A Study on Fatigue Strength Improvement for Tension Clamp of Railway Using Work Hardening

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Abstract. Since the tension clamp is essential for the safe operation of trains, the problem of the broken tension clamp must be carefully managed. The damage of the tension clamp can be caused by various reasons such as track conditions and dynamic behaviours of trains. In this paper, the improvement of durability through the improvement of fatigue strength was studied by considering the experiment results and the FE analyses. First, the analytical model was verified by comparing the results of the stress and strain distributions with the initial clamping force and the results of the FE analyses. And then, the method to improve the fatigue strength characteristics was analytically evaluated by considering the behaviour of tension clamp (middle band and spring arm) and work hardening characteristics.

1. Introduction
The tension clamp is a key device that can withstand the various loads acting on the rail, fixes the gauge, reduces the vibration and sinks of the track bed, and plays a very important role in railway derailment safety. Especially, considering the reduction of the maintenance cost of the track, the maintenance of the tension clamp becomes a very important problem in the recent situation where the installation of the concrete bed track with the large demand of the tension clamp increases when compared to the ballast bed track.

Through many researches and developments, the advanced railway countries of the Europe such as England and Germany have supplied various types of tension clamps to meet the track characteristics around the world. The tension clamps are widely used not only in intercity railways including high-speed railways but also in urban railways in Korea.

In the previous study on tension clamp, Lee et al. [1] verified that it is important to secure proper initial clamping force for improvement of durability through experiments and numerical analyses. Choi et al. [2] analysed the behaviour of the tension clamps according to initial clamping condition, load changes due to train operation, linear/curved tracks, and inner/outer gauge differences using experiments and numerical analyses. In addition, Bae et al. [3] compared the stress state of the tension clamp with the initial clamping force by an experiment and a numerical analysis. However, despite many of the above studies, tension clamps sometimes fail due to operating conditions of various trains,
differences in installation and maintenance status of the tracks, so they tend to fail in securing adequate service life as suggested by the manufacturer.

In this study, we tried to find the analytical model verified by comparing the experiment result of the stress and strain distributions with the clamping force (torque) and the finite element analysis result, and then have tried to find a way to improve the durability considering behaviour of the tension clamp and work hardening characteristics.

2. Characteristics of the tension clamp

2.1 Clamping condition of the tension clamp
The model used in this study is the SKL 15 developed by Vossloh, as shown in Figure 1[4].

![Figure 1. Rail fastening system](image1)

When clamping the clamp screw with a proper tightening torque, the middle band of the tension clamp should be in contact with the frame part of the angle guide plate, and the maximum allowable gap is 0.5(mm).

2.2 Failure of the tension clamp
The tension clamp, which must have long-term durability, is the most important component of the rail fastening system. However, in the case of the real field, fractures frequently occur due to various unknown factors. In fact, most of these showed a fatigue fracture behaviour that propagated from the point near the angle guide plate to the inside, as shown in Figure 2 ~ 3.

![Figure 2. Fractured tension clamp](image2)

![Figure 3. Fracture plane of the tension clamp](image3)

3. Experiment of the tension clamp

3.1 Strain measurement location and experiment method
In order to confirm the deformation of the mid-band and the strain at the beginning point of the fracture according to the clamping force, the displacement and the strain were measured by using LVDT and a 3-axis strain gauge, as shown in Figure 4.
In the case of the strain gauge, it was attached to the portion nearest to the point where the fracture started because it was in contact with the angle guide plate. After the comparison with the experiment results of the strain gauge through the FE analyses, the strain at the crack initiation point was predicted.

Figure 4. Experiment of the tension clamp

Figure 5. Strain results of tension clamp according to clamping forces

3.2 Experiment result according to clamping force
As shown in Figure 5 and Table 1, when the clamping force is 300(N·m) or less, no contact occurs, and when the clamping force is removed, the original shape can be restored. But, in the case of over 300(N·m), the bottom of the middle band contacts the angle guide plate, and after the clamping force is removed, the plastic deformation occurs and the original shape can’t be restored.

Table 1. Experiment results of the tension clamp according to clamping forces

| Torque (N·m) | Vertical middle-band deflection(mm) | Natural frequency(Hz) | Contact   |
|-------------|-----------------------------------|-----------------------|-----------|
| 0           | 0                                 | -                     | -         |
| 180         | 11.96                             | 445                   | 565       | X         |
| 220         | 12.93                             | 463                   | 581       |
| 260         | 14.52                             | 468                   | 582       |
| 300         | 19.52                             | 489                   | 625       |
| 350         | 20.00                             | 513                   | 635       | O         |
| 400         | 20.14                             | 527                   | 631       |

4. FE analysis

4.1 FE modeling and analysis condition
In order to precisely analyse of the tension clamp, a FE model is needed to consider various curvatures. So, we constructed a FE model for the numerical analysis of tension clamps using 3D SCAN of the product, as shown in Figure 6.

Modelling is performed by using Hyperworks[5], a commercial software, and it is meshed using a tetra mesh, which is a general solid element. The applied properties are shown in Table 2,[1,2,6] And the analytical conditions were the same as the experiment conditions of the tension clamp, using the displacement equal to the deflection of the middle band in the vertical direction according to the clamping force.
4.2 Comparison of the experiment result and FE analysis result

To obtain the principle strain according to the clamping force of the experiment result, we applied the each direction result of the 3-axis strain gauge to the equation (1).

\[
\varepsilon_{\text{max}} = \frac{\varepsilon_x + \varepsilon_y}{2} \pm \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + \frac{\gamma_{xy}}{2^2}}
\]

When comparing the principle strain of the measurement point with the finite element analysis results according to the clamping force, the error rates were within the acceptable range (within 7.7%) as a whole except for the clamping force of 300(N-m) since the contact with the angle guide plate occurred. Based on this, it was confirmed that the ratio between the measurement point and the maximum strain point was about 1.83 times, as shown in Table 3 and Figure 7.

### Table 2. Mechanical properties of materials

| Properties          | Value      |
|---------------------|------------|
| Density             | 7.85(kg/m³) |
| Tensile strength    | 1,300(MPa) |
| Yield strength      | 1,000(MPa) |
| Young’s modulus     | 200(GPa)   |
| Poisson’s ratio     | 0.27       |

### Table 3. Comparison of the FEM and experiment result

| Torque (N·m) | Vertical middle-band deflection (mm) | Measure point | Max. point |
|--------------|-------------------------------------|---------------|------------|
|              | X-strain (µε) | Y-strain (µε) | Z-strain (µε) | Theoretical max. principle strain (µε) | FEM max. principal strain (µε)[A] | Error (%) | FEM max. principal strain (µε)[B] | B/A |
| 180          | 11.96       | 1100          | 350          | 5600          | 3550                      | 3575      | 0.7   | 6535                      | 1.83 |
| 220          | 12.93       | 1250          | 370          | 6000          | 3842                      | 3895      | 1.4   | 7120                      | 1.83 |
| 300          | 19.52       | 2074          | 173          | 10334         | 6377                      | 5922      | 7.7   | 10826                     | 1.83 |

4.3 FE analysis considering operation condition
In order to check the behavior of the tension clamp during the operation of the train, we measured the wheel load, lateral force, displacement, the strain of the tension clamp, and the vertical displacement of the rail.

Among these, the vertical displacement of the rail, which directly affects the tension clamp when the train passes through, is shown in Figure 8, and it is confirmed that the behavior is within a range of 1(mm).

![Figure 8. Vertical displacement of rail due to running of train](image)

It can be checked that the bottom of the rail moves to downward direction within a range of 1(mm) due to the running of the train while supporting the rail by using the initial clamping force of the tension clamp. And it can also be understood that the stress-strain acting on the tension clamp is lessened by the running of the train after applying the initial clamping force. So, we constructed a FE analysis model using LS-dyna[7], a commercial software, to confirm the equivalent stress range during train running.

The results of the analysis of the von Mises stress range via the displacement control of the spring arm after applying various initial clamping forces to the tension clamp are shown in Figure 9.

![Figure 9. von Mises stress distribution due to initial clamping force and train running](image)
In the case of initial clamping force of 180(N·m) and 220(N·m), von Mises stress distribution can be confirmed up to the yield strength by the initial clamping force, and we can confirm that the von Mises stress decreases when the displacement of the spring arm is moved down by 1(mm). However, in the case of the initial clamping force of 300(N·m), in which the middle band contacts the angle guide plate, it is already exceeded yield strength by initial clamping force and it can be confirmed that the change of the von Mises stress is not too significant even if the displacement of the spring arm is moved down by 1(mm). Therefore, it is considered that work hardening exceeding the elastic range of the material has already been considered as an initial clamping force.

5. Improvement of fatigue strength by clamping method

5.1 Work hardening
In the initial clamping force condition of 300(N·m) in which the middle band contacts the angle guide plate, plastic deformation exceeding the yield strength occurs and a varying dynamic stress is applied to it by the running of the train. In this case, since it behaves near the yield strength of the material, it is sensitive to fatigue and is very vulnerable to small surface defects.

Therefore, fatigue strength is expected to be improved by using work hardening [8] and additional analysis is performed to confirm it.

5.2 Surface plasticity model and elastic recovery model after surface plasticity
For comparison of the surface plasticity model and the elastic recovery model after surface plasticity, we have performed FE analyses according to two scenarios, as shown in Figure 10.

![Figure 10. Displacement control condition according to two scenarios](image)

For the scenario 1 (surface plasticity model), the displacement of middle band was given as 19.52(mm) using the experiment results of 300(N·m), and then the displacement of the spring arm was reduced by 1(mm) considering the running speed of the train.

But, in the case of Scenario 2 (elastic recovery model after surface plasticity), the displacement of the middle band was increased by 21.47(mm), which is 10% more than Scenario 1, and after restoring elasticity to 19.52(mm) and the displacement of the spring arm is the same as the scenario 1.
Figure 11. Comparison of the scenario 1 and 2 results - 200(ms)

Figure 12. Comparison of the scenario 1 and 2 results - 220(ms)

Figure 13. Comparison of the scenario 1 and 2 results - 350(ms)

Figure 14. Comparison of the scenario 1 and 2 results - 475(ms)

Figures 11 ~ 14 are the FE analysis results showing the time-dependent cross-sectional distribution of the major part where the fracture occurred. These are comparison of plastic strain, von Mises stress, and maximum shear stress according to the two scenarios. And Figure 15 shows the variation of the von Mises stresses of the main regions where the fracture occurred.

In scenario 2, compared to scenario 1, the yield strength increased due to the work hardening effect and then, it can be confirmed that the range of stress variation due to the displacement of the spring arm is the same, but the variation is relatively lower portion when compared with the scenario 1.

Figure 15. Comparison of von Mises stress distribution of major parts by two scenarios

Figure 16. Comparison of Goodman diagram results of major parts by scenario
The fatigue strength is calculated by using the Goodman diagram, as shown in Figure 16, and it can be confirmed that the scenario 2 shows a relatively safe range because its yield strength is increased when compared with the scenario 1.

6. Conclusion
In this paper, the fatigue strength improvement considering experiments of the tensile clamp, FE analyses, and work hardening effect was studied. The results are as follows.
(1) The experiment was performed to confirm the strain distribution according to the clamping force of the tension clamp. At the clamping force of over 300(N-m), the bottom of the middle band was contacted to the angle guide plate, and when the clamping force was removed, it was confirmed that plastic deformation occurred.
(2) The FE analyses were performed using the accurate shape information of the tension clamp via 3D SCAN to verify the analytical model by confirming the similarity between the FE analysis results and the experiment results. And then the strain distribution of the part where the maximum strain occurred is predicted.
(3) As a result of the analysis of the initial clamping force condition of 300(N-m) proposed by the manufacturer, due to the variation of stress activated from the train, it behaves near the yield strength of the material, so it is sensitive to fatigue and is very vulnerable to small defects on the surface.
(4) In order to improve the fatigue weakness, analytical evaluation was performed considering the effect of work hardening.
It is expected that the durability can be improved if the tension clamp is fastened to use the work hardening effect, as suggested in this study.

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