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Experimental modal analysis of railway concrete sleepers with cracks

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Abstract. Concrete sleepers are essential components of the conventional railway. As support elements, sleepers are always subjective to a variety of time-dependent loads attributable to the train operations, either wheel or rail abnormalities. It has been observed that the sleepers may deteriorate due to these loads, inducing the formation of hairline cracks. There are two areas along the sleepers that are more prone to crack: the central and the rail seat sections. Several non-destructive methods have been developed to identify failures in structures. Health monitoring techniques are based on vibration responses measurements, which help engineers to identify the vibration-based damage or remotely monitor the sleeper health. In the present paper, the dynamic effects of the cracks in the vibration signatures of the railway pre-stressed concrete sleepers are investigated. The experimental modal analysis has been used to evaluate the modal bending changes in the vibration characteristics of the sleepers, differentiating between the central and the rail seat locations of the cracks. Modal parameters changes of the 'healthy' and cracked sleepers have been highlighted in terms of natural frequencies and modal damping. The paper concludes with a discussion of the most suitable failure indicator and it defines the vibration signatures of intact, central cracked and rail seat cracked sleepers.

Keywords: experimental modal analysis (EMA); concrete sleeper; structural health monitoring; crack; damping

1. Introduction

Most of modern railway sleepers used worldwide are the pre-stressed concrete sleepers. Their functionality is to distribute loads from the rail foot to the underlying ballasted bed. As an essential railway track component, these structural elements are always subjected to a variety of time-dependent loads which are attributable to the train operations with either wheel or rail abnormalities such as flat wheels, dipped rails, etc. It is observed that the railway sleepers deteriorate greatly due to static and dynamic accidental loads or simply because it has exceeded the life span of the element. In

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both cases, the deterioration shows up as structural hairline cracks (Kaewunruen and Remennikov 2009). Cracks in concrete sleepers lead to serious concerns about their durability, utility and load-carrying capacity. Therefore, these specific failures require special testing procedures.

Over the last decades, vibration-based Structural Health Monitoring (SHM) has been widely used to evaluate the condition of railway tracks. Most of the SMH applications make effective use of Experimental Modal Analysis (EMA) (Kaewunruen and Remennikov 2009). The EMA method consists on the study of changes in the dynamic properties of the structure due to the presence of structural damages. The dynamic properties of an element are a function of its mass, stiffness and energy dissipation. Consequently, the material loss and the presence of a crack will have a direct influence on the natural frequencies, mode shapes and damping ratios of the structure.

Experimental identification of modal parameters is a research topic with more than six decades of history. One of the most important milestones in the development of the subject was provided by Kennedy and Pancu (1947). The quick advance of electronic measurement and analysis techniques in the 1960s led the way for more precise measurements and, thus, more powerful applications. Salter (1969) presented one of the most significant works in this period, in which he developed a relatively non-analytical approach to the interpretation of measured data. Actually, Experimental Modal Analysis is a well-establish field, extensively documented in reference books (Maia and Silva 1997, Ewins 2000) and largely used in practice (Salau 1997). The first relevant report based on a modal analysis on a concrete sleeper in a free-free condition was written by Ford (1988). More recently, Zakeri and Sadeghi (2007) achieved a more accurate understanding of the dynamic behavior of uncracked concrete sleepers, which was completed by Sadeghi (2010). For this purpose, several tests were conducted in sleepers to obtain their natural frequencies, mode shapes and damping properties. Moreover, the effects of the sleeper supporting conditions on the sleeper dynamic behavior were investigated. In addition, Remennikov and Kaewunruen (2006, 2007) evaluated the dynamic behavior of sleeper/ballast interaction and discussed the change in sleeper modal parameters related to the different width of cracks (Remennikov and Kaewunruen 2008). After that, they worked on understanding the dynamic crack propagations in pre-stressed concrete sleepers under repeated impact loading (Kaewunruen and Remennikov 2010).

Over the last decade the improvements on railway design have been focused on accommodating the infrastructure to increasing vehicle weights and faster operating speeds. Therefore, it is particularly important to assess the track damage due to these new conditions in order to decide on the track design and maintenance procedures. Consequently, experimental analysis of railway track damage, due to substantial settlement, was made by González-Nicieza *et al.* (2008). Their work determined the three main elements that may bring failure to the sleepers, which are summarized as heavy loads, defects in the concrete and the poor packing of the ballast. Due to this particularly, many efforts have been devoted to evaluate impulse resistance of concrete sleepers by impact loading test in laboratory (Kaewunruen and Remennikov 2009), (Bhuyan *et al.* 2012) and in situ conditions (Kaewunruen and Remennikov 2011).

This paper presents results of an experimental modal analysis of un-cracked and cracked pre-stressed concrete sleepers in laboratory conditions. The cracks are generated by applying static loads in different locations. The main purpose of the experiments is to evaluate the effects of a hairline crack into the dynamical behavior of the sleeper depending on different positions and widths of the cracks. Generally, due to the positions of load distribution, the central and rail-based areas of the sleeper are the ones more prone to crack. The conclusion highlights these effects in terms of natural frequency displacements and damping variations. Additionally, the vibration signature is defined for each case studied. The importance of the present results is involved in the development of Finite Element Models of cracked sleepers. These models are useful to evaluate the dynamic overturning instability of tracks and the abnormal wheelset movements, which are provoked by damaged sleepers.

2. Experimental modal test principle

The experimental modal analysis is based on the performance of the forced vibration test (FVT), involving the measurement of one or more dynamic excitations and the corresponding structural response. From the relationship between the applied input and the observed output, denoted as Frequency Response Function (FRF), it is possible to accurately identify modal parameters.

$$H(w) = \frac{X(w)}{F(w)} \tag{1}$$

Where $H(w)$ is the Frequency Response Function and $X(w)$ and $F(w)$ are the Fourier transforms of the vibration response of the system and the excitation force, respectively.

One of the techniques widely used in modal analysis is based on an instrumental hammer impact excitation. By using signal processing, the vibration time response of the structures is measured when excited with an impact, and it is transformed into frequency response functions (FRFs) using Fast Fourier Transformation (FFT). The quality of the results obtained from the experimental modal analysis depends on the following technical aspects: the mechanical properties of supporting elements, the excitation of the structure, the transducer elements and the signal processing techniques.

Previous studies state that the cracks tend to have a more significant influence on bending modes of vibration than those associated with the twisting modes. Consequently, the present work is focused on the flexural behavior of sleeper concrete under real support conditions.

2.1 Basic assumption: Multi-Degree of Freedom system with viscous damping

Structural systems with dynamic behavior determined mostly by a combination of inertia and stiffness are designated as Multi-Degree of Freedom (MDOF). Moreover, in every structure there are three primary mechanisms of damping: internal damping related to imperfections, structural damping related with support properties and hysteretic damping related to the constitution of the materials.

The pre-stressed concrete sleeper is classified as an MDOF system with viscous damping for being an element of variable section. Consequently its general equation of motion is

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f\} \tag{2}$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, and $[K]$ is the stiffness matrix.

When the hammer impacts in the testing structure, it will experience a force pulse which is substantially that of a half-shine shape, designated as $\{f\}$. The frequency domain transform of the displacement is $\{x\} = \{X\}e^{jwt}$. Substituting this solution in Eq. (2) and assuming $\{f\} = \{F\}e^{jwt}$, the equation of motion becomes

$$(-w^2[M] + jw[C] + [K])\{X\} = \{F\} \tag{3}$$

Transforming Eq. (3) using modal coordinates based on $\{X\} = [\Phi]\{Q\}$ the accelerance of the system can be obtained with

$$H_{ij}(w) = \frac{X_i(w)}{F_i(w)} = \sum_{i=1}^{n} \frac{\phi_i \phi_i^T}{w_i^2 - w^2 + 2\xi_i w_i w_j} \tag{4}$$

where, w_i is the natural frequency, ϕ_I denotes mass-normalized mode shape, and ξ_I represents the modal damping ratio.

A viscous damping model is not very representative when applied to MDOF systems. As it can be observed in Eq. (4) the damping is frequency-dependent in most of the real structures because of the hysteresis properties of the materials. The solution is to consider the MDOF System as a superposition of several Single Degree of Freedom (SDOF) systems. Thus, each of the natural frequencies should be experimentally characterized by its damping ratio, which is calculated by de Peak-Picking Method.

$$w_a = w\left(\frac{|H_{ij}|_{\max}}{\sqrt{2}}\right)_{left} \tag{5}$$

$$w_b = w\left(\frac{|H_{ij}|_{\max}}{\sqrt{2}}\right)_{right} \tag{6}$$

$$\xi_j = \frac{w_b^2 - w_a^2}{4w_j^2} \tag{7}$$

Where w_j represents the natural frequency identified from the peak value of the FRF amplitude $|H_{ij}|_{\max}$. The half power points at w_a and w_b are located from each side of the identified peak with amplitude $|H_{ij}|_{\max}/\sqrt{2}$. Finally, the damping ratio can be estimated from the width of the resonance peak.

2.2 Timoshenko beam equation

The concrete sleeper, due to its moment distribution, has a predominant flexural behavior based on tensile and compressive stresses. According to experimental studies and dynamic modeling of concrete sleepers, it can be concluded that the Timoshenko beam element is the best approximation of the concrete sleepers. Therefore, it is possible to calculate the natural frequencies of the predominant flexural modes by applying the following equation

$$w_n = n^2 \pi^2 \sqrt{\frac{EI}{\rho L^4}} \tag{8}$$

where w_n is the natural frequency, n the order of the bending mode, E is Young's modulus, I is the area moment of Inertia, ρ is the density of the beam and L the distance between the supports of the beam. Additionally, the Timoshenko equations show the relationship between the natural bending frequencies and the EI factor, which was found on the basis of the effects of cracks in the dynamic behavior of beam elements. However, the limitation of using Timoshenko analytical formulation is that it cannot predict the shapes of other modes except the bending modes.

3. Experimental set up and data collection

3.1 Cracking procedure

The total number of samples subjected to the experimental modal test amounted to 12 pre-stressed concrete sleepers AI-04-EA (UIC 60), with post-tensioned reinforced without adhesion. The dimensions and mass of the test sleeper are shown in Table 1.

To establish optimum final conclusions about dynamic behavior of cracked sleepers, all the samples were subjected to the same cracking setup procedure. Each healthy sleeper was exposed to a controlled continuous load at both central and rail seats by using static presses of 2 kw (Fig. 1).

The cracking procedures were implemented following the guidelines of the current legislation

Table 1 Dimensions and mass of the test sleeper

Mass (kg)	Total length (m)	At railseat (m)		At centre (m)	
		Width	Depth	Width	Depth
315	2.600	0.276	0.235	0.220	0.209

(A) (B)

Fig. 1 Cracking facilities (A) central-cracking static-press (B) rail-seat-cracking static-press

Table 2 Cracking load-crack width relations

	Location of the crack	Press model	Cracking Load	Crack width
PROCEDURE A	Central Section	Hydraulic 15 Tn	100 kN/105.95 kN	0.18 mm/1.5 mm
PROCEDURE B	Railseat	Hydraulic 200 Tn	498 kN	0.18 mm

(A) (B)

Fig. 2 Crack patterns of sleepers (A) 0.18 mm width (B) 1.5 mm width

(UNE-EN 13230-2, 2010). In addition, the applied charges-crack's widths ratios are summarized in Table 2 and generated crack patterns are shown in Fig. 2.

3.2 Experimental modal analysis

Impact hammer excitation technique was used to evaluate the modal data. The instruments used in this study were the PCB impact hammer to excite the sleepers over the frequency range from 0 to 1000 Hz, the PCB accelerometers to register vibration data and the IMC software device to preprocess data. Besides, Matlab® algorithms were designed for post-processing of the measured data and obtaining their frequency response functions (FRFs). Finally, modal parameters were analyzed and vibration signatures were characterized.

The sleepers were bi-supported for central and rail seat modal tests. This supports pretended to simulate the free-free behavior that is usually performed by hanging the element with elastic ropes. The reason for this requirement is to obtain the mechanical properties of the sleeper as an isolated element. The adequate position of the supports, which corresponds to the nodes of the bending vibration modes, so they do not affect the frequency response (Carne *et al.* 2007), had been previously studied with a Finite Element model. Moreover, this model was used to determine the optimum excitation and measurement test points. While the central cracked sleepers were tested over the press structure (Fig. 3A), the rail-seat cracked sleepers were bi-supported on elastomeric materials (Fig. 3B). Although the effect of supports does not influence the natural frequencies, the effects induced in the global damping of the systems are evaluated.

The excitation and measured points were located on the top surface of the sleepers. The relative position between the excitation point and the accelerometers is based on two main principles: the distance between them should be the maximum and the first three bending moment must be registered. The diagram of the experimental modal testing is showed in the following Fig. 4. The

(A) (B)

Fig. 3 (A) Support system for central cracked sleeper testing (B) support system for rail seat cracked sleeper testing

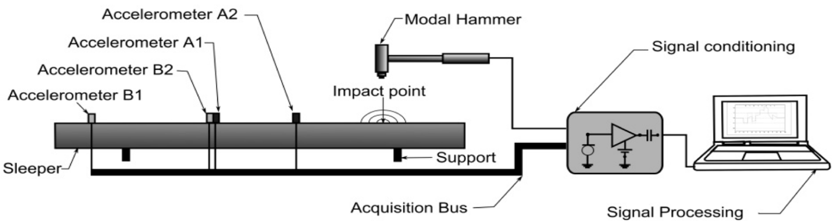


Fig 4 Experimental modal testing setup

excitation force and the acceleration responses on different points were registered per each specimen. The groups of accelerometers A and B correspond to central and rail seat cracks respectively.

It has also been observed that the A1 and B2 positions of the accelerometers are the most suitable to register the bending moments of the cracked sleepers.

4. Discussion of experimental results

The Experimental Modal Analysis was based on the structural dynamic response measured in the time domain, and subsequently its conversion to the spectral domain via the Fast Fourier Transformation Technique. The information related to the dynamic behavior of the sleeper element was analyzed in both time and frequency domain in order to determine which of the measured and/or calculated parameters out to be the optimal crack indicator.

The analyzed sleepers behave as MODF systems. Fig. 5 shows the time responses of un-cracked and cracked sleeper, respectively.

Every system responds to the hammer blow as an exponential decay transient, where the damping ratio plays an important role, as seen in Eq. (9)

$$x(t) = Xe^{-\xi w_o t} \tag{9}$$

where ξ is the damping ratio, w_0 is the natural frequency and t is the time. In addition, a crack in a sleeper tends to relax the structural element, increasing the energy lost per cycle of movement and, therefore, the damping ratio. Consequently, it was found that the appearance of a crack provokes a decrease in the amplitudes of the accelerations and makes the dissipation queues less steep, as it can be observed in Fig. 5.

The evaluation of the potential failure indicators by analyzing the frequency domain was focused on the Frequency Respond Functions obtained from the Experimental Modal Testing. It was found that the vibration behavior pattern of the AI-04-EA (UIC 60) sleeper model is characterized by showing its first resonant modes of vibration clearly dominated by three bending modes bellow 800 Hz. Both amplitudes and frequencies of the spectrums have revealed several significant changes due to presence of cracks in the element. The following figures show the spectrum comparison between uncracked (Fig. 6) and central or rail-seat cracked (Fig. 7) sleepers, respectively.

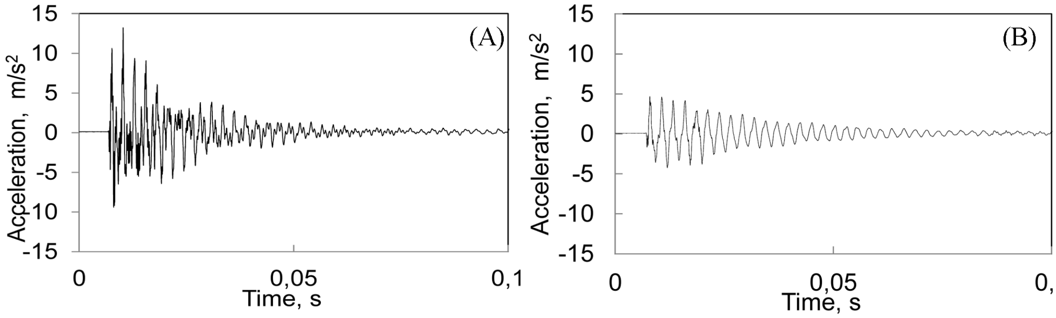


Fig. 5 Transient time responses of un-cracked (A) and cracked (B) sleepers

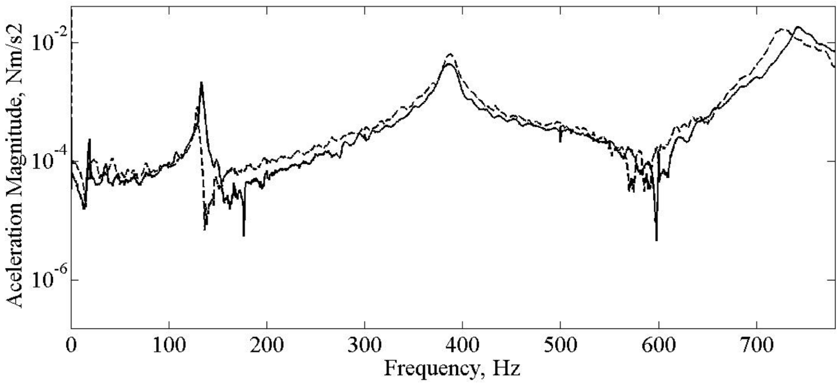


Fig. 6 (——) Vibration signature of uncracked sleepers, (---) vibration signature of central cracked sleepers

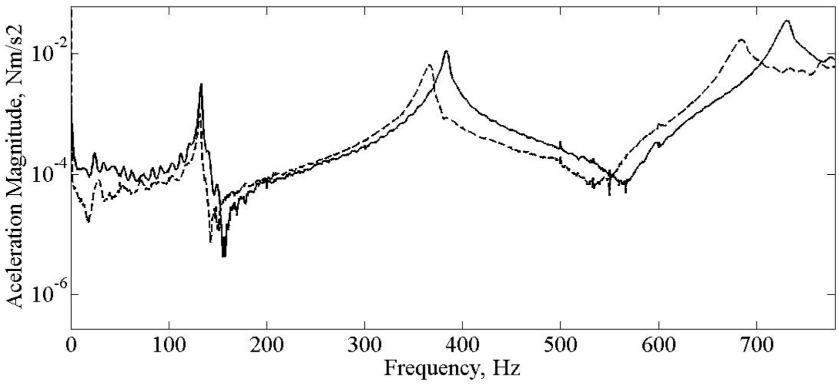


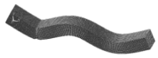
Fig. 7 (——) Vibration signature of uncracked sleepers, (---) vibration signature of rail seat cracked sleepers

Focusing on the evaluation of the signal amplitude, it is noted that the value of the acceleration peaks decreases with the presence of cracks. This phenomenon occurs due to the lost of energy induced by the friction movements of the cracks discontinuities. Although it is the habitual behavior, a significantly different tendency, which is related with the second mode of the central-cracked pattern, was detected in Fig. 6. The presence of a crack in the central section of the sleeper tends to liberate the movement in the relevant node of its second bending mode, inducing an increase of the global energy vibration. In this case, it should be noted that the liberation movement caused by the central crack is more relevant than the induced friction energy lost.

It is time to evaluate the known modal parameters, natural frequencies and damping ratios as pathological crack indicators. The results of modal testing for 'healthy', central cracked and rail seats cracked sleepers are illustrated in Table 3. In this table, the dynamic properties of the first three bending modes of vibration are summarized.

For most of the specimens, the presence of a crack, regardless of its width and position, moves the natural modes to the lower frequencies in the spectrum. Furthermore, the most significant frequency displacements between the uncracked and cracked conditions were detected in the third bending mode. For all bending modes, the changes in frequency were higher with rail seat cracks than with central cracks. Basically, the theoretical foundation of this behavior is that the presence of

Table 3 Modal parameters of AI-04-EA (UIC 60) sleeper model

Mode	Uncracked sleeper			Central Crack width 1.5 mm		Central Crack width about 0.18 mm		Rail-seat Crack width about 0.18 mm	
	Frequency (Hz)	Damping (%)		Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
		TA	TB						
1^{er}	133	0.5	0.6	85	2.6	129	0.8	131,5	0.9
									
2nd	380	1.3	0.8	373	1.5	380.5	*	366,5	1.2
									
3rd	735	1.4	0.4	615.5	1.5	725.5	1.6	684.5	1.3
									

Note: TA: Sleeper modal testing over the press structure, TB: Sleeper modal testing over elastomeric supports

cracks in a specific section of the sleeper tends to reduce the global inertia of the element. Subsequently, according to Timoshenko beam equations, the decreasing of (*EI*) factor leads to a lower natural frequencies of the bending modes Eq. (8). Quite the opposite, the second bending moment does not produce substantial displacements in frequency domain. The explanation of this event is that a central crack provokes a decrease in the inertia factor of a not influential section, for being a node of the second bending mode.

The experimental damping ratio represents the global damping effects of the three previous mechanisms, making their individual contributions really complex. This modal factor is frequency dependent, so each mode has its own damping ratio. The uncracked column of Table 3 represents the damping ratio of identical sleepers which lays down on supports with different dynamic properties. As it is observed, damping ratios measured from the Modal Test A are bigger than the ones measured from the Modal Test 2. This is due to the dissipation of most of the induced vibration in the sleeper along the structure of the press. For all samples, it was found that the appearance of a pathological crack causes an increase of the damping ratios. The most significant changes in damping ratios were presented between uncracked and central cracked sleeper with 1.15 mm of width. In conclusion, the present time domain study and the experimental modal analysis reveal the ‘particular’ dynamic behavior of the second bending mode as a central crack indicator.

5. Conclusions

The results of the experimental modal analysis, which have been implemented in a total of 12 pre-stressed concrete sleepers, both with central and rail-seat cracks, were presented in this paper. The obtained FRF of the sleepers show that the appearance of cracks tends to relax the structure resulting in a decrease of the natural frequencies of the first three bending modes. In addition, the presence of cracks induces an energy lost per cycle of movement because of the development of internal frictions among the concrete and the aggregates. Thus the damping ratios tend to decrease with the appearance of hairline cracks.

Furthermore, the experimental analysis reveals that despite having a global effect on the dynamic behavior of the sleeper, the appearance of cracks is manifested sharply in the bending modes. The vibration signatures revealed the second bending mode as "detection and location" crack factor. This information is founded on the basis of condition monitoring techniques of concrete sleepers. Moreover, the determined dynamic parameters of concrete sleeper are currently used in modeling of pathological cracks in order to evaluate its effects in railway tracks.

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