Simulation Analysis and Application of Super High-rise Tower Construction Process

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Abstract. Wenzhou Lucheng Square Phase IV project, whose main tower reaching 378.8m high, belongs to the super high-rise building structure. Considering the influence of shrinkage and creep characteristics of concrete on vertical deformation differences of components, Midas Gen was used to simulate and analyze the whole construction process of the main tower. The analysis results of different working conditions are compared, the rationality of the construction scheme is checked and a general conclusion is drawn.

1. Introduction
With the advancement of urbanization, super high-rise buildings in China develop rapidly. However, in recent years, in the context of "carbon peak and neutrality", considering the overall spatial form of the city, the actual economic demand and other factors, the super high-rise buildings in China have changed from "height competition" in the past to be adapted to green and low-carbon model, promoting the healthy development of the city. Compared with the past "seeking higher and more", the number and height of super high-rise projects approved are significantly reduced. Now more attention is focused on the participation and contribution of engineering in quality, safety and healthy development. Under this plan, Wenzhou Lucheng Square project is born accordingly.

Focusing on the construction process, the construction of the main tower of the project is taken as an example. The vertical members are mainly shaped steel concrete, so that the effect of shrinkage and creep of concrete on the vertical deformation of structural members must be taken into consideration. The accumulation of displacement difference caused by vertical deformation of components will disrupt the existing construction organization, and even cause rework or other serious losses, resulting in the waste of resources and energy, which is contrary to the strategic goal. Therefore, the whole construction process of the main tower is simulated and analyzed in advance, the vertical deformation results are compared, the construction organization is adjusted and corresponding measures are formulated, so as to reduce adverse effects, ensure the overall quality and safety of the project and green economy.

2. Project Profile
Wenzhou Lucheng Square project phase III and Phase IV are super high-rise commercial complex. The fourth phase of the project is a super high-rise building (including office, property hotel, hotel, etc.), with a land area of about 14,372 square meters and a construction area of about 261,948 square meters. There are 79 floors above ground and a construction area of about 181,000 square meters. There are 3 floors underground and 4 floors underground in some areas, with a construction area of
The structure type is steel structure and core tube reinforced concrete shear wall structure.

3. Analysis Summary and Construction Process
Since most of the connecting beams of the inner cylinder and outer frame of this project are hinged, the vertical deformation has little effect on the stress and deformation of the hinged beams. However, it has a certain impact on the rigid beam and outrigger truss connecting the inner cylinder and the outer frame giant columns, as well as the floor between the inner cylinder and the outer frame. In addition, the vertical deformation difference may also affect the later equipment installation.

Proper construction sequence should be considered in order to minimize the additional force of the components caused by the vertical deformation difference, and the vertical deformation difference of the vertical components of each floor should be predicted, so as to set reasonable construction reservation for the installation of equipment during construction.

Construction sequence: core tube shear wall construction first. After the core tube construction to a certain stage, construct the giant columns of the outer frame. After the construction of the giant columns of the outer frame to a certain height, construct the sub-frame and the beams and slabs between the inner cylinder and the outer frame. When the main structure is constructed to the outrigger truss layer, the outrigger truss shall be placed and positioned first, and welding shall be carried out after the main structure is completed.

4. Analysis Method and Calculation Parameters

4.1. Analysis Method
The software MIDAS/GEN was used to simulate and analyze the construction phases. The calculation model is a whole model. During the analysis of a construction step, the program will passivate and disable all components after the construction step and the later load conditions that need to be loaded. Only the components completed before this step are allowed to participate in the calculation, so that the dynamic process of construction can be truly simulated. The calculation model is completely established in accordance with the structural drawings, and the sections and materials of all components are consistent with the drawings.

4.2. Construction Parameters
The calculation of load mainly considers the self-weight of the structure, the dead load of the floor, the live load of construction, the adhesion force of the tower cranes and the gravity of the construction platform. The creep, shrinkage and strength of concrete with time and the effect of temperature loading should also be taken into consideration. The dead load of the floor is the self-weight of the floor, and the construction live load is 2.0kN/㎡. The construction procedure of tower core tube and frame structure is shown in table 1.
Table 1. Construction procedure of tower core tube and frame structure.

| Construction procedure | Core tube (floor) | Outer frame of core tube (floor) | Number of layers between the inner and outer core tubes (layers) |
|-------------------------|-------------------|---------------------------------|---------------------------------------------------------------|
| Stage 1                 | 1-4               | 0                               | 4                                                             |
| Stage 2                 | 5-8               | 0                               | 8                                                             |
| Stage 3                 | 9-12              | 1-4                             | 8                                                             |
| Stage 4                 | 13-16             | 5-8                             | 8                                                             |
| Stage 5                 | 17-20             | 9-12                            | 8                                                             |
| Stage 6                 | 21-24             | 13-16                           | 8                                                             |
| Stage 7                 | 25-28             | 17-20                           | 8                                                             |
| Stage 8                 | 29-32             | 21-24                           | 8                                                             |
| Stage 9                 | 33-36             | 25-28                           | 8                                                             |
| Stage 10                | 37-40             | 29-32                           | 8                                                             |
| Stage 11                | 41-44             | 33-36                           | 8                                                             |
| Stage 12                | 45-48             | 37-40                           | 8                                                             |
| Stage 13                | 49-52             | 41-44                           | 8                                                             |
| Stage 14                | 53-56             | 45-48                           | 8                                                             |
| Stage 15                | 57-60             | 49-52                           | 8                                                             |
| Stage 16                | 61-64             | 53-56                           | 8                                                             |
| Stage 17                | 65-69             | 57-60                           | 9                                                             |
| Stage 18                | 70-74             | 61-64                           | 10                                                            |
| Stage 19                | 75-79             | 65-69                           | 10                                                            |
| Stage 20                | Engine Room Floors| 70-74                           | 7                                                             |
| Stage 21                |                   | 75-79                           | 2                                                             |
| Stage 22                | Steel Roof        | Steel Roof                      | 0                                                             |
| Stage 23                | Welding of Outrigger Trusses | Welding of Outrigger Trusses | |

4.3. Material Parameters
In the simulation analysis of the construction process, the European standard CEB-FIP (2010) was selected. The time-varying properties of materials are considered, including the development and change of concrete strength with age, and the shrinkage and creep of concrete during construction. For parameters in the model under standard CEB-FIP (2010), the annual average relative humidity of the environment is 70%, the cement type is standard cement N,R:0.25, and the age of concrete at the beginning of shrinkage and creep calculation is 3 days. The curves of shrinkage, creep and compressive strength development over time of C60 concrete under this model are shown in figure 1.

(a) C60 creep coefficient curve of concrete
4.4. Vertical Compression Deformation Analysis Point Selection

Extract the vertical compression deformation of 4 key corner points of core tube and 4 columns after the completion of structural construction. See figure 2 for the location of extraction points.

Figure 1. C60 Concrete material time-varying characteristics.

(b) C60 concrete shrinkage strain curve

(c) C60 concrete compressive strength curve with time

Figure 2. Schematic diagram about extracting position of vertical elastic shrinkage deformation of four corners of core tube and giant columns.
5. Calculation Results and Analysis

5.1. Construction Process Simulation

On the basis of table 1, four calculation results of maximum combined stress of outer steel frame, maximum vertical displacement of giant columns of outer frame, maximum vertical displacement of core tube and overall vertical displacement of structure are added for each construction step. In this way, the simulation analysis results of the whole construction process can be shown in table 2. As there are many contour plots, the results of stage 1, 4, 8, 16 and 23 are taken as examples here. The contour plots of the above four data items are shown in figure 3 to figure 7.

Table 2. Simulation analysis results of the whole construction process.

| Construction procedure | Core tube (floor) | Outer frame of core tube (floor) | Maximum combined stress of outer steel frame (MPa) | Maximum vertical displacement of giant columns of outer frame (mm) | Maximum vertical displacement of core tube (mm) | Overall vertical displacement of structure (mm) |
|------------------------|------------------|---------------------------------|-----------------------------------------------|-------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Stage 1                | 1-4              | 0                               | -                          | -0.5                                           | -2.0                                          | -24.6                                         |
| Stage 2                | 5-8              | 0                               | -                          | -1.4                                           |                                               |                                               |
| Stage 3                | 9-12             | 1-4                             | -96.3                        | -0.5                                           | -2.0                                          | -24.6                                         |
| Stage 4                | 13-16            | 5-8                             | -96.4                        | -0.9                                           | -2.9                                          | -24.9                                         |
| Stage 5                | 17-20            | 9-12                            | -96.5                        | -1.5                                           | -4.0                                          | -25.1                                         |
| Stage 6                | 21-24            | 13-16                           | -96.8                        | -2.3                                           | -5.6                                          | -25.4                                         |
| Stage 7                | 25-28            | 17-20                           | -97.1                        | -3.0                                           | -7.1                                          | -25.6                                         |
| Stage 8                | 29-32            | 21-24                           | -97.5                        | -3.9                                           | -8.5                                          | -25.9                                         |
| Stage 9                | 33-36            | 25-28                           | -97.8                        | -4.6                                           | -9.9                                          | -26.1                                         |
| Stage 10               | 37-40            | 29-32                           | -98.2                        | -5.5                                           | -11.6                                         | -26.4                                         |
| Stage 11               | 41-44            | 33-36                           | -98.5                        | -6.5                                           | -12.9                                         | -26.7                                         |
| Stage 12               | 45-48            | 37-40                           | -98.7                        | -7.9                                           | -14.6                                         | -26.9                                         |
| Stage 13               | 49-52            | 41-44                           | -99.0                        | -9.1                                           | -16.2                                         | -27.1                                         |
| Stage 14               | 53-56            | 45-48                           | -99.2                        | -10.4                                          | -17.7                                         | -27.3                                         |
| Stage 15               | 57-60            | 49-52                           | -99.4                        | -11.7                                          | -19.4                                         | -27.5                                         |
| Stage 16               | 61-64            | 53-56                           | -99.6                        | -13.0                                          | -21.0                                         | -27.6                                         |
| Stage 17               | 65-69            | 57-60                           | -99.8                        | -14.6                                          | -23.6                                         | -27.8                                         |
| Stage 18               | 70-74            | 61-64                           | -100.0                       | -15.8                                          | -26.1                                         | -28.0                                         |
| Stage 19               | 75-79            | 65-69                           | -100.1                       | -17.8                                          | -29.0                                         | -29.6                                         |
| Stage 20               | 70-74            | 70-74                           | -100.3                       | -19.4                                          | -31.4                                         | -31.4                                         |
| Stage 21               | 75-79            | 75-79                           | -101.7                       | -21.0                                          | -33.2                                         | -34.9                                         |
| Stage 22               | 104.5            | 21.6                            | -35.0                        | -90.3                                          |                                               |                                               |
| Stage 23               | -104.8           | -21.8                           | -35.5                        | -91.2                                          |                                               |                                               |


Figure 3. Maximum vertical displacement of core tube in Stage 1.

(a) Maximum vertical displacement of core tube. 
(b) Maximum vertical displacement of giant columns of outer frame.

(c) Maximum combined stress of outer steel frame. 
(d) Overall vertical displacement of structure.

Figure 4. Analysis results in Stage 4.
Figure 5. Analysis results in Stage 4.
(a) Maximum vertical displacement of core tube.  
(b) Maximum vertical displacement of giant columns of outer frame.  
(c) Maximum combined stress of outer steel frame.  
(d) Overall vertical displacement of structure.

**Figure 6.** Analysis results in Stage 4.
5.2. Analysis of Vertical Compression Deformation of Structure Core Tube and Huge Columns of Outer Frame

The vertical compression deformation of core tube and outer frame columns on each floor is shown in table 3. It can be seen from the table that the maximum vertical compression deformation of core tube and outer frame columns is 19.81mm and 32.99mm respectively after the construction. The maximum vertical compression deformation difference between the core tube and the outer frame columns is 13.18mm, which occurs in the middle of the structure.

Table 3. Vertical compression deformation of core tube and frame columns.

| Floor | Outer frame columns | Core tube | Compression deformation difference between outer frame columns and core tube |
|-------|---------------------|-----------|----------------------------------------------------------------------------|
| 1     | 0.00                | 0.00      | 0.00                                                                       |

Figure 7. Analysis results in Stage 4.
|   |     |     |     |
|---|-----|-----|-----|
| 2 | 2.63| 3.43| 0.80|
| 3 | 3.83| 5.06| 1.23|
| 4 | 4.87| 6.54| 1.67|
| 5 | 5.75| 8.00| 2.25|
| 6 | 6.20| 8.72| 2.52|
| 7 | 7.04|10.17| 3.13|
| 8 | 7.86|11.58| 3.72|
| 9 | 8.67|12.95| 4.28|
|10 | 8.87|13.52| 4.64|
|11 | 9.65|14.89| 5.24|
|12 |10.40|16.24| 5.84|
|13 |11.14|17.58| 6.44|
|14 |11.06|17.72| 6.66|
|15 |11.77|18.91| 7.14|
|16 |12.47|20.10| 7.63|
|17 |13.14|21.28| 8.15|
|18 |12.84|20.94| 8.10|
|19 |13.49|22.13| 8.64|
|20 |14.13|23.28| 9.15|
|21 |14.75|24.39| 9.63|
|22 |14.41|23.63| 9.22|
|23 |15.01|24.71| 9.70|
|24 |15.60|25.75|10.15|
|25 |16.18|26.74|10.57|
|26 |15.65|25.59| 9.94|
|27 |16.25|26.60|10.35|
|28 |16.85|27.61|10.76|
|29 |17.43|28.60|11.18|
|30 |16.74|27.29|10.55|
|31 |17.30|28.27|10.97|
|32 |17.84|29.21|11.36|
|33 |18.37|30.11|11.74|
|34 |17.44|28.40|10.97|
|35 |17.94|29.29|11.35|
|36 |18.44|30.17|11.73|
|37 |18.92|31.05|12.13|
|38 |17.80|29.22|11.42|
|39 |18.47|30.50|12.04|
|40 |19.36|32.15|12.79|
|41 |19.81|32.99|13.18|
|42 |17.42|29.74|12.32|
|43 |17.84|30.60|12.76|
|44 |18.25|31.43|13.19|
|45 |18.64|32.26|13.62|
|46 |16.79|29.49|12.71|
|47 |17.15|30.56|13.40|
|48 |17.51|31.47|13.97|
|49 |18.03|32.36|14.32|
|50 |16.23|28.89|12.66|
|     |     |     |     |
|-----|-----|-----|-----|
| 51  | 16.73 | 29.69 | 12.97 |
| 52  | 17.20 | 30.46 | 13.26 |
| 53  | 17.66 | 31.24 | 13.57 |
| 54  | 15.94 | 27.73 | 11.79 |
| 55  | 16.37 | 28.58 | 12.21 |
| 56  | 16.78 | 29.36 | 12.58 |
| 57  | 17.18 | 30.09 | 12.91 |
| 58  | 15.15 | 26.37 | 11.22 |
| 59  | 15.51 | 27.10 | 11.59 |
| 60  | 15.81 | 27.96 | 12.15 |
| 61  | 16.41 | 28.73 | 12.32 |
| 62  | 13.81 | 25.54 | 11.74 |
| 63  | 14.36 | 26.25 | 11.89 |
| 64  | 14.90 | 26.90 | 12.01 |
| 65  | 15.41 | 27.56 | 12.16 |
| 66  | 13.28 | 23.94 | 10.66 |
| 67  | 13.75 | 24.72 | 10.97 |
| 68  | 14.20 | 25.51 | 11.30 |
| 69  | 14.74 | 26.47 | 11.73 |
| 70  | 15.17 | 27.24 | 12.07 |
| 71  | 10.91 | 22.16 | 11.25 |
| 72  | 11.24 | 22.64 | 11.40 |
| 73  | 11.55 | 23.08 | 11.53 |
| 74  | 11.83 | 23.48 | 11.65 |
| 75  | 12.09 | 23.84 | 11.75 |
| 76  | 8.12  | 19.20 | 11.08 |
| 77  | 8.35  | 19.53 | 11.19 |
| 78  | 8.56  | 19.83 | 11.27 |
| 79  | 8.74  | 20.09 | 11.34 |
| Engine room floor 1 | 8.93  | 20.35 | 11.42 |
| Engine room floor 2 | 4.86  | 14.66 | 9.81 |
| Steel roof          | 5.07  | 14.83 | 9.76 |

The relationship between floor height and vertical deformation after considering construction leveling is shown in figure 8, and the relationship between floor height and vertical deformation difference is shown in figure 8 and figure 9.

**Figure 8.** The relationship between floor height and vertical deformation.  
**Figure 9.** The relationship between floor height and vertical deformation difference.
6. Conclusion
As the construction process progresses, the construction step increases, the floor increases, and the four parameters mentioned above (maximum combined stress of outer steel frame, maximum vertical displacement of giant columns of outer frame, maximum vertical displacement of core tube and overall vertical displacement of structure) gradually increase, the maximum displacement is about 35.5mm, which occurs in the middle of the whole building. It is consistent with the theoretical experience and meets the requirements of the code.

Considering construction leveling, the vertical compression deformation difference between core tube and outer frame columns is small. In general, the vertical compression deformation of the outer frame columns is smaller than that of the core tube.

By using reasonable construction sequence, the vertical compression deformation difference between the core tube and the outer frame giant columns can be leveled, the error between the floor and the original elevation can be reduced, and the relative value of the vertical deformation difference between the inner tube and the outer frame can be minimized.

In addition to the core tube, super high-rise structures are mostly steel structures and steel structures. With the construction of shear wall, the embedded parts should be positioned and installed in advance. Construction leveling can avoid or reduce the internal stress caused by installation errors and displacements on both sides of the steel structure.

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