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Improved structural performance of railway sleepers using macro synthetic fibre reinforced concrete

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Abstract

With the increase in railway traffic and axle loads over the last few decades, traditional sleepers are experiencing more premature failure, resulting in significant maintenance costs. While such concerns about the conventional materials have long been acknowledged, replacement with composite alternatives remains fairly limited in practice. In this paper, a comprehensive assessment (i.e. experimental & numerical) of the conventional concrete sleepers reinforced with high-strength, prestressed steel and macro synthetic fibres are provided to improve structural performance. Indeed, by incorporating macro synthetic fibres that possess adequate structural and sustainable characteristics, this study aims to address innovatively the current cracking and corrosion issues commonly associated with the prestressed concrete railway sleeper. Moreover, to further validate the structural behaviour of macro synthetic fibre reinforcement in prestressed concrete sleepers, numerical models are compared with the experimental results that demonstrate the design feasibility for the current specifications and future demands. Finally, using a life cycle costing approach, the long-term financial benefits of macro synthetic fibre reinforcement in sleepers are acknowledged despite their relatively high investment costs. Accordingly, the findings in this paper provide an improved understanding of the reinforcing capabilities and financial feasibility of macro synthetic fibre towards the development of innovative sleepers for the railway industry

Keywords: railway sleeper, fibre reinforced concrete, structural performance, prestressed concrete.

1 Introduction

Railway sleepers are crucial structural components of the track, whose primary function is to redistribute the loads (i.e. static & dynamic) to the substructure [1]. Generally, sleepers are made from timber, steel and concrete, with the preferred option for ballasted track being prestressed concrete. However, despite concrete sleepers possessing desirable properties such as superior structural capacity and good track stability for high-speed traffic, the sections are experiencing more premature failures over the last few decades because of increased traffic and axle loads [2]. For instance, the prestressed concrete sleeper usually experiences premature failure at critical locations (i.e. rail seat & centre), resulting from excessive wheel/impact loads, the poor tensile strength of concrete and material deterioration (i.e. corrosion of steel reinforcement) through interaction with the environment. While these concerns about sleeper materials have long been acknowledged, replacement with composite alternatives remains relatively limited in practice. These composite alternatives characterise synthetic sleepers made from natural rubber, recycled plastic, glass fibre waste and fibre reinforced polymer, engineered to provide better resistance to deterioration, cracking, corrosion and improved elasticity. However, the complex and expensive manufacturing processes are the main reasons for the composite sleepers' prohibitive costs, rendering them not financially viable for the railway industry [3]. Moreover, these composite sleepers are relatively new with unknown in-situ and long-term performance that would require years to investigate and implement on track. Therefore, it is believed that reinforcing or improving the existing prestressed concrete sleeper design can provide a cost-effective alternative while re-engineered to meet the demanding requirements of railway sleepers.

By incorporating macro synthetic fibres that possess good durability, adequate strength and sustainable characteristics [4], this study investigates the reinforcing capability and cost-efficiency of macro synthetic fibre reinforced concrete (MSFRC) for sleeper applications. Indeed, incorporating macro synthetic fibres into concrete is expected to lessen the sleeper's corrosive behaviour while considerably enhancing the ductility and post-cracking performances at larger crack widths [5, 6]. This is particularly beneficial for maintenance purposes, allowing sleepers to remain on track when cracked because of the substantial residual capacity. Therefore, through comprehensive numerical and experimental investigations, this study identifies an optimised design for the partial replacement of prestressing steel with fibre reinforcement to reduce corrosion risks, improve post-cracking behaviour and reduce life cycle costs of prestressed concrete sleepers. Hence, an optimal MSFRC sleeper design is proposed that is economically and practically feasible for the railway industry.

2 Methods

The experimental and numerical investigations were conducted on the typical full-depth, standard gauge, heavy-duty 30 tonnes axle load sleeper, as shown in Figure 1. Two types of sleepers comprising conventional prestressed (PO) and prestressed with fibres (PF) were evaluated, for which the geometrical characteristics, manufacturing process, prestressing tension and design mixes were all kept constant, in accordance with [7]. That is, a high early strength M55 concrete mix was used in both PO and PF samples to achieve the workability requirement and prestressing wires' release strength of 30 MPa within the first 48h. However, despite the primary reinforcement in both types of sleepers being identical (i.e. 20 indented steel wires), PF sleepers also encompassed high-performance polypropylene fibres at an optimum fibre dosage of 1.0% (by volume), based on the recommendation of [8]. Table 1 presents the mechanical and geometrical characteristics of the primary and secondary reinforcement systems implemented in the sleepers. It should be noted that the steel reinforcement detailing was omitted from this paper because of intellectual property rights.

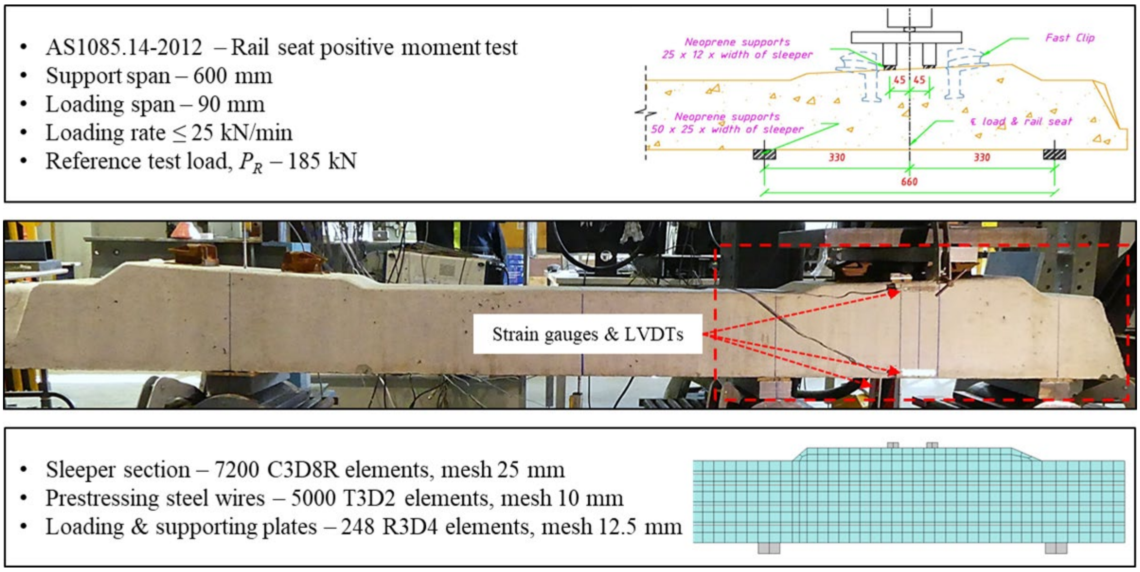

Figure 1: Experimental and numerical parameters for sleeper investigation at rail seat positive moment.

Reinforcement type	Sleeper type	Length (mm)	Base Material	Tensile Strength	Young's modulus
Primary (prestressing wires)	PO PF	2500	High-tensile steel wire	1700 MPa	205 GPa
Secondary (Fibre: BC48)	PF	48	Virgin Polypropylene	640 MPa	12 GPa

Table 1: Physical and mechanical properties of the reinforcement types in sleepers.

The prestressed concrete sleepers are currently designed using the permissible stress approach for which the rail seat section must satisfy the benchmarking load tests without exhibiting structural cracks. Accordingly, the test arrangement shown in Figure 1 is comparable to the vertical load test defined in [7], for which two individual specimens were tested per sleeper's type, further equipped with four strain gauges and two linear variable differential transformers at the mid-span. All the static instrumentations and associated parameters were recorded at a maximum sampling rate of 5 Hz.

For the numerical investigation, the sleeper model characterises an accurate reproduction of the experimental specimens (i.e. PO & PF) assessed under static conditions and performed using Abaqus/Explicit analysis under time control [9]. However, to simplify the model and efficiently avoid meshing/convergence issues, the sleeper's inward cants (i.e. slope) and fastclip connectors at the rail seat sections were flattened and excluded, respectively. In terms of reinforcement, the prestressing steel wires were modelled as deformable parts, while the macro synthetic fibres were characterised through the material's constitutive laws. Moreover, the loading and supporting conditions were made equivalent to the experimental specifications to replicate best the typical four-point bending setup as well as the displacement-controlled load applied through two discrete rigid plates perpendicular to the concrete sleeper.

3 Results

The rail seat positive bending moment (RP) test is crucial for the design of sleepers in achieving the railway operational and safety requirements. Accordingly, the PF sleepers' performance was compared to the conventional PO sleepers in assessing the structural and cost benefits of incorporating fibre reinforcement. The load-deflection curves for PO and PF sleepers' individual behaviours when vertically loaded at RP is shown in Figure 2.

From the experimental results obtained, PF performed comparably to PO by satisfying the benchmarking load test without exhibiting structural cracks. In fact, the initiation of cracks occurred around 35% above the performance criteria at loads of 225 kN. However, the fibres' contribution mostly activated once the concrete section cracked to redistribute the stresses as the steel wires yielded and best perform at larger crack states through the bridging mechanism. This behaviour was noticeably identified in Figure 2, where the PF sleepers demonstrated an extended deflection-hardening phase followed by progressive deterioration. Conversely, PO experienced a sudden drop in load capacity due to severe local crushing and steel reinforcement fracture. Based on the number of steel wires failing, an abrupt yet partial or complete loss in load capacity was observed in PO specimens compared with PF that benefited from the addition of fibres to provide adequate warning through enhanced ductility.

In terms of numerical results, validation of the model was achieved by comparing the ultimate loads and failure modes to the experimental observations, as shown in Figure 3. Note that the differences between the numerical and experimental loads were within an acceptable discrepancy of 5% while demonstrating comparable failure modes. Moreover, the results demonstrated that the ultimate capacity mainly depends on the location and number of steel wires, which effectively act in the tensile region. Although the addition of fibres does not directly influence the cracking or ultimate load capacities, its incorporation into the sleeper significantly increased post-peak reliability to provide superior warning time and fracture toughness prior to failure. Accordingly, the fibres allow for the strategic exclusion of up to 15% of the prestressing wires, with the ultimate capacity only decreasing by 1.5%. Based on further analytical analysis, sleeper model with a reduced number of reinforcement wires satisfies the permissible stress criteria to provide manufacturers and track owners with potential savings while being within safe operational limits.

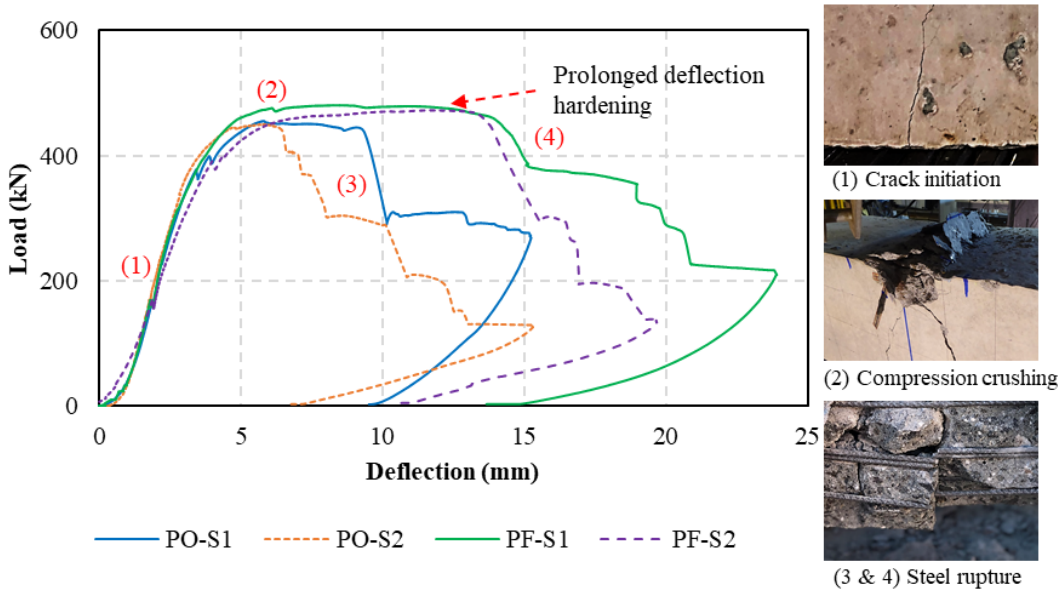

Figure 2: Load-defection comparison of sleepers at rail seat positive moment test.

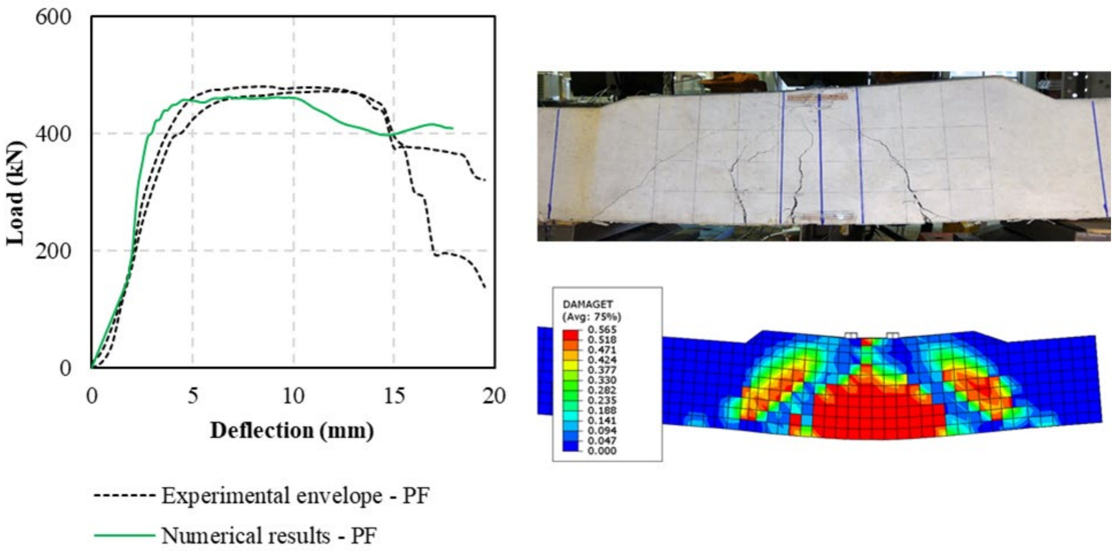

Figure 3: Comparison of the numerical and experimental results.

4 Conclusions and Contributions

Through the experimental and numerical investigations of MSFRC sleepers, this paper briefly discusses the structural performance and optimisation of the reinforcement design, providing a more reliable and cost-efficient railway sleeper. Although not methodically presented herein, key aspects considered for the life cycle cost assessment includes production, installation, operation and maintenance, and disposal costs expected over the sleeper's service life. Moreover, as receiving one dollar today is worth more than receiving a dollar tomorrow, actual discount and inflation rates were adopted to appraise from future dollar amount to the current value necessary in assessing the financial risk.

Accordingly, the 15% theoretical reduction of prestressing wires and the inclusion of macro synthetic fibres at a 1.0% volume dosage resulted in estimated cost savings of $4.67 per MSFRC sleeper because of the reduced material and labour required to manufacture. However, despite the initial cost being 5% more expensive than PO, the reduced maintenance and improved design life (i.e. five years on average being conservative) of the optimised sleeper resulted in an overall life cycle cost saving of ~$11,000/km of railway tracks for a 100-year study period [10]. Therefore, concerning the implementation of macro synthetic fibre for railway sleeper applications, the following conclusions were identified:

- The post-failure observations of PO and PF specimens were relatively comparable, with both types of sleeper suffering from flexural-shear cracks and local compression crushing that led to failure. However, PF sections were more effective at resisting crack propagation and fracture, providing structural adequacy and a safe margin of residual capacity that may allow sleepers to remain operational on track once cracked.
- The cracking and failure mechanisms were effectively predicted for both PO and PF numerical models towards evaluating the performance limits in partially eliminating prestressing wires. Despite the models' limitation that relied on various essential assumptions, it was concluded that the partial substitution of up to three wires was permissible through the incorporation of macro synthetic fibres.
- The inclusion of fibre reinforcement in conjunction with partial removal of prestressing wires in railway sleepers permitted considerable life cycle cost savings, which are projected to become even more competitive as the optimised design is commercially available and manufactured in bulk.

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