Improving the Performance of Rail Fastening System Evaluation

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Regarding Japanese test methods for rail fastening systems, it was confirmed that the rail tilting angle obtained in a biaxial loading test did not agree with the angle calculated using a conventional rail tilting analysis model. To address this problem, a calculation method for biaxial loading using an FEM analysis model, where various stiffness properties regarding the rail fastening systems can be expressed as non-linearity, was proposed and its validity was confirmed. In addition, a study on the optimization of a method for testing rail restraint was carried out through experimental validation under various conditions.

Keywords: rail fastening systems, performance verification, FEM analysis, rail tilting angle, rail restraint

1. Introduction

Different tests are conducted for the purpose of confirming the performance of rail fastening systems which are among the track components used on railway tracks. Among these tests, in Japan, biaxial static and repeated loading tests are conducted for the purpose of verifying the performance of these systems in terms of fatigue durability.

Conventionally, the loading conditions for static and repeated biaxial loading tests, using a single fastening system set, are determined so that the rail tilting angle calculated using the proposed rail tilting analysis model [1-4] agrees with the rail tilting angle obtained in the test. However, it was confirmed these two rail tilting angles do not agree in practice.

Therefore, in this study, the rail tilting angle calculated using the proposed finite element method (FEM) model was compared with the angle obtained through a uniaxial loading test on a test track to verify the validity of this proposed analysis model when a low stiffness fastening system was applied. In addition, the validity of the biaxial loading condition for testing to be applied to a single rail fastening system set calculated using the proposed analysis model was verified by comparing it with the response values obtained in a biaxial loading testing on a test track.

2. Rail tilting angle and loading condition

There are two methods of static and repeated loading tests conducted in Japan for verifying fastening system fatigue durability; one is conducted using a single fastening system set and the other is conducted using a test track as shown in Fig. 1. When a fastening system of the same type is laid continuously on the track at regular intervals, a single fastening system set was selected. When different types of fastening systems are used on a track or when the rail profile is not constant in the track longitudinal direction, as is true of a jointed rail, tests are conducted using a test track.

Static loading tests are conducted to examine responses such as rail displacement and rail clip stress. Rail displacement during static loading tests is verified against the rail lateral displacement limit value. The combined rail clip stress is verified by checking whether the plot representing the combination is inside the acceptance area of the Goodman diagram defined by the types of spring steels as shown in Fig. 2.

In static loading tests, the distributed force to be applied in tests using a single fastening system set is derived from the design loads - load ‘A’ and load ‘B’ - based on beam theory on an elastic foundation. Load ‘A’ cor-
responds to a rarely occurring load, while load ‘B’ is the more common load. Load ‘A’ exerts a force on the track which broadens the track gauge while load ‘B’ narrows the track gauge. Following the estimation of distributed forces, the rail tilting angle is derived using the rail tilting model as shown in Fig. 3. This is called “conventional method” and the rail tilting angle calculated by means of this method is called “practical solution.” When the force distributed and rail tilting angle are calculated, biaxial loading conditions for the test by a single fastening system set are also derived, and the rail tilting angle is measured in the loading test under that condition. Here, a small difference in the rail tilting angles is expected between the calculation and the measurement, but in practice there is some deviation.

3. Rail tilting analysis model

3.1 Outline of the proposed rail tilting analysis model

To solve the problems described above, a non-linear FEM rail tilting analytical model [5] was proposed, as shown in Fig. 4. This model enables us to reproduce and simulate half a railway track consisting of twenty-seven rail fastening systems and a rail, and its validity was confirmed with stiff rail pads, or more specifically, when the rail pad constant was 110 MN/m. However, it is not possible to ignore the effect on the rail tilting angle, of stiffness non-linearity in low-stiffness rail support fastening systems. Therefore, in this study, in consideration of its properties the most typical Japanese fastening systems were applied: D8 fastening system used for JIS 60kg rail (Fig. 5). This fastening system was used on a slab track and the rail pad stiffness was equal to or above 30 MN/m.

In this model, lateral springs were set as horizontal springs, and rail clip springs, lower rail springs, and lower rail support springs were set as vertical springs. In particular, the stiffness of the rail clip springs and the lower rail springs are set either as linear or bilinear in the conventional model, but in the proposed FEM model and shown in Fig. 6, they were set as non-linear. At the beginning of the analysis, the offsets of the initial fastening force were set taking into consideration the non-linear properties of this stiffness.

3.2 Validation of the analysis model by loading test

To evaluate the proposed analysis model, a loading analysis using the proposed model in which loading tests on a test track could be reproduced, and loading tests on a test track were conducted, so that these two results could be compared. A loading analysis using the conventional model was also carried out for comparison. The parameters applied to these analyses models are indicated in Table 1.

To validate this FEM model, FEM loading analyses and loading tests on a test track were conducted. The test track was composed of seven fastening systems and a single rail on the test bed as shown in Fig. 7. The loading conditions were common to both the analyses and the tests on
the test track. The uniaxial loading from 0 to 100 kN was carried out at each loading angle – 45, 55 and 65 degrees, and the rail tilting angles were measured and compared with each other.

3.3 Result and discussion

Figure 8 compares the rail tilting angles obtained through analyses and those obtained through loading tests. Both the “practical solution” and the angle calculated by the proposed FEM analysis were larger than the angle obtained in the loading tests, at any loading angle, and results of the proposed FEM analysis were closer to the test results obtained on the test track than the practical solution.

It was considered that one reason for this was that the influence of the frictional force generated by contact between the rail and the base plate shoulder could not be ignored in these types of rail fastening systems which contain a baseplate. It was thought that, for the reason given above, the tilting angles obtained through loading tests were smaller than those obtained from calculation.

From these results of the above-mentioned comparison, it is considered that the proposed FEM analysis model was validated.

4. Method for calculating loading conditions in biaxial loading tests

4.1 Method for verifying loading conditions in biaxial loading

Following the validation of the proposed FEM model, the validity of the method for calculating the biaxial load-
ing conditions for the FEM model was also confirmed.

Figure 9 shows the comparison of responses such as rail tilting angle, rail displacement and rail clip stress between the three different methods applied. To confirm the validity of the method for calculating biaxial loading conditions by means of the proposed method, the conventional calculation method was also examined for comparison. The biaxial loading conditions obtained by each of the two methods were then applied in biaxial loading tests using a single fastening system set. Furthermore, biaxial loading tests on a test track were also conducted, applying design loads directly. The validity of the proposed calculation method was examined by comparing the response values obtained from each test.

### 4.2 Calculation of load distribution and rollover moment

In the proposed method for calculating biaxial loading conditions, the load distribution and the rail rollover moment were derived using the proposed FEM analysis model and the balance of forces under the loading point in the FEM model was considered. Figure 10 shows the balance of forces when the design loads such as the wheel load and the lateral force are applied on the rail head.

At the center of the rail bottom of the fastening system under the loading point, the distributed vertical force \( W \) was derived as the sum of the reaction of lower rail springs and rail clip springs, and the distributed horizontal force \( H \) was derived as the sum of the reaction of lateral springs. The rail rollover moment \( M \) was derived in consideration of these forces, the rail height and so on.

### 4.3 Method for calculating biaxial loading conditions

Biaxial loading conditions are derived following the above calculation. When the derived vertical and horizontal forces are applied to the rail head directly, the rail rollover moment becomes excessive and the lateral force doesn’t match the calculated lateral force. Therefore, the height of the test rail is determined in consideration of the balance of between distributed forces and rail rollover moment.

In addition, force \( L_0 \) is applied from the opposite side while Load A and Load B are applied because of the stabilization of the biaxial load testing as shown in Fig. 11. The load \( L_0 \) is normally 10 kN. Therefore, the effect of these forces is also considered in this calculation.

Based on these calculation methods, the biaxial loading conditions to be applied to a single fastening system set were calculated as shown in Table 2. The design axle load was set at 150 kN, which is a standard load for conventional lines, and the design forces of the Load A and Load B were also derived. Loading conditions were derived separately using both the proposed method and the conventional method.

### 4.4 Test result and discussion

Figure 12 compares the rail tilting angle and rail displacement while loading using the three methods. The
A single fastening system set

However, overall, regarding the method for calculating biaxial loading conditions, it is safe to say that the proposed method is more suitable than the conventional method when judging from the comparison of the test results.

Figure 13 shows the comparison of rail clip stress during loading at the gauge corner side. Here, the rail clip stress measured on the clip fastened at the gauge corner side was adopted for comparison because stress measured at this point is most severe. A comparison of rail clip stresses on a Goodman diagram, shows that the stress measured in the test using the proposed method agreed more with results obtained on the test track than the stress measured using the conventional method.

Considering these results, the proposed method enables us to reproduce actual track conditions more appropriately than with the conventional method, as is seen from the comparison with the biaxial loading test results on a test track.

5. Validation of the test method for obtaining rail restraint force

In this chapter, the effect of the test conditions such as the loading position, the number of fastening system sets and test temperature, on the result of the rail restraint force tests were verified. A type direct 8 fastening system used for JIS 60kg rail, comprising a rail pad with a steel slide plate of stiffness 60 MN/m, was adopted in each verification test.

Table 2  Biaxial loading conditions to be applied to a single fastening system set

| Items          | Unit | FEM analysis | Practical solution |
|----------------|------|--------------|--------------------|
| Load A Load    | kN   | 64.9         | 40.1               |
| Angle degree   |      | 36.3         | 39.5               |
| Load B Load    | kN   | 35.5         | 30.6               |
| Angle degree   |      | 46.5         | 48.2               |
| Height of the loading position | mm | 80           | 80                 |

Fig. 11  Schematization of biaxial loading conditions

Fig. 12  Comparison of the rail tilting angle and rail vertical displacement

Fig. 13  Comparison of the rail clip stress during loading at the gauge corner side
5.1 Effect of loading position and number of fastening system sets

In order to determine the influence of loading position on results from tests to obtain rail restraint force, three tests were carried out placing the load in three different positions: neutral position, and head and bottom of the rail. Figure 14 shows the three loading positions and Fig. 15 shows the test results.

Of the three obtained results, the rail restraint force closest to the target value was when the bottom of the rail was loaded. Furthermore, when considering real-life situations where rail axis force is generated by thermal expansion, and in order to ensure that in the tests to obtain rail restraint force rail displacement is in the same longitudinal direction, the line along which external force is exerted should be the same as that of the rail fastening restraint force. As a result of the rail restraint test, it became clear that the bottom of the rail was the most suitable loading position.

Next, rail restraint force tests using both a single fastening system set and seven fastening system sets were conducted to grasp the effect of number of sets of fastening system on the test result. Figure 16 compares test results. The difference between the averages of these results was 0.6 kN. When tests were conducted using a single fastening system set, the difference in rail restraint force caused by changing components in the fastening sets between trials was within 0.9 kN. Therefore, it is safe to say that the above-mentioned difference in restraint force was also caused by individual differences between sets. These results made clear that the influence of the number of rail fastening system sets on test results, was very small.

5.2 Effect of rail pad temperature

EN (European Norm) 13146-1 defines the test temperature for when rail restraint force tests are conducted, which is not the case for test methods in Japan. Therefore, rail restraint force tests were conducted at various temperatures to verify its effect.

Figure 17 shows the test apparatus. The test rail with an electric heater was fastened to a type direct 8 fastening system, and rail restraint force tests were conducted while the temperature of the surface of the rail pad was measured to be able to adjust it gradually to the target temperature.

Figure 18 shows the test results. When the fastening conditions were constant by adjusting the axle force of the rail fastening bolts, no significant relationship were confirmed between the rail pad temperature and the rail restraint force between 10 to 45 degrees Celsius, which is a wider range than defined in the EN. Therefore, with reference to SBR rail pads, the effect of the temperature on the rail restraint force was very small while the effect of friction between the rail and the rail pad was relatively dominant.

6. Conclusions

A FEM analysis was carried out using the proposed rail tilting analysis model on a low-stiffness rail support fastening system and the validity of the proposed analytical model was confirmed following comparison with test results from uniaxial loading tests on a test track. In addition, biaxial loading tests were conducted by applying loading conditions calculated through both the proposed FEM analysis and the conventional model; results from these
In addition, in order to optimize the test method, tests for obtaining rail restraint force were conducted under various test conditions relating to different factors such as loading position, number of fastening system sets used and temperature of rail pads, and the effects of these factors were clarified.

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