Reinforcement Design of Three -Valves Towers and Effect Evaluation Based on Monitoring Data

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Abstract. Numerous three-valves towers for communication distributed around urban districts suffer from structural degradation during operation. The traditional methods using encased steel to strengthen the structure are not suitable for three-valves towers. To address this issue, a reinforcement method based on the combined section is proposed for improving the structural performance of three-valves towers. In this method, main bars are added at the side of the maximum stress axis of the original tower with multi-point hinge joints, which are also connected with the flange plate of the original tower by welding. After that, to evaluate the reinforcement effect precisely, the structural health monitoring (SHM) system for towers is established to obtain the data of horizontal displacement continuously before and after the reinforcement. Finally, the reinforcement of an actual three-valves tower is implemented using the method described above, with relatively low costs and a short period of construction. And the data acquired from the SHM system shows that the structural performance of this tower has been improved notably after the reinforcement.

Keywords. Three-valves tower, reinforcement method, SHM system, effect evaluation.

1. Introduction

Urban three-valves towers for communication and power served as important components of civil infrastructure, are often in a variety of complex environmental conditions, which poses risks on the structural safety of towers. Moreover, as the 5G time has arrived, burdens of three-valves towers increase because of the antennas on towers growth, with the undermining of structural capacities to resist local buckling [1]. Previous studies [2, 3] showed that bolts connected with towers are weakness in structures, where occur damage frequently, such as loosening and breakage. To improve the mechanical performance of bolt joints, several optimizations of reinforcing structures have been investigated [4]. Encased steel has been applied to strengthen the lower part of towers extensively [5], and the performance of co-working between the plate and column can be greatly enhanced without increasing the cross section significantly. However, this method requires to stand on the tower for measurement, which is difficult for the site construction of three-valves towers because of massive webs.

Another method is to use combined sections to increase the section resistance moment of towers [6]. Different applications use three main forms of combined sections: square, cross-shaped and I-shaped combined sections, among which cross-shaped combined sections have less steel consumption, and square sections are identified to have better ductility. Although the structural performance of towers can be improved using reinforcement methods of combined sections mentioned above to a certain...
extent, considering the lesser diameter and more webs of the three-valves tower, it is necessary to investigate a novelty strengthening method suitable for three-valves towers. In addition, of particular concern is the evaluation of reinforcement effect. Methods for finite element numerical simulations have been proposed to address estimation of mechanical properties after reinforcement of towers, but the calculation consequences of finite element model (FEM) are difficult to directly use because there may be unignored differences between measured and analytical structural properties. A feasible way is to set up a simple SHM system for each tower, e.g., the horizontal displacement monitoring system, using measurement data obtained from continuously operating SHM systems to evaluate the effect of the structural reinforcement precisely.

As discussed above, this study proposed a reinforcement method based on the combined section suitable for three-valves towers, and an approach is proposed to evaluate the performance of structural reinforcement by measurement data from SHM systems.

2. A Reinforcement Method for Three-valves Towers and Applications in an Actual Structure

2.1. A Reinforcement Method for Three-valves Towers

An approach based on the combined section is presented to strengthen the structural performance in terms of characteristics of three-valves tower. First, main bars are added outside the original tower mast using horizontal connectors, as shown in figure 1, making them connected with the flange plate closely. The horizontal connectors can be drilled on site or prefabricated, with fitting with the connecting plate instead of adjustment angles on site. Then, at the original foot bolts of the member, the new attached bars are welded with the concrete by the flange plate to increase the moment of resistance, which also addresses a problem of insufficient capacities of bolt pull-out and shear bearing. To ensure the durability of reinforced bars, anti-corrosion treatment at the connection parts of holes is implemented finally [7-9].

Figure 1. Photographs of a reinforcement method for three-valves towers.

In this method for reinforcement, principal bars are added at the side of the maximum stress axis of the original tower, with multi-point hinge joints in vertical direction to restrict the displacement of the three-valves tower effectively. Then, the rigid connections between the attached member and the foundation improve the performance of co-working of the structure. For reinforcement construction technology, it has numerous advantages such as light weight, a high prefabrication rate and low costs.

2.2. An Actual Application and Numerical Tests

The method of reinforcement described above is utilized to strengthen an actual structure of the three-valves tower. As shown in figure 2, this tower is built of steel material and approximately 40 m tall, with communication equipment installed on the top and supporting bracings held at the bottom part of the structure by 8 high strength bolts. Additional bars are connected with the main body by steel hoops where there are 5 connection points in each section, between which are connected by bolts, and the horizontal ties are used to limit the out of the plane displacement.
3D3S steel structure software is used to obtain the FEM of the tower before and after the reinforcement, which consists of 362 nodes and 345 finite elements [10]. The mechanical properties under wind loads are obtained by the FEM of the tower structure as shown in figure 3. According to the code of architectural structure load (GB 50009-2012), the wind load is calculated as the following equation:

\[ W_k = \beta_z \cdot \mu_z \cdot \omega \cdot \alpha_b \]  

(1)

where \( \alpha_b \) represents Basic wind pressure, and \( \beta_z \), \( \mu_z \), \( \mu_z \) are the coefficient of wind vibration, wind load shape and Wind pressure height variation at \( z \) altitude, respectively.

As shown in table 1, four sizes of main bars are used for reinforcement of the three-valves tower structure, whose column diameters are 123, 140, 160 and 196, respectively. Compared with the structural strength before reinforcement, the max promotion rate of structural strength of above four types main bars are 18%, 20%, 22% and 22%, respectively; Thus, the performance of the three-valves tower structure is to improve significantly after reinforcement implemented by the method, which approximately also has positive correlation with the size of the main bars.

| Main bars sizes (mm) | Strength of the tower before reinforcement (Stress ratio) | Strength of the tower after reinforcement (Stress ratio) | Increased strength (Stress ratio) | Promotion rate (%) |
|----------------------|----------------------------------------------------------|----------------------------------------------------------|---------------------------------|-------------------|
| 123                  | 0.91                                                     | 0.73                                                     | 0.18                            | 10                |
| 140                  | 0.93                                                     | 0.74                                                     | 0.20                            | 12                |
| 160                  | 0.95                                                     | 0.75                                                     | 0.20                            | 12                |
| 196                  | 0.96                                                     | 0.75                                                     | 0.21                            | 14                |

3. Reinforcement Effect Evaluation Based on SHM Systems

To evaluate the changes of the three-valves tower structural performance before and after reinforcement, a SHM system for monitoring the security status of the tower is established [11, 12], consisting of sensing module, data acquisition and transmission module, data storage module and software module, as shown in figure 4. The inclinometers (SCL3300-D01 3-axis inclinometers) is installed on the top of the tower to acquire the tower tip horizontal displacements, which are sent to the wireless network and are stored in the local server for later analysis.
Figure 4. Photographs of the inclinometers and the installation of the SHM system.

For the tower with SHM systems, horizontal displacement data can be collected along the north-south (NS) direction and the east-west (EW) direction simultaneously, with the data acquisition frequency of 10 minutes. A total of 5000 sets of data samples under the normal conditions of environment are obtained, in which the first 4000 sets of data samples are obtained before reinforcement, while the last 1000 sets of data samples correspond to the structure state after reinforcement. As shown in figure 5, the actual monitoring data of the three-valves tower before and after reinforcement presents remarkable changes that the degree of data volatility after reinforcement is reduced. The range of the fluctuation along two directions decreases from 0.15 and 0.11 before reinforcement to 0.09 and 0.05 after reinforcement, respectively. Therefore, the method of reinforcement based on the combined section can be completed to effectively improve the overall performance of the three-valves tower structure and limit the displacement of the tower top.

![Inclinometer](image)

Figure 5. Displacement monitoring data of towers before and after reinforcement.

4. Conclusion
This study proposed a reinforcement method for three-valves tower based on the combined section and evaluated the performance of structural reinforcement by measurement data from SHM systems. The following conclusion are drawn:

1) The reinforcement method based on the combined section for three valves tower was investigated to improve the bearing force and performance of co-working of the structure, also with the properties of light weight, high prefabrication rates and low costs.

2) As shown in the actual example, improvement rates of structural performance after reinforcement have positive correlation with the size of the main labs.

3) For practical applications, the data acquisition and analysis through SHM systems of the three-valves tower is an effective and accurate method to evaluate the effect of reinforcement.

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