Mechanical Mechanism Analysis of Warping and Bulging Of Track Slab of High-Speed Railway in Service

Yali Liu¹, Jun Dong¹⁺, Guohua Li¹, Xi Chen² and Yunkai Zhang¹

¹ Beijing Higher Institution Engineering Research Center of Structural Engineering and New Materials, Beijing University of Civil Engineering and Architecture, Beijing, 102616, China;
² School of Humanity and Law, Beijing University of Civil Engineering and Architecture, Beijing 102616, China
Email: jdongcg@bucea.edu.cn

Abstract. Due to warpage and ballooning of high-speed rail track slab caused by debonding and environmental temperature changes during the deterioration of CA mortar layer being extremely concerned in practical engineering, it is based on numerical simulation of typical working conditions and analysis of test model that the deformation dynamics mechanism of track slab of high-speed rail in service is studied in this paper. Firstly, three kinds of damage conditions of CA mortar layer are designed to simulate the partial stress state of track slab under normal, warping and bulging conditions, and the results of model test are compared with those of finite element analysis so that the accuracy and credibility of the numerical simulation method and results are verified. Then, through finite element numerical simulation, the dynamical mechanism of actual full-scale high-speed rail track slab under vibration load is studied. The results show that the warping deformation around the track slab and the bulging deformation in the middle part under the action of positive and negative temperature gradient load caused by environmental temperature change will have a great impact on the structural performance of itself and CA mortar layer; Bulging deformation of track slab is more destructive to its structure than warping deformation. It is of great practical significance to further study the critical position of track plate warpage and bulging deformation, and to optimize and strengthen the structure of this part; The research results are of great significance to further study the deterioration.

1. Introduction
When CA mortar layer is repeatedly soaked by rainwater and underground seepage for a long time, the bonding effect between CA mortar layer and track plate will fail. Then, under the action of positive and negative temperature gradient load caused by ambient temperature change, the track plate that loses the bonding effect of CA mortar layer will have large surrounding warping deformation and bulging deformation in the middle [1-4]. CA mortar layer is constantly damaged under the alternating action of warping and bulging deformation of track plate, resulting in the loss, falling off and deformation of CA mortar, and the corresponding track plate will have diseases such as void and joint separation.

In this paper, three working conditions will be designed to study the stress characteristics of track plate under normal, maximum warpage and maximum bulging. In this paper, the scaled experimental model is established, the vibration load is applied by WS-Z30 shaking table, and the Abaqus finite
element numerical simulation is used to compare the two results to verify the accuracy of the numerical simulation results. Then, the stress mechanism of actual full-scale high-speed rail track slab beam under vibration load is analyzed by finite element method.

2. Verify the Accuracy of Numerical Simulation Results

2.1. Model Experiment

Model test is mainly used to verify the accuracy of finite element numerical simulation. According to the similarity principle, when the main variables are similar, the secondary variables can be appropriately ignored. In this test, plexiglass plate is used to simulate track plate and support layer, and rubber pad is used to simulate CA mortar layer. According to the research results of Yilong Liu and Junlin Liu [5-10], the test vibration load frequency is 12.5Hz in the longitudinal direction and 80Hz in the vertical direction. Due to the limited conditions of the shaking table selected in this test, only the longitudinal vibration load is applied to verify the accuracy of the numerical simulation results.

WS-Z30 small precision simulation shaking table system is selected as the test instrument, as shown in figure 1 below. The system is composed of shaking table, electromagnetic exciter, power amplifier, shaking table control sensor, model, shaking table controller, computer and software. The test model is shown in figure 2 below. Three working conditions are designed for the test: working condition 1 is non-destructive, as shown in Figure 3 below; Working condition 2 is that the middle of CA mortar layer is not stressed due to the bulging of track plate, as shown in figure 4 below; Condition 3 is that the edge around the CA mortar layer is not stressed due to the warping of the track plate, as shown in figure 5 below. The parameters of test materials are shown in table 1 below.

![Figure 1. Vibration table system.](image1)

![Figure 2. Test model.](image2)

![Figure 3. Working condition I.](image3)

![Figure 4. Working condition II.](image4)

![Figure 5. Working condition III.](image5)

| Table 1. Experimental material parameters. |
|-------------------------------------------|
| Structure                     | Material    | Size (mm) | Elastic modulus (MPa) | Poisson ratio | Density (kg/m³) |
|-------------------------------|-------------|-----------|----------------------|--------------|-----------------|
| Track plate                   | Organic glass | 420 × 170 × 10 | 2.5 × 10³         | 0.37         | 1200            |
|                               |             | 420 × 170 × 5 |                     |              |                 |
| CA Mortar layer               | Rubber      | 1180 × 20 × 5 | 15                  | 0.47         | 1300            |
|                               |             | 400 × 150 × 5 |                     |              |                 |
| Supporting layer              | Organic glass | 450 × 90 × 20 | 2.5 × 10³         | 0.37         | 1200            |
2.2. Model Finite Element Analysis
Using Abaqus finite element analysis software, the finite element model of equal size and equal material which is exactly the same as the model test is established. Apply the same vibration load as the model test. The finite element model is shown in figure 6-8 below.

![Finite element models](image1)

Figure 6. Working condition I.  Figure 7. Working condition II.  Figure 8. Working condition III.

2.3. Comparative Analysis of Model Test Results and Finite Element Analysis Results
In this study, the maximum acceleration of track plate in the process of model test and finite element analysis is selected as the index to evaluate the vibration level. The following figure 9 (a) - (c) respectively shows the maximum acceleration change curve of track slab beam during model test and finite element analysis from condition 1 to condition 3, and Figure 9 (d) shows the comparison of the maximum acceleration difference of track slab from condition 1 to condition 3 during model test, Figure 9 (e) shows the comparison of the maximum acceleration difference of the track plate from condition 1 to condition 3 during the finite element analysis.

![Comparison diagrams](image2)

(a) Comparison diagram of working condition I  (b) Comparison diagram of working condition II

(c) Comparison diagram of working condition III  (d) Comparison diagram of test working conditions I - III
As can be seen from figure 9 (a) - (c), in the process of simulating the partial stress state of the track plate during normal, warping and bulging, the test results are relatively consistent with the finite element analysis results, and the inconsistency of some secondary conditions leads to small differences in some results. As can be seen from Figure 9 (d) and (e), in the model test, the maximum acceleration of the track plate in condition 1 is 7.377m/s², 9.206m/s² in condition 2 and 11.525m/s² in condition 3; In the finite element simulation, the maximum acceleration of the track plate in condition 1 is 7.396m/s², that in condition 2 is 9.335m/s², and that in condition 3 is 11.375m/s². It shows that the warpage and bulging of track plate will have a great impact on its mechanical properties, which is in line with the law. Through the comparative analysis between the model test results and the finite element analysis results, the accuracy of the numerical simulation results is fully verified, which provides a strong basis for the next finite element analysis of the stress of the actual full-scale high-speed rail track slab beam under vibration load.

3. Finite Element Analysis Actual Equal Size Model

Using Abaqus finite element analysis software, the finite element model of high-speed rail track system with actual equal size and equal material is established. The frequency of vibration load applied to it is: longitudinal 12.5Hz, vertical 80Hz. The finite element model of track system is basically similar to figure 6-8 except for different dimensions, which will not be shown here. See Table 2 below for actual material parameters of track system.

| Structure            | Size(mm)      | Elastic modulus (MPa) | Poisson ratio | Density(kg/m³) |
|----------------------|---------------|-----------------------|---------------|----------------|
| Track plate          | 6450 × 2550 × 200 | 35.5 × 10³           | 0.167         | 2450           |
|                      | 6450 × 2550 × 50  |                      |               |                |
| CA mortar layer      | 17500 × 250 × 500 | 7 × 10³              | 0.160         | 1800           |
|                      | 5950 × 2050 × 50  |                      |               |                |
| Supporting layer     | 7000 × 2950 × 300 | 30 × 10³             | 0.2           | 2500           |
Figure 10. Acceleration variation diagram of track plate under working conditions I – III.

It can be seen from figure 10 that in the actual equal size finite element simulation, the maximum acceleration of the track plate in condition I is $5.120\,m/s^2$, that in condition II is $9.045\,m/s^2$, and that in condition III is $9.681\,m/s^2$. It is consistent with the law of the above test. It shows that the warpage and bulging of track plate will have a great impact on its mechanical properties.

Figure 11. Stress nephogram of working condition I.

Figure 12. Stress nephogram of working condition II.

Figure 13. Stress nephogram of working condition III.

It can be seen from figure 11-13 that the maximum longitudinal stress of track plate under condition I is $1.040\,MPa$, $5.035\,MPa$ under condition II and $1.037\,MPa$ under condition III; Most of the longitudinal stress of CA mortar layer under working condition I is $0.111\,MPa$, $0.131\,MPa$ under working condition II and $0.643\,MPa$ under working condition III. It shows that the bulging of track plate is more destructive than warping. Through the stress nephogram, it can also be found that when the track plate warps and bulges, the stress concentration will occur at the contact edge between the track plate and the CA mortar layer. Under the alternating action of track plate warping and bulge, this
part of the area will be destroyed first, and vice versa.

4. Conclusion
(1) Under the action of positive and negative temperature gradient loads caused by the change of ambient temperature, the warping deformation around the track plate and the bulging deformation in the middle part will have a great impact on the structural performance of itself and CA mortar layer;
(2) The bulging deformation of track plate is more destructive to its structure than warping deformation;
(3) It is of great practical significance to further study the critical position of track plate warpage and bulging deformation, and to optimize and strengthen the structure of this part;
(4) The research results are of great significance to further study the deterioration mechanism of CA mortar layer and the loss identification and monitoring of track slab.

5. Acknowledgments
Authors wishing to acknowledge assistance or encouragement from BUCEA, and financial support from the Project of Beijing Natural Science Foundation (No.8202012), the Teaching and Research Project of Beijing University of Civil Engineering and Architecture (201802), the Changjiang Scholars and Innovation Team Development Plan (IRT-17R06) and Beijing Advanced Innovation Center for Future Urban Design, Beijing University of Civil Engineering and Architecture (UDC2019021424).

Reference
[1] Xu H, Cao X G. 2019 Analysis and Research on warpage deformation of CRTs III track slab in severe cold area [J] Journal of railway engineering 36 (05) 20-24 + 84.
[2] Yi X. 2015 Study on warpage deformation of embedded track plate in hardened Section [D] Southwest Jiaotong University.
[3] Chen J. 2020 Study on temperature and stress evolution law of CRTs III ballastless track slab [D] East China Jiaotong University.
[4] Yang J J, Zhang N, Gao M, Sun J L. 2016 Temperature warping deformation of CRTSII ballastless track and its influence on dynamic response of train track [J] Engineering mechanics 33 (04) 210-217.
[5] Ma L X, Liu W N, Liu W F. 2012 Dynamic response of floating slab track under moving resonant load [J] Engineering mechanics 29 (12) 334-341.
[6] Wang T Y, Ding J M, Lou M L. 2010 Load and analysis method of site vibration caused by subway operation [J] Engineering mechanics 27 (01) 195-201.
[7] Liu Y L. 2017 Study on vibration propagation law of high speed railway transportation [D] Shijiazhuang Railway University.
[8] Lou P. 2007 Vertical vibration analysis of train track (bridge) system [D] Central South University.
[9] Tao L. 2015 Vibration analysis of station overpass caused by high-speed train [J] Railway architecture (05) 34-37.
[10] Liu J L. 2019 Study on dynamic characteristics of saturated sand foundation under high speed railway vibration load [D] China University of mining and technology.