

Article

Evaluation of Spring Stiffness of Resilience Pads for Sleeper Floating Track Through Modal Testing

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Abstract

The resilience pads of sleeper floating tracks (STEDEF) are key components that absorb shock loads and vibrations induced by train traffic. Currently, under the Korean domestic guidelines for track facility performance evaluation, one sample per 500 m is collected from the field, and the static spring stiffness is assessed through laboratory testing. However, this approach requires nighttime track possession, incurs significant manpower and cost, and provides limited reliability because the condition of an entire section is inferred from a small number of samples. Therefore, this study proposes an impact-hammer–FRF-based method for evaluating the spring stiffness of resilience pads without pad extraction. Field impact-hammer tests were conducted to identify the dominant first-mode natural frequency of the track-support system. Configuration-specific finite element models were then used to derive frequency–stiffness relationships for the investigated STEDEF configurations. The novelty of the proposed method lies in converting the local first-mode frequency measured in situ into a static-equivalent stiffness index that can be directly compared with the maintenance reference value used in the Korean inspection framework. The finite element model reproduced the mean natural frequencies of the reference configurations with differences of 0.08–3.61%. Based on the configuration-specific relationships, estimation equations were developed to support in situ screening of resilience-pad stiffness at the measured locations.

Keywords: impact-hammer–FRF test; sleeper floating track systems; spring stiffness; resilience pads; evaluation



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1. Introduction

Urban transit systems in Seoul, Daejeon, Daegu, and Busan have adopted sleeper floating track systems (STEDEF) to reduce noise and vibration. As shown in Figure 1, STEDEF separates reinforced concrete (RC) sleepers from the concrete bed, and the resilience pads inside the sleeper boots absorb track vibrations transmitted to the structure. This alleviates vibration and impact loads and provides the required elasticity under wheel loads, thereby securing train running performance [1].

The shape, hardness, and elasticity of resilience pads change significantly and deteriorate over years of service due to repeated loads from operating trains and external factors such as temperature and moisture. This deterioration in the properties of the resilience pads increases the impact load and vibrations transmitted to the concrete bed, resulting in

complaints due to the deterioration of the riding environment. In metro systems, wheel–rail contact forces are the primary excitation sources governing vehicle–track vibration transmission, and changes in rail–support stiffness (e.g., resilience-pad stiffening) can alter the dynamic response level and perceived ride/noise–vibration performance [2]. Although this study does not explicitly model the operational wheel–rail contact, we incorporate this context to motivate the need for an efficient in situ stiffness evaluation method. Therefore, resilience pads require timely maintenance, such as condition evaluation and replacement, depending on their long-term use. For this purpose, a quantitative evaluation of the spring stiffness of the resilience pads is important.

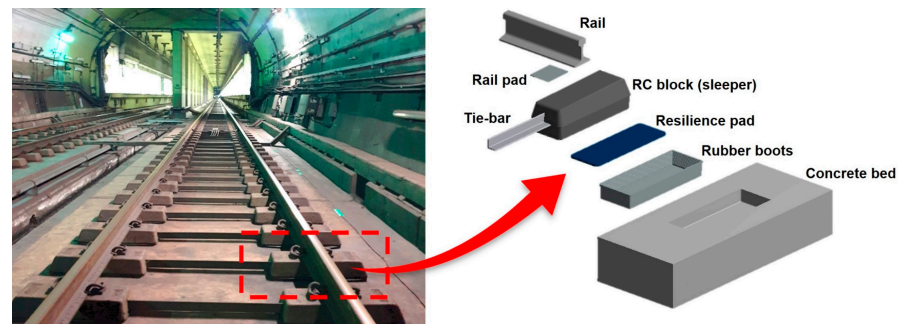


Figure 1. Sleeper floating track systems configuration.

Resilient support elements are widely used in railway tracks to modify track dynamics and mitigate the transmission of train-induced vibrations to the surrounding structure and ground. Auersch [3] demonstrated that soft support elements and increased track bending stiffness can influence vehicle–track–soil interaction and reduce railway-induced ground vibration. Chen et al. [4] evaluated the vibration-reduction performance of a damping device for a damping-pad floating slab track, highlighting the importance of support-system properties in controlling vibration transmission. In addition, Rivas et al. [5] experimentally demonstrated that mechanical and environmental aging can alter the dynamic stiffness of EPDM and EVA rail pads. These findings indicate that the long-term condition of elastomeric support components should be considered in the maintenance and dynamic evaluation of railway tracks.

Previous studies have investigated the relationship between resilience-pad stiffness and track dynamic response using fatigue testing, field measurements, and numerical analysis. Park [6] estimated the spring stiffness of resilience pads by combining fatigue-test results and numerical analysis with concrete-bed vibration acceleration measurements under train loading. Bong [7] analyzed the effect of resilience-pad stiffness variation on the track impact factor and proposed a maintenance-oriented replacement criterion before pronounced nonlinear behavior develops. Choi et al. [8] further proposed a vibration-response-based method for estimating resilience-pad stiffness in sleeper floating tracks.

More broadly, modal and impact-response approaches have been used to evaluate railway support conditions without removing track components. Choi et al. [9] demonstrated that modal testing can qualitatively identify variations in sleeper support conditions in ballasted tracks. Remennikov and Kaewunruen [10] investigated the dynamic interaction between railway sleepers and ballast, whereas Lam and Wong [11] proposed an impact-hammer-based approach for ballast diagnosis. De Bold et al. [12] demonstrated the applicability of impulse-response testing for identifying ballast fouling in railway trackbeds. In addition, Alzhrani et al. [13] reported that ballast fouling can alter track stiffness and settlement, emphasizing the importance of evaluating local support-condition variability. Although these studies focused mainly on ballasted tracks or rail-pad systems, they support

the applicability of dynamic-response-based approaches for identifying changes in railway support conditions.

Under the Korean domestic guidelines for urban railway track facility performance evaluation, resilience pads are assessed through visual inspection and laboratory stiffness testing of sampled specimens. For the stiffness test, approximately one sample per 500 m is collected from the field, and the condition of the evaluation unit is inferred from the limited number of sampled pads [14]. However, this sampling-based approach requires track possession, pad extraction, laboratory testing, and substantial manpower and cost. Moreover, local differences in rail condition, sleeper movement, sleeper-boot condition, and pad degradation may cause spatial variation in track-support stiffness. Therefore, an in situ method capable of evaluating the stiffness condition of installed resilience pads without extraction is required.

Existing in situ approaches for evaluating railway support conditions can be classified into train-induced response methods, impact- or impulse-response methods, and vibration-attenuation indicators such as track decay rate [6–16]. These approaches can detect changes in track-support conditions; however, they do not directly convert a local FRF-derived frequency into a static-equivalent stiffness index for installed STEDEF resilience pads. Accordingly, the present study develops an impact-hammer–FRF-based screening method that maps the dominant local resonance frequency to a configuration-specific static-equivalent resilience-pad stiffness without pad extraction.

2. Field Measurements

2.1. Introduction to Field Measurements

In this study, field measurements were performed to analyze the natural frequency according to the change in the spring stiffness of resilience pads embedded directly under RC sleepers on an urban transit sleeper floating track system that had been in service for approximately 27 years. To analyze the natural frequency of the track, an impact-hammer–FRF test was performed to obtain the frequency response function (FRF) of the track system. In addition, the measured FRF was used to verify the appropriateness of the numerical model for analyzing the natural frequency of the track. Accelerometers were installed on the left and right sides directly above the RC sleeper to measure the load and acceleration generated over time when the impact hammer was struck. The FRF was derived from the measurement results to analyze the natural frequency.

The field measurement section was selected to have the same sleeper floating track systems configuration, but the spring stiffnesses of the rail pads and resilience pads were different; therefore, sections with different spring stiffnesses at the rail support point were selected. Figure 2 shows the field survey and an overview of the field measurement section. The field measurement section has been in service for approximately 27 years. Section A is an aging section, with a cumulative passing tonnage of approximately 700 million tons. Sections B–D had recently been replaced with new rail and resilience pads, and were sections with a service life of approximately 0.5 years and a cumulative passing tonnage of approximately 100 million tons.

Although all test locations employed the STEDEF track type, Sections A–D were intentionally selected to represent different track-support configurations. Sections A and B share the same design configuration (rail pad stiffness, resilience-pad stiffness range, and sleeper boot stiffness), and Section B is evaluated as a post-replacement condition relative to the baseline/design condition. By contrast, Sections C and D differ in the design stiffness and material combinations of the rail pads, resilience pads, and sleeper boots. These configuration differences lead to distinct dynamic characteristics; therefore, a single unified frequency–stiffness mapping is not physically appropriate.



Figure 2. Field survey and overview of the tested tracks for field measurement: (a) field investigation; (b) view of the field measurement section.

The rail surface of the field measurement section was sound with no undulations or uneven wear, as shown in Figure 2a. A track gauge was used to check the track gauge and cant at each RC sleeper location; the track gauge was ± 3 mm, and the cant ranged from 0 to 5 mm, both within the track irregularity management standards. The concrete bed, RC sleeper, and tie bars were in good condition. The spring stiffness values of the elastic materials designed in the measurement section are listed in Table 1 [17,18]. In this study, “Section” refers to a distinct track-support configuration defined by the design stiffness/material combination of (rail pad, resilience pad, and sleeper boot). Therefore, section-specific equations should be interpreted as configuration-specific mappings rather than location-specific curve fittings.

Table 1. Design the spring stiffness of the elastic material using the measurement section.

Component	Design Spring Stiffness (kN/mm)		
	Rail Pads	Resilience Pads	Sleeper Boots
Section A	450	12.5 ± 2.5	750
Section B	450	12.5 ± 2.5	750
Section C	100	17.0 ± 2.5	2000
Section D	450	17.0 ± 2.5	2000

The shape and dimensions of the sleeper boots in the target sections were the same for all sections A–D, and the spring stiffness was different (750 kN/mm for Sections A and B and 2000 kN/mm for Sections C and D); however, the effect of the spring stiffness at the rail supporting point was minimal [17,18]. Resilience pads such as ethylene propylene diene monomer (EPDM), ethylene vinyl acetate (EVA), natural rubber (NR), and polyurethane (PUR) can be manufactured to meet the performance requirements of resilience pads [17,18]. The shapes and dimensions of the resilience pads in the field measurement section were the same as those in Sections A–D. The resilience pads in Sections A and B were made of EPDM, a synthetic rubber classified as M-class rubber under ASTM standard D-1418 [19]. Sections A and B used EPDM resilience pads, whereas Sections C and D used NR resilience pads. The rail-pad, resilience-pad, and sleeper-boot stiffness values differed among the investigated configurations, as summarized in Table 1 [17,18].

The static spring stiffness test of the resilience-pads was performed in accordance with KS M 6604 (resilience pad test method), as shown in Figure 3, and the results are listed in Table 2 [20]. Although rubber-based pads exhibit nonlinear load–displacement behavior, the stiffness used for design acceptance and maintenance in Korean railway practices is reported as an equivalent (secant) vertical stiffness, defined from the slope between two prescribed load points on the static load–displacement curve [20–24]. The

definition of stiffness is also referenced in the European Standard Framework. EN 13146 provides test methods for determining the static and low-frequency dynamic stiffness of rail fastening components (including rail pads and assemblies), with static stiffness evaluated as the secant slope over a prescribed load interval [25]. Furthermore, the performance requirements and track category context for fastening systems are commonly reported in accordance with the EN 13481 series [26]. In this study, the static secant stiffness was adopted as the maintenance reference value. The finite element model uses an equivalent linear support stiffness to reproduce the modal response within the tested frequency range; therefore, this parameter should not be interpreted as the intrinsic frequency-dependent dynamic stiffness of the rubber pad. The explicit measurement and calibration of the frequency-dependent dynamic stiffness in accordance with EN 13146 will be discussed in future studies.

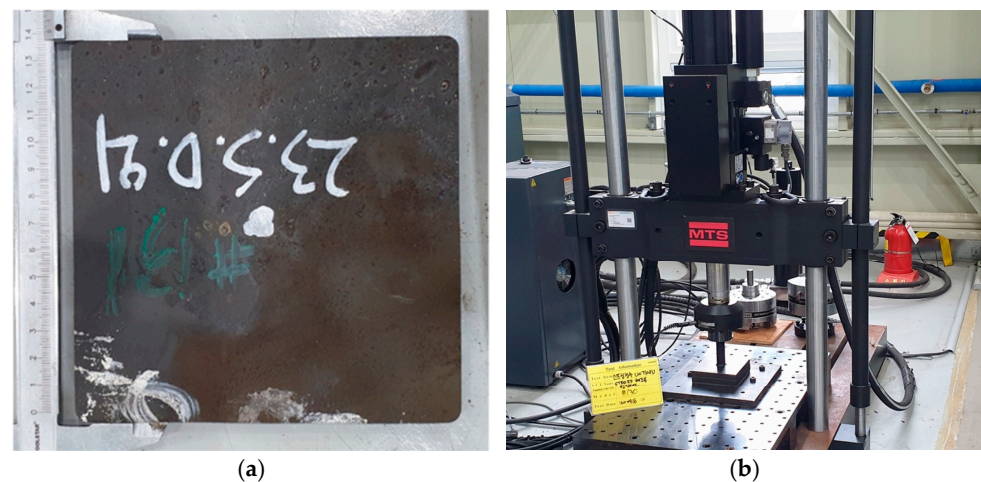


Figure 3. Laboratory test of spring stiffness of resilience pads: (a) specimen and (b) photograph of laboratory test.

Table 2. Laboratory test results of spring stiffness of resilience pads.

Resilience Pads (12.5 ± 2.5 kN/mm) (Section B)		Resilience Pads (17.0 ± 2.5 kN/mm) (Section C, D)	
No.	Result of Conversion (kN/mm)	No.	Result of Conversion (kN/mm)
1	11.90	1	16.88
2	12.35	2	17.81
3	12.67	3	16.61
Average	12.31	Average	17.10

In the laboratory tests, the static vertical spring stiffness was measured using $141 \text{ mm} \times 141 \text{ mm}$ test specimens. The STEDEF resilience pads had dimensions of $660 \text{ mm} \times 230 \text{ mm}$, and the area ratio was considered in the laboratory test results. The area conversion ratio was 7.64; the static vertical spring stiffness of the resilience pads is the value that is considered 7.64 times in the laboratory test results. Table 2 shows that the spring stiffness of the resilience pads in Section B was from 11.90 to 12.67 kN/mm, with an average of 12.31 kN/mm. This difference was approximately 1.5% of the standard spring stiffness value of 12.5 kN/mm at the time of production. The spring stiffness of the resilience pads in Sections C and D was from 16.61 to 17.81 kN/mm, with an average of 17.10 kN/mm, which was similar to the standard spring stiffness value of 17.0 kN/mm at the time of production. The rail pads of Sections A, B, and D were made of EVA, and the spring stiffness was 450 kN/mm. The rail pad in Section C was composed of EPDM, and the spring stiffness was 100 kN/mm.

2.2. Measurement of Track Natural Frequencies Using Impact-Hammer–FRF Testing

The field experiment was conducted as an impact-hammer–FRF test. The force input from the impact hammer and the acceleration response measured at the RC sleeper were used to obtain the frequency response function (FRF). The FRF-derived first resonance frequency, f_1 , was used as the field parameter for stiffness evaluation. The sensitivity and installation locations of each sensor in the measurement system are listed in Table 3.

For each track-support configuration, five RC sleepers were tested at the inner and outer measurement locations, and three repeated impacts were applied at each location. Accordingly, 120 raw impact records were obtained from four configurations, five sleepers, two measurement locations, and three repeated impacts. The impact force and acceleration responses were synchronously acquired to calculate the frequency response function (FRF). Only impact records with a force peak within $\pm 3\%$ of the target level and without apparent abnormal noise or residual vibration were accepted. The three repeated impacts were used as an acceptance and averaging step at each sleeper-side location. Only records satisfying the force-consistency criterion and without apparent abnormal noise or residual vibration were retained to obtain a representative FRF. The dominant first-mode frequency was extracted from each representative FRF, and the mean value (X_c) and standard deviation (SD) were calculated for each track-support configuration.

The measurement equipment and impact-hammer–FRF test layout are shown in Figure 4.

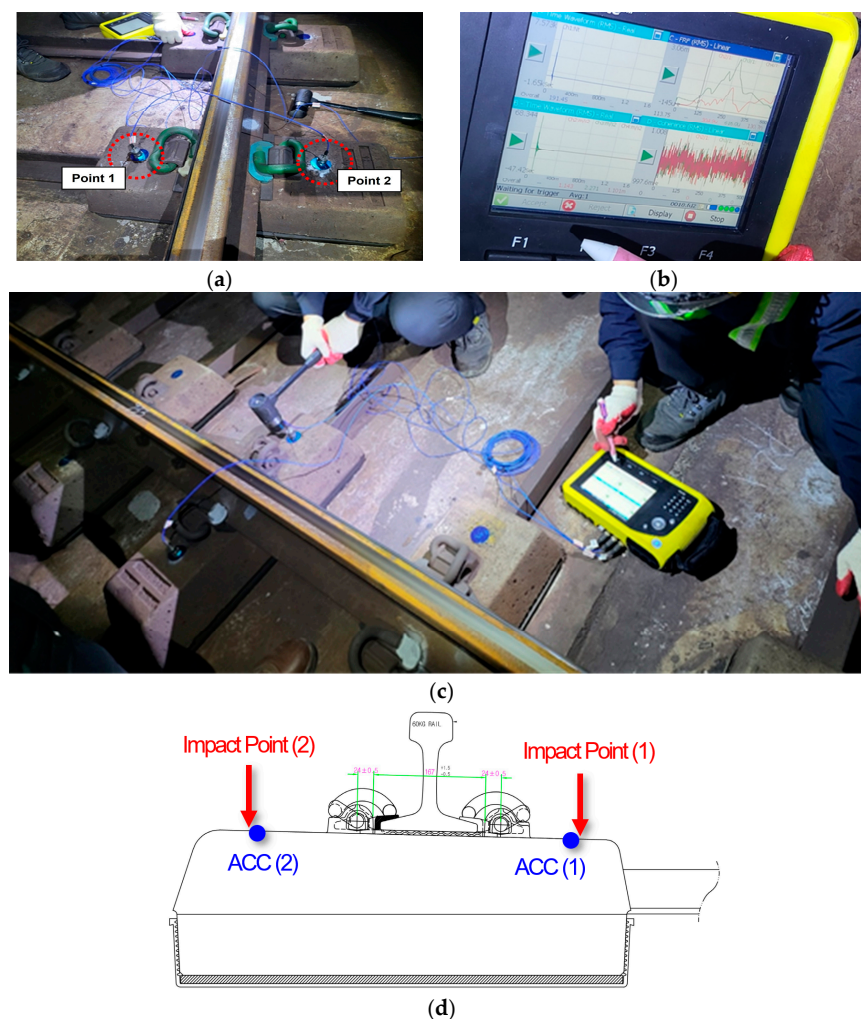


Figure 4. Installation of measuring equipment and impact-hammer–FRF test overview: (a) view of measuring equipment, (b) calculation of the frequency response function, (c) impact hammer strike, (d) local impact and acceleration-measurement layout.

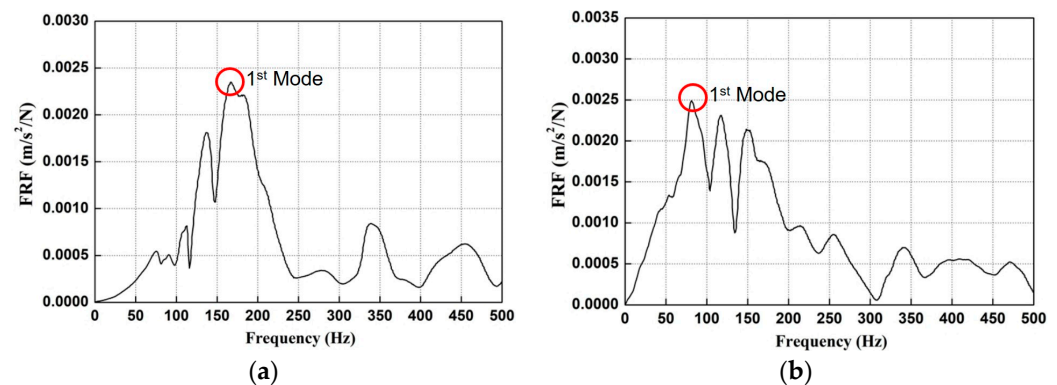
Table 3. Sensor sensitivities and installation locations for field impact-hammer–FRF testing.

Components	Impact Hammer	Acceleration Meter	
		Point 1	Point 2
Sensitivity	0.2473 mV/N	988 mV/g	1006 mV/g
Install location	-	RC sleeper inside	RC sleeper outside

Field tests were conducted within a short time window under quasi-steady environmental conditions (ambient temperature: 20–25 °C). Because rubber-based pads exhibit temperature-dependent stiffness, the reported mean $\pm$ SD band is interpreted as field dispersion that may include environmental variability. A dedicated temperature-correction model will be discussed in future research. The present study uses the FRF-derived first resonance frequency, denoted as f_1 , for stiffness evaluation. The corresponding first local support mode was identified from the finite element modal analysis, whereas the field test was used to obtain the resonance frequency from the measured FRF. The impact location was selected directly above the rail-support point to maximize the sensitivity of this mode to changes in resilience-pad support stiffness. Higher-frequency peaks were not used for stiffness estimation because the proposed method was developed using the monotonic relationship between the first-mode frequency and the equivalent support stiffness derived from the finite element model.

2.3. Analysis Results of Measurement Track Natural Frequency

In this study, the dynamic responses in Sections A–D were measured using impact-hammer–FRF testing. An example of the FRF measurement results presented in Section B is shown in Figure 5.

**Figure 5.** Measurement results of the frequency response function of Section B: (a) RC sleeper inner side (inside, Point 1) and (b) RC sleeper outer side (outside, Point 2).

The first resonance peak was subsequently extracted from the representative FRF at each measured location and used for the statistical analysis. In this study, the FRF was measured for each track-support configuration based on the inside and outside of the RC sleeper, and the results are shown in Figure 6.

Figure 6 compares the FRFs obtained from the four track-support configurations. The primary role of these FRFs is to identify the configuration-dependent first resonance frequency, f_1 , rather than to compare the absolute FRF amplitudes. Section A showed a clear difference between the inner and outer first-mode responses, whereas Sections B–D showed relatively similar inner and outer responses. This result supports the use of the inner-side frequency as the representative value for older people, Section A, and the use of location-level statistical values for the recently renewed Sections B–D. The extracted first-mode frequencies are summarized in Figure 7.

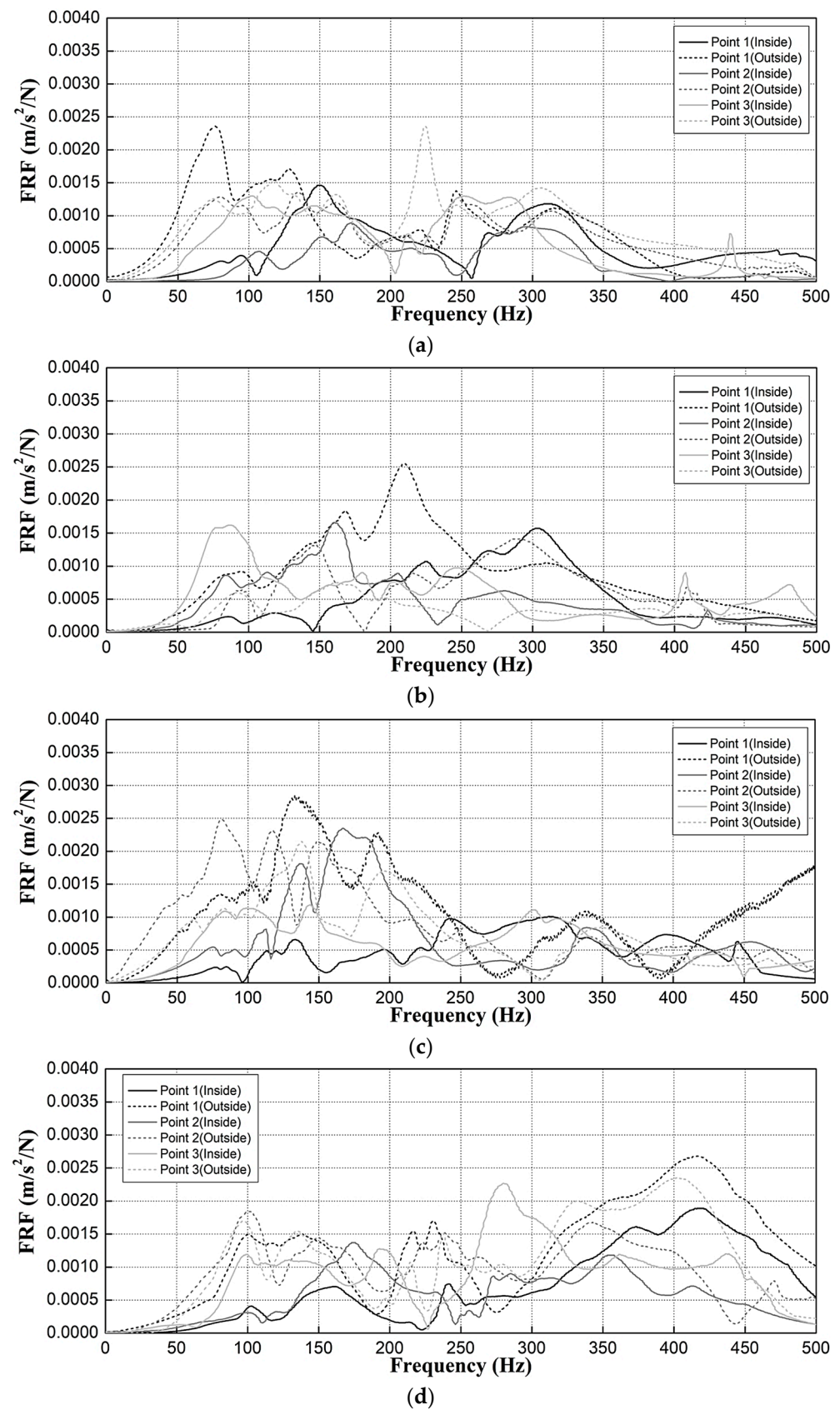


Figure 6. Frequency response functions of each track-support configuration: (a) Section A, (b) Section B, (c) Section C, (d) Section D.

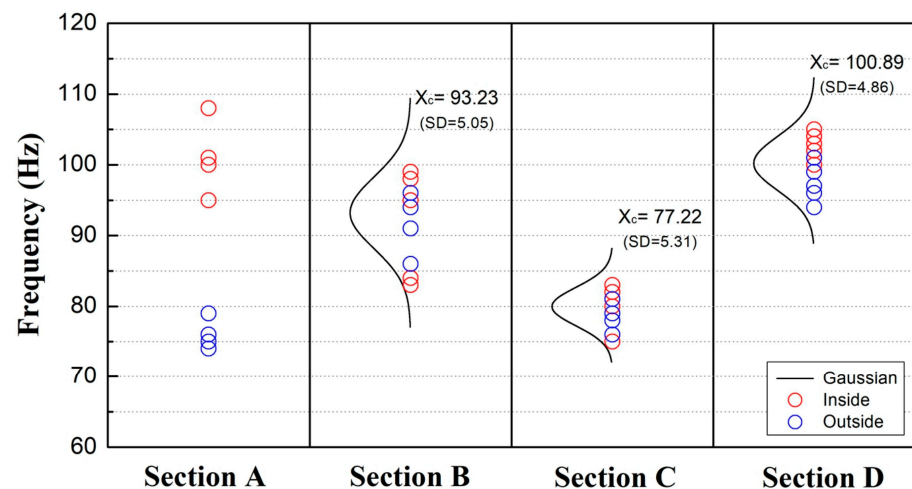


Figure 7. Distribution of the measured first resonance frequencies for each track-support configuration.

Three accepted impact records at each sleeper-side location were averaged to obtain one representative FRF. Accordingly, the 120 raw impact records yielded 40 representative FRFs, corresponding to ten location-level first-mode frequencies for each track-support configuration. The statistical analysis was therefore performed using the ten representative frequency values per configuration, whereas the three repeated impacts were used to confirm the repeatability of the FRF measurement at each location. A Gaussian analysis of the natural frequency showed that the natural frequency for Section B ranged between 88.18 and 98.28 Hz (average X_c : 93.23 Hz, SD: 5.05 Hz), as shown in Figure 7. The natural frequency for Section C ranged between 71.91 and 82.53 Hz (average X_c : 77.22 Hz, SD: 5.31 Hz). The natural frequency range for Section D ranged between 96.03 and 105.75 Hz (average X_c : 100.89 Hz, SD: 4.86 Hz). When a wheel load is applied to the STEDEF, the RC sleeper rotates inward from the track gauge. Thus, the load burden on the resilience pads located inside the RC sleeper increases more than that outside the sleeper. As shown in Figure 7, the average age of Section A was approximately 27 years; however, the resilience pads were aging, resulting in a large difference between the natural frequencies measured inside and outside the RC sleepers. In contrast, the pads in Sections B–D were recently replaced with new pads, and the natural frequencies inside and outside the RC sleeper were similar. Moreover, although the average age was approximately 0.5 years, the deviation in the natural frequency of Section B was larger than that of Sections C and D under the same conditions. This is because the manufacturing tolerance of the resilience pads in Section B was larger than that in Sections C and D.

In this study, the natural frequency of the track was measured and evaluated through modal tests in Sections A–D. For Sections B–C, the natural frequencies measured on the inside and outside of the track gauge were similar. This is because the new pads are approximately 0.5 years old, so the difference between the inside and outside is small. On the other hand, although the design conditions of Section A and Section B are the same, it was found that Section A had a difference in natural frequency due to long-term use. For Section A, the inner-side and outer-side frequencies formed two separate response groups. Therefore, Gaussian fitting was not performed for Section A, and the measurements were evaluated using the observed frequency ranges for the inner and outer sides. The inner-side resonance frequency was used to estimate the local static-equivalent stiffness at the corresponding inner rail-support point, where the wheel-load influence is expected to be greater. This result should not be interpreted as an effective average stiffness for the entire Section A. The outer-side measurements were retained to indicate the spatial asymmetry of older people's support condition.

3. Finite Element Analysis

3.1. Overview of Finite Element Analysis

In this study, the influence of the change in the spring stiffness of the resilience pads on the natural frequency of the track under different rail support spring stiffnesses for each section was analyzed using a commercial structural analysis program (ANSYS Workbench Ver. 2023 R1) [27]. Among the track components, the rails, rail pads, RC sleepers, concrete beds, and sleeper boots were modeled as three-dimensional solid elements, and the resilience pads were applied as spring elements. The analysis model, boundary conditions, and load conditions are shown in Figure 8.

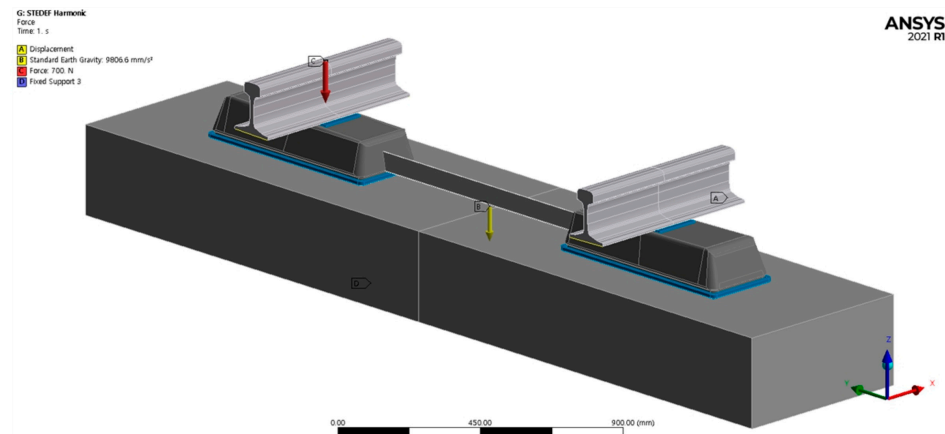


Figure 8. Finite element analysis modeling.

As shown in Figure 8, the lower surface of the concrete bed was fixed in all translational directions, and gravity was applied as a load condition. The rail ends and the lateral end faces of the concrete bed were free. Therefore, the model represents a local rail-support unit rather than an infinitely long track. The same geometry and end conditions were applied to all configurations, and only the rail-pad, resilience-pad, and sleeper-boot stiffness conditions were changed. Accordingly, the calculated frequencies are interpreted as comparative local responses, while the possible influence of the finite model length is considered a common limitation of all configurations. The data used in the finite element analysis are presented in Table 4 [17,18,23,24].

Table 4. Material properties in the finite element analysis.

Components	Young's Modulus (MPa)	Mass Density (kN/m ³)	Poisson's Ratio (ν)
Rail/Tie-bar	210,000	77.01	0.30
RC sleeper/ Concrete bed	35,000	22.56	0.18
Sleeper boots	21.6	7.85	0.2
Rail pads	71.4	8.83	0.2

In this study, the equivalent linear support stiffness, k_{eq} , was not directly identified from the field impact-hammer–FRF test. Instead, a series of k_{eq} values was prescribed parametrically in the finite element model over the investigated stiffness range, while the rail-pad stiffness, sleeper-boot stiffness, geometry, material properties, and boundary conditions were maintained for each track-support configuration. For each prescribed k_{eq} value, harmonic response analysis was performed by applying harmonic excitation at the rail-support point. The first resonance frequency, f_1 , was identified from the first dominant peak of the resulting harmonic response curve. The paired values of k_{eq} and f_1 were then

used to establish a configuration-specific frequency–stiffness relationship. During field evaluation, the first resonance frequency obtained from the measured impact-hammer-FRF was applied to the relevant frequency–stiffness relationship to estimate the static-equivalent resilience-pad stiffness. Therefore, k_{eq} is a model-based screening parameter used to connect the measured resonance frequency with the maintenance-oriented static stiffness reference. It should not be interpreted as the intrinsic frequency-dependent dynamic stiffness of the rubber material. Accordingly, the FE model was used to establish a configuration-specific mapping between f_1 and k_{eq} over the investigated stiffness range. It was not intended to reproduce the intrinsic nonlinear constitutive behavior of the rubber pad, large-amplitude operational loading, or the complete dynamic behavior of an infinitely long track.

3.2. Harmonic Response Analysis of Track Resonance Frequencies by Track-Support Configuration

To reproduce the frequency response behavior observed in the field impact-hammer-FRF test, harmonic response analyses were conducted for the baseline A/B configuration and the C and D track-support configurations. Harmonic excitation corresponding to the field impact location was applied at the rail-support point, and the response was extracted at the corresponding measurement location on the RC sleeper. The first resonance frequency, f_1 , was identified from the first dominant peak of each FE-derived harmonic response curve. The numerical response curves were used to identify the resonance frequency and establish the frequency–stiffness relationship; the response amplitudes were not directly compared with the measured FRF amplitudes.

As shown in Figure 9, the first resonance frequency of the baseline A/B configuration was 89.98 Hz, whereas those of Sections C and D were 79.88 Hz and 100.81 Hz, respectively. Sections A and B have identical FE response curves because they share the same design rail-pad, resilience-pad, and sleeper-boot stiffness conditions. Therefore, the A/B result represents one common design baseline configuration and is not intended to reproduce the older people’s field conditions of Section A. The local condition of Section A was estimated by applying its measured inner-side resonance frequency to the baseline A/B frequency–stiffness relationship. The frequency–stiffness relationships shown in Figure 10 were obtained by repeating the harmonic response analysis while varying only the equivalent resilience-pad support stiffness, k_{eq} , within the investigated range.

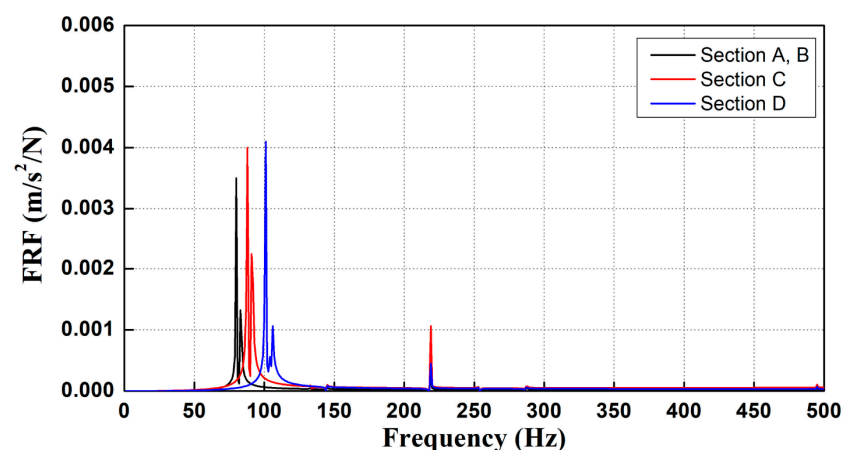


Figure 9. FE-derived harmonic frequency response curves and identified first resonance frequencies for the baseline A/B configuration and the C and D track-support configurations.

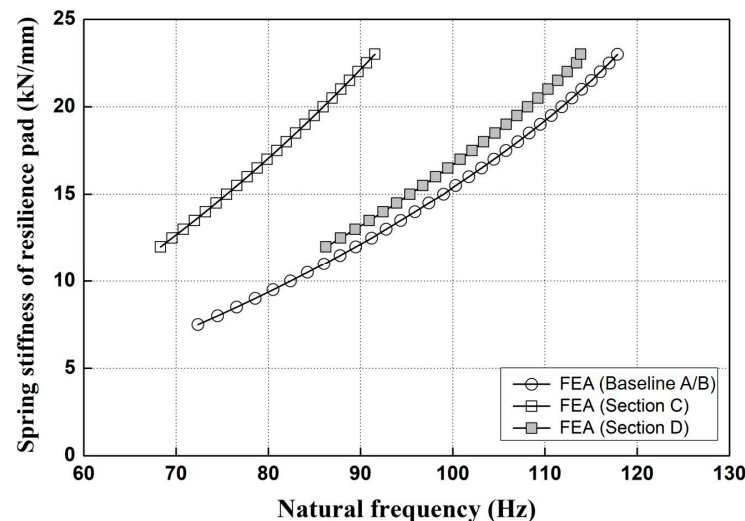


Figure 10. Analysis results of the track natural frequency according to the change in spring stiffness.

Figure 10 shows that the track's natural frequency was 89.98 Hz based on a design spring stiffness of 12.5 kN/mm. When increasing the spring stiffness of the resilience pads from 7.5 to 23 kN/mm in increments of 0.5 kN/mm, the natural frequencies were 72.38 Hz at 7.5 kN/mm and 117.87 Hz at 23 kN/mm. Therefore, the track's natural frequency at 16.25 kN/mm, at which the spring stiffness of the resilience pads increased by more than 30%, was determined to be 102.5 Hz.

In Section C, when the spring stiffness of the rail pads was 100.0 kN/mm, and that of the resilience pads was 17.0 kN/mm, the natural frequency was 79.88 Hz. When the spring stiffness was increased from 12 to 23 kN/mm at 0.5 kN/mm intervals, the natural frequency was 68.317 Hz when the spring stiffness was at least 12 kN/mm and 91.57 Hz when the spring stiffness was at most 23 kN/mm. Therefore, the natural frequency of the track at approximately 22 kN/mm, where the spring stiffness of the resilience pads increases by more than 30%, is approximately 89.75 Hz.

In Section D, when the spring stiffness of the resilience pads is 17.0 kN/mm, the natural frequency is 100.81 Hz. When increasing the spring stiffness from 12 to 23 kN/mm in 0.5 kN/mm intervals, the natural frequency was 86.25 Hz when the minimum was 12 kN/mm and 113.43 Hz when the maximum was 23 kN/mm. Therefore, the natural frequency of the track at approximately 22 kN/mm, where the spring stiffness of the resilience pads increases by more than 30%, is approximately 112.43 Hz. In this analysis, only the resilience-pad support stiffness was varied, whereas the rail-pad stiffness, sleeper-boot stiffness, geometry, material properties, and boundary conditions were maintained for each configuration. Therefore, the results represent the sensitivity of the natural frequency to the resilience-pad support stiffness within the investigated range.

In this study, the natural frequency of an RC sleeper with the same measurement location as the field measurement was calculated via numerical analysis and compared. The same load conditions as those in the field measurements were applied, and the first natural frequency was analyzed at the same measurement location as in the modal test. The results of the comparative analysis of the measured and analyzed natural frequencies are shown in Figure 11 and listed in Table 5.

The relative differences between the FE-derived and measured mean first resonance frequencies were 3.61%, 3.33%, and 0.08% for Sections B, C, and D, respectively. These results indicate agreement between the harmonic-response model and the mean field responses of the reference configurations. The SD values represent spatial dispersion among the measured locations and are not interpreted as numerical-model errors.

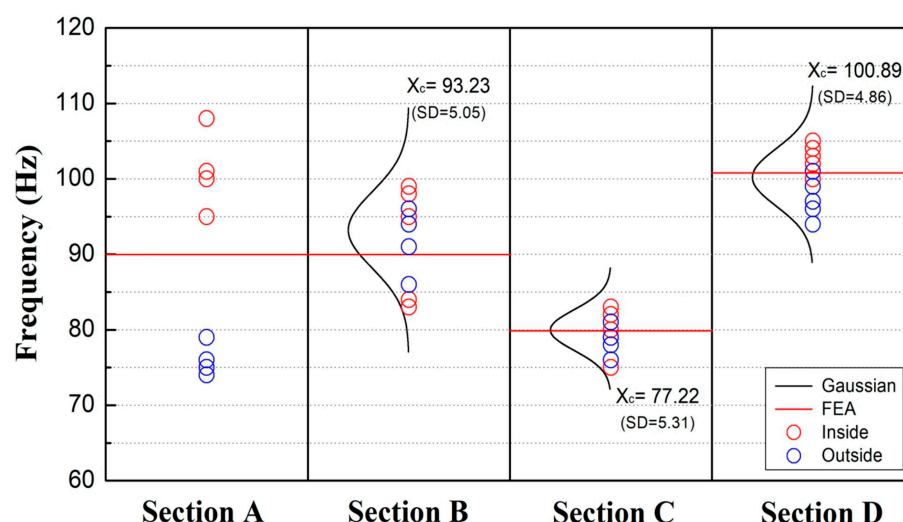


Figure 11. Measurement and analysis results of the track natural frequency for each track-support configuration.

Table 5. Comparison results of track natural frequencies from field measurements and numerical analysis for each track-support configuration.

Components		Section B	Section C	Section D
(A) Field measurement		93.23 ± 5.05 Hz	77.22 ± 5.31 Hz	100.89 ± 4.86 Hz
(B) FEA		89.98 Hz	79.88 Hz	100.81 Hz
(B – A)/A (%)	Xc	3.61	3.33	0.08

4. Analysis and Discussion

4.1. Calculation of Spring Stiffness of Resilience Pads Using Track Natural Frequency

In this study, the correlation between the measured track natural frequency and spring stiffness of the resilience pads by section was analyzed, as shown in Figure 11. Finite element analysis was performed using the analytical model verified by comparison with the measured track natural frequency to analyze the track natural frequency of the STEDEF according to the change in the spring stiffness of the resilience pads. Based on the correlation between the track's natural frequency and the spring stiffness of the resilience pads, an estimation equation was presented that calculates the spring stiffness of the resilience pads from the measured track natural frequency. The results of the analysis of the measured sections are shown in Figure 12.

The regression equations are not empirical curve fitting for each site; they are compact representations of monotonic FE-derived frequency–stiffness mappings for each track-support configuration introduced to enable practical field implementation without repeatedly running the FEA analyses.

Because the target parameter is the equivalent stiffness (single-valued index) and the numerically obtained relationship between the natural frequency and pad stiffness is approximately linear over the investigated stiffness range, a first-order regression was adopted to derive an estimation equation that is transparent and readily applicable in field maintenance practice.

The spring stiffness estimation equation for the resilience pads based on the correlation between the track's natural frequency and the spring stiffness for each measurement section is presented in Table 6.

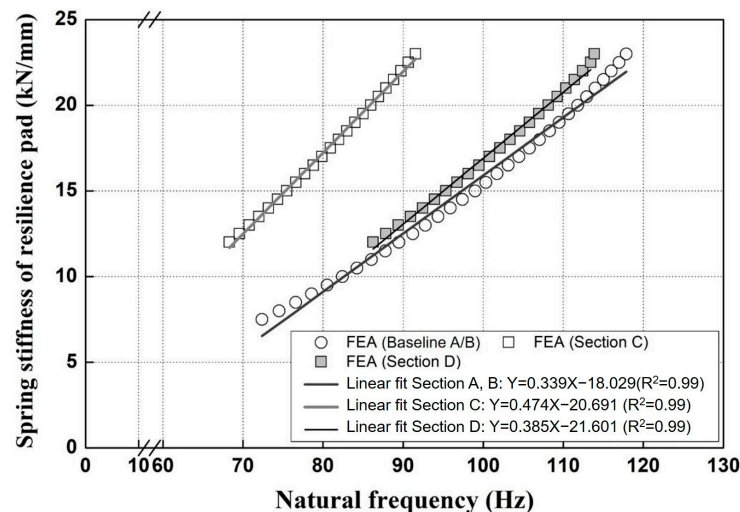


Figure 12. Analysis results of the correlation between spring stiffness and track natural frequency for each track-support configuration.

Table 6. Configuration-specific equations relating the first-mode natural frequency to the static-equivalent resilience-pad stiffness.

Section	Estimation Formula of Resilience Pads Spring Stiffness
A, B	$Y = 0.339X - 18.029$ ($R^2 = 0.989$)
C	$Y = 0.474X - 20.691$ ($R^2 = 0.998$)
D	$Y = 0.385X - 21.601$ ($R^2 = 0.996$)

Where Y is the spring stiffness of the resilience pads (kN/mm), X is the natural frequency of the track (Hz), and R^2 is the coefficient of determination. The proposed equations are limited to the STEDEF track-support configurations described in Table 1 and to the stiffness and frequency ranges investigated in this study. A separate frequency–stiffness calibration is required when the rail-pad, resilience-pad, sleeper-boot, geometry, or boundary conditions differ. The spring stiffness of the resilience pads was calculated from the natural frequency of the track using the estimation formulae presented in Table 6, and the results are listed in Table 7.

Table 7. FRF-based static stiffness estimates for each track-support configuration.

Section	Measured Natural Frequency (Hz)	Spring Stiffness Analysis Results of Resilience Pads (kN/mm)
B	93.23 ± 5.05	13.60 ± 1.71
C	77.22 ± 5.31	15.91 ± 2.52
D	100.89 ± 4.86	17.25 ± 1.87

The outer-side measurements were retained only to indicate the asymmetric field response of Section A and were not used for the maintenance-screening estimate. The maximum rate of change in the spring stiffness of the inner resilience pads was 48.96%, and the spring stiffness of the outer resilience pads was smaller than the design spring stiffness. This is because, in a previous study, the RC sleepers of the STEDEF were fixed to the inside of the gauge with a tie bar, the outside of the gauge was free, and the resultant force of the dynamic wheel load and lateral wheel load, which are train loads, acted on the outside of the gauge. Consequently, slight lifting may occur outside the RC sleeper during field measurements under static conditions. In addition, the sleeper floating track systems may have a gap between the RC sleeper bottom and the concrete bed owing to track construction

errors. There may be cases where the RC sleeper settles unevenly owing to factors such as imbalance of the train load owing to excessive or insufficient cant in the curved section, change in the wheel load of the left and right wheels owing to track irregularity, and diagonal motion. Such geometric imperfections can introduce asymmetric boundary conditions and apparent natural frequency. Therefore, inside/outside measurements and repeated impacts were used, and the mean $\pm$ SD band was reported to represent field dispersion. For practical use, sleepers exhibiting visible gaps or abnormal FRF shapes should be flagged and excluded (or evaluated separately). Therefore, it is necessary to perform modal tests inside and outside the RC sleeper and analyze the natural frequency of the track considering the field conditions. The results of the spring stiffness analysis using the spring stiffness estimation formula and spring stiffness of the new resilience pads from Sections B to D are listed in Table 8.

Table 8. Analysis results of the spring stiffness of resilience pads by each track-support configuration.

Components	Section B	Section C	Section D
(A) New resilience pads (Design)	^(b) 12.5 ± 2.5 kN/mm	^(c) 17.0 ± 2.5 kN/mm	
^(a) (B) Estimated results	13.60 ± 1.71 kN/mm	15.91 ± 2.52 kN/mm	17.25 ± 1.87 kN/mm
(B – A)/A (%)	0.00~8.80	0.00~6.41	0.00~1.47

^(a) Using the formula of Table 6. ^(b) Manufacturing tolerance $\pm 20\%$. ^(c) Manufacturing tolerance $\pm 14.71\%$.

Table 8 shows that for Section B, the design spring stiffness of the resilience pads was 12.5 ± 2.5 kN/mm, and the spring stiffness estimated using the formula in Table 6 was 13.60 ± 1.71 kN/mm. The difference between the design value and the result obtained from the estimation formula in this study was approximately 8.8%. For Section D, where the design spring stiffness of the resilience pads was 17.0 ± 2.5 kN/mm, the spring stiffness calculated using the measured natural frequency was 17.25 ± 1.87 kN/mm. The difference between the design value and the result obtained by applying the estimation formula proposed in this study was approximately 1.5%. Furthermore, the estimated spring stiffness of Section C, where the spring stiffness of the resilience pads and the rail pads were 17.0 ± 2.5 and 100 kN/mm, respectively, was 15.91 ± 2.52 kN/mm, which is smaller than that of Section D, and the difference from the design value was approximately 6.4%. The spring stiffness of the resilience pads, calculated from the measured natural frequency of the track proposed in this study, was relatively similar to the designed spring stiffness for each section. In addition, the difference between the calculated result using the design value and the estimated formula was within the manufacturing tolerance, experimentally and analytically verifying the appropriateness of the spring stiffness evaluation method for the resilience pads using the modal test proposed in this study.

The spring stiffness of the resilience pads was calculated using the estimated formula for each section, and the rate of change was evaluated by comparison with the indoor test results. The current spring stiffness evaluation standard for resilience pads evaluates the spring stiffness adequacy of resilience pads based on design values. The stiffness change rate was evaluated by comparing the modal-test-based static stiffness estimate with the laboratory static stiffness of the new reference pads. Under the domestic maintenance framework, a change rate exceeding 30% is used as a screening threshold for prioritizing detailed inspection.

As shown in Table 9, the estimated stiffness change rate of Section A was 33.31%. Because older people's pads were not extracted from Section A, this value should be interpreted as a FRF-based screening estimate. Therefore, detailed inspection and, where necessary, confirmatory sampling are required before a replacement decision is made. For Section B, which was in operation for approximately 0.5 years, the average rate of change in the spring stiffness of the resilience pads was approximately 10.48%. In Sections C and D,

the change rates in the spring stiffness of the resilience pads were approximately 5.93% and 2.31%, respectively. Therefore, the evaluation method proposed in this study can be used to easily evaluate the spring stiffness of resilience pads, thereby supporting a potentially less intrusive screening procedure for maintenance planning.

Table 9. FRF-based test-based screening evaluation of the spring stiffness change rate by track-support configuration.

Components	Section A	Section B	Section C	Section D
	(12.5 ± 2.5 kN/mm)		(17.0 ± 2.5 kN/mm)	
(A) Laboratory static stiffness of new pads	12.31 kN/mm		16.86 kN/mm	
(B) Modal-test-based static equivalent stiffness estimate	16.41 kN/mm	13.60 kN/mm	15.91 kN/mm	17.25 kN/mm
(B – A)/A (%)	33.31	10.48	5.93	2.31

It should be emphasized that the Section A value in Table 9 is not a direct laboratory-measured static stiffness of pads removed from the older people section. Because pad extraction was not conducted in Section A, the value of 16.41 kN/mm was obtained by applying the configuration-specific modal frequency–stiffness mapping for Sections A/B to the measured inner-side natural frequency of Section A. The corresponding change rate was calculated relative to 12.31 kN/mm, which is the laboratory-measured static secant stiffness of newly replaced pads in Section B with the same track-support configuration. Therefore, the 33.31% value should be interpreted as an in situ screening estimate for maintenance prioritization. Exceeding the 30% criterion indicates the need for detailed inspection and, where appropriate, targeted pad sampling and confirmatory laboratory testing; it does not constitute an autonomous replacement decision. Direct comparison with laboratory-tested pads removed from aged sections remains a limitation of the present study and should be addressed in future work.

4.2. Evaluation Method of Spring Stiffness of Resilience Pads Using Impact-Hammer–FRF Testing

The conventional evaluation of resilience pads is based on specimen extraction and laboratory static stiffness testing. Although this procedure provides a direct stiffness measurement for the extracted specimen, it requires track possession, pad removal, and subsequent restoration work, and the condition of an entire track section is inferred from a limited number of samples. In contrast, the proposed method uses the dominant first-mode frequency obtained from an impact-hammer modal test and converts it into a static-equivalent stiffness index using a configuration-specific frequency–stiffness relationship. Therefore, the proposed method is intended to provide an in situ screening result without pad extraction, rather than to replace confirmatory laboratory testing when a detailed maintenance decision is required.

The internal consistency of the proposed method was evaluated using the field and numerical results obtained in this study. A total of 120 raw impact records were obtained from four track-support configurations, five sleepers, two measurement locations, and three repeated impacts. These records were processed into 40 representative FRFs, corresponding to ten location-level first-mode frequencies for each configuration. For the reference configurations, the differences between the FEA-predicted and measured mean first-mode frequencies were 3.61%, 3.33%, and 0.08% for Sections B, C, and D, respectively. In addition, the estimated stiffness change rates for the recently renewed Sections B, C, and D were 10.48%, 5.93%, and 2.31%, respectively. These results indicate that the proposed configuration-specific method can provide consistent stiffness-screening results under the investigated field conditions. However, the present study did not quantify field time, labor

cost, or lifecycle economic benefits; these aspects should be examined in future implementation studies. However, the operational durability of resilient components is influenced by repeated loading and severe environmental exposure (temperature cycling, moisture/water, and freeze-thawing), which are addressed through standardized laboratory procedures (e.g., repeated loading and severe environmental condition tests) for fastening system components. Recent experimental evidence also indicates that mechanical and chemical aging can significantly increase the static stiffness of EPDM/EVA rail pads under degradation conditions, implying that field-condition variability should be considered when interpreting changes in stiffness.

Therefore, field tests were conducted under an ambient temperature of approximately 20–25 °C. Humidity and long-term environmental aging were not explicitly monitored, a limitation that will be addressed in future studies.

5. Conclusions

This study proposed an impact-hammer–FRF-based technique to evaluate the spring stiffness of resilience pads in the STEDEF. Field impact-hammer–FRF tests were conducted on a STEDEF section that had been in service for approximately 27 years at the time of measurement and on recently renewed reference sections. A section-wise analytical model was then established to derive the natural frequency of the track as a function of the spring stiffness at the rail supporting points. The finite element model reproduced the mean natural frequencies of the reference configurations, with differences of 0.08–3.61% for Sections B–D. A correlation analysis between the measured natural frequency and the resilience-pad stiffness for each track-support configuration was performed to construct a natural frequency–stiffness relationship. Based on this relationship, an estimation equation was developed to predict the spring stiffness of the resilience pads from the measured natural frequency. For the recently renewed reference configurations, the estimated static-equivalent stiffness values were close to the corresponding design reference ranges. For older people, Section A, the inner-side result indicated a 33.31% increase relative to the new resilience-pad stiffness and was interpreted as a location-specific screening estimate requiring confirmatory inspection. Compared with conventional sampling and laboratory testing, the proposed technique enables in situ, location-specific screening at selected rail-support points without pad extraction. It does not provide a section-average stiffness and does not replace confirmatory laboratory testing before a final replacement decision is made.

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Abbreviations

The following abbreviations are used in this manuscript: STEDEF: Sleeper floating track system, RC: Reinforced concrete, FRF: Frequency response function, TDR: Track decay rate, TIF: Track impact factor, FE: Finite element, FEA: Finite element analysis, EPDM: Ethylene propylene diene monomer, EVA: Ethylene vinyl acetate, NR: Natural rubber, PUR: Polyurethane, SD: Standard deviation, KS: Korean Industrial Standards, EN: European Standard /European Norm, ASTM: American Society for Testing and Materials.

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