CETRA[2018]

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

IRF GLOBAL

FEHRL

Organizer
University of Zagreb
Faculty of Civil Engineering
Department of Transportation

CETRA^2018

5th International Conference on Road and Rail Infrastructure

17–19 May 2018, Zadar, Croatia

TITLE

Road and Rail Infrastructure V, Proceedings of the Conference CETRA 2018

EDITED BY

Stjepan Lakušić

ISSN

1848-9850

ISBN

978-953-8168-25-3

DOI

10.5592/CO/CETRA.2018

PUBLISHED BY

Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE

minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY

“Tiskara Zelina”, May 2018

COPIES

500

Zagreb, May 2018.

Proceedings of the
5th International Conference on Road and Rail Infrastructures – CETRA 2018
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

EDITOR
Stjepan Lakušić
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Zagreb, Croatia

CETRA[2018]
5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

ORGANISATION

CHAIRMEN

Prof. Stjepan Lakušić, University of Zagreb, Faculty of Civil Engineering
Prof. emer. Željko Korlaet, University of Zagreb, Faculty of Civil Engineering

ORGANIZING COMMITTEE

Prof. Stjepan Lakušić
Prof. emer. Željko Korlaet
Prof. Vesna Dragčević
Prof. Tatjana Rukavina
Assist. Prof. Ivica Stančerić
Assist. Prof. Maja Ahac
Assist. Prof. Saša Ahac
Assist. Prof. Ivo Haladin
Assist. Prof. Josipa Domitrović
Tamara Džambas
Viktorija Grgić
Šime Bezina
Katarina Vranešić
Željko Stepan
Prof. Rudolf Eger
Prof. Kenneth Gavin
Prof. Janusz Madejski
Prof. Nencho Nenov
Prof. Andrei Petriaev
Prof. Otto Plašek
Assist. Prof. Andreas Schoebel
Prof. Adam Szeląg
Brendan Halleman

INTERNATIONAL ACADEMIC SCIENTIFIC COMMITTEE

Stjepan Lakušić, University of Zagreb, president
Borna Abramović, University of Zagreb
Maja Ahac, University of Zagreb
Saša Ahac, University of Zagreb
Darko Babić, University of Zagreb
Danijela Barić, University of Zagreb
Davor Brčić, University of Zagreb
Domagoj Damjanović, University of Zagreb
Sanja Dimter, J. J. Strossmayer University of Osijek
Aleksandra Deluka Tibljaš, University of Rijeka
Josipa Domitrović, University of Zagreb
Vesna Dragčević, University of Zagreb
Rudolf Eger, RheinMain Univ. of App. Sciences, Wiesbaden
Adelino Ferreira, University of Coimbra
Makoto Fujiu, Kanazawa University
Laszlo Gaspar, Széchenyi István University in Győr
Kenneth Gavin, Delft University of Technology
Nenad Gucunski, Rutgers University
Ivo Haladin, University of Zagreb
Staša Jovanović, University of Novi Sad
Lajos Kisgyörgy, Budapest Univ. of Tech. and Economics
Anastasia Konon, St. Petersburg State Transport Univ.
Željko Korlaet, University of Zagreb
Meho Saša Kovačević, University of Zagreb
Zoran Krakutovski, Ss. Cyril and Methodius Univ. in Skopje
Dirk Lauwers, Ghent University
Janusz Madejski, Silesian University of Technology
Goran Mladenović, University of Belgrade
Tomislav Josip Mlinarić, University of Zagreb
Nencho Nenov, University of Transport in Sofia
Mladen Nikšić, University of Zagreb
Andrei Petriaev, St. Petersburg State Transport University
Otto Plašek, Brno University of Technology
Mauricio Pradena, University of Concepcion
Carmen Racanel, Tech. Univ. of Civil Eng. Bucharest
Tatjana Rukavina, University of Zagreb
Andreas Schoebel, Vienna University of Technology
Ivica Stančerić, University of Zagreb
Adam Szeląg, Warsaw University of Technology
Marjan Tušar, National Institute of Chemistry, Ljubljana
Audrius Vaitkus, Vilnius Gediminas Technical University
Andrei Zaitsev, Russian University of transport, Moscow

ALLOWABLE WHEEL LOADS OF PRESTRESSED CONCRETE SLEEPERS STANDARDIZED BY JIS

Keiichi Goto[1,2], Tsutomu Watanabe[1], Masamichi Sogabe[1]
[1] *Railway Technical Research Institute, Japan*
[2] *University of Birmingham, United Kingdom*

Abstract

In this study, allowable wheel loads for prestressed concrete sleepers standardized by Japanese Industrial Standard (JIS) were calculated. The results revealed that the difference between the allowable wheel loads calculated using FEM and those calculated using the conventional method based on the load distribution coefficient was less than or equal to 5 %. Relaxing the limit value of the edge tensile stress intensity of concrete based on the actual conditions increased the allowable wheel loads by 35 %. Moreover, the influence of the rail type, ballast depth and ground deformation coefficient were around 10 %.

Keywords: prestressed concrete sleeper, design, dynamic analysis, load distribution, bending tensile strength

1 Introduction

In Japan, prestressed concrete sleepers (PC sleepers) began to be introduced on the Tokaido line in 1951. A large number of PC sleepers was manufactured for the construction of the Tokaido Shinkansen line from 1961. Since 1962, PC sleepers were used to replace wooden sleepers in conventional lines. Compared to conventional wooden sleepers, PC sleepers are superior in terms of flexural capacity and durability. In addition, track irregularity is less likely to occur due to their relatively larger weight. Consequently, PC sleepers demonstrate high maintainability in Japan. Initially, PC sleepers were designed based on the allowable stress method. In this method, the section force is calculated after considering three assumed ballast support conditions against the combination of dynamic wheel loads (two times static wheel loads) and wheel lateral forces. As part of this method, whether the concrete stress at the tensile edge remains within the allowable stress (0 or 2 N/mm^2) is confirmed as well.

In 1990, the Japanese Industrial Standard (JIS) JIS E 1201 (“pre-tension-type PC sleepers”) and JIS E 1202 (“post-tension-type PC sleepers”) were published. These standards specified flexural proof loads (bending cracks) and flexural fracture loads for 17 kinds of PC sleepers. In 1993, “The Manual for Running-Speed Improvement of Conventional Railways and Commentary, [1], hereinafter referred to as the Improvement Manual, was established and the limit values for wheel loads measured in commercial lines (i.e., allowable wheel loads) were proposed. In this manual, considering the actual conditions of PC sleepers that are factory products, allowable wheel loads are calculated by relaxing the allowable stress at the tensile edge to 3.0 N/mm^2. This manual is utilized when introducing new types of vehicles and maintaining tracks. In 2012, “Design Standard for Railway Structures and Commentary (Track structure)”, [2], hereinafter referred to as the Track Standard, was published and performance-based design method was introduced to track structures. As for the design of PC sleepers, a method for calculating the response values according to the shapes and material characteristics of each part member constituting the tracks has been introduced. Additionally, in this method, whether the values are within each prescribed limit state is also confirmed, [3]. With the abovementioned background, in this study, an examination of PC sleepers standardized by JIS has been conducted by referring to changes in the Track Standard based on the following viewpoints:

1) To analyse the differences between the results obtained using 2 methods, i.e., the method using FEM (as recommended by the Track Standard) and the method using the conventional method based on the allowable stress method.
2) To quantitatively evaluate how the parameters of shapes and material characteristics of each part member constituting the tracks influence the allowable wheel loads of PC sleepers (the wheel loads when the tensile stress at the tensile edge of concrete reaches the bending tensile strength of the concrete).
3) To calculate the allowable wheel loads of PC sleepers standardized by JIS.

2 Study method

2.1 Design conditions

Some PC sleepers standardized by JIS are shown in Table 1. In Fig. 1, the outline of Type 3 pre-tension PC sleeper (3PR) is provided. This study subjects included 7 types of PC sleepers that are commonly used in conventional lines (the Running-Speed Improve Manual refers to only two types of PC sleepers). In Table 2, the design conditions are listed. PC sleepers are designed based on full pre-stressing, which allows no tensile stress to occur, or partial pre-stressing, which allows tensile stress up to certain levels to occur. While the sleepers, excluding Type 6 and Type 7 sleepers, were designed under full-prestressing, some of them did not satisfy the conditions of full pre-stressing during the trial of restoration designs. As there were limited existing data concerning the design history, this study assumed the limit values of bending tensile strength at the design base for each type of sleeper (1.0 N/mm^2 for Type 3, 2.0 N/mm^2 for Type 6, 1.0 N/mm^2 for Type Rail-joint, and 0.0 N/mm^2 for Type 1-F).

Table 1 PC sleepers standardized by JIS

Type	Tension	B [mm]	H [mm]	L [mm]	Remark
3PR	Pre	240	174	2000	Straight line (R800 + curve)
3PO	Post				
6PR	Pre	240	200.8	2000	Curve lin (R300 to R800)
6PO	Post				
JPR	Pre	300	225.7	2000	Rail joint
JPO	Post				
1F	Post	300	225	2000	Cold Weather Region

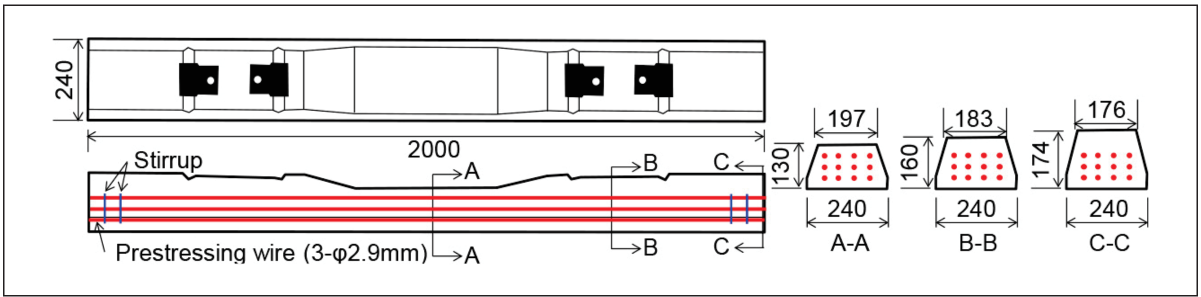

Figure 1 Outline of Type 3 pre-tension PC sleeper (3PR)

Table 2 Design conditions

Rail type	50 kgN
The number of sleepers (pieces / 25 m)	39
Rail pad (MN / m)	100
Ballast thickness (mm)	250
Ground deformation coefficient K_{30} (MN / m³)	110
Wheel load (kN)	80
Lateral load (kN)	40 (Type 3 and 1F) 60 (Type 6 and Rail joint)

Table 3 Material specifications

a) Concrete	
Design strength f'_{ck} (N / mm²)	49.1
Modulus of elasticity E_c (kN / mm²)	33
Ultimate strain μ	3500
Bending compresive strength f'_{cde} (N / mm²)	19.6 (= 0.4 × f'_{ck})

b) Prestressing steel

Sleeper type	Type and number	Initial prestress (kN per one)	Effective prestress rate (%)
3PR	3 - φ2.9, 12 wires	28.7	65
3PO	φ10, 4 tendons	72.6	80
6PR	3 - φ2.9, 12 wires	30.3	65
6PO	φ10, 4 tendons	72.6	80
JPR	3 - φ2.9, 16 wires	28.7	65
JPO	φ11, 4 tendons	88.3	80
1F	φ11, 4 tendons	83.4	80

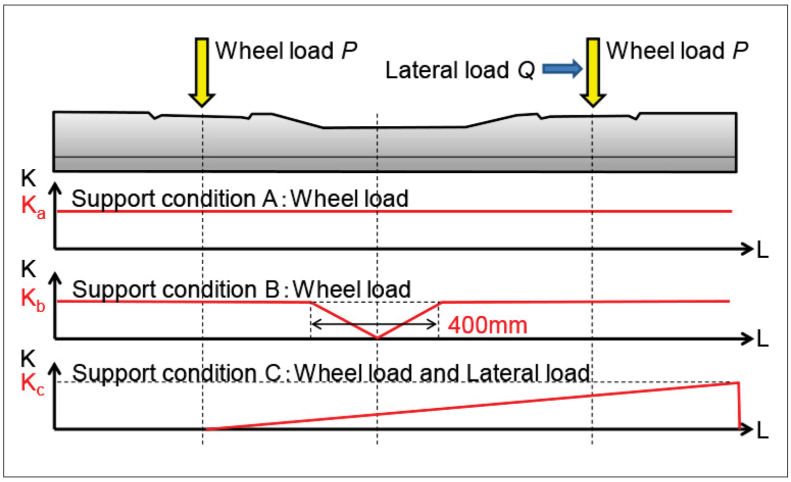

Figure 2 Loads and support conditions

Table 3 lists the material specifications. In this study, parameter analyses were also conducted by referring to these values. In Fig. 2, loads and support conditions are shown. These support conditions were determined based on those used in the conventional allowable stress method, [4]. The wheel load P used in the designing stage was determined by multiplying the static wheel load (80 kN) by a dynamic impact factor (i_v = 2.0) according to the Track Standard. As for the sleeper used at rail joints (JPR and JPO), considering the impact caused when a wheel passes a rail joint gap, a dynamic impact factor (i_v = 3.0) was used for multiplication according to the Track Standard. For the support condition C, only the case of combining with contingent lateral forces, which was the dominant combination, was considered herein. In particular, lateral forces of 40 kN were applied to the Type 3 and Type 1-F sleepers, while lateral forces of 60 kN were applied to the Type rail-joint sleeper.

2.2 Calculation method of design response values

To calculate the section force exerted on a PC sleeper when a train passes over, a technique of simply settling the load distribution coefficient along the rail based on the load distribution phenomenon is used in the allowable stress method [4]. In other words, the distribution rate of the load to the PC sleeper right below a wheelset was estimated based on the theoretical equations of a beam resting on an elastic floor: 0.5 for conventional lines and 0.6 for Shinkansen lines.
In contrast, for the Track Standard, it is basic to calculate the design response values with dynamic analysis method (e.g., FEM) when examining the performance of PC sleepers. However, it would be cumbersome to apply FEM to all sleepers in the actual design process, thus, the application range of the conventional method based on the load distribution coefficient was verified in this study. FEM is based on three-dimensional models and is used to accurately reproduce the effect of the load distribution along rails. The analysis was based on a general-purpose structural analysis program for railway structures called DIARIST (Dynamic and Impact Analysis for Railway Structure) in which railway vehicles are assumed as a non-oscillatory constant load line, [5]. In this program, railway vehicles are modeled as a moving load row with a constant load and speed. Arbitrary structure types can be modeled in detail for a track structure using finite elements.
In Fig. 3, the outline of analysis model produced using FEM is shown. An analysis model of 30 m in length was build. All elements were assumed to be linear. Rails and PC sleepers were modeled as beam elements. The fastening span of each rail and the length of each sleeper were discretized into 4 and 27 sections, respectively. Rail pads were modeled as three-degree-freedom scalar spring elements. The springs were also on the bottom of the sleepers. The corresponding spring constants were modeled as single springs by obtaining the spring constants for each ballast and roadbed according to the track standard and combining them in series, [2]. The support condition C was obtained assuming a triangular distribution, whereby the sum of the support-spring forces was expected to equal the support condition A. In the aforementioned analysis model, 1582 nodes and 3089 elements were used.

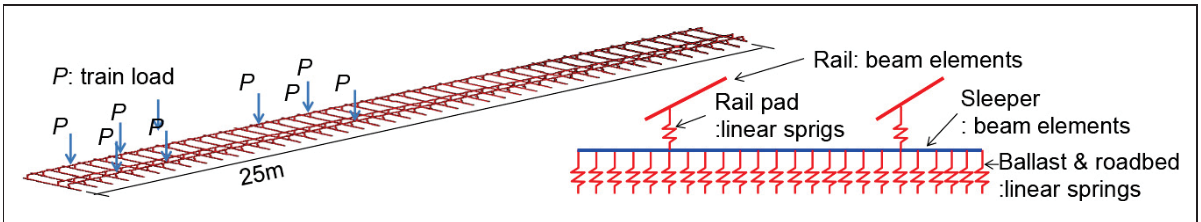

Figure 3 Outline of analysis model

2.3 Calculation method of design limit values

The design limit values for crack occurrence were obtained as allowable wheel loads, i.e., calculated wheel loads with which the bending moments reach the limit moments. These limit moments are derived using Eq. (1) and (2), which correspond to the sleeper cross-section below the rail (the cross-section of rail seat) and that at the sleeper center (the cross-section of sleeper center).

$$M_{cr} = M_o + f_{bcd} \cdot W \tag{1}$$

$$M_o = \left(\sum P_e / A \pm \sum P_e \times e_p / W\right) \cdot W \quad (2)$$

Where, M_{cr} represents the design bending moment of crack occurrence for a PC sleeper (kNm), M_o represents the design bending moment of decompression for a PC sleeper(kNm), P_e represents the effective pre-stressing force of prestressing steel in a PC sleeper (kN), A represents the cross-section area of a PC sleeper (m^2), W represents the section modulus of a PC sleeper (m^3), e_p represents the eccentricity of the prestressing steel in a PC sleeper (m), and f_{bcd} represents the bending tensile strength for calculating allowable wheel loads applied to commercial lines (N/mm^2). Considering that the PC sleepers are factory products that are expected to have considerable safety margins in the design stage, a bending tensile strength f_{bcdof} 3.0 N/mm^2 was adopted, [1]. This value was determined based on the Improvement Manual.

3 Study results

3.1 Effects of the structural analysis method

In Fig. 4, as an example of the bending moment occurring in PC sleepers, the distribution of the maximum bending moment in Type 3 pre-tension (3PR) is shown. It can be seen that the distribution of the bending moments varies as the support conditions change.

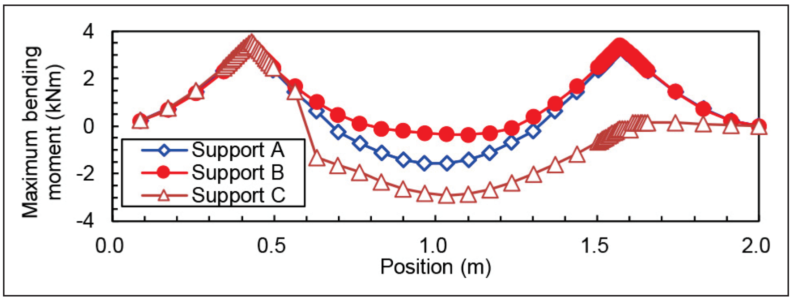

Figure 4 Distribution of the maximum bending moment (3PR)

In Fig. 5, the effect of the difference between the structural analysis methods on the allowable wheel loads at the design base is shown. From the figure, it is confirmed that both FEM and the conventional method using the load distribution coefficient yielded similar results, with an error margin less than 5 %. In the examination of the design method, the finalizing case of FEM for all sleepers was the support condition C, along with the effect of the accidental lateral forces. This pattern was the same when the load distribution coefficient was used.

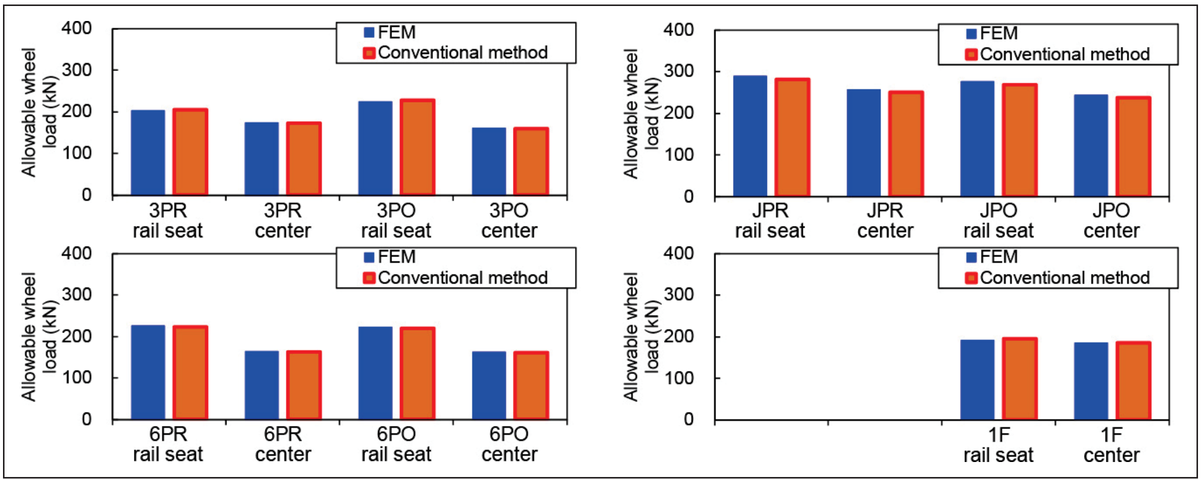

Figure 5 Effect of the difference between the structural analysis methods

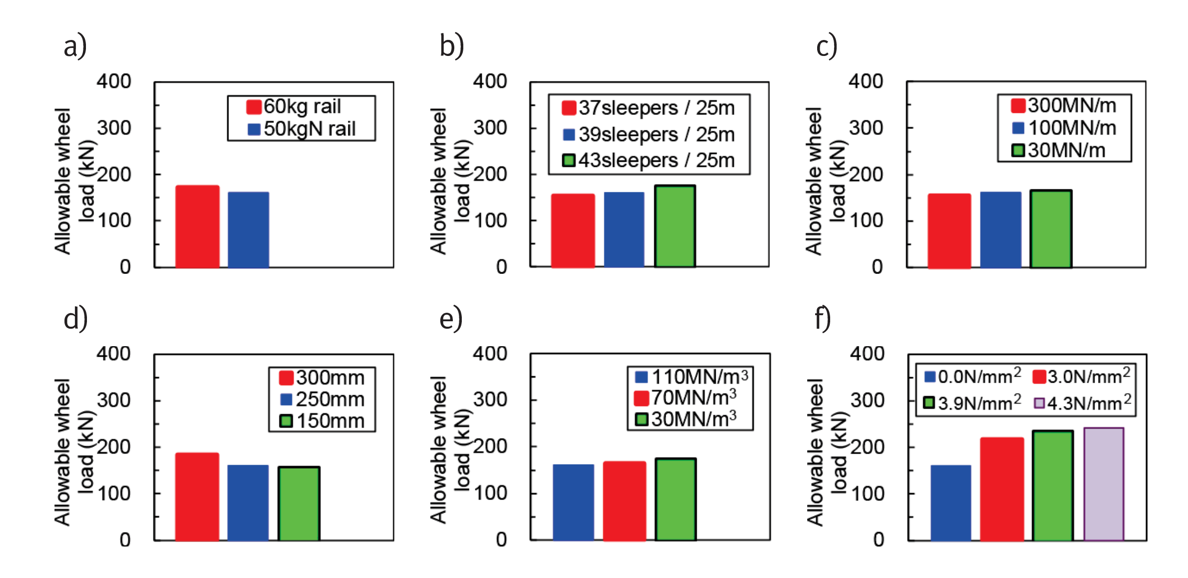

Figure 6 Effects of various parameters (3PO, FEM, Support condition C): a) rail type, b) the number of sleepers, c) rigidity of track pad, d) ballast depth, e) ground deformation coefficient, f) bending tensile strength

3.2 Effects of various parameters

In Fig.6, the effects of various parameters on the allowable wheel load at the design base are shown. Here, the influence of various parameters in the support condition C and Type 3 post-tension PC sleeper (3PO) was evaluated. Changing the rail type from a 50 kgN rail to a 60 kg rail increased the allowable wheel load by approximately 7 %. This is because the rigidity of the rail increased, thereby reducing the response value per sleeper.

It was observed that varying the number of PC sleepers laid every 25 m (for instance, 37, 39, and 43 pieces) made the allowable wheel load vary between -4 % and 9 % in comparison with the scenario in which the standard 39 pieces were used. This is because the load per sleeper PC sleeper changes.

Compared to the standard value of 100 MN/m, when the rigidity of the track pad was change to 30 and 300 MN/m, the allowable wheel load changes by only 2 %. This indicates that the influence of the track pad rigidity is small.

Changing the ballast depth to 150, 250 and 300 mm resulted in a 14 % decrease in the allowable wheel load with a depth of 150 mm in comparison with the case in which the standard thickness was 250 mm. This is because the effect of load distribution to the roadbed decrease when the ballast thickness reduces, making the load per sleeper larger.

Changing the ground deformation coefficient to 70 or 30 MN/mm^3 from 110 MN/mm^3 increased the allowable wheel load by 7 % in comparison with the case in which the standard value was 110 MN/mm^3.

The changes in the material properties of concrete, particularly the tensile strength, exhibited the most influence. When the tensile strength was changed to 3 N/mm^2, the allowable wheel load increased by approximately 35 %. Furthermore, a tensile strength of 4.3 N/mm^2 (equivalent to a compression strength of 80 N/mm^2, which is often noticed in the quality test of actual sleepers) exhibited an additional 25 % increase in the allowable wheel load.

3.3 Calculation of the allowable wheel load in commercial lines

In Fig.7, an example of examining the allowable wheel load at the actual strength base is shown. In this figure, the allowable wheel load back-calculated based on a tensile strength of 3.0 N/mm^2 is shown. This tensile strength is referred to as an indicator in the Improvement

Manual. These results were calculated based on the Type 3 pre-tension PC (3PR) sleeper and the conventional load distribution coefficient. The figure shows that the result in the design wheel load case is given at the central cross section of the sleeper with the support condition C, while the result that in the actual strength base is given at the central cross section of the sleeper with the support condition A. A similar study was conducted on the other target JIS PC sleepers.

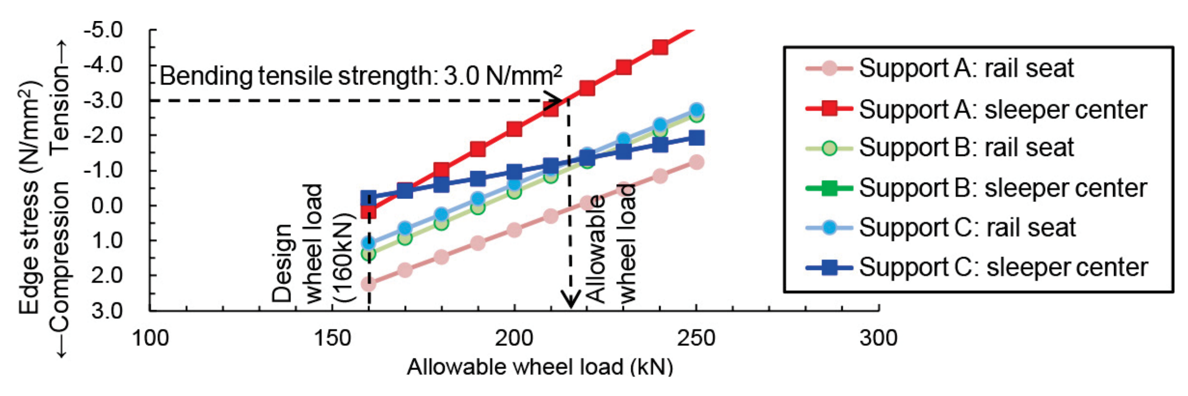

Figure 7 Example of examination the allowable wheel load at the actual strength base (3PR, conventional method)

In Fig. 8, a comparison of the allowable wheel loads is shown. It can be seen that at a bending tensile strength f_{bcd} of 3.0 N/mm², compared to the case of the design wheel load, the allowable wheel load for each sleeper increases by 20 to 48 %. The allowable wheel loads obtained by the conventional load distribution coefficient are also shown. It is confirmed that the allowable wheel loads obtaining using FEM are generally comparable to those obtained using the conventional method based on the load distribution coefficient.

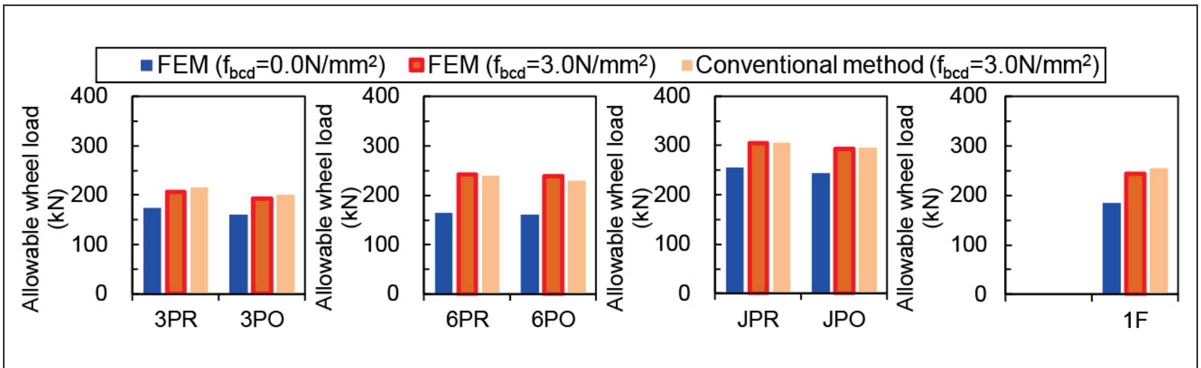

Figure 8 Comparison of the allowable wheel loads

4 Conclusion

The results of this study are summarized as follow:

1) Based on the Track Standard, the design-base allowable wheel loads for the 7 types of PC sleepers standardized by JIS were calculated using FEM. The results were comparable to the allowable wheel loads obtained using the conventional method based on the load distribution coefficient.
2) Using the Type 3 post-tension PC sleepers, it was confirmed that how the constitution of track members and various material characteristics influenced the allowable wheel loads. As a result, the tensile strength of concrete exhibited the most influence, increasing the allowable wheel load by approximately by 35 % in comparison with the case in which

the tensile strength was set to zero. The influence of the rail type, ballast thickness, and ground deformation coefficient was approximately 10 %.

3) The results revealed that calculating the allowable wheel loads allowing 3.0 N/mm^2 of bending tensile strength resulted in a 20 – 48 % increase in the allowable wheel loads in comparison with the design wheel load. The allowable wheel loads calculated according to the track standard were generally comparable to those calculated using the conventional method based one the load distribution coefficient.

References

[1] Railway Technical Research Institute: The Manual for Running-Speed Improvement of Conventional Railways and Commentary, Ken-yusha, 1993, (in Japanese).

[2] Railway Technical Research Institute: Design Standard for Railway Structures and Commentary (Track Structure), Maruzen, 2012. (in Japanese).

[3] Wakui, H., Okuda, H.: A Study Limit-State Design Method for Prestressed Concrete Sleepers, Concrete Library of JSCE, 33, pp. 1-25, 1999.

[4] Miyamoto, T., Watanabe K.: Railway Track (Design and Management of Track), Sankaido, pp. 90-131, 1980, (in Japanese).

[5] Sogabe, M., Matsumoto, N., Kanamori, M., Sato, T., Wakui, H.: Impact factor s of Concrete Girders Coping with Train Speed-up, Quarterly Report of RTRI, 46 (2005) 1, pp. 46-52, doi: https://doi.org/10.2219/rtriqr.46.46

[6] Railway Technical Research Institute: Design Standard for Railway Structures and Commentary (Concrete Structure), Maruzen, 2012, (in Japanese).