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Research Article

Nonlinear Analysis Method for Serviceability Investigation of Bridge Deck Ends with a Concrete Slab Track

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In this study, a nonlinear analysis method was proposed to evaluate the serviceability review of a rail fastening system on concrete slab track at railway bridge ends. The serviceability review of the end deck is time-consuming in that it is necessary to calculate the force of fasteners; also, the design is complex because of the many girders, fasteners, and loads. In addition, there is also a case in which a special, expensive fastening device is installed because the stiffness of the rail fastening device is assumed to be linear, and excessive design results are produced by the linear analysis method. In this study, a clamping force test of the fastening system was performed to confirm the real stiffness and the force versus displacement relationship. The test results were applied in the conventional linear analysis method and the proposed nonlinear analysis method to a railway bridge model specimen with concrete slab tracks. The results of the nonlinear analysis method considering the nonlinear stiffness of the rail fastening system through the clamping force test confirmed that the uplift force acting on the rail fastener was considerably reduced compared with that in the linear analysis method.

1. Introduction

Use of concrete slab track has been increasing worldwide in attempts to reduce the cost of track maintenance and ensure a stable ride. A railway bridge with a concrete slab track is separated from a protective concrete layer (PCL) and track concrete layer (TCL) by an intermediate layer, but the behaviors of the longitudinal and lateral directions are constrained due to the cam plate. In high-speed lines fitted with slab track, the bridge ends are of special importance because of problems created by displacement and rotation, as well as extreme forces in the rail fastenings that may develop in this area [1, 2]. The rotation of the bridge deck end enforces a curvature of the track in the transition area to the abutment and at the expansion joints on the piers, which additionally stresses the superstructure in these areas [3]. These additional stresses are called uplift force and compression force and can cause breakage of the fastener clip and plastic deformation of the elastic pad in the rail fastening system of the bridge end, thereby increasing the maintenance cost. The concrete slab track serviceability review of a railway bridge deck end is classified as rotation and vertical displacement to deformation of the superstructure caused by various loading conditions. The force generated at the rail support point and the rail should be within the range of the initial fastening force of the rail fastener and the plastic deformation limit of the elastic pad [3, 4]. Park et al. [5] analyzed the factors influencing the serviceability of the concrete slab track rail fastening system during bridge end rotation and used parameter analysis to determine the influence degrees. Many studies considering track-bridge interaction have been performed to evaluate the serviceability at a railway bridge deck end [6–8]. Choi [9] used a continuous support model and a discrete support model to analyze the influence of rail support point spacing and rail fastener stiffness on the force acting on the rail support [10–12]. Choi [13], using the unequal space discrete supported beam model, performed an analysis of rail support point force according to the distance between the bridge end rail support points and the distance between the bridge support and the last rail support point of the bridge end. Lim et al. [14] and Sung and Han [15] studied the characteristics of deformation for a concrete slab track on a railway bridge deck end induced by bridge end rotation. Recently, many studies related to nonlinear behavior of fastening systems have been conducted [16]. Yang and Jang [17] developed a numerical algorithm as a practical solution to the nonlinear system equation and on the basis of their testing established longitudinal track stiffness laws for concrete slab track. Recently, Yang et al. [18] suggested the need for a study that reflected the nonlinear behaviors of fastening systems in railway bridge end concrete slab track serviceability reviews.

In this paper, a nonlinear analysis method was proposed to evaluate the serviceability of a rail fastening system on a concrete slab track at railway bridge ends. In order to confirm the behavior of an actual rail fastening system, a clamping force test was performed. The details of the test are explained in a section on the nonlinear behavior of the rail fastening system. The conventional linear analysis method and the proposed nonlinear analysis method were numerically applied for a railway bridge model specimen with concrete slab track, and the uplift forces acting on the fastening systems as determined using both methods were compared.

2. Serviceability Review of a Concrete Slab Track Fastening System

2.1. Deformation of Track at a Railway Bridge End. As shown in Figure 1, the rail and rail support points of concrete slab track fixed on a bridge deck can be deformed due to rotation of the end of the bridge. This deformation curvature generates a compressive force at the bridge side rail supporting point and an uplift force at the rail supporting point of the abutment side. The uplift force generated at rail support points should be within the initial clamping force, and the compression force should not exceed the elastic pad deformation limit [3, 4].

2.2. Conventional Method for Serviceability Investigation of Fastening System. For railway bridges with concrete slab track, DS804 [3] and KR C-08090 [4] present criteria for evaluating the serviceability of the ends and suggest major factors influencing bridge deformation. Figure 2 shows the procedure for calculating and investigating the force of a rail fastening system by the conventional method.

A serviceability review of a concrete fastening system is performed by calculating the force acting on fastening devices by unit load applied to the railway bridge (LF1: unit rotation angle, LF2: vertical deflection, and LF3: unit wheel load), as shown in Figure 2. Then, the rotation angles and vertical offsets at the end of the railway bridge deck are calculated for several loads such as the creep and shrinkage and train vertical load. The final uplift forces (F_d) acting on the fastening system are calculated using the force by unit load and the deformation of the actual bridge. That is, F_d is calculated by multiplying the acting force of the fastener by the unit load and the deformation in an actual girder, as follows:

$$\begin{aligned} F_{\mathrm{d}} = {} & \phi_{\mathrm{d,stat}} F\left(\mathrm{LF1}; k_{\mathrm{stat}}\right) + \phi_{\mathrm{d,dyn}} F\left(\mathrm{LF1}; k_{\mathrm{dyn}}\right) \\ & + \delta_{\mathrm{d,stat}} F\left(\mathrm{LF2}; k_{\mathrm{stat}}\right) + \delta_{\mathrm{d,dyn}} F\left(\mathrm{LF2}; k_{\mathrm{dyn}}\right) \\ & + \frac{P_{\mathrm{d}}}{100} \min F\left(\mathrm{LF3}; k_{\mathrm{dyn}}\right), \end{aligned} \quad (1)$$

where F_d is the design value for the largest uplifting force, $\phi_{d,stat}$ and $\phi_{d,dyn}$ are the actual angles of rotation in ‰ at the bridge deck end, $\delta_{d,stat}$ and $\delta_{d,dyn}$ are the actual vertical offset in mm at the bridge deck end, k_{stat} is the static stiffness of the rail support point in kN/mm, k_{dyn} is the dynamic stiffness of the rail support point in kN/mm, $F(\mathrm{LF1})$ is the forces of the support point in kN according to the unit angle of rotation ($\phi = 1$‰), $F(\mathrm{LF2})$ is the forces of the support point in kN according to the unit vertical offset ($\delta = 1$ mm), $F(\mathrm{LF3})$ is the forces of the support point in kN according to unit vertical load (100 kN), and P_d is the efficient wheel load of the service load train in kN.

2.3. Nonlinear Behavior of Rail Fastening System. The conventional method of evaluating the serviceability of a concrete slab track fastening system is implemented under the assumption that the railway bridge and fastening system behave linearly. However, the railway bridge and the fastening system actually exhibit nonlinear behavior.

In this study, a clamping force test was performed to confirm the real stiffness of the fastening system. The names of each part involved in the clamping force test are shown in Figure 3(a). Figure 3(b) shows a real test photograph of the clamping force test of the fastening system as presented in the Korean Railway Standards and British Standards [19, 20].

Briefly, the procedure of the clamping force test is as follows:

(i) Apply an upward force (P) on the rail until the rail pad is removed

(ii) Reduce the load until the displacement of the rail bottom becomes zero and record the load (P) at this time

(iii) Reduce the load until the load reaches 0.9 P

(iv) Increase again the load until 1.1 P

Figure 4(a) shows the results of the clamping force test implemented via the above procedure. The load-displacement curve of the fastening system is shown in Figure 4(b). In this paper, Figure 4(b) was used to simulate the fastening system.

Figure 5 shows the load and displacement relation graph of the linear (30 kN/mm) and the nonlinear stiffness of System 300-1 fastening device. When the displacement of the fastening system is 1 mm, the load acting on the fastening system is 30 kN in the linear case and about 14 kN in the nonlinear case.

In the conventional method, if the stiffness of the fastening system is assumed to be linear, the fastening system can be overdesigned, and an expensive special fastening device may need to be installed.

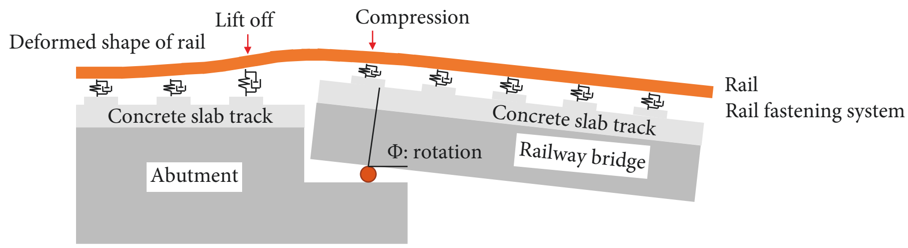

FIGURE 1: Deformed shape of rail at bridge deck ends.

2.4. Serviceability Review Method considering Nonlinear Behavior of Fastening System. In this paper, a nonlinear analysis method is proposed that simplifies the existing complex design process, reduces overdesign by linear analysis, and reflects nonlinear behavior characteristics of the fastening system.

Figure 6 shows the conventional procedure for investigating the serviceability of a railway bridge end concrete slab track. Figure 7 shows the procedure for reviewing the serviceability of the end of the railway bridge while considering the nonlinear behavior characteristics of the fastening system proposed in this study.

In the procedure shown in Figure 6, the forces acting on each fastening system are calculated after the finite element analysis for each unit load (LF1, LF2, and LF3). Then, the angle of rotation and the vertical offset are calculated for each influence factor present at the end of the railway bridge. The final results are calculated by multiplying the force of each fastener and the actual deformation of the deck by each influence factor; finally, the serviceability is evaluated using Equation (1).

On the other hand, in the proposed nonlinear method shown in Figure 7, the rotation angle and the vertical offset for each influence factor that may occur at the railway bridge end are multiplied by the partial safety factor.

The load (rotation angle, vertical offset, and vertical force) to be used in the finite element analysis is calculated using Equation (2). Nonlinear analysis of the railway bridge model is performed to confirm the forces (uplift force and compression force) acting on each fastening system.

$$
\begin{aligned}
P_{\phi d} &= \sum \phi_{\text{stat}} \times \gamma_{\text{F}} + \sum \phi_{\text{dyn}} \times \gamma_{\text{F}},\\
P_{\delta d} &= \sum \delta_{\text{stat}} \times \gamma_{\text{F}} + \sum \delta_{\text{dyn}} \times \gamma_{\text{F}},\\
P_{\text{pd}} &= mP \times \gamma_{\text{F}},
\end{aligned}
\tag{2}
$$

where ϕ_{stat} is the actual angle of rotation in ‰ at the bridge deck end due to static effects such as creep and shrinkage, the temperature difference between the upper and lower surfaces of the deck, and differences in the settlement of the foundation. ϕ_{dyn} is the actual angle of rotation in ‰ at the bridge deck end due to dynamic effects (train vertical load). δ_{stat} is the actual vertical offset in mm at the bridge deck end due to static effects (vertical offset by rotation of the pier top due to the temperature difference between the rail and deck, vertical offset due to rotation of the pier top due to temperature differences in the pier), and δ_{dyn} is the actual vertical offset in mm at the bridge deck end due to dynamic effects (rotation of the pier top due to braking and acceleration, vertical deflection of bearing due to the train's vertical load, and compressive deformation due to direct loading). m is a coefficient that considers the vertical load effect. P is the vertical load. γ_{F} is a partial safety factor.

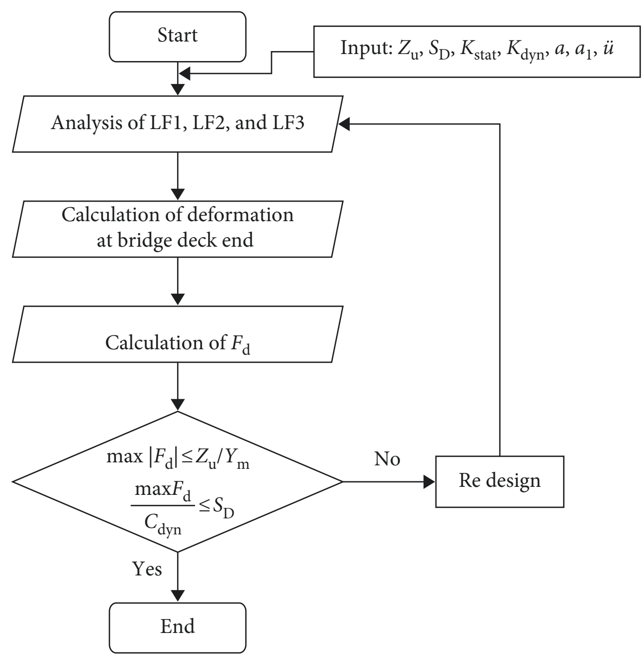

FIGURE 2: Flowchart for serviceability review of fastening system [3, 4].

The main difference between the two procedures is whether the finite element analysis is performed early or later. That is, conventional analysis method (unit load method) implements the finite element analysis linearly on the unit load in the first step, while the nonlinear analysis method implements the finite element analysis nonlinearly as the last step for the combined load.

3. Analysis Model

To compare the results of the proposed nonlinear analysis method and the conventional method, a railway bridge specimen was used as shown in Figure 8. Table 1 shows the properties of the girders, rail, sleepers, and fastening system.

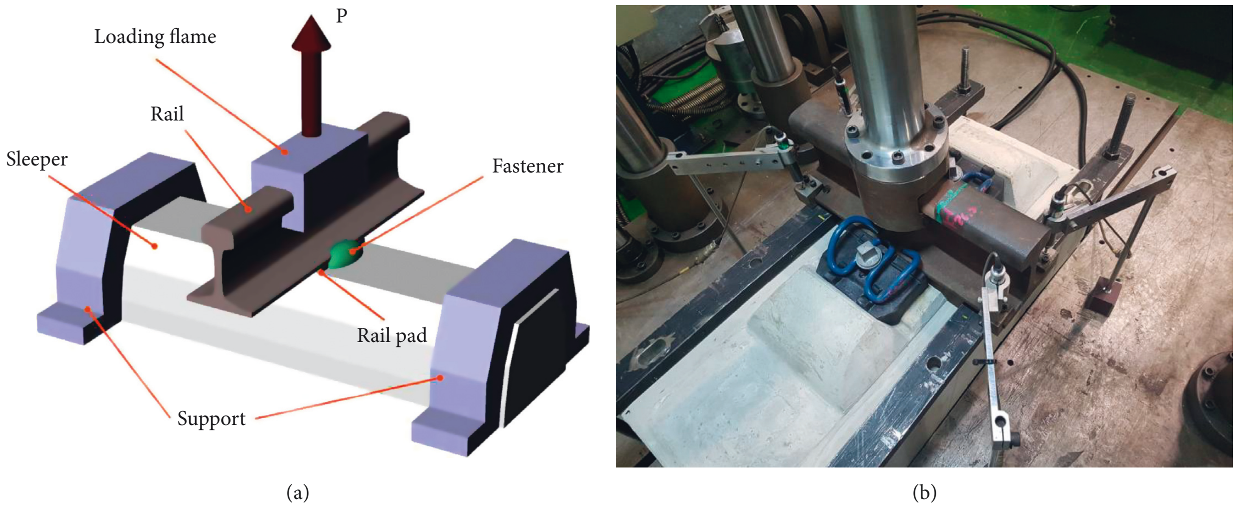

Figure 3: Clamping force test of fastening system. (a) 3D picture for understanding. (b) Real test for System 300-1 fastener.

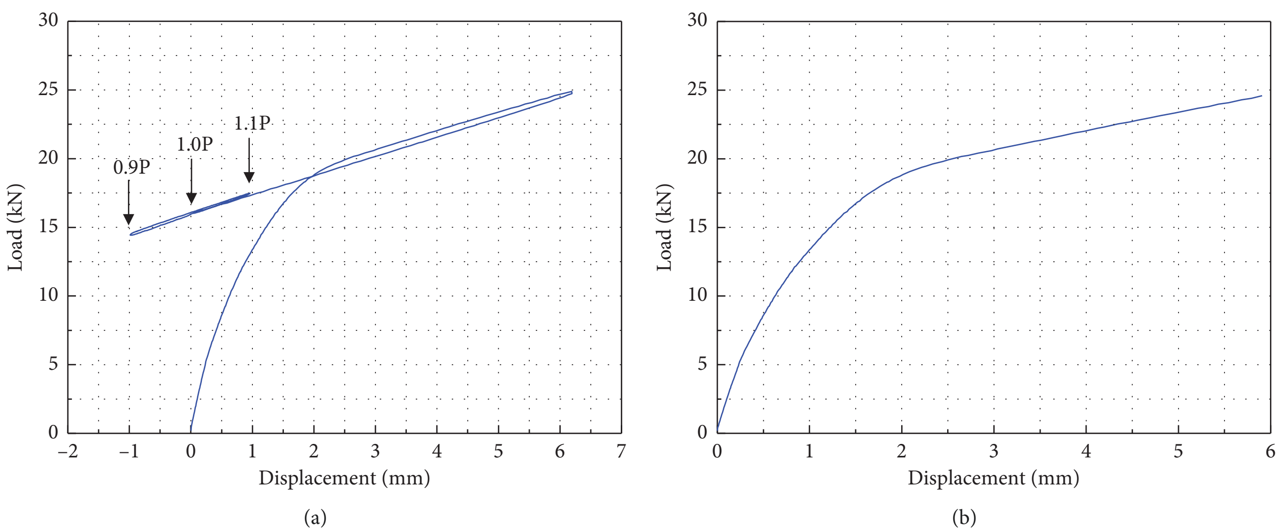

Figure 4: Test results of the fastening system (System 300-1). (a) Results of the clamping force test; (b) load vs. displacement graph of fastening system.

Finite element analysis software, SAP2000, was used to analyze the railway bridge concrete slab track end shown in Figure 8, and the bridge girders, rail, and fastening system were modeled in two dimensions (Figure 9). The bridge girders and rail were modeled using beam elements. As shown in Figure 10, the fastening system in linear analysis was modeled by linear link elements with a stiffness of 30 kN/mm for both the compression and tensile range, while the fastening system in the nonlinear analysis was modeled by multilinear elastic links using the clamping force test results (Figure 4(b)). The longitudinal stiffness of the fasteners was set at 13.5 kN/mm, as in a previous study [21].

4. Applied Loads

Analysis of the uplift force of the railway bridge end concrete slab track fastening system should take into account the loads that cause deformation of the bridge deck, the creep and shrinkage, the temperature difference between the upper and lower surfaces of the deck, the residual settlement of the pier foundation, differences in temperature between the rail and the deck, the temperature differences in the piers, train vertical load, braking and acceleration load, and the compressive deformation due to direct loading.

Loads that cause rotation and vertical offset at the end of deck are briefly described in this section.

4.1. Long-Term Deflection by Creep and Shrinkage.

Angle of rotation of the deck end due to long-term deflection of the superstructure via creep and shrinkage after installation of the railway bridge can be expressed as in the following equation:

$$\phi_\infty = \phi_0 + \phi_{C+S}, \quad (3)$$

where ϕ_∞ is the angle of rotation due to long-term deflection on deck end, ϕ_0 is the angle of rotation due to self-weight of bridge and track, and ϕ_{C+S} is the angle of rotation due to creep and shrinkage [4].

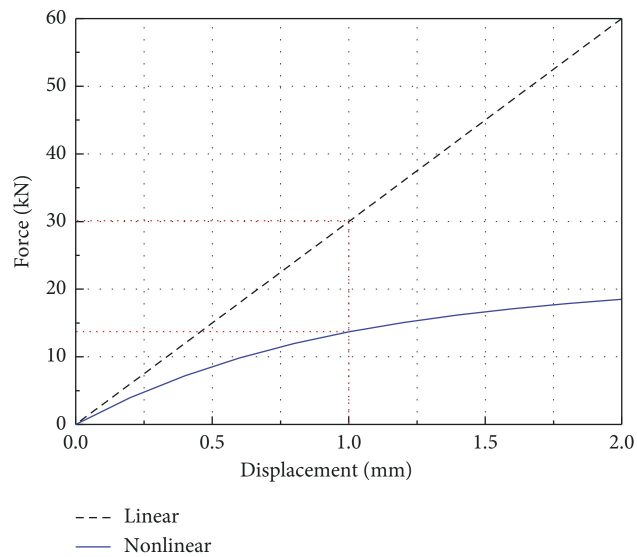

FIGURE 5: Linear and nonlinear behavior of fasteners.

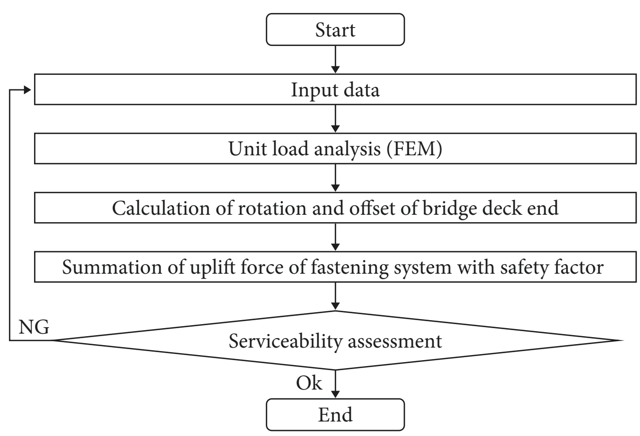

FIGURE 6: Flowchart of concrete slab track serviceability review in railway bridge.

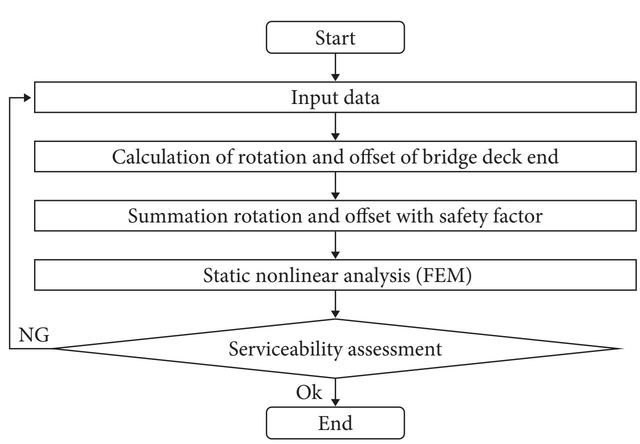

FIGURE 7: Flowchart of proposed method.

4.2. Temperature Difference between Upper and Lower Surfaces of Deck. Angle of rotation of the deck end due to temperature difference (ΔT) between upper and lower surfaces of the deck can be calculated using the following equation:

$$\phi = \frac{\alpha \Delta T L}{2h}, \tag{4}$$

where α is the coefficient of thermal expansion of concrete, L is the length of the span, and h is the depth of the deck.

4.3. Residual Settlement of Pier Foundation. Angle of rotation on the deck end due to residual settlement of the pier foundation can be calculated using the following equation:

$$\phi = \frac{\Delta s}{L}, \tag{5}$$

where Δs is the residual settlement of the pier foundation and L is the length of the span.

4.4. Temperature Difference between Rail and Deck. In cases of the difference between the rail and deck, the deck is subjected to horizontal load via interaction between the rail and the deck. The piers are horizontally deformed by the load, and vertical offsets occur. Vertical offsets can be determined by track-bridge interaction analysis [22]. In this paper, the effect of track-bridge interaction was not applied.

4.5. Temperature Difference between Front and Rear Surface of Pier. A vertical offset on the deck end due to temperature differences in the pier can be calculated using the following equation [4]:

$$\delta = \varphi_{\mathrm{p}} d_{\mathrm{br}},$$
$$\varphi_{\mathrm{p}} = \alpha \Delta T_{\mathrm{p}} \frac{H_{\mathrm{p}}}{D_{\mathrm{p}}}, \tag{6}$$

where φ_{p} is the rotation angle of the top of the pier, ΔT_{p} is the temperature difference between the front and rear surfaces of the pier, H_{p} is the height of the pier, D_{p} is the pier diameter, and d_{br} is the distance between the two bridge bearings. The effect of temperature differences in the pier was not applied in this paper.

4.6. Vertical Vehicle Load. Angle of rotation on the deck end due to vertical vehicle load can be obtained by finite element analysis under vertical vehicle load. The vertical vehicle load can be applied by multiplying the uniform load and the impact factor $(1+\phi)$ by the coefficient λ. The value of λ can be determined according to the type of train. The impact factor can be determined according to the length of the span and the train velocity. In this paper, 1.0 and 1.11 were adopted as λ and $(1+\phi)$, respectively [4].

The vertical offset on the deck end due to braking and acceleration load of the train is specified in track-bridge longitudinal interaction analysis [22]. Finally, the load

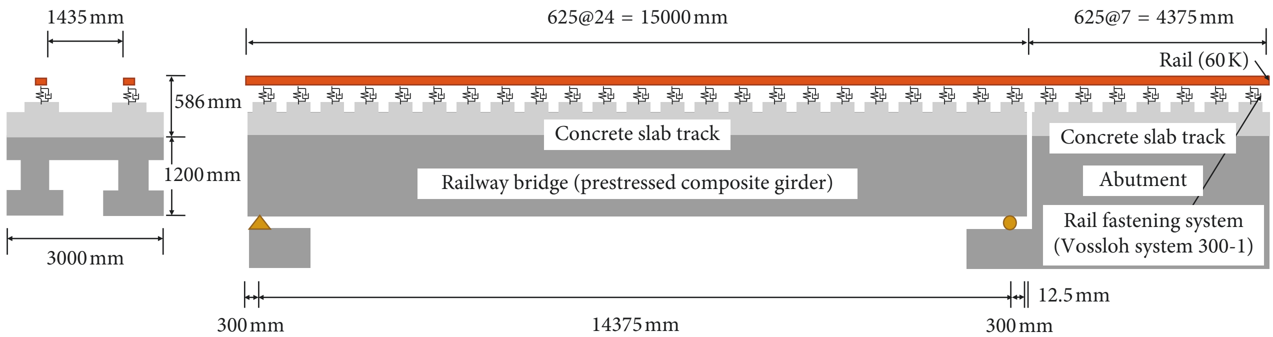

Figure 8: Railway bridge model.

Table 1: Properties of the girder and track system.

Item	Index	Modulus of elasticity (N/m^2)	Area (m)	Moment of inertia (m^4)
Girder	Prestressed composite girder	$2.686e+10$	3.3191	0.6974
Rail	60 kg/m (KR CODE)	$2.059e+11$	$7.742e{-3}$	$3.083e{-5}$
Sleeper	ERS sleeper (RC sleeper), 625 mm	—	—	—
Rail resilient pad	Static spring stiffness: 30 kN/mm	—	—	—
Rail fastening system	Vossloh System 300-1	—	—	—

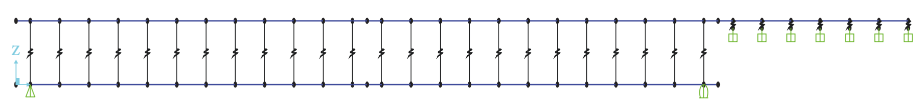

Figure 9: FEM model for assessment of railway bridge system.

applied directly to the rail support point by the vertical load is calculated using the following equation:

$$P = f_{\text{dyn}} f_{c} P_{\text{stat}}, \tag{7}$$

where f_{dyn} is the dynamic impact factor and f_c is the coefficient of the wheel load with respect to centrifugal force on the curved part.

However, the purpose of this study was to investigate the effect of the nonlinear analysis method considering the nonlinear behavior characteristics of the fasteners. Therefore, among the loads mentioned in this paper, only the creep and shrinkage, the temperature difference between the upper and lower surfaces of the deck, differences in settlement of the foundation, and the train's vertical load were used for the analysis.

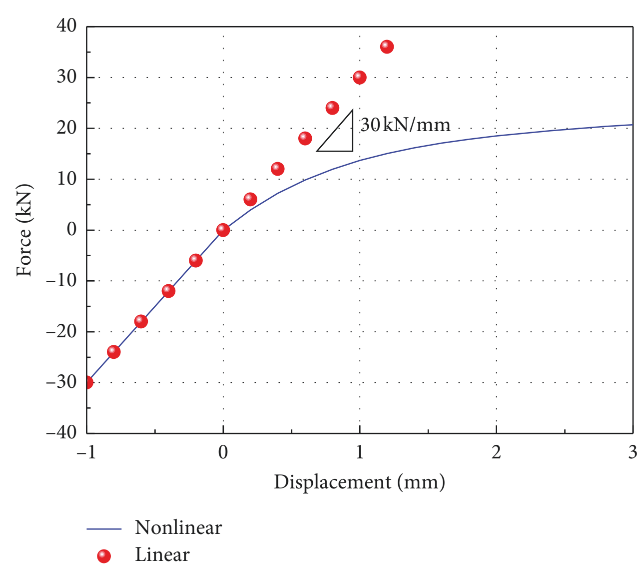

Figure 10: Load-displacement curves of the linear and nonlinear fastening systems applied in the analysis.

5. Results and Discussion

Using the conventional unit load method, the uplift forces of the fastening system of the railway bridge end, considering the nonlinear behavior of the rail fasteners, were compared with the uplift forces of the fasteners. As shown in Figure 11, the uplift force of the fasteners was confirmed for the five support points on the left and right ends. Tables 2 and 3 show the uplift force of the fastening system as obtained using the unit load method and nonlinear analysis.

Table 2 shows the results obtained using the conventional method. (1) Static and (2) dynamic indicate the uplift force due to unit load LF1, (3) creep/shrinkage, (4) temperature/gradient, (5) residual settlement, and (6) vehicle load are the rotation angles of the deck end for the factors (creep and shrinkage, temperature gradient, residual settlement, and train load) that affect the deformation of the bridge deck. The uplift forces due to LF1 are multiplied by the rotation angles and the factor column. The final uplift forces of the fastening system when using the conventional method are shown in the Summation column.

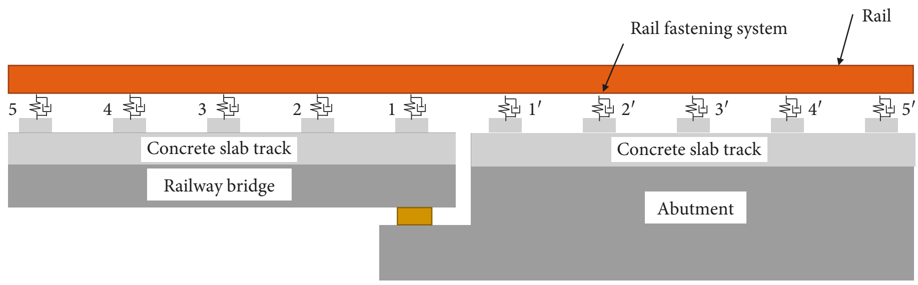

Figure 11: Definitions of notations corresponding to positions of fastening system.

Table 2: Uplift force using conventional method.

No.	Unit load LF1 (1) Static (kN)	Unit load LF1 (2) Dynamic (kN)	Static (‰) (3) Creep/shrinkage	Static (‰) (4) Temperature/gradient	Static (‰) (5) Residual settlement	Dynamic (‰) (6) Vehicle load	Multiplication factor (kN) (1)·(3)	(1)·(4)	(1)·(5)	(2)·(6)	Summation (kN)
5	0.38	0.12	0.37	0.30	0.33	0.92	0.14	0.11	0.13	0.15	0.53
4	1.08	1.07	0.37	0.30	0.33	0.92	0.39	0.32	0.36	1.28	2.36
3	1.68	2.57	0.37	0.30	0.33	0.92	0.62	0.50	0.56	3.08	4.76
2	0.54	1.83	0.37	0.30	0.33	0.92	0.20	0.16	0.18	2.19	2.73
1	−5.62	−9.04	0.37	0.30	0.33	0.92	−2.06	−1.69	−1.87	−10.84	−16.46
1′	−0.19	0.81	0.37	0.30	0.33	0.92	−0.07	−0.06	−0.06	0.97	0.78
2′	1.17	2.02	0.37	0.30	0.33	0.92	0.43	0.35	0.39	2.42	3.59
3′	0.88	0.95	0.37	0.30	0.33	0.92	0.32	0.26	0.29	1.14	2.02
4′	0.36	0.16	0.37	0.30	0.33	0.92	0.13	0.11	0.12	0.19	0.55
5′	0.06	−0.09	0.37	0.30	0.33	0.92	0.02	0.02	0.02	−0.10	−0.05

Table 3: Uplift force using proposed nonlinear analysis method.

No.	Unit load LF1		Static (‰) (3) Creep/shrinkage	Static (‰) (4) Temperature/gradient	Static (‰) (5) Residual settlement	Dynamic (‰) (6) Vehicle load	Multiplication factor (‰) (3)’	(4)’	(5)’	(6)’	Summation (‰)	Results (kN)
5	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	0.97
4	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	2.21
3	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	3.13
2	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	1.26
1	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	−11.97
1′	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	−0.01
2′	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	2.11
3′	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	1.72
4′	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	0.85
5′	—	—	0.37	0.30	0.33	0.92	0.37	0.30	0.33	1.20	2.20	0.24

Table 3 shows the results by the proposed nonlinear analysis method. The rotation angles at the bridge deck end for each influence factor are shown in the columns marked static and dynamic in Table 3. Partial safety factors for the static and the dynamic effects were applied, with values of 1.0 and 1.3, respectively. The rotation angles at the bridge deck end that was input to the nonlinear analysis model are shown in the summation column, and the uplift forces for each fastening system are shown in the results column.

In the unit load method and the nonlinear analysis method, the maximum uplift forces on the fastening system of the bridge deck ends were 4.76 kN and 3.13 kN, respectively, and the uplift force when using the nonlinear analysis method decreased by 34%. The uplift forces at the 2′ position are 3.59 kN and 2.11 kN. The uplift force was reduced by about 41%. Furthermore, the compressive force of the fastener decreased from 16.46 kN to 11.97 kN. The decrease ratio was 27%. The lift and compression forces at positions of fasteners are shown in Figure 12. Although the kinds of influence factors used in the uplift force analysis of the fastening system when using the unit load method and the nonlinear analysis method were small, it was confirmed that the differences in uplift force were large.

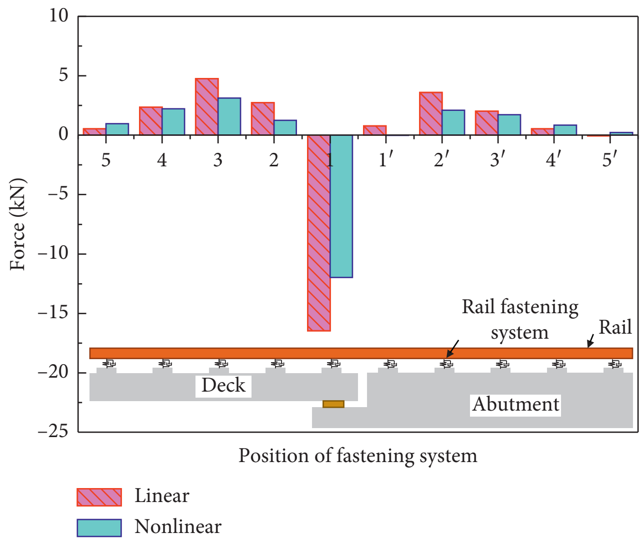

Figure 12: Comparison of uplift force and compression force on support points.

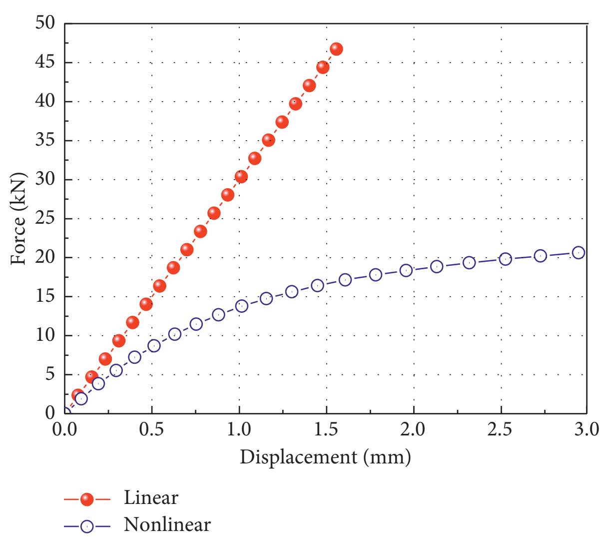

Figure 13: Force vs. displacement graph at point 2′ under an increasing load.

Figure 13 provides a graph of the uplift force and the displacement for both methods at the right (2′) second point. These results were obtained by increasing the rotation angle from 2‰ to 40‰ on the deck end. As shown in Figure 13, when the displacement of the fastening system was small, the difference between the linear analysis and the nonlinear analysis was not large. However, when the displacement of the fastener was 1 mm, the uplift force of the fastener obtained using nonlinear analysis dropped to about 50%.

6. Conclusions

In this paper, a nonlinear analysis method was proposed for evaluating the serviceability of a rail fastening system on a concrete slab track at railway bridge ends. In order to confirm the nonlinear behavior of the rail fastening system, a clamping force test was carried out, and the load-displacement curve of the fastener was obtained by experiment. Analysis of the serviceability review was performed on a specimen railway bridge using the unit load method (linear analysis method) and the proposed nonlinear method. The creep and shrinkage, the temperature differences at the upper and lower surfaces of the deck, differences in settlement of the foundation, and the train's vertical load were considered in the analysis.

It was confirmed that the uplift force and the compression force were reduced by up to 34% and 27% in the nonlinear analysis, respectively. As the load acting on the end of the railway bridge increased, the uplift force obtained using the nonlinear analysis method decreased more than that of the unit load method.

In future studies, it will be necessary to verify the numerical analysis of the entire railway bridge by considering the forces of all factors affecting the deformation of the superstructure; testing of the clamping force for various rail fastening devices will also be necessary. Verification must also be implemented by using numerical analysis and experiments to compare the responses of the fastening system.

Data Availability

The experimental data used to support the findings of this study are temporarily restricted in order to protect patent and further research.

Conflicts of Interest

The author declares that they have no conflicts of interest.

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References

[1] T. Moelter, *Bridges for High-Speed Railways: Closed and Open Joints for Bridges on High Speed Lines*, Taylor & Francis, New York, NY, USA, 2004.

[2] Z. Chen, B. Andrawes, and J. R. Edwards, "Finite element modelling and field validation of prestressed concrete sleepers and fastening systems," *Structure and Infrastructure Engineering*, vol. 12, no. 5, pp. 631–646, 2015.

[3] A. G. Deutsche Bahn, *DS804 Appendix 29: Bridge Deck Ends, Check for Serviceability Limit State of Superstructure. Regulation for Railway Bridges and Other Civil Constructions*, Deutsche Bahn AG, Berlin, Germany, 2008.

[4] Korea Rail Network Authority, *KR C-08090. Check for Serviceability Limit State of Concrete Track on Bridge Deck Ends*, Korea Rail Network Authority, Seoul, South Korea, 2014.

[5] H. K. Park, S. Y. Jang, and S. C. Yang, "A parametric study on the serviceability of concrete slab track on railway bridge," *Journal of the Korean Society for Railway*, vol. 12, no. 1, pp. 95–103, 2009.

[6] P. Ruge and C. Birk, "Longitudinal forces in continuously welded rails on bridge decks due to nonlinear track-bridge interaction," *Computers and Structures*, vol. 85, no. 7-8, pp. 458–475, 2007.
[7] F. Schanack, O. R. Ramos, J. P. Reyes, and M. J. Pantaleon, "Relative displacement method for track-structure interaction," *Scientific World Journal*, vol. 2014, Article ID 397515, 7 pages, 2014.
[8] P. Ryjacek, M. Howlader, M. Vokac, B. Stollenwerk, and P. Ondovcak, "The rail-bridge interaction-recent advances with ERS fastening system for steel bridges," *Transportation Research Procedia*, vol. 14, pp. 3972–3981, 2016.
[9] J. H. Choi, "Analysis of the internal forces of the rail supports for the serviceability of concrete slab track bridge," *Journal of the Korean Society of Civil Engineers*, vol. 33, no. 4, pp. 1303–1313, 2013.
[10] C. Esveld, *Modern Railway Track*, MRT Productions, Zaltbommel, Netherlands, 2nd edition, 2001, ISBN: 90-800324-3-3.
[11] A. D. Kerr, *Fundamentals of Railway Track Engineering*, Simmons-Boardman Books, Omaha, NE, USA, 2003.
[12] B. Lichtberger, *Track Compendium: Track System, Substructure, Maintenance, Economics*, Eurail Press, Hamburg, Germany, 2011.
[13] J. H. Choi, "Influence of rail supporting spacing of railway bridge deck ends on bridge-track interaction forces," *Journal of the Korean Society for Railway*, vol. 17, no. 4, pp. 245–250, 2014.
[14] J. I. Lim, S. O. Song, and J. Y. Choi, "Experimental study on characteristics of deformation for concrete track on railway bridge deck end induced by bridge end rotation," *Journal of the Korean Society for Railway*, vol. 16, no. 3, pp. 217–225, 2013.
[15] D. Y. Sung and S. C. Han, "Experimental study of effects of track systems on static and dynamic behavior of railway bridges," *Advances in Structural Engineering*, vol. 21, no. 2, pp. 214–226, 2017.
[16] J. Turek, "Non-linear response of the track," *Vehicle System Dynamics*, vol. 24, no. 1, pp. 265–279, 2007.
[17] S. C. Yang and S. Y. Jang, "Track-bridge interaction analysis using interface elements adaptive to various loading cases," *Journal of Bridge Engineering*, vol. 21, no. 9, pp. 131–141, 2016.
[18] S. C. Yang, H. H. Kim, and J. S. Kong, "Evaluation of uplift forces acting on fastening systems at the bridge deck end considering nonlinear behaviors of the fastening systems," *Journal of the Korean Society for Railway*, vol. 20, no. 4, pp. 521–528, 2017.
[19] Korean Railway Standards, *KRS TR 0014-15R. Rail Fastening System*, Korea Railroad Research Institute, Uiwang, South Korea, 2009.
[20] British Standards, *BS EN 13146-7. Railway Applications-Track, Test Methods for Fastening Systems, Part 7: Determination of Clamping Force*, British Standards Institution, London, UK, 2012.
[21] K. M. Yun, B. H. Park, K. H. Min, and N. H. Lim, "Experimental study of characteristics of longitudinal resistance behavior of fasteners in concrete track on bridges," *Journal of the Korean Society for Railway*, vol. 19, no. 5, pp. 638–646, 2016.
[22] Korea Rail Network Authority, *KR C-08080. Track-Bridge Longitudinal Interaction Analysis*, Korea Rail Network Authority, Seoul, South Korea, 2017.