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Normalised curvature square ratio for detection of ballast voids and pockets under rail track sleepers

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Abstract. After a railway track experiencing dynamic loading, the track settles and causes ballast to deform, spread and sometime damage. Without appropriate maintenance, void and pocket of ballast underneath railway sleepers can establish overtime and impair the ride quality of train services. In this study, the emphases will be placed on the application of non-destructive vibration-based technology, to investigate and evaluate dynamic characteristics of voided railway concrete sleepers, which are the fundamental element to provide track support to railway systems. The study has developed a curvature-based damage detention method to identify ballast voids under railway track sleepers. This method can be easily deployed in the field by using fibre bragg grating strain sensors to measure strains for curvature analysis. In this study, the assumption is that the time-dependent material degradation negligibly affects the curvature ratios. The dynamic finite element model has been established and validated for railway sleepers in the field. A variety of losses of ballast support have been simulated using the validated model. The dynamic mode shape has been analysed to evaluate curvature ratios under different types of ballast losses. Although the method provides positive outcomes, the advantages, disadvantages and limitation of the method are then identified and discussed.

1. Introduction

Modern railway tracks are constructed using several components grouped into two categories: substructure and superstructure. The substructure includes ballast, sub-ballast, and subgrade, while the superstructure includes sleepers (or sometimes called ‘crosstie’), rail pads, fasteners, and rails. Figure 1 illustrates the typical ballasted railway tracks. Rolling stocks usually travel over the rails to transport passengers, goods, etc. The burden of vehicle and transported mass will transfer to axle, to wheel, and then to track structures. The loading conditions acting on railway tracks are normally time dependent since the wheels interacts with rails, causing dynamic effects. The dynamic loads often excite the railway track components with increased magnitudes at specific frequencies associated with such components. It is found that the railway concrete sleepers deteriorate greatly when they are subjected to dynamic loads at their resonant frequencies, especially in flexural modes of vibration [1-8].

Therefore, resonant characteristics of in-situ railway concrete sleepers are essential in their own analysis and design. Based on a number of research studies, it has been found that the resonant vibrations of sleepers affect not only the sleepers themselves, but also the wheel–rail interaction forces [9-16]. The vibrations of sleepers are also affected by the deterioration of ballast support conditions.

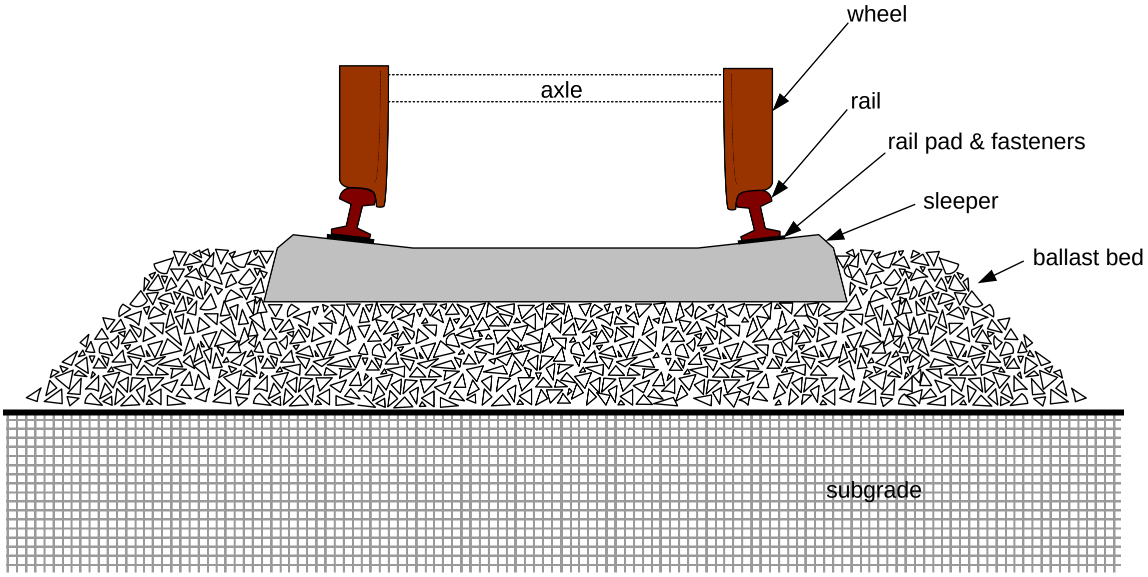


Figure 1. Typical railway tracks

Esveld [3] discovered that the ballast breakage increases substantially at a track resonance, so-called in-phase vibration. This phenomenon causes the voids and pockets, or even the poor packing of ballast support underneath railway concrete sleepers [17-23]. A sleeper having voids and pockets underneath is hereafter referred to as ‘voided sleeper’. There are several investigations on free vibrations of in-situ railway sleeper in track system. Based on the literature survey, although the influence of voids and pockets on the dynamic behaviors of local railway concrete sleepers has been investigated, the damage detection and structural health monitoring of the ballast voids and pockets have not been fully established. In addition, although the sleepers are pressed down onto the ballast when a train passes, no one can guarantee whether under any circumstances the voids (at least most of them) are closed and the ballast fully supports the sleepers at the train passages. The fundamental reason of derailment and track overturning can be of numerous theories. One possible way is the high risk of overturning instability of railway tracks whereas the resonances due to void effects could enhance the overturning instability of global tracks [1-3].

This study is the world-first to investigate the potential of normalized curvatures and dynamic mode shapes of railway sleepers to detect ballast voids and pockets. Based on a study by Kliewer and Glisic [24], the normalized curvature ratio can be used to detect damages in concrete beams and girders over bridge. The potential of the method has inspired this study with the aim to provide an alternative method to detect ballast voids and pockets in the field. In this study, the nonlinear finite element model of ballast voids and pockets has been established and calibrated with experimental data. The simulation results are used to explore the possibility of the normalized curvature ratio method and to develop a novel curvature-based approach capable of detecting ballast voids and pockets using free vibration characteristics of the sleepers. The lowest mode of flexural vibration has been considered in this study since free vibration occurs primarily in the first or lowest mode in most cases in real structures [24-26]. The insight into this novel approach will pave itself as a supplement technique that helps rail track engineers evaluate the ballast support conditions, which cannot be visually inspected in practice [26-31].

2. Normalised curvature ratio

This study develops and explores a novel curvature-based method capable to detect ballast voids and pockets under railway sleepers using free vibration characteristics that can be predicted by simulations or measured in the field using either experimental modal testing or operational modal analysis. This novel technique has been inspired by a recent work [24] that depicts a potential to use this method for bridge girders. In general, the modeshapes and curvature modes under free vibration are not expected to change unless the structure experiences irregular behavior. This forms a basis for the key assumption of this curvature-based method. In real life, sleepers are embedded in the ballast and the support condition of the sleepers cannot be inspected or monitored. There is currently no sensor that could directly detect the ballast damage and voids underneath the sleepers. This study aims to develop an alternative non-destructive testing technique that can be used as a supplemental method in the field to detect ballast voids and pockets underneath the rail track sleepers.

The equation of motion of a railway sleeper under transverse free vibration with a small amplitude can be described by:

$$\frac{\partial}{\partial \mathrm{x}}\left(kAG_r\left[\phi(x,t)-\frac{\partial w(x,t)}{\partial \mathrm{x}}\right]\right)+m_r\frac{\partial^2 w(x,t)}{\partial \mathrm{t}^2}=\bar{\mathrm{p}}(x,t) \tag{1}$$

$$EI_r\frac{\partial^2\phi(x,t)}{\partial \mathrm{x}^2}-kAG_r\left[\phi(x,t)-\frac{\partial w(x,t)}{\partial \mathrm{x}}\right]-m_r r_r^2\frac{\partial^2\phi(x,t)}{\partial \mathrm{t}^2}+P_a\phi(x,t)=0 \tag{2}$$

where: $w(x,t)$ is the vertical deflection of rail; $\phi(x,t)$ is the rotation angle of rail neutral axis; EI_r is the rail flexural rigidity; kAG_r is rail shear distortion rigidity; m_r is the rail mass per unit length; r_r is the radius of gyration of rail cross-section; P_a is the rail axial force; and $\bar{\mathrm{p}}(x,t)$ is the generalized distribute force on the rail. Note that these equations are based on Timoshenko beam theory [32-33]. The curvature (κ) of a sleeper at a point along the sleeper can be written as:

$$\kappa=EI\frac{\partial^2 w(x,t)}{\partial \mathrm{x}^2} \tag{3}$$

Based on equation (3), for any sleeper under free vibration in a single mode, the ratio of the curvature of the sleeper at one location and the curvature of the sleeper at another location should remain a constant value. This is true regardless of the boundary conditions of the system and is independent of the amplitude of motion [24]. This ratio between curvatures as normalized curvature ratio (NCR) can be defined by:

$$\mathrm{NCR}_{\mathrm{i,j}}=\kappa_{\mathrm{i}}/\kappa_{\mathrm{j}} \tag{4}$$

where κ_{i} is the curvature of the sleeper at a location i and κ_{j} is the curvature of the sleeper at a location j. The curvature of the sleeper is based on the lowest bending mode of vibration of the sleepers since free vibration occurs primarily in the first or lowest mode in most cases in a real structure. In this study, a more sensitive curvature square is also considered. The ratio between normalized curvature square (NCSR) can be defined by:

$$\mathrm{NCSR}_{\mathrm{i,j}}=\kappa_i^2/\kappa_j^2 \tag{5}$$

For this curvature-based method, either analytical or numerical model can be used for the NCR and NCSR evaluations. If there is a preexisting sensor network installed on the sleepers, the real-time data can be used to detect the ballast voids and pockets. Note that a benefit of the NCR and NCSR methods is that they do not require any correction of data related to temperature change [24].

3. Nonlinear Simulation of In-situ sleeper

A nonlinear finite element simulation of the in-situ railway concrete sleeper, which was developed earlier in two dimensions and successfully validated [1-2], has been adopted for this study. The railway concrete sleeper is modelled using fifty Timoshenko beam elements with a trapezoidal cross-section while rail pads and ballast systems were modelled as a spring-dashpot element and the elastic beam support features in STRAND7 [34]. The elastic support feature allows the changes in any element along the beam, making it possible to investigate any type of potential void configurations. The standard input data and engineering properties of those components have been adopted from previous investigations [1-2]. The in-situ boundary condition is simplified using spring elements as rail pads connected to rails. Verifications of the model have been done earlier in both free-free and in-situ conditions. The results of either eigenvalues or eigenmodes are in very good agreement with the previous findings in [1, 2]. The results have clearly proven that the finite element model and the simplified approach are capable of predicting the dynamic characteristics of in-situ railway concrete sleepers in a track system [35-36]. Figure 2 shows an example of simulation results.

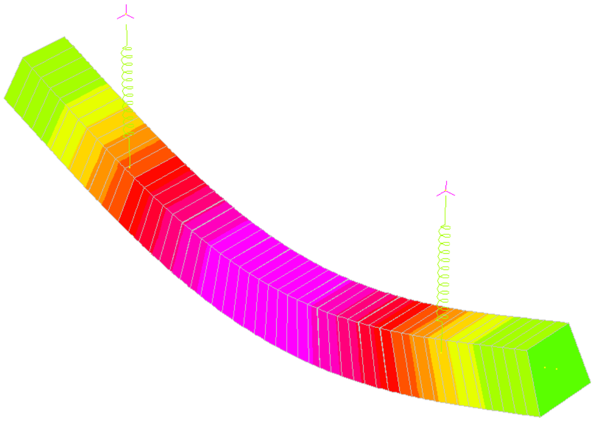


Figure 2. The lowest mode of flexural vibration of a sleeper (135 Hz)

Figure 3. Experimental setup [1]

4. Experimental Study

Commonly, experimental modal analysis (EMA) or modal testing is a non-destructive testing strategy based on vibration responses of the structures. Over the past decade, the modal testing has become an effective means for identifying, understanding, and simulating dynamic behaviour and responses of structures. One of the techniques widely used in modal analysis is based on an instrumented hammer impact excitation. By using signal analysis, the vibration response of the structures to the impact excitation is measured and transformed into frequency response functions (FRFs) using Fast Fourier Transformation (FFT) technique. Subsequently, the series of FRFs are used to extract such modal parameters as natural frequency, damping, and corresponding mode shape. In a wide range of practical applications the modal parameters are required to avoid a resonance in structures affected by external periodic dynamic loads. Practical applications of modal analysis span over various fields of science, engineering and technology. In this study, the modal testing is sound and has been employed in the experiments as shown in Figure 3 [1].

5. Results and discussion

The comparison between the nonlinear finite element simulations and the experimental results can be demonstrated in Figure 4. In the small range of ballast voids (a: void length; L: the total length of sleeper), only 1-2% difference between experimental and numerical results can be observed. Over the larger range of ballast voids, up to 3-4% of discrepancy can be observed. On this ground, the numerical model is considered in excellent agreement with the experimental studies.

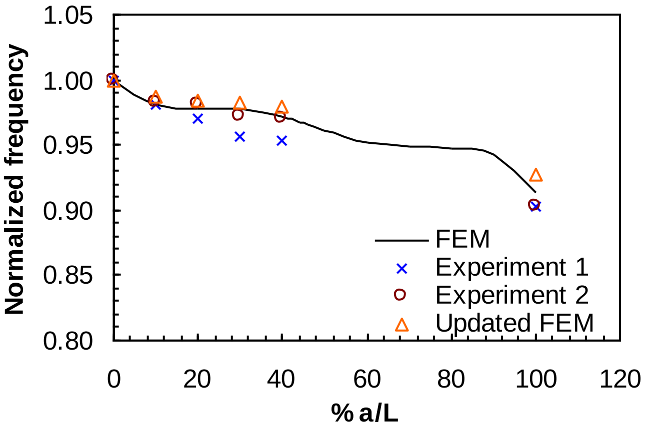


Figure 4. Comparison between numerical and experimental results of voided sleepers

The numerical studies have been further extended to evaluate the free vibration behavior of the sleepers under 5 cases: full ballast support condition; minor ballast void at railseat; severe ballast void at railseat; severe ballast void over midspan; and total loss of ballast (or hanging sleeper). Figure 5 shows the dynamic modeshapes of the sleeper under various cases. It can be observed that small variation of the shapes can be observed.

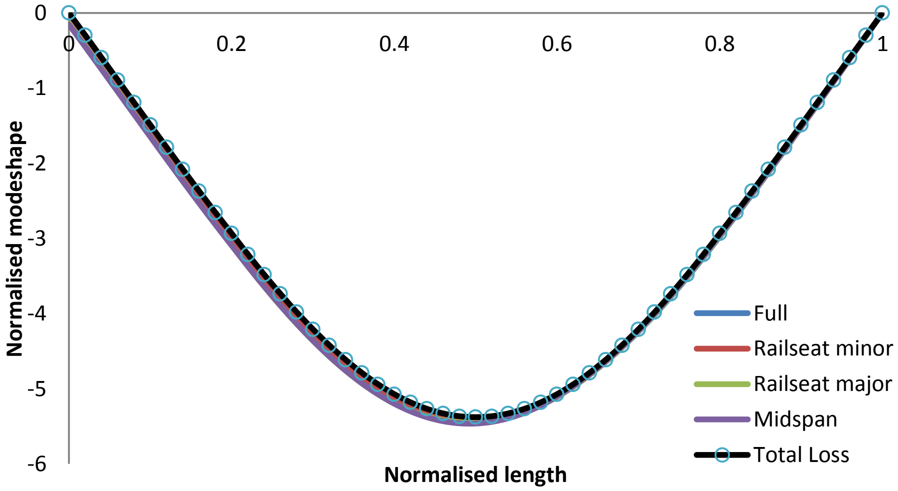
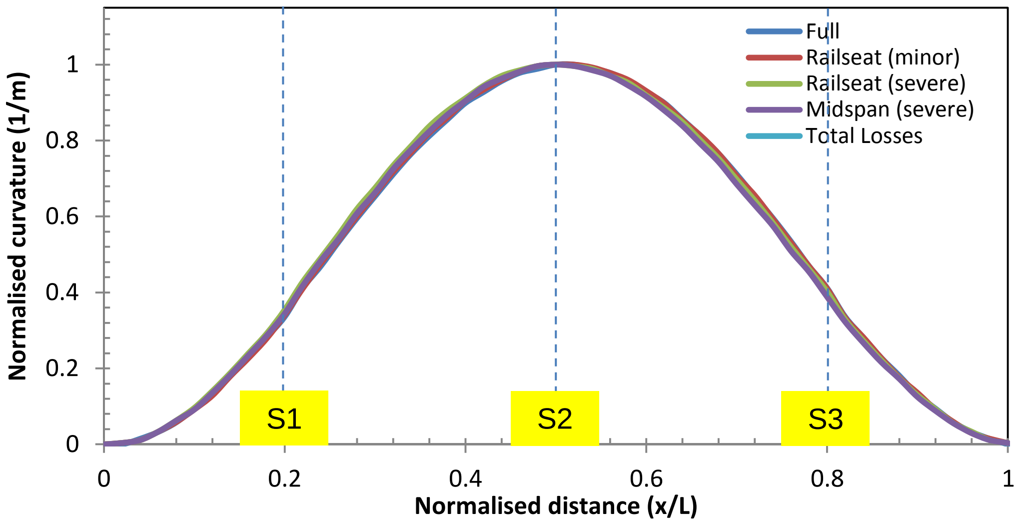
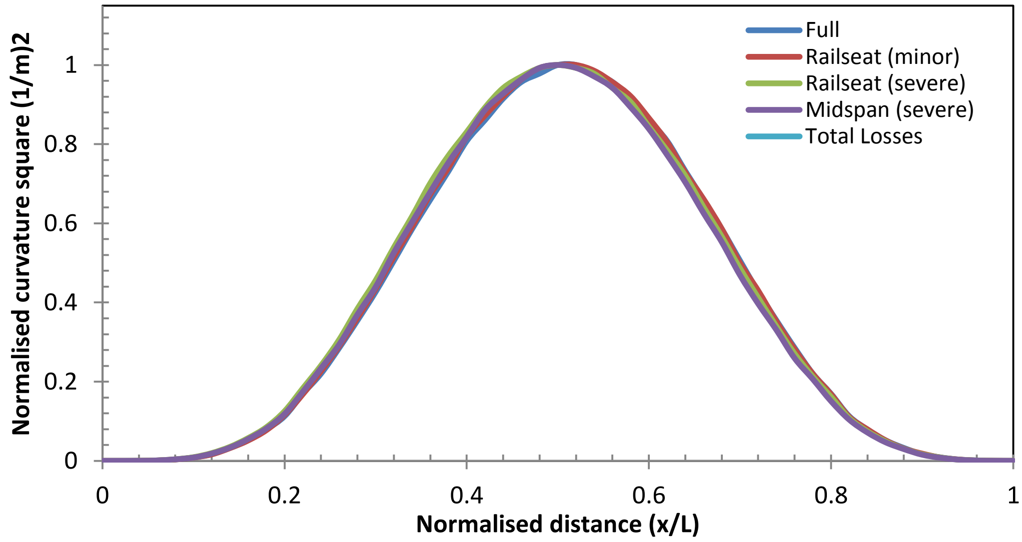


Figure 5. Lowest modeshapes of voided sleepers

The curvatures and curvature squares of the sleepers can be seen in Figure 6. It is clear that the voids and pockets can slightly affect the normalised curvature. However, the curvature squares show relatively more sensitive to the effect of ballast voids and pockets.



a) normalised curvature

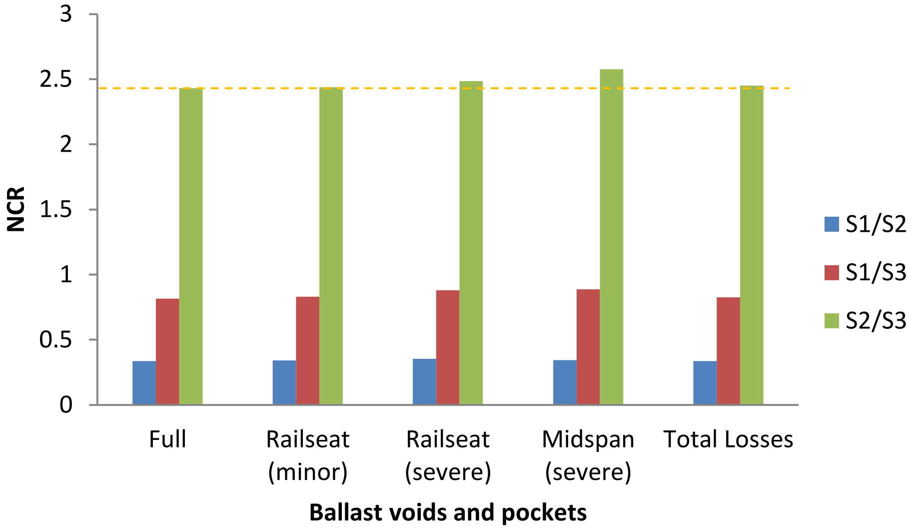


b) normalised curvature square

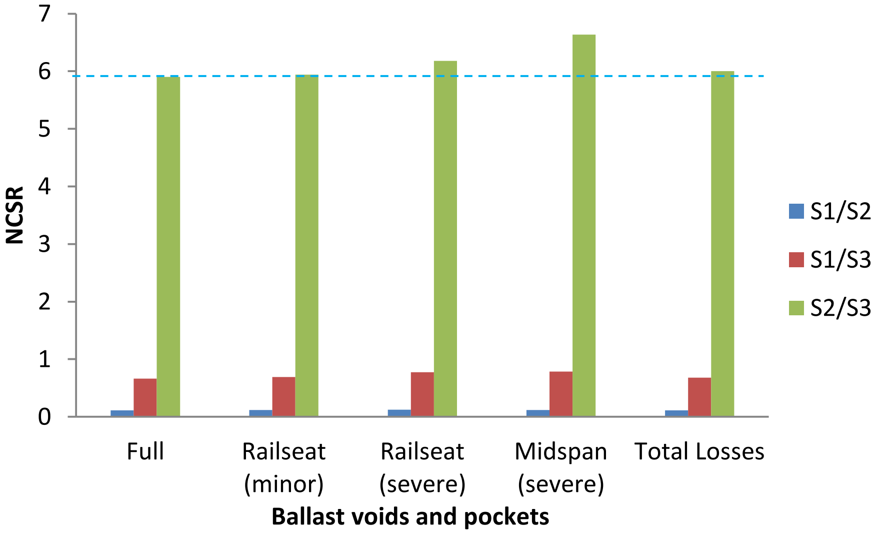
Figure 6. Lowest bending curvatures of voided sleepers (Location indicators: S1 at railseat; S2 at midspan; and S3 at the other railseat)

It can be observed that the ballast conditions do not significantly affect the curvature or the curvature square of the *in-situ* sleeper. NCR and NCSR can be evaluated as shown in Figure 7. It can be seen that NCR is not sensitive to the ballast voids, when compared with NCSR. Based on this study, it is apparent that NCR and NCSR do not present major precursor for the detection of ballast voids and pockets. It is because the sleepers tend to behave symmetrically under free vibrations. It is clear from the case of total loss of ballast contact. In the total loss case, the sleepers vibrate symmetrically so the NCR and NCSR become less sensitive. This indicates that a given configuration of sensors is not equally sensitive to the damages occurring symmetrically.

However, for the cases of asymmetrical ballast voids (e.g. midspan and railseat loss), NCSR can be seen a more suitable ratio as the precursor used to detect the ballast voids and pockets. The dominate precursor for detecting ballast voids and pockets is S2/S3 (midspan over railseat). This NCSR ratio can be used for direct detection of the ballast voids at midspan and at railseat.



a) normalised curvature ratio (NCR)



b) normalised curvature square ratio (NCSR)

Figure 7. Lowest bending curvature ratios of voided sleepers

6. Conclusion

This paper presents a novel and simplistic condition monitoring method based on dynamic curvature approach. The method uses the normalized curvature ratio (NCR) and the normalized curvature square ratio (NCSR) as the precursor for detection of ballast voids and pockets underneath the rail track sleepers. The method is initially presented through the analytical study of the railway sleeper using Timoshenko beam theory. The experimental and numerical studies have been performed to validate the nonlinear finite element model. An excellent agreement between the experimental and numerical results can be found. The model has been further extended to evaluate the effect of ballast support conditions for this curvature-based method. The aim of this study is to develop a novel alternative method that could be used as a supplement technique to detect ballast voids and pockets, which cannot be normally inspected visually in practice.

The study found that the curvature-based method is sensitive to asymmetrical damage of ballast conditions. It does not well respond to symmetrical vibrating behavior of sleepers (such as in the case of full support or total loss of ballast condition). In fact, it can be found that the NCSR is a more suitable precursor for damage detection of ballast voids and pockets underneath the rail track sleepers. The insight into this free vibration characteristics can be simply used to guide railway and track engineers to identify voided sleepers in the field using either modal testing or operational responses of the sleepers.

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