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Document Version
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Citation for published version (Harvard):
Kaewunruen, S, You, R & Goto, K 2019, Benefit of damping in structural concrete for railway structures and track components. in AM Ivanković, MK Marić, A Strauss & T Kišiček (eds), *International Conference on Sustainable Materials, Systems and Structures (SMSS 2019): Challenges in Design and Management of Structures.* vol. 4, RILEM Publications S.A.R.L., pp. 63-70, RILEM SPRING CONVENTION and SUSTAINABLE MATERIALS, SYSTEMS AND STRUCTURES CONFERENCE, Rovinj, Croatia, 18/03/19.
<https://www.rilem.net/publication/publication/493?id_papier=11338>

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Checked for eligibility: 25/03/2019

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BENEFIT OF DAMPING IN STRUCTURAL CONCRETE FOR RAILWAY STRUCTURES AND TRACK COMPONENTS

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Abstract

There are two types of modern railway tracks including ballasted and ballastless tracks. Ballasted tracks are optimally designed for suitability to railway operations with train speed less than 250 km/h, while ballastless tracks are more suitable for tunnelling work or higher speed trains. In both types of railway track systems, concrete is often used. However, the systems requirements for this material for real world applications are particularly demanding. Statistically, impact loading conditions comprise of nearly 25% of annual track loads. Also, abrasion from curve effects of train-track interaction causes high wear and tear. For example, railway concrete sleepers have been generally used in ballasted railway track and concrete slabs have been used for ballastless tracks around the world for over 50 years. Both safety-critical track components are commonly used to redistribute wheel forces onto track structure and to assure stable track gauge for safe passages of rolling stocks. The dynamic behaviours of concrete components are commonly well known; however, its damping characteristic is often neglected. With the increased demand for heavier and faster trains, the nature of track forces applying onto each track component is no longer static or quasi-static. The ignorance of damping can no longer be persisted as pre-mature damage or failure of track components can take place at a faster rate. A single sleeper failure may not affect open, plain track operations but it can give rise to the risks of rail breaks at rail joints, welds, bridge ends, switches and crossings, curved track, etc. Such the risks can later result in detrimental train derailments. This paper will highlight the development of high-damping concrete and the benefits of damping on the vibration mitigation of railway concrete sleepers in a track system. An established and validated finite element model of sleeper has been adopted for further studies. The model has been validated by experimental results. The insight into the vibration suppression of railway sleepers will help track engineers to decide the better choice of materials for manufacturing railway concrete sleepers.

Keywords: dynamic damping, railway tracks, track components, vibration reduction material

1. INTRODUCTION

Majority of civil infrastructures is built using concrete material, currently produced at a rate of 2 billion tonnes per year [1]. This is somehow responsible for 5% of global carbon dioxide emissions annually [2-6]. On the other hand, it is well known that concrete has several disadvantages such as low tensile strength, low ductility, brittle, low damping (low energy dissipation), and high susceptibility to cracking. This interior weakness causes concrete structures to deteriorate and lose its integrity when subjected to repeated harsh environmental conditions and dynamic loading conditions [7-10]. Thus, when exposed to these high-intensity conditions, concrete structures are at a risk of failure. In addition, the high global usage of concrete material combined with the large amount of pollution its production produces every year, is a major concern. Paris Agreement in 2016 has imposed the limit of carbon emission so that global warming can be limited to be less than 2°C in 2100 [11-12]. This implies that the use of high-carbon materials such as cement should be even more efficient and effective as much as possible. Therefore, a sustainable policy needs to be taken to discover a solution to these existing issues in material production and selection for design and manufacturing [13]. The sustainable approach within this study involves developing a method to reduce carbon emissions and to improve the resilience of concrete structures. This study comprises of novel concrete innovation incorporating waste materials (see Figure 1) for the purposes of reducing carbon emissions and also improving damping of concrete [14-16].

Figure 1: Waste car tyres

It is well known that railway sleepers (also called 'railroad tie' in North America) are a vital safety-critical component of railway track structures. Railway sleepers are the cross beam element supporting rails in order to provide load support and to secure rail gauge. Today, the most common material for manufacturing sleepers is concrete [17, 18]. The experience of design and application of railway concrete sleepers have been over 60 years around the world. Their key functions are to redistribute loads from the rails onto the underlying ballast bed, and to secure rail gauge for safe and smooth train passages. Based on the current design approach using static and quasi-static theory of solid mechanics, the design life span of the concrete sleepers is targeted at around 50 years in Australia and around 70 years in Europe [19, 20]. In design practice, dynamic problems have not fully been taken into account, giving rise to the lack of new innovation for concrete sleepers. Current industry practice is still based on the topological optimisation using static analysis and the selection of tailored or bespoke dynamic factors for quasi-static design [21-23]. This is because the current design and testing standards are rather primitive and overly simplified. Figure 2 shows a typical ballasted railway tracks. The track superstructure includes rail, rail pads, fasteners, sleepers and ballast; and the track substructure contains ballast mat, subballast (or capping layer), geosynthetics, subgrade and formation.

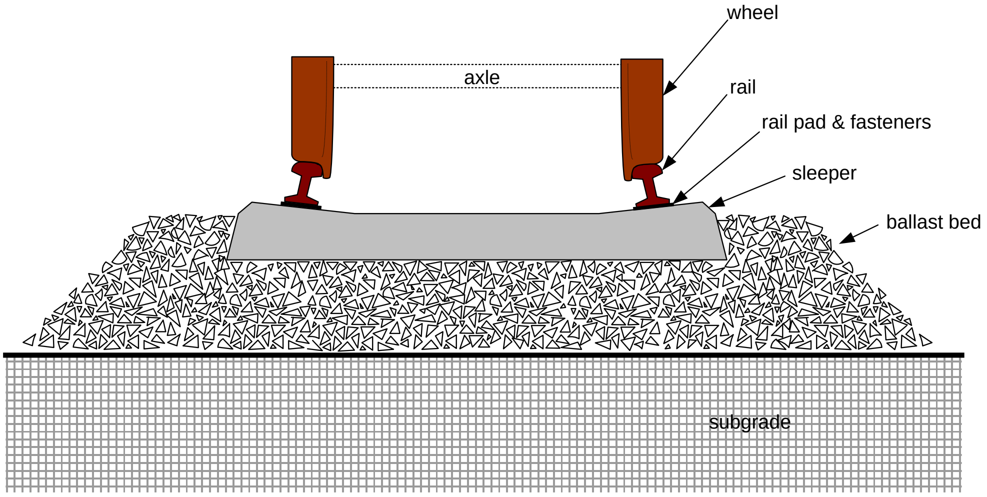

Figure 2: Typical ballasted track and its components

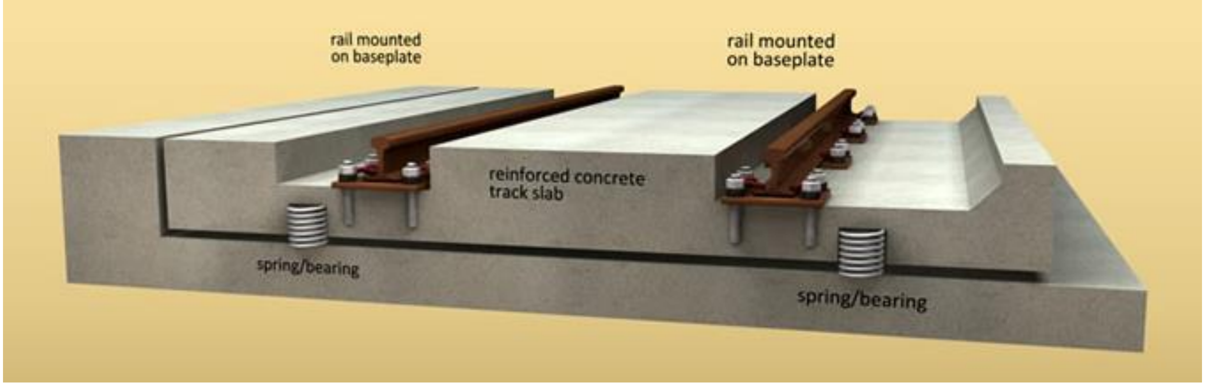

Figure 3: Typical ballastless track and its components

With concrete track slab systems as shown in Figure 3, the ballast is replaced by a rigid concrete track slab which transfers the load and provides track stability. Resilience is introduced into the track system by means of elastomeric components. These elastomeric components may be pads, bearings or springs depending on the type of slab track system. The rails are mounted on fastening systems over the concrete track slab. A resilient layer or spring system supports the slab to isolate track vibration from the ground and support structure.

Both ballasted and ballastless tracks are inevitably exposed to dynamic loading conditions [18]. However, the concrete material damping aspect has never been fully investigated. This paper is the first to present an advanced railway concrete sleeper modeling capable of analysis into the vibration attenuation effects of dynamic loading on the dynamic behaviors of railway concrete sleepers. The emphasis of this study is placed on the nonlinear dynamic design of railway concrete sleepers subjected to effective viscous damping of concrete material. It is the first time that the responses of concrete sleepers incorporating material damping have been investigated. The insight into the vibration attenuation will help structural and track engineers making a better choice in advanced material design and selection. It will also inspire materials engineers to further improve the dynamic material capabilities.

2. HIGHLY-DAMPED CONCRETE USING CRUMB RUBBER FROM RECYCLED CAR TIRES

There are 3 types of rubber, which researchers have tested so far. They are ground rubber, rubber chips and crumb rubber. Mendis [24] presented that compressive strength of concrete dramatically decreases when rubber is added inside. Compared with different types of rubber, Li et al [25] concluded that rubber chips and ground rubber reduce more compressive strength than crumb rubber. In order to reduce the effect of waste rubber, Thomas et al [26] proposed to replace a part of natural aggregate in concrete with some crumb rubber.

In this study, Ordinary Portland cement type I with characteristic strength of 52.5 MPa was selected to prepare concretes. Clean water supplied from the laboratory was used to make hydration reaction in the concrete mixtures. Natural sand and crushed gravel provided by civil engineering laboratory were used as fine and coarse aggregate. Sand has a maximum particle size of 5 mm, and crushed gravels have a maximum size of 10 mm. Before using in the mixture, moisture contents of these materials were investigated in order to adjust the proportion of concrete mix and keep water cement ratio (w/c) constant following the design [10, 27]. Table 1 shows the mixture proportion of highly damped concrete.

Table 1: Mixture proportions of concrete, Unit in kg/m^3.

No.	Mixes	Cement	Water	Gravel	Sand	Silica Fume	425 µm rubber
1.	RFC (Control)	530	233	986	630	-	-
2.	SFC (Control)	477	233	986	630	53	-
3.	SFRC-425-5	477	233	986	598.5	53	31.5
4.	SFRC-425-10	477	233	986	567	53	63

The vibration testing was conducted based on the vibration theory. The exponential curve fitting is used for the direct damping calculation method using the natural frequency and vibration response of the sample. As illustrated in Figure 4, the RFC had average damping ratio of 0.02146 at 28 days, and it improved around 21.76% when replacing cement with 10wt% of silica fume due to the large interface area between silica fume particles and cement matrix which can better dissipate vibration energy. In this study, SFRC-425-10 was the concrete mix which has the highest damping ratio (0.04128 and 0.04038 at 7 and 28 days).

3. NONLINEAR FINITE ELEMENT MODELLING

Using a general-purpose finite element package STRAND7 [28], the numerical model of railway tracks included the beam elements, which take into account shear and flexural deformations, especially for modeling a more realistic concrete sleeper as shown in Figure 5. In this study, the realistic support condition is simulated using the tensionless beam support feature in STRAND7. This attribute allows the beam to lift or hover over the support while the tensile supporting stiffness is omitted. This attribute creates nonlinear boundary conditions to the sleeper model, requiring Newton Raphson's numerical iterations to resolve the sleeper-ballast contact perimeter. The tensionless support option can correctly represent the ballast characteristics in real tracks. The geometrical and material properties of the finite element model has been validated with experimental results of a specific rail track [29, 30].

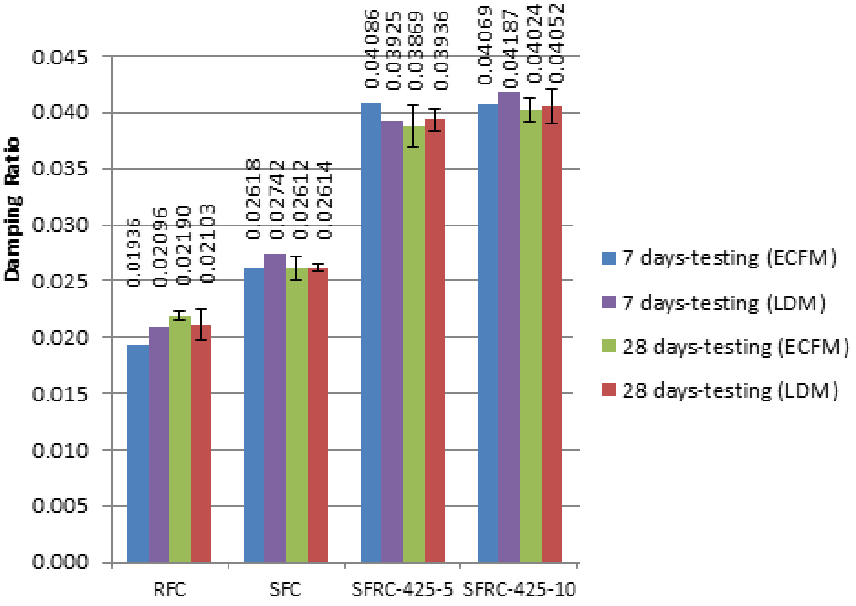

Figure 4: Damping ratio of concrete

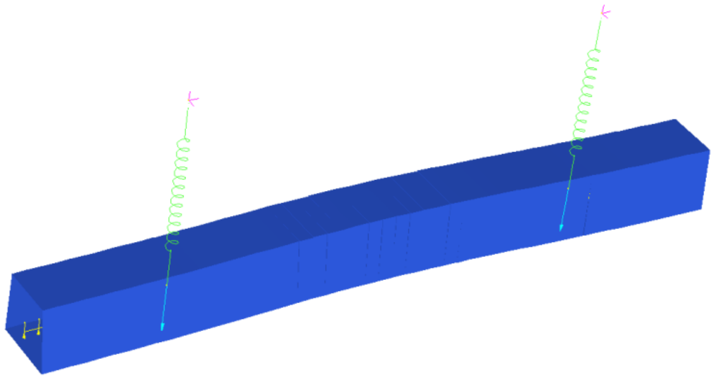

Figure 5: Highly damped concrete sleeper modelling

4. BENEFIT OF CONCRETE DAMPING IN TRACK DYNAMICS

The dual wheelset impact loads of 100 kN magnitude and 3 msec duration are applied at both railseats to stimulate impact vibrations. This impulse is equivalent to the effect of common wheel burns (e.g. 3-5mm flats) on railway tracks. The effects of material damping on the vibration loss of railway concrete sleeper at railseats in a railway track system can be illustrated in Figure 6. It is clear that material damping affects the track dynamics across the frequency span. Especially at the low frequency range associated to the crack of sleepers (<200 Hz), the higher level of vibration loss can be observed. The damping of concrete can suppress well the impact vibrations at railseats of the concrete sleeper where the structural damage often occurs. This can be implied that the improvement in material damping can considerably suppress vibrations that can cause breakage of sleeper and underlying ballast. This insight can also be observed for railway bridge viaducts [31, 32, 33]. The dynamic load effects can be suppressed, resulting in lesser dynamic defections and bending stresses. Since the concrete sleepers are generally designed to be 'uncracked' under serviceability limit state (i.e. dynamic impact factor of 2.0 to 2.5), the results clearly show that damping enhancement (>4% of damping ratio) can significantly improve the long-term performance and durability of the concrete sleepers. It is important to note that most of track load spectra tend to be a low frequency range (e.g. <20 Hz), it is clear that the damping improvement can yield a better life cycle of railway concrete sleepers and associated track components.

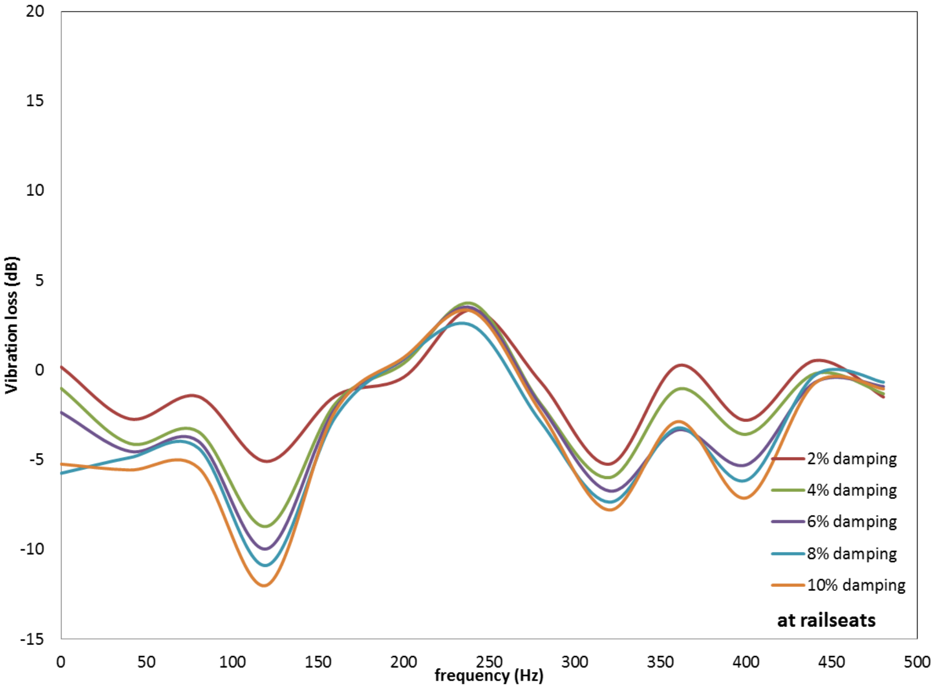

Figure 6: Vibration loss (in dB) of each railway sleeper in a track system

5. CONCLUSION

The insight into vibration attenuation of the sleeper due to the material damping is rather limited in both academic and industry. The ignorance of damping in design has resulted in very little research into advanced concrete technology for railway applications. This study is the world first to incorporate advanced knowledge of novel concrete with high damping for dynamic design of railway concrete sleepers. This paper highlights the effects of concrete damping on the vibration attenuation of railway concrete sleepers in a track system. Using an established and validated finite element model of concrete sleepers, realistic sleeper-ballast contact conditions have been adopted for nonlinear transient analysis. This study is the first to reveal that the concrete damping can provide high level of vibration attenuation in concrete sleepers in a track system across wide range of frequencies. This insight will help structural and track engineers to make a better choice of advanced concrete and composite materials for manufacturing railway concrete sleepers.

ACKNOWLEDGEMENTS

The authors are sincerely grateful to European Commission for the financial sponsorship of the projects H2020-S2R Grant No. 730849 "Switch and Crossing Optimal Design and Evaluation"; and H2020-MSCA-RISE Grant No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network," which enables a global research network that tackles the grand challenge of railway infrastructure resilience and advanced sensing in extreme environments (www.risen2rail.eu).

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