Investigation of Load Environment and Bending Load Capacities of Aged Prestressed Concrete Sleepers

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Abstract: In this study, field measurements of the bending moments of prestressed concrete (PC) sleepers installed on commercial lines were obtained, and numerical analyses to identify the effects of different parameters on their bending moments were conducted. The bending load capacities of aged PC sleepers collected from commercial lines via bending tests were also determined. According to the field measurement results of the wheel loads and bending moments of the PC sleepers, the measured values were smaller than the design values. In addition, neither the wheel load nor the bending moment depended on train speed. The numerical analysis results indicate that the positive bending moment at the rail seat section is unlikely to exceed the design decompression moment (DDM). However, the negative bending moment at the center section may exceed the DDM if center support is provided with a reduced spring constant under the rail (“hanging” rail seat section). In addition, the bending moment increased with the rail surface roughness, so the rail should be kept smooth. Moreover, the results of the JIS E 1201 bending tests on the aged PC sleepers showed that the crack generation load and ultimate load decreased gradually with increases in age and passing tonnage. However, all samples satisfied the JIS standard values. Furthermore, the bending moments generated in the PC sleepers during train passage were considerably smaller than the crack generation load and ultimate load during the bending test. Thus, Japanese PC sleepers aged more than 50 years currently satisfy the standard flexural fracture values specified by the JIS, and safety is not immediately compromised.

Keywords: concrete sleeper; railway; track; maintenance; numerical analysis

1. Introduction

Sleepers are important track components that support rails, maintain the distance between the left and right rails, and distribute the load transmitted from the rails to the ballast. Prestressed concrete (PC) sleepers, the subject of this study, were installed for the first time in European countries, such as England and Germany, in the latter half of the 1940s. PC sleepers are widely used worldwide and are an indispensable track component for comfortable, safe, and stable high-speed railway transportation [1]. Japan’s PC sleepers were first installed on a trial basis in 1951. Since then, over 40 million sleepers have been built by Japanese National Railways and the Japan Railway Group alone (excluding private railway companies).

PC sleepers are generally expected to last approximately 50 years [1], but in recent years, a large number of PC sleepers have exceeded this life span. Therefore, various studies have been conducted on the evaluation of the service lives and remaining lives of aged PC sleepers [2]. The static and impact loads acting on PC sleepers should be considered in evaluating their service lives and remaining lives. Various studies have been vigorously performed worldwide on related topics, such as the examination of design methods [3–5] and the evaluation of impact loads [6–9]. In addition, studies have been
conducted on the damage to PC sleepers [10], their fatigue lives considering abrasion [11], fatigue life evaluation methods based on wheel loads acting on PC sleepers [12], and fatigue conditions of PC sleepers, which considerably affect the bending moments generated in PC sleepers [13]. The support conditions of PC sleepers, which considerably affect the bending moments generated in PC sleepers, have likewise been studied [14–16]. Altogether, valuable information has been obtained for evaluating the service lives of PC sleepers.

In summary, researchers worldwide are exploring PC sleepers using various approaches. However, except for a few examples [2], researchers have not evaluated the load-bearing capacities of aged PC sleepers installed on commercial lines. Therefore, in the current study, we investigate the load environment of aged PC sleepers installed on commercial lines and evaluate their bending load capacities. Although the target PC sleepers in this study are limited to those in Japan, the actual load-bearing capacities of PC sleepers that have been used for nearly 50 years are evaluated. These results will be valuable for the literature on PC sleepers. In addition, the load environment evaluated in this study targets the straight section. Naturally, it is thought that the load environment will be different in curved sections and turnout sections, but we would like to address these issues in the future.

In Japan, maintenance vehicles run every day before the first Shinkansen trains run, and detailed track inspections are conducted. However, the soundness assessments of PC sleepers remain based on visual inspections, and this evaluation method is not necessarily linked to the load-bearing performances of the PC sleepers [17]. Contrary to the large number of installed PC sleepers, the number of sleepers that can be replaced in one night’s work is limited. Thus, if existing PC sleepers fail to meet their load-bearing capacities at a certain time, replacement work may fail to resolve the issue, and safety will be affected. To avoid this situation, Japan plans to set a quantitative service life and conduct systematic maintenance.

In this study, we address the following objectives to establish a new maintenance management system for PC sleepers:

1. To investigate the actual load environment of PC sleepers installed on commercial lines by measuring their bending moments.
2. To verify the effects of various parameters on the bending moments of PC sleepers via numerical analyses.
3. To collect a wide range of aged PC sleepers on commercial lines and evaluate their bending load capacities by conducting bending tests specified by the Japanese Industrial Standard (JIS) E 1201 [18].

2. Investigation of Load Environment of PC Sleepers

2.1. Investigation Methods

2.1.1. Outline of a PC Sleeper

Figure 1 shows the outline of a PC sleeper. The target PC sleepers are high-speed railway PC sleepers classified as 3T in the JIS E 1201. The length of one PC sleeper is 2400 mm, and the heights of its rail seat section and center section are 190 mm and 175 mm, respectively. The design standard strength of concrete is 49.1 N/mm², and three φ2.9 mm strands constitute a PC steel strand. The design wheel load is 160 kN, which is double the 80 kN static wheel load based on the variable wheel load factor, which considers the dynamic components associated with train running. The target PC sleepers are designed to satisfy the full cross-sectional prestress against the design load [3,9].
Figure 1. Outline of PC sleeper (classified as 3T in JIS E 1201).

Figure 2 shows the field measurement points. The location was a straight, ballasted track on a reinforced concrete viaduct, and trains passed at approximately 130–300 km/h. The PC sleepers were installed at intervals of 0.58 m, and the rails were 60 kg rails [19].

2.1.2. Methods of Measuring Wheel Loads and Bending Moments of PC Sleepers

Figure 3 shows the arrangement of the wheel load and concrete gauges attached to the rails and sleepers. Two strain gauges (KYOWA ELECTRONIC INSTRUMENTS CO., LTD. Japan) were attached to each sleeper: one at the upper end and one at the lower end of the rail seat section. The strains of five continuous PC sleepers were measured, and the measured strains were converted into bending moments. In addition, the strain gauges were connected to a National Instruments module that was connected to a personal computer using a LAN cable to save the data. The data were saved automatically using a LabVIEW program, with the vibration acceleration of the PC sleepers serving as the trigger for automatic saving. The sampling frequency was 10 kHz. In total, 337 trains were assessed.

2.1.3. Analysis Method

Figure 4 shows the outline of the 3D numerical analysis model used in this work. The simulation program Dynamic Interaction Analysis for Shinkansen Train and Railway Structures was used for numerical analysis [20–22].
Figure 4. Outline of 3D numerical analysis model. (a) Dynamic model of vehicle; (b) dynamic model of track; (c) rail surface roughness.

Figure 4a shows the dynamic model of the vehicle, which was generated assuming that the body, bogies, and wheelsets were rigid. These rigid three-dimensional elements were linked by springs $K_N$ and dampers $C_N$ ($N$ is a subscript number in Figure 4a) according to their characteristics. Each train car had 31 degrees of freedom. Each train consisted of multiple vehicle models linked together by springs $K_C$ and dampers $C_C$ attached to the ends of the vehicle models. The vehicles were given the specifications of a vehicle passing through the measurement point (a 56.6 kN static wheel load). The vehicle occupancy rate was set at 50%.

Figure 4b shows the dynamic model of the track, which was created using the finite element method. The track was modeled as a 160 m unit. The rails were modeled as beam elements, with each rail fastener divided into four segments by nodes. Each PC sleeper was modeled as a beam element divided into 10 segments by nodes. The track pads were modeled as spring elements. The ballast and roadbed were modeled as an integrated spring element. In total, the analysis models had 4634 nodes and 8468 elements. Since the measurement point was on a viaduct, the concrete member of the viaduct was assumed to be sufficiently rigid, and the boundary condition at the lower end of the spring element simulating the ballast was fixed. Figure 4c shows the rail surface roughness of the test section, which was statically measured using a surface roughness measuring device with a length of 1 m. The measured rail surface roughness was used to reproduce the exciting force generated between the wheel and the rail.

The equations of motion concerning the vehicle and the track were modally converted for numerical analysis efficiency. The resulting equations of motion on the
modal coordinate system of the vehicle and the track were progressively solved in time increments of $\Delta t$ using the Newmark method. For modal analysis, mode orders that can reproduce vibrations of up to approximately 10 kHz were used, and the analysis was executed at 0.1 msec intervals. An attenuation constant of 0.1 was used to ensure consistency with the time history response analysis [23].

2.1.4. Material Constants and Analysis Cases for Numerical Analysis

Table 1 shows the material constants in the numerical analysis. These constants were based on the Design Standards for Railway Structures and Commentary and nominal values [24, 25].

<table>
<thead>
<tr>
<th>Material constants</th>
<th>Material constants</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rail</strong></td>
<td>60 kg rail (JIS E 1101; Young’s modulus $E_S = 200$ GPa)</td>
</tr>
<tr>
<td></td>
<td>Track gauge = 1435 mm</td>
</tr>
<tr>
<td><strong>Track pad</strong></td>
<td>Spring constant $D_T = 50$ MN/m</td>
</tr>
<tr>
<td></td>
<td>Type 3T (JIS E 1201), PC steel strand = $\phi 2.9$ mm, $N = 16$</td>
</tr>
<tr>
<td></td>
<td>Length $L_T = 2400$ mm</td>
</tr>
<tr>
<td><strong>Sleeper</strong></td>
<td>Bottom width $B_T = 283$ mm (rail seat section), 230 mm (center section)</td>
</tr>
<tr>
<td></td>
<td>Height $H_T = 190$ mm (rail seat section), 175 mm (center section)</td>
</tr>
<tr>
<td></td>
<td>Young’s modulus $E_C = 33$ GPa</td>
</tr>
<tr>
<td><strong>Ballast</strong></td>
<td>Ballast thickness $h = 250$ mm</td>
</tr>
<tr>
<td></td>
<td>Support spring constant $D_B = 200$ MN/m (per rail)</td>
</tr>
</tbody>
</table>

In track maintenance in Japan, as shown in Figure 5a, the center sections of PC sleepers are generally not supported by ballasts (rail seat (center void) support) to reduce the reaction force from the ballast. However, in this study, assuming that a certain amount of time had passed since the latest track maintenance activity, the support conditions of the PC sleepers were assumed to be uniform rather than hollow (Figure 5b). Uniform support was set as the basic case.

![Figure 5. Support conditions of PC sleepers: (a) rail seat (central void) support; (b) uniform support; (c) center support.](image)
Table 2 shows the analysis cases. We focused on the parameters for which constant fluctuations were assumed, specifically, the train speed, vehicle occupancy rate, rail surface irregularity, track pad spring constant, and ballast support spring constant. According to previous research, each value was set assuming its deterioration over time. Regarding the support conditions of the PC sleepers (last row of Table 2), as shown in Figure 5c, the support spring constant of an entire PC sleeper was reduced for only one evaluation sleeper, and the support spring constant under the rail was reduced (the range of the center support of 600 mm at the center did not reduce the spring constant). The underlined constants constituted the basic case. A total of 14,400 cases were analyzed.

Table 2. Analysis cases.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train speed (km/h)</td>
<td>200, 250, 270, 300, 320</td>
</tr>
<tr>
<td>Vehicle occupancy rate (%)</td>
<td>50, 100, 200</td>
</tr>
<tr>
<td>Spring constant of track pad (MN/m)</td>
<td>50, 100, 150, 250</td>
</tr>
<tr>
<td>Spring constant of ballast (MN/m)</td>
<td>10, 30, 50, 100, 200</td>
</tr>
<tr>
<td>Rail surface roughness</td>
<td>None, original (measured on-site), three times the original, and five times the original</td>
</tr>
<tr>
<td>Support condition of PC sleeper</td>
<td>Uniform support with reduced spring constant ((\alpha \times D_b)) (support condition R)</td>
</tr>
<tr>
<td></td>
<td>Center support ((\alpha \times D_b)) (support condition C)</td>
</tr>
<tr>
<td></td>
<td>(\alpha = 1/100, 1/10, 1/2, 4/5)</td>
</tr>
</tbody>
</table>

As shown in Table 3, the rail surface roughness (Figure 6; 2500 μm maximum amplitude), measured at the rail joint of a conventional line, was set. The reason for this setting was that although this condition is unlikely to occur under general use conditions in Japan, it was established to verify the effect of its occurrence on the bending moments of PC sleepers.

Table 3. Number of PC sleepers.

<table>
<thead>
<tr>
<th>Age</th>
<th>~10</th>
<th>~20</th>
<th>~30</th>
<th>~40</th>
<th>~50</th>
<th>~60</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>14</td>
<td>8</td>
<td>4</td>
<td>34</td>
</tr>
</tbody>
</table>

Figure 6. Rail surface roughness at rail joint of conventional line.

2.2. Investigation Results

2.2.1. Measured Wheel Loads and Bending Moments of PC Sleepers

Figure 7 shows the measured wheel loads and bending moments. The maximum wheel load was 79.51 kN, and the maximum bending moment at the rail seat section of the PC sleeper was 3.81 kN-m. The maximum wheel load and bending moment are the largest wheel load and bending moment generated by each axle of one train set. Each
value was compared with the corresponding design value. The measured values were smaller than the design values. The wheel load was 49.7% of the design wheel load of 160 kN, and the bending moment was 34.7% of the design decompression moment (DDM) of 10.95 kN·m. In addition, neither the wheel load nor the bending moment depended on speed. The reasons for the margin between the measured and design values included the fact that the actual wheel load was smaller than the design wheel load, the consideration of the variable wheel load coefficient, and the conservative assumption for the design’s lateral force and sleeper support condition.

**Figure 7.** Measurement results: (a) wheel loads; (b) bending moments (five continuous sleepers).

2.2.2. Numerical Analysis Verification Results of Effects of Various Parameters on Bending Moments of PC Sleepers

Figure 8 shows a comparison of the analyzed and measured bending moments at the rail seat sections of the PC sleepers. The bending moment obtained from the data of 337 measurements was approximately 2.0 kN·m, which is the average value shown in Figure 7, at a train speed of 300 km/h. As can be seen in Figure 8, the analysis and measurement results were generally identical, and the actual average phenomenon was reproduced using the material constants in Table 1.

**Figure 8.** Comparison of analysis and measurement results.

Figure 9 shows the numerical analysis results of the effects of the parameters on the positive bending moments at the rail seat sections. Figure 9a–g show the effects of each parameter on the basic case. The yellow plot in the figure is the basic case. According to Figure 9, similar to the measurement results, the bending moment did not depend on the train speed and increased with the vehicle occupancy rate, the spring constants of the track pad and ballast, and the rail surface roughness. In addition, when the support spring constant of a PC sleeper decreased, the adjacent PC sleeper bore the load, so the bending moment of the PC sleeper decreased.
Figure 9. Numerical analysis results of effects of various parameters on bending moments at rail seat sections: (a) trail speed; (b) vehicle occupancy rate; (c) spring constant of track pad; (d) spring constant of ballast; (e) amplitude of rail surface roughness; (f) support condition R (Table 2); (g) support condition C (Table 2).

Figure 10 shows the numerical analysis results of the effects of the parameters on the negative bending moments at the center sections. Only the results of the support conditions of the PC sleepers are shown here. The descriptions of the other parameters are omitted because they are similar to those shown in Figure 9. Figure 10a shows the result of a PC sleeper with a uniform support with a reduced spring constant; the trend is almost the same as that in Figure 9f. Figure 10b shows the result of the center support, where the negative bending moment at the center section of the PC sleeper greatly increased. Specifically, when the support spring constants at the rail seat section were 1/2, 1/10, and 1/100 of the constant at the center section, the bending moments at the center sections were approximately doubled, approximately quintupled, and approximately nonupled, respectively. PC sleepers are commonly provided rail seat (central void) support during track maintenance. Our findings suggest the possibility of increasing the negative bending moments at the center sections of PC sleepers by providing center support.
Figure 10. Numerical analysis results of effects of various parameters on bending moment at center section. (a) Support condition R (Table 2); (b) support condition C (Table 2).

Figure 11 shows the numerical analysis results of all cases shown in Table 2. As shown in the figure, the positive bending moment at the rail seat section did not exceed the DDM. In the cases in which the sleeper was uniformly supported or the spring constant under the rail was reduced to 1/2, 1/5, or 1/10 of that at the center section, the negative bending moment at the center section did not exceed the DDM. In contrast, when the spring constant under the rail was 1/100 of that at the center section, this bending moment exceeded the DDM.

Figure 12 shows the numerical analysis results of the case in which the rail surface roughness was measured at the rail joint of the conventional line (Figure 6). Shinkansen trains do not encounter this scenario, but if the amplitude of the rail surface roughness ever becomes approximately 2.5 mm, such as at the rail joints, the bending moment may exceed the DDM. Furthermore, if the amplitude becomes approximately 7.5 mm, the bending moment may also exceed the yield moment of steel.
Figure 12. Numerical analysis results of the case in which rail surface roughness is measured at rail joint of conventional line (Figure 6).

The above results indicate that the primary factor causing cracks and bending fractures in the target PC sleepers was the rail surface roughness, which had large local amplitudes, such as at the rail joints. In addition, assuming the PC sleepers had center support, the negative bending moments at the centers of the sleepers may increase. Therefore, the current track maintenance practice in Japan, that is, providing PC sleepers with rail seat (central void) support, should be continued. Although wheel flats were not considered in this study, their effects should be verified in the future because they generate impact loads in the same way as rail surface roughness [3,26–28]. However, if the current maintenance level of wheel surfaces in Japan is maintained, impact load due to wheel flats will be unlikely, so the numerical analysis in this study is worth evaluating.

3. Evaluation of Bending Load Capacities of Aged PC Sleepers

3.1. Test Methods

3.1.1. Collection of PC Sleepers

Table 3 shows the number of collected PC sleepers. The target PC sleepers are those specified in the JIS E 1201 (type 3T; Chapter 2). These sleepers were placed in the same line section as the site where the field measurement (Chapter 2) was conducted, and they were aged 10–60 years.

3.1.2. JIS E 1201 Bending Test

Figure 13 shows an outline of the bending test specified in the JIS E 1201 [18]. Positive and negative bending tests were conducted on the rail seat and center sections of the PC sleepers, respectively. The loading span was 700 mm. The flexural proof load \( P_c \) and flexural fracture load \( P_u \) specified in JIS E 1201 were obtained using Equations (1) and (2), respectively. In the test, no cracks occurred when the \( P_c \) was applied, and the PC sleepers did not break when the \( P_u \) was applied.

\[
P_c = 4 \times (\sigma_{CPV} \times 0.9 + f_u) \times \frac{Z}{L} \tag{1}
\]

\[
P_u = 4 \times 3\sigma_{pe} \times \frac{Z}{L} \tag{2}
\]

where \( \sigma_{CPV} \) is the concrete stress due to the applied prestress force, \( f_u \) is the allowable tensile stress (3 N/mm²), \( \sigma_{pe} \) is the concrete stress due to the effective prestress force (65% effective rate), \( Z \) is the section modulus, and \( L \) is the loading span (700 mm). Regarding test results, the relationship between the aging and accumulative passing tonnage...
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(hereafter, the “passing tonnage”) was determined for the crack generation and ultimate loads. The crack generation load was the load at which a crack was first detected via visual observation. The ultimate load was the maximum load, past which the PC sleeper could no longer hold the load due to bending.

![Figure 13. Outline of JIS E 1201 bending test.](image)

3.2. Test Results

Figures 14 and 15 show the bending test results, including the flexural proof load and the flexural fracture load. The figures indicate that the crack generation load and the ultimate load decrease gradually with increases in age and passing tonnage. The crack generation load and the ultimate loads of all PC sleepers satisfied the JIS standard values of $P_{cr}$ and $P_u$. In addition, the right axes of these figures show the bending moments generated in the PC sleepers. As shown in Figure 7, the bending moments generated in the PC sleepers during actual train passage were quite small compared with the crack generation loads and ultimate loads during the bending tests. Furthermore, the bending moment obtained from the numerical analysis (Figure 11), except for the analysis results involving the rail surface roughness at the rail joints (Figure 12), was smaller than the crack generation load in the bending tests.

![Figure 14. Relationship between bending load-bearing capacities of PC sleepers and passing tonnage. (a) Positive bending moments at rail seat section; (b) negative bending moments at center sections.](image)
Figure 15. Relationship between bending load-bearing capacities and ages of PC sleepers. (a) positive bending moments at rail seat sections; (b) negative bending moments at center sections.

The above results indicate that at present, even aged PC sleepers that are approximately 50 years old satisfy the standard $P_{cr}$ and $P_u$ values specified by the JIS, and safety is not immediately compromised. However, the bending load-bearing capacity decreases with age and an increase in passing tonnage. Sudden, continuous, non-satisfying bending load-bearing performance should be avoided at any given time. In the future, a quantitative service life should be established, and a shift to a systematic maintenance management system is necessary.

4. Conclusions

In this study, the actual load environment of PC sleepers was investigated via field measurements on commercial lines. In addition, numerical analyses were conducted to verify the effects of various parameters on the bending moments of PC sleepers. Moreover, aged PC sleepers installed on commercial lines were collected and subjected to bending tests specified in JIS E 1201 to evaluate their bending load capacities. The findings of this study are summarized below.

(1) According to the field measurement results of the wheel loads and bending moments of the PC sleepers, the maximum wheel load was 79.51 kN and the maximum bending moment at the rail seat section was 3.81 kN·m. The measured values were smaller than the design values. The wheel load was 49.7% of the design wheel load of 160 kN, whereas the bending moment was 34.7% of the DDM of 10.95 kN·m. In addition, neither the wheel load nor the bending moment depended on train speed.

(2) The numerical analysis results indicated that the positive bending moment at the rail seat section was unlikely to exceed the DDM. However, the negative bending moment at the center section may exceed the DDM if center support were provided with a reduced spring constant under the rail (the “hanging” rail seat section). In addition, the bending moment increased with the rail surface roughness, so the rail should be kept smooth.

(3) The results of the JIS E 1201 bending tests on the aged PC sleepers showed that the crack generation load and ultimate load decreased gradually with increases in age and passing tonnage. However, all samples satisfied the JIS standard $P_{cr}$ and $P_u$ values. Furthermore, the bending moments generated in the PC sleepers during train passage were considerably smaller than the crack generation loads and ultimate loads during the bending tests.

(4) Thus, Japanese PC sleepers aged over 50 years currently satisfy the standard flexural fracture values specified by the JIS, and safety is not immediately compromised.

In the future, we plan to formulate a maintenance management plan and a replacement plan for PC sleepers according to the service life of a PC sleeper obtained in this study. We also recommend the continuation of maintenance and management.
practices that do not generate impact loads. Present track maintenance work, which involves the use of rail seat (central void) support for PC sleepers and is commonly practiced today, should also be continued to maintain the safety and stability of railway transportation.

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