Study on Behavior Characteristics of Turnout and Bridge

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Abstract

When CWR (continuous welded rail) turnout is installed on a viaduct, thermal stress exerted by the expansion of deck on the viaduct can cause rail buckling and break. This additional stress may cause anti-creeper damage between tongue rail and stock rail, and get worse the stability of train operation. Therefore, it is important to ensure stability of axial force through comprehensive consideration on interface between viaduct and the CWR turnout on viaduct.

A numerical analysis program was developed to analyze axial force and displacement of turnout considering interface between a viaduct and a turnout. The program also makes it possible to examine the influence of track resistance of turnout sleeper, and lateral resistance of fastener. Also, the program can be extensively used to evaluate the effects of anti-creeper to give limitation on excessive relative displacement between stock rail and lead rail. Validity of the developed program was verified by comparing the analysis results with general FEM analysis program - LUSAS, as well as the field test results for the turnout installed on the bridge of Pyeongnae station.

Variation of track resistance forces with varying according to different sleeper lengths were obtained by field tests. Using the test result, an estimated formula for factors on track resistance force was determined, and it was considered in numerical analysis for turnout.

And using the developed program, the parametric study was conducted to clarify the main influence factors on axial force and displacement of turnout. The viaduct type, presence of turnout, turnout location, turnout type, longitudinal resistance of fastener, and continuity of rail in turnout were considered as main parameters.

From results of this study, the following criteria for turnout installation were suggested:

- All rails in turnout are recommended to be CWR.
- When a rail expansion joint is required by excessive axial force, the REJ should be installed at least 100m apart from the end of the turnout.
- A turnout is not recommended to be installed on a movable bearing of viaduct.
- A turnout is not recommended to be installed over an expansion joint of viaduct.

1. Introduction

Following the result of study that the CWR axial force increases by 35% or more(1) as the turnout is extended in the general embankment, turnout couldn’t be completely extended so far because of concerns in securing buckling stability. CWR installation on the turnout section is located preferably on the embankment or rahmen bridges, lower structure of which is relatively stable.

Recently there has been increasing number of viaducts and tunnels since a straight section of track is one of the critical factors for ensuring top speed in terms of track alignment. Even the plans of under-rail station where station is built below the elevated bridge tend to increase. Thus, in such under-rail stations, turnout and cross over that are essentially required at the front and rear of the station are often witnessed on viaducts instead of embankment because of its geographical condition. Yet, when installing turnout on a viaduct, there are more risks of occurring buckling or breakage owing to additional axial force arising from thermal stress exerted by expansion or contraction of bridge deck in addition to the extra axial force that occurs by the interface between stress stock rail and lead rail.

Therefore, in order to install turnout on the viaduct, it is essential to prepare safe design through precise analysis, for which it is important to develop the analysis technique that enables to simulate the site condition in relation with number of decks, number of shoe per deck, location of fixed and movable stand, length of deck, distance between fixed points, locations of rail expansion joints,
number of turnouts, type of turnouts, characteristics of longitudinal resistance of switch sleeper and turnout sleeper and fastener in relation with the viaduct. These are the critical factors exerting influence on the interface between turnout and structure. Furthermore, in the analysis method, the essential loads such as temperature load, starting/braking loads, vertical load that basically cause interface should be considered. Recently the elastic turnout installed on the existing railway incorporates the anti-creeper specially designed to limit the excessive relative displacement between stock rail and lead rail, and such influence should be taken into account. Especially, the accuracy and adoptability at site of the analysis technique needs to simulate the longitudinal resistance force of switch sleeper that exerts critical influence on the interface between turnout and viaduct. For this, it is necessary to model the longitudinal resistance force of switch sleeper through site measurement.

In this study, the elements that exert influence on the interface between viaduct and turnout suggested as above was observed, parameter research was carried out using numerical analysis program, and finally the technical standards at the time of designing the turnout on the viaduct was intended to be established based on such result of research.

2. Basic Theory of Viaduct/Track Interface

2.1 Modeling of Resistance Force of Ballast
Track longitudinal resistance force is the force of track per unit length resisting against the longitudinal displacement, which is a critical element that exerts influence on the track/viaduct interface. It varies depending on track structure, loading or unloading, degree of maintenance of ballast or ballastless track, track installation method, loading frequency, etc. When measuring the track longitudinal resistance force on site, it shows non-linear characteristic depending on the rail longitudinal displacement (u) as shown in the Figure 1, resulting in different features by sleeper locations and places having the width in variety more or less. When analyzing the interface of track/viaduct, it can be shown in bilinear shape as indicated in continuous line to simplify the calculation. Bilinear shape is an important factor to decide the characteristic of track longitudinal resistance force, which is the correlation between marginal displacement(uo) and final friction force (Fo), and the longitudinal resistance force within the marginal displacement gets increased in linear manner, but the size is expressed in a certain friction force at the marginal displacement or more.\(^2,3\) When analyzing the interface of rail/viaduct, the value of the Figure 1 as per the track and loading condition, but 20.0kN/m is applied when reviewing rail stress, while 12.0kN/m when reviewing the structure displacement.

![Fig. 1 Load-displacement curve by track type and loading condition](image)

2.2 Track/Viaduct Interface Element
Interface between track and viaduct is acquired through gravel ballast. For the resistance force of ballast where the longitudinal displacement that occurs on the upper place to the viaduct depending on the rotating displacement of viaduct taken into account, as shown in the Figure 2, it can be modeled by uniting the rigid link from viaduct deck neutral axis to the upper plate of viaduct and
bilinear spring. However, in this way, such modeling work takes time and efforts, and therefore it is required to develop the method of modeling the resistance force of ballast with a certain interval in convenient way. Interface element is the element developed to model the resistance force of ballast with a certain interval conveniently. A force of interface is activated through the ballast when longitudinal and rotating displacement of viaduct deck and longitudinal displacement of rail occurs, and such force is expressed into an element.

In case of considering the behavior of axial direction only without vertical load of vehicle in analyzing the longitudinal interface of track and viaduct, it can be modeled as shown in the Figure 3. In this case, the formula on the force of elastic area and displacement in the element of interface between rail and viaduct can be expressed as (1).

\[
P = \frac{kL}{6} \begin{bmatrix}
2 & 1 & -2 & 0 & -2h & -1 & 0 & -h \\
1 & 2 & -1 & 0 & -h & -2 & 0 & -2h \\
-2 & -1 & 2 & 0 & 2h & 1 & 0 & h \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-2h & -h & 2h & 0 & 2h & h & 0 & h^2 \\
-1 & -2 & 1 & 0 & h & 2 & 0 & 2h \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-h & -2h & h & 0 & h^2 & 2h & 0 & 2h^2
\end{bmatrix} \begin{bmatrix}
U_1 \\
U_2 \\
U_3 \\
U_4 \\
U_5 \\
U_6 \\
U_7 \\
U_8
\end{bmatrix}
\]
Here, \( k \) is the spring constant defined as the force inducing unit displacement in longitudinal way related with the unit length of the rail, where \( U_i \) is the node displacement. When in the plastic region, load vector is given as the formula (2).

\[
\begin{bmatrix}
P_1 \\
P_2 \\
P_3 \\
P_4 \\
P_5 \\
P_6 \\
P_7 \\
P_8 \\
\end{bmatrix} = \frac{(\Omega_{max}L)}{2} \begin{bmatrix}
1 \\
1 \\
-1 \\
0 \\
0 \\
-1 \\
0 \\
0 \\
\end{bmatrix} 
\] (2)

Here, \( k \) is the longitudinal resistance force of the track and \( L \) is the length of the interface element. Assuming the length of interface is short, one element can be assumed to have elastic region or plastic region only. Here, to judge whether the interface element is in the elastic and plastic regions or not, the following formula can be used.

\[
\left| \frac{(U_1 + U_2)}{2} - \frac{(U_3 + hU_5) + (U_6 + hU_8)}{2} \right| = \delta_u 
\] (3)

\( \delta_u > u_o \) : plastic region, \( \delta_u \leq u_o \) : elastic region

3. Analysis of Interface of viaduct/turnout

3.1 Resistance Force of Ballast in the Turnout Section

In calculating the ballast forces of resistance of ballast, if the share ratio assigned to each face of the sleeper is clarified, it is possible to design the feature sleeper so as to enhance the resistance force of ballast, and further prepare the technical ground enabling to determine the sleeper exposure limit and change in acceptable temperature taking the rail axial force stability into account during the ballast work.

In testing the measurement of the resistance force of ballast, the gravels at the end plate and side of the sleeper were removed (F1) to check the influence of sleeper weight, gravels at the end part of the sleeper were removed (F2) to check the friction force at the side of sleeper, gravels at the side of sleeper were removed (F3) to measure the friction force of gravel at the end side of the sleeper. Furthermore, measurement was conducted at the state gravels were not removed (F4) to measure the resistance force of ballast per sleeper.

The result of the measurement shows that in case that the ballast was not stabilized after its installation, the influence of gravels was not critical as shown in (a) of the Figure 4, but the influence of self-weight of sleeper was higher. In case of a large number of passed gross-ton and the ballast being stabilized, the friction force of gravels at the side and end part of the sleeper exerted critical influence on the resistance force of ballast as shown in (b) and (c) of the Figure 4.

Therefore, after result of considering the site condition for the transverse force of resistance of ballast against the switch sleeper, and deriving the formula similar to the resistance force of ballast actually worked, the formula (4) was extracted.
For the longitudinal resistance force of ballast for the switch sleeper, the following formula (5) was extracted using the method of RTRI.\textsuperscript{4,5}

\[ F = 1.4W + 2.4\gamma G_e + 29\gamma G_s \]  
(5)

(a) Poor compact ballast (sleeper length 310cm)  
(b) Well compact ballast (sleeper length 287cm)  
(c) Well compact ballast (sleeper length 297cm)

Fig. 4 Measurement results of ballast lateral resistance force for each sleepers in turnout

3.2 Rail fastener longitudinal resistance force

In measuring the longitudinal force of resistance, the force added to the rail fixed at the left side when the relative longitudinal displacement between rail and sleeper starts was measured using the measuring device as shown in the Photo 2. During the measurement, the curved load v.s. longitudinal displacement curve was recorded as shown in the Figure 5.

Photo.2 Test equipment to measure longitudinal resistance of fastener

For this test, the rail specimen in the length of approx. 0.5 ~ 0.6m was fixed to the sleeper bound solidly, and pulling force was added, but special care should be paid so that no displacement occurs.
to the sleeper being bound. Then the load v.s. longitudinal displacement is automatically recorded. The performance on each rail fastener is compared as shown in the Table 1.

Table 2: Performance comparison for each fasteners

<table>
<thead>
<tr>
<th>Item</th>
<th>Front Spring Constant (tonf/cm)</th>
<th>Transverse Spring Constant (tonf/cm)</th>
<th>Fastener Longitudinal Resistance Force (tonf/pair)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pandrol</td>
<td>1.2</td>
<td>130</td>
<td>1.6</td>
</tr>
<tr>
<td>Vossloh</td>
<td>4.0</td>
<td>50</td>
<td>1.3</td>
</tr>
<tr>
<td>Nabla</td>
<td>0.8</td>
<td>-</td>
<td>2.2</td>
</tr>
</tbody>
</table>

3.2 Turnout Section Modeling

Turnout consists of the stock rail with CWR and the lead rail that ends at heel as shown in Figure 6. There are several types of turnout; existing turnout where stock rail and lead rail are rigidly connected on the heel, high-speed turnout where stock rail and lead rail is not connected, and improved turnout where the relative displacement of stock rail and lead rail is limited within a certain extent on the heel. In this study, the connecting system of stock rail/lead rail/sleeper/structure was modeled with spring as shown in Figure 7 to achieve the modeling of all these turnouts. Here, turnout coupler and resistance force of ballast were modeled in bilinear type.

3.3 Sync Program for Stress/Displacement Analysis on the Turnout on Viaduct

Based on CWRAP that was developed to facilitate the analysis of track axial force on the viaduct, a program was developed for the analysis of axial force of the turnout on the viaduct.

In order for the easy analysis of axial force of turnout on the viaduct, GUI(Graphic User Interface) was introduced to the Sync Program, which can be easily used by the site engineer who is not accustomed to finite element model.
When inputting the number of bridge, deck length, length of embankment except bridge abutment that are the influential elements of the viaduct that effects track axial force, elements are divided and node numbers are automatically created. Furthermore, a selection can be made out of 12 conditions including elastic pad method in order to easily consider each different type of shoe condition. In the meantime, the property for track and ballast is determined depending on the type of track in general, and therefore it can be selected from the information that is in the form of database.

4. Numerical Analysis

4.1 Axial Force in Normal Embankment

In case No. 12 cross over is installed on the embankment, the analysis of rail stress and displacement for the stock rail showed higher value in turnout as shown in Figure 9. When the displacement of stock rail was 0.8mm on the heel, the additional axial force of approx. 6.3% occurred.

![Fig.9 Axial force and displacement of rails in turnout on embankment](image)

4.2 Comparison between when turnout exists and doesn’t exist on the viaduct

When comparing the axial forces with and without turnout on the viaduct, the outcome is as shown in Figure 10. That is, it shows 129.3N/mm² when taking viaduct only into account, but 135.4N/mm² when cross over is installed, and in this case the axial force is approx. 27.67N/mm². Relative displacement between rail and viaduct shows the displacement difference of approx. 2 mm at the operating stage where the turnout was installed as shown in (c) of the Figure 10.

Stress of lead rail showed 43N/mm² - the highest level near 310m, which is deemed to have increased as the main line at both sides was rigidly connected by nine (9) long sleepers installed between the cross-over.

![Stress in stock rail](image)
4.3 Influence depending on the turnout position on the viaduct

Assuming the layout of viaduct position at intensive fixed position and intensive movement position (FFMM) as shown in the Figure 10, comparison was made with the heel area location of turnout at each different area.

In case of arranging the turnout heel area at the fixed position of viaduct, the axial force was 133.5N/mm² as shown in the Figure 12, while at the movement position, the axial force was 139.83N/mm² making difference of 6.33N/mm², and therefore it is advantageous to arrange the turnout heel area at the fixed position.

4.4 Influence by the clearance of anti-creeper

In case of installing CWR including turnout, it is the structure of heel area that exert critical influence on the rail stress and displacement. The structure of heel area consists of fixed type, anti-creeper type, and flexible type, as shown in the Photo 3.
In this study, the clearance of anti-creeper was set up in five (5) types such as 0, 3, 5, 7mm, and limitless case considering the structure of heel area. Clearance 0 falls under the fixed type where stock rail and lead rail are rigidly connected at the heel area. Furthermore, anti-creeper type reflected the clearance of anti-creeper in ±7mm, and the medium clearance values such as 3 and 5mm were laid from which the change in axial force was observed. Limitless falls under the case of not controlling the flexibility of lead rail as in the high speed turnout. In case of the stress worked on stock rail, as shown in the Figure 13, as the clearance of anti-creeper increases, stress and displacement worked on stock rail and lead rail reduced. The stress of stock rail depends on the degree of stress of lead rail transmitted to the stock rail. Therefore, as the clearance of anti-creeper is small, rail stress and displacement become larger.
4.5 Analysis of Influence of not installing CWR at the side of turnout of cross over

In the conventional railway, it is normal to install turnout CWR, weld on straight section but couple the joint plate without welding on diverted track of turnout to reduce the additional axial force. As the additional efforts such as track difference by the impact force during the joint section, clearance management, etc., are required, research was conducted on the case of installing CWR including the side of turnout and the case of installing CWR including the side of straight line.

As shown in the Figure 14, modeling was conducted for the northern area of Pyungnae Hopyeong Station, CWR was not arranged at the side of turnover. Under condition of calculating the rail stress, it was put under the condition of 45℃ for the difference of rail temperatures, 25℃ for the difference of viaduct temperature, 7mm for the clearance of anti-creeper and 6mm for the clearance of rail joint.

As shown in the result of analysis in (a) and (b) of Figure 15, the rail stress increases as stock rail and lead rail are rigidly connected when it exceeds the acceptable range of displacement of anti-creeper at the position of anti-creeper.

In the lead rail, as the crossing area was welded, the change in the stress was not great as shown in (c) and (d) of the Figure 15.
4.6 Analysis of influence of rail fastener longitudinal resistance force in turnout

As the weight of the switch sleeper used in turnout becomes heavier, resistance force of ballast also gets higher, and therefore the bearing force can be concentrated on the rail fastener that connects between rail and sleeper. Then, longitudinal resistance force of fastener may cause its displacement and stress. As shown in Figure 16 and Table 2, when the longitudinal resistance force of rail fastener is 21.6kN/m/rail (1.3tonf/pair/rail) and 36.6kN/m/rail (2.2tonf/pair/rail), it was 134.68N/mm² and 182.11N/mm² respectively, showing the increase of additional stress by 35.2%. Accordingly when using the fastener with high longitudinal resistance force, it exerts influence on the stability of buckling.

![Fig. 16 Rail stresses according to longitudinal resistance force of fastener](image)

Table 2: Rail stresses according to longitudinal resistance force of fastener

<table>
<thead>
<tr>
<th>Shoe Longitudinal Resistance Force Per Shoe (tonf/pair/rail)</th>
<th>Unit Length (kN/m/rail)</th>
<th>Max. Compression Absolute Stress (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>21.6</td>
<td>134.68</td>
</tr>
<tr>
<td>1.6</td>
<td>26.6</td>
<td>162.81</td>
</tr>
<tr>
<td>2.2</td>
<td>36.6</td>
<td>182.11</td>
</tr>
</tbody>
</table>

5. Conclusion

When installing turnout on a viaduct, very high level of occurs caused by the flexible temperature of viaduct deck in addition to the extra axial force that occurs by the interface between stress stock rail and lead rail, bringing forth high risks of buckling or split web at rail end. In order to analyze this phenomenon in quantitative manner, it is essential to investigate the factors that influence on rail stress and displacement, and have a program to analyze it. In this study, research on the influential factors was carried out, investigation was implemented on the program to analyze the interface between viaduct and turnout developed by Korea Railroad Research Institute, and then following results were obtained through the research of parameters on viaduct structure, turnout position, turnout type, influence of cross over on non-CWR at the side of turnout, turnout fastener longitudinal resistance force, etc.

1. More correct basis for analysis was obtained by deriving the formula that calculates the longitudinal resistance force of ballast for the switch sleeper that acts important role in the interface of turnout/structure through tests.

2. In case there is a cross over in the general embankment and viaduct, it was confirmed that turnout is a major factor influencing the additional stress.

3. As result of comparing the location of cross over on the viaduct by placing it at operating point and fixed point, it was found that the additional stress at higher level occurred in case of having installed at the operating point. Accordingly it was known that the additional stress can be reduced by installing turnout at a fixed point.
4. As result of reviewing the effect of additional stress taking the structural characteristic of heel area into account, in the structure where stock rail and lead rail are rigidly connected, additional stress increase more, compared to the structure where both rails are in flexible movement. In this case it was also found that the relative displacement between stock rails becomes larger. Absolute displacement between stock rail and lead rail was relatively small though. Consequently, it was known that the structure of heel area where stock rail and lead rail is flexibly moved is advantageous in securing the stability against buckling.

5. In case of CWR on diverted track of cross over, additional stress increases more compared to the case of non-CWR. Nevertheless, as the relative displacement gets smaller, it becomes relatively safer from the adhesion of tongue rail, the perpendicular irregularity of tongue rail, distortion of sleeper, etc., that indicates it is desirable to have complete CWR including the side of turnout.

6. As result of analyzing the longitudinal resistance force of rail fastener in turnout, it was longitudinal resistance force of rail fastener rather than resistance force of ballast by sleeper that govern the stress and displacement, which was different from normal section. This means ballast longitudinal resistance force of switch sleeper is larger than the rail fastener of longitudinal resistance force. From the viewpoint of safety against rail buckling, it was advantageous to use a small fastener with less longitudinal resistance force.

In future study, focus should be made on the buckling strength in relation with CWR turnout. As the track panel rigidity is higher in the turnout, the buckling strength also get larger, so it is difficult to apply the buckling strength method fur the regular section Furthermore, more data can be secured by repeatedly implementing the site test for the turnout on viaduct, based on which it would be possible to compliment the program, exactly investigate the factors and compliment the design criteria.

References

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