Analytical Study of the Wide Sleepers on Asphalt Trackbed in Consideration of Nonlinear Contact Condition

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***Abstract*—Recent years, domestic and international interest towards high-speed railway increases dramatically. As a consequence, researchers have shown interested on the track types and upper structure of railway too. Currently, generally used roadbed structure utilizes classical track. This structure has shown drawbacks including increased maintenance costs, train operation/run-ability at high speed, and decrease of passenger comfort. Therefore, many researches were conducted in order to overcome these challenges, by developing a concrete track structure, and asphalt trackbed system. The objective of current study was to evaluate the applicability of developed materials for an asphalt trackbed structure. Frictional force at the attached boundary between the developed asphalt materials and upper concrete slab were assessed for performance evaluation. In the end, nonlinear contact model was developed, according to the result from performance evaluation. A wide sleeper for the actual asphalt trackbed was also designed using a developed non-linear attachment boundary model. Then, the structural safety evaluation was performed at HL-25 train load (the design load). In the case of HL-25 design load, RC wide sleepers showed a limitation on usability due to the tensile stress occurred in the lower part of the slab from the interaction with the asphalt trackbed. PC sleepers, with improved lower part tensile stress using a PC tendon, showed relatively stable structural behavior.**

Keyword-Wide Sleeper, Asphalt, PC Sleeper, High-Speed Railway, Frictional Force

I. Introduction

Current trend in railway system is safety and speed of railway transport. Therefore, focus was on acceleration of train speed, improvement of passenger comfort, and reduction of maintenance costs. In addition, dynamic response of driving train track and the environmental impact were another area of focus. The reduction of noise and vibration of driving train track become a necessity in the railway system. Most of the railway environmental noise and vibration came from the interaction between track and wheel. Therefore, the railroad track was one of the most important factors to influence the safety, economics, and comfort of entire railroad system.

The classical track structure consists of ballast and gravel, and it maintained its safety by friction of pebbles and elasticity of roadbed, which absorb the shock and vibration. This system has been used in worldwide, because of economic reasons (low construction cost) and the simple replacement of track components. However, when used in a long-term basis, the reduction of elasticity of roadbed could cause the deformation of the track. In that case, the maintenance cost increases because of the cumulated track irregularity, which in turn, affects the train drivability, as well as the passenger comfort.

The concrete slab track system typically has high initial construction costs. In order to improve the problems associated with ballasted track and concrete slab track, two main strategies were applied: 1. embedded rail sleepers in the track and/or 2. rail was directly applied to concrete slab. Asphalt track has lower initial investment cost than that of concrete construction. While Asphalt track system requires a precise orbit construction, the maintenance costs after construction decreases significantly, if the track rigidity improved. In a long run, asphalt system does not require a frequent maintenance work, while providing a comfortable ride to the passengers. With these advantages, many researches were conducted in the asphalt track recently, as previously reported in the recent Railroad Research Institute Report [1].

Current work presents the safety evaluation of structural behavior under the possible design load on wide-sleeper structure for asphalt track roadbed structure. For the performance evaluation, the cross-boundary conditions between asphalt track-concrete slabs were experimented, and the new non-linear attachment analysis modelling were developed according to the findings. Finally, 3-dimensional finite element modelling, using a contact boundary condition, on the previously designed wide-sleeper for directly attached wide-sleeper was developed. Then, the structural safety of Heavy Load (HL)-25 train load, which was the current design load, was evaluated. Further, the new wide-sleeper structure was presented.

II. Experimental Test of Frictional Force Between Asphalt-Concrete Slabs

A. *Experimental Test*

For a better understanding of friction contact model between asphalt trackbed and concrete slab, research was conducted under the guidance of Korean Railroad Research Institute (KRRI). The experiment on the friction contact between asphalt roadbed and concrete panel were designed according to a study on friction between slab and different types of concrete pavements [2]. Fig.1 and Fig. 2 showed the appearance of specimens during the actual experiments, and the specification for the attached friction dimension. In this experiment, two major variables were set according to the boundary conditions. The performance evaluation of an improved friction using a non-woven fabric between the asphalt-concrete interface, and a resistance only by the friction of its own, without use of non-woven fabric were each evaluated. Fig. 3 illustrated the experimental test results by using a non-woven fabric condition and without use of non-woven fabric condition at 70 KN of rail gravity load.

Fig. 1. Experimental test of frictional force between asphalt-concrete structures

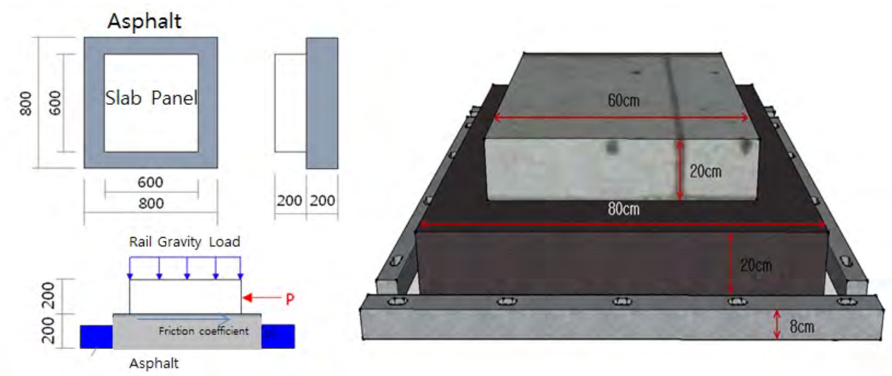

Fig. 2. Experimental test layout

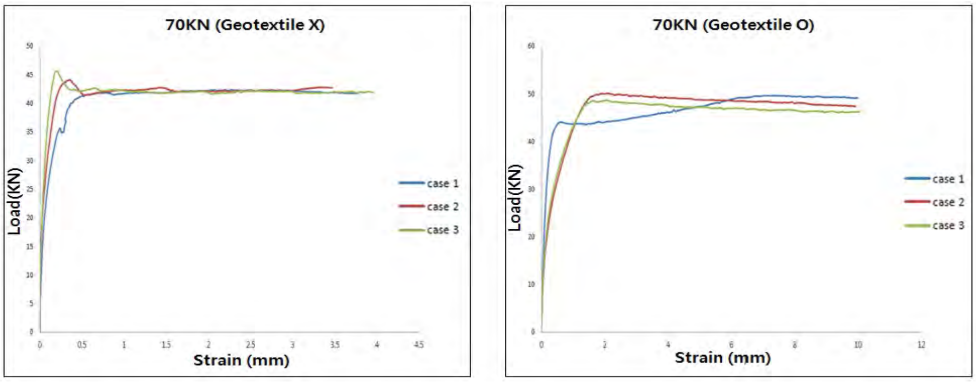

Fig. 3. Experimental test results at 70 KN

B. *3-Dimensional Finite Element Model*

Based on the results from this study, the non-linear 3-dimentional Finite Element (FE) model on concrete slab-asphalt edge was practically modelled using ABAQUS library [3]. For the case of 3-dimensional analysis modelling, same size of specimen were set in the FE package as in the experimental specimen, for a better comparison of results. The ABAQUS 3D model can be found in Fig. 4

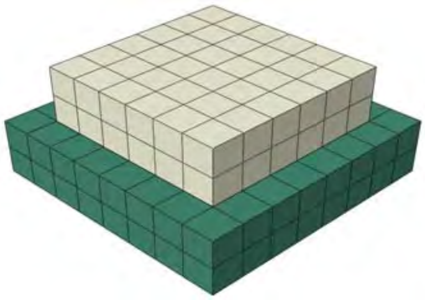

Fig. 4. 3D Finite element model of the experimental test

C. *Validation of Finite Element Model*

In order to build 3-D non-adherence boundary modelling, the FE model for interfacial shear concrete specimen (considered in the actual experiment) was composed of 3-D solid element. For interpretation of the results, displacement control analysis was performed, in a same manner as in the actual experiment. Finally, the boundary force-displacement relationship was investigated. The optimum boundary attachment model was applied for analysis modelling on boundary friction properties, considering the friction coefficients with minimum error between numerical results and each experiment data. As an example, green line shown in Fig. 3 showed high correlation with actual analysis results, relatively. This showed that analysis based on the interpretation data seemed to be a better way. The kinetic friction coefficients was constant in the displacement increase, as shown in Fig. 5. In the region that appeared constant displacement increase, kinetic coefficient was calculated by lateral load. This kinetic coefficient was set as a key variable for contact model in the 3-D non-linear modelling, as seen in Fig. 6.

Fig. 7 showed a comparison between the actual experimental results and the final analysis results derived from the FE model. For the maximum load, about 500(N) differences were reported in the absence of non-woven materials, and this difference was closer to experimental data than what was shown in the presence of non-woven materials. Therefore, the 3-D boundary attached FE model, as presented in this paper, was validated for the reliability of model by comparing the experimental results. This could provide the higher performance prediction and the reliability of results for the design and analysis of the track slab specific for asphalt track, which were currently planned to develop without any elastic pad or fillers.

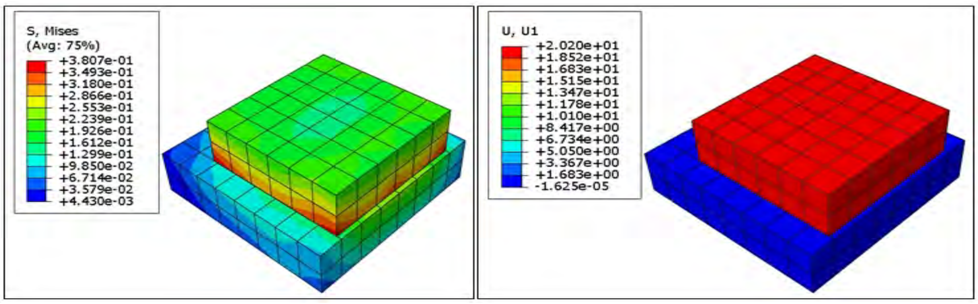

Fig. 5. 3D Nonlinear FE model results

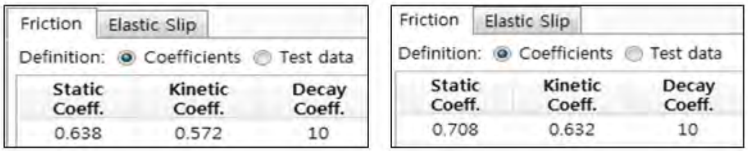

Fig. 6. 3D FE model friction material properties

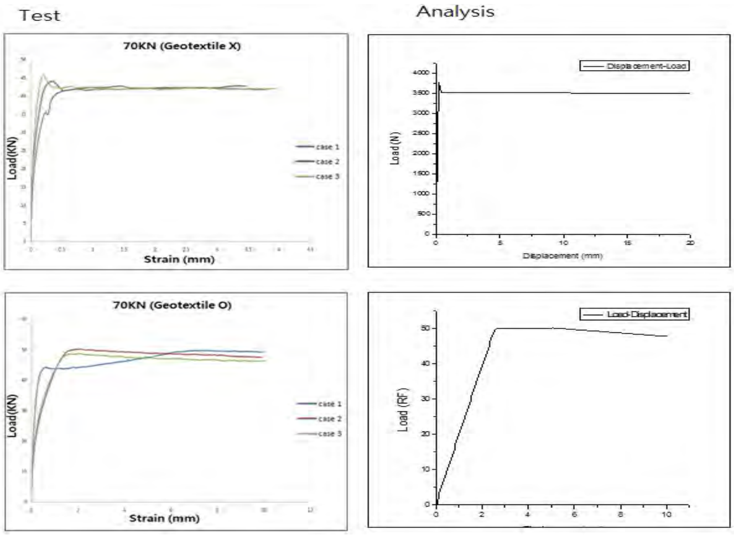

Fig. 7. Validation of the 3D nonlinear FE model

III. COMPREHENSIVE EVALUATION OF A RC WIDE SLEEPER ON ASPHALT TRACKBED

A. Wide Sleeper Dimension

The specifications of wide sleepers used in the proposed 3-D finite element analysis can be found in Table I and II. Fig. 8 showed the details of wide sleepers as an upper structure of the asphalt trackbed. The specifications and properties shown from Table I-III were applied. The necessity of using a 3-D model shown in 3-Dimensional Finite Element Simulations of Ground Vibration Generated by High-Speed Trains and Engineering Countermeasures [4] were based for 3-D finite element modelling of asphalt linear track wide sleeper structures (Fig. 9). In the case of existing asphalt trackbed, visco-elastic material model was applied. This visco-elastic material model was based on the existing road asphalt material model. 3-D non-linear boundary attachment (friction contact) model was applied at the boundary between RC wide sleeper and asphalt trackbed, and the spring model was applied at the fastening and wide sleepers.

TABLE I
Wide Sleeper Dimensions

Concrete Sleeper	Length (L)	500 mm
	Wide (W)	2400 mm
	Height (H)	180 mm
Asphalt Trackbed	Length (L)	13000 mm
	Wide (W)	3000 mm
	Height (H)	300 mm
Concrete Shear Anchor	Height (H)	170 mm
	Diameter (Ds)	100 mm
PC Tendon	Area (As)	6.61 mm^2
	Diameter (Ds)	2.9 mm

TABLE II
Material Properties of Wide Sleeper

	Elastic Modulus (MPa)	Poisson Ratio	Density (t/mm^3)
Slab	31928	0.3	2.452E-09
Rail	200000	0.3	7.5E-09
PC Tendon	200000	0.3	7.5E-09

TABLE III
Asphalt Visco-Elastic Material Properties

Elastic Modulus (MPa)	Poisson Ratio	Density (t/mm^3)	Regression Coefficients	
			C_1	C_2
2000	0.3	2.3E-09	17.947	155.03

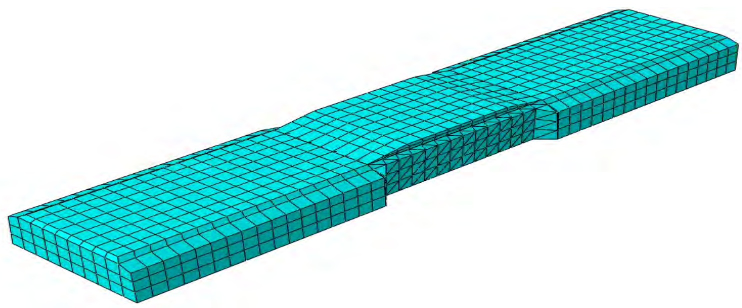

Fig. 8. The FE model of wide sleeper

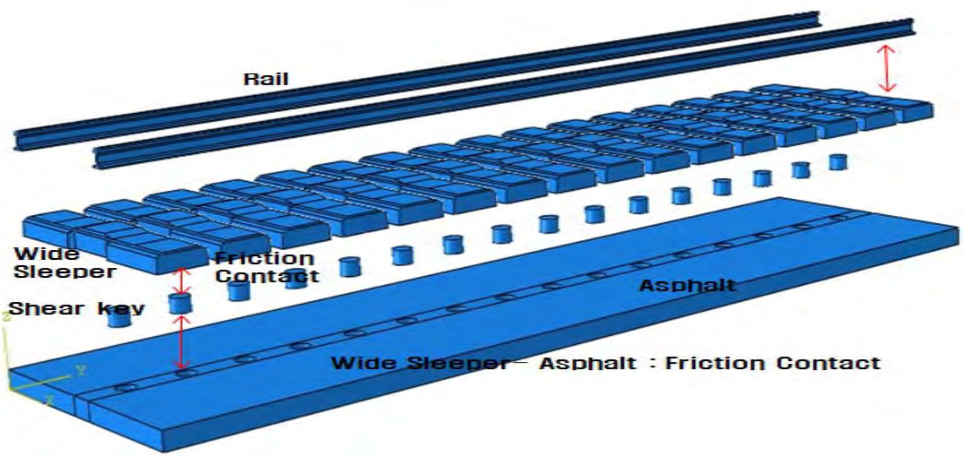

Fig. 9. The 3D FE model of the Track System

B. Loading Condition

The design load (HL-25), widely applied in the Korean high-speed train design [5], was selected for the loading force, and the distance between axis of the vehicle can be found in Fig. 10. In addition, the loading force (P) was implemented using the following equation (1):

$$\begin{aligned} P &= P_o \times i(1 + \Delta P_c / P_o) \\ &= \frac{250kN}{2} \times 1.5(1 + 0.2) = 225\ (kN) \end{aligned} \quad (1)$$

Where, P_o = the half of design axle wheel load (kN)

ΔP = the extra force in curves

i = dynamic impact ratio

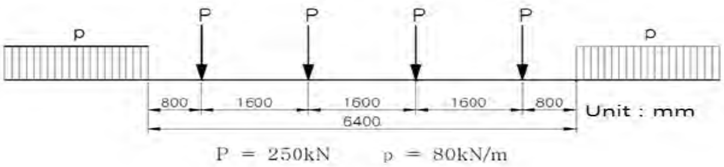

Fig. 10. HL-25 live load for the design

While it was true to assume the impact rate in a reasonable range, the recommended values can be applied when no measured values exists. Therefore, for the simpler analysis, it was calculated using the following equation (2), in consideration of dynamic effects [5].

$$i = 1 + \beta_s = 1 + \beta(n\phi) = 1.5 \tag{2}$$

Where, β= layer level (3.0) and soil layer (1.0)

n = 0.10

φ = 1.63

C. Application of High-Speed Train Load

The actual train load typically has different axle load and axle distance than the design load. Therefore, the program was developed to find the optimum location to maximize the axial load during the evaluation of the impact of actual loadings, in order to minimize the effects from each variable. Fig. 11 showed the methods to calculate the optimum location of train load using an influence-line program. For the analysis of wide sleeper, optimal position was determined first (Fig. 12). Based on the obtained reaction from the axle load analysis of each rail, the actual distributed load on the wide sleepers was conducted and analysed.

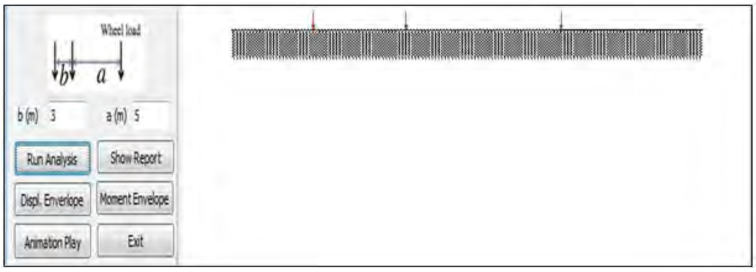

Fig. 11. Influence-line program

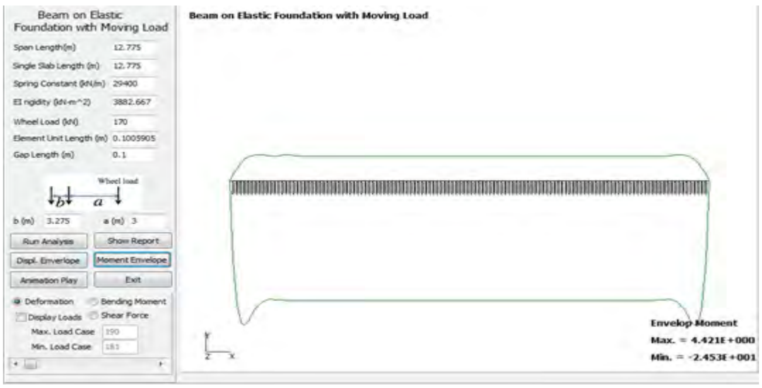

Fig. 12. The location of maximum moment performed by influence-line program

D. Analysis Results

The concrete flexural tensile stress allowance, permitted tensile-compressive stress was evaluated according to the Urban rail technology development report [5], and the Concrete structural design criteria [6]. Fig. 13 showed the analysis results of elastic and visco-elastic model of asphalt material in order to understand the asphalt trackbed behavior, considered in the static analysis. Table IV showed the results considering concrete flexual tensile stress and compressive stress using Reinforced Concrete (RC) sleepers.

As shown in Table IV, for the application of elastic material model and visco-elastic material model on the asphalt trackbed showed similar results in static analysis, unlike the results of dynamic behavior. The behavior as an elastomers were also considered in the actual trackbed, in order to prevent the long-term settlement. Therefore, use of asphalt visco-elastic material model in the static analysis seemed acceptable. For RC wide sleeper, at HL-25 standard live load, it did not come in the range of 1.7MPa, which was the maximum allowable flexural tensile stress. this can lead to a usability problems when applied at the filed. Therefore, in the next section, the study replaced RC wide sleeper with Prestressed Concrete (PC) wide sleeper will be discussed.

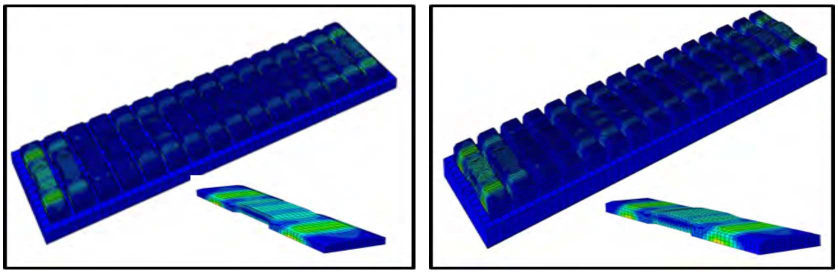

Fig. 13. Stress contour of RC Wide Sleeper by the trackbed material types

TABLE IV
RC Wide Sleeper Stresses

	Allowable stresses	**Elastic Model**	**Stress Check**	**Visco-Elastic Model**	**Stress Check**
Tensile stress	1.70 (MPa)	2.12 (MPa)	NG	2.19 (MPa)	NG
Compressive stress	20 (MPa)	3.74 (MPa)	OK	3.87 (MPa)	OK

IV. NUMERICAL ANALYSIS OF PC WIDE SLEEPER

A. The FE Model of PC Wide Sleeper

The specifications of PC wide sleeper used same specifications as mentioned above (RC wide sleeper), and HL-25 train load was used. The geometric design of PS tendon was the most important factors in the PC sleepers. In this study, PS tendon was reinforced, utilizing the prestressed concrete design concepts [7]. The PC-designed tendon was composed of 4-fold bundle with 2.9mm diameter, and remained 20,000N tension force. Fig. 14 and Fig. 15 showed the details of the PC tendon dimension and design.

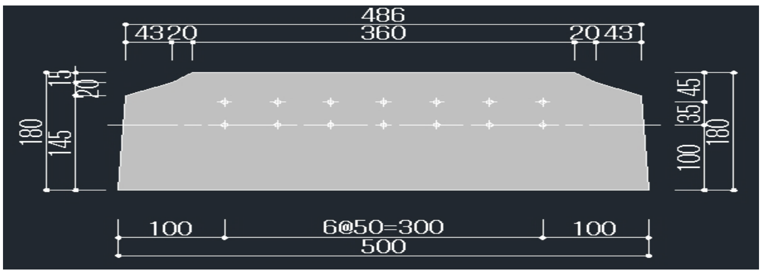

Fig. 14. PC tendon locations

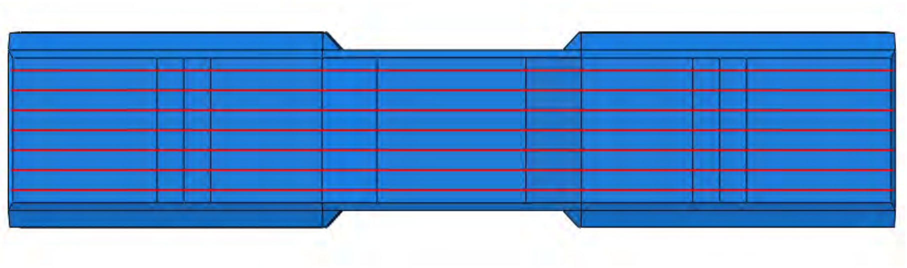

Fig. 15. PC tendon design of the FE model

B. Results of the Numerical Analysis of the PC Wide Sleeper

Fig. 16 showed the stress distribution of PC sleepers according to the analysis. Unlike existing RC wide sleeper, all the stress in the applied area, were transferred to compressive stress by the prestressing force. This showed that the crack prevention effect was at large due to the reinforcement by the tendon. Table V was the review results of stress of PC sleepers, and it was in the range of allowance limit.

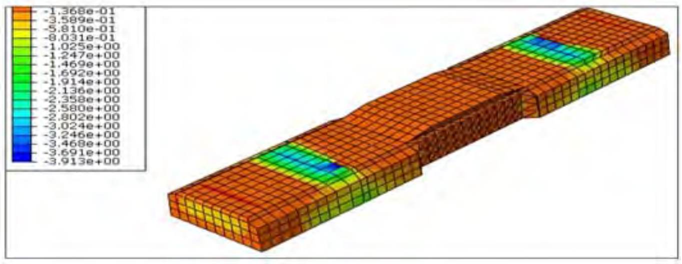

Fig. 16. The stress contour at a PC wide sleeper

TABLE V
PC WIDE SLEEPER STRESSES

	Allowable Stresses (MPa)	Stresses (MPa)	Stress Check
Tensile Stress	1.70	-	OK
Compressive Stress	20	3.19	OK

V. CONCLUSION

This paper focused on the evaluation of the wide sleeper on asphalt trackbed considered by nonlinear contact model. The conclusions of this study were as followings:

- The attached boundary friction experiment on the asphalt-concrete slab panel was conducted in consideration of characteristics of the contact condition. Based on the results, the non-linear finite element modeling on the non-attachment boundary was developed. Developed non-linear attached boundary analysis modeling was validated for its reliability by comparison of actual experimental results. This finding can provide the more precious analysis results for future slab design and structural analysis of asphalt trackbed structure.
- For the asphalt trackbed material modeling, elastic and visco-elastic material model was applied, respectively. No differences were found between elastic and visco-elastic material models in static condition. Therefore, using an asphalt elastic materials specification seemed no problem for the future asphalt trackbed static analysis, because asphalt elastic materials considered road material elastic behavior patterns.
- RC wide sleepers for asphalt trackbed, as suggested from current research, structural safety was not at satisfactory under the allowable stress range at HL-25 load (design load). However, PC wide sleepers utilizing PC tendon, seemed satisfactory as an upper structure for asphalt trackbed.

ACKNOWLEDGMENT

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