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DAMPING CHARACTERISTICS OF COMPOSITE SLEEPERS AND BEARERS IN RAILWAY SWITCHES AND CROSSINGS

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In recent years, composites and plastics have been developed for some applications in railway industry. Clear examples are 'fibre-reinforced foamed urethane (FFU)', 'geopolymer concrete', 'recycled polymer', and 'CarbonLoc composite'. The development fundamentally takes advantage of timber-like dynamic properties with which the sleepers can sustain realistic track dynamic loading conditions and last much longer than concrete counterparts. Railway sleepers and bearers are critical for safe and reliable operations of railway switches and crossings. The deterioration process of sleepers depends largely on the materials of which they are made. The adoption of composite material as turnout bearers in railway switches and crossings has raised several concerns if they can cope with the exposure to aggressive environments. Importantly the dynamic properties of bearers influence the functional constraints and serviceability of the switches and crossings. Excessive turnout vibrations at switches can cause malfunction of crawlock or signalling gear systems. Although such the understanding into dynamics aspect is well-known, the actual effect of environmental variance on the dynamic properties of the bearers has yet been pointed out clearly. Inexperienced practitioners are still confused about what properties they should use for analysis and design. The aim of this study is to identify the damping characteristics used for the design and practical selection of full-scale composite materials in railway turnout systems. The alternative composite material, 'fibre-reinforced foamed urethane (FFU)', is investigated since FFU has been used in several railway switches and crossings around the world. The dynamic damping of the FFU materials will be determined using the instrumented impact hammer testing method. The dynamic damping and natural frequencies of the full-scale specimens are determined from the FRF and vibration data in the frequency range between 0 and 1,600 Hz. These component-based dynamic properties are critical for mitigating track serviceability exposed to dynamic problems from wheel-rail irregularities and crossing impacts.

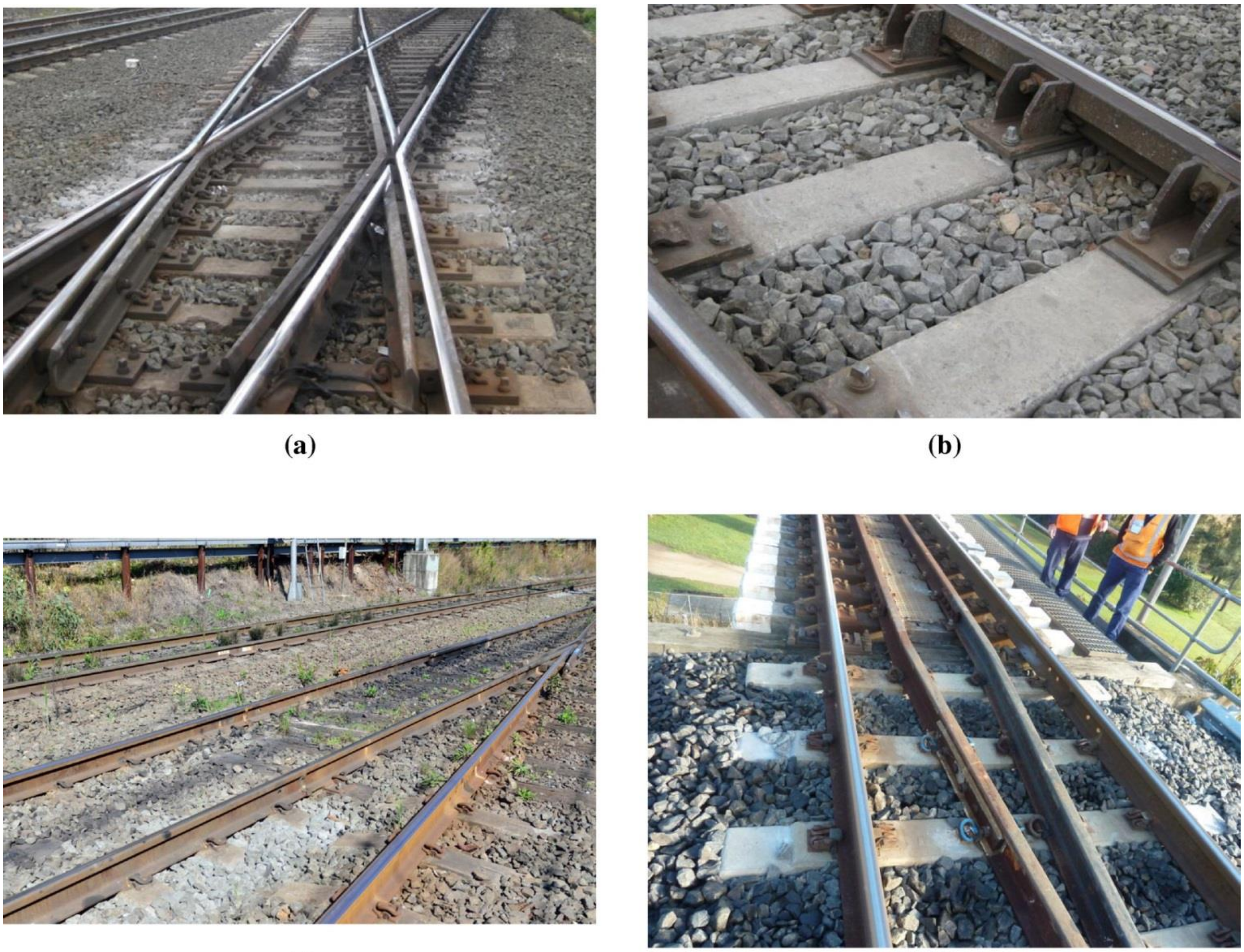
Keywords: damping, vibration control, railway bearer, composite materials, crossing impacts

1. Introduction

It is well-known that track loading conditions are rather dynamic than simple static (or quasi-static). The dynamic loading conditions are attributable to complex wheel/rail interaction and the complexity of railway track structures where rails are supported by crossties and the train loads are further redistributed to formation and foundation. Experienced engineers are well aware that railway track support components such as sleepers, bearers and transoms are safety-critical and structural elements in ballasted railway track systems. Their main functions are not only to withstand static and dynamic loads imposed by the wheels and transfer them to the ballast and underlying formation, but also to secure the rail gauge to allow trains to travel safely [1-3]. The behaviours of sleepers and bearers in track systems are correlated to the loading and support conditions. Many evidences revealed that their structural failure, cracks, and poor serviceability (high deformation and rotation) are due to the resonances generated by the components excited by the dynamic train loads [4-7]. Therefore, the dynamic resistance (derived from dynamic properties of materials and structural component) is critical to enhance durability and endure service life of railway sleepers and bearers in track systems. However, many practitioners still neglect the dynamic testing due to the lack of understanding into the realistic track performance. A clear example is the non-existence of realistic dynamic testing in design standards (e.g. European Standard EN 13230). On the other hands, a few countries have already developed dynamic resistance testing for sleepers and bearers (e.g. Australian Standard AS1085.14 and AS1085.19 – Impact attenuation tests; German DIN delivery guideline for Impact test for derailment resistance, etc.). These evidences show the inconsistency and different level of maturity of practices internationally.

In general, the structural performance of sleepers and bearers must be instigated and assured at all time through inspection (safety-related assessment functions), monitoring (surveillance functions) and maintenance [8-10]. Another important function of the track components in a ballasted railway track system is to help provide lateral track resistance to improve the stability and stiffness of the track structure. Any structural damage to or poor conditions of the components could influence the safety, reliability and quality of the railway track, resulting in impaired rail services. For example, if the sleepers cracked severely they would deform highly under the dynamic loads imposed by wheel–rail interaction. This large differential settlement accelerates the damage to other railway components, which in turn shortens the maintenance period of the railway track. On the other hand, if the sleepers are too flexible (low elasticity, low stiffness), the track can significantly deform and result in a large differential local track surface (top smoothness) [11-12]. These induce higher dynamic loads, poor ride comfort and excessive train energy consumption [13-15]. In addition, if the lateral resistance of the track is insufficient to support lateral forces (i.e. because of loosened ballast or abraded sleepers), rail buckling may occur [16]. If the track gauge is widened excessively, the train can derail either on curved tracks or at switches and crossings. As such, the performance of sleepers and bearers are vital for public safety and operational reliability.

At present, the scarcity of high quality timber, the environmental concerns, recyclability and sustainability of critical materials are among the incentives for researchers around the world to develop new materials capable of satisfying the functional requirements (i.e. dynamic performance) as well as improving their recyclability. One practical problem in the railway industry nowadays is the replacement of ageing, damaged and deteriorated railway (timber) sleepers in existing tracks [17-18]. Especially in special locations such as railway switches and crossings, railway bridges, transition zones, the need for alternative materials to replace old timber components is unquestionably significant [19-20]. Railway switches and crossings are a special track system or called ‘turnout system’, which is used to divert a train from a particular direction or a particular track onto other directions or other tracks [21-23]. A turnout system is a structural grillage system that consists of steel rails, points (or called ‘switches’), crossings (special track components), steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation. It is well known that traditional turnout generally imparts high impact forces on to structural members because of its blunt geometry and mechanical connections between closure rails and switch rails. This has raised the importance of dynamic performance and vibration modes of the components used in railway systems, whether resonance effects can be mitigated. Figure 1 demonstrates a dynamic resonance problem in turnout systems where low-damping materials tend to crack, break and damage under dynamic loading conditions coupled with dynamic resonances.


(a) (b)

(c) (d)

Figure 1: Dynamic problems in track and turnout systems [24].

It is important to note that fibre reinforced foamed urethane (FFU) composites have been used in the construction of railway track systems for over 35 years. Sekisui Chemical & Co [25] is the main producer of this material. Various studies using Japanese testing standards are carried out for this material in order to define it limits of use or validated them in specific and particular cases [25]. However, based on the critical review for composites [26], it is found that there is no previous work to evaluate the damping characteristics of the full-scale FFU composites. In this study, the aim is to highlight the dynamic properties of the composite bearers used in railway switches and crossings. Since the use of such composite sleepers is relatively new in railway industry globally, this paper offers new useful information for the industry. There is a misconception that standard testing procedures (or laboratory type testing for manufacturing quality) could replace a design method. It is therefore important to highlight the necessity of reliable design methods to ensure that future track maintenance does not suffer from the lack of design information so that the service life of the structural and safety-critical component could be determined at a given time in adverse rail environments and realistic dynamic load conditions. Commercially, plastic and composite sleepers are often manufactured and fabricated by small and medium-sized enterprises whose product line may not last as long as railway lines do (i.e. the average lifespan of a start-up company is about 5–8 years, whereas a railway line is normally built to last 50+ years). Knowledge of the fundamental dynamic characteristics is therefore crucial for mitigating dynamic track serviceability. In this paper, the modal experimental analyses of composite sleepers are presented.

2. Modal analysis

Measurements of vibration responses in structures result in the modal parameter identification to obtain the dynamic characteristics of the structures. There are a number of methods to extract the dynamic characteristics, depending on the format of data obtained.

In a dynamic system, the equation of motion of the system can usually be represented by

$$\left[M\right]\left\{\ddot{x}\right\}+\left[C\right]\left\{\dot{x}\right\}+\left[K\right]\left\{x\right\}=\left\{f\right\} \tag{1}$$

where $\left[M\right]$ is the mass matrix, $\left[C\right]$ is the damping matrix, and $\left[K\right]$ is the stiffness matrix. The harmonic force applied to the system with magnitude F and loading frequency ω is given by

$$\left\{f\right\}=F\sin\omega t=Fe^{j\omega t} \tag{2}$$

The analytical solution can be contrived by Fourier Transform and can be found in [27, 28].

3. Modal testing

The basic feature of the measurement phase in modal test is that a certain stimulus or compression must be applied, and the obtained response must be measured at as many "points" as possible when necessary. Subsequent measurement data will be presented in the form of a response function, which is a series of ratios between response and excitation, or may also describe a function characterization of the response to any harmonic excitation (FRF) or impulse excitation (IRF). The properties of Fourier transform enable us to convert the original data from any of these excitation modes into the required FRF or IRF format through appropriate signal processing. The other parameter, damping, the actual physical mechanism of damping in the structure is many and complicated. Meaningful damping amount can be extracted from the measured FRF data. Although the characteristics that affect damping include surface smoothness, temperature, wear and other variable factors such as itself, even with these influences, damping is still an important factor for structural dynamic behavior reference. It directly affects the vibration level experienced by structures subjected to forced and free vibration. Therefore, we must continue our efforts to better characterize it and ensure that its effect is more repeatable and predictable in structure. In the modal testing of sleepers, an impact hammer excitation technique is adopted at a target frequency range of 0-1600 Hz. The frequency response function (FRF) is measured using the PROSIG modal test system. FRF is processed using the PROSIG modal analysis suite to identify the natural frequency and corresponding modal shape of the sleepers.

4. Materials

Nine full-scale beams (160 mm depth x 260 mm width x 3300 mm length) using fibre reinforced foamed urethane composites (designed for railway track components) have been supplied by an industry partner, Sekisui. The sleepers have been placed on the very soft spring support to generate **free-free**

condition as shown in Figure 2. 34 uniform points are marked on the sleeper surface as the excitation point of the impact hammer. An accelerometer has been installed at the edge as a fixed position to maximise vibration acquisition. An instrumented impact hammer has been used to excite the impulse to 20 positions around the bearer, to create dynamic frequency response functions (FRFs). The FRFs have been used to form and identify the natural frequencies and corresponding mode shapes of the full-scale bearers.

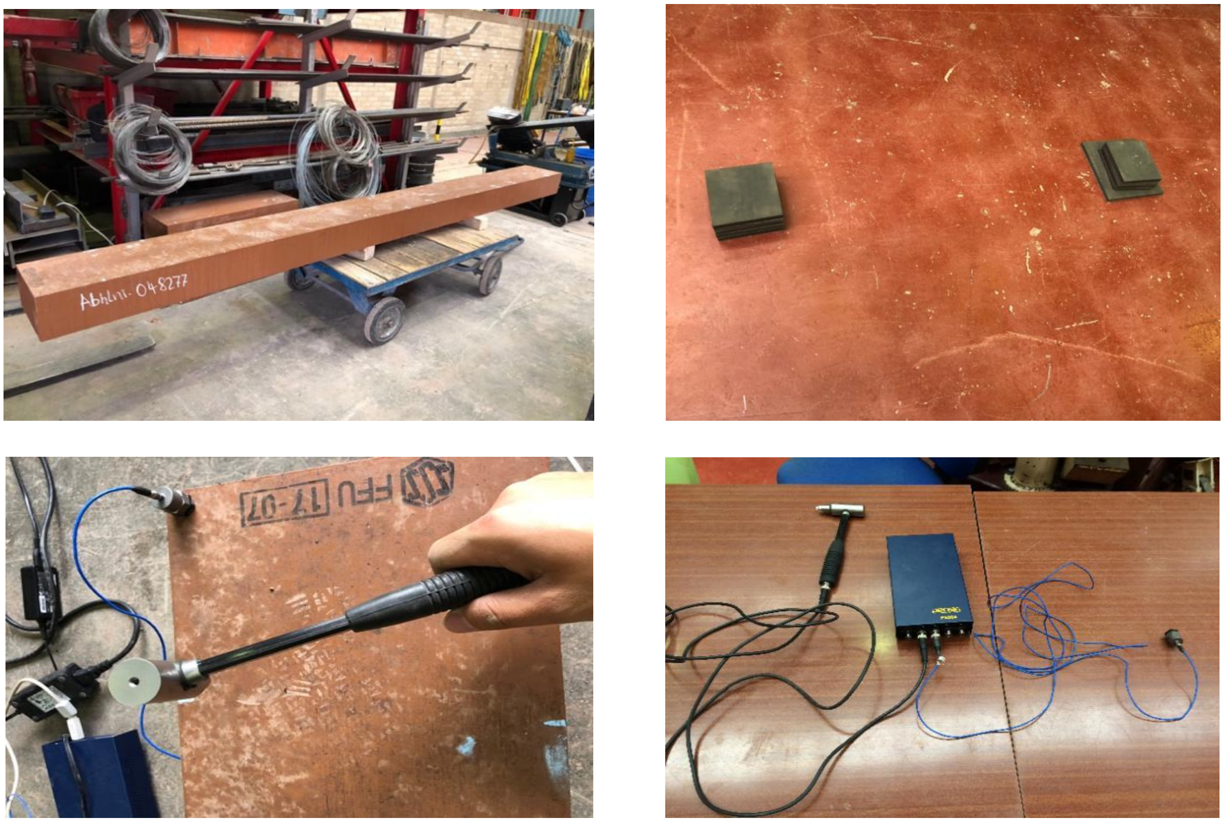


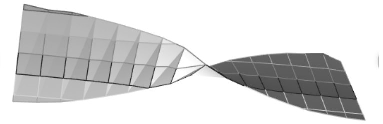
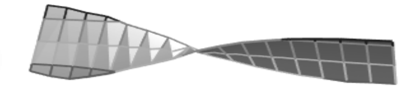
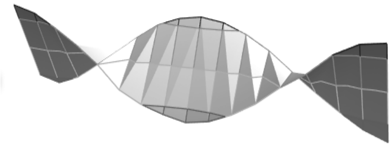
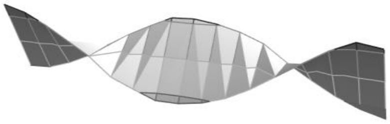
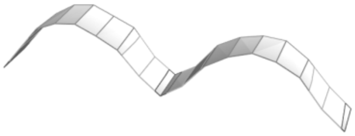
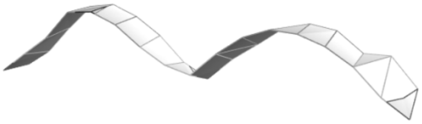
Figure 2: Test setup.

5. Results and discussion

Data extracted by hammer test are in Table 1. The sleeper has been tested at healthy stage. Then, the sleepers are subjected to static loading until they reach its static failure in accordance with EN 13230. The modal testing has been applied again to the damaged sleepers. Generally, for healthy sleeper, first mode is first bending, second mode is first torsion, third mode is second bending, fourth mode is second torsion, fifth mode is third bending. Variation of dynamic properties of healthy and damaged sleepers shows that internal property of sleeper has been changed.

It is clear that the natural frequencies of the composite sleepers have reduced after damage. This frequency reduction incurs across all frequency span and all modes of vibration of the sleepers. The reduction in natural frequencies can be varied from 12% in the low-frequency range to 25% in higher modes of vibration. It can be found that the higher the frequency, the more the reduction can be observed. On the other hand, it is found that damping characteristics tend to increase in the low frequency range due to the frictional damping of fibre damages. Such effect does not happen at high frequency range. It is found that the damping is likely to reduce at high frequencies. This could be because the damage mode of sleepers tends to be brittle and the high frequency properties rather correlate with global behaviour of the sleepers. It is clear that the damping characteristics are dependent to the fracture and damage on the bearers, which can influence in the dynamic behaviours. Longitudinal damage of composite fibres could affect both low and high frequency range damping characteristics.

Table 1: Dynamic properties and corresponding mode shapes for full-scale composite sleepers

Mode	Healthy condition		After damage	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1				
	68.23 (1st bending)	3.96	56.92 (1st bending)	5.9
2				
	85.78 (1st twisting)	2.98	75.94 (1st twisting)	3.83
				
	143.61(2nd bending)	3.37	121.87 (2nd bending)	2.8
4				
	180.14 (2nd twisting)	3.85	139.68 (2nd twisting)	3.99
5				
	247.96 (3rd bending)	4.96	185.28 (3rd bending)	2.53

6. Conclusion

In this study, fibre-reinforced foamed urethane (FFU) composite sleepers have been tested under full scale condition. Modal testing of the components under free-free condition has been carried out in order to identify the dynamic damping and vibration characteristics of the FFU materials. The modal parameters are determined using the instrumented impact hammer testing method. The dynamic damping and natural frequencies of the full-scale specimens are determined from the FRF and vibration data in the frequency range between 0 and 1,600 Hz. The full-scale composite sleepers are tested before and after damage. The damage has been artificially carried out using static load tests in accordance with European Standard EN 13230. The dynamic properties and corresponding mode shapes have been identified for both healthy and damage conditions. The results exhibit that the natural frequencies tend to reduce when damage occurs. However, it is shown that the low frequency damping tends to increase from frictions of broken fibres. These component-based dynamic properties are critical for mitigating track serviceability exposed to dynamic problems from wheel-rail irregularities and crossing impacts.

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