Estimation of the Transverse Crack Propagation of a Heat Treated Rail

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Rail breakages due to transverse cracks originating from gauge corner cracks have been occurring in heat-treated rails. Railway Operators conduct periodic maintenance by replacing rails, through visual inspection and rail ultrasonic flaw detection. These measures represent a significant cost, creating the need for research on crack propagation. As part of this research, rail bending tests were carried out on rails which have been given artificially introduced cracks on the rail head, to investigate the transverse crack growth rate. In addition, a method was developed for estimating transverse crack growth using FEM. This method was verified by comparing estimated values with actual rail bending test results.

**Keywords:** rail, heat treated rail, residual stress, transverse crack growth rate

1. Introduction

Rails are an important component of railway tracks. Rail maintenance for preventing rail breakage is very important in ensuring railway safety. Rolling contact fatigue (RCF) is one type of failure in the rail head caused by repeated train passage. In recent years, rail breakages due to transverse cracks originating from gauge corner cracks have occurred in heat treated rails in Japan. In order to maintain heat treated rails appropriately, there has been increased research on crack propagation. To date, a significant number of sophisticated crack propagation models have been proposed [1-3]. Generally, elemental test pieces taken from the rail head are used, which means that the properties of transverse crack growth on a full-scale rail have not been so far been sufficiently elucidated.

Figure 1(a) shows the outline of a squat on the rail head. In the process of squat development due to the rolling contact fatigue damage to the rail head, horizontal crack growth occurs, and branches toward the bottom of the rail (hereinafter referred to as “Transverse cracking”). On the other hand, in the head of heat treated rails in recent years, rail breakage due to transverse cracks originating from a gauge corner crack have occurred. Therefore, railway operators conduct periodic visual inspections, rail ultrasonic flaw detection, etc. and install fish plates or ensure timely replacement of rails. However, these measures are expensive, creating a need for research into crack propagation to optimize inspection cycles and measures.

As part of this research, rail bending tests were carried out on various rails with an artificially introduced crack in the rail head to investigate the transverse crack growth rates and tendencies (hereinafter referred to as the “Transverse crack propagation test”). In addition, a method was developed to estimate transverse crack growth by FEM. This method was verified by comparing estimated values with rail bending test results.

2. Transverse crack propagation test

In order to ascertain the growth rate of transverse fractures in the head of various rails, transverse crack propagation tests were carried out using a rail-bending fatigue test machine on actual rails with artificially induced cracks in the top of the rail head. Two test methods were applied:

(1) Transverse crack propagation testing with the rail head pointing down (hereinafter referred to as ‘head down’)

In the transverse crack with the rail head pointing down, in order to develop a transverse crack, tensile stress is generated in the head of the rail by means of a load repeatedly applied to the bottom of the rail. In order to evaluate the influence on the transverse crack growth rate under different rail conditions such as whether it has been used or not in service, whether it has been heat treated or not, whether it has residual stress or not and where the crack is positioned, this test is performed in a simple stress state.

(2) Transverse crack propagation test with the rail head pointing up (hereinafter referred to as ‘head up’)

It is a test in which a static axial force and a repeated vertical load are applied simultaneously to the head of the rail with the head pointing up to develop a transverse crack. This condition is assumed to be the stress state of the rail installed in actual service.
2.1 Head-down transverse crack propagation test

The transverse crack propagation test was carried out, using a rail bending fatigue testing machine as shown in Fig. 2(a), with the rail head pointing down. The specimens in this test are shown in Table 1. Table 2 shows the conditions of this test. In order to investigate the rate of propagation of the transverse crack in the head, head-down transverse crack propagation tests were performed on various actual rails. Annealed rails (reducing the residual stress) were used in the tests to evaluate the effect of the residual stress and heat treated rail with a deviation artificial flaw of 10 mm assuming a gauge corner crack. Scratches were made on the top of the rail head top surface to induce an initial crack. In order to prevent uneven deformation and plastic deformation from occurring at the tip of the artificial flaw, it was produced by electric discharge machining. The stress conditions were set as follows: stress amplitude of 140 N/mm² was generated until an initial crack was generated from the artificial scratch to a propagation depth of about 5 mm (about 10 mm from the top of the head), then the stress amplitude was reduced to 100 N/mm². However, since this was a head-down crack propagation test, it was necessary to distinguish the transverse crack propagation in this test from the propagation in actual rails where temperature stress and variable compression stress from the train load are also applied. To investigate the amount detected by the crack strain gauge attached to both sides of the artificial scratch in the head top surface into the transverse depth.

Figure 3 shows that the fatigue fracture generally spreads out from the artificial scratch in an elliptical shape. Therefore, the crack length detected by the crack gauge was multiplied by the elliptical flattening ratio to obtain the transverse depth.

![Image](image1)

**Fig. 2** Transverse crack propagation test (a) overview of test (b) position of crack gage for central crack location (c) off-center position

| Rail type (50kgN JIS Rail) | Used or not | Annealed | The location of artificial crack | Stress amplitude |
|----------------------------|-------------|----------|---------------------------------|-----------------|
| Ordinary (Non-heat treated) | —           | —        | Centre                          | 100 (N/mm²)     |
| Used                      | —           | Annealed | Centre                          |                 |
| Used                      | Annealed    | Centre   |                                 |                 |
| HHI 340 (heat treated)    | —           | —        | Off center                      |                 |

**Table 1** Specimen conditions

The results of the transverse crack propagation test are shown in Fig. 4, and an example of the fractured surface after the test is shown in Fig. 3. In this case, the horizontal axis of Fig. 6 shows the number of loading cycles, and the vertical axis shows the transverse depth from the top surface. All specimens were broken. The test results are as follows:

(a) As a whole, the transverse crack propagation rate tended to increase as the transverse depth increased.

(b) Fig. 4(a) shows the data for two ordinary rails and two heat treated rails. The crack propagation speed in one heat treated rail was slower than that of the other three. This variation is presumed to be due to the different residual stress of the rail head in each specimen. The effect of the steel type was small compared to other factors to be described later.

(c) As shown in Fig. 4(b), the crack propagation speed in both rails that had been annealed to reduce the residual stress was relatively slow compared with the non-treated products. Although the residual stress of the rail was balanced inside the rail, compression and tensile stresses were present locally, and it is thought that they strongly affected the rate of transverse crack propagation. It is known that tensile residual stress is generated in the center of the rail head. The results of these tests show that the residual stress affects the rate of transverse crack propagation. Furthermore, in this test, there was no significant difference between the new and used rails.

(d) According to Fig. 4(c), there was no clear difference in the transverse crack propagation rate tendency between cases when the artificial crack was at the center of the rail head and when it was off center. Figure 3 however, shows that the fracture occurred in a shallower position in the case of deviation compared to the
case of deviated. This means that when the transverse crack is generated near the gage corner, the rail breaks at a shallower depth.

![Fatigue fracture area](image1)

![Fatigue fracture area](image2)

**Fig. 3** Example of fractured surface after tests (a) when crack is centrally located (b) located off center

![Depth of transverse crack](image3)

![Depth of transverse crack](image4)

**Fig. 4** Results of transverse crack propagation test (a) different rail type (b) effect of residual stress (c) effect of crack position

### 2.2 Transverse crack propagation test with head up

The tests were carried out assuming the stress state of a rail installed in actual service, in a situation where axial forces and vertical loads were applied repeatedly to the rail head with head pointing up.

Transverse cracks from a gauge corner crack in heat-treated rails tend to grow diagonally but at a sharper angle (almost perpendicularly) compared to squats. Therefore, in this test, an artificial scratch similar to the transverse crack was added vertically, offset by 10 mm from the center towards the gauge corner side. Before performing the head-up transverse crack test, the rail head was loaded head down as shown in Fig. 5, to incur an initial crack. The vertical load was repeatedly applied by four-point bending with a support point length of 1000 mm and a loading point length of 150 mm.

Test conditions are shown in Table 3. Examples of the fractured surface after the test are shown in Fig. 6. The tensile axial force is 754 kN (corresponding to a 50°C temperature change), 566 kN (corresponding to 38°C) or 357 kN (corresponding to 25°C). The head bending stress amplitude was 100 N/mm² or 60 N/mm². The specimen in test No. 2 was loaded 2 million times with a tensile axial force of 357 kN and a head bending stress amplitude of 100 N/mm², but the crack did not progress. Therefore, after changing the tensile axial force to 566 kN, the vertical load was repeatedly loaded again.

Figure 7 shows the test results from these tests (relationship between number of loadings and length).

(a) In the test with a tensile axial force of 754 kN, as the head bending stress amplitude was larger, the transverse crack growth rate was also faster (comparison of results from Tests No. 1 and 3).

(b) By comparing the test results from tests using the tensile axial forces of 754 kN, 566 kN and 377kN, and results where the crack did not grow with a tensile axial

![Vertical Load](image5)

**Fig. 5** Transverse crack propagation test (head up)

**Table 3** Specimen conditions in the transverse crack propagation test (head up)

| Test No | Rail type (50kgN JIS Rail) | Used or not | Location of artificial crack | Stress amplitude (N/mm²) | Axial load (kN) |
|--------|-----------------------------|-------------|-------------------------------|--------------------------|-----------------|
| 1      | HH340 Off center            |             |                               | 60                       | 754             |
| 2      | Heat treated Used           | Off center  | 100                           | 377 → 577 (After 2 million cycles) |
| 3      |                             |             |                               | 100                      | 754             |

![The area of fast crack rate](image6)

![](image6)

**Fig. 6** Example of fractured surface after test (a) centrally located crack (b) off-center crack
force of 377 kN, as described above, it is estimated that the transverse crack progress rate is small when the axial force is small. In fact, a comparison of the results from the test using 754 KN and the test using 566 kN, shows that the number of vertical loadings required to obtain a crack length of 25 mm, is smaller. However, the growth rate of the crack after it has reached a length of 13 mm is almost the same due to the slope of the relationship between the number of loadings and the length of the crack. (Comparison of results from test No. 2 and 3).

Figure 10 is a conceptual diagram of the stress intensity factor range and the stress ratio obtained from each stress generated in the head of the rail in the transverse crack propagation test. It is obvious that the crack propagation rate accelerates when the stress intensity factor range \( \Delta K \) and the stress ratio \( R \) are larger, based on the test results (Fig. 3) obtained so far. In the transverse crack propagation test, as the vertical load acts on a state where residual stress exists, a bending stress amplitude of tension is generated at the head of the rail. Since the residual stress has a positive value, the stress intensity factor due to the bending stress amplitude is in the stress intensity factor range \( \Delta K \). \( \Delta K \) has the same value in each transverse crack test because the tensile stress by vertical force was the same in each test.

Next, the stress ratio \( R \) is defined as minimum stress / maximum stress. The stress conditions of the head-down test were as follows;

- **Minimum Stress:** Residual Stress
- **Maximum Stress:** Residual Stress + Bending Tensile Stress Amplitude by Vertical Load

As the tensile residual stress increases, the stress ratio also increases. It is believed that the difference in the stress ratio has a large effect on the difference in the rate of transverse crack growth found in tests on annealed and non-annealed rails.

### 3. Measurement of residual stress

In order to investigate the influence of residual stress on the transverse crack propagation rate, the rail head residual stress inside the rail was measured using the MIRS method.

In recent years, residual stress measurement methods for the inside of various metals have been developed, one of which is the MIRS method. As shown in Fig. 8, a vertical hole is made downwards from the center of the top of the rail head surface, and the diameter of the hole is precisely measured using a micro air probe. Next, the periphery of the hole is cut off in a cylindrical shape to release the residual stress, and finally the diameter of the hole is measured again so that residual stress is measured from the difference between the diameter of the hole before and after cutting. The measurement results are shown in Fig. 9. As a whole, tensile residual stress was observed at a depth of 10 to 30 mm, and the average value in that range was 66 N/mm\(^2\), 72 N/mm\(^2\) for new ordinary rail and a heat treated rail, respectively. From the top surface to the depth of about 10 mm, the change in residual stress in relation to depth is significant.

The principle of relieving stress by introducing a hole

The measurement results are summarized in Table 4.

Measurement of residual stress using the cutting method has already been applied in past studies [4-6], and produced results similar to those found in this research.

The residual stress measurement results were then considered along with results from the transverse crack propagation tests. The residual stress of the annealed rail specimen used in the transverse crack tests was about 0-50 N/mm\(^2\) inside the head, whereas for the non-annealed rail it was about 100 N/mm\(^2\), which is clearly much higher than the annealed rails at the same depth. This suggests that there is an increase in the crack growth rate due to the existence of a larger residual stress.
Table 4  The measurement result of residual stress

| Rail type | Annealed | Measurement Method | Position for measurement (mm) | Residual stress (N/mm²) |
|-----------|----------|--------------------|-------------------------------|------------------------|
| Ordina-ry | -        | Cutting            | The rail head surface         | Around 50              |
|           |          |                    | Inside rail head              | 0                      |
|           |          | MIRS               | Depth 0-10 mm                 | 50-200                 |
|           |          |                    | Depth 10-30 mm                | 45-100                 |
| HH340     | -        |                    | Depth 0-10 mm                 | -50-0                  |
|           |          |                    | Depth 10-30 mm                | 0-80                   |

![Diagram of stress intensity factor range](image)

**Fig. 10** Conceptual diagram of stress intensity factor range and stress ratio

4. Analysis of Transverse crack propagation using FEM

4.1 Verification of the analysis method

In order to understand the transverse crack growth rate of the rail head, using the virtual crack growth method and crack growth analysis system FINAS / CRACK [7] with automatic meshing, and the large scale nonlinear structural analysis system FINAS / STAR [8], a finite element method analysis was carried out.

To verify the validity of the analysis method, an analysis simulating the head-down transverse crack propagation test on a new normal rail was carried out. The analysis outline is shown in Fig. 11. In this analysis, a one-point swing and four-point bending test with a support interval of 1000 mm and a load interval of 150 mm was simulated. A 50 kg N rail was modeled, and the section between the two loading points was made of tetrahedron secondary elements with a mesh size of 5 mm, and other sections 10 mm. The load was repeatedly applied vertically from the bottom of the rail at the center of the rail longitudinal direction. The magnitude of the load P was a maximum value of 120 kN and a minimum value of 10 kN. Vertical displacement was restrained at the two rail support positions spanning a distance of 1000 mm, while the center of one of the two rail support positional areas was constrained in the longitudinal direction. Young’s modulus E and Poisson’s ratio v were used as E = 2.06 × 10^5 MPa and v = 0.3, respectively. Also, the Walker law was used as the fatigue crack growth law. The material properties of the rails obtained through separate material tests were: (C, n, m) C = 3.85 × 10⁻¹², n = 0.62, m = 3.0.

As shown in Fig. 11, the initial crack formed a semicircle of a depth of 5 mm in the longitudinal center of the rail, 10 mm away from the center of the rail on the gauge corner side. The residual stress measurement results obtained for a new standard rail using the MIRS method mentioned above, were applied. In order to verify the validity of the analysis method, a comparison was made between results from the analysis of the ordinary rails, with the test results. Figure 12 shows the relationship between the number of loadings and the transverse crack depth. The analysis results of the residual stress of the new ordinary rail agreed well with the test results of the new ordinary rail, and it was found that this analysis method was effective for predicting the lateral fracture of the rail.

![Diagram of analysis outline](image)

**Fig. 11** Analysis outline (a) Analysis model (b) The position of crack (c) Loading and restraint conditions

![Diagram of relationship between number of loadings and transverse crack depth](image)

**Fig. 12** Relationship between number of loadings and transverse crack depth

4.2 Construction of fracture progress prediction method

From the above examination, it was suggested that this analysis method could be used to predict the development of a transverse crack in a rail. The flowchart is shown in Fig.13. Therefore, the method was used to predict the...
progress of a transverse crack in a rail on a revenue line as described below.

The previously developed crack growth analysis tool 4) was improved, and estimated to propagate the transverse crack. This requires taking into account the characteristics of the train load, track conditions, and thermal stress due to temperature fluctuation. The transverse crack growth analysis was applied to a revenue line as follows:

1. Input track conditions (track alignment, track structure conditions) and vehicle conditions into the vehicle motion analysis software Simpack [9], and calculate the wheel load lateral pressure, the wheel position, and the contact area between the wheel and rail.

2. Crack growth analysis (FINAS / CRACK) Input: Crack (shape, angle, position, etc.), axial force and residual stress crack growth characteristics. The relationship between crack propagation, stress intensity factor range and stress ratio was determined between crack propagation, stress in the rail head displayed a slower progression rate than in non-annealed products. Differences in crack propagation tendencies and transverse crack growth rates between heat treated specimens that were given artificial scratches on the top of the rail head 10 mm off-center towards the gauge corner and specimens given artificial scratches at the center of their rail head surface were examined. A comparison of tests results showed that, specimens with the off-center artificial scratches fractured at relatively shallower depth.

3. Set the annual passing tonnage (the number of times the train traveled in the year \( \times \) train weight), temperature fluctuations, etc. obtained from revenue lines.

4. Calculation of transverse crack development Input: Annual passing tonnage, temperature fluctuations

5. Conclusions

In order to ascertain the rate of transverse crack propagation in heat treated rails, a crack propagation test was carried out on various real rails with artificial scratches added to the rail heads, following which, the crack propagation tendency in each rail was examined. In addition, a method was developed for estimating transverse crack growth using FEM. The results were as follows:

1. Results of the head-down transverse crack propagation test revealed no noticeable difference in the progress tendency and the transverse crack propagation rate between the ordinary rails and heat treated rails. In addition, the transverse crack rate of ordinary rails annealed for the purpose of reducing the residual stress of the rail head was improved, and applied to estimate the propagation of the transverse crack.

2. Head-up transverse crack propagation tests were carried out. Results showed that the rate of transverse crack growth rose as the head bending stress amplitude and axial forces were increased. However, variations due to the influence of residual stress also appeared.

3. Using a model to simulate the actual shape of a rail, an FEM simulation of the transverse crack propagation test was performed using an automatic mesh function that made it possible to take into account the effective stress intensity factor range and stress ratio during crack propagation. A comparison of the test results and results of the analysis showed that the transverse crack growth rate was almost matched, indicating the effectiveness of this method. A lateral crack progress prediction method was proposed that could be applied under various conditions.

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