Dual-Approach Verification of Enhanced Fatigue Life in Macro Synthetic Fibre Reinforced Concrete Sleepers

Christophe Camille[1,2], Olivia Mirza[2], Todd Clarke[1]

[1]: BarChip Australia Pty Ltd, Woolloongabba, Queensland, Australia

[2]: Western Sydney University, Locked Bag 1798, Penrith, NSW 2751, Australia

Abstract

The structural integrity of prefabricated railway sleepers is increasingly challenged by higher axle loads and extended maintenance intervals, requiring a shift toward performance-based design validation. This study investigates the structural behaviour and fatigue performance of prestressed concrete sleepers incorporating macro synthetic fibres reinforcement (PF), demonstrating a significant improvement in service life compared to conventional prestressed concrete (PO) sleepers without fibres. Fatigue testing was conducted under constant-amplitude cyclic loading with analysis focused on the stiffness degradation as a direct, performance-based measure of structural health and crack resistance. The experimental results were further validated against traditional stress-based fatigue assessment methods to ensure model reliability. The PF specimens exhibited a 34.8% higher initial stiffness and a subsequent 75.9% slower damage rate than the PO sleeper, indicating vastly superior resistance to damage accumulation and crack propagation. This enhanced structural behaviour translates directly into a life multiplier of 4.15 times before the 10% remaining stiffness serviceability limit is exceeded. The verified methodology and superior durability performance support the adoption of macro synthetic fibre technology in practice and future design codes, promoting more resilient, cost-effective and sustainable railway infrastructure. The strong correlation between the two validation approaches provides a robust foundation for performance-based modelling, confirming that fibre reinforcement offers a durable, high-performance alternative with demonstrated extension of service life in prestressed concrete sleepers.

Keywords

Fibre reinforced concrete, railway sleeper, fatigue design, post-crack performance

1 Introduction

Railway sleepers are subjected to a combination of static, dynamic and impact loading throughout their service life due to wheel-rail interactions. The magnitude of these repeated loads depends on train speed, track geometry and support conditions, all of which influence the mechanisms of fatigue damage. Fatigue failure in sleepers can occur at stress levels below material strength when subjected to cyclic loading and is characterised by the magnitude of the stress range and the number of load cycles (You et al., 2017). Under such conditions, fatigue in concrete initiates and propagates as micro-cracks that evolve into macro-cracks, accompanied by increasing permanent strains and a progressive reduction in structural stiffness. In prestressed concrete sleepers, repeated loading also induces micro-cracking in the prestressing wires, resulting in stress concentration and premature fracture.

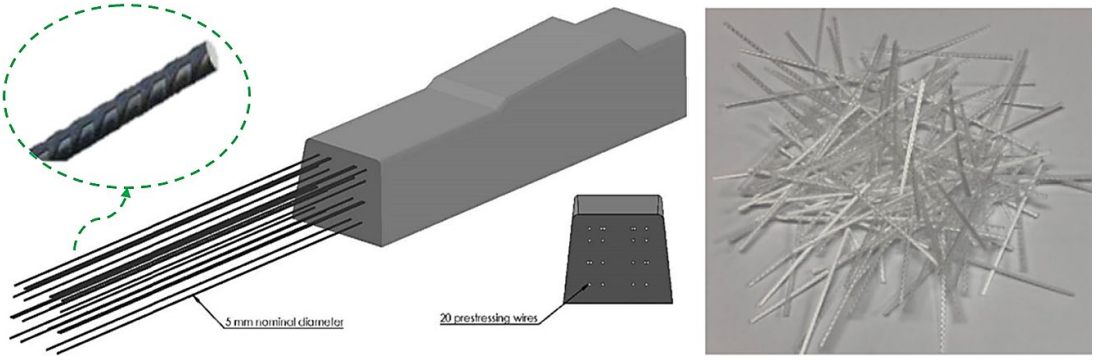
Current design approaches for prestressed concrete sleepers are primarily based on elastic analysis and permissible stress concepts, with fatigue resistance assessed through standard repeated load testing (Nairn & Stevens, 2010; Standard Australia Online, 2012). While uncracked sleepers generally exhibit adequate fatigue performance, cracking under service conditions is often unavoidable due to high-intensity impact loads (Parvez & Foster, 2017). The presence of cracks significantly increases the stress range in the prestressing steel, accelerating fatigue damage and reducing service life. Therefore, the fatigue life of prestressing steel becomes a critical indicator for determining maintenance and replacement intervals of concrete sleepers. This is particularly important for standards adopting partial prestress design, where tensile stresses are permitted in the concrete under service loading, increasing the likelihood of cracking and fatigue-related deterioration (Goto et al., 2018). Consequently, the development of reliable fatigue-life assessment methods for prestressed concrete sleepers is increasingly important.

In recent years, fibre reinforced concrete (FRC) has emerged as a promising solution for enhancing the performance of quasi-brittle materials. Advances in fibre technology have enabled the development of highly engineered macro synthetic fibres that enhance ductility, toughness, energy absorption and durability. An extensive experimental program conducted by the authors, including material characterisation, static testing and dynamic performance assessment, has demonstrated that macro synthetic fibres can significantly improve sleeper residual bending strength, energy absorption capacity and cracking resistance (Camille, 2021; Kahagala Hewage et al., 2024). This paper represents a continuation of this research program, focusing on the fatigue performance of macro synthetic fibre reinforced concrete (MSFRC) prestressed railway sleepers. To address the current gap in relating structural response to fatigue mechanisms, a dual-approach verification framework is proposed that combines stiffness- and stress-based assessments. The analytical results are validated against experimental fatigue data, enabling a comprehensive evaluation of the benefits of fibre reinforcement in reducing damage accumulation, lowering stress demand and extending service life. This work contributes to the development of more resilient and durable railway sleeper systems, supporting improved track performance and reduced maintenance requirements.

2 Experimental and Analytical Methodology

The experimental component of the investigation evaluated the fatigue performance of prestressed concrete sleepers incorporating macro synthetic fibres (PF) compared with

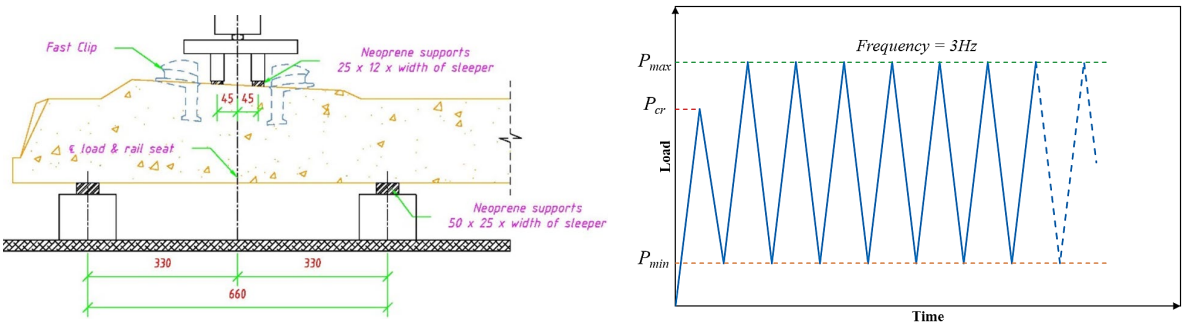
conventional prestressed sleepers without fibres (PO). All specimens were manufactured using identical geometry, prestressing configuration and base concrete mix to isolate the influence of fibre reinforcement. Fig. 1 illustrates the sleeper designed for heavy-haul applications, with a 30-tonne axle load and primarily reinforced with 20 chevron-patterned indented steel wires. PF sections were also reinforced with BarChip 48 (BC48) macro synthetic fibres made from a high-performance polypropylene material and classified as Class II fibres (i.e. Ø ≥ 0.3 mm, (European Standard, 2006)). The dosage was representative of that used in structural applications (9.1 kg/m^3), with the aim of enhancing post-cracking behaviour and fatigue resistance, consistent with findings from previous studies by the authors (Camille, Kahagala Hewage, et al., 2022; Camille et al., 2021).



(a) (b)

Fig. 1: Reinforcement systems implemented in sleepers – (a) prestressing steel wire and (b) BC48 fibres

Prior to the sleeper's fatigue assessment, the fresh and hardened properties of concrete were tested and complied with the requirements of AS 1085.14, as reported in (Camille, Mirza, et al., 2022). The fatigue test generally followed the setup specified in AS 1085.14 (Fig. 2a), including the loading configuration, support conditions and cyclic procedure. However, given the inherently time-intensive nature of fatigue testing and the need to achieve failure within three million cycles, the upper fatigue load limit (P_{max}) was increased to approximately 45% above the standard-specified value. Prior to fatigue loading, the specimens were pre-cracked under static loading to approximately 235 kN (P_{cr}) at the rail seat, ensuring testing was conducted under representative cracked in-service conditions. These adjustments enabled an accelerated assessment of fatigue performance while maintaining consistency with the prescribed test methodology.



(a) (b)

Fig. 2: Repeated load test – (a) loading configuration and (b) loading protocol

Four sleepers were tested over a load range of 15 kN (P_{min}) to 285 kN (P_{max}) at 3 Hz (Fig. 2b). Note that P_{max} corresponds to approximately 68% of the ultimate static capacity of the sleeper, determined experimentally from monotonic rail seat testing. Accordingly, fatigue performance was assessed using a dual-approach methodology: (i) a stiffness degradation analysis derived from experimental measurements and (ii) a stress-based fatigue model based on effective stress range calculations.

2.1 Stiffness-Based Fatigue Assessment

Fatigue performance of the sleepers was quantified using a stiffness-degradation approach based on load-deflection responses measured under cyclic loading. For each selected cycle interval, the structural flexural stiffness (K_n) was calculated using the applied load amplitude ($P_{max} - P_{min}$) and the corresponding deflection range. This applied loading (15 – 285 kN) corresponds to approximately 61% of the sleeper's ultimate static capacity and an associated stress ratio $R \approx 0.05$, representing a highly aggressive and tensile-dominant regime followed by partial unloading. This promotes cyclic crack opening and closing, leading to progressive stiffness reduction. To establish a consistent reference state, the initial stiffness (K_0) was defined from the first stable fatigue cycles following pre-cracking, representing the in-service cracked condition at the onset of fatigue loading. The evolution of stiffness with increasing fatigue cycles was then used as a direct indicator of damage accumulation in the sleeper's structural response.

$$K_n = \frac{P_{max} - P_{min}}{\delta_{max,n} - \delta_{min,n}} \tag{1}$$

$$R = \frac{P_{min}}{P_{max}} \tag{2}$$

where:
K_n: Structural stiffness | R: Stress ratio

2.2 Analytical Stress-Based Fatigue Model

The analytical fatigue life of the prestressed concrete sleepers was evaluated using a stress-based model, where the cyclic stress range in the prestressing steel was taken as the governing fatigue parameter. The methodology follows a force-equilibrium sectional approach, similar to that adopted in You et al. (2017) for prestressed concrete sleepers and is extended herein to account for the presence of macro synthetic fibre reinforcement. Note that the fatigue life herein predicted was obtained using the parameters defined in Table 1, which are generally specified as lower-bound values for design purposes and are inherently conservative.

For a given bending moment, the internal force distribution was determined assuming plane sections remain plane, with equilibrium satisfied between internal forces and the applied moment. The internal force system consisted of concrete compression and prestressing steel tension, with an additional tensile force introduced for PF sections to represent the post-cracking bridging capacity of macro synthetic fibres. The applied fatigue loads (P_{min} & P_{max}) were converted into bending moments (Eq. 3) using the test configuration (Fig. 2a) at rail seat section to determine the corresponding steel stresses. Given that the specimens were pre-cracked prior to fatigue testing, the analysis was conducted assuming cracked section behaviour. That is, in the PO section, tensile concrete contribution was neglected and equilibrium was satisfied between the concrete compression block and prestressing steel force.

For PF, this equilibrium was extended by including an equivalent tensile force to represent fibre bridging, derived from residual strength parameters at ULS (i.e. f_{R3}). This enables the reduction in tensile demand on the prestressing steel due to fibre reinforcement to be captured within the sectional analysis. Note that the prestressing force, including effective losses, was incorporated as an initial internal force, enabling the interaction between external loading and prestress, particularly at low load levels where prestress governs crack closure behaviour.

Table 1: Material properties and model parameters

Material	Variable	Symbol	Value
Concrete	Mean compressive strength (MPa)	f_{cm}	68
	Flexural tensile strength (MPa)	f_{cf}	5.56
	Modulus of elasticity (GPa)	E_c	35.7
	Mean residual flexural strength (MPa) (for PF only)	f_{R3}	5.92
Prestressing wire	Ultimate tensile strength (MPa)	f_{pu}	1700
	Yield strength (MPa)	f_{py}	1410
	Nominal modulus of elasticity (GPa)	E_s	205
	Design stress range (MPa)	$\Delta\sigma_N$	300

$$M_{R+} = \frac{P_{max/min}}{2}(0.33 - 0.045) \tag{3}$$

$$\sigma_{s,eff} = \alpha.\sigma_{s,closed} + (1-\alpha).\sigma_{s,open}$$
$$\sigma_{s,open} = \psi.\sigma_{s,cr} \tag{4}$$

$$\log N_f = \begin{cases} \log N^* - k_1\left(\log \Delta\sigma_{s,eff} - \log \Delta\sigma_N\right), & \Delta\sigma_{s,eff} > \Delta\sigma_N \\ \log N^* + k_2\left(\log \Delta\sigma_N - \log \Delta\sigma_{s,eff}\right), & \Delta\sigma_{s,eff} \le \Delta\sigma_N \end{cases} \tag{5}$$

where:

M_{R+}: Positive bending moment at rail seat

$\sigma_{s,eff}$: Effective steel stress | $\sigma_{s,closed/open}$: Steel stress from close-open section equilibrium | $\sigma_{s,cr}$: Cracked section steel stress

α: Crack reopening factor | ψ: Average stress factor

N_f: Number of cycles to failure (for pre-tensioning steel k_1=5 & k_2=9)

Accordingly, a moderate nonlinear crack reopening model was introduced to describe the transition between closed and fully open crack states under cyclic loading, with fibre bridging influencing the post-reopening response. The effective steel stress at a given load level was therefore obtained by interpolating between closed-crack and cracked section responses, defined by Eq. (4). Note that an average stress factor (ψ) was introduced to convert the local peak steel stress obtained from cracked section equilibrium into an effective cyclic stress range that accounts for tension stiffening, crack spacing and stress redistribution. Separate values of ψ were adopted for PO and PF to reflect their different post-cracking performance, capturing the contribution of fibres in reducing stress concentration. Subsequently, the prestressing steel's fatigue life under constant-amplitude cyclic loading was estimated in accordance with the fib Model Code 2010, defined in terms of the stress range, with failure governed by a bilinear S-N relationship. The effective stress range in the prestressing steel ($\Delta\sigma_{s,eff}$) obtained from the

sectional analysis was adopted as the fatigue-driving parameter to determine the number of cycles to failure (N_f), as defined in Eq. (5). The resulting fatigue life predictions are subsequently compared with the mean experimental results to assess the accuracy and reliability of the adopted analytical approach. Therefore, the proposed methodologies provide a practical and physically interpretable framework for fatigue life prediction through a dual-approach verification framework, namely stiffness-based and stress-based analyses, each capturing different aspects of the sleeper response.

3 Results and Discussion

Fatigue testing was conducted under constant-amplitude cyclic loading in accordance with AS1085.14 and required an average of 35 days to reach 3 million load cycles. The fatigue performance of both PO and PF sleepers was evaluated and subsequently compared with analytical predictions from the stiffness- and stress-based approaches. Fig. 3 illustrates the experimental deflection-cycle results under maximum load (P_{max}) for all sleepers.

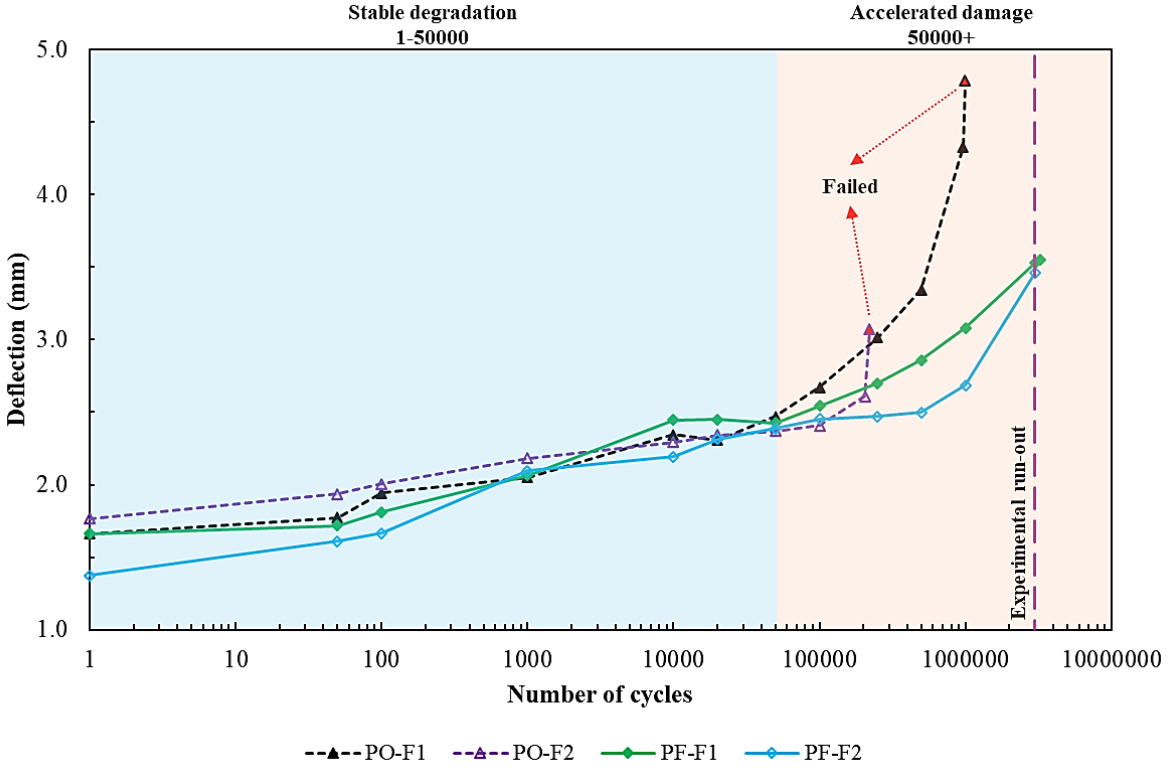


Fig. 3: Log deflection-cycle at maximum load

The experimental results showed that the conventional sleepers (PO-F1 & PO-F2) failed at approximately 222,472 and 991,400 cycles, both below one million cycles, indicating a relatively rapid accumulation of damage under cyclic loading. In comparison, the fibre reinforced sleepers (PF-F1 & PF-F2) exhibited significantly improved fatigue performance, achieving experimental run-out conditions by exceeding 3×10^6 cycles without failure. As the sleepers were pre-cracked prior to fatigue loading, initial deflections corresponding to early damage were observed, with PF exhibiting, on average, 11.5% lower deflections than PO, attributed to the contribution of fibre bridging in limiting crack opening and increasing post-cracking stiffness.

During cyclic loading, deflections increased progressively with the number of cycles due to stiffness degradation, with an initial stage of relatively low-rate deflection growth for all specimens, corresponding to stable crack development. Subsequently, an accelerated damage phase beyond 5×10^4 cycles led to the failure of PO sleepers, whereas PF exhibited a more progressive degradation response, with the average deflection being 19% lower. This behaviour indicates improved crack control and reduced stiffness loss, as further examined in the stiffness-degradation-based fatigue assessment that compares the evolution of stiffness for both PO and PF sleepers (Fig. 4).

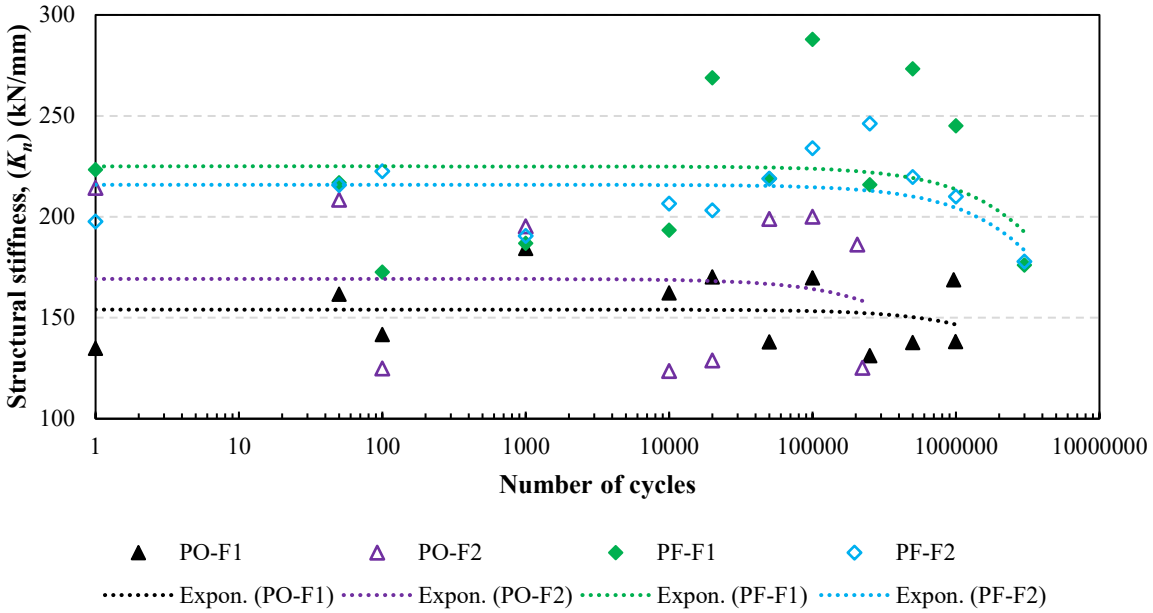


Fig. 4: Structural stiffness vs. load-cycles illustrating exponential degradation in PO and PF

The evolution of structural stiffness (K_n) with increasing load cycles was modelled using an exponential trendline, reflecting progressive, nonlinear damage accumulation. Based on the results, PO sleepers exhibited a steeper exponential decay, indicating faster stiffness degradation and earlier fatigue failure compared to PF, which maintained higher stiffness (i.e. flatter degradation) with a reduced rate of damage progression. The difference in exponential decay rates provides an empirical indicator of fatigue performance, with the lower degradation rate observed for PF corresponding to an increase in fatigue life of ~4.15 times that of PO sleepers. Note that apparent stiffness increases in PF are attributed to crack stabilisation, fibre engagement and sensitivity of stiffness calculations, rather than true material hardening, with overall behaviour governed by fatigue degradation. Accordingly, while this relationship offers a useful measure of the relative improvement in fatigue resistance, it should be interpreted as a comparative indicator rather than a direct predictive tool, with the stress-based approach providing a more rigorous assessment of fatigue life.

Based on the effective stress range calculated from the force-equilibrium model, the fatigue behaviour was interpreted in terms of cyclic stress demand in the prestressing steel. Accordingly, the analysis indicated that PO sleepers were subjected to a 15% higher effective stress range than PF, consistent with their earlier fatigue failure and reduced post-cracking load redistribution. This difference in stress demand explains the observed variation in fatigue performance and is further supported by analytical predictions that showed good agreement

with the experimental results, accurately estimating failure cycles (N_f) of approximately 8.8×10^5 for PO and 3.3×10^6 for PF. A comparison of the experimental results and analytical stress-based predictions is summarised in Table 2.

Overall, both approaches consistently capture the observed fatigue behaviour, with the stiffness response providing an empirical measure of damage progression and the stress assessment explaining the underlying mechanism controlling fatigue life. The agreement between these observations reinforces the dual-approach verification framework and highlights the role of fibre reinforcement in reducing damage accumulation and extending fatigue life in railway sleepers.

Table 2: Summary of experimental and analytical fatigue performance (Camille et al., 2025)

Specimen	Avg. Static Capacity (kN)		Number of cycles to failure	
	P_{cr}	P_u	Experimental	Stress-based analytical
PO-F1	220	453	222,472	883,341
PO-F2			991,400	
PF-F1	232	477	$> 3\times10^6$ (run-out)	3,312,391
PF-F2				

4 Concluding remarks

In this study, the fatigue performance of prestressed concrete sleepers (i.e., PO & PF) was evaluated using a dual-approach framework that combined stiffness- and stress-based assessments and was validated against the experimental results. From the comparison herein, the following conclusions were drawn:

- PF sleepers demonstrated significantly improved fatigue behaviour, achieving experimental run-out beyond 3×10^6 cycles, while PO failed below 3×10^6 cycles.
- The stiffness-based assessment emphasised the progressive damage behaviour, showing reduced degradation rates in PF and an estimated life improvement factor of ~4.1.
- The mechanistic interpretation through the analytical stress-based approach calculated a reduced effective stress range (~15%) and a corresponding fatigue life increase of ~3.7, in good agreement with experimental results.

As a result, the consistency between stiffness and stress responses confirmed the reliability of the proposed dual-approach verification framework, demonstrating that macro synthetic fibre reinforcement enhances fatigue performance through improved crack control, stress redistribution and reduced stress concentration, ultimately enabling a more resilient and durable sleeper design with improved track performance and reduced maintenance requirements.

5 Acknowledgements

The authors gratefully acknowledge the Australian Research Council's Industrial Transformation Training Centres Scheme (ARC Training Centre for Advanced Technologies in Rail Track Infrastructure: IC170100006), which provided the catalyst for undertaking this research, as well as BarChip Inc and Western Sydney University for their support of the authors' work described herein.

6 References

Camille, C., Kahagala Hewage, D., Mirza, O., & Clarke, T. (2022). Full-scale static and single impact testing of prestressed concrete sleepers reinforced with macro synthetic fibres. *Transportation Engineering*, *7*, 100104. https://doi.org/https://doi.org/10.1016/j.treng.2022.100104

Camille, C., Kahagala Hewage, D., Mirza, O., & Clarke, T. (2025). *Enhancing the fatigue resistance of prestressed concrete sleepers using macro synthetic fibres* CORE 2025: Conference on Railway Excellence: Kaitiaki - Guarding the Future, Auckland. https://search.informit.org/doi/10.3316/informit.T20251209000153008881849582

Camille, C., Kahagala Hewage, D., Mirza, O., Mashiri, F., Kirkland, B., & Clarke, T. (2021). Performance behaviour of macro-synthetic fibre reinforced concrete subjected to static and dynamic loadings for sleeper applications. *Construction and Building Materials*, *270*, 121469. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.121469

Camille, C., Kahagala Hewage, D, Mirza, O, Mashiri, F, Kirkland, B, Clarke, T. (2021). Post-cracking strength classification of macro-synthetic fibre reinforced concrete for sleeper application.*Fibre Reinforced Concrete: Improvements and Innovations* RILEM-fib International Symposium on Fibre Reinforced Concrete: Improvements and Innovations, BEFIB 2020,

Camille, C., Mirza, O., Kirkland, B., & Clarke, T. (2022). Structural behaviour of prestressed concrete sleepers reinforced with high-performance macro synthetic fibres. *Engineering Failure Analysis*, *141*, 106671. https://doi.org/https://doi.org/10.1016/j.engfailanal.2022.106671

European Standard. (2006). Fibres for concrete - Part 2: Polymer fibres - Definitions, specifications and conformity, EN14889-2:2006. In. European Committee for Standardization (CEN).

Goto, K., Watanabe, T., Hosoda, M., & Minoura, S. (2018). Commentary: Fatigue Life Assessment Method for Prestressed Concrete Sleepers [General Commentary]. *Frontiers in Built Environment*, *Volume 4 - 2018*. https://doi.org/10.3389/fbuil.2018.00019

Kahagala Hewage, D., Camille, C., Mirza, O., Mashiri, F., Kirkland, B., & Clarke, T. (2024). Effect of post-peak flexural toughness on the residual performance of macro synthetic fibre reinforced concrete sleepers subjected to impact loading. *Engineering Structures*, *307*, 117913. https://doi.org/https://doi.org/10.1016/j.engstruct.2024.117913

Nairn, J., & Stevens, N. (2010). *Rational Design Method for Prestressed Concrete Sleepers* Conference on Railway Engineering - CORE 2010: Rail, Rejuvenation and Renaissance, Wellington, N.Z. https://search.informit.org/doi/10.3316/informit.761251021902120

Parvez, A., & Foster, S. J. (2017). Fatigue of steel-fibre-reinforced concrete prestressed railway sleepers. *Engineering Structures*, *141*, 241-250. https://doi.org/https://doi.org/10.1016/j.engstruct.2017.03.025

Standard Australia Online. (2012). Railway Track Materials - Part 14: Prestressed concrete sleepers, AS1085:14:2012. In. SAI Global database.

You, R., Li, D., Ngamkhanong, C., Janeliukstis, R., & Kaewunruen, S. (2017). Fatigue Life Assessment Method for Prestressed Concrete Sleepers [Review]. *Frontiers in Built Environment*, *Volume 3 - 2017*. https://doi.org/10.3389/fbuil.2017.00068