demands that a one-kilometer tall tower requires. By nature of this system, every piece of concrete in the tower is utilized in resisting both vertical gravity and lateral (wind and seismic) loads. The overall slenderness of the tower's form (12:1 - *height:width*) demanded this level of structural engagement. Fig. 2.0.1 provides an illustration of Jeddah Tower's structural system.

Sinn (2016) provides a detailed overview of the structural analysis and design performed in the development of the structural system of Jeddah Tower. The principal components and their corresponding wall thicknesses of

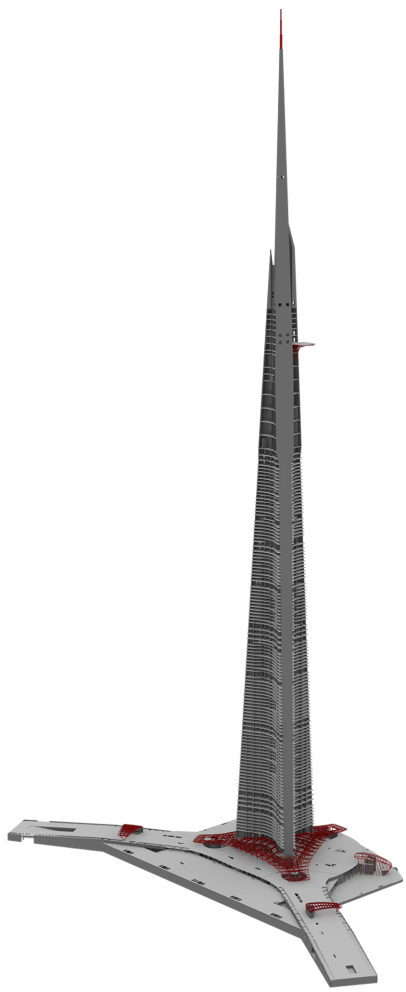

Figure 2.0.1. Structural Revit Model of Jeddah Tower.

†Corresponding author: John Peronto
Tel: +1-312-596-2000; Fax: +1-312-596-2001
E-mail: JPeronto@ThorntonTomasetti.com

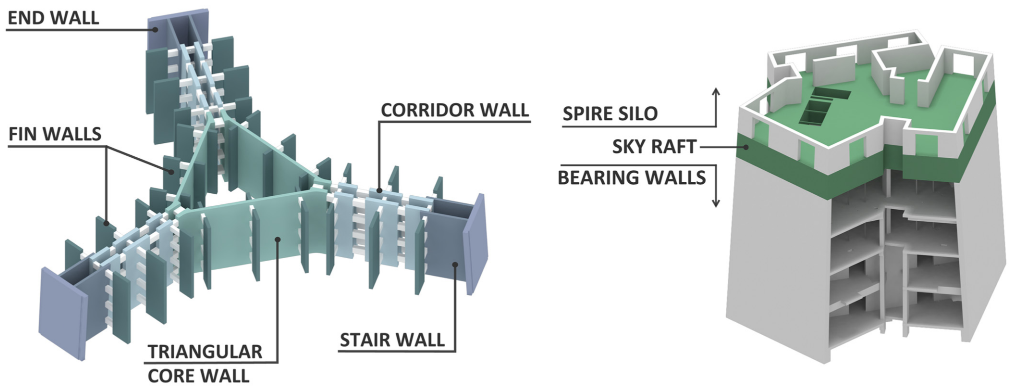

Figure 2.0.2. Structural System Components.

the bearing structural system are as follows (see Fig. 2.0.2);

- Triangular Core Walls (800 mm to 600 mm)
- Corridor Walls (1000 mm to 600 mm)
- Fin Walls (800 mm to 600 mm)
- Stair Walls (1000 mm to 600 mm)
- End Walls (1200 mm to 600 mm)
- Spire Silo Walls (600 mm Typical)

Each of the wall components of the structural system are fully linked over the tower height at each level through a network of coupling beams. These "links" provide the collective engagement of each concrete wall element, which further optimizes the structure's resistance to lateral load and also helps to mitigate long-term vertical shortening differential movements between adjacent wall elements.

The vertical simplicity of the structural form allows for highly formable and repetitive construction. No vertical elements of the bearing wall system are transferred over the tower height and no outrigger walls are present in the system. Fig. 2.0.3 provides a site photo of the jump-form system utilized on the project at the start wall construction.

Figure 2.0.3. Jump-Form System.

3. Key Challenges in Evaluation of Vertical Shortening Effects

Extreme height is the main challenge for Jeddah Tower in the mitigation of the effect of vertical shortening. An ideal situation would be a bearing wall system that is designed/sized to have a constant compressive stress due to vertical gravity loads, such that each level would have a constant shortening due to the effects of elastic compressive stress, creep strain of concrete, and shrinkage strain of concrete. This implies that the more floors (or height) a tower has the more cumulative vertical shortening occurs and has to be accommodated in the design, planning of floor levelness, and construction compensation methodology.

The extreme height of the tower necessitated the use of high strength concrete in all vertical elements of the structure. Characterization of the time-dependent creep and shrinkage effects in high-strength concrete was a challenge that had to be overcome through a comprehensive High Strength Concrete Testing Program.

With the fully interconnected structural system, the prediction of load redistribution, in addition to deformations of the frame, was considered an important aspect to be comprehensively explored utilizing three-dimensional analysis methods.

The final key challenge was analyzing the combined effects of vertical shortening with the planned construction sequence of the tower superstructure, given the redundancy and three dimensional nature of the structural system.

4. High-strength Concrete

The highest strength concrete available in the region, with locally available coarse aggregate, was utilized for Jeddah Tower both to minimize the self-weight and maximize the overall modulus of elasticity (stiffness) of

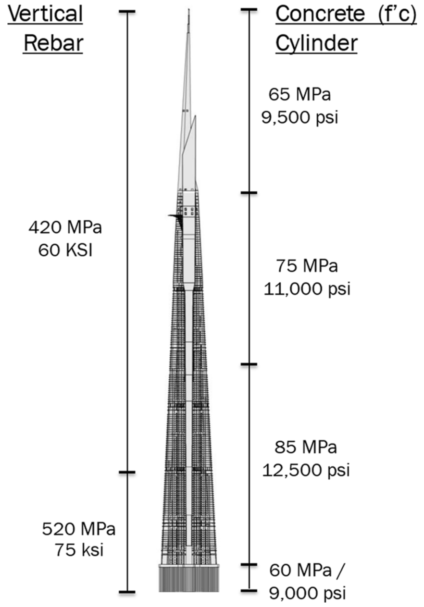

Figure 4.0.1. High-Strength Concrete in Tower Superstructure.

Figure 4.1.1. CTL Group Creep and Shrinkage Test Samples.

the concrete superstructure. Concrete cylinder compressive strength of the vertical elements ranged from 85 MPa (at 90 days) to 65 MPa (at 56 days) over the tower height, and flatwork utilized 40 MPa compressive strength (at 28 days). Fig. 4.0.1 provides an overview of the high-strength concrete and reinforcing materials utilized on the superstructure.

4.1. High-strength Concrete Testing Program

A detailed High Strength Concrete Testing Program was developed by Thornton Tomasetti to evaluate high-strength concrete mix designs prior to and during construction. This testing program focused on the following critical properties of a proposed high strength concrete mix design.

- Concrete cylinder compressive strength maturity
- Average static modulus of elasticity
- Predicted creep and shrinkage strains
- Heat of hydration
- Flowability and Pumpability

Concrete testing was performed both off site in Skokie, Illinois, USA at the CTL Group, and in Jeddah, KSA at Material Testing Laboratory (MTL), and on site by the contractor Saudi Binladen Group (SBG). Concrete testing conducted by CTL Group was of particular interest, as CTL Group conducted the controlled experiments to evaluate the predicted creep and shrinkage strains of the tower wall concrete mix designs. The CTL Group conducted creep and shrinkage cylinder tests in accordance ASTM C512 (2010) for both sealed and unsealed samples, reinforced and unreinforced, at different ages of initial loading, and at different levels of loading to fully characterize creep and shrinkage behavior of a particular mix design. These tests have been conducted for 2+ years in CTL Group's laboratory (see Fig. 4.1.1).

Concrete material testing by MTL and SBG on site is ongoing and being continuously utilized to verify that installed concrete has the appropriate design strength and average static modulus of elasticity specified by TT.

4.2. Concrete Material Models

During the design phase of the project, prior to the engagement of CTL Group, TT utilized both the GL2000 (Gardner, 2001) and B3 (Bažant, 2000) models for the preliminary estimation of creep and shrinkage concrete properties. Until a preliminary mix design was provided, the GL2000 model was solely utilized. Both of these methods are recommended state-of-the-art concrete models in ACI 209.2R (2008). However, as these material models were developed for unreinforced concrete, corrections to the predicted creep and shrinkage curves were made through modifying the predicted creep and shrinkage strains proportional to the area of concrete and steel rebar.

4.3. Modulus of Elasticity Correction

Modulus of elasticity is a function of the mean concrete strength varying with time. The assumed mean concrete strength is a function of the design concrete strength. The cross section is assumed to undergo uniform deformations, therefore assuming strain compatibility. We can estimate how much stress is in the concrete versus the steel reinforcing by setting the strains equal:

$$\varepsilon_{conc} = \varepsilon_{steel}$$

Given the condition of equal strain total stiffness of a given element can be described as the sum of the concrete stiffness and the steel stiffness:

$$K_e = K_{eStl} + K_{eConc}$$

The concrete and steel stiffness are defined as:

$$K_{eStl} = \frac{\rho \times A_g \times E_s}{L}$$

$$K_{eConc} = \frac{(1-\rho) \times A_g \times E_c}{L}$$

where:
ρ = Concrete Reinforcement Ratio
A_g = Gross Concrete Area
E_s = Modulus of Elasticity of Steel
E_c = Modulus of Elasticity of Concrete
L = Element Length

Substituting individual stiffness into the total elastic stiffness and simplifying,

$$K_e = \frac{A_g}{L}(\rho \times E_s + (1-\rho) \times E_c)$$

The value within the parentheses can be utilized as the adjusted modulus of elasticity including the effect of the steel reinforcing.

$$E_{EQ} = \rho \times E_s + (1-\rho) \times E_c$$

This adjusted modulus of elasticity will vary as a function of reinforcement ratio, and with time.

4.4. Shrinkage Correction

Concrete shrinkage is a function of time, relative humidity, cement type, concrete strength and volume-to-surface ratio. The process as defined by GL2000 is used to calculate an ultimate shrinkage based on strength and cement type. The ultimate shrinkage is modified by two functions; one for relative humidity effects, and one for time and volume to surface ratio. These functions are multiplied by the ultimate creep shown below:

$$\varepsilon_{sh}(t, t_c) = \varepsilon_{shu} \times \beta_h \times \beta_s(t, t_c)$$

where:
ε_{sh} = Shrinkage Strain
ε_{shu} = Ultimate Shrinkage Strain
β_h = Correction Term for Humidity
β_s = Correction Term for the Time of Drying

Additionally, the concrete shrinkage equation shown above is defined as a function of t, and t_c; where t is the time of interest, and t_c is the start of drying. In relation to construction, t_c is the age at which the forms are assumed to be stripped from the walls.

Basic concrete shrinkage curves should be adjusted to account for steel reinforcing. Because modulus of elasticity is not a factor in shrinkage calculations, adjustment may be applied directly to the strain.

$$\varepsilon_{sh\_cf}(t, t_c, \rho) = \sum_{i=t_c+2}^{t} ((\varepsilon_{sh}(i, t_c) - \varepsilon_{sh}(i-1, t_c)) \times R_{cf}(\rho, i)) + \varepsilon_{sh}(t_c+1, t_c) \times R_{cf}(\rho, t_c)$$

where:
ε_{sh_cf} = Shrinkage Strain with Strain Correction for Reinforcement
R_{cf} = Reinforcement Correction Factor

4.5. Creep Correction

Concrete creep due to sustained loads is a function of time, loading, modulus, and volume to surface ratio. GL2000 breaks total creep into two distinct portions: drying creep, and basic creep. The creep functions are defined in terms of time (t), the time of initial loading (t_o), and the start of drying (t_c). The total creep strain can be calculated as the ratio of the 28-day creep coefficient to the modulus of elasticity, per ACI 209.

$$\varepsilon_{cr} = \frac{\varphi_{28}}{E_c}$$

Three techniques were evaluated for incorporation of reinforcement into creep strains. The first technique utilizes the adjusted modulus when performing the above referenced creep calculation. The adjusted modulus is utilized to reduce the amount of creep predicted. The modulus is calculated at 28-days in this technique.

$$\varepsilon_{cr\_cE28}(t, t_c, \rho) = \frac{\varphi_{28}(t, t_o, t_c, \rho)}{E_{EQ}(28)}$$

where:
ε_{cr} = Creep Strain
ε_{cr_cE28} = Creep Strain with Adjusted 28-day Modulus for Reinforcement
φ_{28} = 28-day Creep Coefficient
$E_{EQ}(28)$ = Adjusted 28-day Modulus for Reinforcement

The second technique is similar to the above process, except that the modulus is variable with time. This technique predicts slightly higher creep strains during the initial 28 days and slightly lower creep strains for time after 28 days. The following creep strain equation outlines this technique.

$$\varepsilon_{cr\_cE}(t, t_c, \rho) = \frac{\varphi_{28}(t, t_o, t_c, \rho)}{E_{EQ}(t)}$$

where:

ε_{cr_cE} = Creep Strain with Adjusted Modulus for Reinforcement

$E_{EQ}(t)$ = Adjusted Modulus for Reinforcement at time, t

The third technique is to modify the predicted strains directly in a manner similar to shrinkage.

$$\varepsilon_{cr\_cf}(t,t_o,t_c,\rho)=\sum_{i=t_o+2}^{t}((\varepsilon_{cr}(i,t_o,t_c)-\varepsilon_{cr}(i-1,t_o,t_c))\times R_{cf}(\rho,i))+\varepsilon_{cr}(t_o+1,t_o,t_c)\times R_{cf}(\rho,t_o)$$

where:

ε_{cr_cf} = Creep Strain with Strain Correction for Reinforcement

5. Construction Sequencing and Schedule

The initial construction sequence for the tower superstructure considered the following three components in the process;

Step 1: Pour tower central triangular core walls
Step 2: Pour tower wing walls (3 thus)
Step 3: Pour tower flatwork (slabs)

It was assumed that an average 5-story lead would exist between Step 1 and Step 2 in the process. Initial concrete pour cycle times provided by SBG during the design phase assumed 5 to 7 days per story near the base of the tower, and reducing to 4 to 5 days near the upper portion of the tower. As construction commenced on site, modest deviations to this sequence occurred, which is to be expected on large scale projects of such complexity. Fig. 5.0.1 provides an illustration of the wing wall and core wall groups.

6. Vertical Shortening Finite Element Analysis Model

In order to analyze the three dimensional time dependent behavior of the highly-linked Jeddah Tower superstructure, the Midas Gen and Strand7 software platforms were employed to conduct a vertical shortening analysis. Midas Gen served as the main finite element analysis (FEA) platform, due to its ability to input user-defined creep and shrinkage time-dependent material curves directly. Strand7 was utilized initially as a verification software platform due to its much greater complexity in assigning time-dependent material properties to a stage construction analysis model.

Rebar-adjusted creep, shrinkage, and modulus curves were input and assigned to appropriate wall segments in the FEA models. For creep and shrinkage curves, these were further subdivided into model material types with different volume-to-surface ratios and different age at loading for creep. Fig. 6.0.1 provides an illustration of the Midas Gen FEA model.

In addition to the time-dependent material properties, structural members are grouped and assembled in the FEA model into stages that match the assumed construction sequence of the tower. These groups are then organized

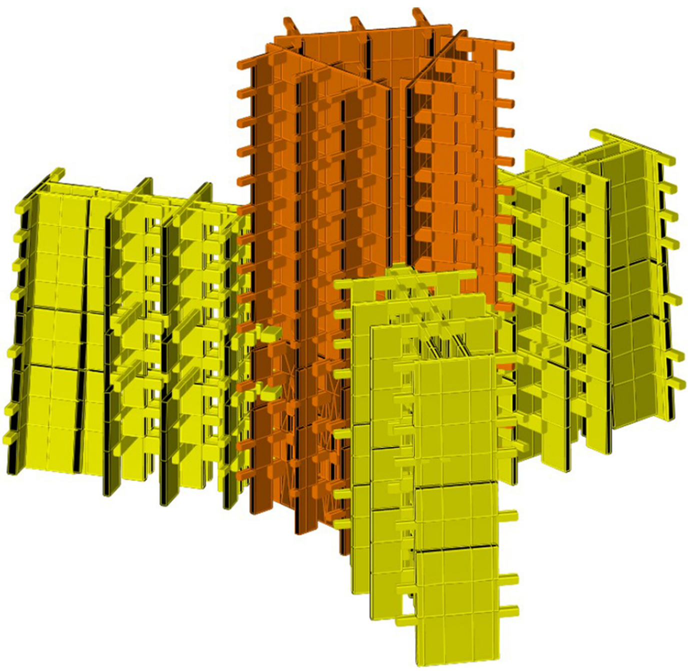

Figure 5.0.1. Wing and Core Wall Groups.

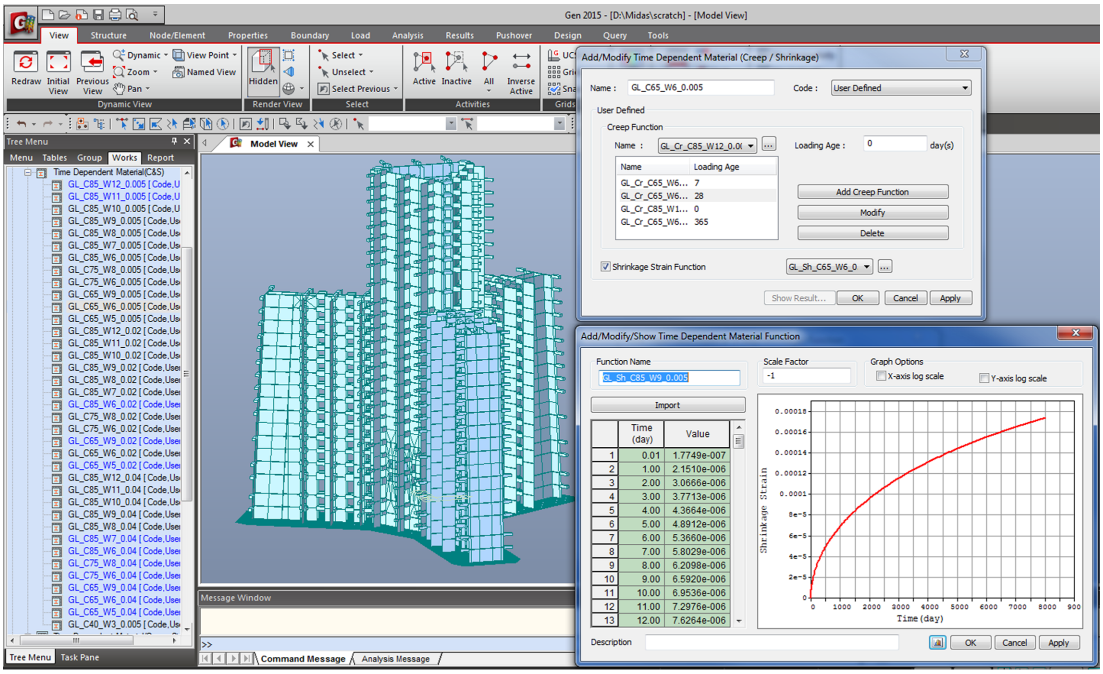

Figure 6.0.1. Midas Gen Vertical Shortening FEA Model.

into construction staged analysis load cases that correspond to the assumed construction schedule. Fig. 6.0.2 provides an illustration of the different construction stages present in the FEA model.

The comprehensive 3-dimensional vertical shortening FEA model has the capability to provide predictions for member force development or deformation extent at any point in the structure and at any point in time. Fig. 6.0.3 provides as illustration of coupling beam shear and moment over time. It can be observed from this plot that creep and shrinkage effects, in conjunction with the construction sequence, can cause coupling beam loads to either increase

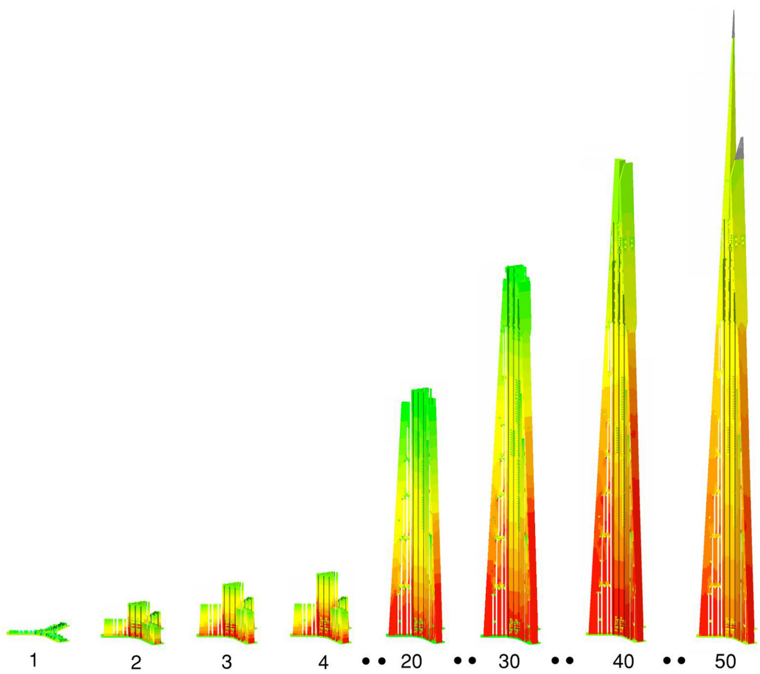

Figure 6.0.2. Midas Gen FEA Model Construction Stages.

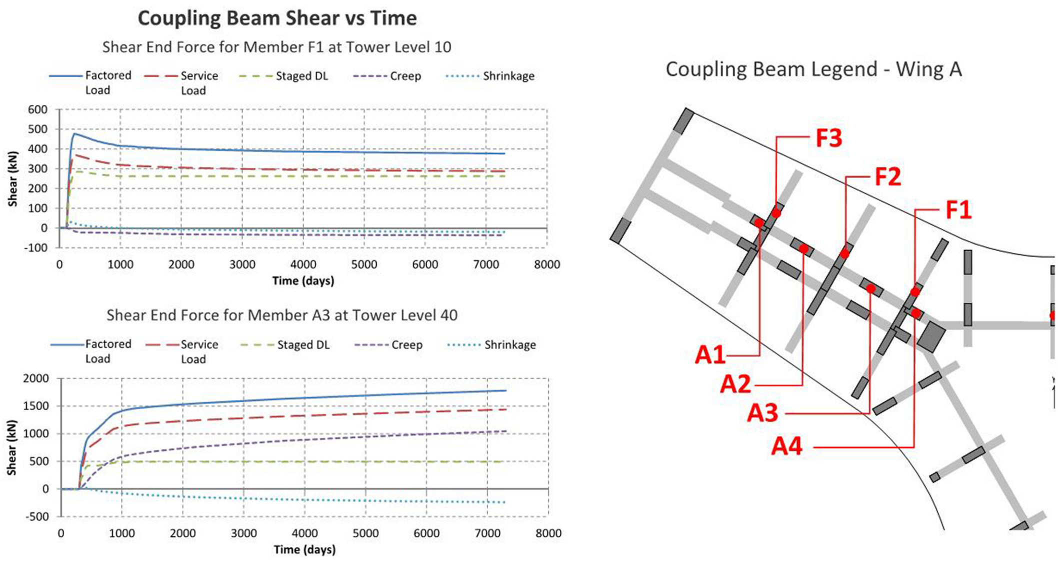

Figure 6.0.3. Coupling Beam Load vs. Time Examples.

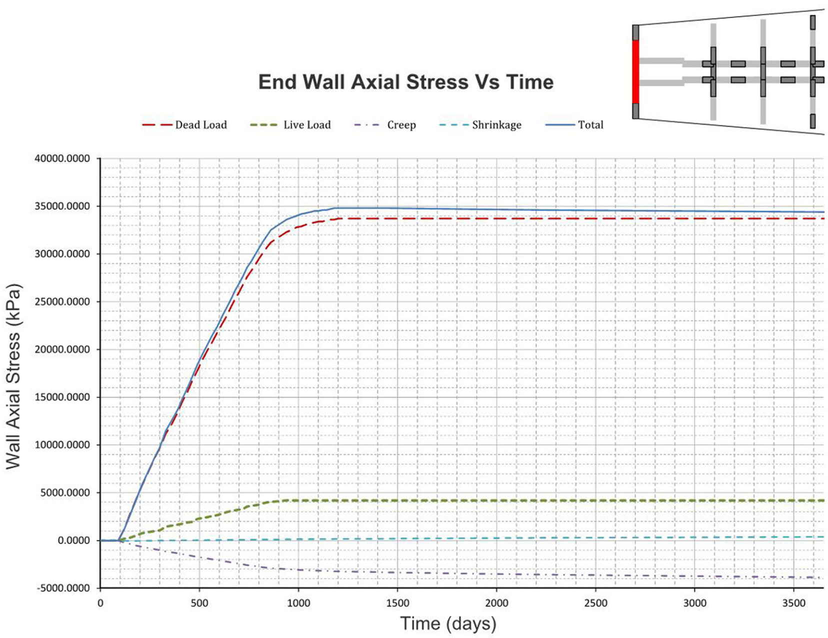

Figure 6.0.4. End Wall Axial Load vs. Time.

in a standard fashion or can reduce over time due to gradual load distribution.

Similarly, near the base of the tower critical End Wall elements of the structure directly above the raft experience a strain relaxation (load reduction) over time due to the effects of creep and shrinkage. Fig. 6.0.4 provides an illustration of this end wall load reduction.

In addition to load evaluation of wall and coupling beams, the FEA model is utilized to predict the vertical and horizontal movements of the tower over time. The following are the critical movements extracted from the analyses over time.

- Vertical shortening of the Triangular Core Walls
- Vertical shortening of each Wing Wall
- Horizontal movement of tower “plan center”

These vertical movements over time are utilized to determine the vertical camber of the core walls to ensure that at the time the wing walls are formed and poured, the

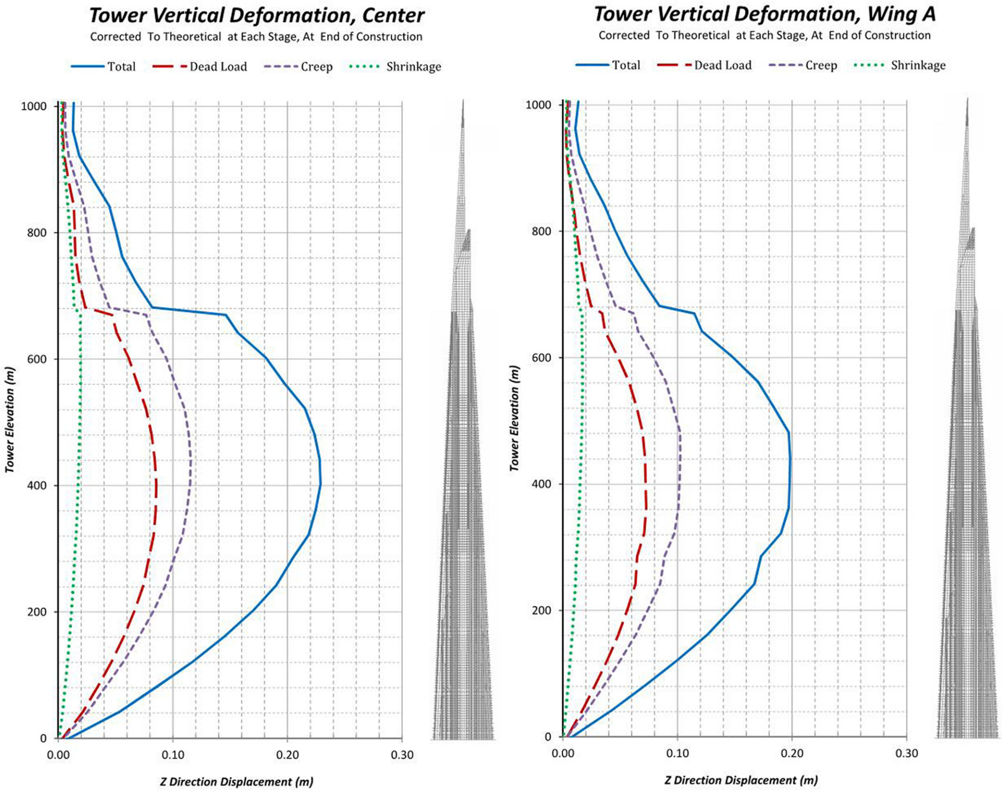

Figure 6.0.5. Wing Wall and Core Wall Vertical Shortening at the End of Construction.

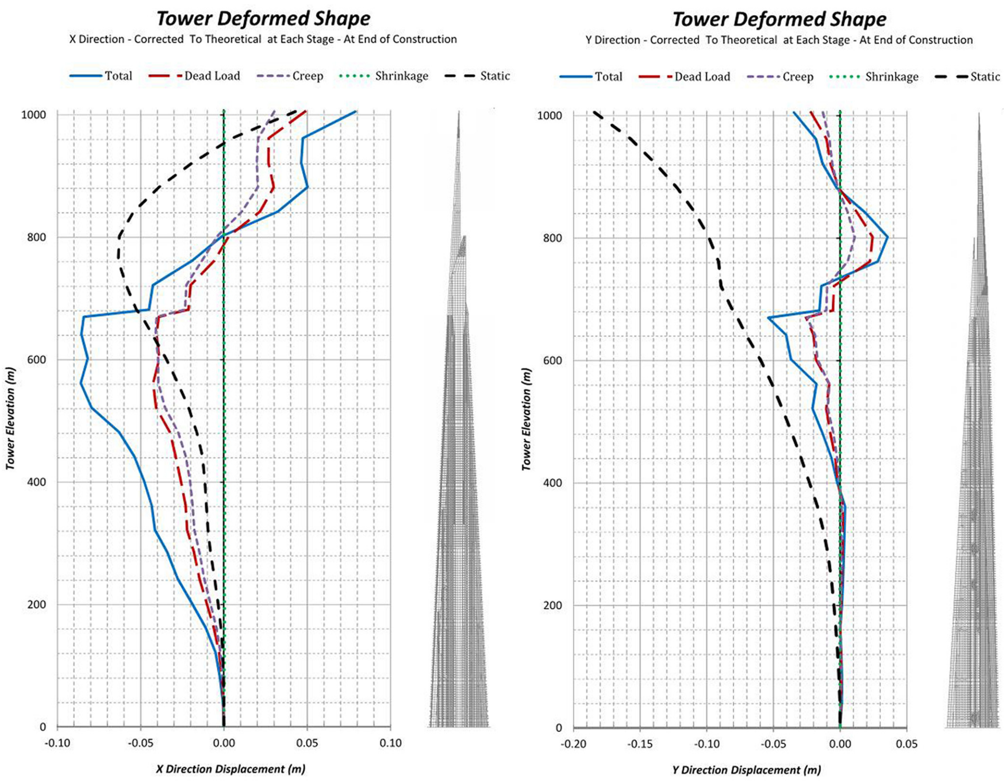

Figure 6.0.6. Tower Horizontal Movement at the End of Construction.

core walls are elevationally at or very near theoretical elevation of the connecting wing wall. The horizontal movements of the tower are also utilized to inform the contractor of the predicted lateral movements anticipated during construction in order to plan for formwork re-centering as the triangular core walls are being poured. Fig. 6.0.5 provides the vertical shortening of the tower wing and core walls at the end of construction. Fig. 6.0.6 provides the horizontal movements of the tower at the end of construction assuming plan re-centering of the triangular core throughout construction.

7. Material Model Calibration

As described in Gardner (2001) a linear regression method for long duration creep and shrinkage extrapolation based on short duration test data has been developed (Bažant and Zebich, 1983). As creep and shrinkage test data was received from CTL laboratories, this method was utilized to update the time-dependent material curves for both creep and shrinkage that are then re-input into the vertical shortening FEA model. Fig. 7.0.1 illustrates typical creep and shrinkage curves updated utilizing CTL

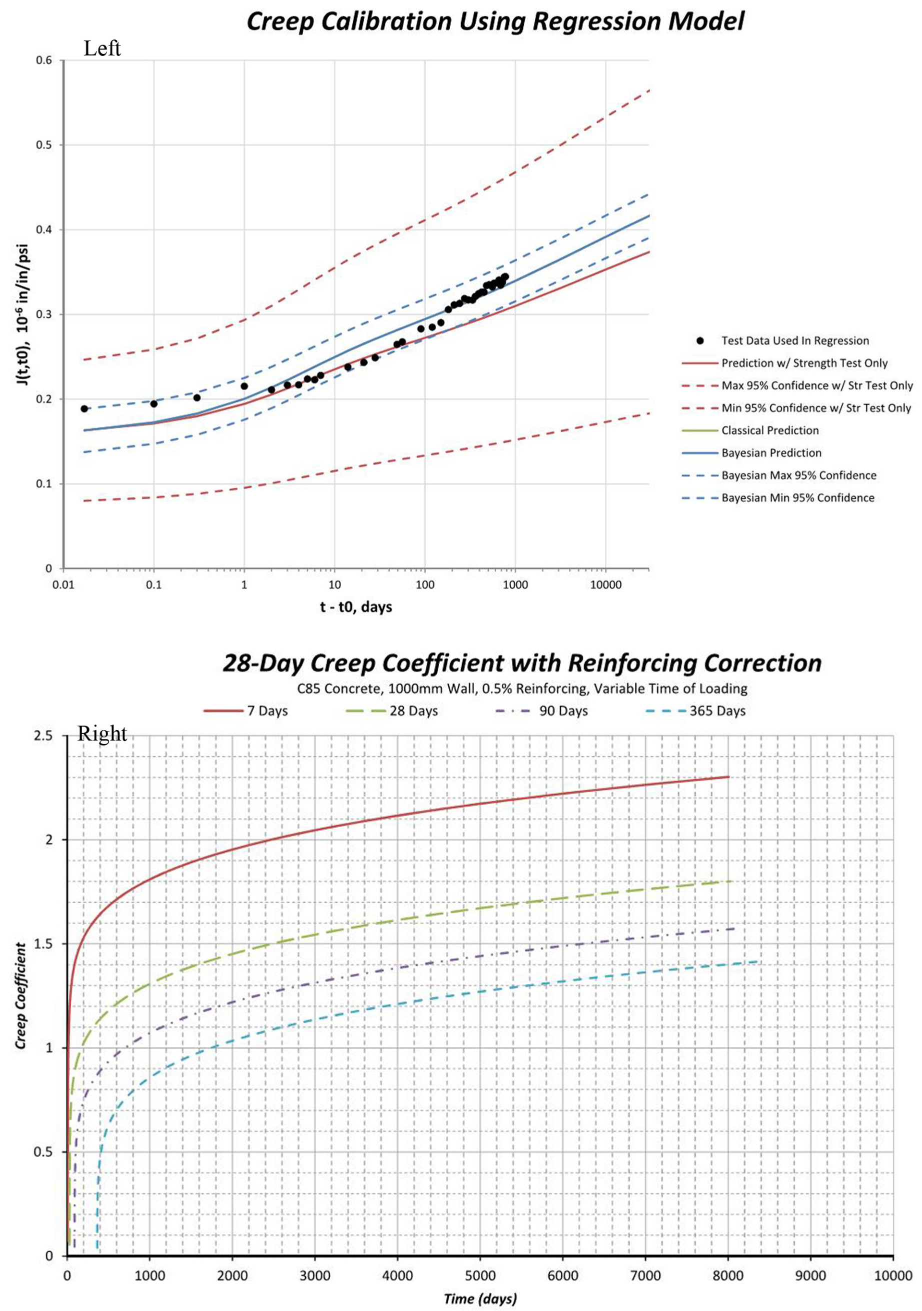

Figure 7.0.1. Example Calibrated Creep and Shrinkage Curves.

Figure 8.0.1. Current Site Photo.

test data.

8. Construction Guidelines, Compensation and Reanalysis

Utilizing the findings of the vertical shortening analysis, Thornton Tomasetti informed the contractor of the anticipated tower behavior during construction. These predictions were outlined in a series of Construction Guidelines in the Construction Documents that included the following.

- Required High-Strength Concrete Preconstruction and Onsite Construction Testing
- Required Construction Surveying and Monitoring of the Structure
- Assumed Construction Sequence and Schedule
- Anticipated Tower Movements
- Recommended Wall Camber and Horizontal Plan Correction

Onsite and during construction of the walls, the contractor has been continuously collecting cylinder samples to evaluate and confirm material conformance of the concrete with the design requirements outlined in the Construction Documents. This not only includes compressive strength testing programs to evaluate the strength maturity of the as-placed concrete, but also average static modulus of elasticity testing programs to ensure the concrete is meeting the required stiffness. This data is then regularly reported back to Thornton Tomasetti for evaluation. Similar to the inclusion of the Creep and Shrinkage test data from CTL, this onsite strength and modulus of elasticity data is included in updated vertical shortening analyses and construction recommendations moving forward.

As-built and continuous onsite surveying is conducted by the contractor and also reported back to Thornton Tomasetti. This elevational and horizontal positional data is utilized to determine if the tower is moving as predicted, as well as providing data that corresponds to the actual as-built construction schedule. This onsite survey data, along with regularly provided construction schedule updates, are also included with concrete material updates in vertical shortening analysis updates performed by Thornton Tomasetti periodically throughout construction.

An updated vertical shortening analysis has been conducted on an annual basis by Thornton Tomasetti to regularly confirm the tower behavior and provide the contractor refined movement predictions with updated wall compensation recommendations. Fig. 8.0.1 provides a current site photograph of the tower under construction.

Current construction progress of the structural walls has reached 200 m in height above the raft foundation. The authors intend to provide details of the vertical shortening predictions and construction-phase results as the work progresses. Structural topping-out for the Tower is scheduled for the end of 2019.

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