Multi point monitoring method of prestressed tendon based on distributed sensors

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Abstract—This paper presents a multi-point strain monitoring method based on distributed sensors, which can monitor the multi-point stress of prestressed tendons in concrete. Firstly, the special sensor protection device is installed in the designated position of the component. Then, the sensor is placed in the device and attached to the monitored prestressing tendon. After concrete pouring, the device can form a closed space around the sensor to ensure that the sensor can freely expand and move in a small range when the prestressed tendon is tensioned. The proposed method is applied to the monitoring of the construction period and initial operation period of a large-span spatial structure, and the research results show that the method proposed in this paper can well realize the multi-point monitoring of the prestressed tendon strain in the concrete, and effectively solve the engineering problems; through the analysis of the long-term monitoring data, we can accurately grasp the influence of each construction condition on the structure stress, and clarify the actual stress state and long-term change trend of the structure. The obtained monitoring data play a positive role in guiding the construction of prestressed structure, and the construction safety can be objectively evaluated by analyzing the monitoring data.

1. Introduction
Prestressed concrete structure is a very important structural form in the field of civil engineering. It has the characteristics of good crack resistance and superior mechanical performance, and is widely used in the construction of various large-span structures. However, compared with ordinary reinforced concrete structures, the construction technology of prestressed concrete structures is complex and requires high construction quality. It is very important to ensure that the prestressed reinforcement meets the design tension requirements during construction. Moreover, the performance of prestressed concrete structure will be affected by material aging, overuse, environmental erosion, lack of maintenance and many other adverse factors and gradually deteriorated. Therefore, the safety of prestressed concrete structures in long-term service is also worthy of attention[1-4].

At present, the most effective measure to accurately grasp the service state of the structure is to carry out effective real-time monitoring of the structure[5-8]. It can effectively prevent disaster of engineering structure during construction period and service period. Nowadays, the structure service state monitoring is mainly based on the nondestructive testing technology of the sensor, through the analysis of the structure stress state and response characteristics, to achieve the purpose of controlling the structure safety state and development trend[9-11]. Many large engineering structures under construction and already built have taken service state monitoring measures[12-14].

This paper proposes a monitoring method for prestressed tendons of prestressed concrete structures. Based on distributed sensor cluster, this method can monitor the strain of prestressed reinforcement in...
the whole length range. The proposed method is further applied to the long-term monitoring of the stress state of prestressed members of a long-span cantilever structure. The monitoring results effectively reflect the actual stress state of the structure, and provide important data reference for formulating the follow-up construction plan of the structure, and achieve good application effect. At the same time, the validity of the proposed method is verified.

2. Strain Monitoring Method of Prestressed Tendons Based on Distributed Vibrating String Sensor

2.1. Selection of sensors
The distributed stress monitoring method of prestressed tendons proposed in this paper is realized by fixing vibrating reinforcement strain gauge on the prestressed tendons. At the same time, the cable force at the tension end or anchorage end was measured by vibrating core-piercing anchor cable dynamometer. The technical performance index of the vibrating string sensor selected in this paper is: The range of 0~20000με, adapt to the ambient temperature range of -20 ~ 80℃, measurement error ≤0.2%FS.

2.2. Basic principles of distributed monitoring methods
The stress at the end anchor of prestressed tendons can be monitored by installing a core-piercing anchor dynamometer. However, it is difficult to directly monitor the stress state of any point in the length range of prestressed tendons by reinforcement strain gauge. Especially the prestressed concrete member constructed by post-tension method, its prestressed tendons are first cast in concrete and then carried out tension. Therefore, this paper presents a kind of reinforcement strain gauge protection device. The device can form a closed space inside the concrete which around the reinforcement strain gauge to ensure that the reinforcement strain gauge can expand freely and move in a small range with the tension of the prestressed tendons, and then realize the purpose of monitoring. In the full length range of the prestressed tendons, the multi-point monitoring of the stress state can be realized by setting several reinforcement strain gauge protection devices and coordinating with it.

The structure of the protection device is shown in Figure 1. The protective casing is made of round steel pipe. In order to enhance the anchoring between protective casing and concrete, spiral reinforcement can be welded on the surface of casing.

3. Engineering Application and Analysis of Monitoring Results

3.1. Project overview
The method proposed in this paper is applied to the monitoring of prestressed members in the cantilever position of a large public structure. The formwork support system of this project is complex, and its disassembly process has great influence on the stress and safety of the structure during construction. At the same time, the prestressed tendons adopt the slow bonding prestressing technology [15].

3.2. The arrangement of sensors in the structure
Due to the large number of prestressed concrete components to be monitored and limited space, only representative key components are introduced in this paper. A group of sensors is formed by placing multiple reinforcement strain gauges along the length direction of the prestressed tendons in a distributed
way to monitor the strain. The anchor cable dynamometer is arranged at the tension end anchor of the prestressed reinforcement, and the tension end stress is monitored. The layout position of distributed sensor cluster is shown in Figure 2.

![Figure 2: Sensor distribution diagram of monitored beam](image)

3.3. The working conditions of monitoring
During the construction and operation stages of the main structure, the structure has experienced several major changes in load conditions, and all previous load changes have a significant impact on the construction and operation. The important time nodes of the structure are shown in Table 1.

3.4. Analysis of monitoring results
In order to investigate the stress changes of the monitored prestressed tendons, the monitoring data of it shown in Fig. 2 in each stage are listed in Table 2 (the two gauges numbered B-M607 and B-M615 failed to survive after being tensioned, so they are not reflected in the table).

Firstly, the most obvious construction process that has an impact on the stress of prestressed tendons is the tensioning of it, that is, time node ①. In the first stage of working condition before tensioning the prestressed tendons, the sensor monitoring data shows that the prestressed tendons are in a low strain state. However, in the condition 2, the monitoring data of prestressed reinforcement and end anchor cable dynamometer have obvious abrupt increment. This reflects that the prestressed tendons immediately enter a state of high strain under the action of tension load. At this point, the anchor cable dynamometer D-M61 and D-M64 at the tension end of the prestressed tendons show readings of 208.6kN and 209.5kN respectively. The design tension load of prestressed tendons is 200kN. It can be seen that the overtension amplitude of the prestressed tendons is controlled within 5%, which meets the construction requirements. The readings of anchor cable dynamometer D-M62 and D-M63 are obviously smaller than those of D-M61 and D-M64 at the tensile end, which is due to the slow bonding prestressing technology and the long prestressing tendon. The viscous resistance caused by the retarder to the prestressed tendons counteracts the transfer of tension to the distal end of the reinforcement, making the force at the end of the reinforcement obviously smaller than that at the tension end.

Secondly, according to the monitoring data of each reinforcement strain gauge in working condition 2, it can be seen that after the tensioning of prestressed tendons is completed, the stress along the whole length is unevenly distributed. The basic rule is that the strain data near the tension end is larger, while the force far away from the tension end gradually decreases, for the same reason as above.

Finally, the monitoring data of each working condition after time node ② are further investigated, and it can be seen that: The concrete pouring and formwork removal of the upper structure have limited influence on the stress of the prestressed tendons.
Table 1 Construction conditions of monitored beam

| Condition | Time |
|-----------|------|
| Condition 1: | From concrete pouring to prestressed tendon tension |
| Condition 2: | After tensioning prestressed tendons, before concrete pouring of upper members |
| Condition 3: | After upper structure concrete pouring, before the prestressed tendon of the upper concrete member is tensioned |
| Condition 4: | After the prestressed tendons of the upper concrete members are tensioned, before the structural formwork are removed |
| Condition 5: | From structural formwork removed to structural decoration |
| Condition 6: | Structural decoration completed, into the operation stage |

Table 2 Corresponding monitoring data before and after each time node of the monitored beam

| Sensor | Time node 1 | Time node 2 | Time node 3 | Time node 4 | Time node 5 | Time node 6 |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|
| B-M601 | 96.949 με   | 4455.045 με | 4254.041 με | 4152.036 με | 4145.040 με | 4122.087 με |
| B-M603 | 56.878 με   | 5555.891 με | 5512.931 με | 5248.823 με | 5240.066 με | 4934.156 με |
| B-M605 | 107.936 με  | 6610.606 με | 6583.836 με | 6367.958 με | 6348.818 με | 6059.210 με |
| B-M609 | 160.552 με  | 3885.939 με | 3859.919 με | 3578.538 με | 3554.307 με | 3339.124 με |
| D-M61  | 75.909 με   | 8336.040 με | 8350.502 με | 8103.982 με | 8065.199 με | 7724.359 με |
| D-M63  | 12.165 kN   | 208.606 kN  | 204.060 kN  | 198.057 kN  | 172.943 kN  | 175.747 kN  |
| D-M62  | 1.378 kN    | 48.814 kN   | 41.370 kN   | 48.8139 kN  | 54.561 kN   | 55.320 kN   |
| D-M64  | 13.875 kN   | 209.501 kN  | 213.0865 kN | 209.7396 kN | 204.561 kN  | 200.845 kN  |

From the analysis results of monitoring data, it can be seen that the influence of construction steps corresponding to each working time node on the stress state of the structure is effectively controlled.

Limited by space, only representative anchor cables B-M609 and B-M613 are selected for illustration, as shown in Fig. 3. From the overall development trend of 2-year monitoring data in the figure, the characteristics of the curve are as follows: Before June 25, 2013, the strain value of the prestressed tendons decreased significantly, indicating that the prestressed loss range was obvious during this period due to various factors. After that, the data curve tends to be stable and fluctuates slightly with the temperature change. Based on the analysis of the actual construction situation, the reasons are as follows: First, the prestress loss caused by end-anchor relaxation after prestressing tendons are tensioned; the second is the relaxation of prestressed reinforcement caused by temperature rise. After June 25, 2013, as the exterior curtain wall structure was basically completed, the construction environment of the monitored structure was designed for the indoor environment, effectively reducing the impact of temperature. In addition, the tension of prestressed tendons of upper structure and the redistribution of internal force caused by the disassembly of the framework also have a certain influence on the stress of prestressed tendons.

During the period of decoration and service, the variation of prestressed tendons is relatively stable, and temperature is the most important factor affecting the stress state. The law of the change of prestressed tendon strain and temperature is that the temperature increases, the prestressed tendon relaxes and the strain decreases. On the contrary, the temperature decreases, the prestressed tendons become tense, and the strain increases.
4. Conclusion

A multi-point strain monitoring method for prestressed tendons based on distributed sensor cluster is proposed in this paper. Using the reinforcement strain gauge protection device, the sensor can be kept alive in concrete effectively, so that the multi-point monitoring of prestressed tendons in the whole length range is possible. The method proposed in this paper is used to monitor the stress state of a long-span cantilever structure. Through the analysis of the monitoring data, the actual state and change trend of the structure are deeply understood, and the influence of various construction conditions on the structure is mastered, so as to make an objective evaluation of the safety of the structure in time. It also plays a guiding role in all stages of construction and provides a strong guarantee for safe construction. At the same time, it has been recognized by the development, construction and supervision units. The site monitoring results show that the monitoring data are basically consistent with the design theoretical analysis results, and the structure is in a safe state. Meanwhile, it provides effective experience and data for the design and construction of this type of project in the future.

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