Construction Process Monitoring of CCTV Main Building Structure in China

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Abstract: The main building of CCTV (China Central Television) new site project consists of two leaning towers, which are linked together at the top via a large cantilever link element. During construction of the tower, it has the particularity in deformation of the structure and stress state of components, consequently, the safety control of the structure in the construction process is very important. The monitoring techniques and results are introduced, including the foundation settlement, the main structure stress, the structure deformation, and the cantilever deformation. The applications of monitoring and simulation analysis technologies in the construction process provide data support and guarantee the construction safety of the CCTV main building.

1. Introduction of Project

1.1 General

The main building of CCTV is comprised by two tower buildings, a skirt building and a base. There are three floors in the basement with one local interlayer. In total, the building area overground is 400000 square meters, the two towers are 51 and 44 floors respectively, both leaning 6° along the height in bi-direction, and linked by the fold-type cantilever with 14-floor-high\textsuperscript{[3]}. The position of the cantilever bottom is at the 37\textsuperscript{th} floor. The overhanging length of the cantilever from the main tower is 75m and 67m respectively. The bottom face of the cantilever is in the horizontal plane, the top face of the cantilever is in the same inclined plane with the top of the tower. The maximum height of the building is 234m. The skirt building with 9 floors links the two towers as a whole. The appearance of the architecture is shown in Fig.1 and the names of structure parts are presented in Fig. 2 (W: Cantilever; RF: Inclined roof; T: Tower 1; X: Tower 2; U: Skirt building).

![Figure 1. The building effect drawing.](image1)

![Figure 2. Display of parts of the building.](image2)
1.2 Foundation

The length of the foundation pit in north-south direction is 293m, and the width is 220m. The basement elevation under the tower is -21.0m ~ -27.4m, and -20.5m ~ -15.6m in the other areas. The piled raft foundation is arranged under the towers and at the locally extended area of the towers, the diameter of the bored pile is 1.2m. The mainly kinds of raft thickness are 4.5m, 6.0m, and 7.0m, while raft thickness reaches 13.9m in the area of elevator shaft. The raft thickness is 0.8m ~ 2.5m in the area outside the tower. The uplift piles with 0.6m diameter are set at the skirt building and base areas, piles with 0.8m diameter are set below the columns which carry heavy load in the local part of the skirt building area.

1.3 Construction of the Large Cantilever

It is the key point in constructing the large cantilever structure at high elevation of the CCTV building. The general construction scheme is briefly described as follows. Two separate towers were independently installed to the top firstly, and then two cantilever structures were extended outside from the tower by segment, and connected in the air consequently. After that, the rest components in the cantilever structures were set up, and a few delayed components were installed last.[1]

1.4 Particularities in the Deformation of Structure and the Stress State of Components

Compared with the traditional high-rise buildings, the deformation and stress states of the CCTV main building have its own characteristics: 1) There are discrepant compressive deformations on different columns at the same floor, 2) Under the gravity load, obvious transverse deformation is generated in the structure, 3) The vertical deformation of the large cantilever is remarkable, 4) Uneven settlement may happen at the foundation raft, 5) Some corner columns and many diagonal braces are in tension, 6) Many high stress concentration areas exist in the structure, 7) The bearing capacity of the structure is relatively weak before the closure of the cantilever.

2 Monitoring Techniques

2.1 Measuring Methods and Monitoring Points Arrangement

2.1.1 Control Network Establishment for Measuring Deformation

The arrangement of the control network for measuring deformation is shown in Fig. 3. K2~K5 are elevation reference points, GPA, GPB and GP1 are plane reference points, the leveling working reference points BM1~BM3 are set at one side of the foundation pit, plane observation points GP1~GP6 and Z1 around the foundation pit are made to form the plane surveying control network.

Figure 3. Arrangement of the reference points for measuring the deformations of the main structure.  
Figure 4. Distribution of the optical and hydrostatic level points for measuring the settlement of the basement.
2.1.2 Foundation Settlement Monitoring

Both optical and hydrostatic level measuring methods are used to monitor the foundation settlement. The hydrostatic level system, comprised by 19 hydrostatic level instruments, is set in the bottom floor of the basement. 70 monitoring points for optical level system are placed in the interlayer of the underground 3rd floor. Fig. 4 shows the arrangement of the raft monitoring points. The relative reference point for hydrostatic level is S15, and T10 correspondingly for optical level.

2.1.3 Component Stress Monitoring

Vibrating string strain gauges are used to measure the stresses in components, some monitoring points are checked by fiber grating strain gauges, the temperature compensation is considered in the measurement appropriately.

The components for stress monitoring mainly include the typical key components (columns, beams and braces), transfer trusses, the delayed installation components, the components concerned by designers and so on. Totally 211 monitoring points are installed on 78 tested components, and one temperature monitoring point is installed on each test section of the component.

The name of the stress monitoring point is represented as ‘floor number-installed component number-monitoring point number on the test section.’ The names of external frame columns in the tower and skirt buildings of CCTV are shown in Fig. 5.

![Figure 5. External frame columns of the tower and skirt building.](image1)

Figure 5. External frame columns of the tower and skirt building.

![Figure 6. Deformation monitoring points in the tower, skirt and cantilever.](image2)

Figure 6. Deformation monitoring points in the tower, skirt and cantilever.

2.1.4 Deformation Monitoring of the Main Structure

Two methods are used to measure the space deformation of the tower: direct measurement method by the total station instrument outside the building and step-by-step method inside the building.

The name of measuring point is represented as ‘floor number-measuring point number in the floor.’ skirt building and cantilever areas are demonstrated in Fig. 6. 300 step-by-step measuring points are placed inside the building. 140 prism measuring points, used for direct measuring with the total station instrument, are installed around the exterior surface of the building.
2.1.5 Special Monitoring for the Cantilever Deformation

There are 7 closure seems to be connected by horizontal components in the first step of cantilever closure, 5 seams are in the 37th floor, as shown in Fig. 7; the other 2 seams are placed in the 39th floor, and at the same place to that of No.1 and No.2 of the 37th floor in plane. In addition, the vertical deformation of the cantilever should be monitored specially, 32 elevation monitoring points are settled in the 37th floor.

![Figure 7. Cantilever closure seam of the 37th floor.](image)

![Figure 8. Measured curve of the foundation settlement recorded by the hydrostatic level monitoring points at the raft of T area.](image)

2.2 Monitoring Frequency

The time interval of measurement is that: the hydrostatic level instrument, 1 time at noon every day, and other foundation settlement monitoring points, 1 time every 2 weeks; for stress monitoring points, 1 time per week; for cantilever closure positions, 1 time per hour and continuing for 30 hours; the vertical settlement deformation of the large cantilever bottom, 2 times per week; the deformation monitoring points of external frame prism, 1 time per week, and the other deformation monitoring points, 1 time every 2 weeks.

3 Simulating Analysis Technologies of Construction Process

In order to understand and evaluate the reasonability of the monitoring data, the work of construction process simulating analysis of the main structure were synchronously put forward during the monitoring process, and the monitoring data was compared with the simulating analysis result, when the deformation or stress monitoring values is close to the design limits, or the monitoring results deviate from the simulating results obviously, it should be warning in time and the reason should be found out.

4 Monitoring Results

4.1 Foundation Settlement

The hydrostatic level monitoring result is represented by the relative deformation value with that of the point S15. The curve of the foundation settlement recorded by the hydrostatic level monitoring points is shown in Fig. 8; the variabilities of settlement recorded from all hydrostatic level monitoring points in different seasons are shown in Fig. 9; Fig. 10 shows the variabilities of settlement recorded from the optical level monitoring points around the line.
between the 2 towers’ centers in different seasons; the settlement curves recorded by the hydrostatic level monitoring point S7 and the optical level monitoring point X01 in the same plane place are compared, as shown in Fig.11; contour lines of the foundation settlement at two different periods are shown in Fig. 12.

Summary of the foundation settlement monitoring result:
1) The maximum value of settlement in the T and X area under the tower is -29.8 mm (at the point of T04) and -22.7 mm (at the point of X07) respectively, the inclination value of raft in the T and X areas is 1/3200 and 1/3300 respectively, both the settlement values and the raft inclination values meet the specification limits.
2) The distribution of foundation settlement is in accordance with the loading state of the foundation in the special building structure. In general, the settlement curve changes slowly, the foundation settlement values and its discrepancy values increase slightly faster during the construction process of the cantilever, the settlement becomes stable when the construction of the main structure has finished.
4.2 Space Deformation

According to the deformation monitoring results, the relationship between the deformation and time can be plotted to reflect the values and the variation trend of the deformation during the construction period. The vertical deformation curves of corner column T01 at different floors in the T area of the tower are shown in Fig. 13, where the maximum value of the vertical deformation appeared in the middle-upper position of the tower near the 28th~37th floors, because the vertical loads caused by the upper floors and the accumulated compression deformations of the vertical components in the lower floors are both relatively high. The vertical deformation curves of the 10th floor in the T area of the tower can be seen in Fig. 14.

The plane deformation curve of the measuring points of 4 corner columns at the 20th floor in the X area and the measuring points in the 24th floor in the T area by the step-by-step method, is demonstrated in Fig. 15 and Fig. 16, respectively. The measuring results show that the plane deformation of T area has the tendency to move to the southeast corner direction during the construction, while that of X area moves to the northwest corner direction. The deformation trend of T area and X area of the tower was in accordance with the inclination direction and the mechanics characteristics of the structure with large cantilever.

The measured and simulated vertical deformations of the corner column T03 in the 37th floor are compared in Fig. 17, and the measured and simulated plane deformations of T01 point at the 16th floor of the tower are compared in Fig. 18. There is no postfixes for the names of the measuring points, The postfixes of ‘C’ and ‘CT’ are added to the names of the simulated deformation curves without and with considering the temperature effect, respectively.
According to Fig. 17 and Fig. 18, it can be found that: 1) By considering the temperature effect, the simulated results can fit the measured results with higher precision, 2) The influence of the seasonal temperature changes on the vertical deformation for the high-rise building is obvious, but not on the result of the plane deformation, 3) Considering the influence of the foundation settlement and the seasonal temperature changes, the construction simulation results are in good coincidence with monitoring values.

4.3 Stress of Components

Fig. 19–24 are the monitored stress curves from the following components: the corner compression column C71 in the 2nd floor, the diagonal brace between the column C71 and column C72 in the 10th floor, the delayed component and its adjacent component, the closure and external frame components of the cantilever in the 31st floor, the frame beam between column C56 and column C57 in the 10th floor, and the diagonal web member of a truss.
Figure 22. Monitored stress curves of (a) the cantilever closure component No.1, (b) the cantilever external frame component A1.

Figure 23. Measured and simulated stress curves of the frame beam in the 10th floor.

Figure 24. Measured and simulated stress curves of the brace of a truss.

Until July, 2008, the statistical result on the maximum stress of the monitored components and the cantilever closure components is listed in Table 1 and Table 2, respectively.

Summary of the stress monitoring results:

1. The measuring stresses of the components show a similar regularity and good agreement with the simulated results.
2. The measuring results show that the welding installment can cause the additional welding stress in measured components. Thus, the component stress level higher than design expected value should be avoided by using reasonable installation and welding scheme to reduce the additional welding stress in the components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Type of stress</th>
<th>Maximum stress(MPa)</th>
<th>Tested component’s number</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam</td>
<td>compressive stress</td>
<td>-96.0</td>
<td>F37-C56-C121</td>
</tr>
<tr>
<td></td>
<td>tensile stress</td>
<td>71.9</td>
<td>F10-C56-C57</td>
</tr>
<tr>
<td>column</td>
<td>compressive stress</td>
<td>-129.8</td>
<td>F31-C55</td>
</tr>
<tr>
<td></td>
<td>tensile stress</td>
<td>90.0</td>
<td>F31-C56</td>
</tr>
<tr>
<td>diagonal brace</td>
<td>compressive stress</td>
<td>-136.4</td>
<td>F31-C71-C72</td>
</tr>
<tr>
<td></td>
<td>tensile stress</td>
<td>77.9</td>
<td>F39-C2-C3</td>
</tr>
<tr>
<td>diagonal web</td>
<td>compressive stress</td>
<td>-86.5</td>
<td>TR1B-E</td>
</tr>
<tr>
<td>member of truss</td>
<td>tensile stress</td>
<td>56.7</td>
<td>TR6-F37</td>
</tr>
</tbody>
</table>
Table 2. Statistic maximum stress of the cantilever closure components.

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>Name of measured components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H1</td>
</tr>
<tr>
<td>number of measured points</td>
<td>-1</td>
</tr>
<tr>
<td>-2</td>
<td>-108.6</td>
</tr>
<tr>
<td>-3</td>
<td>-74.2</td>
</tr>
<tr>
<td>-4</td>
<td>10.7</td>
</tr>
</tbody>
</table>

4.4 Special Monitoring of the Cantilever Deformation

4.4.1 The Closure Seam

Table 3 presents the statistic values of 5 closure seams. According to the monitoring results, the temperature difference in 24 hours per day was 7 ºC during the cantilever closure, while the change of temperature in 22:00~7:00 was usually controlled within 2 ºC. Thus, the good environment condition was the base for cantilever closing. Compared with average value, the maximum discrepancy of cantilever components in the longitudinal direction was 6.8 mm. Based on the monitoring results, the welding time of the closure components was determined at night of December 8, 2007. The 7 seams for cantilever closing were successfully constructed in one time.

Table 3. Statistic values at cantilever closure seams.

<table>
<thead>
<tr>
<th>Number</th>
<th>Monitoring time</th>
<th>Reference length D₀(mm)</th>
<th>Statistic value</th>
<th>T(℃)</th>
<th>Relative deformation X(mm)</th>
<th>Relative deformation Y(mm)</th>
<th>Length change (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>2007-12-5 12:55 ~ 2007-12-6 17:50</td>
<td>6620</td>
<td>Min.</td>
<td>-1.5</td>
<td>-6.0</td>
<td>8.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>3.5</td>
<td>5.0</td>
<td>16.0</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>0.3</td>
<td>-2.9</td>
<td>11.8</td>
<td>6.6</td>
</tr>
<tr>
<td>2#</td>
<td>2007-12-5 12:08 ~ 2007-12-6 17:43</td>
<td>4200</td>
<td>Min.</td>
<td>-0.5</td>
<td>-16.0</td>
<td>-8.0</td>
<td>-2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>2.0</td>
<td>-4.0</td>
<td>2.0</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>0.6</td>
<td>-7.4</td>
<td>-2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>3#</td>
<td>2007-12-5 13:15 ~ 2007-12-6 17:39</td>
<td>4280</td>
<td>Min.</td>
<td>-2.0</td>
<td>-14.0</td>
<td>-12.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>5.5</td>
<td>10.0</td>
<td>2.0</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>0.6</td>
<td>-5.0</td>
<td>-3.2</td>
<td>7.8</td>
</tr>
<tr>
<td>4#</td>
<td>2007-12-5 13:10 ~ 2007-12-6 17:51</td>
<td>4700</td>
<td>Min.</td>
<td>0.0</td>
<td>-8.0</td>
<td>-10.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>4.0</td>
<td>5.0</td>
<td>4.0</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>1.8</td>
<td>-4.4</td>
<td>-2.3</td>
<td>5.8</td>
</tr>
<tr>
<td>5#</td>
<td>2007-12-6 07:38 ~ 2007-12-6 17:45</td>
<td>4690</td>
<td>Min.</td>
<td>--</td>
<td>-12.0</td>
<td>0.0</td>
<td>-2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max.</td>
<td>--</td>
<td>8.0</td>
<td>11.0</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>--</td>
<td>-1.8</td>
<td>5.1</td>
<td>3.1</td>
</tr>
</tbody>
</table>

4.4.2 Vertical Deformation of the Bottom of the Cantilever

The relative vertical deformation curves from the measuring points of the outside bottom edge of the cantilever are shown in Fig. 25. The measured and simulated vertical deformation curves of TW09 and TW15 at the intersection points of bottom edges of the cantilever are shown in Fig. 26. From the figures, the development trend of vertical deformation was stable during the construction process, and became slow when the construction of the main building structure finished. The measured values are in good accordance with the simulated values.
5. Conclusion

Based on the project characteristics and the site situation of the CCTV main building structure, the targeted design scheme for construction process monitoring was made, and the suitable monitoring methods and instruments were used, according to the basic principles of applicability, validity and economy. By the effective organization and implementation, the 4 monitoring works of the foundation settlement, the main structure deformation, the structure stress, and the cantilever deformation were successfully accomplished. With the timely comparison of monitored and simulated results, the working state of the structure in construction process can be reflected objectively, it also provides the data support and guarantee for the safe construction of the project.

References

