A Study of Track and Train Dynamic Behavior of Transition Zone Between Concrete Slab Track and Ballasted Track

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Abstract

When a train is traveling along the transition such as slab and ballasted track, dynamic behaviors of rail system and train are abruptly changed. In R&D project, the newly-developed precast slab track system and track transition between slab and ballasted track was planned to construct in 2006 on the newly-built Jeolla-line. Maintenance demand, settlement and component degradation were predicted by a large dynamic response of rail transit system, so it was need to improve the performance the transition for the mitigation of the dynamic response of track. Some technical remedies, such as the use of gradual pad stiffness transition and auxiliary rail, were suggested, it was necessary to verify the design, before the commercial operation on the site.

In this study, to estimate interface problems in the transition between slab and ballasted track, a dynamic interaction analysis technique was developed. The track and train coupled model was developed for the evaluation of dynamic behavior and the design of newly developed slab track transition on site. A procedure based on time history analysis was presented for solving problems concerning the dynamic interaction considering auxiliary rail and pad stiffness transition. After reinforcement of transition on site, the field tests have been carrying out under operating condition to evaluate the behavior of the transition zone and slab track.

1. Introduction

When a train is traveling along the transition such as slab and ballasted track, dynamic behaviors of rail system and train are abruptly changed. The variation of the wheel load and dynamic behavior take place mainly due to the difference of track support stiffness and the rail irregularity. The fluctuations of wheel load may leads to instability of running track and track deterioration which increase maintenance costs.

In R&D project which aims to develop technologies for the performance enhancement of newly developed track system and software, the newly-developed precast slab track system and track transition between slab and ballasted track was planned to construct in 2006 on the newly-built Jeolla-line. After completion of the laboratory tests, a 650m test track was planned to construct in 2006 on the newly-built Jeolla-line. Track transition was also planned to construct between ballasted and concrete slab track. Maintenance demand, settlement and component degradation were predicted by a large dynamic response of rail transit system, so it was need to improve the performance the transition for the mitigation of the dynamic response of track. Some technical remedies, such as the use of gradual pad stiffness transition and auxiliary rail, were suggested to improve the performance of track transition. It was necessary to verify the design, before the commercial operation on the site. For specific transition design, it is required to evaluate track dynamic response before and after improving track transition. Accordingly, it is required to develop the analytic method with which the behaviors of train vehicle and track can be evaluated quantitatively at transition for the track design.

2. Construction of slab track test section

The slab track and transition were constructed in the summer of 2006 on the newly-built Jeolla-line. After completion of the laboratory tests, a 650m test track was constructed in September
2006 on the newly-built Jeolla-line as shown in Fig 1. The slab track section consist of 236 meter of PSTS slab tracks, transition track 36 meter long between each end of the slab track and the adjacent ballasted track.

3. General of Mathematical Modeling

In the present study, the half model of power car model with one bogie was considered. If the whole composition of train vehicle is considered, the actual motion of vehicle train may be different on long wave irregularity of track. Nevertheless this developed model can be used for the prediction of track and train system.

In this study, to estimate interface problems in the transition zone, a dynamic interaction analysis technique was developed as shown in Fig 2. The track and train coupled model with 5 degree of freedom was developed for dynamic interaction analysis in two dimensional space.

3.1 Equation of Motion

The train vehicle is modeled as a 5-degree-of-freedom lumped mass system comprising the car body, bogie and wheels as shown in Fig 2. The equations of motion for the train model are derived, which considers the motions of power car including bouncing motions. The motion of train is represented by the following expression of degrees of freedom. $q_i$ is denote the vector of degree of freedom.

$$q_i = (y_c, \theta_c, y_{bi}, y_{wi1}, y_{wi2})^T$$

Where, $y_c$, $\theta_c$, $y_{bi}$, $y_{wi}$ are the vertical displacement of car body, rotation of car body, rotation of i-th bogie, the vertical displacement of wheel. $q_i$ denote the vector of degree of freedom and load vector.

The contact mechanism between the wheel and rail was modeled with Herzian nonlinear contact spring.

$$C_H = \sqrt{\frac{32}{9} \frac{1}{A} \left(1 - \frac{v^2}{E}\right)^{1/2}}$$

$$P = C_H \Delta^{3/2}$$

Where, $C_H$, $\lambda$, $E$ is herzian spring coefficient, a value for $\theta = \cos^{-1}(B/A)$, elastic modulus of steel. Train vehicle and track system can be coupled as an integral entity at the wheel/rail contacts.

3.2 Track Transition Model

Rail was modeled as a continuous beam element, which was supported discretely by a rail pad and sleeper. For each discrete supporting point, the sleeper, ballast and subgrade were
modeled as concentrated mass and spring and attenuation supporting the mass at the joint point. In order to simulate track behaviors when train passes the transition zone between concrete slab track and ballasted track, precast slab track was modeled as a continuous beam element and the gradual change of pad stiffness in the track support coefficient was considered. Numerical studies are performed to assess the effect of various parameters of track system considering reinforcement rail, varying pad stiffness and settlement of roadbed.

3.3 The solution of track and vehicle system

The combination of track and vehicle can be regarded as one system. The individual vehicle and track system matrix are combined to formulate a following equation.

$$[M_{\text{total}}][\ddot{u}] + [C_{\text{total}}][\dot{u}] + [K_{\text{total}}][u] = [P]$$

(4)

Where, $[M_{\text{total}}]$ , $[C_{\text{total}}]$ , $[K_{\text{total}}]$ denotes the mass matrices, the damping matrices, and the stiffness matrices of total system. And $\{\ddot{u}\}$ , $\{\dot{u}\}$ , $\{u\}$ are the acceleration, velocity and displacement vectors, respectively. $\{P\}$ is the corresponding force vector containing the wheel/rail interface forces.

$$[M_{\text{total}}] = \begin{bmatrix} [M_u] & 0 & 0 \\ 0 & [M_{uv}] & 0 \\ 0 & 0 & [M_{TT}] \end{bmatrix},
\quad [C_{\text{total}}] = \begin{bmatrix} [C_u] & 0 & 0 \\ 0 & [C_{uv}] & 0 \\ 0 & 0 & [C_{TT}] \end{bmatrix},
\quad [K_{\text{total}}] = \begin{bmatrix} [K_u] & 0 & 0 \\ 0 & [K_{uv}] & [K_{uv}'] \\ 0 & [K_{Tv}] & [K_{TT}] \end{bmatrix}$$

(5)

Where, $[M_u]$ , $[M_{uv}]$ , $[M_{TT}]$ denote the mass matrices of carbody, unsprung and track system. $[C_u]$ , $[C_{uv}]$ , $[C_{TT}]$ denote damping matrices of carbody, herzian contact spring and track system and stiffness matrices respectively. $[K_{uv}']$ $[K_{Tv}]$ mean wheel and rail coupled matrix.

The equation of dynamic equation provided equation (4) was solved in the time domain. A dynamic analysis was conducted with the modified Newmark-$\beta$ method.

4. Dynamic Analysis

4.1 Properties

The dynamic properties of track and vehicle are listed in Table 1. A dynamic interaction analysis was performed considering track irregularities, the change of track modulus. To evaluate track dynamic response before and after improving track transition, dynamic analysis was performed.
Table 1. Properties of model

<table>
<thead>
<tr>
<th>vehicle</th>
<th>track</th>
</tr>
</thead>
<tbody>
<tr>
<td>54979 carbody mass (kg)</td>
<td>60.3 rail mass per unit length (kg/m)</td>
</tr>
<tr>
<td>3500 bogie mass (kg)</td>
<td>3090 x 10^-8 rail bending stiffness (kN/m^4)</td>
</tr>
<tr>
<td>2065 Wheelset mass (kg)</td>
<td>150 x 10^3 rail pad stiffness (kN/m)</td>
</tr>
<tr>
<td>1516 primary suspension stiffness (kN/m)</td>
<td>20.0 rail pad damping (kN s/m)</td>
</tr>
<tr>
<td>30 primary suspension damping (kN·sec/m)</td>
<td>260 sleeper mass (kg)</td>
</tr>
<tr>
<td>940 secondary suspension stiffness (kN/m)</td>
<td>1980 x 10^3 sleeper support stiffness (kN/m)</td>
</tr>
<tr>
<td>40 secondary suspension damping(kN·sec/m)</td>
<td>600 sleeper support damping (kN·s/m)</td>
</tr>
</tbody>
</table>

4.2 The examination in the case of no performance improvements on transition

Figure 4 shows the results of analysis in the case no improvements were applied with 20mm variation of track irregularity. The contact forces, rail accretion and vertical deflection are abruptly changed in transition of slab track and ballasted track. A change in the track vertical stiffness and track irregularities lead to the wheel and track to experience impact load. Dynamic impacts on wheel and rail may develop track irregularity growth. The contact forces and rail accretion are more increased than transition without irregularity.

4.3 The examination in the case of performance improvements on transition

The increasing impact force may results in the damage of track components and the increase of maintenance cost. To reduce the increase of dynamic impacts, a number of remedies may be used to provide gradual stiffness transition. In this study, we considered the use of auxiliary rail, pad stiffness transition. The elastic change of pad stiffness was applied to lessen the subsidence of the track. The stiffness step change is modified with a gradual increase in stiffness. Fig 5 shows the rail deflection diagram for static design in transition. Fig 6 shows the results of dynamic analysis for transition considering the use of auxiliary rail and pad stiffness transition.

Fig 7 (a) and (b) shows the maximum contact force and rail acceleration. The case 1 and case 2 mean the dynamic behavior of track transition according to the train direction (slab track to ballasted track). The case 3 and case 4 express the behavior of the opposition direction (ballasted track to slab track). The case 1 and case 3 means the state no improvements are taken, and others the state improvements, such as auxiliary rails and pad transition, are taken.
If the irregularity is managed within 5mm, the growth of rail irregularity will be reduced and the dynamic behavior of track related to impact load could be reduced.

![Graph showing the relationship between distance and rail vertical deflection in the case of 10-Wheel Load](image1)

**Fig 5.** Static design in transition

![Graph showing contact force and rail deflection versus wheel position](image2)

(a) Contact Force  
(b) Rail Vertical Deflection

**Fig 6.** Dynamic behaviors of transition after improvements

![Graph showing the relation between maximum contact force and rail irregularity](image3)

(a) Maximum Contact Force  
(b) Rail Acceleration

**Fig 7.** Relation between track behavior and rail irregularity in the transition

5. Construction on Test Site

So Test track was constructed on the site. The following performance improvements were applied for the transition. The slab track design at the transition follows the principles of the DB Guideline RiL804 and the provisions of the EBA Certificate.
1) Installation of auxiliary rails
2) Transition of track stiffness
3) Elongation of HBL and FPL layer
4) FPL reinforcement of Geogrid textile
5) Bond between the Precast Slab Frames and the reinforced concrete base for prevention of uplifting Frames

Auxiliary rails were used for the prevention of growing irregularity and the reducing the variation of wheel load. Actually, auxiliary rails enable for train vehicles to operate smoothly between slab track and ballasted track. Auxiliary rails were combined on the precast slab for 5.2 m section and the 30 m rails were extended to the ballasted track. The transition sleepers (German Rheda type, a special B355.3) are use for fasten auxiliary rail and load distribution.

For the uniform and gradual change in track modulus, rail pads with appropriate vertical stiffness were used. The elastic change of pad stiffness was applied to lessen the subsidence of the track by changing the elasticity from 22.5kN to 50kN/mm in 5 steps. The substructure of slab track as HBL layer and FPL layer were elongated for prevention of subsoil settlement.

The ground bearing capacity was reinforced especially by strengthening the lower part of DS 804 through the Geogrid.

The bond between the PSTS Frames and the reinforced concrete base has to be provided by steel dowels. To seal the joint between pre-cast element and the cast in place concrete fill a material was placed at the PSTS Frame opening. The bond between the cast in place concrete base and the HSB layer has to be pro-vided by steel dowels.

Finally, the field tests have been carrying out under operating condition to evaluate the long term behavior of the transtion zone and slab track. After construction, there was train passage in the transition. To test the track system, field measurements are carrying out on the site under regular operation conditions to evaluate the long term behavior of permanent way systems under operating conditions. There have been no abnormal responses of track transition. Only some void sleepers were founded, so we conduct maintenance.

6. Conclusion

In this paper, train/track interaction analytic method was developed to estimate interface problems in the transition between slab and ballasted track. We analyzed the dynamic behavior before and after improving the performance of track transition. As a result of analysis, it is deduced that technical remedies for transition are necessary. So the gradual pad stiffness transition, auxiliary rail, elongation of HBL and FPL layer and bond between the precast slab frames and the reinforced concrete base were applied for track improvements. Track irregularities monitoring and field tests are performed, during monitoring period, there was no abnormal responses of track transition.
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REFERENCE