IOP Conf. Series: Earth and Environmental Science **170** (2018) 042099 doi:10.1088/1755-1315/170/4/042099

Research of Full-scale Transmission Tower Deformation Caused by Unbalanced Tension

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Abstract. An experiment of the full-scale transmission tower is carried out to study the deformation of the tower under unbalanced tension. By adding extra load on the transmission wire connected to the tower and using distributed angle sensors to record the continuous changes of deformation, the deformation rule of the full-scale tower under the unbalanced tension is studied. The experimental results show transmission tower has some complicate performances as a kind of statically indeterminate structure under unbalanced tension as it will incline, twist and vibrate under unbalanced horizontal tension and the creep happen partially in the tower, which reveals the limitation of simulation and the necessity of real tower tests. The results can be used as the theoretical basis of monitoring and optimization of the transmission towers' health status.

1. Introduction

Deformation such as tilt and torsion happen when transmission tower is under unbalance tension. In extreme cases, the towers can be pulled down by strong wind, icing and other severe conditions of unbalanced tension [1]. When a tower topples, it will lead to a chain reaction of adjacent towers' deformation, which aggravates the accident and increases the difficulty of reconstruction [2].

A series of accidents of transmission line were caused by tornadoes in suburb of Guangzhou during the attack of No.22 Typhoon "Rainbow" in 2015. The tower # 12 and # 13 of an 110kV line collapsed and different degrees of deformation or damages were found in tower #10, #11, #14, #15. Specific damaged conditions are listed in Table 1.

Table.1 Damaged condition of the transmission towers

Tower	Damaged Condition
#10	Ground cross-arm bended
#11	A side of ground cross-arm damaged
#12	Totally toppled
#13	Partially Toppled
#14	Wire cross-arms and Ground cross-arm bended

(a) #11 Tower (b) #12 Tower

Figure 1. The damaged tower “110kVYinxinYi#11&12”

According to figure 1, the #12 tower toppled totally and exerted large force on the ground cross-arm of #11 tower through the power transmission wire between these two towers, resulting in the deformation of #11 tower. The damage of the two towers further caused other towers’ deformation. Therefore, it is obvious that the deformation caused by the unbalanced tension of transmission tower has a serious impact on the safety of transmission lines. It is of great significance to understand the complicated deformation rules to design and reinforce transmission towers.

With its statically indeterminate structure, the transmission tower has strong load capacity and can maintain its geometric invariability despite external change to a certain degree. However, its deformation rule is so complicated to study，especially the creep of transmission tower under long-term load. It is difficult to get an accurate conclusion through calculation or simulation. Thus a representative transmission tower is selected for the full-scale tower test. By adding extra load on the transmission line and installing a series of sensors on the tower, the deformation of the tower under unbalanced tension is studied. The results show the transmission tower deforms and creeps as a statically indeterminate structure under unbalanced tension.

2. The Full-scale Test of Transmission Tower Under Unbalanced Tension

2.1. Testing Tower-line System

The uncharged tower-line system for teaching in Guangzhou University of South China University of Technology was selected for the test (Fig.2). The tower is an 110kV single-loop steel pipe combination of dry-type tower (25 meters of total height, 16 meters of practical height, 3. 5 meters of root span). The conductor type is 4 × JL / G1A-240/30 ACSR and the ground wires are respectively JL / G1A-70/40 ACSR and LBGJ-70-30AC aluminum clad steel strand. The testing site of the wires and the adjacent tower are as Figure 3 (b).

Figure 2. Single loop testing tower

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(a) (b)

Figure 3. Angle sensors and the weight adding on the line

2.2. Testing Process

In the test, a 9-axis motion processing unit (MPU9250) with wireless communication function was used as an on-line monitoring sensor to measure the deformation (mainly the node angle) of the tower. Considering the similarities and symmetries of the tower, the angle sensors were set in three layers of the tower (Fig.4). The data obtained by the angle sensor is transmitted to the computer through wireless communication.

During the test, load were applied to the wire to generate unilateral unbalanced tension acting on the tower. Taking into account the carrying capacity of the wire and safety, the load was up to 400kg. The process of load shedding was also taken into account. The whole process was recorded in photos (Figure 3 (b)).

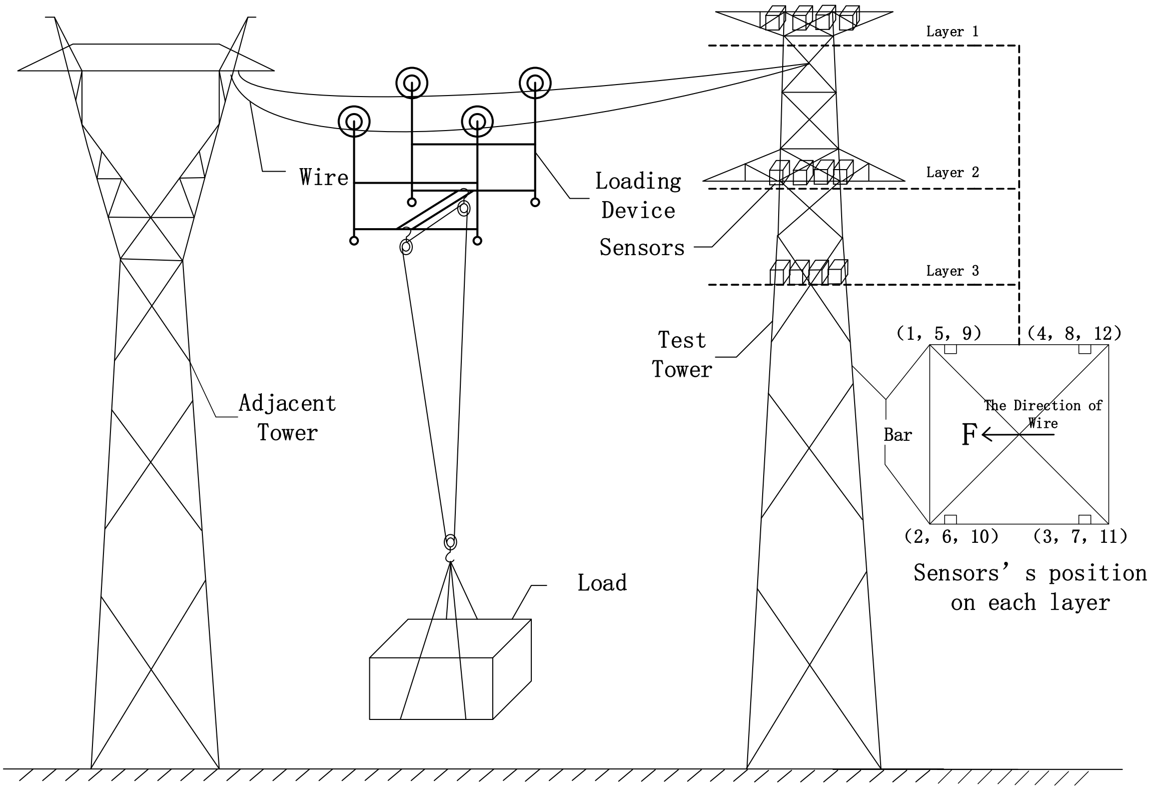

Figure 4. Diagram of testing site

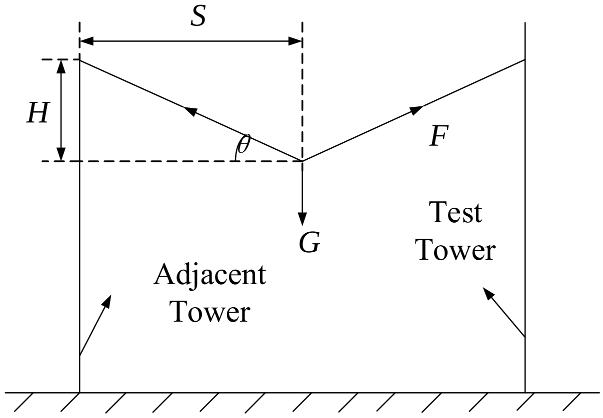

Figure 5. Force analysis

2.3. Calculation of Unbalanced Tension on the Tower

The load (G, Fig.5) exerted the horizontal unbalance tension (F, Fig.5) to the tower through the wire. Figure 5 is a schematic diagram of the force analysis.

The horizontal tension of the conductor on the tower calculated from Fig.5 is:

$$F = \frac{G}{2 \cdot \tan\theta} \tag{1}$$

Where G is the total weight of the load including the loading device of 52kg; θ is the angle between the wire and the horizontal direction, tan θ can be measured from Figure 5:

$$tan\,\theta = \frac{H}{S} \tag{2}$$

Where S (8.8m) is the horizontal distance between the lowest point of the wire and the adjacent tower; H is the offset of the wire and it was calculated with following steps.

As the vertical height of the loading device changed solely, the ratio of the size of the loading device in the photograph is equal to the ratio of its actual size. Therefore, the offset of the wire can be calculated by the proportional relationship between the size in the photos and the actual condition. The vertical distance of the four-split conductor is 450mm and the length of the middle lever of the loading device is 337.5mm. As shown in Fig.6, the pictorial vertical distance of the four-split conductor is *d*:

$$d = \frac{450}{337.5} \cdot l \tag{3}$$

Where *l* is the pictorial size of the middle rod of the loading device in Fig.6. The pictorial offset of the wire is *h* + *d*.

$$\frac{H}{337.5} = \frac{h+d}{l} \tag{4}$$

Where *h* is the distance between the sub-conductor of the four-split conductor and the head of the loading device. Substituting Eq. (3) into Eq. (4):

$$H = \frac{337.5 \cdot h + 450 \cdot l}{l} \tag{5}$$

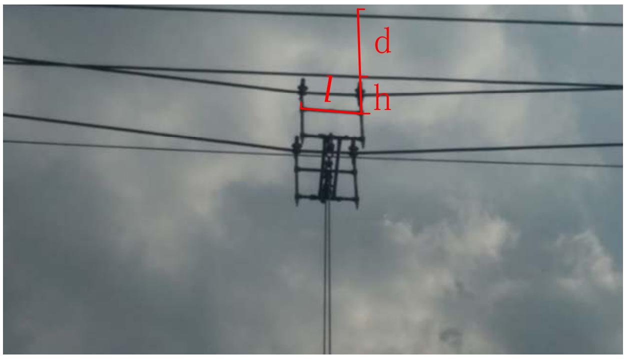

Figure 6. Deformation of conductors on quad bundled with load

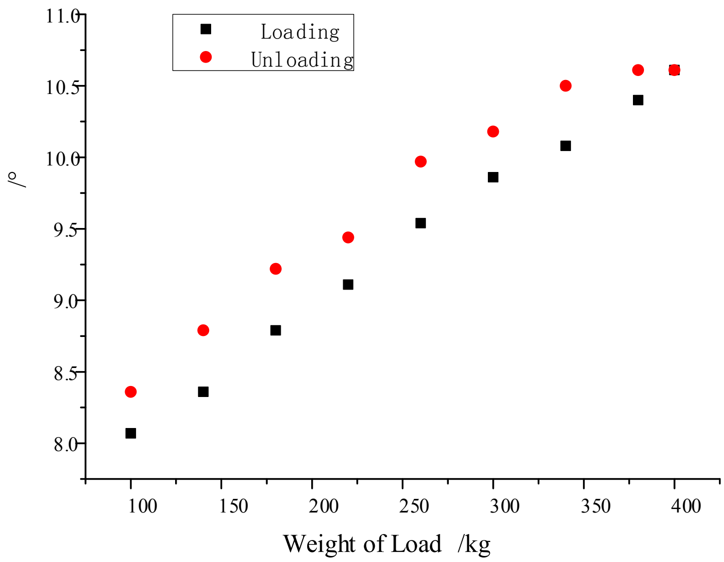

Figure 7. Correlation between horizontal angle and load

According (1) ~ (5) and the information got from the photos, the relationship between the horizontal angle of the wire and the weight of the load is worked out and shown in Fig.7.

It can be seen from Fig. 7 that the processes of adding and reducing load have different trends, which shows hysteresis of the recovery happens when the unbalanced tension on the wire-tower system reduces, which has a significant impact on the deformation of the transmission tower.

3. Test Results and Analysis

3.1. Horizontal Tilt along the Direction of the Wire

The relationship between the horizontal tilt angles along the direction of the wire and the calculated horizontal tension on the wire during the processes of adding and reducing load is shown in Fig.8.

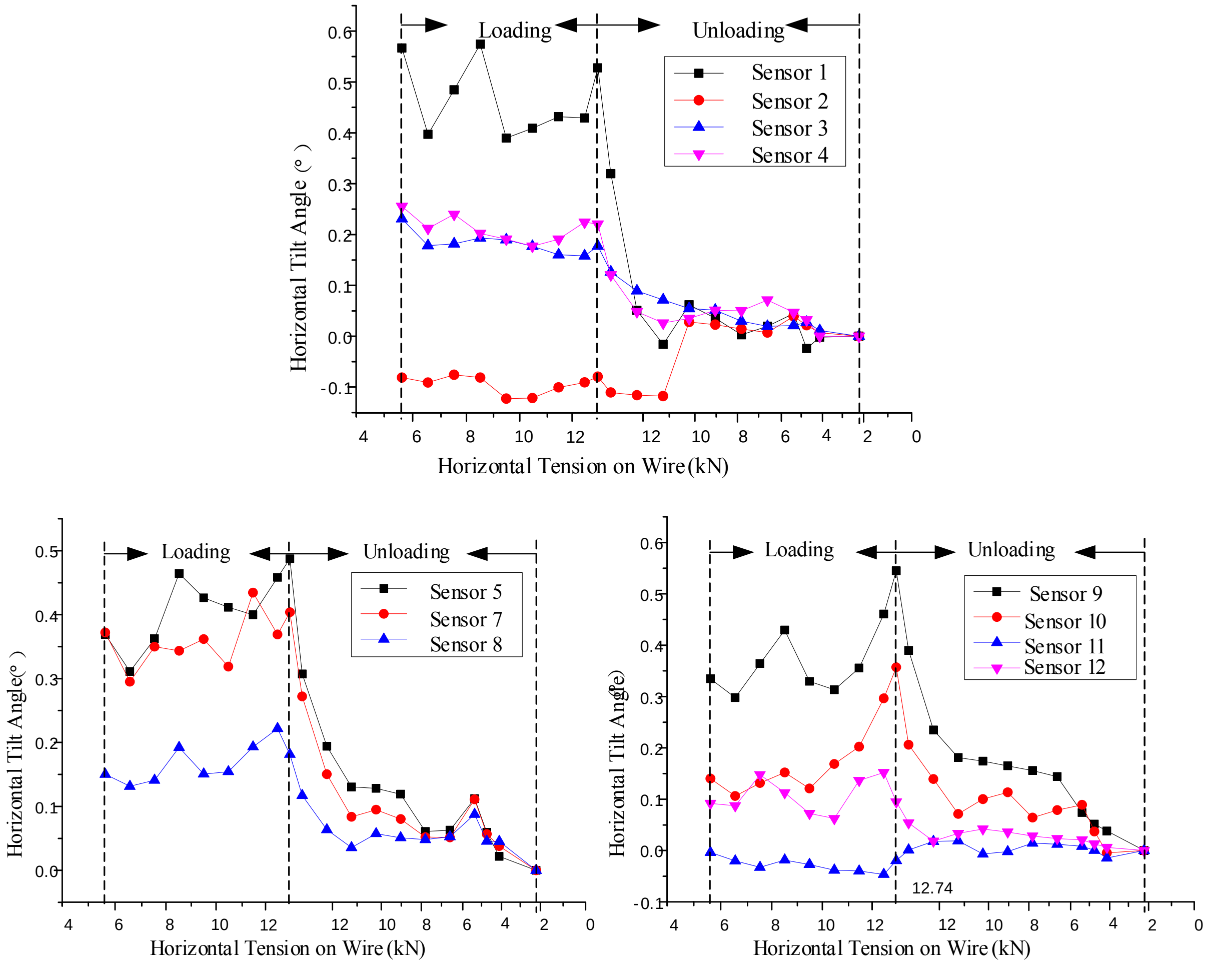

Figure 8. Scatter diagrams of angle sensors' data of adding and reducing load

(Sensor # 6's data was lost)

From Fig.8 (a) to (c), it can be seen that within the experimental horizontal tension's range (0 ~ 13kN), the change of the horizontal tilt angles along the direction of the wire is within 1 °. Differences were found between the four sensors in the same layers. The sensor which was near the main bar has relatively large tilt angles (No. 1, 5 and 9, near to the same main bar of the tower (Fig. 4)) and there was a significant reciprocal change of the angles during the adding, while the tilt angles on the other side were significantly smaller (No. 2 and 11), with a variation range within 0.1 °. The rest of the sensors' tilt angles also changed obviously with roughly same rules: the angle changed obviously when the horizontal tension increased, but the angle changed slowly when the horizontal tension reduced.

It is noteworthy that, at the early moment of load shedding, the horizontal tilt angles of inclination of the tower changes suddenly.

3.2. Torsion in Vertical Direction

According to the analysis of the tilt angle in 4.1, it can be seen that there is a significant difference in the angle change of the sensors at the same layers, indicating that the tower has been twisted under the unbalanced tension. This section will further analyze this by showing the relationship between the horizontal tension on the tower and its torsion angle in vertical direction (Fig.9).

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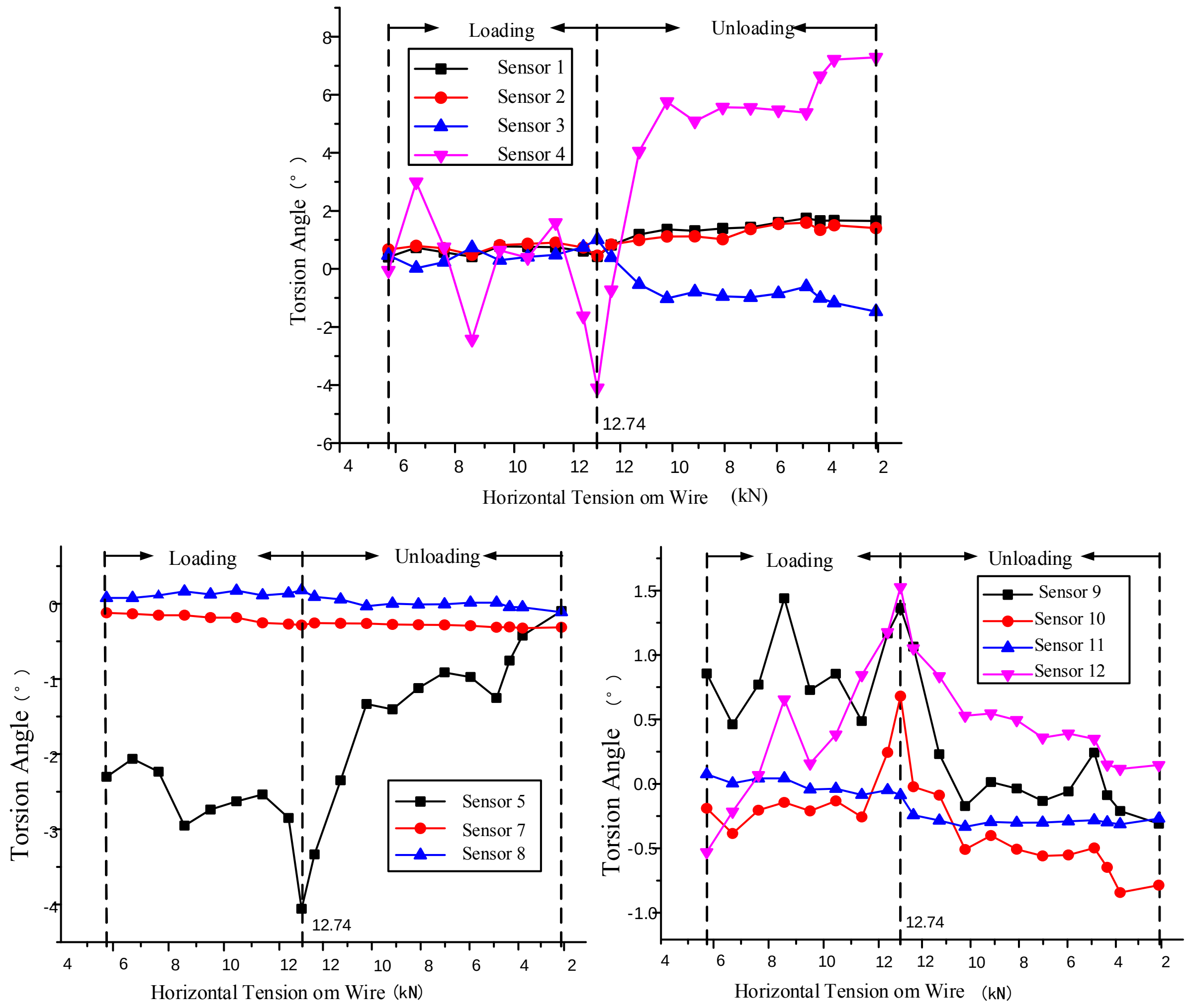

Figure 9. Scatter diagrams of angle sensors' data

It can be seen from Fig. 9 that the torsion angles of the tower during the load adding process also have some reciprocal changes. The torsion angles of the sensors in each layer have significant change between loading and unloading. The torsion of different layers is quite different: the higher the sensor was set, the torsion angle it had was larger (up to 7.29° while the smallest angle is only 1.4° of the lowest sensor); the first and the second layer had a more prominent twist (No. 4&5, corresponding to the same side of the two main bars of the tower (Fig.4)).

The experimental results show that the deformation rule of the transmission tower under unbalanced tension shows its characteristic as the indeterminate structure: 1. The horizontal tilt along the direction of the wire and the vertical torsion change reciprocally with the monotonous change of the horizontal tension, indicating that the transmission tower has certain vibration under the action of environmental load; 2. The change of the angle of the same monitoring point has obvious difference in the stages of loading and unloading, and there is a mutation between the two stages, indicating that the tower of statically indeterminate structure will creep under long-term load (unbalanced tension), which can eliminate the concentrated stress inside the tower structure and make the stress redistribute evenly. However, the tower's deformation will continue until it reaches a stable state after a long period of time; 3. There is a prominently changing position on each layer and the maximum torsion position on different layers are different, indicating the torsion of tower is not overall elastic; 4, The higher the position is, the larger the angles of tilt and torsion are.

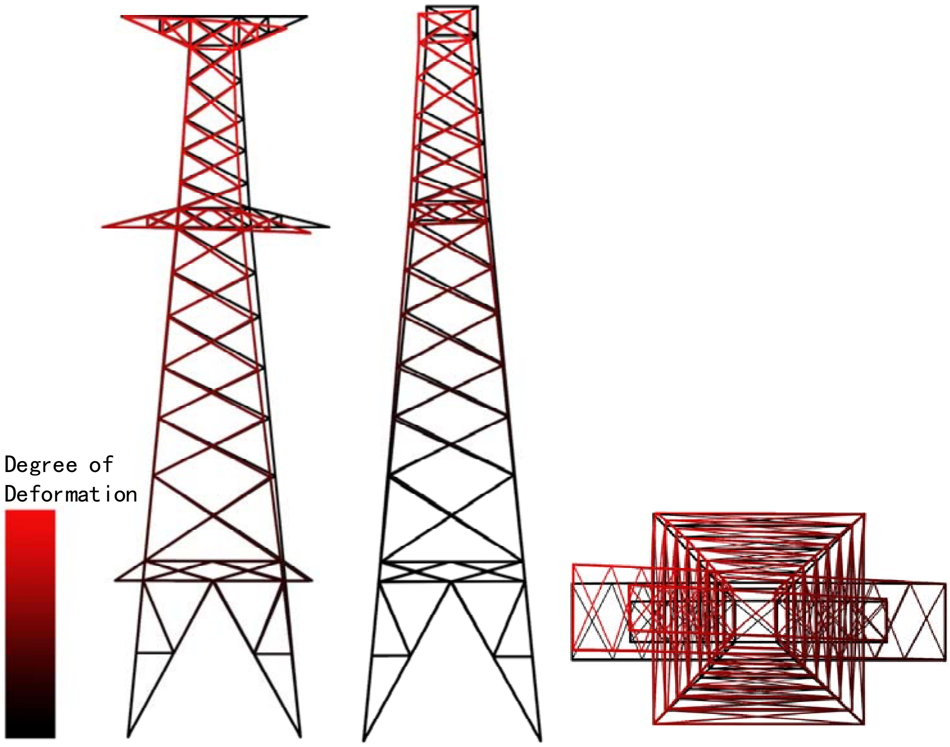

Figure 10. Diagram of deformation mode of the tower

Due to the limited test conditions, the maximum horizontal tension applied to the tower was only 12.74kN while actually the transmission tower is often subjected to severer unbalanced tension due to extreme environmental factors such as typhoon and icing, so the actual tower's tilt and torsion angle will be greater.

According to the deformation rule analysis above, the deformation mode can be visually shown in Fig.10.

4. Conclusion

In this paper, we design a full-scale test that simulates the unbalanced tension of transmission tower by adding load to the wire. The deformation of the tower under unbalanced tension was studied by analyzing the sensors set in different positions of the tower. The conclusions are as follows:

(1) The deformation of the wire-tower system under unbalanced tension will have a hysteresis effect in the recovery state, which can't be neglected when studying the rule of the deformation of a transmission tower;

(2) The tower is bent and twisted under the unbalanced tension in the direction of the wire. These deformations happen partially in the tower; The tilt and torsion angles of the tower change non-monotonously with the tension changes; The deformation cures of the two stages of loading and unloading are different and the deformation recovers immediately at the beginning of load shedding; Through the above rules, the transmission tower's creeping feature is clearly demonstrated as a statically indeterminate structure; Its ability of creeping caused by unbalanced tension is an advantage for its endurance and safety but makes the rule of deformation complicated to study.

(3) The mechanical system of the transmission tower cannot simply be regarded as "node structure" or "ideal truss structure" in the traditional sense. The finite element analysis and other simulation methods are difficult to cope with the complex constraints of the transmission tower. Therefore, it is more credible and more persuasive to carry out the full-scale test in the study of transmission tower's deformation under unbalanced tension.

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Acknowledgments
This work was financially supported by China Southern Power Grid Company Limited Technology Project (GDKJ00000016) fund.

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