Performance-based design method for railway asphalt concrete-reinforced roadbed

Y. Momoya & E. Sekine
Track Structure Division, Railway Technical research institute, Tokyo, Japan

ABSTRACT: The asphalt roadbed (asphalt concrete-reinforced roadbed) is widely used for ballasted tracks in Japan, primarily to firmly support ballasted tracks and to reduce track irregularities. The current design standard of asphalt roadbeds in Japan does not take into account the effects of the number of train passing. To alleviate this drawback, it was necessary to develop a more rational performance-based design method that can reduce the total life cycle cost. It is considered that the new performance-based design of railway asphalt roadbeds should be based on fatigue criteria for asphalt concrete. In the design of pavement for highways, the fatigue criteria of asphalt concrete are specified in terms of maximum resilient tensile strains that are evaluated by multi-layer elastic analysis. However, it is not known whether the same methodology can be applied to railway roadbeds, which are subjected to much more complicated load conditions due to complicated track structures, composed of rails, sleepers and ballast. In this study, a series of scale model tests were performed to validate the three-dimensional elastic FEM analysis to evaluate resilient strains in the asphalt concrete layer in railway roadbed. On the ground of that, appropriate analysis procedure to obtain the asphalt concrete strain was proposed in present study. Thereafter, the service life of asphalt roadbed was obtained by new design method. It was confirmed that the current asphalt roadbed has a service life of 50 years in general high speed line in Japan.

KEYWORDS: railway, asphalt, roadbed, design, FEM.

1 INTRODUCTION

The asphalt roadbed (asphalt concrete-reinforced roadbed), cross section of which is shown in Figure 1, is widely laid under ballasted railway tracks in Japan, primarily to support ballasted tracks firmly and reduce the track irregularities. Furthermore, asphalt roadbeds are designed to reduce the load level in subgrade so that the subgrade is not excessively deformed. In the current design standards of railway asphalt roadbed, the thickness of asphalt roadbed is determined to limit the maximum resilient settlement at the surface of the asphalt roadbed evaluated by the elastic half-space theory to 2.5mm (Sunaga and Sekine, 1994). This current design standard does not take into account the number of train passing. To alleviate this drawback and to develop a more rational performance-based design method that can reduce the total life cycle cost, a new design method of asphalt roadbed was developed. A performance-based design method has been applied to asphalt concrete pavement for highways, in which the service life of the asphalt roadbed is determined based on a fatigue criterion of asphalt concrete layer. It is considered that the new performance-based design of railway asphalt roadbed should also be based on a similar fatigue criterion for asphalt concrete. For the basic study to introduce fatigue criterion of asphalt concrete into the design of railway asphalt roadbed, deformation characteristic of railway asphalt roadbed was investigated in this study.

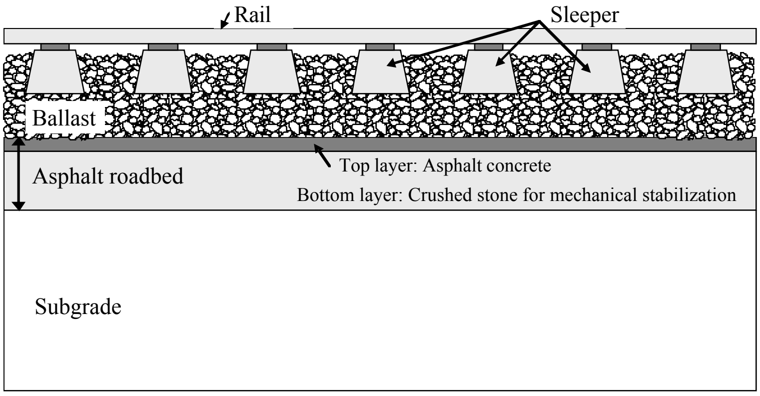

Figure1: Typical cross-section of railway asphalt roadbed.

In the design of pavement for highways, a fatigue criterion of asphalt concrete is specified in terms of maximum resilient tensile strains that are evaluated by multi-layer elastic analysis. However, railway asphalt roadbeds are subjected to complicated load conditions due to complicated track structures, composed of rails, sleepers and ballast. In order to apply the fatigue criterion of asphalt concrete, it is necessary to clarify the resilient deformation characteristics of asphalt roadbed under repeated loading.

To investigate the deformation characteristics of railway roadbeds, fixed-point loading tests have frequently been conducted by applying a repeated load to the same point of a rail (Momoya et al., 2002). However in fixed-point loading tests, there is an inevitable problem in that the settlement of the sleeper beneath the loading point becomes greater than that of adjacent sleepers (Hirakawa, 2002). As a result of fixed-point loading test, maximum load applied to the sleeper beneath the loading point gradually decreases with repeated loading. Therefore, fixed-point loading cannot evaluate resilient deformation characteristic of railway roadbed properly. To alleviate this drawback, a moving-wheel loading method was developed to move a wheel on the rail at a constant load, simulating the traveling trainload on a railway track. To obtain resilient deformation characteristics of asphalt roadbed, the resilient deformation in the scale model test was simulated by three-dimensional FEM.

On the ground of the result of moving-wheel loading test and its simulation, a procedure to obtain proper maximum resilient strains of asphalt concrete layer in asphalt roadbed was discussed. Thereafter, a new design method to estimate the service life of railway asphalt roadbed was proposed.

2 MOVING-WHEEL LOADING TEST

2.1 Test method

Figure 2 shows the model test apparatus developed for moving-wheel loading test, in which a loading wheel moves back and forth repeatedly at a speed of 60 cm/min between the ends on a pair of rails. The wheel load was applied constant load by using air cylinder. The model scale was 1/5, which was composed of two rails, fifteen sleepers, an asphalt roadbed and subgrade.

Figure 3 shows the longitudinal cross section of the scale model in detail. In a prototype track, an asphalt roadbed is composed of an asphalt concrete top layer and a crushed stone bottom layer. In this scale model, the asphalt roadbed was made of CA (cement asphalt) mortar for the asphalt concrete layer and sandy gravel for the crushed stone layer. The subgrade was made of gravelly sand, which is used in the construction of railway embankment.

The thickness of top layer (asphalt concrete layer: CA mortar in the scale model) was 1cm and that of bottom layer (crushed stone layer: sandy gravel in the scale model) was 3 cm. The thickness of the subgrade was 20 cm. The length of the scale model was 200 cm and the width was 30 cm. Firstly, the case without ballast layer was carried out and then the case with ballast layer was carried out to investigate the effect of the existence of ballast layer on the strain of asphalt concrete top layer in asphalt roadbed.

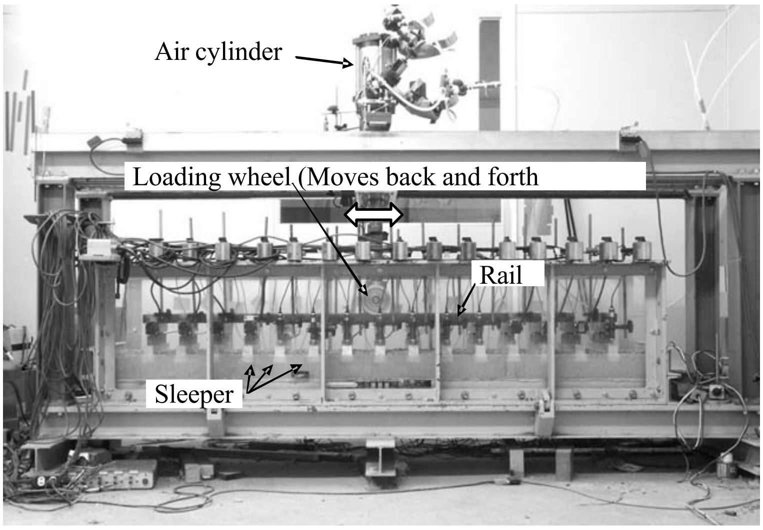

Figure2: Moving-wheel loading test apparatus.

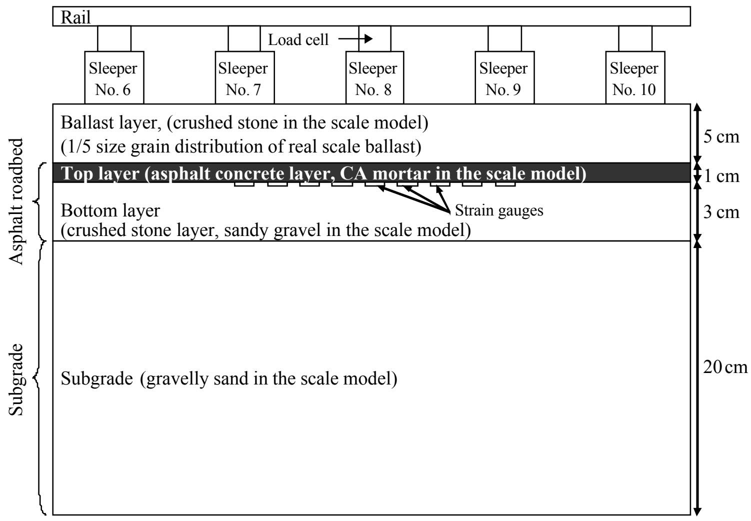

Figure3: Longitudinal cross-section of scale model.

2.2 Resilient deformation characteristics of asphalt roadbed under moving-wheel loading test

It is important to investigate the resilient deformation characteristics of railway asphalt roadbed under repeated moving-wheel loading because the fatigue criterion of asphalt concrete layer is specified in terms of max imum resilient tensile strains.

Figure 4 shows the transition of vertical d isplacement amplitude of sleeper and asphalt roadbed at the center of the scale model by the number of repeated moving-wheel loading cycles. At the beginning of the 1.5 kN -wheel load moving-wheel loading, the sleeper vertical displacement amplitude slightly decreased due to the increase of stiffness in ballast layer. On the other hand, vertical displacement amplitude of asphalt roadbed was almost constant. With the increase of wheel load up to 3 kN, the sleeper and asphalt roadbed vertical d isplacement amplitude increased to approximately twice value linearly.

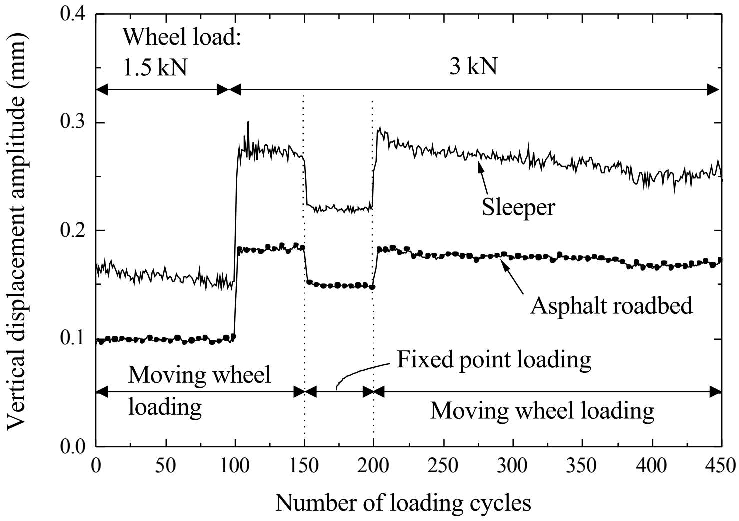

Figure4: Vertical displacement amplitude of sleeper and asphalt roadbed.

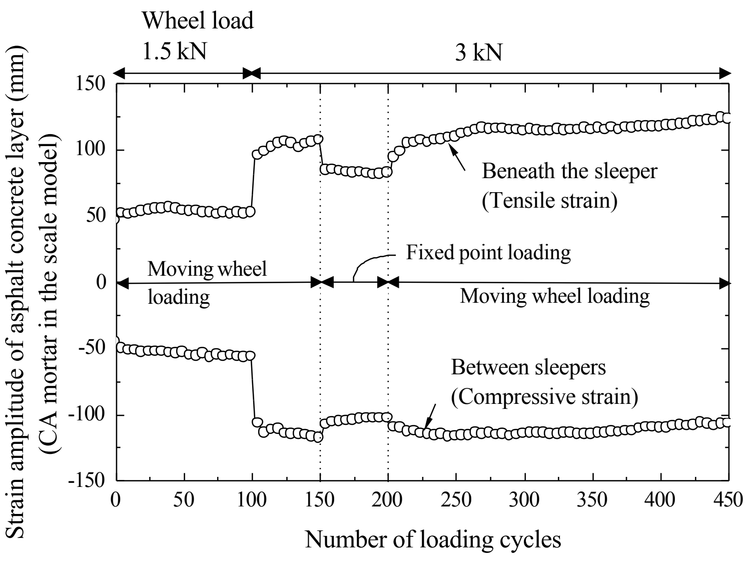

Figure5: Strain amplitude of asphalt concrete layer.

During otherwise 3 kN-wheel load moving-wheel loading, fixed-point loading was carried out applying a repeated load to the same point of a rail. The vertical displacement amplitude of sleeper and asphalt roadbed decreased immediately after starting fixed-point loading. This is due to the decrease of the vertical load applied on the sleeper beneath the loading point. In fixed-point loading, due to a rigidity of rails, the load distribution pattern among different sleepers about the loading point changes with cyclic loading, resulting into non-uniform resilient and residual settlements among different sleepers. The vertical displacement amplitude of sleeper in moving-wheel loading after fixed-point loading increased again with gradual decrease of amplitude due to the increase of stiffness of ballast layer. The vertical displacement amplitude of asphalt roadbed was almost constant also under the 3 kN-wheel load moving wheel loading.

Figure 5 shows the transition of horizontal strain at the bottom of asphalt concrete layer (CA mortar in the scale model). The strain of asphalt concrete layer just beneath the sleeper was tensile, and that between the sleepers was compressive. The magnitude of the strain was almost constant during moving wheel loading test.

Those results showed that the resilient deformation of railway asphalt roadbed under the moving wheel loading is almost constant condition even the repeated wheel load was applied on the rail.

2.3 Simulation of the scale model test by FEM

Figure 6 shows the FEM model to simulate the resilient deformation characteristics of the scale model described above. The FEM model was three-dimensional and the physical properties of the asphalt roadbed and subgrade materials were determined from the results of unconfined compression tests and triaxial compression tests. Figure 7 shows the maximum resilient strain of asphalt concrete layer in the case with and without ballast layer with 4-cm thick asphalt roadbed. From the results, it was confirmed that the FEM model properly simulated the strain in the scale model tests. Although the asphalt roadbeds are subjected to complex railway track structures, three-dimensional FEM becomes an effective method to obtain the accurate resilient strain of asphalt concrete layer. Therefore, by introducing three-dimensional FEM to estimate the resilient strain of asphalt concrete layer in railway asphalt roadbed, it becomes possible to apply fatigue criterion of asphalt concrete to the design of railway asphalt roadbed.

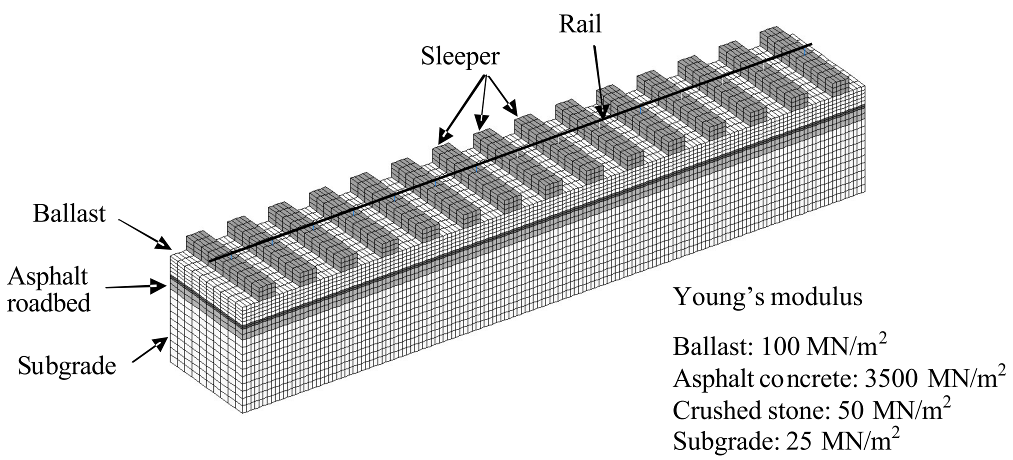

Figure 6: Three-dimensional FEM model to simulate the scale model test.

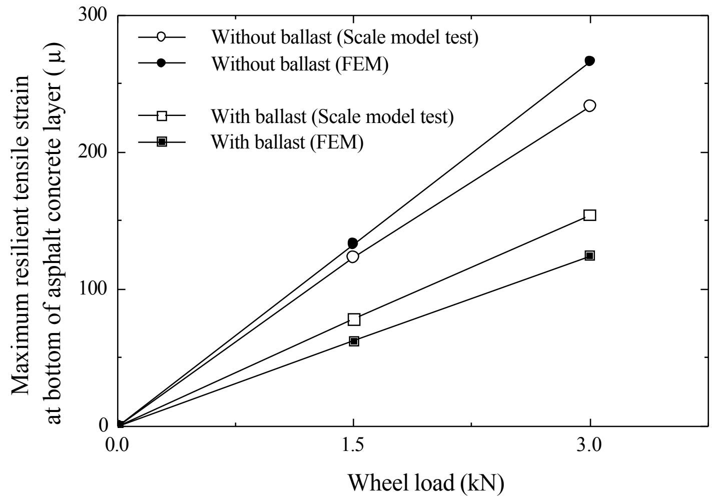

Figure7: Maximum resilient strain of asphalt concrete layer in the scale model test and FEM

3 PERFORMANCE-BASED DESIGN METHOD OF ASPHALT ROADBED

3.1 FEM model

Figure 8 shows three-dimensional FEM model to investigate the resilient deformation characteristics of prototype asphalt roadbed. Sleeper, ballast, asphalt roadbed and sub grade were modeled by solid elements and a rail was modeled by a beam element. The model was 1/4 symmetric to decrease the number of elements. The parameters for the FEM are described in Table 1. The wheel load of 80 kN was applied to the rail at the point of bogie axle.

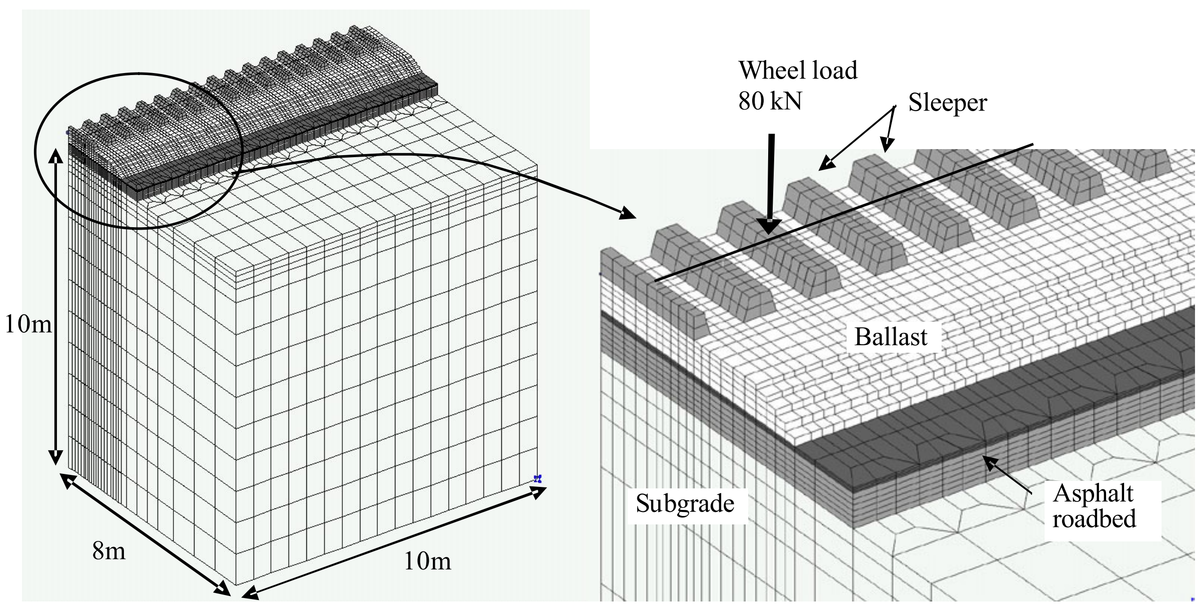

Figure8: Three-dimensional FEM model of prototype asphalt roadbed

Table1: Parameters for FEM

	Young's modulus, E (MN/m^2)	Poisson's ratio, ν
Rail	210000	0.3
Sleeper	35000	0.2
Ballast	100	0.3
Asphalt Concrete	1000～10000	0.3
Crushed stone	180	0.3
Subgrade (K_{30} = 70 MN/m^3)	42.6 (depth: 0-3m) 85.2 (depth: 3-10m)	0.3
Subgrade (K_{30} = 110 MN/m^3)	67.0 (depth: 0-3m) 133.9 (depth: 3-10m)	0.3

3.2 Deformation characteristics of asphalt roadbed in FEM analysis

Figure 9 shows vertical displacement at the surface of asphalt roadbed. The displacement of asphalt roadbed distributed to wide span of 6-9 m. Although the displacement of asphalt roadbed became smaller with thinner asphalt roadbed, its effect was not significant. On the other hand, as shown in figure 10, the strain at the bottom of asphalt concrete layer became largest just beneath the sleeper under the position of loading wheel. The distribution pattern of asphalt roadbed displacement and asphalt concrete strain was substantially different. The magnitude of strain in asphalt concrete significantly became smaller with thicker asphalt concrete layer.

Figure 11 shows the maximum tensile strain of asphalt concrete in the direction of parallel to rail, perpendicular to rail and maximum principal strain. The magnitude of the principal strain became larger than the strain in the direction of parallel to rail or perpendicular to rail. In the railway asphalt roadbed, the direction of the maximum principal strain does not coincide with the direction parallel to rail or perpendicular to rail. Therefore, to apply fatigue criteria of asphalt concrete to the design of railway asphalt roadbed, it is necessary to obtain maximum principal strain by three-dimensional FEM.

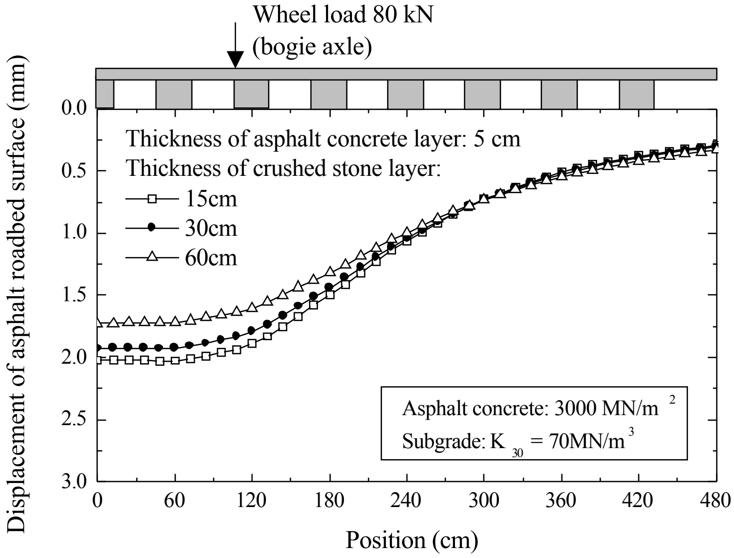

Figure9: Vertical displacement of asphalt roadbed surface

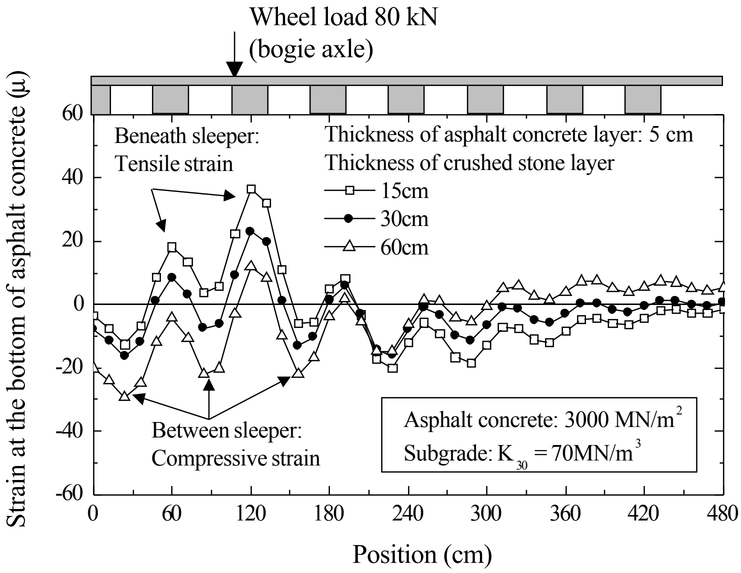

Figure 10: Strain at the bottom of asph alt concrete layer

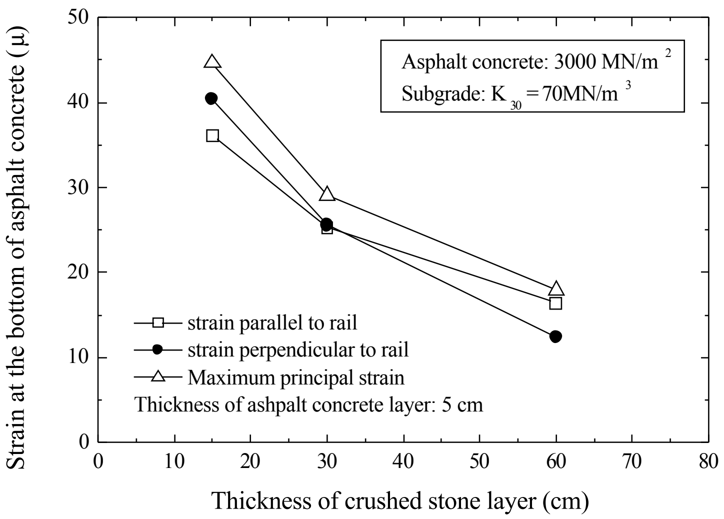

Figure 11: Maximum tensile strain at the bottom of asphalt concrete layer

3.3 New design method for railway asphalt roadbed

The new design method for railway asphalt roadbed should be based on fatigue criteria of asphalt roadbed. However, in the railway asphalt roadbed, maximum resilient strain of asphalt concrete is always generated at the same point of asphalt concrete layer, because the positions of sleepers are fixed. On the contrary, in the case of highways, locus of running wheels scatters by each vehicle. Tsuchida and Maruyama (2000) showed that the number of load applications to cracking decrease to approximately 60 % without scattering of wheel running locus. Therefore, a fatigue criterion for asphalt concrete layer in railway roadbed should be expressed by an equation (3.1) and (3.2), based on the fatigue criteria of asphalt concrete proposed by Asphalt Institute.

$$N_A = 0.6 \times 18.4 \times C \times 6.167 \times 10^{-5} \times \varepsilon_t^{-3.129} \times E_A^{-0.854} \quad (3.1)$$

$$C = 10^M \qquad M = 4.84\left(\frac{V_b}{V_v + V_b} - 0.69\right) \quad (3.2)$$

N_{fA} = Number of load applications to cracking
ε_t = Tensile strain repeatedly applied
E_A = Young's modulus of asphalt concrete
V_v = Void ratio of asphalt concrete (%)
V_b = Volume of asphalt (%)

In the design of asphalt pavement for highways, not only fatigue criterion of asphalt concrete layer, but also the compressive strain criterion of subgrade is considered to limit rutting. However, the deformation characteristics of railway subgrade are substantially different from that of highway. In the design of railway roadbed, quality of subgrade is specified by K_{30} value in the plate loading test. For the ballasted track with asphalt roadbed, K_{30} value should be larger than 70MN/m^3. In the current design standard of asphalt roadbed in Japan, vertical displacement of asphalt roadbed surface is limited to 2.5 mm with considerable maximum wheel load that applied during the service life. Therefore, not only the fatigue criterion, but also the limit of vertical displacement of asphalt roadbed is necessary for the new design method.

The design condition of asphalt roadbed discussed here is as following.

(1) Tonnage: 18 MGT / year
(2) Service life of asphalt roadbed: 50 years
(3) Average wheel load: 85 kN (To estimate fatigue life)
(4) Maximum wheel load: 101 kN (To estimate maximum roadbed displacement)
(5) Maximum velocity: 300 km/h (To estimate maximum roadbed displacement)
(6) Impact coefficient to estimate fatigue life: 1.45
(7) Impact coefficient to estimate maximum displacement: 1+0.3V/100 (Maximum 1.8)
(8) Young's modulus of asphalt concrete layer:
4000MPa (spring), 2000MPa (summer), 3000MPa (autumn), 7000Mpa (winter)

Figure 12 shows fatigue life of asphalt concrete layer obtained by the fatigue criterion described in equation (3.1) and (3.2). Thicknesses of asphalt roadbed in current design standard are 30 cm for K_{30} = 70 MN/m^3 subgrade and 65 cm for K_{30} = 110 MN/m^3 subgrade. It was confirmed that the fatigue life of current asphalt concrete layer was more than 50 years.

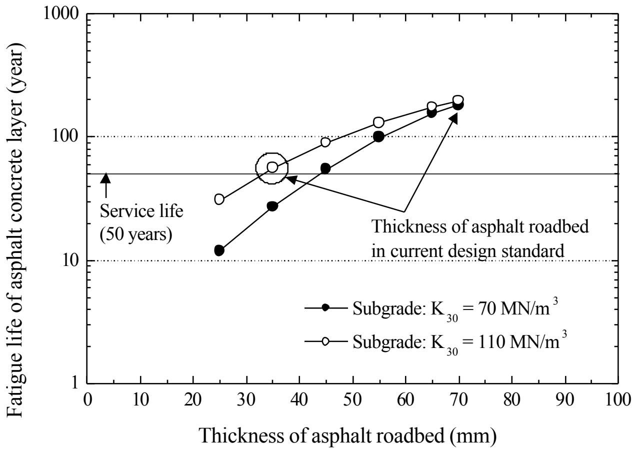

Figure 12: Fatigue life of asphalt concrete layer obtained by fatigue criteria

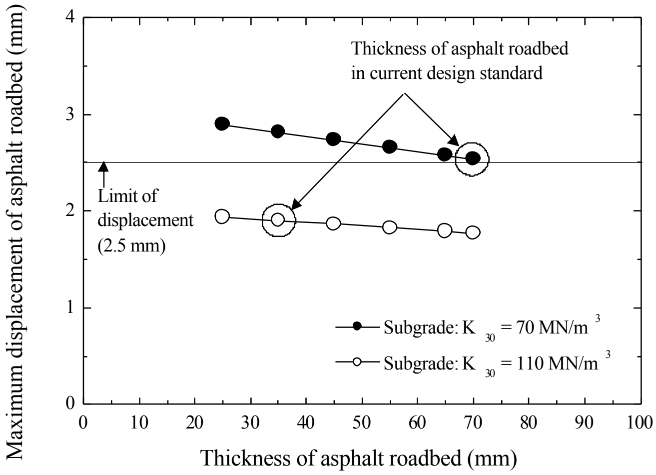

Figure 13: Maximum displacement of asphalt roadbed

Figure 13 shows maximum displacement of asphalt roadbed. The displacement of asphalt roadbed with the thickness less than 65 cm became larger than limit of displacement 2.5mm with K_{30} = 70 MN/m^3 subgrade. The displacement of 70 cm thick asphalt roadbed in current design standard barely satisfied the limit of 2.5 mm. Therefore, asphalt roadbed thinner than current design standard does not satisfy the limit of maximum displacement for K_{30} = 70 MN/m^3 subgrade. In this new design method, fatigue life of asphalt concrete in K_{30} = 70 MN/m^3 subgrade was longer than 50 years even with 45 cm thick asphalt roadbed. However, thin asphalt roadbed does not satisfy the limit of displacement. In this design method, thickness of asphalt concrete is controlled by fatigue criteria and by maximum displacement.

4 CONCLUSIONS

The maximum resilient tensile strains at the bottom of the asphalt concrete layers, which control the fatigue failure of the asphalt concrete layer, can be predicted accurately by the FEM analysis method described in this paper. The new design method proposed in this paper gave rational asphalt roadbed thickness. By introducing this method, flexible design of asphalt roadbed which considers train frequency or train load becomes possible.

REFERENCES

Hirakawa,D., Kawasaki,H., Tatsuoka,F. and Momoya,Y. (2002): "Effects of loading conditions on the behaviour of railway track in the laboratory model tests," 6th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields, Lisbon, Vol. 2, pp.1295-1305.

Momoya, Y., Ando, K. and Horiike, T. (2002): Performance tests and basic design on solid bed track on asphalt pavement, 6th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields, Lisbon, Balkema, Vol. 2, pp. 1307-1322

Sunaga, M. and Sekine, E. (1994): A study on decrease of reinforced roadbed thickness in railway, Journal of Construction Management and Engineering, JSCE, No. 498/VI-24, pp.57-66. (In Japanese)

Tsuchida, M. and Maruyama. (2000): A study on the reliability of fatigue life design of asphalt pavement, 8 th Hokuriku Road Pavement Conference, pp. 83-86. (In Japanese)