University of Southern Queensland

STATIC AND FATIGUE BEHAVIOUR OF COMPOSITE RAILWAY SLEEPERS

A Thesis submitted by

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ABSTRACT

Several composite sleepers have recently been developed as alternatives to hardwood timber. However, the mechanical properties of these alternative sleepers vary greatly with the bending modulus ranging from 1 to 37 GPa even though these sleepers have been developed as replacements for timber. This variation poses a significant challenge for the designers and track owners as they adopt these new technologies because of the lack of performance data. This thesis systematically evaluated the static and fatigue behaviour of timber and composite sleepers for their effective design and application in railway tracks.

In the first study, the behaviour of timber and its alternative sleepers supported by ballast was investigated by using a section of a railway track. The effect of varying bending and compression moduli was investigated. The Digital Image Correlation (DIC) technique was employed and validated with strain gauges to capture full bending profile and local decompression. The results showed that soft sleepers will exhibit a W-shaped profile while stiff sleepers show a U-shaped profile. The local decompression of soft sleepers accounts for 6% of total rail seat deflection on low modulus support and as high as 10% on stiff support, suggesting a significant difference in the behaviour of alternative sleepers on a simulated railway track.

The second study developed a new and simple test method called “five-point bending” to induce the positive bending moment at the rail seat and the negative bending moment at the centre as experienced by railway sleepers in the track. Three different support types at the mid-span: steel, ethylene propylene diene monomer (EPDM) rubber, and neoprene were considered. The suitability of this method was evaluated by testing different sleeper materials and by validating using the Beam on Elastic Foundation (BOEF) design method. The results showed that the neoprene rubber as mid-span support would mimic the deflection profile and magnitude of bending moments experienced by the sleepers. The developed analytical equations were found to accurately predict the bending moments in any location of the sleeper.

The developed five-point bending test method was implemented in the third study to study the behaviour and failure mechanisms of composite sleepers under static load. The flexural failure loads of alternative sleepers were shown to be lower than that of timber sleepers, i.e., 85% for concrete, 56% for synthetic composites, and 42% for plastics. Moreover, all the sleepers showed distinct failure mechanisms, i.e., flexural crack for timber, longitudinal shear cracks for composites, and permanent deformation for plastics. Local decompression was also captured for foam-based sleepers due to the softness of the foam. The results of this study highlighted the significant difference in the static behaviour of alternative composite sleepers compared to that of timber.

Finally, the fatigue behaviour and degradation of timber alternative composite sleepers were investigated as the fourth study. Small- and full-scale samples were tested and correlated through the established fatigue degradation factors. The failure behaviour of small- and large-scale sleepers was similar but the scaled-down specimens degraded 3.2 and 7.4 times faster than full-scale composites and plastic sleepers, respectively. Timber and composites lost 10% of their stiffness while the plastics exhibited a 6 mm permanent deformation after 1 million load cycles.

The results of this thesis enrich the understanding of the structural behaviour of timber-alternative sleepers, which have different mechanical properties. These new findings are very useful for their effective design, manufacture and implementation in the construction of new and interspersed railway tracks.

CERTIFICATION OF THESIS

I, Choman Salih, declare that the PhD Thesis entitled "static and fatigue behaviour of composite railway sleepers" is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This Thesis is the work of Choman Salih except where otherwise acknowledged, with the majority of the contribution to the papers presented as a Thesis by Publication undertaken by the student. The work is original and has not previously been submitted for any other award, except where acknowledged.

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STATEMENT OF CONTRIBUTIONS

The articles produced from this study were a joint contribution of the authors. The details of the scientific contribution of each author are provided below:

Manuscript 1:

Salih, C, Manalo, A, Ferdous, W, Yu, P, Abousnina, R, Heyer, T & Schubel, P 2021, 'Effect of bending and compressive modulus of elasticity on the behaviour of timber-alternative railway sleepers supported by ballast', *Case Studies in Construction Materials*, p. e00597. (Impact Factor: 3.328; SNIP 2.707; Cite Score: 5.1)

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The overall contribution of Choman Salih was 65% related to the data collection, critical review of related literature, analysis and interpretation of data, drafting and revising the final submission. Allan Manalo, Wahid Ferdous, Peng Yu, Rajab Abousnina, Tom Heyer, and Peter Schubel contributed to the structuring of the manuscript, analysis and interpretation of data, editing and providing important technical inputs.

Manuscript 2:

Salih, C, Manalo, A, Ferdous, W, Abousnina, R, Yu, P, Heyer, T & Schubel, P 2021, 'Novel Bending Test Method for Polymer Railway Sleeper Materials', *Polymers*, vol. 13, no. 9, p. 1359. (Impact Factor: 4.329; SNIP 1.2; Cite Score: 4.7)

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The overall contribution of Choman Salih was 60% to the concept development, design of experiments, experimental works, analytical investigations, model development, analysis and interpretation of data, drafting and revising the final submission. Allan Manalo, Wahid Ferdous, Rajab Abousnina, Peng Yu, Tom Heyer, and Peter Schubel contributed to the concept development, design of experiments, analysis and interpretation of data, editing and providing important technical inputs.

Manuscript 3:

Salih, C, Manalo, A, Ferdous, W, Yu, P, Heyer, T & Schubel, P 2022, 'Behaviour of timber-alternative railway sleeper materials under five-point bending', *Construction and Building Materials,* vol. 316, p. 125882. (Impact Factor: 6.141; SNIP 2.483; Cite Score: 8.8)

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Manuscript 4:

Salih, C, Manalo, A, Ferdous, W, Yu, P, Heyer, T & Schubel, P 2022, Fatigue degradation of timber alternative composite railway sleepers, *Composite Structures* (under review). (Impact Factor: 5.407; SNIP 2.04; Cite Score: 9.6)

The overall contribution of Choman Salih was 65% to the concept development, design of experiments, experimental works, analysis and interpretation of data, drafting and revising the final submission. Allan Manalo, Wahid Ferdous, Peng Yu, Tom Heyer, and Peter Schubel contributed to the concept development, design of experiments, analysis and interpretation of data, editing and providing important technical inputs.

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TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

BOEF	Beam on elastic foundation
d_f	Degradation factor
d_{f250}	Degradation factor after 250,000 cycles
DIC	Digital image correlation
DMA	Dynamic mechanical analysis
DT	Displacement transducer
E_1	Longitudinal bending modulus
E_2	Compression modulus
E_s	Bending modulus of elasticity of sleeper
EPDM	Ethylene propylene diene monomer
FEA	Finite element analysis
FFU	Fibre reinforced foamed urethane
GFRP	Glass fibre reinforced polymer
SC	Synthetic composite
MOE	Modulus of elasticity
I	Second moment of Inertia
k	Track stiffness

k_b	Ballast stiffness
k_p	Rail pad stiffness
k_s	Sleeper stiffness
k_{sb}	Subgrade stiffness
LVDT	Linear variable differential transformer
M_c	Bending moment at centre of sleeper
M_R	Bending moment at rail seat of sleeper
QR	Queensland Rail
R	Stress ratio
RS	Rail seat
RSL	Rail seat load
S	Sleeper spacing
UHMWPE	Ultra-high-molecular-weight polyethylene
USP	Under sleeper pad

CHAPTER 1

INTRODUCTION

1.1 Background and motivation

Railway sleepers are one of the most important components of a railway track. They are the beams that transfer train loads onto the ballast and hold and maintain track gauges as shown in Figure 1 (Esveld 2001). Hardwood timber has been the material of choice for railway sleepers for more than 150 years due to its excellent mechanical properties and easiness of handling (Manalo et al. 2010). The major drawback of timber sleepers is their frequent maintenance and replacement due to biological and mechanical deteriorations over time requiring millions of dollars annually for rail track maintenance. In the United States alone, around 20 million new timber sleepers are purchased and installed every year to replace deteriorated timber sleepers (Smith 2019; TieTek 2019a). In the UK and India, the track maintenance cost during 2016–2017 was \$775 million and \$2.08 billion, respectively (Sasidharan, Burrow & Ghataora 2020). It costs \$37500–125000 /km per year to maintain the European railway tracks (Giunta, Bressi & D'Angelo 2018) while in Australia, the railway industry spends 25–35% of the total operational cost for maintaining the railway networks (Senaratne et al. 2020). Recycling and reusing the old timber sleepers are also environmental issues because of the preservative chemicals (creosote) originally used to protect the timber sleepers. This problem has motivated many railway industries to seek alternative materials to replace traditional timber railway sleepers.

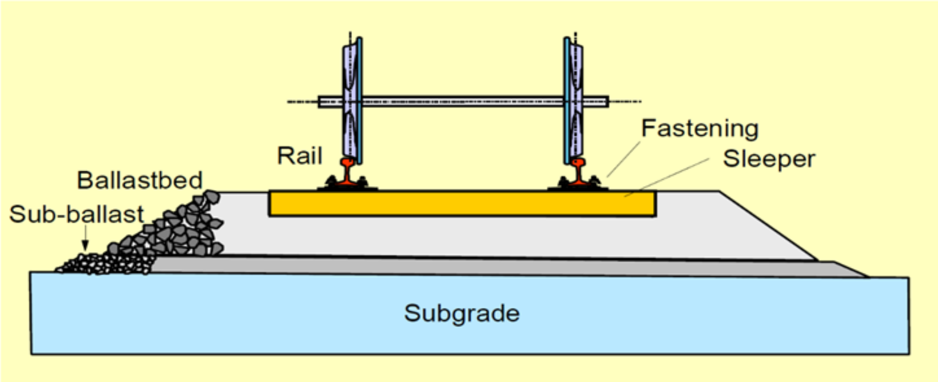

Figure 1.1. Railway track structure (Esveld 2001)

In the last decade, several technologies have been introduced as alternatives to timber sleepers including plastic sleepers (Lankhorst Rail 2019), Fibre Reinforced Foamed Urethane (FFU) (Koller 2015), and Fibre Reinforced Polymer (FRP) (Manalo, A. et al. 2010), and among others. Despite their promising and innovative designs, the market uptake of these sleeper technologies is rather slow due to the limited understanding of their mechanical properties and long-term in-track performance data. A review of available alternatives revealed that the bending stiffness of alternative sleeper materials, a dominant composite material property, varies significantly, ranging from 1.2 GPa (Lampo, Nosker & Sullivan 2000) to 8.1 GPa (Ming 2013). On the contrary, the stiffness of hardwood timber sleepers could be as high as 16 GPa (Silva et al. 2017). As the design of composite materials is usually governed by stiffness rather than strength, it is important to understand how stiffness affects the behaviour of sleeper materials. However, the effect of sleeper's stiffness has not been considered in the available design methods nor in the evaluation of their structural performance.

A few studies investigated the effect of varying bending stiffness on the behaviour of alternative composite sleepers. The results of a numerical investigation indicated a change in the modulus of elasticity (MOE) of turnout railway sleepers from 1 GPa to 10 GPa would increase the bending moment by 75% (Manalo et al. 2012). Analytical investigations of sleepers with different stiffness revealed that deflection and bending moment are sensitive to change in the MOE with the sleepers with lower values of MOE having a greater effect (Shokrieh & Rahmat 2007). It was shown that rail seat loads would reduce by 20% while the deflection increases by 214% for polymer sleepers compared to concrete sleepers (Belkom 2020). These studies however lack validation from experiments where the real sleepers are tested on ballast (realistic condition). Moreover, the effect of varying compression modulus on the behaviour of railway tracks is completely missing in the literature. The compression properties of alternative sleepers are important as the rail seat areas are under very high compression stress due to rail loading. The overall static behaviour of composite sleepers against existing timber sleepers has not been understood in detail. As composite railway sleepers are designed to replace timber sleepers, it is important to understand on how their behaviour varies from that of timber sleepers and what would be the effect of their different mechanical properties on the behaviour of a railway track.

The fatigue behaviour of alternative sleeper materials is only reported in a few studies with most of the published research being on prestressed concrete sleepers. It has been shown that the addition of 0.5% steel fibre reinforcement to prestressed concrete sleepers extends its fatigue life by at least 200% (Parvez & Foster 2017). It has also been proven that the material properties, manufacturing quality, and the density of the train traffic affect the fatigue life of prestressed concrete sleepers (You & Kaewunruen 2019). In relation to new composite alternative sleepers, the post fatigue behaviour of glue laminate timber showed that their performance is comparable to solid timber sleepers (Bhkari et al. 2016a). On the other hand, FFU sleepers will have 25% higher settlement in a long run than concrete sleepers (Ferro, Harkness & Le Pen 2020). Different to plastic sleepers, the fatigue performance of FFU sleepers is not affected by temperature variations (Koller 2015). Moreover, the in-situ observation of recycled plastic sleepers indicated that cracking could happen within the first 15 years of their track installations (McHenry, Gao & Billargeon 2018). These studies have shown that the fatigue behaviour of composite sleepers is different from one to another. Similarly, recent studies highlighted that the behaviour of most composite materials depends on the loading conditions. For example, dynamic mechanical analysis (DMA) showed that the MOE of the polymeric sleepers can vary between 1.5 GPa and 2.7 GPa depending on the procedure they are tested, i.e. high modulus at low temperature or high frequency (Amjadi & Fatemi 2020; Zhao, Gao & Li 2021). Therefore, the results of one study cannot be correlated to another due to different testing conditions. What makes this more challenging is the scarcity of long-term research on the fatigue resistance of composite sleepers. Accordingly, there is a need to comprehensively evaluate the fatigue behaviour of alternative sleeper materials under similar testing conditions so that a direct and scientific comparison is obtained. Detailed knowledge on the fatigue resistance of composite sleepers is essential since railway sleepers are subject to millions of load cycles (wheel loads) during their service life. This would also provide more certainty to track owners to facilitate the adoption of the new alternative sleepers if proven safe under fatigue resistance evaluation tests.

This thesis investigates the static and fatigue behaviour of different composite railway sleepers with a focus on the effect of material properties on railway track behaviour. The static behaviour of a railway track supported by different sleeper technologies was studied using the ballast box simulation method. The effect of varying bending and compression modulus on the overall bending profile, rail seat deflection and decompression were investigated with the aid of the Digital Image Correlation (DIC) technique. The Finite Element Analysis (FEA) method supported by Beam on Elastic Foundation (BOEF) design method was implemented and validated by the experimental results. The findings of the aforementioned study revealed the limitations of the existing sleeper testing standards which motivated the development of a novel five-point bending test method. The development and validation of this new test method under the static behaviour of composite sleepers were presented in detail in this thesis. Numerical and analytical methods were then established to describe the bending moment at the critical location of the sleepers (i.e., rail seat and centre) under the five-point bending test configuration. Finally, the fatigue resistance of composite sleepers was studied using full-scale specimens and correlated with small-scale materials tests through the fatigue degradation factors. The findings of this thesis broaden the knowledge of the static and fatigue behaviour of composite sleepers for their effective design and application in the railway track. The new test methods developed would also provide an accurate evaluation method to track owners and sleeper manufacturers in the optimal design and development of timber alternative composite sleepers.

1.2 Objectives

This study aims to investigate the static and fatigue behaviours of composite railway sleepers, with the aim of comparatively evaluating their structural performance and determining how the difference in their material properties affects their responses to railway load through extensive experimental and analytical works. To achieve this objective, the following specific objectives are considered:

1. To perform a thorough literature review and identify gaps in the literature.
2. Methodology and analysis: to address the gaps identified through the literature review which includes:
    a) To evaluate the effects of bending and compression modulus on the behaviour of railway sleepers supported by ballast;
    b) To develop a new bending test method for composite sleepers and to evaluate the static behaviour of timber alternative composite sleepers under this test method;
    c) To examine and analyse the static failure behaviour of composite sleepers and its effect on railway track performance; and
    d) To evaluate the fatigue behaviour of composite railway sleepers and predict the long-term degradation of different composite sleepers.
3. To provide recommendations and conclusions based on the main findings of 2.

1.3 Study limitations

This thesis studied the static and fatigue behaviour of timber and its composite replacements, i.e., low-profile concrete, synthetic composite, and plastic sleepers. These sleeper types were selected based on their availability and as the commonly used alternatives in the market. Their mechanical properties, especially the bending and compression moduli as reported throughout this study, might be different from one manufacturer to another due to different reinforcement and mix designs. However, the types of the materials such as reinforcements and base mix materials are reported in each study conducted for validation and repetition of the test results.

The results obtained in this thesis are limited to the test conditions implemented. For example, manual ballast tamping in the laboratory as compared to the automated method in railway tracks. Notwithstanding, ballast settlement and stability checks were performed to ensure adequate tamping. Moreover, ballast stiffness was scientifically measured using a plate load test and reported for clarity and transparency. Therefore, the results of this thesis, despite its limitations, are reliable and can be correlated to future investigations since all parameters affecting sleeper behaviours are reported.

1.4 Thesis organisation

This thesis comprises 7 chapters as follows:

- **Chapter 1** is the **Introduction** chapter providing background and motivation to the works conducted in the thesis.
- **Chapter 2** provides an extensive **Literature Review** through which state-of-the-art activities in the field are presented and the research gaps are identified.
- **Chapter 3** is the first technical chapter in which the behaviour of timber-alternative railway sleepers was analysed using a ballast box. This chapter address the first literature gap identified in Chapter 2.
- **Chapter 4** is the second technical chapter in which a new testing method called ‘five-point bending’ was developed which addresses the limitations of the existing testing methods identified through the literature review.

- **Chapter 5** is another technical chapter that provides a detailed investigation of the static behaviour of sleepers under the five-point bending test. This chapter also addresses the third literature gap identified in Chapter 2.
- **Chapter 6** is the last technical chapter in which the fatigue behaviour and degradation of various railway sleepers are studied and discussed aiming to address the relevant literature gap mentioned in Chapter 2.
- **Chapter 7** provides a detailed **conclusion** statement highlighting the main findings and contributions of this thesis. New opportunities and future study recommendations are also presented in Chapter 7.

From the works conducted in this thesis, four journal articles are published or are currently under review in high-quality (first quartile) international journals as follows in addition to the papers and posters published and presented in national and international conferences with the Abstracts provided in Appendix B:

Manuscript 1:

Salih, C, Manalo, A, Ferdous, W, Yu, P, Abousnina, R, Heyer, T & Schubel, P 2021, 'Effect of bending and compressive modulus of elasticity on the behaviour of timber-alternative railway sleepers supported by ballast', *Case Studies in Construction Materials,* p. e00597. (Impact Factor: 3.328; SNIP 2.707; Cite Score: 5.1)

DOI: https://doi.org/10.1016/j.cscm.2021.e00597

This manuscript addresses the first objective of this thesis where the effects of bending and compression modulus on the behaviour of railway sleepers were evaluated. In this study, a section of a railway track was simulated in the laboratory using a steel box filled with track ballast. The bending and compression properties of different railway sleepers were evaluated experimentally before testing in the ballast box. Realistic service load in a standard railway track in Queensland was applied on the rail seats through two sections of track rail. Digital Image Correlation (DIC) technique was used to measure the rail seat and full-profile deflections. The results showed that stiff sleepers in bending such as a concrete bend in a U-shaped profile while sleepers softer than timber bend in a W-shaped profile. The effect of varying compression modulus accounts for as high as 10% of the total rail seat settlement. The results from the study provided new comprehensive insight into the actual behaviour of different railway sleepers under similar loading conditions (on ballast), but also highlighted the challenges in this test method. This provided a scientific basis for the design and development of a simpler test method to simulate the behaviour of a railway sleeper in track, which was implemented to evaluate the static and fatigue behaviour of full-scale composite railway sleepers.

Manuscript 2:

Salih, C, Manalo, A, Ferdous, W, Abousnina, R, Yu, P, Heyer, T & Schubel, P 2021, 'Novel Bending Test Method for Polymer Railway Sleeper Materials', *Polymers*, vol. 13, no. 9, p. 1359. (Impact Factor: 4.329; SNIP 1.2; Cite Score: 4.7)

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In this study, a new bending test method known as five-point bending is developed and its suitability for testing of composite sleepers having distinct mechanical properties is assessed. To account for the varying stiffness of the sleepers, different support types at the centre, i.e., steel, neoprene, and ethylene propylene diene monomer (EPDM) rubber was considered. The bending profile, shear force, and bending moments at the rail seat and the centre was numerically studied for the five-point bending and are compared to that of the sleeper on ballast using beam on elastic foundation (BOEF). Experimental tests are carried out on the different support types and are correlated to the numerical results. Based on the similarity to that of in-situ sleepers (i.e., shear force and bending moment), the most appropriate span configurations and support types were selected. It was found that neoprene rubber at the centre with a minimum shear span of 300mm (rail seat to the external support) can reliably predict the behaviour of most composites. Finally, the analytical equations of the bending moments at the rail seat and centre of the sleepers were developed with and without the middle support settlement due to the rubber support.

Manuscript 3:

Salih, C, Manalo, A, Ferdous, W, Yu, P, Heyer, T & Schubel, P 2022, 'Behaviour of timber-alternative railway sleeper materials under five-point bending', *Construction and Building Materials*, vol. 316, p. 125882. (Impact Factor: 6.141; SNIP 2.483; Cite Score: 8.8)

DOI: https://doi.org/10.1016/j.conbuildmat.2021.125882

This paper investigates the strength and failure mechanisms of different composite railway sleepers. The five-point bending test method developed in Manuscript 2 was used in predicting the in-situ bending behaviour of different sleepers. DIC technique was used to capture the full-field deformation and strain mapping which was validated with strain gauges at the centre of the sleepers. The results showed that the timber sleepers have the highest flexural strength followed by low-profile prestressed concrete (85%), synthetic composite (56%), and lastly engineered plastic (42%). In general, it was found that the capacity of the alternative sleepers is proportional to their bending stiffnesses. Their failure behaviours were found to be different, i.e., flexural crack for timber, longitudinal shear cracks for synthetic sleepers, and permanent deformation for plastic sleepers. It was also discovered that foam-based sleepers suffer from permanent decompression at the rail seat (around 2 mm) due to the softness of the foam. This investigation has provided new insight into the direct comparison of failure mechanisms of alternative sleepers under static loads which is useful in future designs of railway tracks supported by composite sleepers.

Manuscript 4:

Salih, C, Manalo, A, Ferdous, W, Yu, P, Heyer, T & Schubel, P 2022, Fatigue degradation of timber alternative composite railway sleepers, (manuscript is ready for publication)

This paper investigates the fatigue performance and degradation of composite sleepers under service loading conditions. Both small-scale (1:6) and full-scale tests were considered, and a correlation was obtained between the results of the two tests. The five-point bending test method for full-scale, representing actual sleepers, and three-point bending for small-scale sleepers, due to its simplicity and popularity, were followed. Sleepers were tested for up to 1 million service load cycles and their post-fatigue behaviour was studied through a stiffness loss study. The results showed that a similar fatigue failure between the materials and full-scale sleepers can be expected that is flexural crack for timber, longitudinal shear crack for synthetic composite, and permanent deformation for plastic sleepers. The correlation of the testing methods indicated that synthetic composite could degrade 3.2 times and plastic could degrade

7.4 times faster than their full-scale testings. The results obtained about the fatigue performance and correlation factors would guide the design and testing of composite sleepers.

1.5 Summary

Composite railway sleepers provide the advantage of longer service life than timber sleepers due to their resistance to environmental degradation. However, their static and fatigue behaviour is not well understood limiting their adoption and implementation on actual railway tracks. This research experimentally and analytically evaluated the static and fatigue behaviour of the mostly used timber-alternative composite sleepers through materials and full-scale tests. In doing so, the effect of different material properties on the in-situ (on ballast) behaviour, deflection profiles, failure mechanisms, and fatigue degradations were investigated and reported in four technical journal papers, which comprised the technical chapters of this thesis. The results of this thesis enrich the overall understanding of the static and fatigue behaviour of timber-alternative sleepers having different mechanical properties for their effective design, manufacture and implementation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Railway sleeper is a critical component of railway track structures because of their important functions such as transferring the wheel load to the ballast and holding the rails in place (maintaining gauge-width) (Esveld 2001). Due to its excellent mechanical properties and easiness of handling, hardwood timber has been the material of choice for railway sleepers for more than 150 years (Manalo et al. 2010). Timber sleepers, however, has major drawbacks due to their biological and mechanical deteriorations over time resulting in millions of dollars required annually for rail track maintenance and sleeper replacement. In the United States alone, around 20 million new timber sleepers are purchased and installed every year to replace deteriorated timber sleepers (Smith 2019; TieTek 2019). The track maintenance cost in the UK and India during 2016–2017 was $775 million and $2.08 billion respectively (Sasidharan, Burrow & Ghataora 2020), and it costs 37500–125000 $/km per year to maintain the European railway tracks (Giunta, Bressi & D'Angelo 2018) while 25–35% of the total operational cost is for maintaining the railway networks in Australia (Senaratne et al. 2020). This high cost of maintenance has motivated many railway industries to seek alternative materials to overcome this issue. In this review, the traditional railway sleeper materials are reviewed followed by the alternative materials. The mechanical properties, performance, and methods of performance evaluation of alternative sleepers are also reviewed.

2.2 Review of existing sleeper materials

2.2.1 Timber

Timber sleepers have the longest (more than 150 years) use history in railway tracks around the world. This is because timber is adaptable, easy to manufacture and install, and can be fitted with any type of track (Manalo et al. 2010). Their history started with their immediate availability and accessibility to the track owners. To secure and keep the rail system in place, the Camden and Amboy Railroad in New Jersey ordered stone sleepers in 1832. Due to the slow delivery of these stone sleepers, they were replaced by timber sleepers that had been hand-hewn from the trees along the right-of-way (Gallery, Gauntt & Webb 1999). It was soon learnt that the timber sleepers provide a smoother ride and hence they replaced the stone sleepers. Due to the rapid increase of timber sleepers and the need to regularly maintain them, the industry started to treat the wooden sleepers with creosote preservatives by 1865 (Gallery, Gauntt & Webb 1999). Creosote is still the main preservation chemical used which has various environmental concerns and its use has recently been limited in the UK and various European countries (Jordan & Morris 2006; Turner et al. 2018). Harvesting of timber and its negative environmental effects, greenhouse emissions due to manufacturing and delivery, and scarcity of good quality timber are other concerns with the use of timber for railway sleepers (Crawford 2009). Despite timber sleepers having good mechanical properties for railway sleeper applications, they significantly suffer from environmental degradation. Hence, timber sleepers have a relatively short service life which is around 20 years (Manalo et al. 2010). Ferdous and Manalo summarise the main causes of timber sleeper failures (from a survey by Railway of Australia) with fungal decay being the most prominent one as shown in Figure 2.1 (Ferdous & Manalo

2014). From Figure 2.1, it is obvious that not only the timber sleeper appears to have reached its end of structural life, but also it is unable to hold the spikes used to attach the rails through rail pads. This deterioration could be accelerated due to the damages caused by the effects of ballast abrasion and plate-cutting which leads to premature failure and hence high replacement rates of sleepers (Qiao, Davalos & Zipfel 1998). Therefore, these sleepers need immediate replacement to prevent further damage to the track and to prevent catastrophic traffic accidents. This costs the industry millions of dollars annually as track maintenance costs are very high around the world. The track maintenance cost in the UK and India during 2016-2017 was $775 million and $2.08 billion respectively (Sasidharan, Burrow & Ghataora 2020), and it costs 37500 to 125000 $/km per year to maintain the European railway tracks (Giunta, Bressi & D'Angelo 2018) while 25 – 35% of the total operational cost is for maintaining the railway networks in Australia (Senaratne et al. 2020). This high maintenance cost has led the industry to seek alternative cost-competitive materials, such as composite sleepers, that can perform similar to that of timber but with a significantly longer service life.

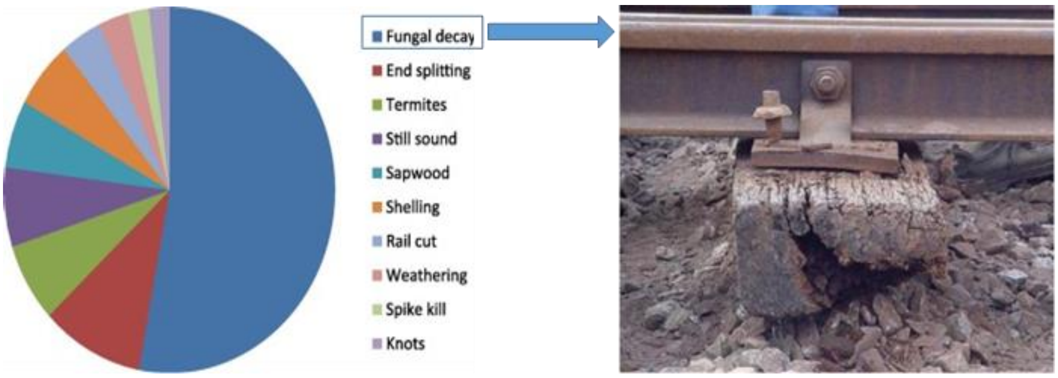

Figure 2.1. Common causes of timber sleeper failures (Ferdous & Manalo 2014).

2.2.2 Steel

Steel sleepers gained popularity and approval as an alternative to timber sleepers in the 1880s because of their lightweight and longer life (50 years) compared to timber sleepers (20 years) (Manalo et al. 2010). It has been reported that steel sleepers, however, settle to a greater amount than timber sleepers and not all sections of the track undergo the same amount of settlement (Mitchell, Baggott & Birks 1987). Considering this issue and knowing that steel is stiffer than timber, rides on steel sleepers are not as smooth as on timber sleepers. Other problems of steel sleepers addressed in the literature are, corrosion, high electrical conductivity, and fatigue cracking in the fastening holes due to moving trains (Manalo et al. 2010; Ferdous et al. 2015). Steel sleepers are only seen suitable for use in tracks having a speed limit of less than 160 km/h and having light traffic. Installation of steel sleepers are more complex than timber ones and it costs more to produce and install a steel sleeper than a timber sleeper. It can be said that steel is a reasonable alternative to timber but not a better or superior one as steel also has limitations.

2.2.3 Concrete

Pre-stressed concrete sleepers have also been used for over 60 years. The compressive strength of pre-stressed concrete sleepers is 50 MPa in Australia, 48.3 MPa in the USA, and more than 50 MPa in India and Iran (Taherinezhad et al. 2013). The pre-stressed tendons are provided to mainly address the flexural weakness of concrete. Similar to steel sleepers, concrete sleepers have a design life of 50 years but they provide a harsher ride than timber sleepers due to their higher stiffness (Mitchell, Baggott & Birks 1987). Concrete sleepers are heavier than their timber equivalents and therefore they are more stable, especially in curves and are also suitable for high-speed lines (Manalo et al. 2010). Their heavyweight could be disadvantageous during installation because of difficulty in handling and the need for special equipment. The main problem with concrete is cracking and the most observed reason is dynamic impact loads (Wang 1996) due to wheel or rail irregularities. This type of cracking has extensively been studied both in the field and in the laboratory (Kaewunruen & Remennikov 2007; Kaewunruen & Remennikov 2008, 2009a, 2009b). The measured impact loads per rail seat could be more than 600 kN while the design static wheel load per rail seat is only 110 kN for a 40-tone axle load (Kaewunruen & Remennikov 2007). Cracking in the centre of the sleepers, however, is the result of the negative bending moment (centre binding) due to moving vehicles (Lutch, Harris & Ahlborn 2009). The most critical problem with concrete sleeper performance in North America is rail seat deterioration (RSD) (Zeman et al. 2010) as shown in Figure 2.2. Although concrete sleepers have longer design life than timber sleepers, they suffer from cracking due to impact loads and rail seat deteriorations. These problems in traditional sleeper materials and their incompatibility with timber have led to the development of alternative polymer-based sleeper materials.

Figure 2.2. Abraded rail seat of a concrete sleeper (Wang 1996)

2.3 Review of polymer composite sleepers

In the past few decades, the motivations and initiatives to replace timber sleepers have overwhelmingly increased due to the continuously increasing demand for higher axle loads and rapid deterioration of the existing sleeper materials (i.e., increased durability with composite sleepers). In the United States, for example, sleepers' spacing has decreased and sleeper cross-sections have increased to accommodate the increasing axle loads (Kerr 1978). To meet the current demands of the growing population, the Australian rail network has experienced increased wheel loads and higher train speeds which in turn accelerates the deterioration of the current rail infrastructure (Mirza et al. 2017). In addition, new legislation in the UK limited the use and reuse of creosoted sleepers (Jordan & Morris 2006) and recent legislation that banned the use of creosote in other European countries have encouraged the railway industries to seek alternatives to timber sleepers (Jordan & Morris 2006; Turner et al. 2018). Hence, various sleeper technologies have been introduced to the market as alternatives to timber sleepers. These technologies are grouped based on recycled plastic sleepers; synthetic composite (continuously reinforced) sleepers, and sleepers under research and development.

2.3.1 Recycled plastic sleepers

In the early 1990s, the plastic lumber industry emerged in the United States and a few plastic recycling manufacturers produced railway sleepers. The service life of these sleepers would considerably be longer than that of timber as plastic is inherently resistant to rot and insects, and has fewer environmental effects than creosote preserved sleepers (Nosker et al. 1998; Lampo et al. 2001). (Grigore 2017) indicated that the use of plastic has increased dramatically in the past 60 years, surpassing the use of aluminium and other metals because of its excellent properties as corrosion resistance and user-friendly design. The introduction of recycled plastic sleepers has been very promising as it helps in reducing the amount of plastic waste from ending up in landfills and it prevents tree logging for sleeper production. Illinois plastic lumber company produced sleepers from high-density polyethylene (HDPE) and installed them on a Chicago-area short line in the early 1990s. According to Lampo et al. (Lampo et al. 2001), this very first trial installation of recycled HDPE sleepers was not completely successful because they did not meet the minimum physical requirements of the track. It was soon realized that incorporating reinforcement elements could improve the behaviour of the recycled HDPE sleepers and hence new types of recycled plastic sleepers emerged that incorporate reinforcement elements such as glass-fibre, rubber particles, minerals, and other reinforcing materials.

Lofty et al. (Lotfy et al. 2016) compared the behaviour of a recycled HDPE sleeper with and without short glass fibres reinforcements (Figure 2.3). They found that the flexural behaviour of HDPE sleepers reinforced with short glass is improved due to the reinforcement effects, fewer impurities and debris, and fewer voids in the newer types of sleepers. These improvements in the quality of the sleepers may also be due to the enhanced manufacturing and recycling technologies. It can be seen from Figure 2.3 that the fibres are homogeneously spread around the perimeter of the sleepers' cross-section, which is the section subject to higher bending stresses. This was achieved by adding a special foaming agent to the matrix that pushes the fibres outwards before curing. This technology has now been adopted, modified, and reinvented by other manufacturers in the US, some European countries, China, and recently in Australia. It is worth noting that the use of plastic sleepers in real-world applications is limited and most of the available literature deals with research and development, or trial installations. A summary of these types of sleepers is provided in Appendix A.

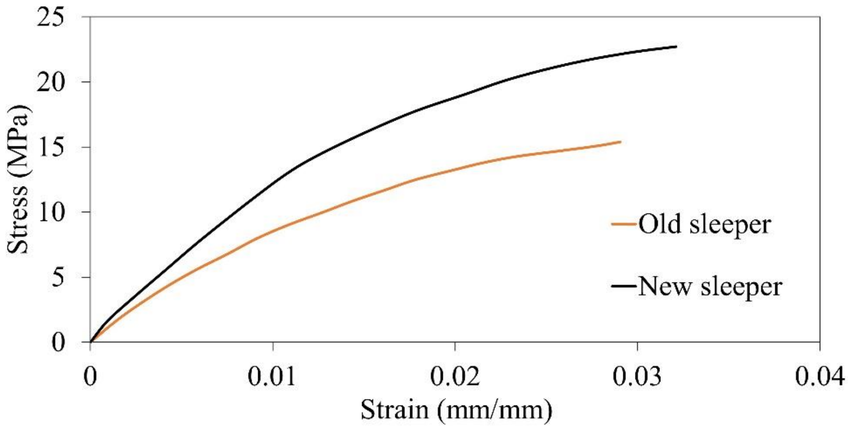

Figure 2.3. The behaviour of reinforced vs unreinforced plastic sleeper; adapted from (Lotfy et al. 2016)

2.3.2 Composite sleepers reinforced with long continuous fibres

Composite sleepers reinforced with long continuous fibres have been developed to closely mimic timber properties while overcoming the issues with the existing sleeper technologies (Ferdous et al. 2015). Sekisui Chemical, a Japanese company, first designed and manufactured a synthetic wood sleeper known as Fibre Reinforced Foamed Urethane (FFU) in the late 1970s (Koller 2009). The early stages of this technology involved the use of a hard type of foamed urethane reinforced with wood or steel. This trial was discontinued because the initial prototypes could not hold the gauge, their strength was not up to the requirements, and their durability was not as expected (Takai, Sato & Sato 2006). FFU sleepers were later modified to use rigid polyurethane foam reinforced with continuous glass fibres and manufactured in a pultrusion process. According to Kaewunruen (Kaewunruen 2014), FFU sleepers have several advantages including weatherability and corrosion resistance, good electrical insulation, stronger and lighter than other polymers, and easy fabrication/assembly. It also has higher damping characteristics than that of concrete which is advantageous for the impact and vibration attenuations. The main disadvantage of this sleeper type is its low shear strength, poor fire resistance, and high price (Ferdous et al. 2015).

Another manufacturer of composite sleepers reinforced with long continuous fibres is from China under the name Sunrui Group. These sleepers were designed and manufactured based on Chinese standard, CJ/T399-2012 - Synthetic Sleepers of Fiber Reinforced Polyurethane Foam (English translated). Until recently, these sleepers have been applied in light rail, metros, mainlines, heavy haul lines, and transoms in more than twenty cities in China and have also been exported to several counties (Sunrui 2019). More recently, AGICO Group Company, which is also China-based, developed synthetic sleepers made from continuous glass fibre reinforced polyurethane foam material similar to the FFU sleepers. However, the minimum available thickness of this sleeper product is 140 mm and the width is 200mm while the FFU sleepers could be tailored according to the client's needs (AGICO 2019; SEKISUI 2019). This could be an issue for the timber alternative for mainline sleepers (standard size) specified by Queensland Rail in Australia as they required that the rail seat depth be only between 110 mm and 125 mm.

The generally high cost of FFU sleepers has motivated an Indonesian company to develop alternative composite sleepers to replace the deteriorated timber sleepers for ballasted and bridge tracks without ballast. The technology is marketed as Polintek Synthetic Sleeper and is made from polymer-based composite reinforced with laminates (Darta Corporation 2019). This product is claimed to cost less than the Sekisui FFU sleepers but has a considerably shorter design life, 20 years compared to 50 years (Darta Corporation 2019; SEKISUI 2019). It appears that this sleeper product is in its early stages of development according to the published data as there are some key characteristics including modulus of elasticity and shear strength that have not been disclosed yet and are still under development. Modulus of elasticity greatly governs the design of composite structures and shear strength directly affects the capacity of the sleeper in the rail seat region to carry and transfer the imposed loads to the ballast safely. These properties are necessary before any sleepers can be installed in an actual railway track even for trial application. A summary of these types of sleepers is provided in Appendix II.

2.3.3 Sleepers under research and development

Many other composite sleepers are still in the research and development stage, which are yet to be introduced to the market or discontinued for various reasons. These types of sleepers are included in this review as they provide useful information to the railway industry for consideration for future development or improvement. Even with the currently approved composite sleeper technologies, it is evident that all these products have first undergone intensive research and development to evaluate the suitability of the concept, to address their limitations, and to demonstrate the overall performance and suitability in supporting a railway track. For example, adding reinforcement fibres to the plastic sleepers (Lampo et al. 2001) and changing the type of reinforcement in the FFU sleepers (Takai, Sato & Sato 2006).

The earliest composite approach of replacing timber sleepers involved the reuse of old timber sleepers in North America in the form of dowel laminated or glue-laminated (glulam) timber. The motivation for this development was the high demand and scarcity of high-quality hardwood timber. The first performance evaluation data of glulam sleepers against solid timber sleepers presented in (Edscorn & Davis 1989) dates back to 1969. Gallery et al. (1999) discuss that glulam sleepers taken out of service over 40 years at a location near Marysville, Washington, showed minimal signs of degradation when compared to solid sawn sleepers of the same age from the same area (Gallery, Gauntt & Webb 1999). They also explained that the strength properties of this type of sleeper could be engineered by changing density, wood species, and the orientation within the laminates. Providing structural test data is therefore difficult due to all of these variations, but it is assumed that the strength properties will be greater than that of conventional timber sleepers.

Research at the Forest Products Laboratory, USA, in 1982 fabricated laminated sleepers from old timber sleepers (Geimer 1982). The target Modulus of Elasticity (MOE) and bending strengths of these sleepers were 7.58 GPa and 31 MPa, respectively, based on the equivalent properties of red oak sleepers containing near-maximum defects allowed by the American railway standards of the time. However, the properties of the full-size laminated sleepers were 21 to 32 percent lower than the expected values due to ineffective flake alignment and variability in the mixing and making processes. This confirms the aforementioned suggestions by Gallery et al. (Gallery, Gauntt & Webb 1999) and this makes it difficult to provide design data and expect the behaviour of glulam sleepers. Research into this type of sleeper is ongoing and some recent studies could be found in (Ticoalu 2008; Carrasco, Passos & Mantilla

2012; Silva et al. 2014; Xiao et al. 2014; Bhkari et al. 2016b). Most recently, it was indicated that four to five discarded sleepers are required to manufacture one glulam sleeper (Carrasco et al. 2019). This means that this approach might not be a commercially viable solution if the manufacturers rely on the old sleeper alone as the raw material.

A similar approach (laminated sandwich), but using new composite materials was implemented by researchers at the University of Southern Queensland (USQ), Toowoomba in collaboration with Austrak Pty Ltd. Manalo et al. (2010) designed, fabricated and trial installed railway turnout sleepers made from fibre composite skins and phenolic foam core glued together to produce the glue-laminated sandwich beams. The experimental results obtained were very promising compared to the AREMA standard and the commercially available composite sleepers, of them the majority are not suitable for turnout applications due to lower mechanical properties. A stiffness of 4 GPa, maximum bending moment of 41.2 kN.m, shear capacity of 507 kN, and minimum screw pullout force of 62 kN were obtained. These mechanical properties meet or surpass the requirements of the AREMA and ISO type C standards.

A different approach by Qiao et al. (Qiao, Davalos & Zipfel 1998) was to design a glass-fibre reinforced polymer (GFRP) reinforced wood sleeper. GFRP was wrapped around wood cores, surfaces coated with resorcinol formaldehyde primer for adequate bonding, in a filament winding process with a thickness of 1.8 mm, warp angle of ± 45^{o}, and fibre volume fraction of 50%. Due to the high cost of full-scale sleeper manufacturing and experimental evaluation, the sleeper samples were scaled down to a length of 914 mm and were tested as simply supported beams under four-point bending. The results of the encapsulated sleepers were compared with the timber sleepers and the results show considerable performance improvements. The maximum deflection, compressive strains, and tensile strains were decreased by 23.8%, 15%, and 17.5% respectively. Also, the ultimate load-carrying capacity was improved by 28% at 12% moisture content and by 70% at saturation moisture content. This, however, might indicate that the samples showed more brittle behaviour than timber samples.

Humphreys et al. (2004) investigated the effect of externally bonded carbon fibre laminates on the strength and stiffness of aged timber sleepers. Two sleepers were treated and statically tested under three-point bending. Figure 2.4 shows the load-deflection curve of the strengthened sleepers and the old timber sleepers. While there is considerable strength improvement, the stiffness increment is marginal. Both bonded sleepers failed to reach the expected load-carrying capacity and failure strain. The researchers related this to the failure mode of the sleepers which was the delamination of the carbon/epoxy laminates, without the surfaces and the laminates themselves being destroyed.

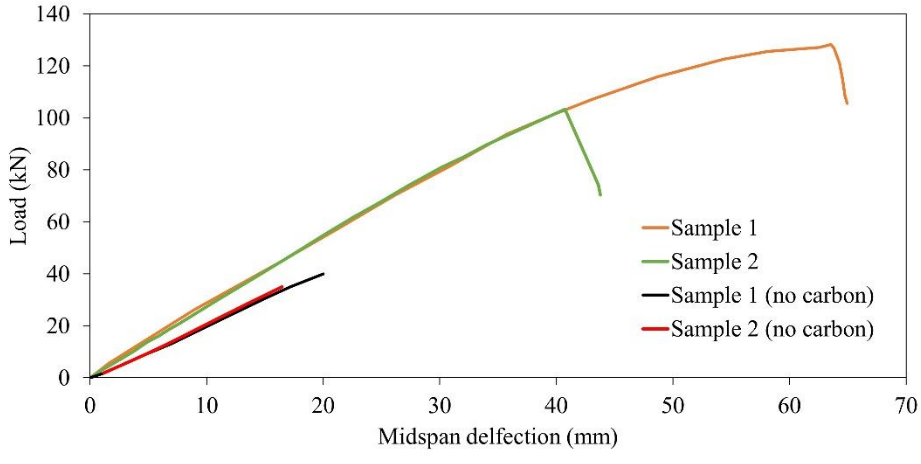

Figure 2.4. Load-deflection curve of laminate/timber and plain sleepers; adapted from (Humphreys & Francey 2004).

Palomo et al. (2007) investigated the feasibility of alkali-activated fly ash concrete for railway sleepers. While no actual product was manufactured, the study concluded that this type of concrete could obtain high strength in a very short curing time with excellent durability properties compared to conventional concrete. Ferdous et al. (Ferdous, Khennane & Kayali 2013) studied the use of a hybrid Fibre Reinforced Polymer (FRP) concrete beam made from rectangular hollow section pultruded profile filled with geopolymer concrete for railway sleepers. The filled beams were tested on a four-point static bending test setup and it was reported that this approach satisfies the minimum requirements of the AREMA standard with some mechanical properties being close to timber sleepers. Hameed et al. (2016) investigated the suitability of rubberised concrete for railway sleepers. They replaced 15% by volume fraction of fine aggregate by crumb rubber and it was found that fatigue failure and impact resistance were improved while there was a reduction in compressive strength. This confirms the findings of a previous study in (Sallam et al. 2008) and one of the findings of recent research in (Kaewunruen et al. 2018) where researchers indicated the addition of rubber (up to 10%) can improve the impact behaviour of concrete with a slight decrease in its compression strength. Meesit and Kaewunruen (20017) discovered that adding crumb rubber to concrete could improve its damping property, an important property of material for railway sleepers to absorb vibration energy, while still satisfying strength requirements. This, however, reduces the compressive strength of the concrete, an important characteristic at the rail seat region of sleepers.

Another research by Carbonloc Pty Ltd, a spin-off company of the USQ, was the development of fibre reinforced polymer sleepers (Van Erp & Mckay 2013). In this approach, the shape of the sleepers was optimized according to the stresses induced when the sleepers are loaded in the track. Accordingly, the material usage was reduced to only 1/3 of the material for a standard size rectangular sleeper. These sleepers could be drilled on-site using the existing tools and can be fitted with standard rail fasteners. Khalil et al. (2017) manufactured and studied composite sleepers made of recycled HDPE, calcium carbonate, and polyester resin reinforced with E-glass fibres. While the modulus of elasticity surpassed the AREMA requirement and was close to hardwood timber for some samples, the flexural strength obtained was between 22.1 MPa and 10.9 MPa, which is much lower than the flexural strength of typical hardwood timber (more than 60 MPa). A summary of these types of sleepers is provided in Appendix III.

2.4 Properties and performance of alternative composite sleepers

The performance of composite sleepers is demonstrated through both laboratory tests and field monitoring and measurements. In fact, all the reviewed standards of composite sleepers in Section 2.4 are established and published after numerous laboratory tests and several years of field demonstrations. It was originally intended to develop alternative sleepers to timber with a longer lifespan and fewer maintenance requirements while safely performing in railway tracks. So, it was highly desirable and expected that the new sleepers would have similar mechanical properties to timber sleepers. This is important because the railway industries often replace failed sleepers only (spot replacement) due to the high cost and impracticality of whole replacement (Manalo et al. 2010). Accordingly, the new sleepers need to be compatible with the existing sleeper system.

The three reviewed groups of new sleeper technologies have distinct mechanical characteristics of their own. The recycled plastic sleepers have the lowest mechanical properties amongst all other sleeper materials (Figures 2.5 and 2.6).

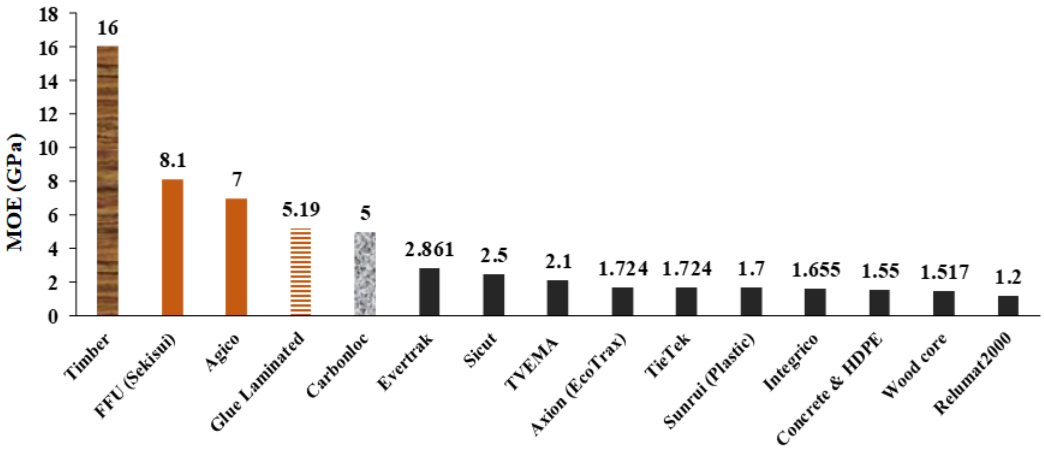

Figure 2.5. MOE of timber-alternative composite sleepers.

The Modulus of Elasticity of this group of sleepers is around 1.2 GPa (Lampo et al. 2001; Dechojarassri 2005; Axion 2019; Integrico 2019; Sicut Enterprises Ltd 2019; TieTek 2019b) while for hardwood timber it is an order of magnitude higher (Humphreys & Francey 2004; Murray 2006; Ticoalu, Aravinthan & Karunasena 2008) with typical Australian hardwood timber being 16 GPa (*AS 1720.1: 2010*). The bending strength of plastic sleepers is also considerably lower than that of timber and other types of sleepers as shown in Figure 2.6.

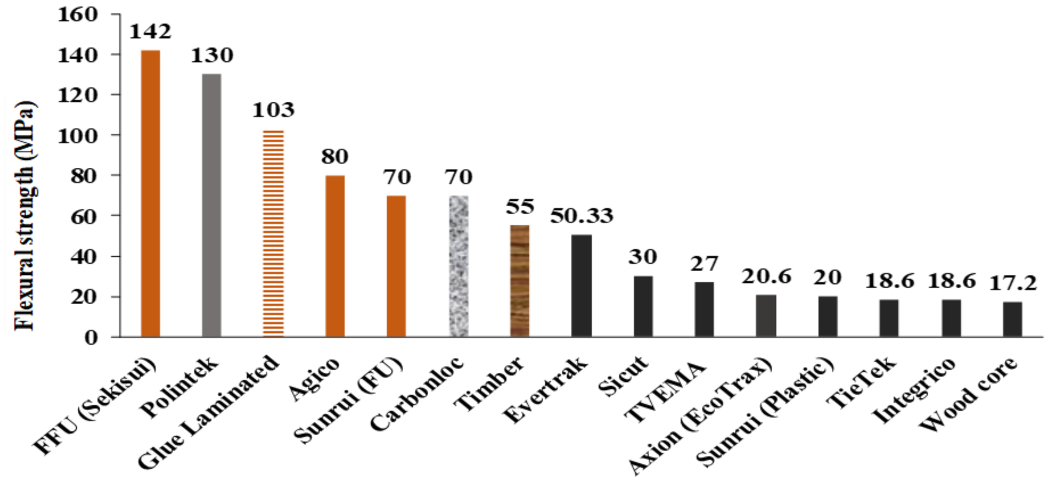

Figure 2.6. Flexural strength of timber-alternative composite sleepers.

It is, however, not very clear on how these differences can affect the performance of these sleepers in a track, especially when interspersed between conventional sleepers due to limited research in this area. Past studies have shown the negative impacts of interspersed steel and concrete sleepers in timber tracks concerning static deflection, percentage of load carried by a single sleeper, ballast damage, rail creep, etc. For example, Birks, Tew and Chitty (1989) proved that steel sleepers settle more into the ballast than adjacent timber sleepers and hence they carry less loads. Kohoutek (1991) also found out that concrete, due to being stiffer than timber, generates less strain in the rails for the same wheel load. This is an indicator that concrete sleepers carry more loads than adjacent timber sleepers. Unfortunately, these types of studies are not available for the new composite railway sleepers. Instead, manufacturers evaluated their sleeper designs according to different standards (laboratory tests) that have some inconsistencies and limitations (full review and limitations are provided in Section 2.4)

Most of the previous laboratory tests lack one important field boundary condition, which is the presence of ballast or applying load directly on the rail seat areas for full-scale sleepers (i.e., testing both rail seats simultaneously). Evidently, rapid deteriorations of the interspersed or the existing sleepers, and hence the track, are possible. Kaewunruen, Lewandrowski and Chamniprasart (2017) employed an FEA tool to show that interspersed tracks deteriorate more than pure timber or concrete tracks. However, there are no reported studies that comparatively evaluate the behaviour of composite sleepers and how they affect the overall performance of a railway track. McHenry et al. (2018), on the other hand, stated that there is no indication that higher MOE reflects on how a plastic sleeper may perform in-track according to the bending tests in the AREMA standard. They claimed that the centre bending test according to AREMA represents worst-case loading scenarios observed during installation, nipping/spiking, and drops during unloading, which are a once-off situation. An increase in the MOR was warranted in the updated AREMA standard (2018) based on these factors rather than the repetitive loads from moving vehicles. Contrary to this claim, field observations have shown that plastic sleepers cracked/failed while in service. The main types of failures are spike hole cracking and centre cracking (Figure 2.7) according to the data collected at the Transportation Technology Center's (TTC) Facility for Accelerated Service Testing (FAST), Pueblo, Colorado over 15 years (McHenry, Gao & Billargeon 2018). Evidently, these sleepers had passed the evaluation tests outlined in the AREMA standards and had successfully passed the installation phase. More investigation is required to conclude on how these issues could be prevented.

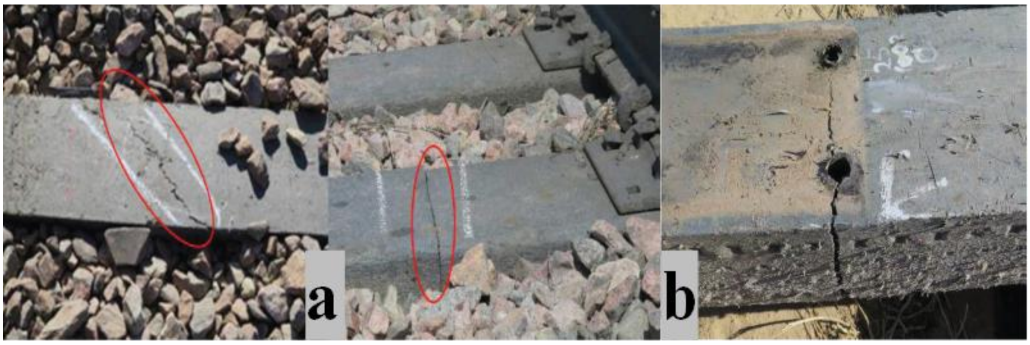

Figure 2.7. Failure modes of plastic sleepers; a) centre cracking; b) spike hole cracking (McHenry, Gao & Billargeon 2018)

The performance data for the second type of composite sleepers are limited to the Sekisui FFU sleepers the other three types are not available in the literature. Some of the first installed FFU sleepers by the Railway Technical Research Institute (RTRI), Japan, were removed in 2011, after 30 years of normal train operations on them, for testing and evaluation by RTRI. They concluded that the mechanical properties degradation were minimal and another 20 years of service life was expected which was practical evidence for the 50-year design life (Koller 2015). However, a recent study indicated that FFU sleepers settle more by 25% than concrete sleepers. There is no direct comparison to timber sleepers even though FFU sleepers were originally designed to replace timber sleepers.

The performance data for the third type of composite sleepers seem to be limited to the results of laboratory tests with little information available on their in-track performance. Since properties of glue-laminated timber could be engineered based on varying density, wood types, and orientation with the laminates, it was assumed that the properties of this type of sleeper are equivalent or higher than timber properties. The visual inspection of glulam sleepers after 40 years in-service reported in (Gallery, Gauntt & Webb 1999) shows that sleepers had minimal and less degradation than similarly aged timber sleepers. These sleepers were treated with preservatives similar to timber, reportedly with creosote. The research presented in (Geimer 1982) however shows that it is difficult to provide design data due to variations in flake alignments in the laminates and the obtained mechanical properties could be much lower than the expected values. The fibre composite glue-laminated sandwich beams considered as railway turnouts by Manalo et al. (2010) showed superior requirements than AREMA requirements. MOE, MOR, and shear strength were 5.01 GPa, 75.5 MPa, and 7.3 MPa respectively compared to 1.17 GPa, 13.8 MPa, and 6.2 MPa of the AREMA standard. In-track performance and the effect of weathering are however not presented.

In 1998, research was conducted on strengthening the old timber sleepers for the first time. The GFRP reinforced wood sleeper approach by Qiao et al. (1998) showed substantial improvements in maximum deflection (by 23.8%), compressive strain (by 15%), tensile strain (by 17.5%), and ultimate load-carrying capacity (by 28%). The externally reinforced wood sleeper with carbon fibre laminates investigated by Humphreys et al. (2004) failed to reach the ultimate expected load carrying capacity due to debonding of the laminates. It can be concluded that the performance data of this type of sleeper cannot be compared due to the diversity of research in this regard.

The above review indicates that direct behaviour comparison of composite sleepers, especially to timber, cannot be established. This is mainly due to limited research in this area in addition to in-consistent evaluation methods followed by different researchers. Moreover, the long-term behaviour of composite sleepers is not well reported in the literature due to their short history and proprietary reasons. As the review presented in this section revealed that the mechanical properties of composite sleepers are distinct, there is a need to comparatively evaluate their static and fatigue behaviours and to determine the effect of varying mechanical properties on their overall performance. This can be achieved in the laboratory provided a suitable evaluation test method is followed.

2.5 Current test methods for alternative sleepers

The flexural behaviour evaluation of alternative sleeper technologies is a fundamental part of understanding sleeper's mechanical properties. It is also one of the required tests for the performance evaluation of a newly developed sleeper design for their acceptance in real-world applications. However, it has been demonstrated that the in-track flexural behaviour of sleepers with significant differences in their elastic moduli are different. For example, the composite sleeper (MOE = 8 GPa) will have a higher deflection when compared to a prestressed concrete sleeper (MOE = 36 GPa) (Ferro, Harkness & Le Pen 2020), and is also different from a typical hardwood timber (Abadi et al. 2019). This has long-term negative effects on the performance of the tracks as stiffer sleepers will attract more loads while lesser stiff sleepers will not carry any load when they are interspersed with timber sleepers (Ferro, Harkness & Le Pen 2020). Hence, accurate evaluation of the flexural behaviour of alternative sleeper materials is essential to manage the tracks appropriately. Accordingly, a few test standards have been published in the last two decades to help facilitate the design and manufacture of alternative sleeper materials. The test methods for evaluating the performance of sleepers suggested in these standards are presented in the succeeding sections.

2.5.1 AREMA –Chapter 30-5 for engineered composite sleepers

After several years of field trials of recycled plastic sleepers in the USA, a subcommittee for engineered composite sleepers was established in 2000 by the American Railway Engineering and Maintenance-of-Way Association (AREMA) (Lampo et al. 2001). The Technical Committee 30 – Ties (sleepers in Australia) of AREMA is responsible for the design specifications and evaluation tests for concrete, timber, and engineered composite sleepers (part 5) (*Track Functional Group* 2020). Engineered composite sleepers include engineered polymer composite (EPC) sleepers and engineered wood product (EWP) sleepers. The emphasis of the standard is on the polymer-based (EPC) sleepers in which the matrix is typically from recycled high-density polyethylene (HDPE) that can be reinforced with long, short, or particle elements. While EPC sleepers shall meet the physical and mechanical properties listed in Table 30.5.1 of the standard, these attributes are for constituting materials and it is highlighted that the performance criteria are not fully developed for EPC sleepers. Accordingly, full-size laboratory tests listed in Part 2 of Chapter 5 are recommended until an improved testing method for alternative sleepers is developed. This is supported by McHenry et al. (2018) wherein they indicated that the static flexural tests in the AREMA standard are not designed to represent actual in-track loading conditions but to simulate the high bending stresses induced during installation, which is a one-off phenomenon (McHenry, Gao & Billargeon 2018). Compliance with AREMA requires bending tests at rail seat positive, rail seat negative, and centre negative bending test. The layout of these tests is shown in Figure 2.8.

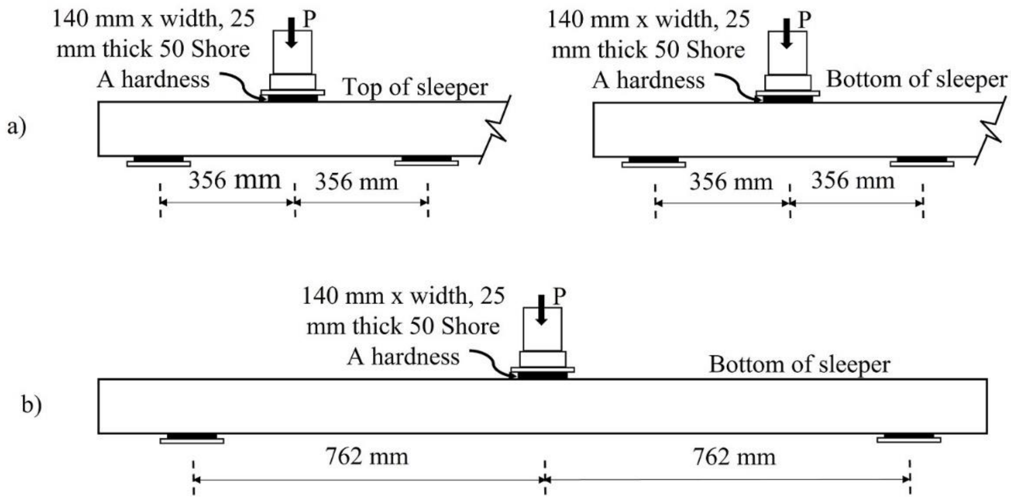

Figure 2.8. Bending tests adapted from AREMA standard (AREMA 2014): a) rail seat positive and negative test; b) centre negative test.

For the rail seat and the centre test, the load is incrementally applied until load (P), where P is the load required to produce the specific bending moments. It is worth mentioning that the magnitude of this load (P) is not clearly stated for EPC sleepers. However, for prestressed concrete monoblock sleepers, P is the load required to produce the bending moments (M) according to Section 4.4.1 of the standard. The P-value for prestressed sleepers corresponds to a four-point configuration (see section 4.9 of the Standard) rather than the three-point configuration shown in Figure 2.8. The procedure for prestressed concrete sleepers states that the load shall be held for at least 3 minutes and determine if any structural cracking occurs. The sleeper is deemed to be passed the test if no structural cracks occurred. This requirement (cracking) is however may not apply to composites and plastics sleepers as they have better deformation capacity than prestressed concrete sleepers due to their relatively lower modulus of elasticity.

2.5.2 JIS E 1203:2007 for synthetic sleepers in Japan

The Japanese Industrial Standard (JIS) JIS E 1203:2007 is developed by the Japanese Railway Civil Engineering Association (JRCEA)/ Japanese Standards Association (JSA) for synthetic sleepers. The standard defines synthetic sleepers as fibre-reinforced foamed urethane, a rigid polyurethane foam that is reinforced with continuous glass fibres. This means that this standard is only applicable for sleepers made of fibre-reinforced foamed urethane, usually continuously moulded into shape. In addition, the performance requirements listed in Table 1 of the JIS E 1203 are based on small scale samples and there are no guidelines for full-scale sleeper evaluation tests in this standard. For example, the bending test is for a sample (cut out from the sleeper or the base material) of 140 mm x 200 mm cross-section and a length of 1400 mm. The specimen shall be tested under a three-point bending setup and must withstand a minimum load of 170 kN for a test span of 1120 mm. This test setup is shown in Figure 2.9. While this suggested test procedure may be applicable for sleepers with a uniform cross-section and material composition, this approach cannot be applied to sleepers with an optimised shape and consisting of different materials along its length and cross-section.

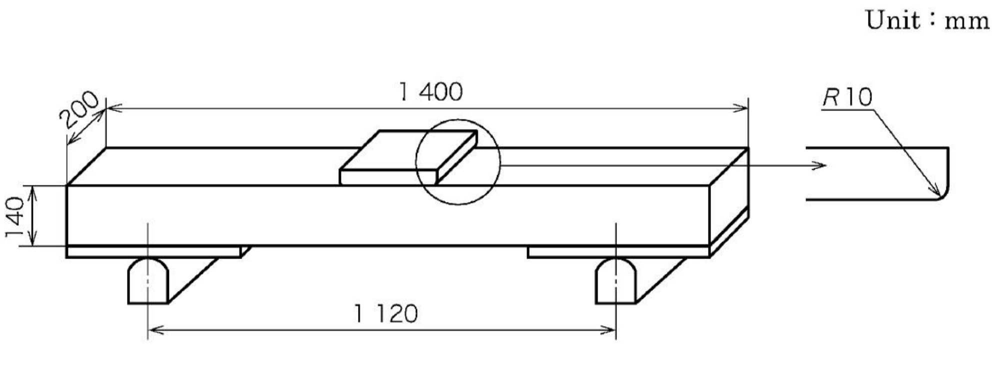

Figure 2.9. Bending test according to JIS 1203:2007 standard (Japanese Industrial Standard 2007)

2.5.3 International Standard ISO 12856-1-3:2014-2018

The International Standard ISO 12856-1-3:2014 (International Organization for Standardization 2014) has specifically been developed for the applications of plastic and reinforced plastic sleepers. The first part of this standard deals with material characterisation (ISO 12856-1:2014), the second part outlines the requirements and procedures for full-size product testing (ISO 12856-2:2018) (International Organization for Standardization 2018), and the last part is on the general requirements of sleepers (ISO/DIS 12856-3: under development) (International Organization for Standardization). The first part of this standard categorised sleeper materials into three types, (1) type A for transoms - axle load of up to 20 t for a speed of 130 km/h and axle load up to 14 t for a speed of 300 km/h, (2) type B - axle load of up to 22.5 t for a speed of 160 km/h, and (3) type C - axle load up to 35 t for a speed of 80 km/h. The dimensions of sleepers made from each material type are also different, type C sleepers are bigger than type B's with type A dimensions being within the two. Consequently, the load applied to the sleeper varies in the rail seat and centre bending tests shown in Figure 2.10. In Figure 2.10, Fr and Fc are the forces applied to the rail seat and the centre of the sleepers respectively to generate specific bending moments. The intensity of the applied force and hence the bending moment depend on the sleeper length and testing span (see Table 3 of the standard). For the rail seat test, the testing span (Lr) also changes depending on the length from the end of the sleeper to the nearest rail seat centre (Lp) (see Table 2 of the standard).

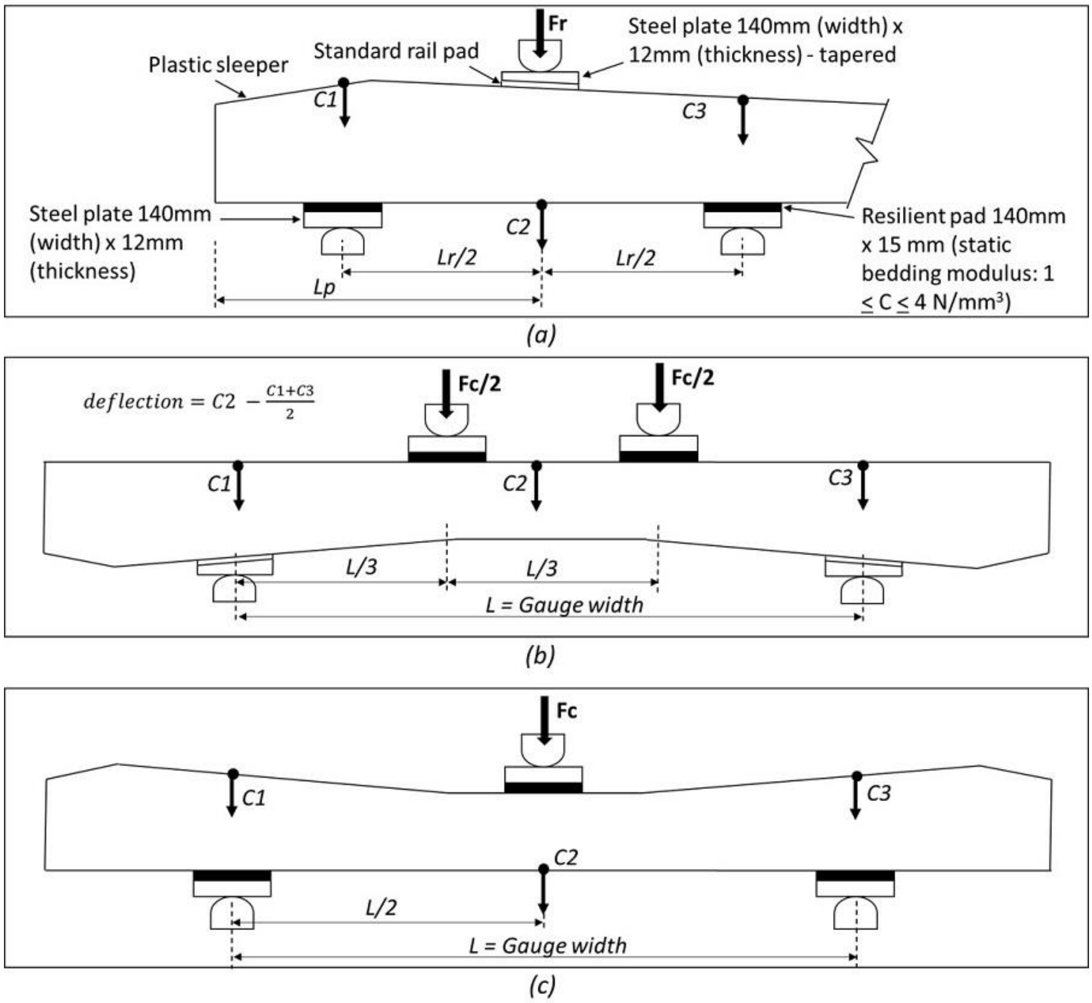

Figure 2.10. Bending tests according to ISO 12856-2:2018 (International Organization for Standardization 2018): a) rail seat positive moment test; b) centre negative moment test; c) centre positive moment test.

2.5.4 AS 1085.22:2020 for alternative sleeper materials in Australia

The Rail Industry Safety and Standards Board (RISSB) in Australia recently developed and published a standard for alternative sleeper materials. The standard contains the requirements for specification, manufacturing, and testing of alternative sleeper materials. Both rail seat positive and centre negative bending tests are required and if the sleeper cross-section is not symmetrical in dimensions and properties, the tests are required to be repeated for the opposite bending directions. In these tests, a vertical load needs to be applied to the desired location at a rate not greater than 25 kN/min and be applied through two neoprene pieces of 25 mm wide x 12 mm thick (Shore A hardness 90) while the sleeper is supported by two neoprene pieces of 50 mm wide x 25 mm thick (Shore A hardness 90) (*AS 1085.22:2020*) as shown in Figure 2.11. The load (P1 – P4 in Figure 2.11) is increased until the desired design moment is obtained, calculated from Table 5.1 of the standard, and the load is held for not less than three minutes. For the rail seat and the centre tests, the sleeper must not crack or break during the tests, and the permanent deflection must be less than 0.5 mm after three minutes from unloading.

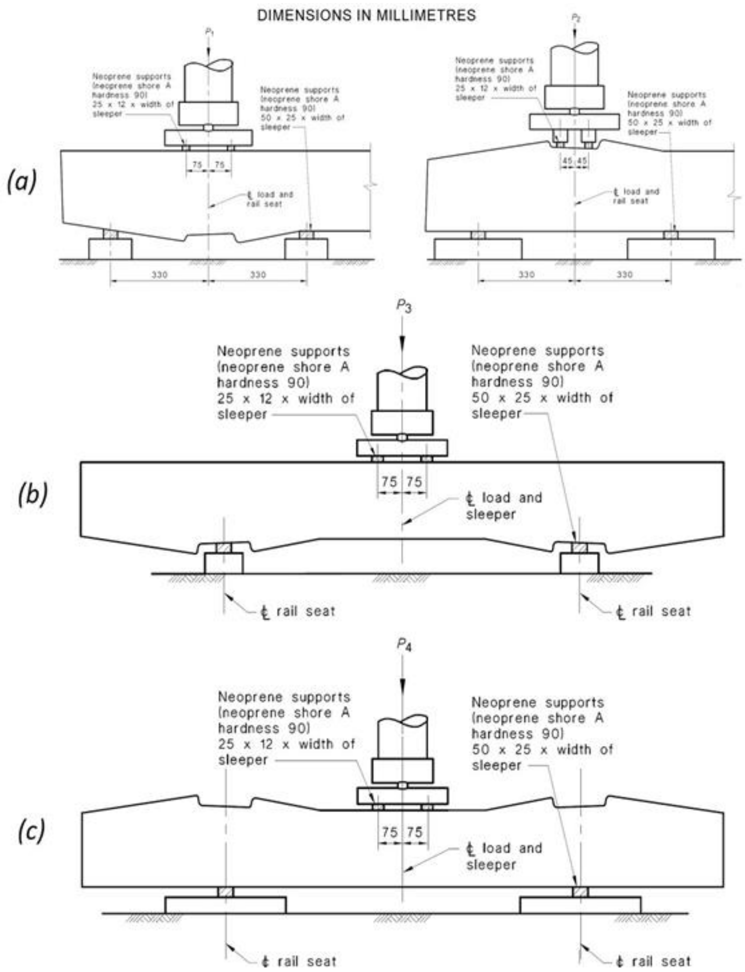

Figure 2.11. Bending tests according to AS 1085.22:2020 (*AS 1085.22:2020*): a) rail seat negative and positive bending test; b) centre negative bending test; c) centre positive bending test.

2.5.5 Evaluation of the existing test standards

The bending tests are requirements for all of the above-mentioned standards to demonstrate the suitability of an alternative sleeper technology. As highlighted through the above sections, these tests are of three-point or four-point bending configurations usually with resilient pads under the loading point and over the supports. Table 1 highlights the main differences among the different standards, focusing on the bending tests.

Table 1. Comparison of different alternative sleeper standards.

	Country of origin	**Sleeper/material type covered**	**MOE requirement (GPA)**	**Full-size bending test**	**Type of resilient support**
AREMA-chapter 30-5	USA	ECP and EWP, but mostly deal with HDPE polymer-based composite products.	1.17	Rail seat positive, rail seat negative, and centre negative.	140 mm x width of sleeper x 25 mm thick (50 Shore A hardness)
JIS E 1203:2007	Japan	Fiber-reinforced foamed urethane	6.0	No full-size testing	-
ISO 12856	International	Plastic and reinforced plastic	1.17 – 6.0	Rail seat positive, centre positive, and centre negative.	140 mm x width of sleeper x 15 mm thick (static bedding modulus: $1 \leq C \leq 4$ N/mm^3)
AS 1085.22	Australia	Not specified	-	Rail seat positive, rail seat negative, centre positive, and centre negative.	Neoprene Shore A hardness 90. Top: 25 mm width x 12 mm thick x width of sleeper Bottom: 50 mm width x 25 mm thick

AREMA standard highlighted that the full test criteria have not been developed for alternative sleepers. Therefore, researchers need to take this into account and be more cautious when designing and evaluating an alternative sleeper according to the relevant standard. For example, material characterisation according to the new Australian standard AS 1085.22 (*AS 1085.22:2020*) is recommended to be carried out based on ISO 12856-1 (International Organization for Standardization 2014) which was specifically developed for plastic sleepers. However, AS 1085.22 (*AS 1085.22:2020*) is intended to cover all alternative sleeper materials that are not timber, concrete, and steel. The same can be seen in the bending test configurations of the AS 1085.22 (*AS 1085.22:2020*) standard for alternative sleepers that are identical to the tests in the AS 1085.14 (Standards Australia 2019) and AREMA-chapter 30-4 (AREMA 2014) which are developed for prestressed concrete sleepers. The tests in both ISO 12856-2 (International Organization for Standardization 2018) and AREMA-chapter 30-5 (AREMA 2014) can be followed in the evaluation of plastic sleepers as both cover plastic sleeper requirements, however, the ISO standard allows the sleepers to be tested with rail pads attached to them while the AREMA does not. Another major difference between the standards is in their test/passing criteria. AREMA (AREMA 2014) does not specify any pass criteria for alternative sleepers; however, prestressed concrete sleepers shall not develop structural cracks when tested according to section 4 of the standard. On the other hand, the Australian AS 1085.22 (*AS 1085.22:2020*) states that the permanent deflection should be less than 0.5 mm after three minutes from unloading in addition to the no crack requirements.

The bending tests according to these standards have limitations regarding how a sleeper on ballast behaves according to BOEF theory. First, these standards evaluate the bending behaviour in two to four separate tests which are not only time and resource-consuming but also do not represent accurately the behaviour of a sleeper on ballast where the sleepers are experiencing both negative and positive bending moments. Second, the available test standards do not consider a rail section or similar-sized steel plates for the application of loads on the rail seats. This can be critical in evaluating if the sleepers will experience any indentation in the rail seat area, especially for alternative designs that omit the use of rail pads. Moreover, the use of resilient pads in the standards may not have a practical reason that reflects the sleeper on ballast behaviour or the necessity according to material characteristics. For example, it might be necessary to use resilient pads for concrete sleepers (as required by AREMA-chapter 30-4 and AS 1085.14 standards) to prevent spalling of concrete and hence preventing cross-sectional loss as shown in Figure 2.12 (b) where the load was applied directly onto the concrete surface (Janeliukstis et al. 2019). It seems that this requirement is carried over to the new alternative standards, according to which the sleepers have much lower moduli of elasticity than that of concrete and hence may not require these elastic pads. A recent study on the improvement of the testing method for plastic sleepers based on the AREMA (AREMA 2014) considers a four-point bending test without any resilient pads as shown in Figure 2.12 (a) (McHenry, Gao & Billargeon 2018). Therefore, the evaluation tests in different standards could be different but they can be followed for similar material types. This might give different results for the bending behaviour sat the rail seats and centre of the sleepers. this is because the alternative sleepers are made of a variety of different materials with different elastic properties. It might be necessary to unify the bending tests by considering appropriate support types and span configurations according to the mechanical properties of the sleeper being tested or the intended track configurations.

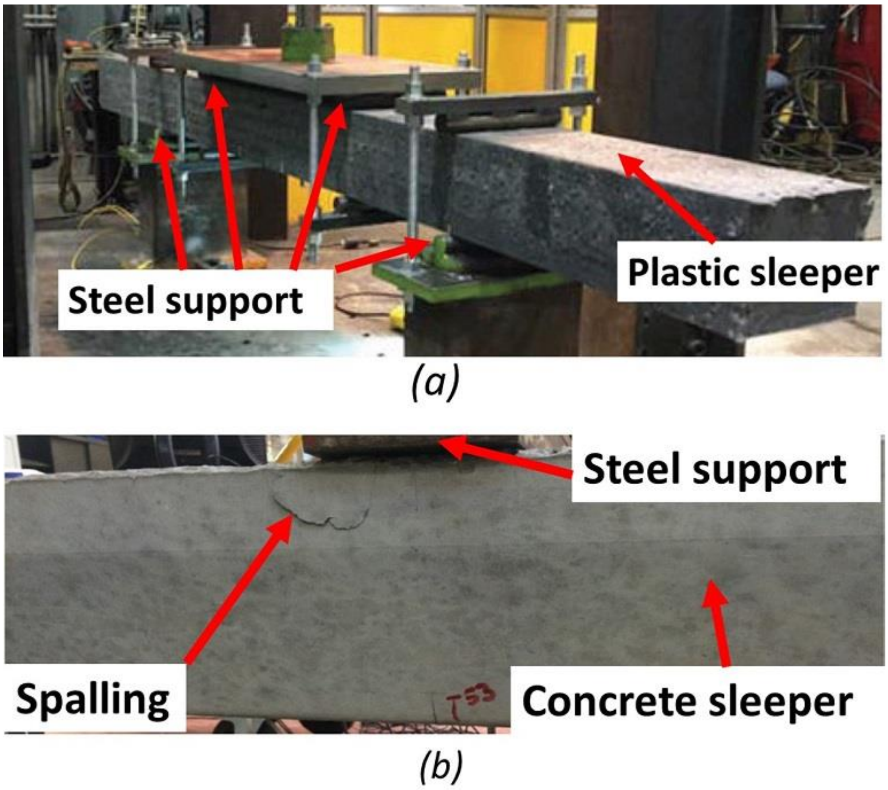

Figure 2.12. a) four-point bending test of a plastic sleeper without resilient pads (McHenry, Gao & Billargeon 2018); b) spalling of the concrete surface under a steel plate (Janeliukstis et al. 2019).

2.6 Research gaps

Many alternative sleepers have been developed to mimic the behaviour of timber sleepers, but their mechanical properties are significantly different from each other and to that of timber sleepers. Unfortunately, there is a limited understanding on the performance of these sleepers and on the behaviour of a railway track supported by these sleeper technologies. In particular, the main research gaps identified from the detailed literature review are as follows:

- There is a limited understanding of the effect of varying bending and compression stiffness on the behaviour of sleepers supported by a ballast.

Previous research only considered the bending stiffness effect but through numerical and theoretical analysis with the compression properties completely ignored. As railway sleepers are under the combined effect of bending and compression, it is important to evaluate their effects simultaneously.

- The test standards of composite sleepers were developed originally based on timber and concrete sleepers. As composite materials have very distinct mechanical properties, these material differences have not reflected on the test configurations of the composite sleepers standards. Therefore, there is a need to develop a new test method that considers the varying mechanical properties of composite sleepers. Moreover, the existing standard test methods do not reflect how sleepers in a track are loaded and hence they do not provide accurate information on how the sleepers behave in real-world applications.
- The failure behaviour and overall structural performance of alternative composite sleepers are not well reported in the literature. It is also not clear how the different designs and materials considered for alternative composite sleepers affect their bending moment capacities and strengths and in comparison to timber.
- There is a lack of understanding on the long-term (fatigue) behaviour of composite railway sleepers based on actual support and loading conditions (under service loading conditions). As railway sleepers are expected to undergo millions of load cycles during their service life, it is imperative to understand the fatigue behaviour of new composite sleepers.

The above research gaps are the main motivations of this work, which are addressed through Chapters 3 to 6.

CHAPTER 3: PAPER 1

Behaviour of timber-alternative railway sleepers supported by a ballast

The literature review in Chapter 2 showed that the alternative railway sleepers have distinct mechanical properties, especially their bending and compressive moduli of elasticity but these material properties are not considered in the design. To understand how these different sleepers behave under this support condition, a section of a railway track was simulated in the laboratory using a ballast box, the significant findings of which are presented in Manuscript 1. Timber sleepers along with three commonly used alternatives, i.e., low-profile prestressed concrete, engineered plastic, and synthetic composite sleepers were considered. Typical ballast (crushed rock) meeting the requirements of AS 2758.7 and Queensland Rail Standard was used under the sleepers while two pieces of rail (61 kg/m) was used as the loading points (rail seats). Three-dimensional Finite Element Analysis (FEA) model was then implemented to validate the typical beam on elastic foundation design method.

The results indicated that the bending and compressive moduli have a significant effect on the overall deflection and bending profiles of the sleepers. However, the results of this study also highlighted the complexity and difficulty in using a ballast box to simulate the behaviour of sleepers in a railway track. A new and simpler test method was therefore proposed, developed, and validated, which is presented in Chapter 4.

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Case study

Effect of bending and compressive modulus of elasticity on the behaviour of timber-alternative railway sleepers supported by ballast

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ABSTRACT

Alternative railway sleeper technologies for replacement of timber are made of materials possessing a wide range of bending and compressive moduli. This poses a great challenge to railway authorities and engineers in designing a railway track supported by different sleeper technologies. This study evaluates the static behaviour of a railway track supported by different alternative railway sleeper technologies, i.e. recycled plastics (1.0 GPa), synthetic composites (7.4 GPa), timber (13.0 GPa), and low profile prestressed concrete sleepers (38.0 GPa), using a ballast box test representing a single sleeper section of a track. The deflection profiles along the length of the sleepers under a full service load was captured using Digital Image Correlation technique combined with the strain measurements at the top-centre of the sleepers. Three-dimensional Finite Element simulation of the sleepers' behaviour based on the Beam on Elastic Foundation theory was implemented and validated by the experimental results. The results show that sleepers with bending modulus of less than 13.0 GPa will have W-shape deflection profile and a high rail seat deflection while sleepers with a bending modulus of 38.0 GPa will show nearly flat behaviour. Local deformation at the rail seat region accounts for almost 6 % of the total deflection of sleepers on a low subgrade modulus and as high as 10 % for high subgrade modulus. The results of this study provide a better insight into the in-track behaviour of alternative sleeper technologies having distinctive material properties.

1. Introduction

Sleepers are one of the most important elements of a railway track [1]. The main functions of a sleeper are to transfer loads to the ballast and to hold and maintain track gauges. Timber has been the material of choice for railway sleepers for more than 150 years due to their ease of handling and installation, and excellent mechanical properties [2]. The major drawback of timber sleepers, however, is their short lifespan due to environmental deteriorations resulting in a high cost of maintenance and replacement [3]. The track maintenance cost in the UK and India during 2016–2017 was $775 million and $2.08 billion respectively [4], and it costs 37500–125000 $/km per year to maintain the European railway tracks [5] while 25–35% of the total operational cost is for

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maintaining the railway networks in Australia [6]. This high maintenance cost has led the industry to seek alternative cost-competitive materials, such as composite sleepers, that can perform similar to that of timber but with significantly longer service life.

In the last two decades, different alternative sleeper technologies have been introduced in the market for replacing deteriorating timber sleepers in existing railway tracks. These sleeper technologies include recycled plastics, synthetic composite (SC), and low profile prestressed concrete sleepers, which are made of materials possessing distinct physical and mechanical properties. A review of the literature indicated that the flexural modulus of elasticity (denoted as MOE or E_1) of available timber-replacement sleeper technologies vary significantly as shown in Fig. 1. Other researchers studied different aspects of these sleepers types such as the in-situ dynamic behaviour of SC sleepers [7], the deflection of concrete sleepers under different ballast conditions [8], and the effect of temperature variations on the behaviour of plastic sleepers [9]. A comparison of these studies indicates that the behaviour of these alternative sleepers is significantly different from each other that could be because of their stiffness variations. For example, Manalo et al. [10] found that the change in MOE of turnout railway sleepers from 1 GPa to 10 GPa would increase the bending moment by 75 %. Shokrieh and Rahmat [11] highlighted that deflection and bending moment are sensitive to change in the MOE of sleepers with lower values of MOE having a greater effect. It was shown that rail seat loads would reduce by 20 % while the deflection increases by 214 % for polymer sleepers compared to concrete sleepers [12]. These studies are however only conducted using numerical and analytical methods, and their results are not directly comparable because of the different assumptions and loading conditions used in their analyses. This limitation can be addressed by experimentally investigating the behaviour of different sleeper technologies with a range of MOE shown in Fig. 1 under similar support and loading conditions so that the obtained data is comparable and to reach a meaningful and relative conclusion that will help in the effective, safe and reliable design of a railway track.

The rail seat load depends on the track stiffness, rail deflection, and sleeper spacing [13,14]. The track or rail support modulus (k) is an important parameter that is often evaluated in the design of sleepers because it has direct implications on the rail deflections and hence on the load distribution of the sleepers. Kerr [15] indicated that both the sleeper bending and compressibility in the rail seat affect the track stiffness. The determination of k value is complex and traditionally involves the use of a loading vehicle because track modulus changes from one place to another along the track [15]. Conventionally, k is found through the relationships of the rail stiffness, rail deflection, and applied load. This means that other important parameters such as rail pad stiffness (if there is any), sleeper material type, ballast and sub-ballast stiffness, and subgrade stiffness are collectively incorporated in the traditional methods of k measurement. Recent developments in railway engineering also add new parameters such as under sleeper pad and ballast mat. A few researchers attempted to evaluate the contribution of each parameter to the rail support modulus individually. Studies on the effect of rail pad stiffness [16–18], the effect of under sleeper pads (USPs) [19,20], and the effect of ballast condition [21,22] found that each of these elements affects the performance of a railway track. Thompson et al. [17] indicated that softer rail pads attenuate track forces more than the stiffer pads, and Gräbe et al. [20] found that the USPs reduce the stress on the ballast while it increases the contact area in the sleeper-ballast interface. Nevertheless, the effect of sleeper material type on the behaviour of ballasted railway tracks has been investigated on a very limited scale. Shokrieh and Rahmat [11] studied the effect of bending MOE on the behaviour of railways sleepers through analytical investigations. The results of their theoretical study showed that the change in MOE greatly affects the behaviour of sleepers. The review of previous research indicated that the simultaneous effect of varying bending and compression moduli on the behaviour railway sleepers have not been studied in detail. There is clearly a lack of experimental investigation of different sleeper types (different materials) on the same testing configurations (ballast box for example). Moreover, the contribution to the change in rail seat deflection due to variation in the compressive modulus of sleepers is still not addressed in the literature, which can be evaluated experimentally using sleepers having different compression properties.

The evaluation tests according to the alternative sleeper materials standards [23–26] are based on rail seat and centre bending tests that do not accurately represent sleepers in-track since the sleepers are supported by the ballast. It was shown that the deflection due to bending evaluated according to the existing standards do not represent how a sleeper bends in the field [27] and the current test methods do not represent the behaviour of sleeper on ballast [28]. Some researchers evaluated the behaviour of railway sleepers using the ballast box test including the static deflection behaviour of Brazillian glulam wood sleepers [29], the effect of under-sleeper pads on the behaviour of tracks [19,20,30], simulation of flooded ballast [31], and ballast performance under cyclic loadings [32]. While these

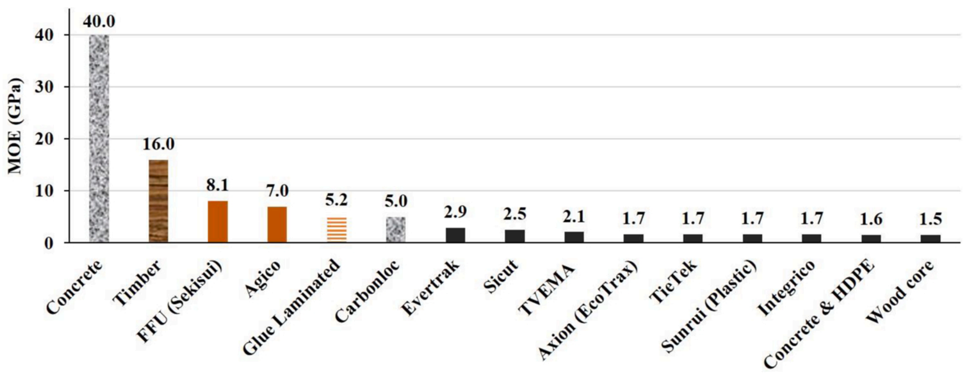


Fig. 1. MOE of different sleeper technologies [8,34–42].

studies employed tests under different conditions, they all showed that the ballast box is a suitable test method of mimicking actual railway tracks for the evaluation purpose. However, there was no attempt to evaluate how the type of sleeper materials affects the behaviour of a railway track. Moreover, the findings from these reported works cannot be adopted for Australian railway tracks due to the difference in gauge width. Experimental research about the full profile bending shape of sleepers is limited. The only reported works were by Carrasco et al. [29] wherein they used only five displacement transducers (TD) to capture the W-shaped profile of only a glulam sleeper and by Ferro et al. [33] wherein they used Linear Variable Differential Transformers (LVDTs) at five different locations of their sleeper samples. A more precise deflection profile of sleepers can be captured using non-contact Digital Image Correlation (DIC) technology, making it possible to track the whole sleeper settlement. Hence, there is a need to study the behaviour of different sleeper types (with a range of MOEs) supported by ballast representing an Australian track configuration.

This study investigates the effect of bending and compressive modulus of different timber alternative sleeper technologies on the behaviour of railway track using a ballast box. This investigation considers four sleeper types, namely hardwood timber, recycled plastic, synthetic composite and low-profile prestressed concrete (referred to as concrete hereafter) sleepers. The bending and compressive moduli of these sleepers were measured experimentally and their effect on track deflection behaviour was demonstrated through a ballast box test simulating narrow-gauge track static loading condition. The Digital Image Correlation technique (DIC) was used to capture the full deflection profile of the sleepers and Finite Element Analysis (FEA) of sleepers on ballast was also carried out to validate the experimental work. The results of this work are anticipated to broaden the view on the deflection behaviour and its effect on railway tracks for timber alternative sleepers made of different materials.

2. Experimental program

2.1. Evaluation of bending and compressive moduli of railway sleepers

All the sleeper technologies considered are designed following the requirements for narrow-gauge track configuration in Queensland, Australia where typical gauge width is 1067 mm (rail centres 1130 mm apart) and sleepers are 2125 mm–2175 mm long [43]. The hardwood timber sleeper was obtained from a local sawmill in Queensland and was identified as Grade 1 other species (spotted gum species) according to the Queensland Rail's material supply specification CT.169 [44]. The concrete sleeper is a low-profile prestressed concrete sleeper designed according to the rational design method [45] and uses concrete with a compressive strength of 60 MPa (28 days) and reinforced with 20 tendons (low relaxed with chevron pattern indentations) of 5.03 mm diameter each. The synthetic composite is a glass fibre-reinforced (continuous in the longitudinal direction) polyurethane foam type sleeper while the plastic sleeper is made out of post-consumer recycled plastics.

The flexural modulus of the sleepers was determined under a three-point bending by following the test method described in ASTM D790:2017 [46,47] and EN 408:2003 standards [46,47]. Full-scale samples were tested non-destructively up to 75 kN load on a test span of 1200 mm with a shear span-to-depth ratio between 5.2 and 4.4. The flexural modulus was calculated using the classical deflection equation (Eq. (1)) [48]. In Eq. (1), E_1 is the longitudinal bending modulus, P is the applied load, L is the test span, I is the second moment of area, and δ is the deflection measured at the centre.

$$E_1 = \frac{PL^3}{48I\delta} \tag{1}$$

The compressive modulus E_2 (also known as perpendicular to the grain for timber and similar materials; and, sometimes denoted as $E_{c,90}$) was determined using a local compression test following the EN 408:2003 standard [48]. This approach was also followed by other researchers when evaluating the mechanical performance of timber in the compression perpendicular to grain [49]. In this test, the rail seat was loaded up to 75 kN using a 150 mm wide by 25 mm thick steel plate and was fully supported at the bottom as shown in Fig. 2. The compression modulus of only timber, SC and plastic sleepers was evaluated as prestressed concrete has a high compression modulus and hence rail seat compression is not a concern for this type of sleepers. Besides, the compression modulus of the concrete

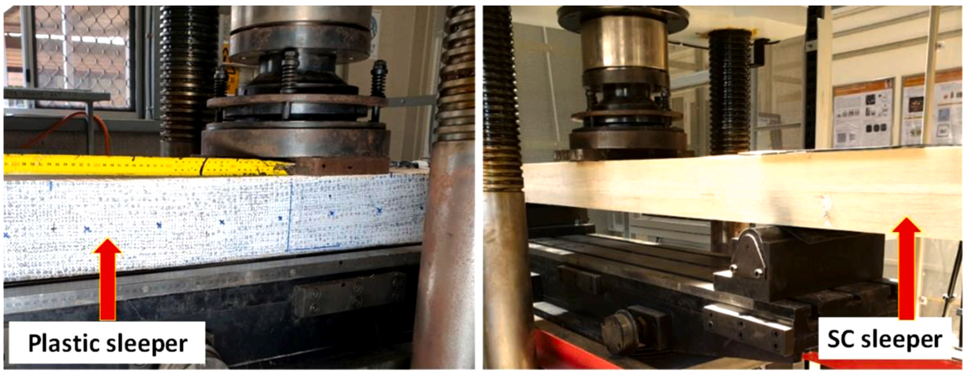


Fig. 2. Local compression (left) and flexural bending (right) test setup.

sleeper can be calculated directly following the methods described in Section 3.1.2 of AS3600:2018 standard [50] ($E_2 = 37{,}400$ MPa). Eq. (2) was used to determine the E_2 of the sleepers [48]. In Eq. (2), m is the slope of the load-displacement curve, h is the thickness of the sleeper, and A is the loaded area (considering the width of the loading plate and the sleeper).

$$E_2 = \frac{m\,h}{A} \tag{2}$$

Fig. 2 shows the actual test setup for the flexural bending and local compression tests while Fig. 3 shows the load-displacement behaviour of the sleepers tested under compression. Table 1 summarises the important properties of sleepers used in this research.

2.2. Ballast box, properties, and tamping

Several researchers have used a ballast box to simulate the behaviour of railway sleepers in actual field conditions. For this purpose, a steel box of 400 mm in depth, 1000 mm in width and 3000 mm in length was built to simulate a single sleeper layout of a railway track. The 1000 mm width of the ballast box ensures that the ballast coverage of at least one actual sleeper can be obtained because sleepers in the narrow-gauge tracks in Queensland are usually 685 mm apart. This extra width of ballast reduces the effect of confining of the ballast because ballast in actual tracks is continuous whereas in the laboratory it is confined within the box. Some researchers considered a soft layer between the wall of the box and the ballast [22,30,51,52] but, these softer layers are not usually a reflection of in-situ ballast pressure perpendicular to the rail. Different elastic layers (rubber and plywood for example) between the ballast and the bottom of the box were utilized by different researchers to represent the softness of the subgrade [19,22,51–53]. The effect of the elasticity of the subgrade is however very small [53] that can be neglected. In the current study, all the sleepers were tested in the same ballast and support condition to capture the effect of the sleeper material type. Notwithstanding, the effect of ballast disturbance was considered (if there is any form one test to another) by measuring the ballast stiffness using a plate load test and carrying out at least 3 tests for each type of sleeper; the results of which are discussed in the next section.

The ballast provides an elastic layer that supports the sleepers and helps transfer the wheel load from the rails and the sleepers to the subgrade The type of ballast used in this study is crushed rock from quarries usually used in QR tracks with specifications meeting the Australian Standard AS 2758.7 and the QR requirements [54]. The aggregates have a maximum particle size of 63 mm (graded) and have a size distribution shown in Table 2.

Ballast depths of 150–500 mm were reported in the literature for Australian railway tracks [43,55] with QR limiting the maximum depth to 600 mm due to track instability [56]. In this research, a ballast depth of 300 mm (measured from the bottom of the sleeper) was considered. A ballast depth of 300 mm was also considered in some track simulations [22,29] showing the acceptability of this ballast depth in supporting a railway track. The ballast was laid in two layers of 150 mm with manual tamping using a 10 kg sledgehammer and a 400 mm long piece of a timber sleeper as shown in Fig. 4. After levelling of each layer, the hammer was freely dropped (from 2.5 m height) onto the timber piece resting on the ballast for four times; and repeating the process until the whole surface was covered. The sleepers were not covered by ballast from the sides to make the deflection measurement at various depths of the sleeper possible. It is assumed that this will not affect the behaviour since the sleepers are only loaded vertically with no lateral loads.

2.3. Evaluation of sleeper support stiffness

Ballast stiffness is one of the parameters of a track stiffness (k) as shown in Eq. (3) [15].

$$k = \frac{1}{1/k_p + 1/k_s + 1/k_b + 1/k_{sb}} \tag{3}$$

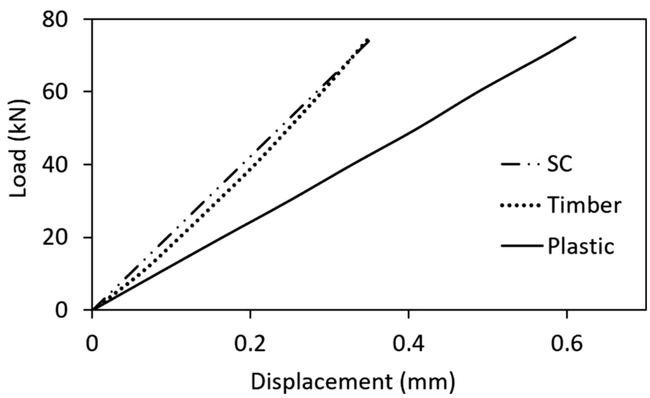


Fig. 3. Load-displacement behaviour of sleeper under local compression test.

Table 1
Sleeper sample properties.

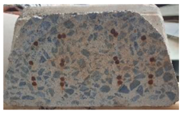
Sleeper type	Cross-section	Length (mm)	I (mm^4)	E_1 (GPa)	E_2 (MPa)
Timber		2130	29150104	13.0	800
Recycled plastic		2050	36621094	10.0	450
Synthetic composite		2120	28389667	7.40	750
Prestressed concrete		2130	48699500	38.0	37400

Table 2
Ballast size distribution and properties [54].

Photo	Sieve size (mm)	% passing	Bulk density (kg/m^3)	Particle density (kg/m^3)
	63.0	100	> 1350 according to AS 1141.4	> 2500 according to AS 1141.4
	53.0	85 to 100		
	37.5	50 to 70		
	26.5	20 to 35		
	19.0	10 to 20		
	13.2	2 to 10		
	9.5	0 to 5		
	4.75	0 to 2		

where k_p is the stiffness of the rail pad (if used), k_s is the stiffness of the sleepers (compressibility at the rail seat and sleeper bending), k_b is the vertical stiffness of the ballast, and k_{sb} is the stiffness the subgrade. Since any change in k changes rail deflection, and hence the distribution of sleeper loads, it is important to quantify the k parameters to understand the precise effect of each parameter. To obtain the pure effects of the compressive and bending modulus of the sleepers, rail pads have not been considered in this research. This situation can also represent an extreme in-track condition when worn or damaged rail pads do not provide much resilience [57]. In this

(a) (b)

Fig. 4. (a) Ballast tamping using a sledgehammer; (b) Plate load test on the ballast.

study, the sleepers are continuously supported by ballast in a steel box placed on a rigid concrete surface. Therefore, the stiffness of the ballast and subgrade can be combined into one parameter. This is referred to as sleeper support stiffness in this research (it is also called ballast modulus). Accordingly, any change in behaviour (settlement) from one test to another depends on the properties of the sleeper and its support as illustrated in Fig. 5. Hence, evaluation of the support stiffness for each test is important to indicate if there is any contribution from the change in the stiffness of the ballast. The values of the support stiffness were also used for comparison and verification of the sleepers behaviour according to the FEA in Ansys Software [58].

The sleeper support stiffness was evaluated using a plate load test as shown in Fig. 4. A 285 mm diameter steel plate was loaded until a contact pressure of at least 300 kPa was obtained, as also followed by Abadi et al. [52]. The displacement was measured using an LVDT attached to the head of the loading ram. The stiffness of the ballast was calculated from the slope of the pressure-displacement curve using Eq. (4) [32,59]. In Eq. (4), $\sigma_{max} - \sigma_{min}$ is the change in the applied stress, and $\delta_{max} - \delta_{min}$ represents the difference in the maximum and minimum displacement.

$$k_b = \frac{\sigma_{max} - \sigma_{min}}{\delta_{max} - \delta_{min}} \tag{4}$$

The test was carried out four times, i.e. the sleeper support modulus was measured before testing each type of sleeper to ensure consistent results and that any changes in the sleeper behaviour were only affected by changes in the bending and compressive moduli of the sleepers. This approach will also show whether the ballast becomes stiffer due to repetitive loads

2.4. Test of sleepers on ballast

The full profile bending of the sleepers and local compression around the rail seat area was captured by using the Digital Image Correlation (DIC) technique. Previous research has shown that the DIC is a powerful and precise non-contact full-field measurement technique [60,61] capable of accurately measuring submillimeter changes using only one camera [62,63]. In recent years, the use of DIC in the field of railway sleepers has been increased such as the deflection of railway sleepers [64,65], turnout sleepers [66] and the crack width measurement of concrete sleepers [67]. Hence the DIC technique was chosen for this research to not only capture the full profile deflection but also the local compression under the sleepers. These behaviours are very difficult to capture using traditional gauges which also highlights the advantages and novelty of using the DIC for this investigation.

The DIC system came from iMetrum Ltd. based in the UK, comprises an industrial PC, a digital video recording camera, low distortion lens, lighting, and tripods. It uses an advanced recording and data analysing software called the Video Gauge software [68] which uses complex algorithms to recognise changes in the sub-pixel patterns. This means it can measure high-resolution deflections of objects ranging in size from microns to hundreds of meters, depending on the lens selection [69]. The video (a series of images) from the DIC uses 256 shades of grey (0–255) to track changes in the material (displacements, distortions, etc) which means a good level of contrast is needed on the surface to be measured. This was achieved by randomly applying black speckles (the plastic and timber sleepers were painted white to obtain the best contrast) on the side of the sleepers. Black marks were also drawn every 100 mm along the length of the sleepers and at 50 mm intervals around the rail seats to capture full-profile deflection at these points. The use of the DIC enabled deflections to be captured in at least 25 points along the length to obtain a more realistic and accurate bending shape of the sleepers. One strain gauge was also attached to the top-centre of the sleepers. Data from the strain gauge was used as an indicator of the bending shape where positive strain represents W-shape while negative strain represents U-shape. After the ballast and the sleeper preparations, a sleeper was laid at the centre of the box, on the ballast, and the box was placed under a structural testing frame. A hydraulic load ram of 444 kN capacity with an LVDT for deflection verification from the DIC was used. The load was applied to two rail pieces sitting on the rail seats (1130 mm apart) through a spreader beam (Fig. 6). Several preloading tests were run using a timber sleeper to ensure the ballast is well compacted. At least three tests were performed for each sleeper type and the deflections were measured for each test. The final deflection measurement was taken when the difference in rail seat deflection between two successive tests was less than 0.1 mm.

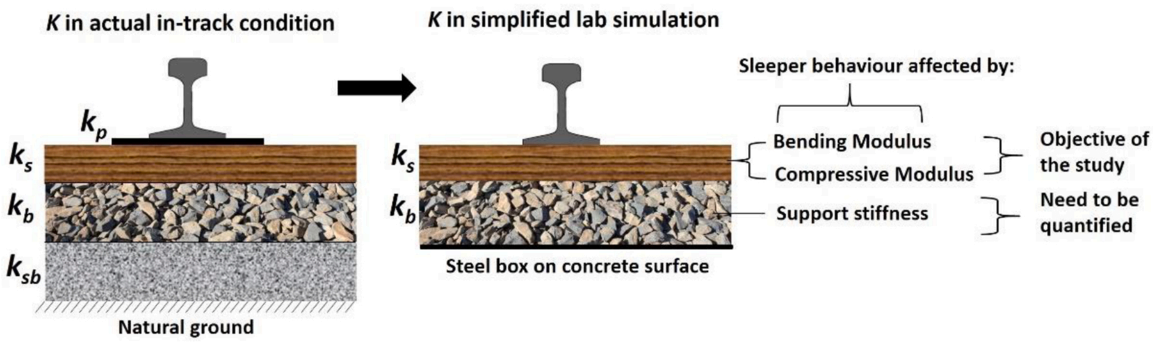


Fig. 5. Simplification made in the laboratory track simulation.

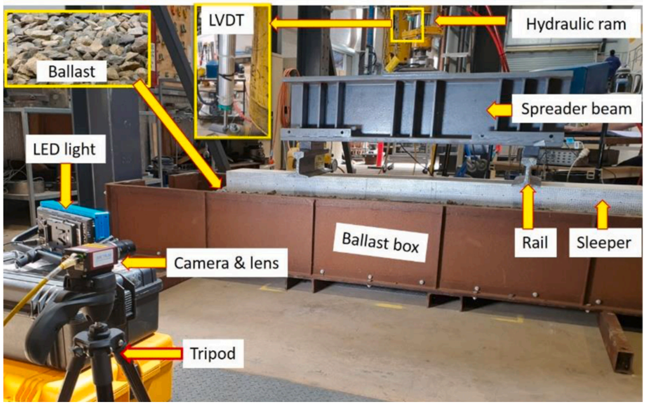


Fig. 6. Sleeper on ballast test.

3. Numerical simulation and validation

FE models of the sleepers using Ansys Workbench software version 2020 R1 [58] was created using the Solid186 element type. This type of element is a 20-node 3D structural element that has three degrees of freedom allowing deflections in the longitudinal (x), vertical (y), and lateral (z) directions. The properties of the sleepers in Table 1 were used to construct 3D models of the sleepers. As explained in Section 2.3, the ballast (k_b) and subgrade (k_{sb}) layers can be represented as one elastic layer resting on a rigid foundation in the ballast box test. The Elastic Support function in Ansys Workbench software was used to introduce the support stiffness of the sleepers (applied at the bottom face of the sleepers) as shown in Fig. 7. The definition of the Elastic Support in Ansys Workbench software coincides with the definitions used to describe the sleeper support stiffness which is the pressure (or force) required to produce a unit of normal deflection of the foundation. A wheel load of 72 kN was applied to each rail seat on an area equal to the contact area between the AS 41 kg rail and the sleeper, i.e. 127 mm times the width of the sleeper. The distance between the centre of the rail seats is 1130 mm. The movement of the sleepers was restrained in the z and x directions while allowing rotations around the z-axis to allow for bending of the sleepers. The vertical movement of the sleeper is only restrained by the elastic support as it is also the case in the experiment. Realistic support stiffnesses reported in Section 3.3 (presented in Section 5.1) were used for each type of sleeper (in N/mm^3 as shown in Table 3).

The FEA was validated with the experimental tests which will be discussed in Section 4.3. To ensure the FE models represent the sleeper on elastic foundation, the Beam on Elastic Foundation (BOEF) theory was used to validate the models in the development stage. The BOEF theory was introduced by Winkler in 1867 and by Zimmermann in 1888 [14]. A century later, Heteneyi [70] presented the full derivation of the deflection equation for a finite beam (sleeper) resting on an elastic foundation and loaded by two equal concentrated forces at the centre of the rail seats [14]. BOEF was used to validate the deflection profile of the sleepers as this analysis approach is based on beam on elastic foundation, which is very similar to an actual sleeper on ballast and an approach that has been used by many researchers for studies on sleeper on ballast [33]. Moreover, this analysis method has also been accepted in the

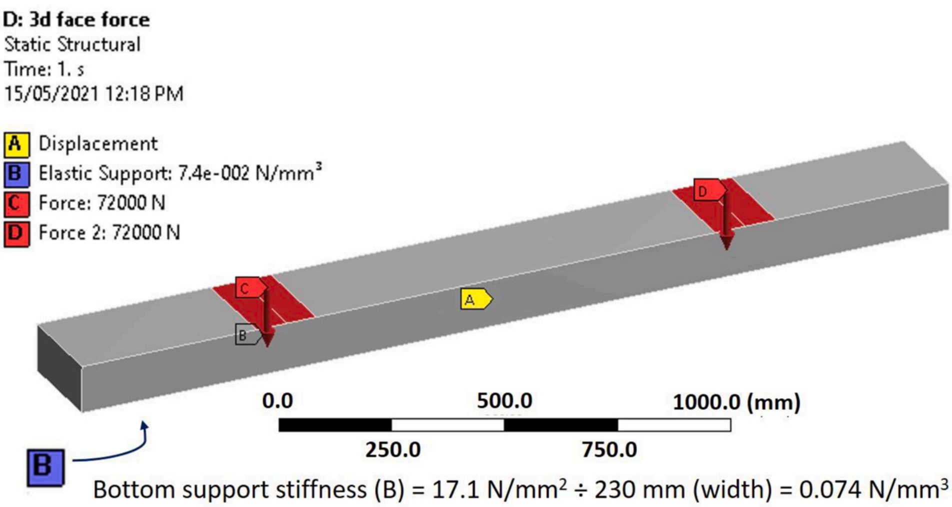


Fig. 7. FE model of the sleeper in Ansys software.

Table 3
Results of plate load test for sleeper support stiffness evaluation.

Sleeper type	Maximum stress applied (MPa)	Max deflection (mm)	Support stiffness (N/mm^3)	Sleeper width (mm)	Support stiffness (MPa)
Timber	0.386	5.2	0.074	230	17.1
Plastic	0.405	5.5	0.073	225	16.6
SC	0.357	4.9	0.073	225	16.4
Concrete	0.398	5.3	0.075	240	18.0

Australian standard for prestressed concrete sleepers AS 1085.14 [23] and steel sleepers AS 1085.17 [71]. According to this model, the deflection of the sleeper is affected by the condition of the ballast (sleeper support stiffness), gauge width/sleeper length, and the MOE of the sleeper. In this model, the sleeper is represented with a finite one-dimensional beam resting on an elastic foundation. The analytical equation according to BOEF (also in AS 1085.14 [28]) may be used directly to predict the vertical displacement of the sleeper at the rail seats only, but the W-shape of the sleepers cannot be predicted with only rail seat deflection data. Besides, the BOEF model only considers the bending modulus of the sleeper which assumes there is no deformation under the rail seat. This means that the effect of the compressive modulus on the rail seat compression of the sleepers cannot be captured by the BOEF theory. Therefore, Finite Element Analysis (FEA), that considers both the bending and compression properties of the sleepers, is a necessity to find out the effects of the sleeper material changes.

The sleepers were first modelled as constant compression modulus with varying the bending modulus in the range provided in Table 1. A support stiffness range of 10−40 MPa (typical for Australian tracks) was used in the comparison to ensure the model is accurate in various sleeper and support conditions. Excel spreadsheet was used to solve Eq. (4).3(2) (BOEF) in the AS 1085.14 [23] with varying sleeper and support stiffness, similar to the FEA. The results of the analytical (AS 1085.14) and the FEA were in very good agreement with almost no difference in the bottom rail seat deflections between the two methods (difference of around 0.01 mm for the range of the bending modulus presented in Table 1). The realistic sleeper support stiffness and sleeper bending, and compression modulus where then applied to the models to validate the experimental tests. The results are discussed in Section 4.3.

4. Results and discussion

4.1. *Support stiffness of different sleepers*

The results of the plate load test are tabulated in Table 3. Eq. (4) was used to calculate the support stiffness.

The obtained support stiffness is very consistent from one test to another with an average value of 0.074 N/mm^3. This indicates minimal ballast disturbance from one test to another, and the sufficient compaction of the ballast. The obtained average stiffness of the support in this research is 17 MPa which is also very close to the stiffness value (16.9 MPa) obtained by Baghsorkhi et al. [19] using a box test. Besides, the obtained values are within the typical ballast modulus values (10–40 MPa) for Australian tracks reported by Jeff and Tew [14]. It can, therefore, be said that the difference in the deflection behaviours of the sleepers is due to the difference in the bending and compressive modulus of the sleepers. The values of support stiffness highlighted in Table 3 are also those used in the FEA.

4.2. *Strain behaviour at midspan of different sleepers*

There is a slight increase in the strain reading from the first to the third test as shown in Fig. 8. This is because of the seating of the samples on the ballast as it was also confirmed from the rail seat deflections of test 1 and test 3 (Section 5.3). This change, although very small, is a reflection of the bending modulus of the sleepers. For example, the plastic sleeper showed almost no change in the strain and exhibited a positive strain for all three tests. This also shows that the plastic sleeper sits well on the ballast. The timber and the SC

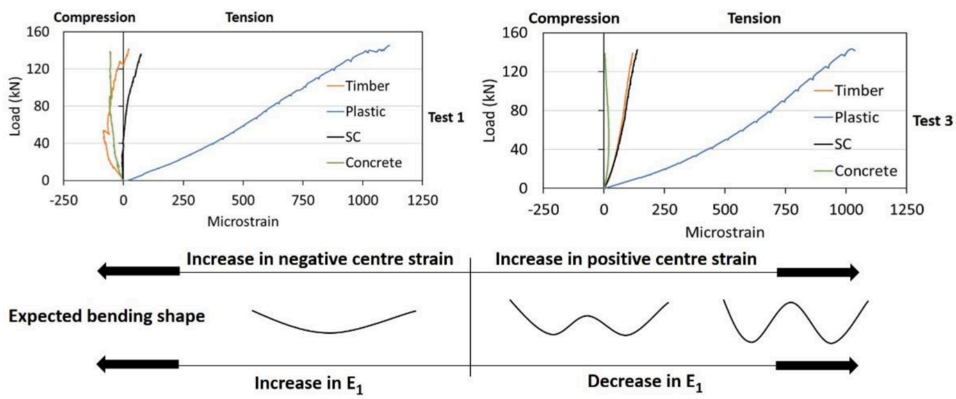


Fig. 8. Test 1 and test 3 top-centre strain data with expected bending shape illustration.

sleepers showed a negative strain up to around 50 kN and then leaned towards the positive side in the first test, but the SC sleeper showed a higher positive strain which is a reflection of its lower bending modulus than a timber. The concrete sleeper showed completely negative strain behaviour in the first test which indicates a U-shaped bending behaviour as was also noticed from DIC deflection measurements. In the third test, the plastic, SC, and timber sleepers showed a positive strain at the centre of the sleeper with values reflecting their bending modulus (a lower bending modulus sleeper has a higher strain). As a result, apparent W-shape bending behaviour is expected for these types of sleepers. The concrete sleeper, on the other hand, showed a positive strain but with values close to zero which indicates that the sleeper had almost flat centre when loaded. The above discussion can be further validated with the full-length deflection graphs presented in the next section.

4.3. Effect of bending modulus

All sleepers showed higher overall deflection in the first test with almost no difference between the second and last tests. Accordingly, the data from the third test is considered as the true sleeper behaviour on ballast and was used for comparison. A similar trend was also reported by Carrasco et al. [29] when they related the first test as ballast compaction and the second test as data acquisition for Citriodora glulam timber sleeper. In addition to the ballast compaction, sleeper settlement into the ballast was observed especially for softer sleepers. There is no permanent ballast settlement after the third test of the first sleeper type (i.e. the test of timber sleeper). Also, a consistent ballast modulus of 17 MPa $\pm$ 0.71 MPa was obtained for all tests, indicating that the ballast condition has not been disturbed after each test even at service load conditions. This was further confirmed with the condition of the ballast grain after the test wherein no crushed edges or broken pieces were observed. However, limitations should be recognised that manual tamping is different to that of the field tamping with a special equipment.

Fig. 9 shows a full profile behaviour of the sleepers measured at the bottom of the sleepers using the DIC (experimental) and the behaviour according to the FEA model implementing similar boundary conditions as explained in Section 3. It is worth noting that the deflection on the left and right-hand side of the sleepers as measured from the experiment are very identical from each other. This showed that a good ballast distribution, equal load application, and compaction along the sleeper length were achieved. This may however not be the case in reality as a slight change from left-to-right rail seat deflection was measured for timber and plastic sleepers [72]. As shown in Fig. 9, a good agreement between the FEA and the experimental results was obtained with slight differences in the deflection behaviour for plastic and the SC sleepers. This is justifiable because of the simplifications made in the FEA wherein the sleepers were modelled as anisotropic materials with solid bodies having different properties in x and y direction. In reality, however, the sleepers are slightly different and are more complex. The plastic sleeper has random pores in the centre of its cross-section that may compress during loading. These voids are created by adding foaming agents in the manufacturing process to minimise weight and the cost of material used [73]. Moreover, the ballast in the FEA model is represented as one elastic layer while it is a contribution of the interaction of many particles, in reality. This explains the slight shift (around 0.1 mm) in the experimental results versus the FEA results which were shown to be the limitation of this kind of simulation (BOEF) [74]. It can be said that the experimental results are in good agreement to that of the FEA model and hence the Australian standard AS 1085.14 [23] with only slight differences that can be neglected.

The expected W-shape deflection of the sleepers supported continuously on a ballast was successfully captured using the DIC. The plastic sleeper has the highest magnitude of deflection (5.8 mm at the rail seat) while the concrete sleeper has the least deflection (3.5 mm at rail seat). This was due to the much lower bending modulus of the plastic sleeper compared to the concrete sleeper. Since the SC sleeper had a lower bending modulus than the timber sleeper, its rail seat deflection of 4.9 mm was higher than the 4.1 mm of the timber sleeper. It is obvious that the change in vertical rail seat deflection is not proportional to the change in the sleeper bending modulus. The FEA of sleepers with support stiffness of 17 MPa also shows this behaviour (Fig. 10). By considering timber sleeper as the benchmark (MOE = 13.0 GPa), the plastic sleeper with a MOE of 1.0 GPa exhibited 42 % higher rail seat deflection while the SC with a MOE of 7.4 GPa had a 20 % higher rail seat deflection. On the other hand, the concrete sleeper (38.0 GPa) had only 13 % less rail seat deflection despite having MOE of three times that of timber sleepers. It follows that sleepers with MOE of around 13.0 GPa and higher do not show much difference in the rail seat deflection. In fact, the W-shape bending profile of these sleepers become less noticeable, with the centre part being almost flat as shown in the case of concrete sleepers in Figs. 9 and 8 (according to the strain data). This finding agrees with the theoretical findings in [11] wherein the researchers indicated that the effect of changing MOE on the deflection

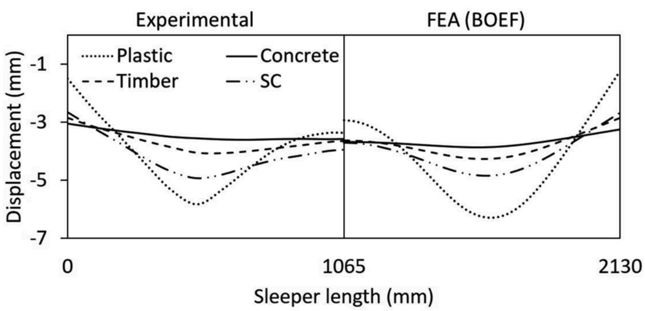


Fig. 9. Sleeper deflection shapes (experimental and FEA investigations).

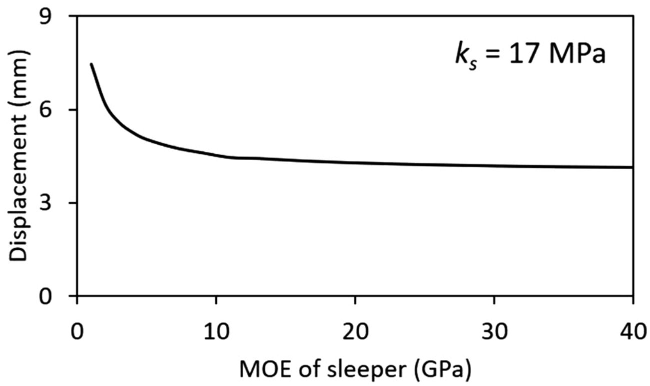


Fig. 10. Rail seat deflection for different sleeper MOE according to BOEF in AS1085.14.

of sleepers is more apparent on low bending modulus (1–15 GPa) sleepers than the higher ones.

Fig. 9 shows that stiffer sleepers exhibited overall lower deflections and the W-shape of these sleepers was less apparent; the concrete sleeper showed almost flat profile. As a result, softer sleepers experience higher stress at the rail seat and the centre due to the higher bending shape. This finding is supported by the higher strain readings at the top-centre of the sleepers (Fig. 8). Another consequence would be on the ballast pressure such that the softer sleepers, i.e. plastic sleepers, experience higher ballast pressure in the rail seat area than the stiffer sleepers (prestressed concrete sleepers). This higher deflection of the softer sleepers in the rail seat region means that these sleepers will be subjected to higher bending stress at service load which may result in material failure if not considered in the design. This agrees with the theoretical and graphical illustrations by Jeffs and Tew [14] wherein they indicated that the increase of the sleeper stiffness may lead to a more uniform pressure distribution under the sleeper. This could be because the bending modulus of these sleepers is much higher than that of the support stiffness (ballast) that makes these sleepers more resistant to bending. This was observed with the concrete sleepers' settlement into the ballast along its length (Fig. 9) without experiencing obvious bending. In conclusion, the bending modulus affects the overall W-shape profile of the sleepers and hence the stress distribution, the vertical deflection of the sleepers especially at the rail seat, and the pressure distribution under the sleepers.

4.4. Effect of compressive modulus

As highlighted in Section 3, the BOEF does not consider the local deformation of sleepers under the rail seat as this analysis approach is considering the sleeper materials to be of isotropic material, i.e. similar modulus of elasticity in all directions. In contrast, most of the timber-alternative sleeper materials as well as hardwood timber have properties different in different directions. This was clearly observed in the experimental investigation wherein the compression properties in the transverse direction has a significant effect on the overall behaviour of the sleepers. From the three-dimensional FEA of the sleepers supported by ballast, local compression at the rail seat contributes to total deflection as revealed in Table 4. The amount of deflection increases with the increase in the support modulus due to the increasing resistance of the support. This finding is especially critical for soft sleepers as there is a high compression effect under and around the rail seat that may induce higher local deformation on the top than the bottom part of the sleepers. Moreover, the compression tests in the sleeper standards only deal with the permanent indentation at the rail seats after removing the load. As no permanent indentation is recorded for the service load applied in this research, the local compression measured under rail can be of concern for the designers of low compression modulus sleepers.

This behaviour was captured in the test using the DIC by measuring the top and bottom deflections along the length of the sleepers. Table 5 shows the difference in the top and bottom deflections of the sleepers due to compression under the rails. The concrete sleeper was the only sleeper type that did not show any local compressive deflection under the rail. This can be explained by the nature of concrete which has a very high stiffness (compression modulus = 37.4 GPa) and will compress very minimally under the level of load applied in this study. This lack of compressibility and higher bending modulus increases track stiffness which in turn attracts more load to the sleeper and it induces high ballast pressure under the sleeper. Since the railway industry started using concrete sleepers more than half a century ago, this lack of compressibility has been realised and has been addressed with the provision of elastic rail pads.

Table 4
The difference in top-bottom rail seat deflection for different k_s values.

Sleeper type	Local compression (mm)			
	$k_s = 10$ MPa	$k_s = 20$ MPa	$k_s = 30$ MPa	$k_s = 40$ MPa
Timber	0.168	0.17	0.171	0.172
Plastic	0.319	0.322	0.328	0.333
SC	0.186	0.189	0.19	0.192
Concrete	0.003	0.003	0.003	0.003

Table 5
Differences in the top and bottom deflections of the sleepers.

Sleeper type	Rail seat top deflection (mm)	Rail seat bottom deflection (mm	Difference (mm)
Timber	4.25	4.10	0.15
Plastic	6.17	5.84	0.33
SC	5.13	4.94	0.19
Concrete	3.55	3.55	0.00

However, all the other types of sleepers showed a local compression deflection when the deflections at the top and bottom of the rail seats were compared. The plastic sleeper had a difference of 0.33 mm (5.7 % of the rail seat deflection) in deflection which was the highest of all the other samples. The second highest top-to-bottom difference in deflection was the SC sleeper which had around 0.19 mm (3.8 % of rail seat deflection). The timber sleeper had a slightly less compression of around 0.15 mm (3.6 % of rail seat deflection). The difference in local compressions under the rail seats can be attributed to the compression modulus of the sleepers. This observation shows that the lower the compression modulus, the higher the deflection under the rail seat (i.e. the top-to-bottom deflection difference). For example, the plastic sleeper had almost twice the deflection difference of the SC and timber sleeper because its compression modulus is almost half of the other two types of sleepers.

The percentages of local compression to vertical rail seat deflection for support stiffness of 17 MPa (experimental) varied from 3.6 % for timber sleepers to 5.7 % for plastic sleepers. This low deflection could be because the sleepers were resting on elastic support that already allows vertical deflection as shown in Fig. 9. For example, the FEA analysis indicated that with a support stiffness of 40 MPa this range increases (spans from 8 % for timber to 10 % for plastic sleepers). This result agrees with the findings of Krishnamoorthy et al. (2018) [75] where they indicated stress (or pressure) can be absorbed by elastic layers under the sleeper. This can be confirmed further by the load-displacement graphs of the sleepers under the local compression test (Fig. 3) where sleepers showed almost twice the deflection recorded in Table 5. This was because the sleepers were supported by rigid steel support that would not allow for any vertical settlement, even though, the load applied was smaller than the ballast box test because the steel plate used in the compression test was larger (18 % more contact area than the rail contact area). It was also because in every case the ballast modulus was much lower than the bending modulus of the sleepers and the ballast was unable to completely resist the rail seat vertical displacements of the sleepers. Notwithstanding, a service load of 72 kN per rail seat was applied so decompression might increase at higher levels of loading. It can be said that the contribution of local compression to the total deformation should be considered especially for sleepers with relatively low compressive modulus on a ballast with high support stiffness.

4.5. In-track behaviour of sleepers with different bending and compression moduli

It is expected that the in-track behaviour of alternative sleeper technologies is different from each other due to variations in their material properties. It has been shown that sleeper stiffness characteristics play an important role in the determination of the rail seat load of a track [14]. Changes in the sleeper stiffness also affect the predicted rail seat load as it is related to the rail deflection which is affected by the sleeper material type. This study has shown that the bending modulus has a greater effect on the vertical deflection of sleepers since the maximum contribution of decompression is only at 10 % of the rail seat deflection. A higher rail seat deflection, however, cannot directly imply that the predicted rail seat wheel load is higher. This is because as the rail deflection increases, the track stiffness decreases for a given track configuration which results in the wheel load being carried by a greater number of sleepers. O'Rourke et al. [76] stated that the product of rail deflection (y_{rail}) and track stiffness (k) is constant. According to Clarke [13], the predicted rail seat load calculated according to BOEF theory is:

$$Rail\ Seat\ Load\ (RSL) = S\ k\ y_{rail} \tag{5}$$

where S is the sleeper spacing.

Since an equal RSL of 72 kN was applied to all the sample sleepers and a single sleeper is loaded (i.e. no variation in S), the difference in rail seat deflections recorded (see Table 5) can also be attributed to changes in the overall track stiffness (k). This means that using softer sleepers would reduce track stiffness and vice versa because the product of the two is constant. While the magnitude of track stiffness cannot be evaluated by testing a single sleeper on ballast, the percentage of this change can be evaluated by rearranging Eq. (5) and using the timber sleeper as a benchmark (Table 6). In this calculation, a sleeper spacing of 685 mm is assumed and the rail deflection is equated to the sleeper rail seat deflection. This is justifiable because the purpose is not to calculate the value of (k) but rather the percentage of its change which is independent of the sleeper spacings. As Table 6 shows, the product of $k.y_{rail}$ is constant which agrees with the findings of O'Rourke et al. (1978) [76].

The change from timber sleeper ($E_1 = 13.0$ GPa) to plastic sleeper ($E_1 = 1.0$ GPa) reduces track stiffness (k) by almost 30 % (31 % with decompression effect) while k decreased by 17 % (17.2 % with decompression effect) when a synthetic composite sleeper ($E_1 = 7.4$ GPa) was used. Despite the concrete sleeper having a bending modulus of 38.0 GPa, three times the timber sleepers' bending modulus, the increase in the k is only 15 %. This change in the track stiffness shows that the bending modulus that affects more the value of track stiffness than the local decompression at rail seat. Moreover, the effect is more on the sleepers with stiffness below that of timber sleeper. This can be justified by studying the rail seat deflection of different sleeper stiffness for a given k_s value (17 MPa) according to BOEF theory. As shown in Fig. 10, the rail seat deflection change is more sensitive to sleepers below the MOE of around 13.0 GPa for a given sleeper support stiffness. From these results, it can be concluded that the change in the sleeper stiffness not only

Table 6
Percentage of k change for different sleeper technologies.

Sleeper type	S (mm)	RSL (N)	Recorded y_{rail} (mm)	k (MPa)	% change in k	$y_{rail}\,k$ (N/mm)
Timber	685	72000	4.10	25.6	Benchmark	105
Plastic	685	72000	5.84	18.0	−29.8	105
SC	685	72000	4.94	21.3	−17.0	105
Concrete	685	72000	3.55	29.6	15.5	105

affect the vertical rail seat and overall deflection of the sleepers but also the track stiffness as shown in Table 6. The change (an increase or decrease) of the track stiffness reflects the sleepers' bending and compressive modulus but the rate of change is not proportional as shown in Table 6. Although the effect of the decompression on track stiffness is minimal (less than 1 %), it was within 10 % of the total rail seat deflection (for stiff support where $k = 40$ MPa) so this effect should be considered in the design of alternative sleepers. Further research in this area however may be needed before the current standards consider the decompression behaviour at the rail seat in the design of railway sleepers. Nonetheless, the findings from this study provided a better understanding of the deflection behaviour of different sleepers (supported by ballast) having distinct mechanical properties, which were demonstrated experimentally and validated by FE analysis.

5. Conclusion

This research evaluated the effect that the bending and compressive modulus had on the behaviour of alternative railway sleeper technologies. Timber, plastic, synthetic composite, and concrete sleepers were statically tested in a ballast box and loaded through two rails to represent a narrow-gauge track configuration. The results of these tests and numerical simulations of sleepers on ballast resulted in the following conclusions:

- Railway sleepers with a low bending modulus such as plastic sleepers have a prominent W-shaped deflected profile along their length when supported by a ballast, whereas stiffer sleepers such as prestressed concrete sleepers have an almost flat profile. Moreover, sleepers with a low modulus of elasticity experience high bending stress in the centre and rail seat and this can lead to material failure if not accounted for at the design stage.
- The compressive modulus has a direct correlation to the level of local compression at the rail seat. Soft sleepers such as plastics (MOE of 1.0 GPa) will have a local deformation of at least 5.7 % of the total rail seat deflection under a service train load (and a support stiffness of 17 MPa) but can go as high as 10 % for stiffer support ($k = 40$ MPa). Local decompression is however negligible to sleepers with high compressive modulus such as prestressed concrete (MOE of 38.0 GPa).
- The bending modulus of sleepers contributes significantly more to the stiffness of a track than decompression. The increase in sleeper bending modulus increases the track stiffness but with the rate of change in track stiffness disproportional to bending modulus. The change in track stiffness is more sensitive to the bending modulus lower than that of the timber sleepers.
- The overall and rail seat deflections are affected by both the changes in the bending and compression moduli, but the bending modulus effect is more prominent.

The findings of this research are limited to the sleeper types tested in the study and considering other sleeper materials beyond the scope of this study is valuable in future research. Although the current design methods account for dynamic load effects through load factors (similar design to static), the true dynamic behaviour should experimentally be evaluated to conclude the effects of the material properties on the dynamic behaviour of a track. Moreover, as the DIC has successfully captured the effect of different sleeper material type on the track modulus, the authors suggest other important studies using the DIC such as quantifying track modulus from various ballast particle size distribution. Despite its limitation, the strategic and systematic method used in this case study can be a guide for future investigations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHAPTER 4: PAPER 2

Novel bending test method for railway sleepers

The results obtained in Chapter 3 showed that the composite sleepers behave differently when supported by a ballast. For example, the concrete sleeper bent in a U-shaped profile while the plastic sleepers bent in a W-shaped profile due to their low bending modulus. However, using a ballast box has been proven to be a complex and complicated test method to simulate the behaviour of sleepers in a railway track. Moreover, the existing standards only consider a section of the full-size sleepers and hence multiple testings are required to evaluate the bending behaviour of composite sleepers such as positive and negative rail seat and centre bending tests. A novel bending test method termed five-point bending test was developed and validated in **Manuscript 2**. This test method consists of two continuous spans (three supports) and two loading points at the rail seat locations (representing actual track gauge). To account for the varying bending stiffness of composite sleepers, three different supports types, i.e., steel, neoprene, and ethylene propylene diene monomer (EPDM) rubber were considered, and the most appropriate support type was determined. Analytical equations were then developed for the bending moments at the rail seat and the centre, considering different support types.

The results showed that the simultaneous positive and negative bending moments experienced by railway sleepers can be captured with the five-point bending test. This new test method was implemented to extensively evaluate the behaviour of timber alternative railway sleepers under static and fatigue loads, the results of which are presented in Chapters 5 and 6, respectively

polymers

Article

Novel Bending Test Method for Polymer Railway Sleeper Materials

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Abstract: Alternative sleeper technologies have been developed to address the significant need for the replacement of deteriorating timber railway sleepers. The review of the literature indicates that the railway sleepers might fail while in service, despite passing the evaluation tests of the current composite sleeper standards which indicated that these tests do not represent in situ sleeper on ballast. In this research, a new five-point bending test is developed to evaluate the flexural behaviour of timber replacement sleeper technologies supported by ballast. Due to the simplicity, acceptance level of evaluation accuracy and the lack of in-service behaviour of alternative sleepers, this new testing method is justified with the bending behaviour according to the Beam on Elastic Foundation theory. Three timber replacement sleeper technologies—plastic, synthetic composites and low-profile prestressed concrete sleepers in addition to timber sleepers—were tested under service loading condition to evaluate the suitability of the new test method. To address the differences in the bending of the sleepers due to their different modulus of elasticities, the most appropriate material for the middle support was also determined. Analytical equations of the bending moments with and without middle support settlement were also developed. The results showed that the five-point static bending test could induce the positive and negative bending moments experienced by railway sleepers under a train wheel load. It was also found that with the proposed testing spans, steel-EPDM rubber is the most suitable configuration for low bending modulus sleepers such as plastic, steel-neoprene for medium modulus polymer sleepers and steel-steel for very high modulus sleepers such as concrete. Finally, the proposed bending moment equations can precisely predict the flexural behaviour of alternative sleepers under the five-point bending test.

Keywords: timber replacement sleeper; composite sleeper; five-point bending test; Beam on Elastic Foundation (BOEF); in-track sleeper behaviour

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1. Introduction

Several composite sleeper technologies have been introduced as alternatives to address the issue of environmental deterioration and scarcity of hardwood timber sleepers. Even 0.5% of in-service traditional prestressed concrete sleepers fail and require replacement annually, while nearly 1% are discarded due to defects in the manufacturing [1]. The main alternative sleepers are synthetic composites (SC) [2] recycled plastics [3,4], low-profile prestressed concrete [5], polymer concrete [6] and steel sleepers [7]. Due to their superior durability, strength/weight ratio, environmental-friendly properties, and excellent resistance to rot and insect attack, alternative sleeper materials from fibre composites and recycled plastics gained significant attention [8–11]. It is estimated that the market share of composites sleepers in the passenger rail will increase to 4.6% in 2024 due to the ever-increasing demand for lightweight materials with exceptional mechanical properties [12]. For example, Queensland Rail in Australia needs at least 100,000 composite sleepers per year in the next 5 years to ensure the continuous operation of its regional rail network [13]. While these alternative sleeper technologies have been available for more than two decades, their use in actual railway tracks is still marginal as compared to timber, concrete and steel sleepers [14]. Qiu et al. [15] related this low usage of composite sleepers to the lack of recognised unified national and international standards for alternative sleeper materials. For example, the AREMA standard specifies the minimum modulus of elasticity of alternative sleepers to not be less than 1.17 GPa [16], while the Japanese standard (JIS 1203:2007) specifies a minimum of 6 GPa [17]. This requirement according to ISO 12856-1:2014 ranges from 1.17 to 6 Gpa [18], while the recently developed Australian Standard AS1085.22:2020 does not specify any value of modulus of elasticity for an alternative sleeper [19]. Moreover, the evaluation tests according to these standards are mostly based on prestressed concrete sleepers, which does not represent exactly the behaviour of alternative sleeper materials supported on a ballast, as reviewed in Section 2.

Railway sleepers are loaded with two wheels on the rail seat areas, which produces positive bending moments on these areas while simultaneously produce negative bending moment at the centre section. Past research indicates that the stress distribution of the rail seat area is significantly higher than that of the centre part [20,21]. It is believed that the AREMA standard overestimates the flexural requirement of concrete sleepers for the rail seat area [22] but not the centre part, as it has been reported that centre cracking is one of the most common failure types of concrete sleepers [23,24]. In-service evaluation of the flexural capacity of concrete sleepers showed higher capacity than that of the AREMA requirement, yet centre cracking was observed [22]. A similar situation can be seen for plastic composite sleepers where the in-service monitoring of these sleeper types indicated centre cracking failure within the first 15 years of their installations [25]. Plastic sleepers are, however, designed to provide an average service life of ~40 years [26]. This indicates that the estimations and test evaluation tests according to the existing standards may not represent the loading condition of sleepers supported by track. This issue was highlighted by McHenry et al. [25], wherein they indicated that the static flexural tests in the AREMA standard were originally designed to simulate the high bending stresses induced during installation, which is a one-off phenomenon. Moreover, a recent study on the hogging bending deflection behaviour of sleepers showed that none of the standard tests completely represent the in-service behaviours [27]. Therefore, a new five-point bending test is proposed in this research aiming to induce realistic in situ bending moments at the rail seat and centre of the sleepers simultaneously. Not only is this research beneficial in the evaluation of the existing composite sleepers, but also in the evaluation of futuristic composite sleepers with different sectional properties due to shape and material optimisations (Figure 1). The latter is important because full-size sleepers will undergo positive and negative bending (known as W-shape), and thus any unexpected failure such as design integrity and materials interface failure might be captured by this type of test. Moreover, as the review of the existing standards in Section 2 indicated, several sleeper sections need to be tested to evaluate sleepers' positive and negative bending moments while in the five-point bending one test can evaluate both bending behaviours.

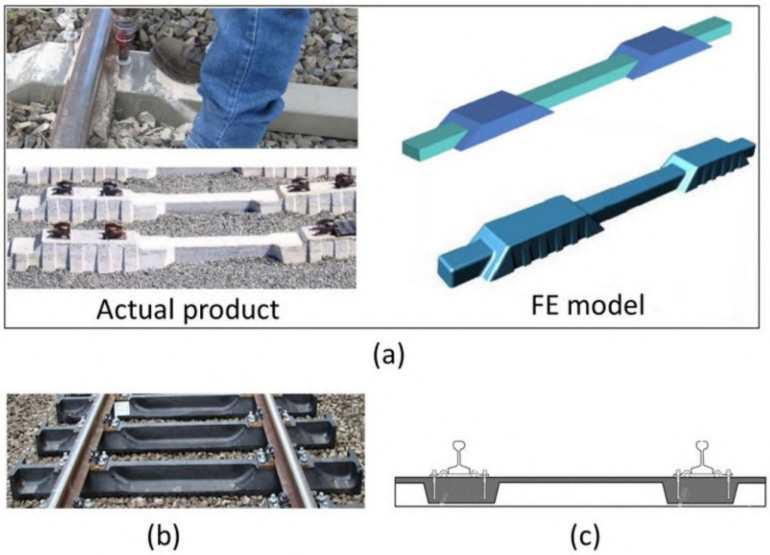

Figure 1. Different shapes of alternative sleepers: (**a**) composite sleepers [28–30], (**b**) recycled plastic sleeper [31] and (**c**) alternative composite sleeper patent [32].

This paper presents the development of the five-point bending test for composite sleepers, and its suitability is demonstrated through full-size static test under service load. First, an analysis of different composite sleepers supported by ballast was conducted using Strand 7 software to understand the bending moment intensity and its variation from the rail seat to the centre of a sleeper and the change to another sleeper type. The full sleeper support condition was assumed as it was shown that the deflection of partially supported sleepers are not very much different (within 5–8%) to that of the full supported sleepers [33]. The Beam on Elastic Foundation theory (Winkler model) was used to validate the computer model due to its reasonable estimation accuracy [20,34] and lack of in-service bending behaviour of various sleepers types. Second, the testing spans were adjusted so that similar bending moments to that of the realistic conditions are induced. Further, to prevent high shear (and possibly shear failure) and to consider the change in the positive-to-negative bending moment ratio from a sleeper type to another, different elastic support types were considered, and the best one is selected for specific material type. The Digital Image Correlation (DIC) technique was employed to capture the bending behaviour through full-profile deflection shapes and the support settlement measurements. Finally, analytical solutions of the five-point bending test based on the classical beam theory were developed and validated with Finite Element Analysis (FEA) to calculate the magnitude of bending moment at the rail seat and centre of an alternative sleeper.

2. Evaluation of the Existing Test Standards

The flexural behaviour evaluation of alternative sleeper technologies is a fundamental part of understanding sleeper's mechanical properties. It is also one of the required tests for the performance evaluation of a newly developed sleeper design for their acceptance in real-world applications. However, it has been demonstrated that the in-track flexural behaviour of sleepers with significant differences in their elastic moduli, E_s, are different. For example, the composite sleepers (E_s = 8 GPa) will have a higher deflection when compared to a prestressed concrete sleeper (E_s = 36 GPa) [35], and this is also different from a typical hardwood timber [36]. This has long-term negative effects on the performance of the tracks as stiffer sleepers will attract more loads while lesser stiff sleepers will carry a very minimal load when they are interspersed with timber sleepers [18,19]. Therefore, accurate evaluation of the flexural behaviour of alternative sleeper materials is essential to manage the tracks appropriately. Accordingly, a few test standards [16–19] have been published in the last two decades to help facilitate the design and manufacture of alternative sleeper materials. The test methods for evaluating the performance of sleepers suggested in these standards are presented and evaluated in this section.

The bending tests are requirements for all of the existing standards to demonstrate the suitability of an alternative sleeper technology. As shown in Table 1, these tests are of three-point or four-point bending configurations usually with resilient pads under the loading point and over the supports. Table 1 highlights the main differences among the different standards, focusing on the bending tests.

Table 1. Comparison of different alternative sleeper standards.

	Origin Country	Sleeper/Material Type Co	E_s (GPa)	Full-Size Bending Test	Type of Resilient Support
AREMA-chapter 30-5	USA	ECP and EWP, but mostly deal with HDPE polymer-based composite products.	1.17	Rail seat positive, rail seat negative and centre negative.	140 mm × width of sleeper × 25 mm thick (50 Shore A hardness)
JIS E 1203:2007	Japan	Fibre-reinforced foamed urethane.	6.0	No full-size testing	-
ISO 12856	International	Plastic and reinforced plastic	1.17–6.0	Rail seat positive, centre positive and centre negative.	140 mm × width of sleeper × 15 mm thick (static bedding modulus: $1 < C < 4$ N/mm^3)
AS1085.22	Australia	Not specified	-	Rail seat positive, rail seat negative, centre positive and centre negative.	Neoprene Shore A hardness 90. Top: 25 mm width × 12 mm thick × width of sleeper Bottom: 50 mm width × 25 mm thick × width of sleeper

The AREMA standard [16] highlighted that the full test criteria have not been developed for alternative sleepers. Therefore, researchers need to take this into account and be more cautious when designing and evaluating an alternative sleeper according to the relevant standard. For example, material characterisation according to the new Australian standard AS1085.22 [19] is recommended to be carried out based on ISO 12856-1 [18], which was specifically developed for plastic sleepers. However, AS1085.22 [19] is intended to cover all alternative sleeper materials that are not timber, concrete or steel. The same can be seen in the bending test configurations of the AS1085.22 [19] standard for alternative sleepers that are identical to the tests in the AS1085.14 [37] and AREMA-chapter 30-4 [16], which are developed for prestressed concrete sleepers. The tests in both ISO 12856-2 [38] and AREMA-chapter 30-5 [16] can be followed in the evaluation of plastic sleepers as both cover plastic sleeper requirements; however, the ISO standard allows the sleepers to be tested with rail pads attached to them, while the AREMA does not. Another major difference between the standards is in their test/passing criteria. AREMA [16] does not specify any pass criteria for alternative sleepers; however, prestressed concrete sleepers shall not develop structural cracks when tested according to Section 4 of the standard. On the other hand, the Australian AS1085.22 [19] states that the permanent deflection should be less than 0.5 mm after three minutes from unloading in addition to the no crack requirements.

The bending tests according to these standards have limitations in regards to how a sleeper on ballast behaves according to BOEF theory. First, these standards evaluate the bending behaviour in two to four separate tests which are not only time and resource-consuming but also do not represent accurately the behaviour of a sleeper on ballast where the sleepers are experiencing both negative and positive bending moments. Second, the available test standards do not consider a rail section or similar-sized steel plates for the application of loads on the rail seats. This can be critical in evaluating if the sleepers will experience any indentation in the rail seat area, especially for alternative designs that omit the use of rail pads. Moreover, the use of resilient pads in the standards may not have a practical reason that reflects the sleeper on ballast behaviour or the necessity according to material characteristics. For example, it might be necessary to use resilient pads for concrete sleepers (as required by AREMA-chapter 30-4 and AS1085.14 standards) to prevent spalling of concrete and hence preventing cross-sectional loss as shown in Figure 2b, where the load was applied directly onto the concrete surface [39]. It seems that this requirement is carried over to the new alternative standards, according to which the sleepers have much lower moduli of elasticity than that of concrete and thus may not require these elastic pads. A recent study on the improvement of the testing method for composite sleepers (plastic sleepers tested) based on the AREMA [16] considers a four-point bending test without any resilient pads, as shown in Figure 2a [25]. In the present study, however, elastic pads were used to redistribute the bending moments according to BOEF theory (accounting for the sleepers' modulus of elasticity), thus mimicking and capturing the behaviour of alternative sleepers on ballast.

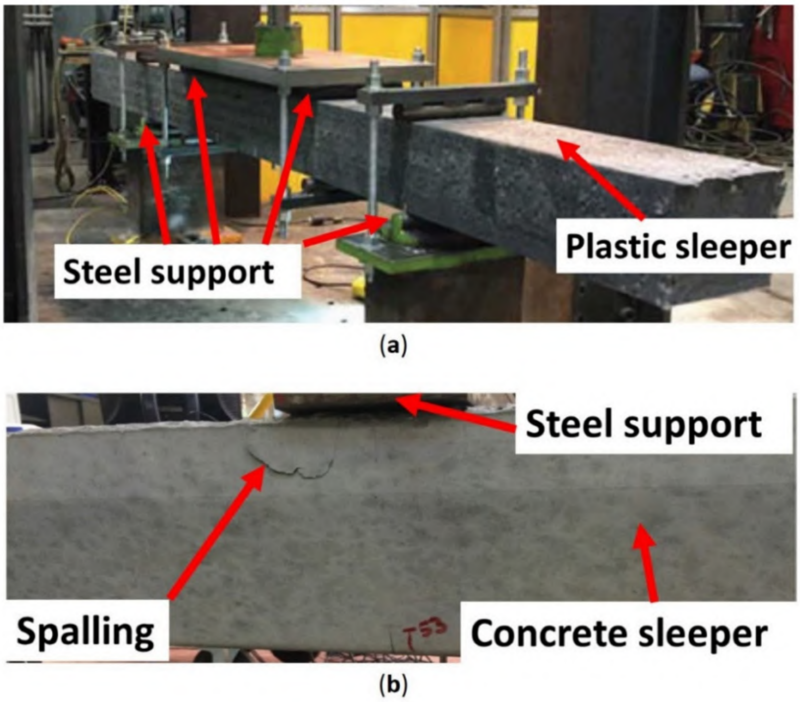

Figure 2. (**a**) Four-point bending test of a plastic sleeper without resilient pads [25]. (**b**) Spalling of the concrete surface under a steel plate [39].

While it is evident that a sleeper in-track is subjected to both positive and negative bending moments at the rail seat and the centre, the intensity of bending moments at the rail seat and centre are different from a sleeper to another because of changes in the stiffness of the sleepers. Therefore, a new test method is proposed with a view of representing the actual behaviour of railway sleepers over the ballast.

3. The Concept of Five-Point Static Bending for Railway Sleepers

As railway sleepers are supported by ballast, the rail seats are under a positive bending moment (sagging moment) while the centre of the sleeper is under a negative bending moment (hogging moment). The design of railway sleepers has been based on the BOEF theory which was first introduced by Winkler in 1867 and Zimmermann in 1888 [40] and later modified by Heteneyi in 1967 [41]. Due to the lack of comprehensive data on the in-tack bending behaviour of composite sleepers with various bending modulus in Australia, this method is used for the estimation of bending behaviour of the sleeper samples with acceptable accuracy as highlighted by Zakeri and Sadeghi (2007) [20]. This model was also introduced in the AS1085.14:2012 [37] as an alternative to the empirical method of sleeper analysis. The limitations of the BOEF model, however, should be noted, such as the lack of the interaction between the supporting layers of the sleeper (ballast, sub-ballast and subgrade) because the model only represents these layers with one support modulus value [42]. According to the BOEF model, the intensity of the bending moments in both the rail seat and the sleeper centre is affected by the condition of the ballast (sleeper support modulus), gauge width/sleeper length and the sleeper material type. This indicates that a composite sleeper with an elastic modulus of ~2 GPa will have a different bending behaviour to that of a 40 GPa prestressed concrete sleeper supported by ballast. The general bending shape of a loaded sleeper in-track (supported by ballast) takes the form of the letter W depending on the gauge-width and material type. The in-service bending behaviour of plastic composite sleepers with control timber sleepers was studied in the US and it was found that the bending shapes are similar, but it is more prominent in the softer sleepers (plastic) than that of the timber as shown in Figure 3 [43]. This is a similar bending shape of sleepers analysed following the BOEF theory as demonstrated by Qiao et al. [44] when they compared the deflection behaviour of timber and enhanced timber with glass fibre-reinforced plastic (GFRP) wrap. The GFRP-timber sleeper showed less deflection in the rail seat and the ends due to increased stiffness as also shown in Figure 3. This bending behaviour can be mimicked with the five-point bending configuration provided that the load is directly applied to the rail seat area. This not only helps demonstrate the bending behaviour of the sleepers, but also the suitability and integrity of a composite sleeper design as a whole structure can be better understood. This is especially important in the case of composite sleepers with different sectional properties throughout the sleeper length (Figure 1) that is made from different materials along its length and cross section. However, due to the sleeper samples being made of same material throughout their length (commonly available alternative sleeper types) and for the sake of simplicity, the effect of this cross-sectional change is not considered in this research.

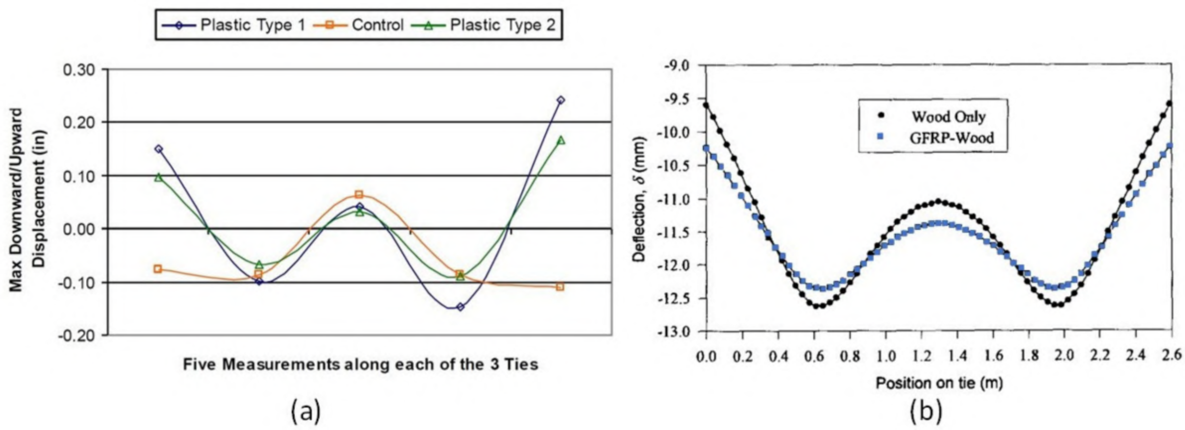

Figure 3. (**a**) In−service bending shape of plastic and timber sleepers [43]. (**b**) Deflection profile of timber with and without reinforcement according to BOEF [44].

The deflected shape and bending behaviour of sleepers shown in Figure 3 cannot be captured in a single test with three-point or four-point bending configurations. On the other hand, the approach of using a ballast box for full-size testing is both costly and time-consuming due to its big size and heavy weight. Moreover, proper compaction of the ballast is critical to this approach to achieve consistent and comparable test results. Therefore, the five-point bending test could be an alternative but a simple way of mimicking the behaviour of sleepers supported by ballast.

3.1. Previous Works on Five-Point Static Bending Test

The five-point bending test is new for railway sleeper applications, and published data on the testing of continuous beams are scarce. Several researchers have successfully applied this testing approach for continuous beams or slabs where the structures are under positive and negative bending moments simultaneously. Kim and Dharan [45] employed this concept for the determination of the interlaminar shear strength of composites. Pouget et al. [46] and Li et al. [47] employed a similar testing method in the study of surfacing systems on orthotropic steel bridges using laboratory-scale samples. Su et al. [48,49] also investigated the behaviour of hollow section aluminium alloy beams under the five-point tests. Mujika et al. [50] modified a three-point bending test into a five-point bending test to do a two-sense bending fatigue test; however, the application was only demonstrated through small-scale laboratory testing. While the five-point bending configuration has been found to be useful by several researchers in evaluating the structural performance of structures, available studies employed a specific testing span, support type and loading type (point load vs. distributed) reflecting the actual application that the test was designed for. A suitable five-point bending test configurations should therefore be determined to best represent the behaviour of sleepers in rail-track.

3.2. Determination of the Appropriate 5-Point Static Test Configuration

The five-point bending test, as its name suggests, consists of three supports at the bottom and two loading points on the top (Figure 4). The external or internal span of this bending test changes the intensity of the induced bending moments at the rail seat and the centre of the specimen. Therefore, the distance "*a*" in Figure 4 was carefully determined such that the bending moments at the rail seat and the middle best represent sleepers on ballast. As there is no in-track bending moment data in Australia for timber and its alternatives, BOEF analysis was implemented. A model of each sleeper type has been developed in Strand7 R2.4.6 software from Strand7 Pty Ltd., Sydney, NSW, Australia [51] and is verified with the bending moment equations in Section 4.3.4 of the AS1085.14 [37] with nearly 100% accuracy. This analysis has been based on a typical narrow-gauge Queensland Rail (QR) track configuration in which the distance between the rails is 1130 mm and the sleeper length, L, is 2130 mm [29] with a cross-section of 230 mm (width) by 115 mm (height). Consequently, the distance between the loading points is chosen as 1130 mm so that the positive bending moment is induced at the same location as if the sleeper was in-track. The typical range of the support (ballast) modulus in Australia is between 10 and 40 MPa [40]; however, the BOEF analysis shows that the support modulus value does not affect the bending moment, shear force and deflected shape greatly as shown in Figure 5. On the other hand, changes in the sleeper stiffness greatly affect the deflected shapes of the sleepers. This means that the moment distribution between the rail seat and the sleeper centre is different from a sleeper to another. According to the BOEF analysis, the ratio of positive to negative bending moment for timber sleeper (E_s = 13.6 GPa) is 2.27, with other sleepers being around the same value.

The ratio of positive to negative bending moment for different distances between the external support and the loading point "*a*" is found and compared to the ratios obtained in the BOEF analysis. Compared to the BOEF analysis, the five-point bending test gives lower positive to negative bending moment ratios due to the higher negative bending moment at the centre. However, it was found that a distance of a = 300 mm gives the highest bending moment ratios as compared to 350 mm and 400 mm as shown in Table 2. Nevertheless, an "*a*" value shorter than 300 mm would produce high compression at the external supports and the rail seat areas and high shear, which is critical for sleeper technologies with relatively low elastic modulus. Yet, Figure 5 shows that the magnitude of shear force in the five-point bending is similar to the existing AS1085.14 standard, while it is marginally higher than that of the shear force according to BOEF theory. The deflection and bending moment from the five-point bending test setup and BOEF analysis are shown in Figure 5. Figure 5 also compares the behaviour of a timber sleeper under the four-point test method suggested by the Australian standard AS1085.22 [19]. While rail seat bending moments are similar between the five-point and the rail seat bending test, a better match of bending shape to that of the BOEF theory can be captured with the five-point bending test. As the rail seat undergoes the highest bending moment, it is expected that the sleeper failure will occur at the rail seat when loaded ultimately. It has been observed that the in-service, plastic sleepers fail or crack near the rail seats [25]. This also shows the advantage of the five-point bending over the existing four-point bending tests. Besides, the FEA of the centre bending test according to the AREMA standard (also similar to AS 1085) shows that the test induces a much higher bending moment and shear force as compared to the five-point test and the in-service sleepers for the same applied load. A recent study also indicated that none of the standard centre bending tests represents the actual loading conditions of a railway sleeper supported by ballast [27]. This comparative study, therefore, indicates that the five-point bending test could set a foundation for designing bending tests for polymeric railway sleepers.

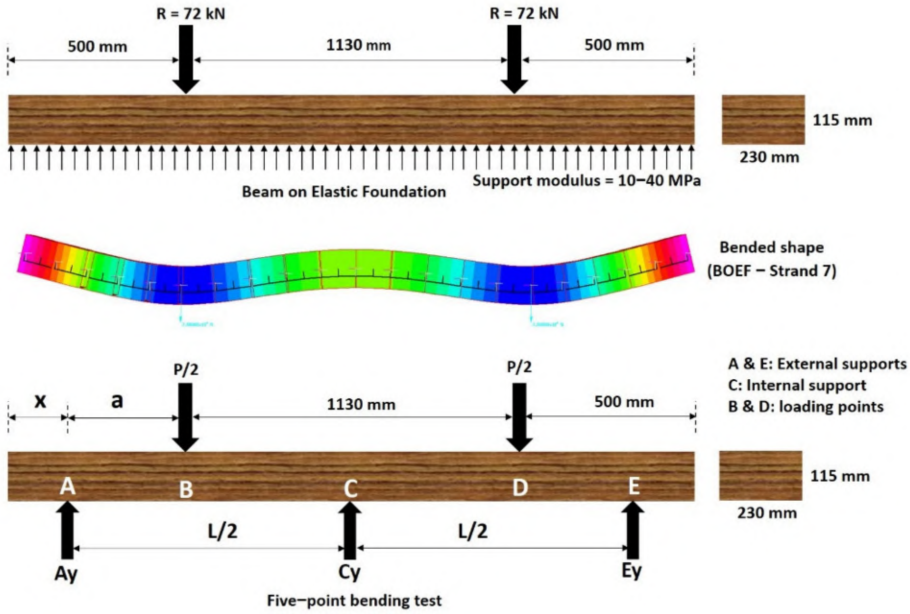

Figure 4. BOEF theory vs. five-point bending test.

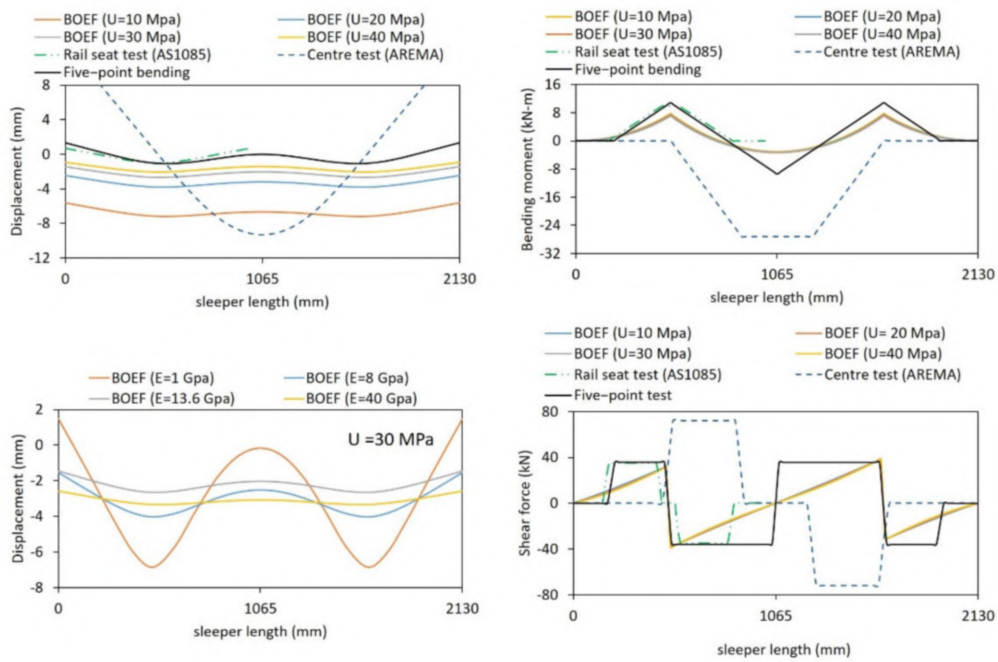

Figure 5. Sleeper behaviour according to BOEF theory, five-point bending, rail seat and centre test.

Table 2. Positive and negative bending moments of different "*a*" values.

Distance '*a*'	Bending Moment (kN-m)		
	Positive	Negative	Ratio
BOEF (timber)	7.3	3.22	2.27
400 mm	11.91	11.92	0.999
350 mm	11.44	10.76	1.063
300 mm	10.81	9.5	1.137

Sleeper designs with optimised cross sections and smaller cross-sections in the middle region than at the rail seats may have a lower bending moment capacity at the centre than the rail seat; therefore, these sleepers may first fail in the centre. This behaviour can be captured from the five-point static bending test, but the test setup should properly induce the level of bending moment in the middle region of the sleepers. To overcome this issue, the researchers have used softer materials namely neoprene and EPDM rubber for the middle support to help redistribute the bending moments accordingly.

4. Experimental Verification of the 5-Point Static Bending Test

4.1. Sleeper Properties and Preparation for DIC Measurements

Four sleeper types—hardwood timber, recycled plastic, synthetic composite (SC) and low-profile prestressed concrete sleepers—are tested under the five-point bending setup. The modulus of elasticity of these sleepers are determined using a three-point bending test with a span of 1200 mm on a Universal Testing Machine from Shenzhen SANS Testing Machine Co., Ltd., Guangzhou, China, following the ASTM D790:2017 standard [36], and using the DIC technique for toe compensation (Annex A1 of ASTM D790 [52]). The flexural modulus and sleeper dimensions are listed in Table 3. The timber sleeper is sourced from Queensland, Australia, purchased from Newton Sawmill & Carrying company representing the typical timber sleepers used by the Queensland Rail (QR), while all of the non-timber samples are designed as alternatives to timber sleepers with dimensions suitable for narrow-gauge QR configurations. The hardwood timber sleeper is Grade 1, other species (spotted gum species), and complies with the Queensland Rail's material supply specification CT.169 [53]. The low-profile concrete sleeper is designed and manufactured by Austrak Pty Ltd., Brisbane, Queensland, Australia following the rational design method [5] with concrete compressive strength of 60 Mpa (28 days) used and contains 20 tendons of low relaxed chevron pattern indentation having a diameter of 5.03 mm each. The synthetic composite (SC) sleeper is a glass fibre-reinforced polyurethane foam type (continuously reinforced in the longitudinal direction) and is supplied by AGICO Group Company, Anyang, Henan, China. The plastic sleeper is manufactured and supplied by Replas plastic recycling company in Melbourne, Victoria, Australia, and it is made of post-consumer recycled plastics with fillers.

Table 3. Properties of the sleeper samples.

Sleeper Type	Cross-Sectional Area (mm^2)	Length (mm)	Second Moment of Inertia (mm^4)	Es (GPa)
Timber	26,450	2130	29,150,104	13.6
Recycled plastic	28,125	2050	36,621,094	1.0
Synthetic composite	25,760	2120	28,389,667	8.1
Prestressed concrete	31,168	2130	48,699,500	38.0

The DIC method is a versatile and effective non-contact full-field technique of measurement that has been employed in various polymer composite research [54–57]. Sui et al. (2018) [58] indicated that DIC technology is an accurate way of measuring full deflection profiles of beams under flexural bending. Xian-rong [59] highlighted that using a single camera correlation technique for deflection measurement can result in an accuracy of

0.1 mm. In addition, Sladek et al. [60] found a difference of only 0.174 mm (minimum 0.010 mm with a mean difference of 0.063 mm) in the deflection measurements of an optical laser and a single camera DIC technique. Accordingly, the single-camera DIC technique was implemented, as this seems a suitable method to capture the full deflection profile of the sleepers under the five-point static bending test.

The DIC method in this research was used to measure the displacement at the supports and the deformed shape of the sleepers along its entire length for comparison with the results from the BOEF analysis. Before testing, all sleepers were painted white and randomly speckled with black ink on the observation side as shown in Figure 6 for the DIC measurement. The random speckle pattern helps with pixel tracking (displacement measurement) as the system uses the 256 levels of greyscale for digitisation of the black and white image considering the light intensity. By default, the DIC system measures displacement with respect to image pixel location and hence it requires calibration or a referencing system to real units. This was achieved by drawing 100 mm squares on the plane of the measurement (observation face of the sleepers) and then calibrating it in Video Gauge software [61].

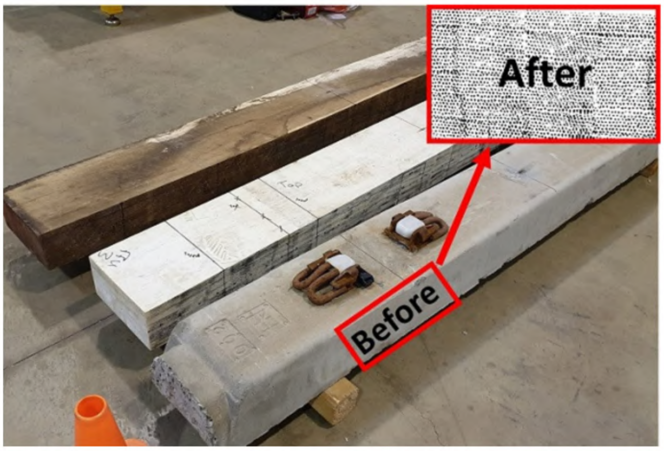

Figure 6. Sleeper samples showing applied speckle pattern.

4.2. Non-Destructive Five-Point Static Bending Tests

As shown in Table 2, the default all-steel support five-point bending test with the shear span of 300 mm produces a high bending moment at the centre as compared to that of the results from the BOEF analysis. The use of resilient pads at the middle support introduces support settlement to flatten the bent shape of the sleepers, thus reducing the centre bending moment. As available timber replacement sleepers have a wide range of elastic modulus, it was expected that the sleepers would have different responses to the softer middle support in terms of moment reduction. Accordingly, two different elastic supports, namely, neoprene and EPDM rubber with a thickness of 25 mm and a width of 150 mm, were considered in addition to steel plates. The external supports are of a steel type of 25 mm thickness and 150 mm width in all cases. The neoprene rubber is a shore A hardness 90 type specified in the bending moment tests for prestressed concrete and alternative sleeper materials [19,37]. The EPDM rubber is a commercially available sealing rubber in Australia with a Shore A hardness of 45 to 60 as reported in the literature [62–65]. According to Ferdous et al. [29], the approximate rail seat load for a timber track based on a 20-ton axle wheel load is 72 kN. Accordingly, a total load of 144 kN was applied to the samples through a spreader beam resting on two rail sections of 1130 mm apart mimicking the narrow-gauge track in Queensland as shown in Figure 7.

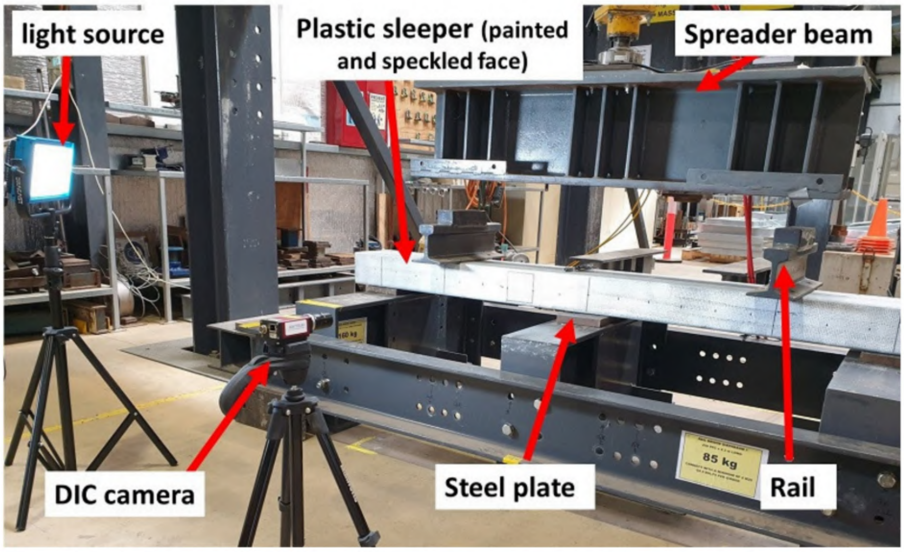

Figure 7. Actual test setup of the five-point bending test, showing the plastic sleeper.

The deflected shape of the sleepers along their length was captured using the DIC camera. A screenshot of the DIC image for each sleeper type is provided in Figure 8. An LVDT instrument was also used to measure the rail seat displacements for validation of the measured displacement using the DIC. From the measured settlement at the middle support (using the DIC), the positive and negative bending moments can be calculated. The ratios of the positive-to-negative bending moments, compared to the BOEF, were then calculated and used as a basis to evaluate the most suitable test configuration that best represents the flexural behaviour of railway sleepers supported by ballast.

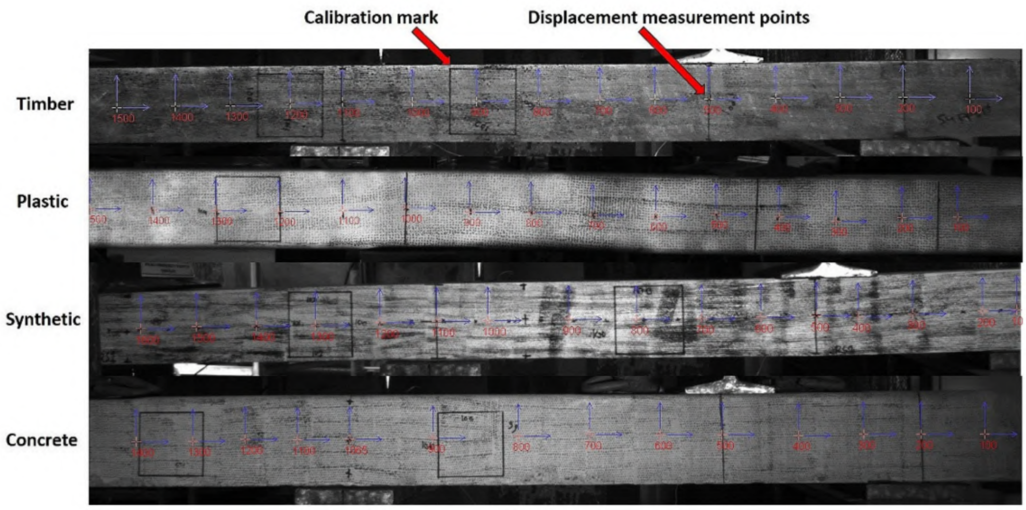

Figure 8. Digital Image Correlation (DIC) images of the sleepers showing displacement points (neoprene support at centre).

5. Results and Discussion

This section presents the experimental results of the full-scale five-point static bending test of different timber alternative sleeper technologies. The load and displacement relationship curves of the rail seat and the centre of the sleepers are presented, highlighting the differences in the settlement of the middle support when resilient pads were used. The deflection profiles of the sleepers along its length measured from the experimental test, and the results of the BOEF analysis are presented. Moreover, the effect of the materials used for the middle support and the modulus of elasticity of the sleepers were analysed and discussed.

5.1. Effect of Materials at the Middle Support

Figure 9 shows the load–displacement behaviour of the sleepers at the rail seat and at the centre, measured using the DIC camera. From the level of load applied, no failure was observed for all the sleepers. The displacement readings from the LVDT at the rail seats are exactly similar to that of the measured displacement from DIC for all sleeper samples. Figure 10 compares the deflected shape according to the five-point static bending test with different materials at the middle support, the BOEF theory and the rail seat test according to AS1085.22 [19] at a service load of 144 kN.

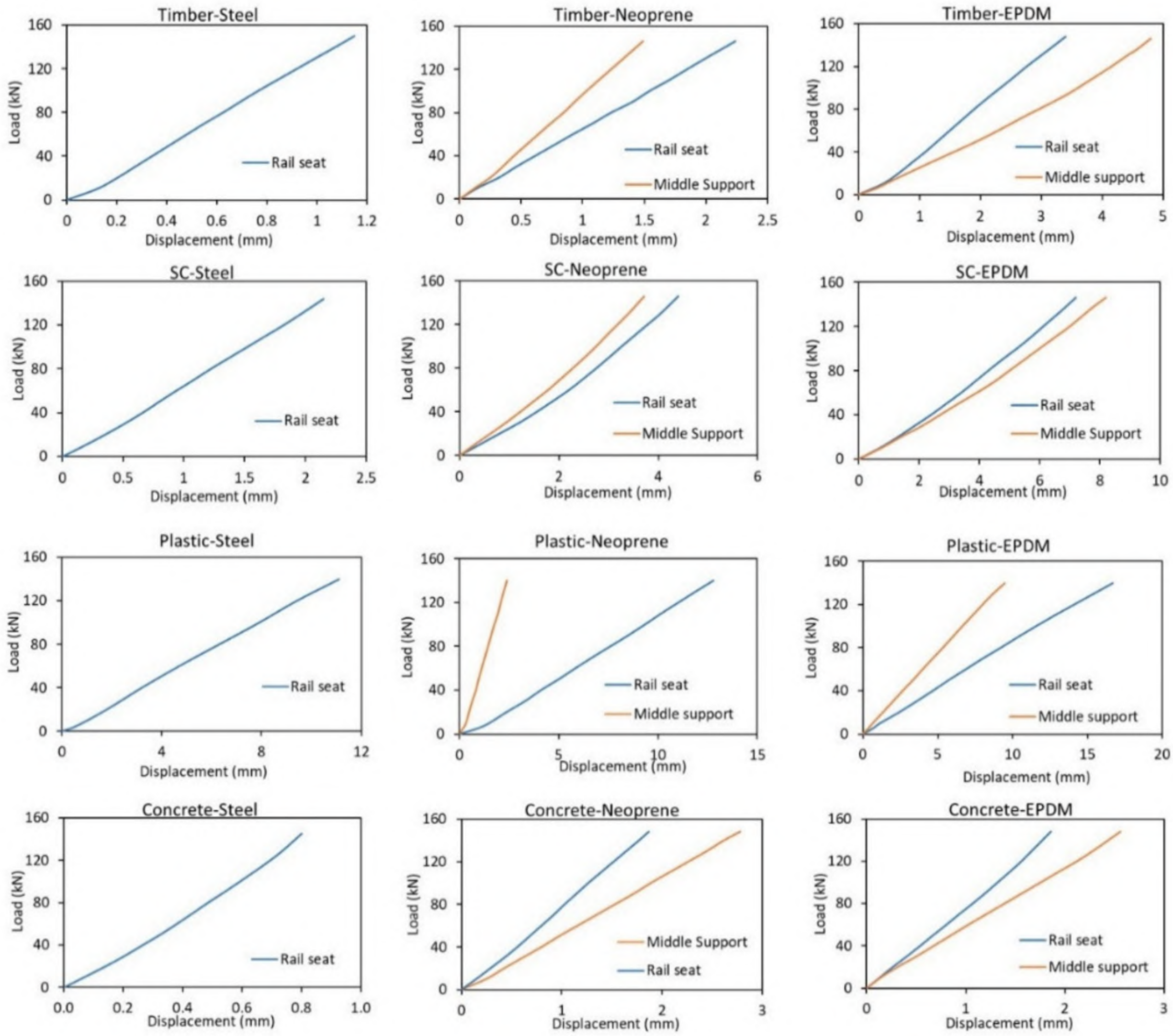

Figure 9. Load–displacement graphs measured at rail seat and centre.

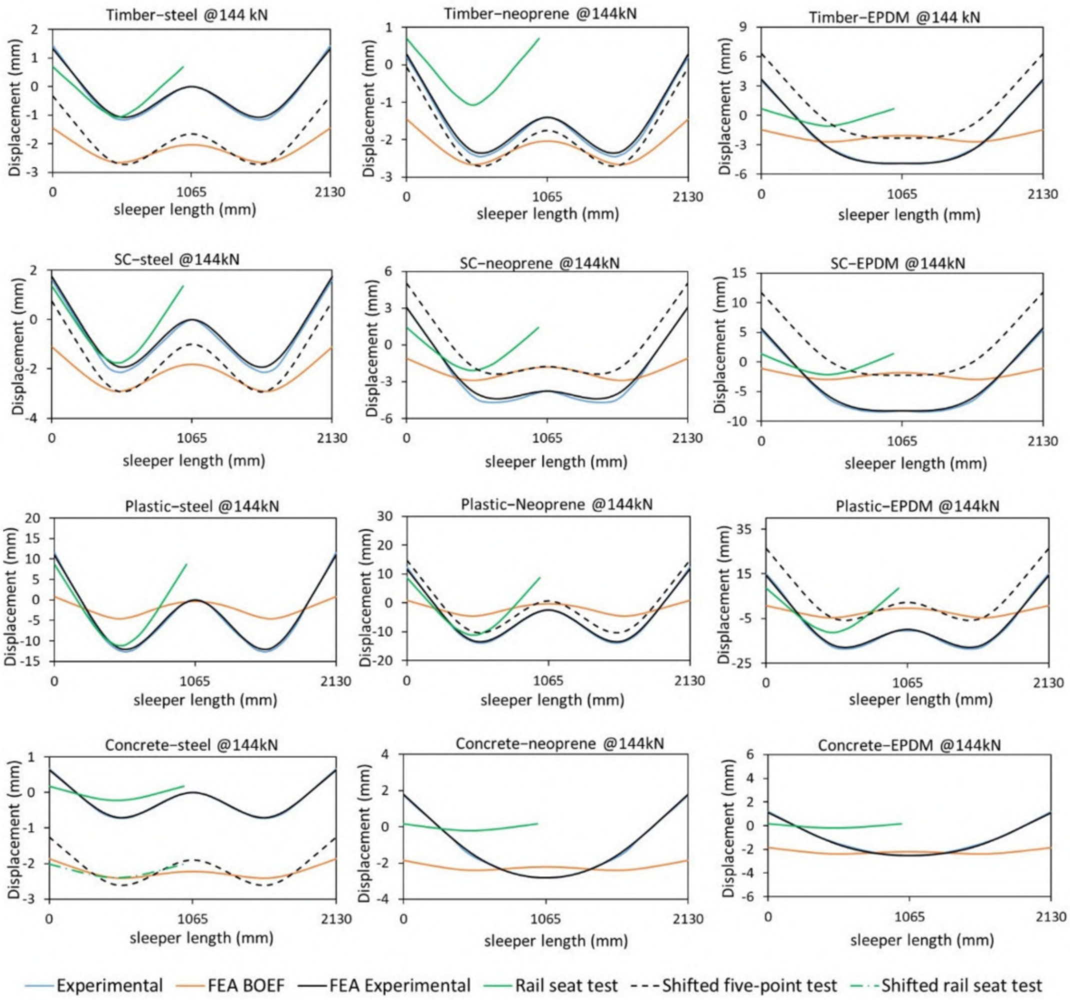

Figure 10. Full-length deflection shape of the sleepers for different support types.

Compared to all-steel supports, the rail seat deflections increased noticeably for all sleeper types when neoprene and EPDM rubber were used at the middle support. The middle support settlement using EPDM is higher than that of the neoprene for all sleeper types with zero settlement using steel at the middle support. Although the use of a softer material at the middle support will introduce more settlement in the sleeper's centre, it will flatten the deflected shape at the centre. This higher settlement value however does not necessarily mean that this support type will reduce the bending moment at the centre. This middle support settlement must be compared to the rail seat deflection and the bending moment envelope from the results of the BOEF analysis. If the middle support settlement is higher than that of the rail seat, this means that the test configuration failed to induce a negative bending moment in the centre as in the case of the concrete sleeper, or the negative bending moment is significantly low as in the case of timber and SC sleepers. This behaviour can be explained further by comparing the deflected shape of the sleepers along their entire length and tested with different support types.

Figure 10 indicates that for most of the tests, the W-shaped bending behaviour was captured. However, differences can be seen between the theoretical (BOEF) and the experimental results. This difference is because, in reality, sleepers are supported by a continuous ballast which results in a gradual bending shape (more subtle). In the bending test, however, the bending profile is more noticeable due to the smaller support areas (three points only). Despite these differences, the success of this test is measured by comparing the intensity of the bending moments at both the rail seat and the centre of the sleepers together with the bending shape profiles. The following paragraphs discuss the bending shape similarity, while the next section discusses the bending moment behaviours.

From Figure 10, it is obvious that the EPDM rubber support is not a suitable material for the middle support for timber, SC and concrete sleepers, as it failed to reproduce a bending moment envelope similar to that of the BOEF as well as very low value of negative bending moment (hogging) at the centre. This is supported by the findings of Carrasco et al. (2012) [66] that sleepers of similar bending modulus would show a clear W-shape bending behaviour, meaning a hogging moment is expected for these sleepers under similar load. This behaviour is caused by the big differences between the stiffness of the resilient pad and the sleepers. Due to the soft EPDM pad, this material kept deflecting (compressing) throughout the test and could not resist the stiffer sleeper material from deflecting at midspan, thus not inducing a negative bending moment. The difference in the FE analytical and the experimental results of the concrete sleepers can be explained similarly for EPDM and neoprene support types. The stiffness of the concrete is so high that the material (EPD or neoprene) of the middle support could not resist the deflection at the centre of the concrete, thus the bending shape is U-shaped. Another reason for this difference could be because of the continuous elastic support in the case of the FEA, whereas in the experimental case the sleeper was supported by two stiff steel supports (external) and one soft internal support. The obtained W-shape deflection of concrete sleepers for steel-steel support also confirms this claim where all the supports have the same stiffness (rigid steel). Out of the tree configurations, the steel-steel support is deemed most suitable for sleepers with very high stiffness (E_s = 38.1 GPa) as the deflection behaviour of the concrete sleeper with all-steel supports shows the best match to that of the BOEF theory (compared to other support types). This can be supported by the findings in [24,34], where the authors indicated that sleepers of very high bending modulus still show a negative bending moment at the centre but it is considerably lower than that of the rail seat. This behaviour could only be captured using the all-steel support as the centre part of the concrete sleepers was considerably flatter than the rail seat section. However, the bending behaviour according to the existing rail seat test shows a better match as compared to the five-point bending. Note that for a higher level of loading (say ultimate load), this may change as the centre steel support does not deflect but the rail seat deflection would increase leading to a more similar behaviour to that of the AS1085.14 standard and the BOEF theory.

There is a slight variation in the bending shape of the timber-steel and timber-neoprene support with the latter being more suitable due to the increased bending at the rail seat and thus increased bending moment. This is due to the settlement of the middle support (EPDM) which resulted in a slightly flatter bent sleeper shape in the centre. It can also be said that neoprene is a more suitable support for SC sleepers due to a flatter centre bent shape which results in a much lower bending moment at the centre than that of the rail seat. On the other hand, the deflected shape of the plastic sleeper shows that the EPDM rubber is the most suitable and closest match to that of the results from BOEF. This means that the EPDM pad, despite its very low stiffness, can resist the bending effect of the plastic sleeper because of its compatible low stiffness (E_s = 1.0 GPa). This high deflection (and thus clear W-shape bending) of plastic sleepers is also noticed from field measurements which require less load to induce the same amount of deflection as timber sleepers [43]. In conclusion, it was found that with the existing span configurations, the most suitable support type for timber and SC sleepers is steel-neoprene, for plastic sleepers is steel-EPDM and for concrete sleepers is steel-steel type.

5.2. Effect of Sleeper Stiffness

Figure 11 illustrates the change in the positive to negative bending moment ratios with the increase in the sleeper stiffness tested with different support types. Equations (1)–(4) were used to calculate the positive to negative bending moment ratios of sleepers supported by all-steel, steel-EPDM and steel-neoprene. These values were then plotted against the corresponding modulus of elasticity of the sleepers to obtain the curves in Figure 11. The plot of the BOEF is based on the average values for a typical ballast modulus range in Australia (10–40 MPa) [40]. Figure 11 helps visualise how the change in the sleeper stiffness affects the bending moment ratios at the rail seat and sleeper centre for different support types. This information makes it easier to compare the closeness of the five-point bending test to that of BOEF for each support type and to evaluate the suitability of the materials used at the middle support for railway sleeper with a different modulus of elasticity (see Table 4).

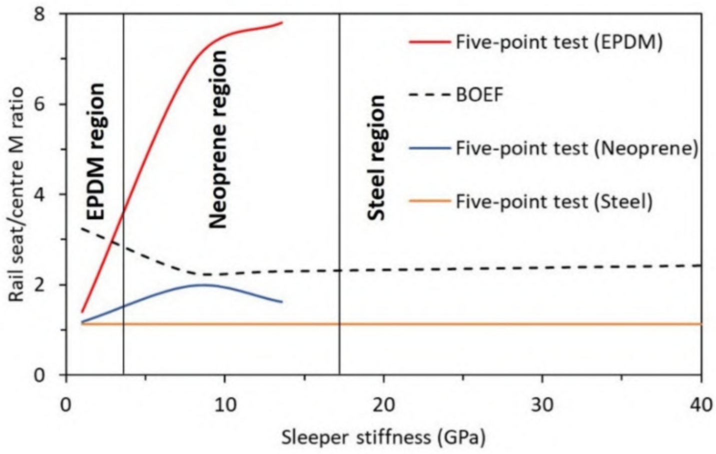

Figure 11. Relationship of positive/negative moment ratio with sleeper stiffness.

Table 4. Bending moment values for different support types (B.M: Bending moment; RS: Rail seat).

Sleeper Type	Support Type	Middle Support Settlement (ΔCR) mm	B.M @ RS (kN-m)	B.M @ Centre (kN-m)	RS/Centre B.M Ratio	Remarks/Most Suitable Support
Timber	Steel	0.00	10.81	−9.50	1.14	Low
	EPDM	4.89	13.51	−1.73	7.81	High
	Neoprene	1.50	11.64	−7.12	1.64	✓
	BOEF	-	7.3	−3.22	2.27	Target
Plastic	Steel	0.00	10.81	−9.50	1.14	Low
	EPDM	9.80	11.32	−8.10	1.40	✓
	Neoprene	2.40	10.94	−9.15	1.20	Low
	BOEF	-	4.94	−1.6	3.09	Target
Synthetic	Steel	0.00	10.81	−9.5	1.14	Low
	EPDM	8.20	13.43	−1.94	6.92	High
	Neoprene	3.75	12.01	−6.04	1.99	✓
	BOEF	-	6.94	−3.11	2.23	Target
Concrete	Steel	0.00	10.81	−9.5	1.14	✓
	EPDM	2.80	18.40	12.36	-	'No negative moment'
	Neoprene	2.55	17.72	10.42	-	
	BOEF	-	8.00	−3.41	2.34	Target

In Figure 11, three regions based on middle support types and sleeper's modulus of elasticity can be derived. It can be seen that the EPDM rubber support is most suitable for sleeper with E_s ranging from 1 to 4 GPa, the neoprene rubber is most suitable for E_s ranging from 4 to 17 GPa and steel support is most suitable for sleepers with E_s of 17 GPa and higher. However, note that these results are for sleepers with a moment of inertia within those reported in Table 3. The values of the bending moment at the rail seat and the centre of the sleepers tested with different middle supports are tabulated in Table 4. While the rail seat to centre bending moment ratio in the second region (4 to 17 GPa) is closest to the ratio-based BOEF, it is expected that EPDM rubber support for sleeper with E_s of

~2.5 GPa would show the closest behaviour to that of the results from the BOEF. When it comes to standardising the five-point bending test, neoprene support could satisfy the requirements of most polymeric railway sleepers. This is because most of the alternative polymer sleepers have a modulus of elasticity within the second bending modulus range illustrated in Figure 11.

Table 4 emphasises the most suitable middle support for a specific sleeper type according to bending moment behaviours. The decision process (column 7 of Table 4) was based on the comparison of the moment ratios of the test and the BOEF theory. For example, the positive-to-negative bending moment ratio of the synthetic sleeper is 1.99 when EPDM support is used, while this ratio is 6.92 when neoprene is used as the middle support. Considering that this ratio for the synthetic sleeper is 2.23 according to the BOEF, it is evident that the EPDM best replicated this behaviour than the neoprene and the steel (steel ratio = 1.14) supports.

6. Analytical Solution of Five-Point Bending and FEA Verification

Table 4 contains the bending moment calculation at the rail seat and centre of the sleepers. As the five-point bending setup is statically indeterminate, two moment equations based on indeterminate beam analysis theories were derived and used for these calculations. This section presents the analytical solution of the five-point bending test set-up with and without middle support settlement using beam theory. The verification of these equations is also carried out using finite element analysis in Ansys Workbench software.

The five-point bending test setup can be represented simply as a supported beam with extra roller support at the centre of the beam or as a continuous beam of two spans as shown in Figure 4. The middle support introduces a new vertical reaction and a negative bending moment in the centre of the beam.

Using equilibrium theory, the general moment equations at the rail seat (M_B) and the centre (M_C) can be expressed as

$$M_B = A_y\, AB \tag{1}$$

$$M_C = A_y\, AB - (P/2 - A_y)\, BC \tag{2}$$

where AB is the distance between points A and B, and BC is the distance between points B and C. P is the total load applied to the sleeper. The unknown reaction at support A (A_y) in Equations (1) and (2) cannot simply be calculated from the equilibrium theory due to the continuity of the beam (extra support at the centre and thus the reaction C_y). When C_y is calculated, the external reactions (A_y and E_y) can easily be calculated from symmetry ($A_y = E_y$). Therefore, an indeterminate beam analysis method can be applied to calculate the middle reaction C_y.

There are several methods of indeterminate beam analysis such as force method, displacement method (slope deflection and moment distribution) and direct stiffness method [67]. The force method, which is also called the consistent deformation method, is considered in the analysis of the indeterminate beam due to its direct relevance and applicability to the 5-point test configuration for sleepers. Similarly, the method of superposition is adopted due to its simplicity. To generate the compatibility equations in the force method, the sleeper is represented with two separate determinate beams as also implemented by [68]. The first beam, which is also called the basis beam, represents the whole sleeper (setup) without the middle support. The second beam, which is called the redundant beam, is a simply supported beam with an upward vertical force (C_y) acting at the middle of the beam (the two rail seat loads are removed), accounting for the middle support effect which was removed in the first (basis) beam. The compatibility equation can now be obtained through establishing the continuity of deformation between the basis beam and the redundant beam for the middle support. When the middle support is removed, the deflection at mid-span (point C) can be written as $\delta C_1 = -\, Pa\,(3L^2 - 4a^2)/(48\, E_s\, I)$. In this relation, E_s is the modulus of elasticity of the sleeper in the longitudinal direction, I is the second moment of inertia of the sleeper and L is the distance between the external supports

A and E. For the redundant member, the mid-span deflection due to the upward force (C_y) can be written as $\delta C_2 = (C_y L^3)/(48 E_s I)$. Writing the compatibility equation for the middle support, i.e., $\delta C_1 + \delta C_2 = 0$, then

$$-Pa\,(3L^2 - 4a^2)/(48\,Es\,I) + C_y\,L^{3/}(48\,Es\,I) = 0$$

$$\therefore C_y = Pa\,(3L^2 - 4a^2)/L^3 \tag{3}$$

In Equation (3), a is the distance between the rail seat and the external support.

For the five-point static bending tests with elastic support at the centre, there is a settlement at the middle support. Therefore, the summation of the displacements in the compatibility equation is not equal to zero and can be written as

$$-Pa\,(3L^2 - 4a^2)/(48\,Es\,I) + C_y\,L^{3/}(48\,Es\,I) = -\Delta C_R$$

where ΔC_R is the relative displacement of the middle support with reference to the external supports. Equation (3) then becomes

$$C_y = (Pa\,(3L^2 - 4a^2) - 48\,Es\,I\,\Delta C_R)/L^3 \tag{4}$$

To validate the analytical solution, a three-dimensional FEA based on a typical QR timber sleeper has been conducted (Figure 12) using Ansys Workbench 19.2 software, from Ansys, Inc. Canonsburg, Pennsylvania, US. The sleeper was modelled using Solid186 homogenous structural solid element. The sleeper has an elastic modulus of 13.6 GPa and a cross-section of 230 mm by 115 mm. A bending strength of 55 MPa, a tensile strength of 34 MPa (parallel to grain) and a compression strength of 42 MPa (parallel to grain) were considered based on the AS 1720.1 [69]. The total load applied is 144 kN (72 kN per rail seat). The external supports were restrained for movement in all directions; however, rotation along the longitudinal axis was set to free to allow for the bending effect. To validate Equation (2), a relative displacement of 1.5 mm (ΔC_R) was applied to the middle support. The support reactions and the bending moments according to the analytical and the results of the numerical solutions are compared in Table 5.

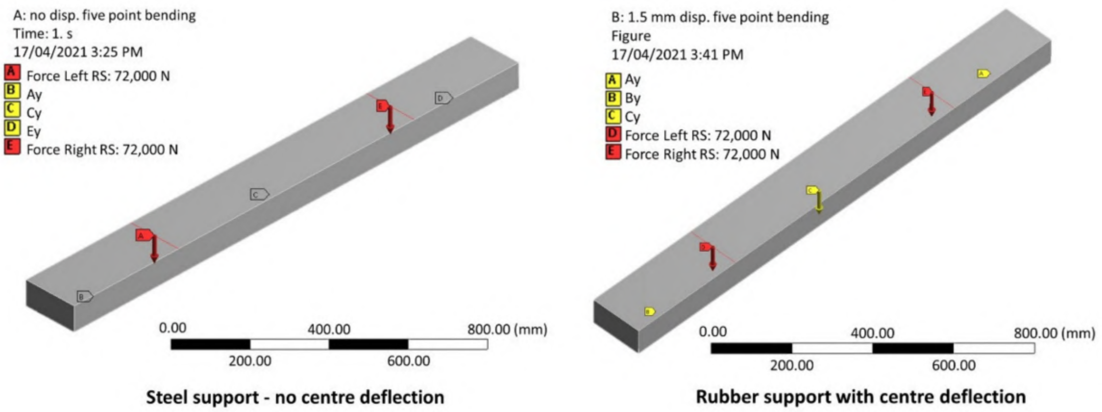

Figure 12. Validation of the analytical solution with finite element (FE) analysis.

Table 5. Comparison of analytical and numerical solutions.

Middle Support Condition	Type of Analysis	Ay and Ey (kN)	Cy (kN)	Moment at Rail Seats, RS (kN-m)	Moment at Centre, C (kN-m)	RS/C Ratio
No settlement	Analytical	36.05	71.91	10.81	−9.50	−1.138
	FEA	36.07	71.85	10.82	−9.47	−1.142
1.5 mm settlement	Analytical	38.80	66.40	11.64	−7.12	−1.635
	FEA	38.70	66.59	11.61	−7.20	−1.613

The numerical solution shows a very good agreement with the analytical solution. The small variations could be due to the compression of the sleeper at the supports and the loading points for the numerical analysis due to the three-dimensional shape. The experimental results were also compared to that of the results of the FE analysis to ensure the bending moments calculated according to the analytical equations represent the experimental results. This was achieved by monitoring the strain redistribution at the rail seat and the centre due to the middle support settlement using the DIC technique. The measurement was obtained on the front face of the sleepers, i.e., bottom rail seat and top centre, where maximum bending moments expected to occur. The strain measurement was justified because the sleeper materials were stressed within their elastic region, as the load-displacement graphs (Figure 9) also demonstrates. This means that the ratio of rail seat to centre strain represents the stress ratio and thus the bending moments for a specific load (144 kN in this case). It was found that the rail seat to centre strain ratio is 1.2 for all steel supports, while it increased to 1.5 when neoprene support used at the centre. Although there is a difference of 0.1 when compared to the bending moment ratios in Table 5, this difference is justifiable as the strain was measured on the front face of the sample, not on the bottom (for rail seat) and top (for centre) faces where maximum strain occurs. Notwithstanding, it is clear that when neoprene support was used, the rail seat strain and thus the bending moment increased, as also shown in Figure 10, where the bending shape at the rail sear is much sharper when neoprene support is used.

Therefore, Equations (1)–(4) can be used to analyse the five-point static bending tests and predict the bending moment distribution along the sleeper for different loading levels and support types with measured relative middle support settlement. This information is useful in the evaluation of the performance of the sleepers as well as in future development. For example, a middle-support settlement of 1.5 mm will result in a middle-support reaction reduction from 71.91 kN to 66.40 kN calculated using Equation (4) (for timber sleeper, i.e., E_s = 13.6 Gpa). Using this value, the magnitude of the external support (A_y) can be calculated as well as the magnitude of the centre bending moment (Equation (2)). A summary of the magnitude of the centre bending moment for timber sleeper under an applied rail seat load of 72 kN is provided in Table 5. Note that the compression of the sleepers at the rail seat and the supports is not considered in the analysis. Finally, any changes regarding the test span because of different gauge-width can be incorporated into the equation simply by changing the values of "*a*" and "*L*".

7. Conclusions

This paper presents a new test method for evaluating the flexural behaviour of timber-alternative sleeper technologies. The effectiveness of the five-point static bending test was evaluated by non-destructive testing of four sleeper types having different modulus of elasticity: timber (E_s = 13.6 GPa), recycled plastic (E_s = 1.0 GPa), synthetic composites (E_s = 8.1 GPa) and low-profile prestressed concrete (E_s = 38.0 GPa) sleepers. Moreover, three materials were considered in the middle support—steel, neoprene and EPDM rubber pads, with the end supports using steel in the verification of the five-point static bending test. From the results of this work, the following conclusions can be made:

- The five-point static bending test is a simple test method to simulate the sleeper behaviour supported by ballast and subject to simultaneous positive and negative bending moments. The closeness of this testing method to that of the in-situ situation is limited to the sleeper behaviour according to BOEF theory and the shear span of 300 mm to prevent high shear stress beyond that of the AS1085.14 standard. The deflected profiles from the five-point static bending test are very similar to that of the deformation behaviour from analysis using the beam on elastic foundation except for the concrete sleepers.
- The bending modulus of the sleeper is a more influential parameter than the support modulus (ballast) when determining the bending moment, shear force and deflected shape of the sleepers. The ratio of bending moment at the rail seat (sagging) to

the centre bending moment (hogging) increases with the increase in the modulus of elasticity of the sleepers. The sagging to hogging moment ratio of recycled plastic sleeper (E_s = 1.0 GPa) increases due to higher bending at the rail seat due to its significantly low elastic modulus.

- The hardness or elasticity of the middle support in a 5-point bending test has a significant influence in inducing appropriately the magnitude of the positive and negative bending moments experienced by railway sleepers. Neoprene rubber is found suitable for timber and FFU sleepers, EPDM rubber seemed suitable for plastic sleepers and steel support for low-profile prestressed concrete sleepers. This indicates the type of middle support is very much dependant on the elastic modulus of the sleeper materials, i.e., the higher the elastic modulus of the sleeper, the stronger the middle support material is required. Neoprene support is however suggested to standardise the five-point bending for polymeric-based railway sleepers.
- The modulus of railway sleepers directly affects the bending moment distribution between the rail seat and centre of the sleepers. The positive-to-negative bending moment increases as the sleeper stiffness increases for neoprene and EPDM support. The high elasticity of the low-profile prestressed concrete sleeper requires a steel pad to induce a negative bending moment at the middle of the sleeper. This was however limited to the loading intensity and type (static) applied in this investigation.
- The developed theoretical equation based on the force method analysis of indeterminate beam and considering the settlement of the middle support and modulus of elasticity of the sleepers can calculate directly the reactions at supports and bending moments along the length of the sleeper. The verification with FEA analysis for timber sleeper showed that the analytical solution can accurately predict the magnitude of the bending moments at the rail seat and centre of the sleeper under 5-point static bending tests.

The above results showed that the 5-point static bending test is a simple and reliable testing method to evaluate the bending behaviour of timber alternative sleeper technologies. Further research is however required to evaluate the effectiveness of this testing method for ultimate and cyclic loading conditions, especially to confirm the failure location and behaviour of different polymer-based sleeper technologies. Moreover, the effectiveness of this new test method in evaluating the bending performance of other alternative sleeper technologies beyond those considered in this study should be conducted. For example, sleepers with different material properties (thus different E_s) or different sectional properties along the length of the sleepers. Once this is achieved, this new test method can lead to the development of a unified test standard for current and emerging railway sleeper technologies.

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CHAPTER 5: PAPER 3

Static behaviour of sleepers under five-point bending

In Chapter 4, it was found that the five-point bending test can precisely mimic the behaviour of railway sleepers supported by a ballast. It was also found that neoprene as the centre support and steel as the external support provide accurate bending behaviour of composite railway sleepers. Accordingly, **Manuscript 3** presents the evaluation of the static behaviour of timber and its replacements, i.e., low-profile prestressed concrete, plastic, and synthetic composite sleepers under the five-point bending test set-up. The DIC technique was used to capture the full-profile bending deflections and full-field strain mappings that was useful to identify crack and damages. The DIC data was validated with strain gauge data at the rail seat and the centre of the sleepers.

The results showed that the effect of sleeper material type on the bending profiles is more significant at the centre part than at the rail seats. It was also found that the alternative sleepers have significantly lower flexural strength at rail seats than timber, i.e., low-profile prestressed sleepers (85%), synthetic composites (56%) and lastly, engineered plastic sleepers (42%). The failure mechanism of the sleepers was found to be different with timber sleepers failing in flexural cracks and the synthetic composite sleepers failing in longitudinal shear cracks. On the other hand, plastic sleepers fail by permanent deformation. The observed difference in the static behaviour of timber alternative railway sleepers highlighted the need of understanding their fatigue behaviour, which is conducted and presented in Chapter 6.

CHAPTER 6: PAPER 4

Fatigue degradation of composite railway sleepers

In Chapter 5, it was found that the flexural strengths of composite sleepers are considerably lower than their timber counterparts. The failure mechanisms of timber and its alternatives are also found to be different. As these results were based on static test, **Manuscript 4** evaluated the behaviour of composite railway sleepers under fatigue service loads. The effect of sample size on the fatigue degradation of composite sleepers was determined by testing small-scale (1:6) sleepers along with the full-scale ones. The fatigue life evaluation of the small-scale sleepers was performed at different stress levels while the fatigue life evaluation of the full-scale sleepers was under service loading conditions. Degradation factors were derived to determine how composite sleepers degrade under fatigue loads and to establish a correlation between the small-scale and full-scale tests.

The results showed a similar static and fatigue behaviour for small- and full-scale sleepers but with distinct fatigue failure and resistance for each sleeper type. The fatigue resistance of timber sleepers is governed by their flexural strength at the rail seat while the behaviour of synthetic composites mainly depends on their shear strength. The plastic sleepers, on the other hand, suffered from permanent deformation at the rail seat and centre of the sleepers. The results also indicated that small-scale sleepers under fatigue will degrade 3.27 and 7.4 faster than full-scale composites and plastics sleepers, respectively. The major findings from this work are highlighted in the Conclusion and recommendations for further studies to understand completely the behaviour of sleepers in a railway track are presented in Chapter 7.

Fatigue degradation of timber alternative composite railway sleepers

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Abstract

Evaluation of the fatigue life is important for the acceptance of alternative railway sleepers but research in this area is scarce. This research evaluates the fatigue degradation of synthetic composite, ultra-high-molecular-weight polyethylene (plastic), and timber sleepers under small-scale (1:6) and full-scale cyclic load tests. Firstly, the static bending tests of the different sleepers samples using small scale and full-scale sleepers were conducted. Secondly, materials fatigue tests under three-point bending tests and at different stress levels were implemented. Thirdly, the fatigue performance of full-scale railway sleepers was evaluated up to 1 million load cycles. Fourthly, the post fatigue bending behaviour of the full-scale sleepers was determined. Finally, degradation factors were established to correlate the materials fatigue behaviour to that of full-scale sleepers' behaviour. The results showed that the static and fatigue behaviour of timber is governed by its flexural strength while the behaviour of synthetic composites mainly depends on its shear strength. On the other hand, plastic sleepers suffered from permanent deformation. It was also found that the small-scale materials under fatigue will degrade 3.27 and 7.4 faster than full-scale composites and plastics sleepers, respectively. The fatigue performance and the degradation factors obtained in this research can be used as a guide in materials testing and design of timber alternative railway sleepers under cyclic loading.

Keywords: composite sleeper; fatigue behaviour; five-point bending test; cyclic loading; sleeper stiffness; timber sleeper

1 Introduction

Sleepers are one of the most critical components of railway tracks. These track components are often subject to fatigue due to repeated loads from the passing trains which cause various types of deteriorations [1]. It is a requirement therefore that railway sleepers demonstrate adequate fatigue resistance during their service lives. Timber sleepers, which have successfully been used for over 150 years around the world, have demonstrated excellent fatigue resistance in actual tracks. However, no literature is available quantifying the fatigue performance of timber sleepers. Moreover, timber sleepers can suffer from environmental degradations leading to premature failure within 10 – 15 years of their installation [2, 3]. In recent years, polymeric and composite-based sleepers have been introduced to replace deteriorated timber sleepers. Among these alternatives, synthetic composites reinforced with longitudinal glass fibres and plastic-based sleepers gained significant attention from researchers and track owners as these materials provide excellent environmental resistance [4]. Being relatively new materials, there is very limited information on the fatigue behaviour of these alternative railway sleepers. Hence, understanding the performance of railway sleepers under this loading condition is of vital importance to facilitate their acceptance in the maintenance and new construction of railway tracks.

A number of research studies have been reported developing and characterising the properties of epoxy polymer concrete [5], crumb rubber and short fibre [6], plastic with softwood and mineral fillers [7], low and high-density polyethylene with steel bar reinforcements [8] for railway sleeper applications. These sleeper materials would require a series of full-scale sleeper static and fatigue validation tests before their in-track acceptance and possible installation. However, most of the performance evaluation tests are limited to static loading with very few investigating the fatigue resistance of composite sleepers. For example, it was shown that orienting the phenolic core sandwich beams of composite sleepers from horizontal to vertical changes their failure mode from brittle to progressive [9]. Compare to timber sleepers, Fibre-Reinforced Foamed Urethane (FFU) exhibited a higher track settlement in a railway turnout [10]. Jing et al.

[11] optimised the shape of synthetic composite sleepers which demonstrated a 19% improved static lateral resistance. Full-scale sleeper concepts made of Particulate Filled Resin (PFR) and Glass Fibre Reinforced Polymer (GFRP) pultruded section filled with rubberised concrete showed equivalent static behaviour to recycled plastic and softwood timber sleepers, respectively [12]. However, no fatigue performance of these sleepers was reported. These performance differences coupled with the relatively short history and knowledge of actual fatigue performance of the timber alternative sleepers motivate more research into the better understanding of the behaviour of these emerging sleeper materials under the repetitive loading caused by a passing train in a railway track.

A comprehensive review on the failure mechanisms of mainline sleepers indicated that fatigue cracking is a major issue for steel and concrete sleepers [3]. There is limited research and industry reports however on the fatigue performance of alternative composite sleepers, with most of the published research being on prestressed concrete sleepers. Parvez and Foster [13] reported that the addition of 0.5% steel fibre reinforcement to prestressed concrete sleepers extends its fatigue life by at least 200% and with overall lower deflection than that of pure prestressed concrete sleepers. You and Kaewunruen [14] discussed that the fatigue life of prestressed concrete sleepers is influenced by the properties of the material, manufacturing quality, and the density of the train. The most commonly used fatigue life assessment methods for concrete sleepers with a recommended simplified method is outlined in [15], indicating that the behaviour of concrete railway sleepers is relatively well-understood. Bhkari et al. [16] studied the post fatigue behaviour of glue laminate timber and found that their performance is comparable to solid timber sleepers. On the other hand, Ferro et al. [17] indicated that FFU composite sleepers will have 25% higher settlement in a long run than concrete sleepers. Koller [18] also indicated that the fatigue performance of FFU sleepers is not affected by temperature variations. The in-situ observation of recycled plastic sleepers indicated the cracking could happen within the first 15 years of their track installations [19]. These studies have shown that the fatigue behaviour of composite sleepers is different from their static performance, but recent studies highlighted that the behaviour of most composite materials depends on the loading conditions. For example, dynamic mechanical analysis (DMA) showed that the modulus of elasticity of the polymeric sleepers can vary between 1.5 GPa and 2.7 GPa depending on the procedure they are tested, i.e. high modulus at low temperature or high frequency [20]. These changes in their viscoelastic properties are also different to that of timber and concrete. Similarly, it was observed that continuous cyclic loading introduces excess deflection (creep) and generates higher temperature at testing which accelerates the creep for polymer sleepers. Hence researchers in [21] proposed an intermittent loading cycle to represent the track conditions allowing the cooling-off period, representing the time between the passing of two trains. As available studies were conducted under different loading conditions, it is hard to correlate the results of one study to another. Besides, most studies considered only a particular type of composite sleeper. Therefore, comparative studies on the fatigue behaviour of different composite sleepers under the same testing conditions will provide a better insight into the actual fatigue performance and differences of these sleeper technologies.

In many civil engineering applications, the results of small-scale tests are used to predict empirically the behaviour of full-scale structures. For example, the prediction of the structural crack arrest of different structures [22], fatigue crack growth (FCG) of different structures [23-25], and the impact fracture properties of various alloys [26] were developed from the results of small-scale laboratory tests. Researchers in [26] indicated that a direct comparison (correlation) between the small-scale and full-scale behaviour can be obtained while other researchers [22] suggested that a correlation method is required to better predict the actual behaviour of full-size structures. Moreover, a comprehensive review on very high cyclic fatigue studies indicated that most studies were carried out on small-scale samples due to the complexity of testing full-scale specimens [27]. Notwithstanding, the results of the small-scale tests have been found to predict with some level of accuracy the behaviour of full-scale structures. However, no available study in the literature compares the small-scale and full-scale fatigue behaviour of railway sleepers. If proven effective, small-scale tests will be very beneficial to investigators and manufacturers to save time and effort in characterising the fatigue behaviour of sleepers instead of heavy and full-scale sleepers. This is the motivation, novelty and significance of the current study.

This study aims to evaluate the fatigue resistance of different composite sleepers while investigating the effect of specimen size. Different sleeper materials including hardwood timber, ultra-high-molecular-weight polyethylene (UHMWPE) plastics (called plastic sleepers hereinafter) and glass fibre reinforced polyurethane foam (called synthetic composite hereinafter) are tested under cyclic loading. Small-scale samples are tested under a three-point bending test up to failure while the full-scale sleepers are tested under the five-point bending test up to 1 million load cycles. Correlations between the results of the fatigue performance of the small-scale materials to that of full-scale sleepers were then conducted, and correlation factors were derived. The results of this study will provide new and critical insights into the fatigue resistance of alternative sleeper materials and facilitate the fatigue resistance evaluation of full-scale sleepers through small-scale tests for their optimised manufacturing and safe design.

2 Static bending behaviour of sleepers

This section presents the results of the investigation and correlation of the static bending behaviour of small-scale and full-scale railway sleepers.

2.1 Sleeper material testing

2.1.1 Sample preparations

The sleeper materials test was implemented using coupon samples cut directly from different full-scale railway sleepers (Figure 1). These samples were carefully selected to obtain defect-free samples such as knots for timber sleepers to provide accurate material fatigue resistance. The cross-section of the sample materials are scaled-down of the full-size sleeper section by approximately a factor of 6 (1:6), i.e., 38 mm (±2 mm) width x 19 mm (±2 mm) depth or nearest as compared to the 230 mm x 115 mm of full-size sleepers. An electric diamond circular saw was used to slice up the full-scale sleepers into small beam specimens. Where needed, the samples were sanded for a more uniform cross-section (see Figure 1). The residual of the plastic and the timber sleepers were constantly removed from the table saw to prevent jamming of the equipment as shown in Figure 1.

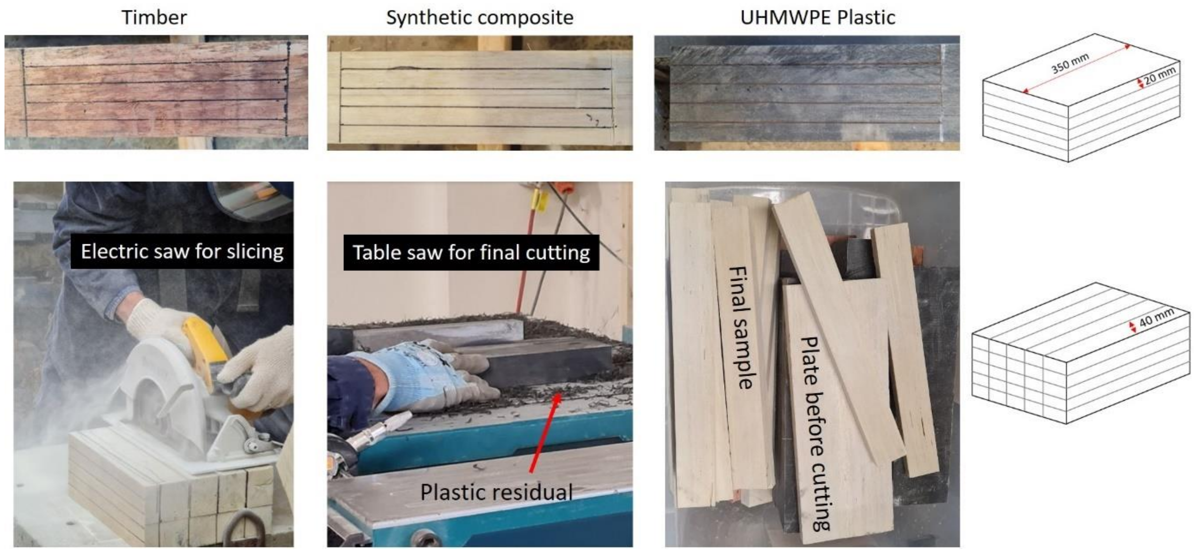
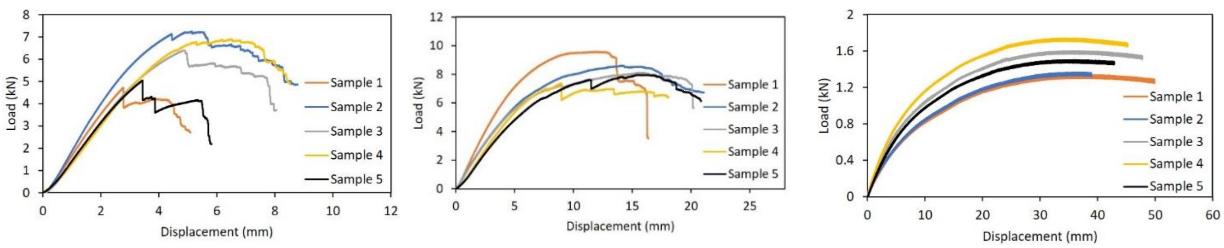


Figure 1. Coupon testing sample preparation

2.1.2 Static ultimate bending test

A three-point bending test was adopted for the sleeper material test as this is one of the most used methods to evaluate the static and fatigue behaviour of composite materials [28-30]. Hence, a three-point bending test of 200 mm span was considered as this test span produces a shear span-to-depth ratio of 5 which exceeds the most commonly used ratio of 2 to 3 for beams [31], ensuring a pure bending effect is obtained. Five samples each of timber, plastic and SC sleepers were prepared and tested up to failure. A servo-hydraulic universal testing machine of 100 kN capacity was used to apply the load through a spreader beam with the loading and supports made of 20 mm diameter rollers following the ASTM D790-17 [32] standard protocols. Equations 1 and 2 of the standards were used to calculate the testing speed (3 mm/min) and the flexural strength of the sleeper materials.

The load-displacement behaviour of all samples is shown in Figure 2 and the failure mechanisms in Figure 3. The load-displacement graphs of timber and synthetic composites indicate progressive failure due to cracks (sudden drops in load) while the load-displacement of the plastic samples show a creep failure. The different failure modes are mainly flexural cracks for timber, longitudinal shear cracks for the synthetic composites (SC), and permanent deformation for the plastics (Figure 3). It is worth noting that flexural cracks at the midspan of the SC material were also observed as well as longitudinal shear cracks at the midspan of the timber samples. The notable differences in the failure mechanisms of the timber and SC materials were the location and extent of the shear cracks. The length of the shear cracks for the SC sleeper covered at least half of the sample whereas for the timber sleeper it was limited to the central region. Horizontal shear cracks were observed at various depths of the SC samples while the shear cracks of the timber were limited to the bottom centre part. Accordingly, the governing failure mechanism of the SC material is longitudinal shear cracks along the glass fibre reinforcement while the governing failure mechanism for timber is flexural cracks. On the other hand, the plastic sleeper showed excessive deflection (around 30 mm at ultimate load) with around 50% of it recovering after 24 hours.



(a) (b) (c)

Figure 2. Load-displacement graphs: (a) timber; (b) synthetic composite; (c) plastic

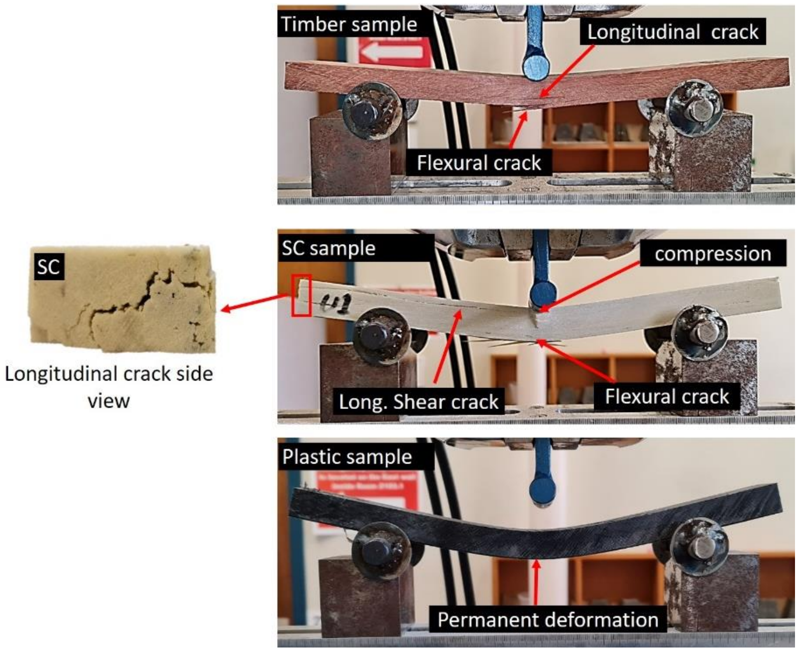


Figure 3. The failure mechanism of timber, synthetic composite, and plastic materials.

Table 1 summarises the ultimate load and flexural strength of the sleeper materials. Although the average ultimate load of the SC samples (8.2 kN) is 40% higher than the timber (5.9 kN), their flexural strength was nearly identical. This is explained by considerably the smaller cross-sections of the timber sample (see Table 1). However, previous research has shown that full-scale SC sleepers are considerably weaker than timber sleepers in their flexural strength [33]. This can be justified by the fact that full-scale sleepers are more prone to have defects such as voids and inconsistent reinforcements. This emphasizes the need for the comparison of full-scale fatigue behaviour assessment of the same sleeper materials which will be provided in the following sections of this research. In the materials tests, the samples were tested at 40%, 60%, and 80% stress level loads (from Table 1) as also implemented by other researchers [34, 35].

Table 1. Material properties of different sleepers

Material	Sample	Dimensions (width × height) mm	Ultimate load (first crack) (kN)	Flexural strength (MPa)
Timber	1	36.0 × 18.8	4.7	109
	2	36.5 × 19.5	6.8	148
	3	36.3 × 18.6	6.4	153
	4	36.8 × 18.7	6.7	152

	5	36.2 × 18.7	5.0	118
Average		36.4 × 18.9	5.9	136
Standard Deviation		0.27 × 0.30	0.9	18.7
Synthetic composite	1	39.8 × 21.5	9.3	152
	2	40.8 × 21.0	8.5	142
	3	39.9 × 22.2	8.1	123
	4	40.2 × 20.2	7.4	135
	5	40.6 × 20.5	7.6	133
Average		40.2 × 21.1	8.2	137
Standard Deviation		0.70 × 0.71	0.7	9.65
Plastic	1	39.0 × 18.6	1.3	29.0
	2	37.6 × 18.3	1.4	32.4
	3	38.0 × 18.8	1.6	35.5
	4	39.0 × 20.0	1.7	33.0
	5	37.5 × 18.9	1.5	33.0
Average		38.2 × 18.9	1.5	32.6
Standard Deviation		0.66 × 0.60	0.15	2.1

2.2 Full-scale sleeper bending tests

One full-scale sample from each sleeper type was tested up to failure under the five-point bending test and the results were compared with the material testing. The five-point bending test, which consists of two continuous spans (i.e., three supports) and two loading points (i.e., rail seat locations), was followed due to its similarity to in-situ sleeper loading conditions [36]. Researchers previously discovered that using steel plates for external supports and neoprene for internal support would induce similar bending moments of composite sleepers on the ballast [36]. Hence, the same configuration was followed in this research as shown in Figure 4. The load was applied at a rate of 20 kN/minute until failure through a hydraulic ram attached to a spreader beam resting two rails (61 kg/m) with a loading span of 1130 mm, representing the common narrow gauge-width tracks in Queensland, Australia.

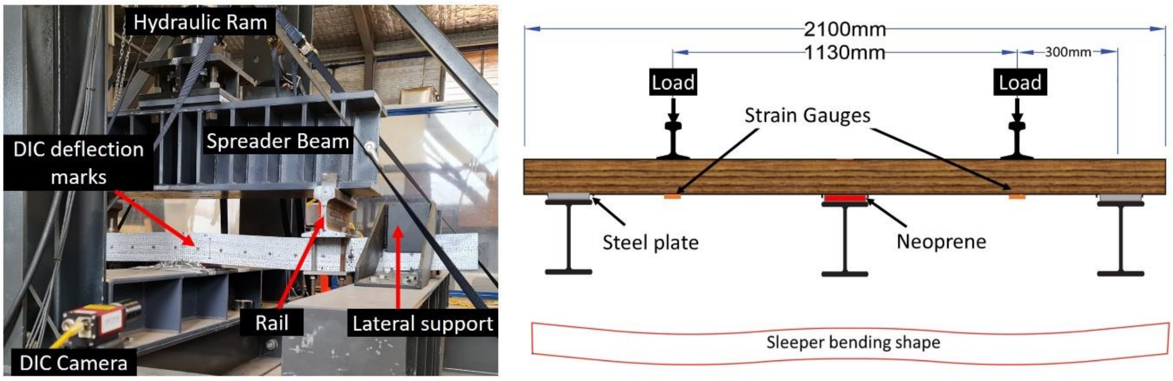


Figure 4. Fatigue test configuration.

The failure modes of all three sleeper types are shown in Figure 5. The timber sleeper failed in flexure under the rail seat followed by horizontal shear cracks between the rail seats and the centre of the sleeper. The synthetic sleeper failed in longitudinal shear cracks while the plastic sleeper failed in permanent deformation. These failure modes are very similar to those observed in the materials tests and those found in the literature under the same bending test for similar materials [37]. Since similar behaviour between the materials test and full-scale sleepers are obtained, it was verified from the static bending test that the material test can be correlated with the test results of the actual railway sleepers. This indicates that the fatigue resistance of the different sleeper materials can be compared and a correlation between the two testing methods can be developed.

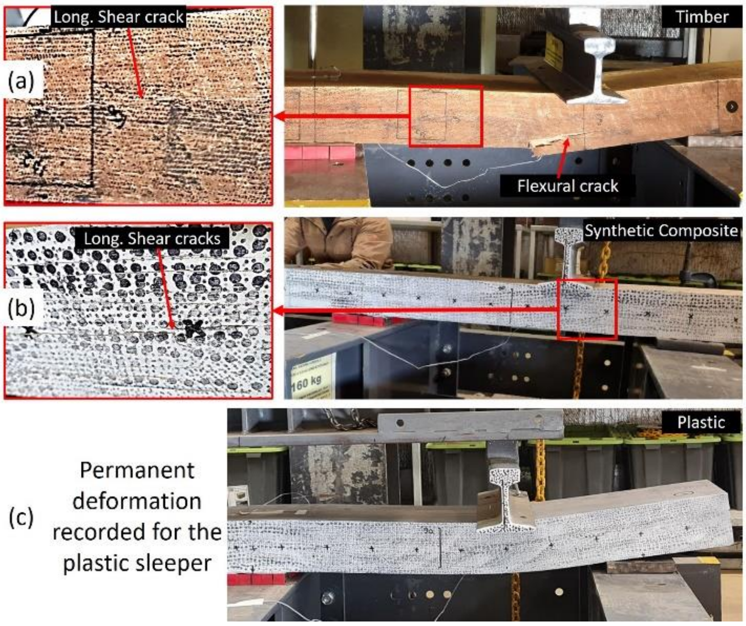


Figure 5. Sleeper failure modes under five-point bending test; (a) timber; (b) synthetic composite; (c) plastic.

3 Fatigue behaviour of different sleeper materials

The fatigue testing program uses the same machine with a different controller software, follows the same testing configurations, and sample dimensions described in Section 2.1.2 but with a cyclic loading pattern. The commonly used stress ratio (R value) of 0.1 by other researchers for materials tests [34, 35, 38] was considered for the fatigue tests. Also, three stress levels, i.e., 80%, 60%, and 40% that are commonly followed by researchers were considered [35, 38]. The corresponding loads of each stress level were back calculated from the average flexural strength shown in Table 1 considering the actual dimensions of the fatigue samples. This load was applied at a frequency of 3 Hz which is in the range specified in the AS 1085.22:2020 standard [39]. Nine samples of each material type were tested under fatigue, i.e., three samples for each stress level. Due to time limitations, the samples were tested up to failure or one million cycles whichever occurred first. According to the EN ISO 13003:2003 [40], a 20% stiffness loss can be considered as failure and hence the tests can be stopped even before 1 million cycles.

Figures 6-8 depict the results of the 80%, 60%, and 40% stress levels fatigue loadings respectively, showing the load-displacement curves at the centre of the samples and their failure modes. The load-displacement curves show both maximum deflection at the highest load and minimum deflection for the lowest load for the stress ratio (R) of 0.1 (i.e., 0.1 of the maximum load). In Figures 6-8 and hereafter, the letters P, SC, and T represent plastic, synthetic composite, and timber, respectively. Also, the first two digits after the sample names represent the stress level, and the last digit represents the sample number. For example, P801 implies plastic material, stress level 80%, and sample number 1.

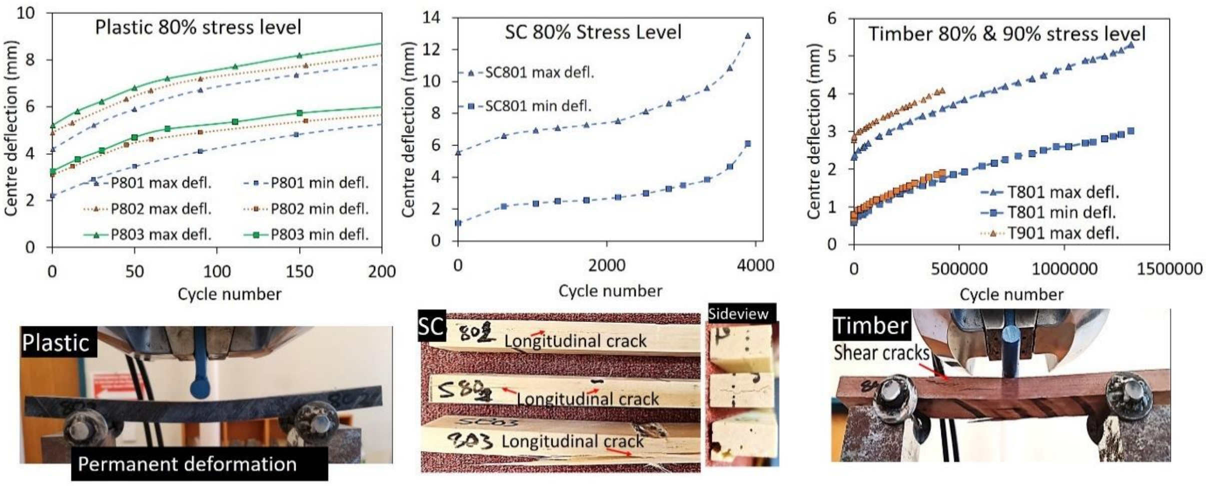


Figure 6. Deflection and failure mechanism of the samples at 80% stress level

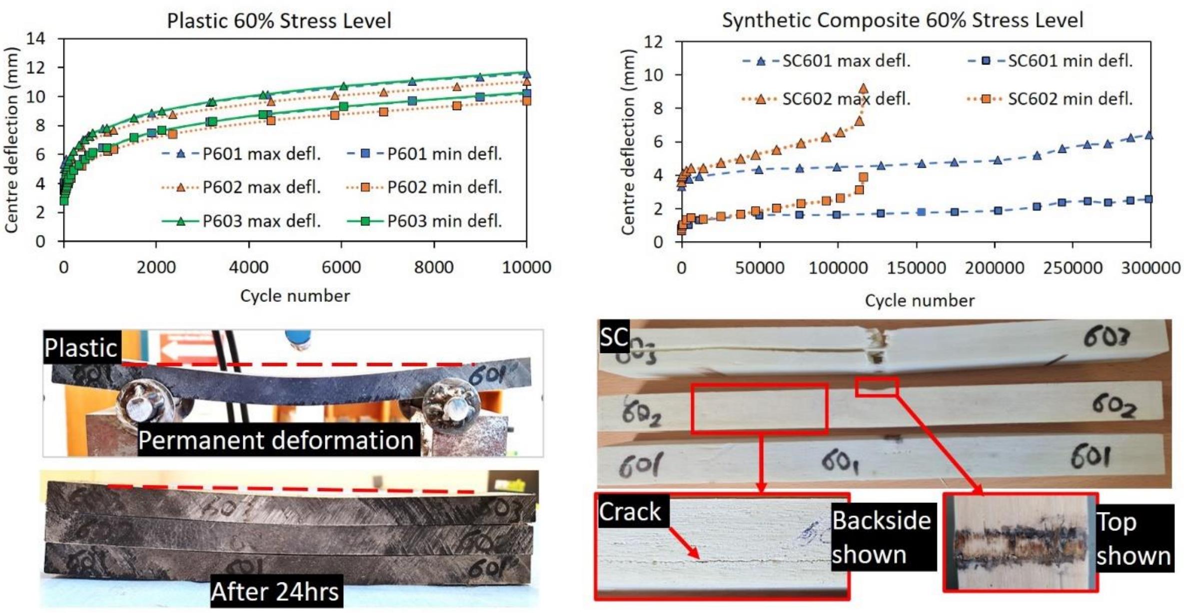


Figure 7. Deflection and failure mechanism of the samples at 60% stress level

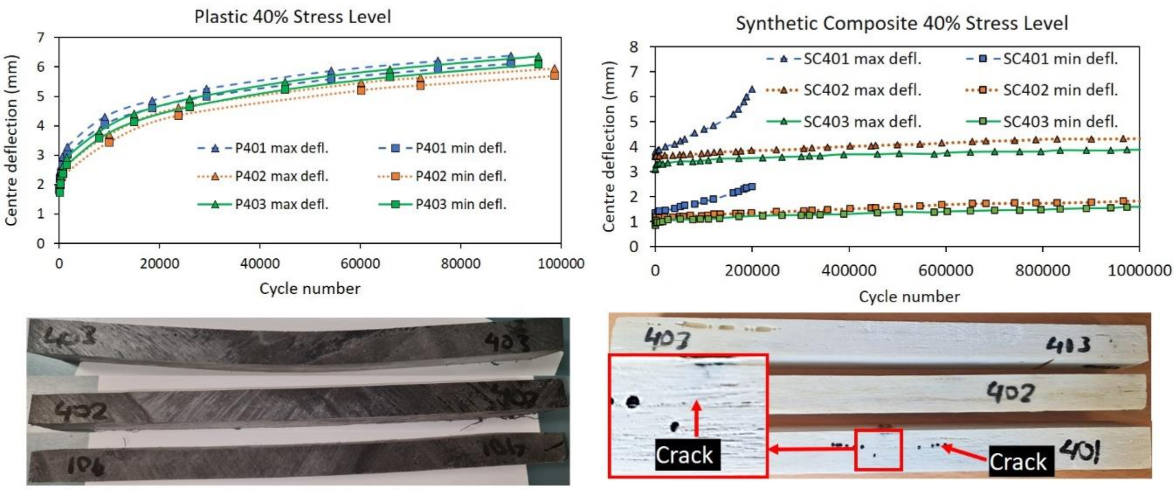


Figure 8. Deflection and failure mechanism of the samples at 40% stress level

The results show that the fatigue life of the sleeper materials, as well as their failure modes, are very different under cyclic loading as depicted in Figures 6-8. One of the notable observations was the accumulated deflection of the plastic material over the lowest number of cycles compared to the other two materials. At 200 cycles (80% stress level), 800 cycles (60% stress level), and 2,000 cycles (40% stress level), the plastic material showed a 100% deflection increment from the starting deflection. It was observed that the difference in maximum and minimum deflections was nearly constant over these initial number of cycles. This indicates that the plastic material tested in this research suffers permanent deflection which is different from the 80% stiffness retention requirement set by the EN ISO 13003:2003 standard [40] for reinforced plastics (also followed in [38] for glass fibre reinforced polymer composite materials). From this, it can be said that the fatigue behaviour of UHMWPE plastic sleepers is governed by permanent deformation rather than stiffness loss considered for composite plastic materials [38, 40]; or cracks reported for post-consumer recycled plastic sleepers while in-service or evaluated in the laboratory [41, 42]. This is because of the nature of high molecular weight polyethylene which is different to that of post-consumer recycled plastics reported in the literature which are known to be brittle. This observation agrees with the findings in [21] where researchers indicated continuous load cycle patterns introduce creep in polymer sleepers. The continuous load cycle pattern applied in this research was justified because the aim is to evaluate the effect of material size rather than the load frequency pattern (i.e., the same load pattern will be applied for the full-scale plastic sleeper). The tests for plastic material were stopped after 100% deflection increment due to the permanent deformation (as shown in Figures 6-8), as researchers observed from other trial static tests. The average permanent deformation recorded after the test was around 5 mm. As suggested by AS 1085.22:2020 [39], measurements were retaken after 24 hours and the final average deformations recorded was 2.4 mm, recovering about 50% from the initial measurement. This is in good agreement with the literature where it was shown that UHMWPE pultruded sections ultimately recover 51% of their creep deformation with 73% of the recovered creep being within the first 17 hours [43]. In Section 6, these permanent (residual) deformations will be factored based on the stress level applied when compared to the full-scale testing so that an accurate correlation is obtained between the two testing methods.

The synthetic composites did not only behave differently to that of the plastics but had varying results for samples of the same stress level. As shown in Figure 6, only the data of one sample is shown for the 80% stress level because the other two samples failed within the first 50 cycles. This sample experienced a stiffness loss of 20% at around 3,000 cycles (4,000 cycles shown in Figure 6) with an obvious longitudinal shear crack covering around 40% of the sleeper length. The failure mechanisms of the second and third samples were also similar with the first showing obvious longitudinal shear cracks after unloading (Figure 6). Similarly, one sample of the 60% stress level (SC603 in Figure 7) failed within the first 100 cycles and the other two showed different fatigue resistance but with similar failure mechanisms. The first sample lost 20% of its stiffness at 225,000 cycles while the second reached only 75,000 cycles. As shown in Figure 8, two samples (SC402 and SC403) of the 40% stress level reached the target 1 million cycles with only a stiffness loss of around 5%. No obvious damage was recorded for these two samples. However, the first sample (i.e., SC401) completely failed at around 200,000 cycles with a 20% stiffness loss recorded at 140,000 cycles. Moreover, for the 80% and 60% stress levels, compression deformation at the loading area was recorded to be around 1.4 mm which is much higher than the value recorded for the timber samples at 0.1 mm. The decompression of the plastic material at the loading area was negligible. Tests of full-scale synthetic and timber sleepers on ballast also showed that the synthetic composites have higher decompression at the loading area due to the polyurethane foam being much softer than the hardwood timber [33]. From observations and the findings in this study, it was clear that the fatigue performance of the synthetic composite material reinforced longitudinally with glass fibres is governed by its shear behaviour, particularly the bond between the reinforcement and the polyurethane foam or the interlaminar shear strength of the polyurethane foam. This is because the shear cracks were usually along the length covering 50% of the sample lengths at constant depth (i.e., not breaking the reinforcement and propagating throughout the depth). The sample inspections showed cracks propagating along the longitudinal voids in some samples. This also explains the variability in the fatigue durability for samples even at the same stress level. As the sleeper is randomly reinforced with glass fibres along its length, some materials samples might have a higher amount of reinforcement than others and some may have higher voids than others. The stiffness degradation of the small-scale testings reported here will be correlated to the full-scale testing in Section 6 so that an accurate correlation between the two testing methods is obtained. In this correlation, the average stiffness loss with load cycles will be considered neglecting the results of those samples which failed immediately due to the presence of air voids. An accurate correlation will make the fatigue resistance study much easier since a test of only a small scale is needed to predict the fatigue resistance as compared to the longer time and higher resource required full-scale tests.

The timber showed a superior fatigue performance than the plastic and the synthetic composites. From the results of the 80% stress level test, it was found out that it takes longer than the target 1 million cycles (1,070,000 cycles) for timber to experience a 20% stiffness loss with only some splitting at the bottom-centre of the sample. The test was then eventually stopped at 1,350,000 cycles after observing an obvious shear crack between the loading point and the left-hand side support (Figure 6). What is different in this shear crack from timber that of the SC material is the length and depth of the crack propagation in addition to the much higher load cycles for this failure to occur. In SC material, the failure was usually a single crack throughout the sample at constant depth while for the timber material not only the crack is shorter, but it also propagated through the depth. This is because the timber is a natural composite material with longitudinal grains while the SC material is a combination of a relatively weaker polyurethane foam material and a much stronger glass fibre. This means when the glass fibres stretch/bend, the foam cannot resist the shear force developed at the bond or the interface of the two materials, hence long cracks along the interface occurred. Due to the time limitations, only one extra timber sample was tested but with a 90% stress loading to reduce the testing time. This can be justified by the fact that timber sleepers have shown excellent service performance while their main issue being environmental decay rather than service loading related failures [3] highlighting the importance of evaluating the fatigue resistance of alternative composite materials as these sleepers are developed as an alternative to timber. The 90% stressed timber sample showed superior performance with a stiffness loss of around 10% when it was stopped at 450,000 cycles due to the time limitations of this research. It is therefore expected that timber material would undergo a 20% stiffness loss at 900,000 cycles if loaded at a 90% stress level.

The observations from the fatigue bending behaviour of sleeper materials have provided valuable insight into their effective design and application in railway tracks. First, the results of the materials test showed that synthetic composites have similar flexural strength to hardwood timber, but the fatigue resistance of timber is better. This observed behaviour motivated the evaluation of the fatigue resistance of full-scale sleepers, and its correlation with the materials fatigue behaviour. Notwithstanding, the Japanese standard JIS 1203:2007 [44] only considered tests of coupon samples to evaluate the performance of synthetic composite materials. Second, the findings indicated that while synthetic composite and plastic sleepers are developed for timber replacement, their flexural strength and failure behaviour are different. It is important therefore that the materials specifications and design standards for alternative sleeper materials should reflect these differences as this may lead to a different overall performance of the railway track. Further, this research revealed that the fatigue resistance of the plastic sleeper is governed by the residual deflection while for synthetic composites, it is the stiffness loss. The comparison and the analysis provided in the later section provides a more in-depth information on the fatigue resistance of different sleeper materials and the relationship of materials fatigue resistance to that of full-scale sleeper's behaviour.

4 Fatigue behaviour of full-scale timber alternative railway sleepers

The fatigue performance of full-scale timber, synthetic composites and plastics sleepers are evaluated up to 1 million cycles under the five-point bending test configuration as shown in Figure 4. Two rail sections of 60kg/m were used as loading points, applying load through a spreader beam. Lateral sleeper supports were provided at the external supports to prevent the lateral movement of the sleeper as shown in Figure 7 while allowing free vertical movement. The load range applied was 15 kN to 72 kN per rail seat in compression-compression (i.e., 30 kN to 144 kN for both rail seats) using a 500 kN capacity servo-hydraulic MTS machine. The maximum load applied represents the equivalent wheel service load of a typical Australian narrow-gauge track [45]. A loading frequency of 3 Hz was based on the Australian standard AS 1085.22:2020 [39], which is also the loading frequency used in materials testing. This loading frequency and the range was also implemented for composite sleepers [18].

The rail seat and full deflection profiles were captured using the Digital Image Correlation (DIC) technique calibrated using a Linear Variable Differential Transformer (LVDT) at the rail seats. DIC is a powerful non-contact full-field measuring technique that recognises changes at sub-pixel patterns making it an accurate data acquisition technique [46-48]. In recent years, DIC technology has increasingly been used in fatigue studies not only due to ease of use and high accuracy but because of its capability of recording data at high speed [49, 50]. The DIC technique also eliminates the effects of the spreader beam and frame deformation, neoprene support settlement, and the sample sitting effect on the supports which means accurate deflection at the sleeper's rail seat can be captured. The DIC technique was also employed at every 250,000 cycles to investigate any changes in the bending profile of the sleepers. Finally, the average load-displacement curves of the rail seats were captured every 250,000 cycles for direct comparison of the different sleeper materials (incremental deformation from one sleeper to another with the increasing number of cycles).

The deflection profiles captured by the DIC at 100 mm intervals are shown in Figure 9 (at maximum load). The bending profiles highlighted the differences between the types of sleepers and how their deflected shape changes with the load cycles. These bending shapes are called W-shaped bending in this research as also termed in other literature [17, 33, 36]. Load displacement graphs measured with the DIC at the rail seats (average) at every 250,000 cycles are also shown in Figure 9.

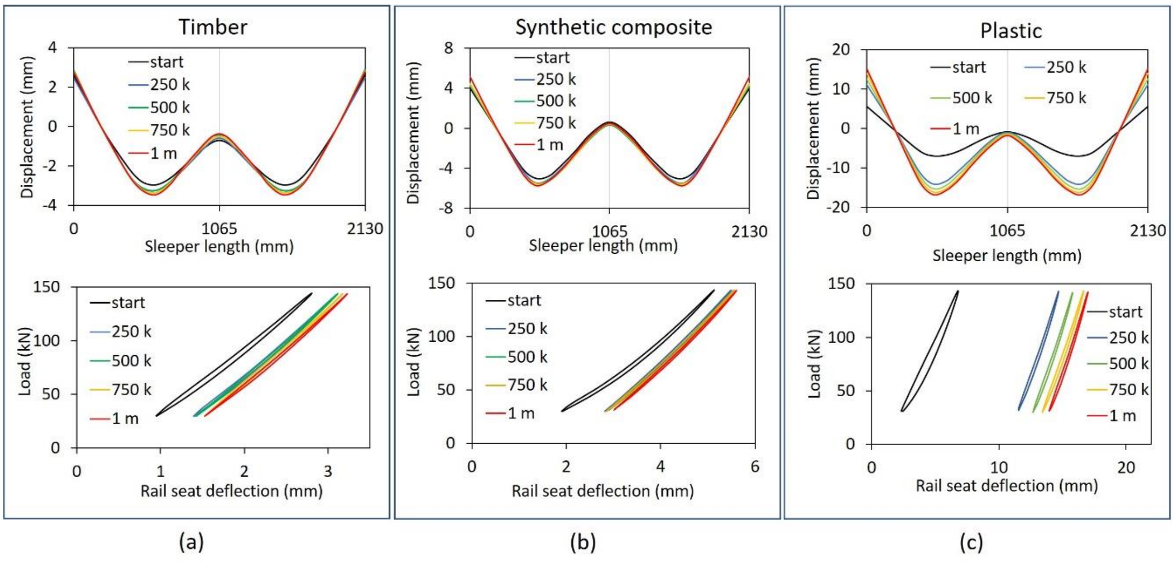


Figure 9. Full-profile and rail seat deflection behaviour under cyclic loading: (a) timber; (b) synthetic composite; (c) plastic.

Figure 9 showed that the timber sleeper has the least overall deflection, i.e., less pronounced W-shape and magnitude of rail seat deflections than the other sleepers. This can be explained by the higher bending modulus of the timber as compared to synthetic composites and plastics as also observed under static five-point bending [36] and sleepers on ballast [33]. The maximum rail seat deflection (at 72kN) of the timber sleeper shown in Figure 9a increased from 2.8 mm at the start to 3.25 mm (16% increment) at 1 million cycles. The visual inspection of the timber sleeper showed no damage after the fatigue test. The synthetic sleeper, on the other hand, exhibited a more prominent W-shaped bending profile with a slightly higher rail seat deflection than timber but with a lesser percentage of deflection increment. The maximum rail seat deflection increased from 5.13 mm to 5.7 mm (11% increment) at 1 million cycles. The visual inspection during and after the test did not show any signs of damage or cracks and the sleeper returned to its original shape without any permanent deflection. This finding showed that scaling down the full-size sleepers by a factor of 6 and conducting the three-point bending test discussed in Section 2.3 would accelerate the fatigue degradation of the material. Therefore, a degradation factor must be considered when testing small-scale samples to correlate with the fatigue performance of full-scale sleepers. Such a comparison and calculation are provided in Section 6. Moreover, all the sleepers showed a high rail seat incremental deflection at the early stages of the loading (i.e, between the start and 250,000 cycles) with very minimal changes for synthetic composites and timber sleepers thereafter. Out of the measured total deflection, 68% and 73% of the change occurred within the first 250,000 cycles for the timber and synthetic composites, respectively. The degradation of composite sleepers tested in natural and accelerated environments also show that composite structures exhibit a higher rate of stiffness loss and shear strength loss at the early stages of installation [51]. The plastic sleeper on the other hand experienced the highest overall and rail seat deflections amongst the tested sleepers. The maximum rail seat deflection increased by 115%, i.e., from 6.8 mm to 14.6 mm within the first 250,000 cycles then reached 17 mm (160% increment from the start) at 1 million cycles. 76% of the total deflection increment occurred within the first 250,000 cycles which is slightly higher than that of timber and synthetic composites. The 160% deflection increment further showed the permanent deformation of the plastic sleepers under fatigue as was also observed in the materials tests. The visual inspection and straightness measurements after 24 hours of fatigue test showed a residual rail seat deflection of 6 mm as shown in Figure 10. This is in comparison to the 13 mm recorded immediately after the fatigue test which indicates nearly 50% deflection recovery. This is also consistent with the 50% deflection recovery after 24 hours from the materials testing and as reported in the literature [43]. This behaviour indicates that plastic sleepers may exhibit permanent deformation in a long run under service load which will have various implications on railway track behaviour. For example, uneven load distribution among sleepers, especially if they are interspersed among timber sleepers. This is because the timber sleepers have a higher resistance to bending (as also shown in this research) and hence they will carry a higher percentage of wheel load than the neighbouring plastic sleepers.

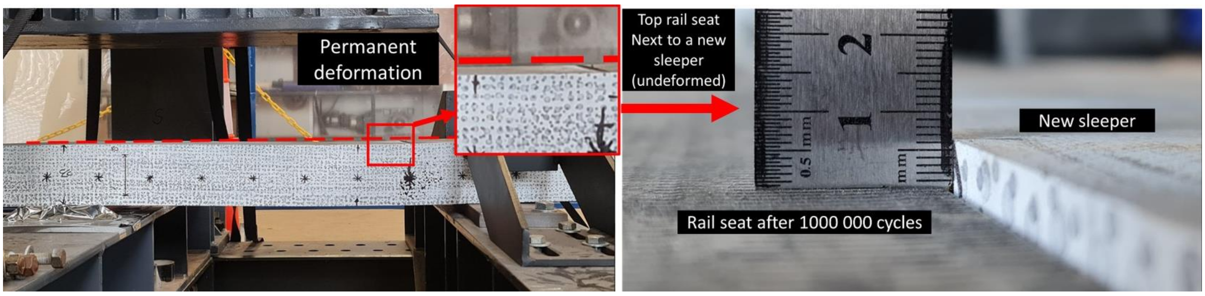


Figure 10. Permanent deformation of the plastic sleeper after 1 million load cycles (after 24 hours)

5 Post-fatigue behaviour of full-scale railway sleepers

The sleepers were evaluated under the five-point static bending up to 72 kN per rail seat (within the elastic region) to study their deflection behaviour. This test was repeated for comparison after the 1 million cyclic loading to determine the post-fatigue behaviour of full-scale railway sleepers. The readings before and after the fatigue tests from the attached strain gauges at the bottom rail were used as an indication of the stiffness degradation of the sleepers.

Figure 11 presents the rail seat deflections before and after the fatigue tests. As also shown in the figure is the ultimate load behaviour of the railway sleepers post 1 million fatigue cycles. The stress ratio for each sleeper was calculated by dividing the service load by that of the ultimate load after fatigue, i.e. 144 kN/ultimate load × 100. This data was used to compare different sleeper materials and to correlate the fatigue performance from full-scale tests to that the materials fatigue tests as presented in the next section.

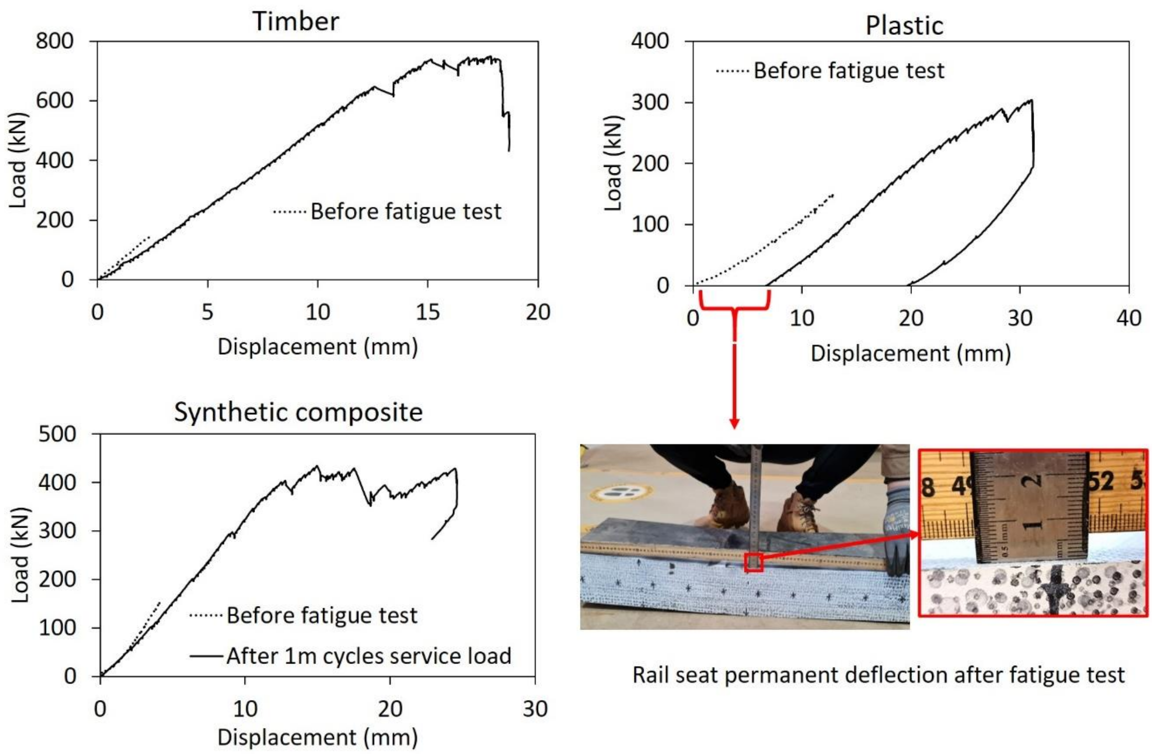


Figure 11. Rail seat deflection behaviour before and after fatigue test for railway sleepers

The load-displacement graphs show that both the timber and the synthetic composites have a higher rail seat deflection after than before the fatigue test (higher curve slopes). On the other hand, the plastic sleeper showed almost the same deflection slope, but the sleeper suffered from permanent deformation due to repeated load cycles as demonstrated by the shift in the load-displacement curve (also deflection of 6 mm is demonstrated in the photos in Figure 11). These results further highlight the findings from the materials test that the fatigue degradation of the synthetic and timber sleepers is in the form of stiffness loss while that of plastic sleepers is in the form of permanent deflection.

The comparison of the static bending behaviour (before and after fatigue) of the timber sleeper indicates a 0.8 mm increase (2.4 mm to 3.2 mm) in the rail seat deflection at a service load of 144 kN (i.e., 72 kN per rail seat). Similarly, the synthetic composites showed a 0.9 mm increase (from 4.1 mm to 5 mm) after the fatigue test. The initial (before fatigue) deflection of the SC sleeper (4.1 mm) is 70% higher than that of timber (2.4 mm). This difference is however only at 56% post fatigue (3.2 mm for timber and 5 mm for SC) which may indicate a slightly higher stiffness loss of the timber. As there is no distinct difference between the slope load-displacement curves before and after fatigue tests of the plastic sleeper, it can be said that plastic sleeper can retain its stiffness after 1 million cycles under 144 kN of wheel load but can suffer considerable permanent deformation. It is worth noting that the 6 mm shift of the graph which represents the permanent deformation of the plastic sleepers in the rail seat exceeds the limit suggested by the AS 1085.22:2020 standard.

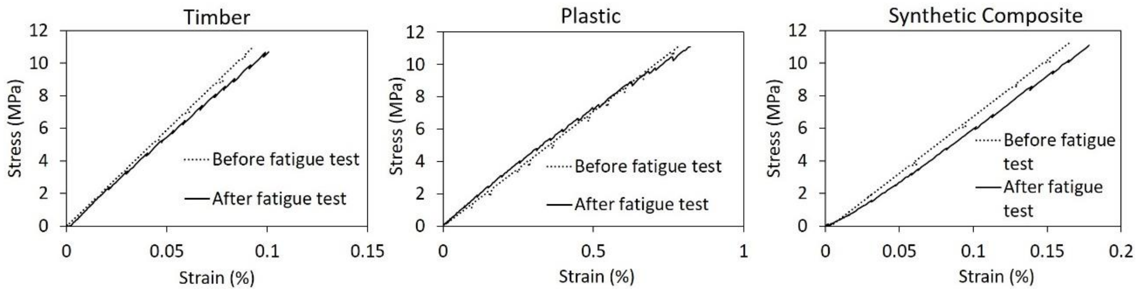


Figure 12. Rail seat and centre strain behaviour before and after 1 million fatigue cycles

The strain behaviour at the rail seat and the centre of the sleepers before and after fatigue are shown in Figure 12. The stress was calculated from rail seat moment equations provided in [36] for the five-point bending test configuration while the strain data was captured using strain gauges attached to the bottom rail seats. The measured average strain at the rail seat further showed the deflection increment due to fatigue loading. The measured strain in the plastic sleeper is the same before and after the fatigue test but with the most noticeable changes recorded for the timber and synthetic composite sleeper. The bending modulus of the timber, calculated from the stress-strain curves, decreased from 11 GPa to 9.9 GPa after fatigue representing a 10% decrease. The bending modulus of the synthetic sleeper meanwhile decreased from 6.9 GPa to 6.3 GPa or around an 8.5% decrease. On the other hand, the bending modulus of the plastic sleeper remained the same at 1.3 GPa. The stiffness properties evaluated with the five-point bending test in this research is very similar to those found using a standardised three-point bending method (ASTM D790:2017 standard [32]) reported in [36] for similar sleeper materials.

Therefore, this research provided accurate information on the stiffness degradation of different sleeper technologies due to fatigue loading.

The accumulation of stiffness degradation up to one million load cycles implemented in this research were analysed and correlated to the number of load cycles caused by the passing train on a railway track. Figure 13 was developed to depict the changes in the rail seat deflection accumulation, which is used as an indication of stiffness degradation of the sleepers. The DIC was used to capture these deflections to eliminate the effect of the seating of the samples and the middle support settlement (neoprene). Figure 13 shows that about 68%, 73%, and 76% of the stiffness loss and deflection accumulation (for the plastic sleeper only) occurred within the first 250,000 cycles for timber, synthetic composite, and plastic sleepers, respectively. This agrees with the findings in [51] where they indicated that composite materials undergo a higher degradation in the early stages of fatigue loading. As the deflection increment stabilised after the 250,000 cycles for the timber and the synthetic sleeper, it is expected that these sleepers would undergo more than three million load cycles before reaching the target 20% stiffness loss as required by the Australian standard AS 1085.22:2020 [33] for alternative sleeper materials. After the fatigue test, the residual rail seat deflection of the plastic sleeper exceeded the dimensional tolerance (+/- 5 mm) of the AS 1085.22:2020 [39]. The authors recommend testing this type of material according to the test protocol outlined in Appendix E of the AS 1085.22:20 which allows 60 min unload intervals in every 10,000 cycles for the sleeper to recover. This contrasts with the continuous load cycles applied in this research for the purpose of direct comparison. This testing method, however, only tests a section of the sleeper up to one million cycles. Therefore, it is highly suggested that the same procedure is followed but under the five-point bending test which considers full-size sleepers. It is worth highlighting that this test protocol would take more than a month (5 working days and 9 working hours a day) because of the pausing time at every 10,000 cycles including inspections. Hence materials testing might be a good alternative to save testing time (see Section 6). It is also realised through this research that this protocol may not be suitable for the synthetic composites as this sleeper did not show any residual deflection after the fatigue test. Therefore, the recovery rest time may not be necessary for sleepers not exhibiting creep due to continuous loading. Besides, the same load cycle pattern was followed for the materials testing for direct comparison between all sleeper types.

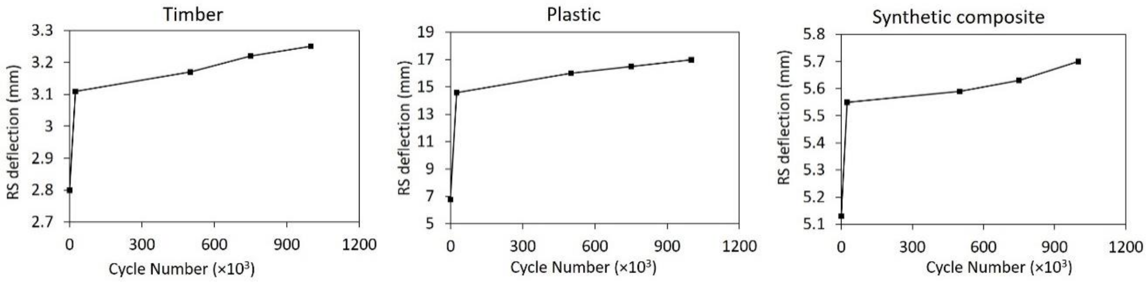


Figure 13. Cumulative rail seat (RS) deflection with load cycle increment.

6 Prediction of fatigue life of different sleeper technologies

A comparison between the small-scale three-point cyclic loading and the full-scale five-point cyclic loading test is carried out to determine the effect of sample size and test configuration have on the performance of different sleeper materials. The three-point bending test was chosen due to its convenience and popularity for the small-scale samples while the five-point bending test was followed for the full-scale sleepers due to its similarity to that of in-situ sleeper loading conditions as highlighted in [36]. The comparison is made based on the stiffness degradation and deflection accumulation (for the plastic sleeper only).

The applied stress ratios of the small scale were 40%, 60%, and 80%. From Figure 11, the stress ratio of individual sleepers can be calculated (i.e., the load applied/failure load × 100). The ultimate load of the timber sleeper at the first major crack is 685 kN which is 2.3 times higher than that of the synthetic composites (300 kN) and the plastic sleeper (295 kN). These load values compared to the service load applied (i.e., 144 kN) gives stress ratios of 21%, 48%, and 49% for timber, synthetic composite, and plastic sleepers respectively. Therefore, the comparison of the materials testing is made based on the average of the 40% and 60% stress levels for both the synthetic composite and plastic small-scale samples (i.e., to determine at around 48% stress level). From the material tests, only 80% and 90% stress levels for timber were applied due to the time limitations of this research and are excluded in these comparisons. Therefore, future research should consider a lower stress level in the materials testing at least similar to that of the applied service load for the full-scale sleeper or between the 40% and 80% range so that a better correlation can be obtained. However, this may require a significantly longer time to obtain failure from both the materials and full-scale sleeper tests.

The degradation or % degradation (for % stiffness loss) under fatigue of sleepers can be expressed in Equation 1.

$$\%\ degradation = cycle\ number \times d_f \tag{1}$$

where, d_f is the degradation factor which is the ratio of 1 to the number of cycles required for 1% stiffness degradation or 1mm residual deflection for the plastic sleeper. As discussed before, nearly 70% of full-scale fatigue degradation happened within the first 250,000 cycles, after which the degradation occurs at a steady slope as shown in Figure 13. Therefore, Equation 1 can be rewritten for full-scale sleepers which shows two factors namely, the first 250,000 cycles and beyond 250,000 cycles because they have different degradation factors.

$$\%\ degradation = cycle\ number \times d_{f250} + cycle\ number \times d_{f250+} \tag{2}$$

where, d_{f250} is the degradation factor for up to 250,000 cycles and d_{f250+} is the degradation factor beyond 250,000 cycles. Table 2 summarises the results of the materials testing and full-scale stiffness degradations with factors calculated. Equations 1 and 2 can be tested for accuracy by substituting values calculated in Table 2 and comparing them with the experimental results. For example, if only 250,000 cycles are considered with a degradation factor of 2.5 x 10^{-5} from Table 2 for synthetic composite, then:

$$\%\ degradation = 250{,}000 \times 2.5 \times 10^{-5} = 6.25\%$$

As stated before (see Figure 13), 73% of the degradation occurred within the first 250,000 cycles. This means the equation can predict the degradation of the sleepers since 6.2% is approximately 73% of the total degradation recorded (i.e., 8.5%). It is worth noting that the same method and equation is used for the degradation of the plastic sleeper, but it will be expressed as the number of cycles needed to induce 1mm residual deflection (i.e., without the % sign).

Table 2. Degradation factor calculation for the synthetic composite sleeper.

Type of test	Stress level	No. of cycles for 1% stiffness loss	No. of cycles for 1% stiffness loss (expected at 48%)	d_f	Small scale-to-full-scale fatigue factor
Small-scale	40%	200,000	99,840	1.0×10^{-5}	
	60%	8,000			
Full scale (up to 250k)	48%	40,000	48,900	2.5×10^{-5}	0.40
Full scale (after 250k)	48%	327,000	327,000	3.06×10^{-6}	3.27

Table 3 summarises the degradation due to deflection accumulation for the plastic sleeper. Comparison of the displacement-cycle number graphs of the full-scale and small-scale plastic sleepers indicate the same deflection increment pattern (i.e., higher slope initially). Therefore, the full-scale degradation was taken as an average from 0 to 1 million cycles, similar to the small-scale (i.e., using Equation 1 only).

Table 3. Degradation factor calculation for the plastic sleeper.

Type of test	Stress level	No. of cycles for 1mm residual deflection	No. of cycles for 1mm residual deflection (expected at 49%)	d_f	Small scale-to-full-scale fatigue factor
Small-scale	40%	41,000	22,500	4.44×10^{-5}	
	60%	4,000			
Full scale	49%	167,000	167,000	6×10^{-6}	7.4

Comparison of the small-scale and full-scale stiffness and residual deflections indicated that overall, the small-scall tests accelerates the degradation time of sleepers by different factors. The exception is only for the first 250,000 cycles of the full-scale tests of the synthetic composites which showed twice the degradation rate compared to small-scale tests. Beyond the 250,000 cycles, the small-scale showed a 3.27 times higher rate of degradation. On the other hand, the small-scale tests of the plastic sleeper showed an overall accelerated degradation rate of 7.4. These acceleration factors are termed “small-to-full scale fatigue factors” in Tables 2 and 3. It is worth noting that the calculations provided here using Equation 2 (and degradation factors) can be used to predict the degradations beyond 1 million load cycles. It is also important to indicate that Table 2 and Table 3 were developed based on the number of samples tested in this research, coupon sample size (i.e., 1:6 ratio), and stress levels applied. Therefore, considering a higher number of sleeper samples and other variables would improve the accuracy of the data provided in this research.

7 Conclusion

This research investigated the fatigue resistance of composites, plastics and timber sleepers under cyclic loading. Continuous cyclic loading at 3 Hz was performed up to 1 million cycles for small-scale sleeper samples (1:6) under three-point bending while full-scale sleepers were tested under the five-point bending configuration. Correlation between the small-scale and full-scale tests at the same stress level was then made and a fatigue degradation factor rate was developed. From the analyses and comparison made in this research, the following conclusions were drawn:

- The flexural strength and failure behaviour including cracking behaviour under static bending tests were the same for both small-scale materials and full-scale railway sleepers. The flexural strength of timber, composites and plastic sleepers were found to be 136 MPa, 137 MPa, and 32.6 MPa respectively. Failure of timber sleepers is governed by flexural crack, composites by horizontal shear crack and plastics by permanent deformation.
- Materials tests showed that the fatigue resistance and failure modes vary with the type of railway sleepers. The fatigue resistance of the synthetic composites is driven by its shear resistance, timber by flexural strength, and plastic by its incremental deflection. The

fatigue resistance of the timber material was better than the synthetic sleeper while the plastic sleeper showed least resistance to fatigue.

- The fatigue resistance of full-scale railway sleepers differs with the sleeper types. Plastics exhibited the highest rail seat deflection due to their low bending stiffness followed by synthetic composites with timber having the minimum overall deflection.
- Timber and synthetic composite sleepers exhibited around 10% stiffness degradation after 1 million fatigue cycles. The plastic sleeper retained its stiffness but showed more than 6 mm residual deformation (50% of the original) after 24 hours of cyclic loading.
- At a similar loading rate and stress levels, small-scale materials will exhibit a higher rate of fatigue degradation compared to full-scale railway sleepers. From the developed correlation, composites and plastics with 1/6 scaled-down section will degrade 3.2 and 7.4 faster, respectively than the full-scale railway sleepers. These degradation factors can be used to save time and effort by testing only small samples to predict the fatigue resistance of full-scale railway sleepers.

This research has provided new insight into the fatigue behaviour and resistance of timber, composites, and plastic sleepers. It is to be noted however that the findings of this research were based on the stress levels applied and the type of materials tested. Therefore, considering other sleeper materials beyond the scope of this research and testing them under different stress levels will generate additional data and further improve the reliability of the findings from this research.

Acknowledgments

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CHAPTER 7

CONCLUSION

Hardwood timber has been the mostly used materials for sleepers to support a railway track but their service life is significantly reduced due to environmental degradation. Recently, a number of composite sleepers are developed as alternatives to timber sleepers. These timber alternative railway sleepers are made of distinct materials possessing very different mechanical properties. Understanding of the structural performance of these sleepers are very limited and the effect of these variations on the behaviour of railway tracks is unknown. This thesis systematically investigated the static and fatigue behaviour of timber and the most commonly used composite sleeper alternatives, i.e., low-profile prestressed concrete, plastic, and synthetic composite sleepers. This was achieved through extensive experimental and theoretical studies to evaluate the behaviour of full-scale railway sleepers in simulated track sections and under a novel bending test set-up developed for composite sleepers. The major findings from this work are presented in the succeeding sections.

7.1 State of the art review of timber-alternative railway sleepers

Composite sleepers are increasingly being used to replace deteriorating timber sleepers. Being a replacement of timber, these alternative sleepers are expected to behave similarly to that of timber. It was found however that composite sleepers are manufactured from distinct materials having very different mechanical properties and information on their in-track behaviour are very limited. Compounding to this problem, available test methods do not represent the behaviour of sleepers in a railway track. From this extensive review, the following findings were drawn:

- Traditional railway sleeper materials are found to perform differently in tracks. Prestressed concrete sleepers suffer from dynamic cracking and rail seat deteriorations while steel sleepers suffer from fatigue cracking, excessive settlements, and rust.
- There exists significant design and material variations on alternative composite sleepers in spite of their development as a replacement to timber. Some sleepers have a varied cross-section than the traditional rectangular sleeper section with some designs considered full-length longitudinal reinforcements while others may use particle and short dispersed short fibres. These design and material variations can affect the overall track performance and pose a great challenge to railway engineers and track owners.
- The change in the stiffness of railway sleepers affects the behaviour of the track as demonstrated by steel and timber sleepers. This finding is however determined only by analytical and numerical studies. Moreover, there is no available literature that evaluated the compressive stiffness of sleepers on the behaviour of railway tracks.
- Available test standards to evaluate the quality and performance of timber alternative sleepers are designed and developed based on specific materials, which only consider a section of a sleeper. These bending tests do not accurately reflect on how sleepers behave in railway tracks wherein they are experiencing positive and negative bending moments at different locations along their lengths.
- The failure type and long term behaviour of alternative sleepers vary depending on the material types, but research in this area is scarce. Moreover, comparative evaluation of their performance to timber is not available despite that they are

developed as replacements to this material. Premature cracking was observed for plastic sleepers in the early stages of their installation, and synthetic composites have a higher settlement than concrete sleepers.

- There is very limited knowledge on the long term (fatigue) behaviour of timber and alternative composite sleepers. Most available literature focused on static bending tests and only on specific sleeper materials. Comparative short and long-term performance of these sleepers to hardwood timber requires immediate attention.

The literature review indicated that the interest in the use of composite sleepers is increasing, but there is still a limited understanding of their performance. The significant variation of their mechanical properties makes it challenging for railway track engineers and asset owners to specify their use in the new construction and maintenance of railway tracks. Therefore, evaluating the static and fatigue behaviour of alternative sleepers, and comparatively evaluating their performance against timber is critical for their effective design and wide adoption and implementation.

7.2 Behaviour of timber-alternative sleepers supported by a ballast

The effect of varying bending and compression moduli on the behaviour of timber and composite railway tracks was studied. A section of railway track was simulated in the laboratory using a ballast box filled with crushed stone ballast. Timber and three common alternatives, i.e., prestressed concrete, plastic, and synthetic composite sleepers were tested under service loading conditions. DIC technique was used to capture the full bending profile and rail seat compression deformations and validated with strain gauge data at the centre of the sleepers. From the findings of this investigation, the following conclusions were drawn:

- A ballast box of 300 mm deep (also ballast thickness) x 1000 mm wide x 3000 mm long with a manual tamping method can represent a typical Australian railway track configuration.
- Low bending modulus sleepers such as plastics exhibited a W-shaped profile while sleepers with a relatively high bending modulus such as concrete sleepers deflected in a U-shaped profile. Sleepers with low stiffness also experienced high bending stress at the centre that needs to be accounted for in the design to prevent premature failure.
- Sleepers with low compression modulus exhibited a significant level of decompression at the rail seat. The local compression is as high as 5.7% of the total rail seat deflection for soft sleepers such as plastics resting on low modulus support and as high as 10% on stiff support. The local decompression of high modulus sleepers such as concrete is negligible.
- The bending modulus contributes more than the compression modulus to the overall track stiffness. Moreover, the overall track stiffness is more sensitive to sleepers having a bending modulus of equal to timber (i.e., 13 GPa) or lower. The track stiffness increases with the increase in sleeper bending modulus.
- Bending and compression moduli have a significant effect on the overall rail seat deflection with the effect of bending modulus higher than that of the compression modulus.

These findings from this study demonstrated that timber and timber-alternative composite sleepers supported by ballast behaved differently under the same level of railway track loads. The results of the study in Chapter 4 also confirmed the complexity and difficulty in using a ballast box to simulate the behaviour of sleepers in a railway track. A new and simpler test method was therefore developed to comparatively evaluate the behaviour of timber and timber-alternative railway sleepers experiencing positive bending moment at the rail seat and negative bending moment at the centre simultaneously.

7.3 Novel five-point bending test method for railway sleepers

The critical review of the literature revealed that available test standards for sleepers do not represent accurately on how they behave in a railway track supported by a ballast. Thus, a new test method that can induce simultaneously positive bending moment at the rail seat and negative bending moment at midspan was developed. The new test method is called five-point bending consisting of two continuous spans (three supports) and two loading points at the rail seats, representing actual track gauge-width. The accuracy of this test method was evaluated by testing full-scale timber, plastic, low-profile prestressed concrete, and synthetic composites and verified using the Beam on Elastic Foundation (BOEF) design method. Three different middle support materials, i.e., steel, neoprene, and EPDM rubber were considered, accounting for the variation in sleeper stiffnesses. From the results of this study, the following conclusions were drawn:

- The five-point bending test can reliably induce the positive and negative bending moments at the rail seats and centre of the sleeper, respectively as experienced by railway sleepers in actual track. The bending profile along the length is also similar to the sleepers supported by a ballast.

- The bending modulus of the sleeper was found to affect more in the magnitude of the bending moment and shear force as well as the bending profile than the ballast (sleeper support) modulus. With the increase in bending modulus of sleepers, the ratio of positive (rail seat) to negative (centre) bending moments increases.
- The hardness or elasticity of the middle support has a significant influence on the induced bending moments and deflection profile of the sleepers. The neoprene rubber is found most suitable support at the mid-span for composite railway sleepers while the hardness of steel is required to induce the centre negative bending moment for concrete sleepers.
- The developed theoretical equations based on the force method of an indeterminate beam with and without middle support settlement can reliably calculate the support reactions and bending moments throughout the length of the sleeper under the five-point bending test.

The results of the study showed that the behaviour of composite railway sleepers can reliably be predicted under the five-point bending test. Full-scale timber-alternative composite sleepers were tested statistically under this test method and loaded statically up to failure to comparatively evaluate their capacity and failure behaviour to timber.

7.4 Static behaviour of sleepers under five-point bending

This study comparatively evaluated the overall static performance of composite sleepers and analysed their failure mechanisms under the five-point bending test. Timber along with plastic, low-profile prestressed concrete, and synthetic sleepers were considered. The Digital Image Correlation (DIC) was employed to capture the full-profile bending shape of the sleepers and full-field strain mapping was used to identify propagation of cracks and final failure. From the results of this study, the following conclusions were drawn:

- The measured data from the DIC and strain gauge provided good indicators of the deflection profile of the sleepers. A high strain at the rail seat and the centre of the low stiffness sleepers implied a W-shaped profile while a negative strain at the centre of high stiffness sleepers (concrete) indicated a U-shaped profile.
- The effect of the material type is more prominent on the bending behaviour and deflection at the rail seat than at the centre of the sleepers. This finding can be used as a guide in designing future composite sleepers.
- Soft sleepers (plastics) exhibited high rail seat deflection and prominent W-shaped profile while the stiff sleepers (concrete) had low rail seat deflection and nearly a flat profile. This behaviour will have various consequences on railway tracks supported by different sleeper materials such as unequal load distribution and uneven ballast pressure.
- Railway sleepers failed differently under the simulated train wheel load. The failure of timber sleepers is governed by flexural cracks, the synthetic composite sleepers by longitudinal shear cracks while plastic sleepers will have permanent deformation. The concrete sleepers fail in a combination of flexural cracks and end-splitting along the tendon reinforcements. These failure mechanisms provide useful guidance in the optimal design of composite sleepers.
- Timber sleepers have the highest flexural strength compared to its alternatives. The synthetic composite sleepers have about 60% of timber sleeper strength while the plastic sleeper has the lowest strength (42%) which is of concern in

case of high magnitude impact forces. The concrete sleepers have nearly the strength of timber sleepers.

- The increase in bending stiffness of the sleepers increases the magnitude of rail seat and centre bending moments, except for concrete sleepers due to having nearly a flat shape due to their resistance to bending. The rail seat bending moment capacity of the concrete sleeper is the highest (63 kN.m) and is 16%, 186%, and 102% higher than that of timber, plastic, and synthetic composites, respectively.

The above findings have demonstrated that timber and timber-alternative railway sleepers have different structural performances under static bending tests. In addition, the new insights into their failure behaviour under similar loading conditions can be a useful guide in designing their use in interspersed railway tracks. In this application, their behaviour under the effect of repetitive actions of a passing train should also be evaluated to ensure their long-term in-track performance.

7.5 Fatigue degradation of composite railway sleepers

This study evaluated the fatigue behaviour and degradation of timber, plastic, and synthetic composite sleepers under the five-point bending test method. The effect of sample size was also investigated by testing small-scale sleepers (1:6) under a three-point bending test. The stiffness loss or failure after 1 million service load cycles was observed for the full-scale sleepers. Degradation factors were then developed to correlate the small-scale and full-scale fatigue tests. The following conclusions were drawn from the main findings of this study:

- Small-scale and full-scale sleepers have similar flexural strength and failure modes but the magnitude of the flexural strength and the type of failure mechanism depend on the sleeper materials. The flexural strengths of timber, synthetic composites, and plastic sleepers were 136 MPa, 137 MPa, and 32.6 MPa, respectively. The governing failure mechanisms are flexural strength for timber, horizontal shear crack for composites, and permanent deformation for plastic sleepers.
- The failure mode of sleepers under fatigue is similar to those from the static bending test. Hardwood timber sleepers will fail in flexural cracks, composites in longitudinal shear cracks, and plastics will have permanent deformation.
- The bending stiffness of timber and composites degraded by 10% after 1 million fatigue load cycles while plastic sleepers retained their stiffness but exhibited 6 mm residual deflection after 24 hours from cyclic testing.
- Under similar stress levels and fatigue load rates, the small-scale samples degrade faster than full-scale sleepers by 7.4 for plastics and 3.2 for composites.

The results of this study have provided new insight into the fatigue behaviour and resistance of timber, composites, and plastic railway sleepers. These obtained fatigue behaviour and resistance can be used as a guide in future testing and evaluation of composite sleeper technologies by characterising only small-scale sleepers to save time and effort in testing.

7.6 New opportunities and future research

The static and fatigue investigation of different composite sleepers conducted in this research revealed new information about the performance of composite sleepers. Based on the results of the studies in Chapters 3 to 6, opportunities and new research areas can be explored to further understand the behaviour of railway tracks supported by a specific composite sleeper or various composite sleepers (interspersed track) as follows:

- The findings of this research were based on the static and fatigue behaviour of timber, composites, and plastic railway sleepers. Therefore, considering other composite sleepers beyond the scope of this research will generate additional data and further improve the reliability of the findings from this study.
- This study considered the static and fatigue loading conditions experienced by a sleeper in the mainline application and based on the track conditions in Queensland Rail. Therefore, consideration of other loading and track conditions and accounting for the dynamic loading due to the moving of train, rail dips, or wheel irregularities would provide additional valuable insight into the dynamic behaviour of composite sleepers.
- The five-point bending test developed can mimic the typical railway tracks in Australia. Considering other span configurations to suit other track configurations around the world would provide valuable information to the track owners in other countries.
- The results of this work have shown that combining steel as external support and neoprene mid-span support can mimic the typical bending behaviour of composite sleepers. It is, therefore, possible to mimic the special cases of

sleeper bending such as centre binding where a negative bending moment occurs at the centre with almost no bending effect at the rail seats due to unsupported rail seat (voided ballast). This can be achieved by swapping over the support types, i.e., steel as mid-span support and neoprene for the external supports. This, however, should carefully be designed as highlighted in Chapter 4 and other softer or stiffer materials than neoprene might be needed to achieve this goal.

- The DIC can successfully capture the full-profile deflection and local compression of railway sleepers. Future research may focus on the feasibility of using DIC for track deflection measurement. Studies like overall track stiffness with DIC is highly recommended as this will provide valuable information to the track designers regarding load distribution among sleepers.
- This thesis determined the effect of sample size on the degradation rate of composite sleepers. This study can further be refined with better accuracy by testing a wider range of sleeper materials and other samples sizes.

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APPENDIX A: SUMMARY OF ALTERNATIVE COMPOSITE SLEEPER TECHNOLOGIES

Table A1: Summary of recycled plastic sleepers

No.	Technology	Country	Technology description	Application type	Image	Reference
1	Axion (EcoTrax)	USA	100% recycled plastics	Standard mainline sleepers, embedded track, tunnels, turnouts, crossing diamonds, and transoms		(Axion 2019)
2	TieTek	USA	85% recycled material. Thermoplastic polymer (40-75%), crumb rubber (4-40%), reinforcing fillers (6-50%), additives (0-6%), and styrenic polymer (0-12%)	Class 1 railroad sleepers, turnouts, and transoms		(Dechojarassri 2005; TieTek 2019b)
3	Sicut	UK Developed in the USA	100% recycled plastics postconsumer plastic bottles and recycled glass fibre filled plastic waste	Standard mainline sleepers, turnouts, tunnel sleepers, and transoms		(Sicut Enterprises Ltd 2019)

4	Integrico	USA	100% recycled plastics Postconsumer plastic bottles and bags	Class 1 railroad, commuter, industrial, and mining		(Integrico 2019)
5	Evertrak 7000	USA	100% recycled plastic (PE, PP and mixed polyolefin) reinforced with glass fiber	Class 1 mainline railroad		(Evertrak 2019)
6	Duratrack	Australia	Flexible and rigid recycled plastics (agricultural films, polystyrene, pipes, drums and bottles)	Heritage & tourist railways. QR mainline (trial application)		(Sustainability Victoria 2018; Integrated Recycling 2019)
7	Relumat2000	Germany	100% recycled plastic. PE (polyethylene), PP (polypropylene), other plastics (without PVC and PET) and other ingredients (glass, sand, aluminium, etc.)	Tram lines, narrow-gauge, and miniature railways	 	(Relumat2000™ 2019)

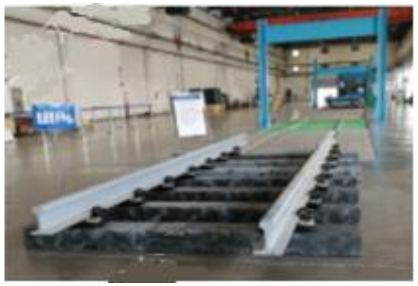
8	MPV	Germany	Mixed Plastic waste, glass fibre waste, and auxiliary agents	N/A		(Graebe, Woidasky & Fraunhofer 2010)
9	TVEMA	Russia	100% recycled plastic	Mainline, turnouts, industrial, subways, and tram lines.		(TVEMA 2019)
10	Sunrui	China	Recyclable composite plastic	N/A		(Sunrui 2019)
11	KLP Hybrid	Netherlands	100% recycled plastics. Reinforced with steel bars	Main track, crossings, transoms, turnouts, and sound and vibration reduction sleepers		(Silva et al. 2017; Lankhorst Rail 2019)

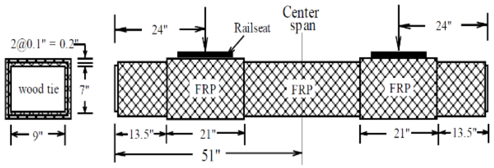
Table A2: Summary of sleepers reinforced with long continuous fibres

Technology	Country	Technology description	Type of application	Image	Reference
FFU	Japan	Continuously reinforced (with glass fibre) rigid polyurethane foam	Mainline, heavy haul, turnouts, crossings, and bridges		(SEKISUI 2019)
Sunrui	China	Continuously reinforced polyurethane foam	Mainline, heavy haul, turnouts, crossings, and bridges		(Sunrui Group 2019)
AGICO	China	Continuous glass fiber, polyether polyol, isocyanate and related components	Mainly in high-speed railways and subways (both ballasted and un-ballasted track sections)		(AGICO 2019)

Polintek (Darta)	Indonesia	Polymer-based composite reinforced with laminates	Ballasted and un-ballasted tracks		(Darta Corporation 2019)

Table A3. Summary of sleepers under research and development

Technology	Country & (year)	Technology description	Advantages	Limitations	Photo	Reference
Reconstituted laminated sleeper	USA (1982)	Discarded read oak sleepers scraped, cleaned, and then chopped down to produce mats. The mats were pressed together to make panels. The panels were later used to produce laminated sleepers. Phenolic resin and wax was used in the process.	Recycling old sleepers and good for the environment	Bending stiffness and strength significantly lower than the original sleepers, difficult to control the uniformity of adhesive distribution, mat densities, and adequate amount of flakes		(Geimer 1982)

Fibre composite sandwich beam	Australia (2010)	glass fibre composite skins and phenolic foam core material	Higher mechanical properties than most of the alternatives, Longer design life than timber but with similar strength properties	Not an economic alternative solution for mainline sleepers, lack of field or long performance data		(Manalo, A. et al. 2010)
FRP-wood	USA (1998)	Glass Fibre Reinforced Polymer (GFRP) reinforced wood core	Improvements in tensile and compression strains, strength and stiffness are improved	Still utilizes large amount of wood, only suitable to rehabilitate deteriorated sleepers, otherwise might be costly, no field evaluation data available		(Qiao, Davalos & Zipfel 1998)
Carbon/timber sleeper	Australia (2004)	Carbon fibre laminate strips bonded to the bottom of timber sleepers	Improved load carrying capacity (strength), and a simple and easy method of rehabilitation	Improved strength depends on the bond quality, development of peel stress, horizontal shear stress, and finally delamination		(Humphreys & Francey 2004)

Hybrid FRP-concrete	Australia (2015)	Glass-fibre reinforced polymer hollow sections filled with geopolymer concrete	Strength and MOE comparable or even better than most of the alternatives.	The size of the sleeper is dictated by the available size of the hollow sections. Debonding of the interior hollow beam surface and the geo-polymer concrete might occur before ultimate failure.		(Ferdous, Khennane & Kayali 2013)
Fibre reinforced polymer (Carbonloc)	Australia (2005)	Polymer concrete (resin and fillers) and fibre composite sandwich panels (longitudinal). A resin content of 25-30% on the top part and 50-60% on the bottom part.	Innovative shape with optimum material usage, good lateral resistance, no rail plate is needed due to similar shape to concrete and having strong surface, high shear strength due to fibre reinforcements in two directions.	Lack of performance or long performance data and the feasibility of commercial mass production is not addressed. Due to its shape, it might not be as easy as timber to install.		(Van Erp, Cattell & Heldt 2005)

Fibre reinforced polymer	Egypt (2017)	Recycled HDPE, iron slag, calcium carbonate (CACO3), polyester resin and E glass fibre	Recycled product and can be re-recycled. Comparable compression and flexural strength to some types of wood used in railway sleepers. Most of the mechanical properties satisfy the AREMA standard.	Modulus of elasticity much lower than timber. Provided data is based on the coupons tested, hence there is a lack of static and dynamic behaviour of full-scale sleeper samples.		(Khalil et al. 2017)

APPENDIX B: CONFERENCE PAPERS

1. 2021 International Conference on Materials Science and Engineering Brisbane, Australia

Behaviour of timber-alternative composite sleepers on ballast having different bending and compression modulus

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Abstract

Due to the environmental degradations, timber sleepers are replaced with alternative composite sleepers designed to last twice the design life of timber sleepers. Hence, the alternative sleepers are meant to be mechanically compatible with the existing timber sleepers since the alternatives are interspersed in timber tracks. However, the review of the literature has shown that there is a wide range of bending and compression modulus of elasticity amongst the alternative sleepers. This poses a great challenge to the designers and track authorities in designing railway tracks supported by different sleepers technologies. This study considers full-scale experimental and numerical means to evaluate the behaviour of a railway track supported by different sleeper technologies including recycled plastic (1.0 GPa), synthetic composites (7.4 GPa), timber (13.0 GPa), and low profile prestressed concrete sleepers (38.0 GPa). In doing so, a ballast box was designed to simulate a single sleeper section of a typical Australian railway track. The effect of the varying bending modulus on the full-profile and rail seat deflection; and the effect of varying compression modulus on the rail seat decompression was studied. The digital image correlation technique, which was combined with the mid-span strain data, was used to measure the full-profile bending and vertical settlements. Three-dimensional Finite Element Analysis of the sleepers' behaviour based on the Beam on elastic Foundation theory was implemented and validated with the experimental results. The results showed sleepers having lower bending modulus than the timber sleepers (i.e, 13 GPa) exhibit a W-shaped profile with high rail seat deflection while stiffer sleepers such as concrete ones show a U-shaped profile under service loading conditions. The local deformation under rail accounts for nearly 6% of total rail seat deflection on a low ballast modulus and as high as 10% for high modulus ballast support. The discussions provided on real track behaviours such as track stiffness change and load distribution will provide new insight into the behaviour of railway tracks supported by different sleeper technologies.

2. 2021 National Symposium on Advanced Materials and Sustainable Technologies, Gold Coast, Australia

Five-point bending as a new test method for the evaluation of sustainable polymeric railway sleepers

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Abstract

New and sustainable polymeric composite sleeper technologies have been developed to address the limitations of failing timber sleepers in railway tracks due to deterioration. These polymeric composite sleepers were designed to last much longer than their timber counterparts. However, a review of the literature has shown that polymeric-based composite sleepers might fail in the early stages of their use in the tracks due to mechanical loading. Current development and acceptance procedures require these alternative sleeper materials to undergo a series of evaluation tests following a range of available standards including AREMA 30-5, JIS E 1203, ISO 12856, and AS 1085.22. These standards require sleepers to be tested separately at the rail seat and middle portion of the sleepers for positive and negative bending moments, respectively, which do not accurately represent the behaviour of sleepers supported by a ballast. This was also realised through finite element analysis of different sleepers on the ballast. A new five-point bending test was therefore proposed for the evaluation of alternative sleepers to induce positive and negative bending moments simultaneously to a sleeper. The five-point static bending test is achieved by applying two point loads at the rail seats representing train wheels while supporting the sleeper on three supports; one middle support with two external supports having a shear span of 300mm to the loading points. The suitability of this new testing method was demonstrated for timber, recycled plastic, synthetic, and low-profile prestressed concrete sleepers. Since these sleepers are made of different materials of different bending modulus, the most suitable middle support material type was also determined. Analytical equations of the bending moments at the rail seat and the centre of the sleepers were also developed with and without the middle-support settlement. The full-profile bending shape of the sleepers was captured using the Digital Image Correlation technique that helped in determining the most suitable support type according to bending shapes. The results indicated that the five-point static bending test can induce both positive and negative bending moments experienced by sleepers under a train wheel load. It was also found that with the proposed testing spans, steel-EPDM rubber is the most suitable configuration for sleeper bending modulus of 4 GPa and lower, steel-neoprene is the most suitable for a range of 4 GPa – 17 GPa, and steel-steel is the most suitable support type for bending modulus of 17 GPa and higher. Neoprene support is however suggested to standardize the five-point bending for polymeric-based railway sleepers. Based on these results, bending moment equations were also developed and verified with Finite Element Analysis that can reliably describe the flexural behaviour of new and sustainable polymeric composite sleeper technologies.