STATIC PERFORMANCE OF PARTICULATE FILLED RESIN COMPOSITE RAILWAY SLEEPERS IN THE RAIL-SEAT REGION

A Thesis submitted by

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ABSTRACT

Polymeric railway sleepers have been increasingly developed as a new alternative to traditional timber sleepers due to their advantages of high strength-to-weight ratio and excellent durability. The material properties of this new technology can be engineered to behave like timber and the particulate filled resin (PFR) cored sleeper demonstrated promising performance. However, adopting this sleeper type is challenging considering the insufficient information to date on the development of sleepers made from PFR mixed with flexible fillers or fibre reinforcement. In addition, the limited understanding of the screw pull-out and lateral restraint behaviour has been indicated as another major challenge. Therefore, this research systematically evaluated the development of the PFR system and the rail-seat behaviour of composite sleepers to increase the confidence in using this new type of technology.

The first manuscript presented the investigation of crumb rubber and short fibre reinforcement introduced into the epoxy-based PFR core of composite railway sleepers to minimise cost and enhance mechanical properties. The physical and mechanical properties including the microstructure of the new polymer mixes were evaluated. The experimental results showed a high correlation between the increasing contents of new ingredients and the engineering properties of the PFR mixes. A simplified prediction equation was proposed to predict critical properties as a function of the compressive strength. Analytical Hierarchy Process was also implemented to determine the most suitable polymer mix for the development of a cost-effective and reliable performance composite railway sleeper.

The effect of material properties on the pull-out behaviour was investigated in the second manuscript. The pull-out strength and the hole microstructure of different sleeper technologies including timber, synthetic composite, recycled plastic and Particulate Filled Resin sleepers were investigated to determine the effect of material properties on their screw pull-out behaviour. The paired samples test revealed a high correlation between the pull-out strength and the shear strength of the materials. A simplified prediction model was developed to predict the pull-out resistance for railway sleepers based on the shear strength of the composite sleepers.

The effect of screw geometry was evaluated in the third manuscript. The influence of the diameter of the screw, embedded length of the screw and sleeper

material properties was determined using the direct pull-out test. The results showed increasing the thread embedded length has a significant effect on the pull-out strength due to the increased thread engaging area while the major diameter is more likely to affect timber rather than composites owing to the strong load-bearing capacity of hardwood timber. Based on the significance of these parameters, an analytical model consisting of three prediction equations was developed to estimate the pull-out resistance and was also verified by the results from the available literature and reports. Each equation corresponds to a specific failure mode which can be determined by the type of fibre reinforcement adopted in the sleeper technology. Compared to other existing theoretical models, the proposed model is found over 50% more reliable.

The lateral restraint behaviour and failure modes were investigated in the fourth manuscript. This study investigated the lateral strength of composite sleepers at the standard required displacement of 5.1 mm and failure. The results showed screw and sleeper material yielding at a very early stage even before 5.1 mm for all tested samples. The grain/fibre shear-out failure was noticed in the orthotropic sleeper materials while the isotropic material mainly exhibited the bearing failure. Based on the isotropic hardening rule and Hill’s criterion, finite element models were developed and well predicted the screw lateral behaviour. The stress distribution in the screw and the sleeper was also revealed and demonstrated a good correlation to the observed lateral failures.

This research provided a detailed understanding of how the critical parameters affect the rail-seat performance of polymer composite sleepers. Additionally, the results of this research offered useful analytical tools which may support researchers and design engineers to develop composite sleepers with desired rail-seat performance and improve the confidence in using this technology.

CERTIFICATION OF THESIS

This thesis is entirely the work of Peng Yu except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Student and supervisors' signatures of endorsement are held at USQ.

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STATEMENTS 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: Peng Yu, Allan Manalo, Wahid Ferdous, Rajab Abousnina, Choman Salih, Tom Heyer, and Peter Schubel, (2021) "Investigation on the physical, mechanical and microstructural properties of epoxy polymer matrix with crumb rubber and short fibres for composite railway sleepers" Construction and Building Materials, vol. 295, 123700. (Impact factor: 6.141).

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

Manuscript 2: Peng Yu, Allan Manalo, Wahid Ferdous, Choman Salih, Rajab Abousnina, Tom Heyer, and Peter Schubel, (2021) "Failure analysis and the effect of material properties on the screw pull-out behaviour of polymer composite sleeper materials" Engineering Failure Analysis, vol. 128, 105577. (Impact factor: 3.114).

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Manuscript 3: Peng Yu, Allan Manalo, Wahid Ferdous, Choman Salih, Rajab Abousnina, Tom Heyer, and Peter Schubel, "New prediction model for the screw pull-out strength of polymer composite railway sleepers" submitted to Composite Structures. (Impact factor: 5.407).

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Manuscript 4: Peng Yu, Wahid Ferdous, Allan Manalo, Choman Salih, Rajab Abousnina, Tom Heyer, and Peter Schubel, (2022) "Screw lateral restraint behaviour of timber and polymeric based railway sleepers" Engineering Failure Analysis, vol. 139, 106514. (Impact factor: 3.114).

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TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

Background and motivation

Sleepers are important components of the railway system. Their main function is to convey the vertical, lateral and longitudinal loads caused by a travelling train to the ballast, sub-ballast and subgrade layers (Sadeghi 2012). In the last 150 years, hardwood timber has been used as a sleeper material due to its excellent mechanical properties. However, they are suffering from serious issues such as deterioration over time (Ferdous & Manalo 2014), high prices and less availability (Ferdous et al. 2017). The premature failure of timber sleepers (e.g., fungal decay, end splitting, and termite attacks (Ferdous & Manalo 2014)) require significant track maintaining costs (Grimes & Barkan 2006). Among the commonly seen failures, fungal decay caused half the failure of timber sleepers while end splitting affected 10% and the termite attack occurred in 7% of the sleepers. Due to the high cost of maintenance, a new sleeper material is required to replace the increasingly scarce timber and demonstrates advantages including great toughness, good durability, and environmental sustainability.

Composite sleepers are emerging as an alternative technology to hardwood timber due to their benefits of high strength-to-weight ratio, good resistance to corrosion, moisture and insect attack, low thermal conductivity, and electrical non-conductivity (Ferdous et al. 2015). Their material properties can be engineered to meet performance and durability requirements and to possess structural behaviour similar to timber (Van Erp & McKay 2013). Ferdous et al. (2015) classified composite railway sleepers into three groups, i.e., Type-1 sleepers which use recycled plastics as the main matrix with short or no fibre reinforcement; Type-2 sleepers which have long continuous glass fibre reinforcement in the longitudinal direction; and Type-3 sleepers which are reinforced with long fibres in both longitudinal and transverse directions. These three types of composite sleepers have varied costs and mechanical performance in the rail seat region due to the different matrices and reinforcement materials. Table 1 depicts the reported screw pull-out force of timber and different types of composite railway sleepers. It is noticeable that the Type-1 sleepers have an inferior pull-out resistance compared to timber while Ferdous et al. (2015) highlighted that while Type-2 and Type-3 sleepers have comparable pull-out resistance to timber, they are generally more expensive than timber sleepers and suffer manufacturing difficulty. Consequently, there are limited material systems that can resist pull-out force. Sleepers made from particulate-filled resin (PFR) with structural components seem to be a promising solution to the timber replacement issue (Shamsuddoha et al. 2013; Ferdous et al. 2016; Khotbehsara et al. 2019; Ferdous et al. 2020; Khotbehsara et al. 2020). This type of innovative design falls under the Type-3 sleepers as both the outer structure component and PFR core are reinforced by either short fibres or continuous fibres in multiple directions. The excessive use of fibre reinforcement guatrantees superior mechanical performance while the arrangement of fibres can also be easily managed to control the cost as per demands. However, the PFR sleepers suffer chipping during drilling due to its brittleness. This highlights the need for further improvement (e.g., the addition of flexible fillers and short fibres) to enhance the material properties of the PFR matrix and its resistance to crack for railway sleeper application (Law et al. 2016). Crumb rubber is adopted as an economic and green (Issa & Salem 2013) filler to enhance the flexibility (Yang et al. 2011; Jokar et al. 2019) of brittle cementitious materials. This type of fillers is expected to prevent chipping failure in sleeper drilling owing to the low elastic modulus of rubber particles.

Table 1: Pull-out performance comparison of different types of composite sleepers (Ferdous et al. 2015)

Sleeper material	Timber	Type-1	Type-2	Type-3
Pull-out force (kN)	>40	31.6-35.6	65	>60

The properties of the sleeper materials dominate the screw pull-out performance as no damage or permanent deformation is observed on the fasteners during pull-out. Ultimate shear strength is often considered as a significant parameter to predict pull-out strength due to the pull-out mechanism that the internal threads on the relatively weak host materials are sheared off by the strong screw (Chapman et al. 1996; Tsai et al. 2009; Shih et al. 2017; Du et al. 2019). In addition, density is believed to directly affect the pull-out resistance of the host material and a high correlation was observed by a number of researchers (Seebeck et al. 2004; Ramaswamy et al. 2010; Çetin & Bircan 2021). Nevertheless, it is still very challenging to predict the pull-out strength of composite materials according to density due to their varied specific strength. Moreover, some researchers correlated the pull-out force with different material properties including porosity (Pujari-Palmer et al. 2018), compressive strength (Lorrain et al. 2011; Al-Sabah et al. 2021), and tensile strength (Mendis & French 2000) but obtained limited success. Their studies also indicated that the observed failure modes are dependent on the affecting material strength, which highlights that a more detailed understanding of the screw pull-out behaviour is needed.

Screw geometry is another significant factor influencing the pull-out performance apart from the material properties. As per the distinct pull-out failure modes (e.g., thread stripping and thread bearing), different geometrical parameters are used to predict the pull-out force. The fundamental thread stripping (FTS) model is developed based on a cylindrical surface defined by the screw major diameter and embedded length (Patel et al. 2010). The thread bearing (TB) model is another pull-out prediction model which features the thread bearing area and the interacted thread number (Juvinall & Marshek 2020). Due to the long shank and the resultant less thread area of rail screws, the TB model may generate a relative low pull-out result for railway sleepers. Thus, it is necessary to carefully consider the screw geometry as well as the failure mode before applying the prediction models. Notwithstanding, the effect of geometry is neglected by the international standards and specifications for railway sleepers. Current composite sleeper technologies are inevitably tested using different types of screws required by railway authorities. The Sekisui FFU sleeper (Sekisui 2019) was tested with SS8-140 rail screws (Ø24mm in major diameter and 140mm underhead length (Bemo Rail)) under DIN EN 13481-2 (European Committee for Standardization 2017) but would fix with Ø16mm screws required by Queensland Rail (QR) when being introduced to Queensland (Murray 2006). Ignoring the influence of the screw geometrical parameters may result in less confidence in evaluating overseas composite sleeper technologies for local usage.

The rail screws are subjected to uplift and lateral forces from the movement caused by the passing train. The repeated lateral forces can fail fasteners and lead to wide gauges and derailments (Roadcap et al. 2019). Dersch et al. (2019) highlighted that the screws were laterally pushed by timber sleepers as the timber marks occurred on the screw shank. Permanent damages observed in both the rail screws and the sleepers indicated screw latera restraint is a composite behaviour in which the screw and sleeper affect each other simultaneously. This behaviour is complex and rarely investigated, and no requirement is clearly presented in current standards or specifications (Standards Australia International 2003; ARTC 2007; Japanese Standards Association 2007; AREMA 2013). Specifically, the lack of test methods or criteria is found to be a serious issue. Due to the complication of lateral restraint, researchers adopted Finite Element Analysis (FEA) to illustrate the stress distribution and failure location in the fastener to sleeper connection. The timber sleeper model was simulated in different approaches including elastic foundation (Dick et al. 2007), user material subroutine (UMAT) defined orthotropic model (Yu & Liu 2019), and constitutive model (Dersch et al. 2019). The elastic model failed to show the post-elastic reaction of timber while the UMAT subroutine requires a high level of programming skills. Therefore, a simple but accurate FEA model seems necessary to build a deep understanding of the screw lateral restraint behaviour.

This thesis systematically investigated the screw pull-out and lateral restraint performance of timber and alternative composite railway sleepers including the plastics (high-density polyethylene) without fibre reinforcement, the synthetic composites with continuous fibres in the longitudinal direction, and short fibre reinforced PFR. It started from an investigation on the influence of short fibre reinforcement on the epoxy-based PFR and developed an optimal matrix as the core material of composite sleepers. Additionally, this study investigated the effect of material properties and screw geometry on the pull-out strength. Based on the high correlation between the shear strength and pull-out resistance, an analytical approach was developed to accurately predict the pull-out force of timber and polymer composite sleepers considering the effect of screw geometry. Finally, failure modes of lateral restraint behaviour were evaluated experimentally and the FEA models were established to illustrate the contribution of different stresses on the screw and sleepers. The results of this thesis added new knowledge on the rail-seat performance of polymeric railway sleepers for their reliable design and safe application in a railway track.

Objectives

The main objective of this research is to investigate the rail-seat performance of timber and fibre reinforced polymer composite railway sleepers and to determine the effect of critical parameters on the screw pull-out and lateral restraint behaviour through extensive experimental and analytical works. To address these objectives, the specific objectives were defined below:

- To evaluate the effect of crumb rubber and short fibre reinforcement on the physical, mechanical properties and microstructure of the epoxy-based PFR matrices;
- To investigate the influence of material properties on the pull-out behaviour of timber and polymer composite sleepers with different fibre reinforcement;
- To examine the effect of screw geometrical parameters on the pull-out behaviour of timber and timber-alternative composite sleepers; and
- To study the lateral restraint behaviour and failure modes of the rail screw to sleeper connection in the rail-seat region of timber and polymer composite sleepers.

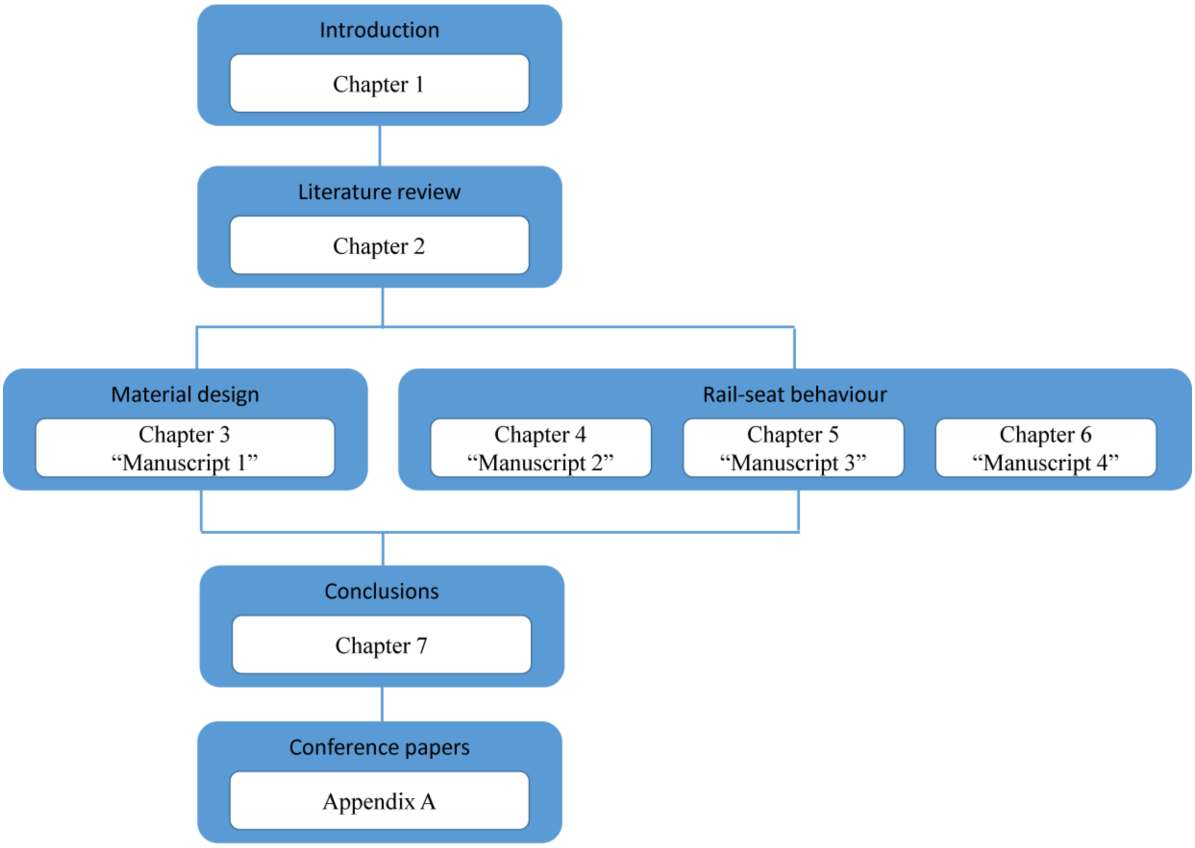
Study limitations

This thesis investigated the rail-seat performance of timber and timber replacement composite sleepers, i.e., plastic, synthetic composite, and PFR cored sleepers. These sleeper technologies are included in this study dependent on their availability and the different fibre reinforcements adopted. Their mechanical properties, screw pull-out resistance and lateral restraint forces as reported in this thesis may be different among different producers due to different designs and manufacturing processes. Nevertheless, the used fibre reinforcement and base matrices are reported in each study conducted for validation and repetition of the test results.

Some test results presented in this study are limited to the applied test conditions. For example, the lateral force of the plastic sleeper continuously increased in the lateral restraint test even when the test had to end as the screw flange had attached to the rail-seat surface. Despite this limitation, the plastic sleeper showed permanent deformation as its main lateral failure which had fulfilled the research aim. Thus, the results of this thesis are reliable for potential evaluation in the future as all relevant parameters have been reported.

Thesis organisation

This thesis is presented in the format of Thesis by Publication. It started from an Introduction in Chapter 1 presenting research background and motivation, objectives, and study limitations. Chapter 2 provided a comprehensive literature review highlighting the state-of-the-art in the field, defining the challenges, opportunities, and research gaps, which facilitated the development of the objectives and the methodology as well as the justification of the research novelty. Then, four experimental studies were well planned and conducted with the important test results and research findings given in Chapters 3 to 6 in the form of published and submitted journal papers. Finally, Chapter 7 concluded the main findings and significant contributions of this study with recommendations suggesting new opportunities and further research. An overview of four journal articles is shown below while the presentations of the significant outcomes in national and international conferences are summarised in Appendix A:



Manuscript 1: Peng Yu, Allan Manalo, Wahid Ferdous, Rajab Abousnina, Choman Salih, Tom Heyer, and Peter Schubel, (2021) "Investigation on the physical, mechanical and microstructural properties of epoxy polymer matrix with crumb rubber and short fibres for composite railway sleepers" Construction and Building Materials, vol. 295, 123700. (Impact factor: 6.141).

DOI: https://doi.org/10.1016/j.conbuildmat.2021.123700

This manuscript evaluated the effect of crumb rubber and short fibre reinforcement on the material properties and microstructure of the epoxy polymer core of composite railway sleepers. The new ingredients include 0-30% volume of crumb rubber, 0-1.5% volume of straight PP fibre / twisted PP fibre, and 0-15% weight of chopped glass fibres. The aim of introducing the new ingredients was to reduce the cost of the polymer matrix and to improve its mechanical performance. The physical and mechanical properties were investigated in various tests and the experimental results demonstrated a high correlation between the dosage of ingredients and the material properties of the polymer mixes. A simplified prediction equation based on linear function was proposed to estimate critical properties as a function of compressive strength. Moreover, Analytical Hierarchy Process was also applied to identify the most suitable PFR mix for the development of a cost-effective and best performing composite railway sleeper.

Manuscript 2: Peng Yu, Allan Manalo, Wahid Ferdous, Choman Salih, Rajab Abousnina, Tom Heyer, and Peter Schubel, (2021) "Failure analysis and the effect of material properties on the screw pull-out behaviour of polymer composite sleeper materials" Engineering Failure Analysis, vol. 128, 105577. (Impact factor: 3.114).

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The second manuscript evaluated the influence of material properties on the pull-out behaviour of timber and composite sleeper technologies, i.e., recycled plastics, synthetic composites, and PFR. The ultimate pull-out force of these sleepers was measured in the screw pull-out test and the pull-out behaviour was also analysed. The hole cross-sections were then observed under the microscope to examine the failure modes and microstructure. The pull-out results were statistically analysed through one-way analysis of variance (ANOVA) to identify the significant difference while the paired samples test was conducted to show the correlation between the pull-out resistance and the sleeper material properties. Based on the highest correlation of the material shear strength, a simplified prediction model was established to estimate the pull-out strength of composite railway sleepers as per the ultimate shear strength. The results of this manuscript are anticipated to address the current challenge of limited understanding of the screw pull-out behaviour of timber alternative sleepers for their wide acceptance in the maintenance of deteriorating railway tracks.

Manuscript 3: Peng Yu, Wahid Ferdous, Allan Manalo, Choman Salih, Rajab Abousnina, Tom Heyer, and Peter Schubel, "New prediction model for the screw pull-out strength of polymer composite railway sleepers" submitted to Composite Structures. (Impact factor: 5.407).

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The third manuscript investigated the effect of screw geometry, i.e., diameter and embedment length, on the pull-out behaviour of timber and timber replacement composite sleepers. The ultimate pull-out force of the tested sleeper types was obtained in the screw pull-out test and then analysed with the variance of thread embedded length and screw major diameter. The normalised stress on the screw was calculated to further identify the influence of the two evaluated parameters. The two-way analysis of variance (ANOVA) was implemented to investigate the influence level of the ultimate shear strength and screw geometry. The increased thread embedded length significantly affect the pull-out strength due to the increase of thread engaging area while the screw major diameter has a considerable influence on timber rather than composite materials owing to timber's continuously high shear strength. As per the statistic results and the distinct failure modes of the tested sleeper materials, an analytical model is developed to predict the pull-out strength of railway sleepers and further compared with other existing theoretical models. The proposed model is found over 50% more reliable than the existing models. The novel findings of this research are expected to eliminate the need for the costly and time-consuming repeated pull-out test, to improve the limited understanding of the effect of screw geometries on the pull-out behaviour of composite railway sleepers, and to ensure the stability of railway track when alternative sleeper technologies are adopted for the maintenance strategy.

Manuscript 4: Peng Yu, Allan Manalo, Wahid Ferdous, Choman Salih, Rajab Abousnina, Tom Heyer, and Peter Schubel, "Experimental and numerical analysis on the screw lateral restraint behaviour of timber and polymer composite railway sleepers" submitted to Engineering Failure Analysis. (Impact factor: 3.114).

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The fourth manuscript investigated the lateral restraint behaviour and failure modes of the screw to sleeper connection in the rail-seat region of timber and timber-alternative polymer composite sleepers. The lateral restraint test was implemented to obtain the lateral forces acting on the steel rail screws embedded in the timber and timber alternative sleeper technologies. The failure modes of the rail screw and the sleeper samples were analysed and correlated with their material properties to gain a better understanding of the complex lateral restraint mechanism. The experimental results showed screw yielding and sleeper material hardening even before 5.1 mm displacement while timber and synthetic composites exhibited ultimate lateral strength almost half of plastics' performance due to the relatively weak shear capacity in the fibre direction. The grain/fibre shear-out failure was noticed in the orthotropic sleeper materials (timber and synthetic composites) while the isotropic material (plastic) mainly exhibited bearing failure. According to the experimental observation, a damaging process was proposed to describe the development of the progressive failure for different sleeper materials. FEA was applied to simulate the lateral restraint behaviour and to analyse the stress distribution in the screw body and the sleeper holes. Based on the isotropic hardening rule and Hill's criterion, the developed finite element models predicted very well the screw lateral deformation and strength of timber and composite sleepers. The results of this manuscript will add new knowledge on how the rail screw and timber/polymer materials behave under lateral forces for their safe design and application in a railway track.

Summary

The interest in polymer composite sleepers as an alternative to traditional timber sleepers is increasing due to their advantages of superior material properties and longer service life. Nevertheless, understanding of their rail-seat behaviour is limited restricting their wide uptake by the railway industry. This study experimentally and analytically investigated the screw pull-out and lateral restraint behaviour of the mostly adopted timber replacement polymer sleepers through pull-out and lateral restraint tests. Then, the effect of material properties and screw geometry was

evaluated, and the lateral restraint behaviour was studied in the listed manuscripts which comprise the technical chapters of this thesis. Understanding the rail-seat behaviour of composite railway sleepers is the main motivation of this research and will increase the confidence in the extensive adoption in the railway sleeper market.

CHAPTER 2: LITERATURE REVIEW

This chapter provides a state-of-the-art review of the literature to identify the different parameters that affect the rail-seat behaviour of railway sleepers. It started with a brief overview of the rail track conditions in Australia and the current issues in railway sleepers focusing on the timber alternative sleepers. It then reviewed the screw pull-out performance of railway sleepers and the available studies that investigated how the material properties and the screw geometry can affect the pull-out and screw lateral performance at the rail seat to ensure that the rails are securely attached to the sleepers. Different theoretical and analytical approaches in predicting the screw pull-out strength were also reviewed and analysed. From this intensive review of literature, the current gaps in knowledge were identified to justify the novelty of the implemented research works.

2.1. Rail track conditions in Australia and problems in railway sleepers

Railway sleepers are critical structural components of the ballasted railway track system. Sleepers are placed underneath the rails to maintain gauge width, convey and distribute the transported rail loads to the ballast, sub-ballast and subgrade layers (Zhao et al. 2007). Hardwood timber has been the preferred sleeper material in the last 150 years due to its adaptability (Zarembski 1993). They are also workable, easy to handle, and applicable for all different types of rail tracks due to their excellent mechanical properties. Timber sleepers account for 2.5 billion and 10 million in-service sleepers worldwide (Rothlisberger 2008) and within Queensland (state of Australia) (Miller 2007), respectively. However, premature failures of timber sleepers increase the cost of track maintenance and deteriorate track efficiency. In Queensland, 2200 timber sleepers were examined and failed in different modes including fungal decay, end splitting, termite attacks, still sound, sapwood, shelling, rail cut, weathering, spike kill, and knots shown in Figure 1.

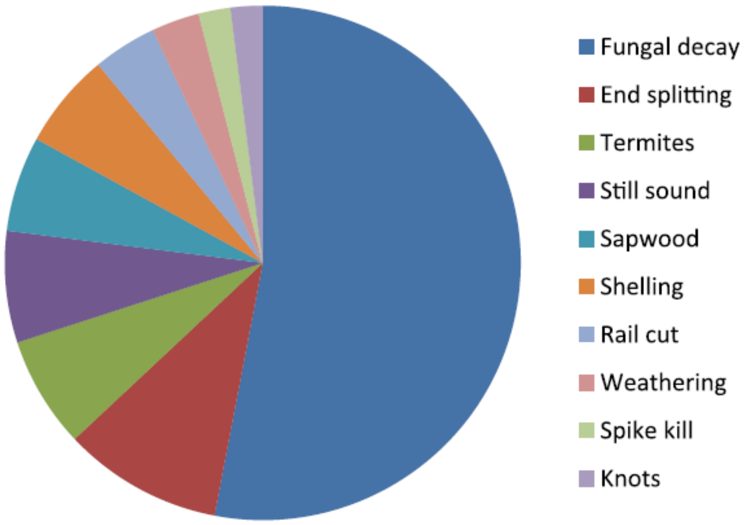

Figure 1: Common causes of timber sleeper failure (Ferdous & Manalo 2014).

The cost of sleeper maintenance is accounted as the main portion of the annual capital program for railway maintenance (Grimes & Barkan 2006). Figure 2 (a) showed that more than 50% of timber sleepers failed due to fungal decay. As an organic material, timber is infected by fungi when absorbing moisture, especially in rainy seasons which negatively influence the structural integrity of a track (Singh 1999). Figure 2 (b) illustrates the end splitting failure that occurred in 10% of the timber sleepers due to large shear loading in the transverse direction (Riley et al. 2001; Manalo et al. 2010). Termite attack failure in Figure 2 (c) is another common failure that accounted for 7% of the sleepers. Under the attack, all the cellulose-containing materials are consumed and damaged permanently (Horwood & Eldridge 2005). Apart from the timber failures, other growing concerns are the less availability of quality timber material and the environmental and health impact of using chemical preservatives to timber sleepers. Creosote has extensively been applied to impregnate timber sleepers (Pruszinski 1999) which can be considered as compromises on the absence of acceptable alternatives to timber (European Rail Infrastructure Managers (EIM) Newsletter 2008). Soon, these treated timber sleepers are much likely to require specialised disposal methods after service as these sleepers are regarded as hazardous waste (Thierfelder & Sandström 2008). Obviously, the railway industry requires an eco-friendly, durable, low maintenance material with longer design life to replace the traditional timber as a new alternative sleeper material.

Figure 2: a) fungal decay (Manalo et al. 2010), b) end splitting, and c) termite attacks (Spillman 2003) in timber sleeper.

2.2. Rail-seat performance of existing polymer composite sleepers

Polymer composites have been increasingly adopted globally owing to their excellence in strength-to-weight ratio, corrosion resistance, moisture resistance, insect resistance, and thermal and electrical non-conductivity (GangaRao et al. 2006). This type of material is regarded as a suitable alternative to traditional sleepers as they can be engineered to behave like timber (Van Erp & McKay 2013). Moreover, the service life of composite materials is generally three times longer than that of timber resulting in a significant reduction in the maintenance cost (Ferdous & Manalo 2014). A variety of composite sleeper technologies have emerged in the railway industry and have been classified by Ferdous et al. (2015) according to the amount, length and orientation of fibre applied in the matrix. The proposed three classifications include sleepers with short/no fibre reinforcements (Type-1), sleepers with long fibre reinforcement in the longitudinal direction (Type-2), and sleepers with fibre reinforcement in longitudinal and transverse directions (Type-3).

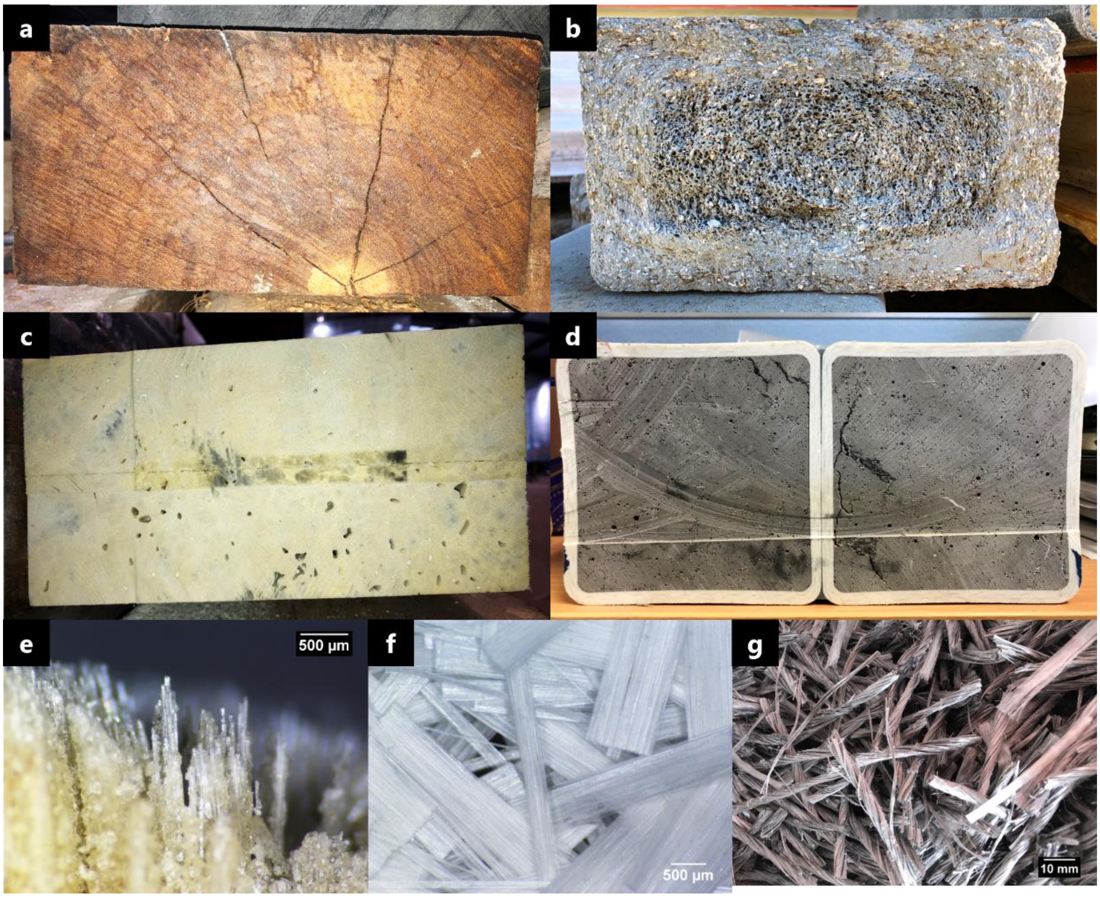

Figure 3: Cross-section of railway sleepers, a) timber, b) recycled plastic, c) synthetic composite, and d) PFR core confined by laminates; adopted fibre reinforcement, e) long continuous glass fibre in the longitudinal direction of synthetic composites, f) short glass fibres or g) macro polypropylene fibres added to the PFR core (Yu et al. 2021).

2.2.1 Type-1 sleepers

The Type-1 sleepers are made of recycled plastics (sourced from plastic bags, waste tyres, plastic cutlery, plastic containers, dairy bottles, laundry detergent bottles, etc.) with/without short glass fibres. The sleepers of this category (e.g., TieTek (2019), Axion (2019), IntegriCo (2019), I-Plas (Cromberge 2005), Tufflex (2019), Natural Rubber (Pattamaprom et al. 2005), Kunststof Lankhorst Product (KLP), and Mixed Plastic Waste (Graebe et al. 2010)) mainly serve in the US tracks and are advantageous in toughness, easy drilling and cutting, consuming recyclable plastic materials, and relatively cheap price. Notwithstanding, their low anchorage capacity is identified as one of the main challenges for their slow acceptance in the railway industry. In order to provide sufficient resistance to vertical and lateral movement of rail, rail screws are inserted into the rail-seat region and hold down the plate/rail to sleepers.

As an effective alternative to timber, polymer composites are required to meet the minimum requirement of 40kN as per timber sleepers required in the Australian Standard (AS 1085.18 (Standards Australia International 2003a)). Nevertheless, Type-1 sleepers generally show an inferior pull-out strength of 31.6-35.6 kN as highlighted by Ferdous et al. (2015) due to the low strength of plastic materials especially under dynamic loading conditions. They were normally tested with the screws having Ø16mm threads and Ø24mm shank following the Test 3A of AREMA (American Railway Engineering and Maintenance-of-way Association (AREMA 2013)) Specifications. The Institute of Railway Technology of Monash University in Australia conducted the screw pull-out test on the plastic-composite sleeper (Qiu & Tew 2017). They reported that the minimum 22.2 kN pull-out force for engineered composite sleepers required by AREMA (AREMA 2013) was met but the test result was lower than the minimum 40 kN specified for hardwood timber mentioned above.

Apart from laboratory testing, spikes/screws loosening were often observed in the field testing. Lampo et al. (Lampo et al. 2001) highlighted stress relaxation occurred in the plastic sleepers over time, which resulted in an unstable track. After the spike/screw installation, the interface between the fastener and the sleeper is in compression. The compressive stress decreases with time due to the nature of plastics if a fixed strain is applied to the material. Derailment failures are likely to appear if the loose spike/screw was not detected in time. Similarly, McHenry and LoPresti (McHenry & LoPresti 2016) observed loose spikes in a track with TieTek plastic sleepers installed. With heavy axle load tonnage accumulated, the uplifted spikes needed to be re-driven into the rail-seat region due to the mechanical loading and in-service elevated temperature. Therefore, short and long fibres are introduced to recycled plastic sleeper technologies to enhance the mechanical strengths and the screw pull-out resistance (Yu et al. 2021).

2.2.2 Type-2 sleepers

Type-2 sleepers are generally represented by the Fibre-reinforced Foamed Urethane (FFU (Koller 2015; SEKISUI 2019)) sleepers installed in Japan, Germany, Austria, China, and Australia due to their lightweight, extended life cycle, water-absorbing resistance, heat and corrosion resistance, and ease of drill properties. This sleeper technology adopts continuous glass fibres in the longitudinal direction and no fibre in the transverse direction. The long fibre reinforcement dominates the longitudinal mechanical performance of the FFU sleeper while the polyurethane foam plays a significant role in the transverse direction. Ferdous et al. (2015) highlighted that FFU sleeper shows sufficient flexural strength but seems not a suitable product under high shear conditions (e.g., screw uplifting or lateral restraint).

The average pull-out strength of the Type-2 sleepers varied between 29 kN and 65 kN. Yu et al. (Yu et al. 2021) tested the synthetic composite sleepers with the same fibre reinforcement sourced from the AGICO company and reported the average pull-out resistance of 29.2 ± 2.1 kN. The relatively low results were observed mainly because of the low shear capacity of the sleeper matrix. Comparatively, the SEKISUI FFU sleepers (SEKISUI 2019) measured by the Technical University of Munich demonstrate higher pull-out results from 47 kN to 73 kN (Freudenstein 2008, 2013). The large variance in the results is probably due to the different test methods used. The AREMA Specifications (AREMA 2013) were followed for the screw pull-out test of AGICO synthetic composites while the European Standard (DIN EN 13481-2 (European Committee for Standardization 2002)) was complied in testing the SEKISUI sleepers. The main difference between the test methods is the different types of rail screws adopted which have distinct geometrical parameters. This part is further discussed in detail in Section 2.4.

2.2.3 Type-3 sleepers

Long fibres are generally introduced to the Type-3 sleepers in both the longitudinal and transverse directions (Manalo 2011; Van Erp & McKay 2013). The flexural and shear performance of this sleeper type is controlled by the fibre reinforcements and significantly thus improved. Ferdous et al. (Ferdous et al. 2015) highlighted their advantages entailing design flexibility (adjusting fibre reinforcement in each direction to have specific structural performance), superior mechanical strength, ease of drilling, and great fire resistance. This type of sleeper has a superior pull-out strength of above 60 kN (Ferdous et al. 2015). Owing to the complex structure, the manufacturing process can be complicated and is a potential challenge that may decrease the uptake of the Type-3 sleepers.

An innovative design of narrow-gauge composite sleeper was proposed by the University of Southern Queensland (USQ) (Ferdous et al. 2017) and tested under AS 1085.18 (Standards Australia International 2003a) and AREMA (AREMA 2013). Its pull-out resistance reached 74 kN on average with a 10% variation due to the composites' excellent mechanical strength contributing to a great screw holding capacity. This design consists of a strong composite core and Particulate-Filled Resin (PFR) coating which protects the internal structural components from environmental impacts. The epoxy-based PFR filled with functional fillers (Fire Retardant Filler, Hollow Microsphere and Fly Ash) is considered a suitable material for composite sleepers due to its sound mechanical performance and durability (Shamsuddoha et al. 2013; Ferdous et al. 2016; Khotbehsara et al. 2019; Ferdous et al. 2020; Khotbehsara et al. 2020). These three different filler materials are acid resistance, chemical inertness, smoke suppression and also have the benefits of weight reduction, shrinkage control and the increase of thermal insulation. However, the PFR core suffers chipping of the brittle PFR coating during drilling. This challenge of installation indicates further improvements on the polymer matrix is highly desired to utilise it with structural components for the railway sleeper application. Owing to the cost-effectiveness and excellent strength, glass fibres are extensively applied as effective reinforcement for construction materials (Fu et al. 2000; Tlaiji et al. 2020). Adding a 30% weight ratio of short glass fibres to textile-reinforced concrete increased the ultimate tensile strength by around 2.5 times and enhanced the crack resistance (Homoro et al. 2018). This is possible because the strong bond between glass fibres and polymer matrix is essential to fully utilise fibre strength and its resistance to crack (Law et al. 2016). Apart from that, Altoubat et al. (2009) highlighted that 1% addition of polypropylene fibres improved the ultimate shear strength of concrete beams by 30-45%. Similar findings were reported by Arslan et al. (2017) who observed an improvement of shear strength thanks to the reinforcing effect of polypropylene fibres. It is noticeable that composite sleepers' material properties can be engineered and dramatically affect the screw pull-out strength of different composite technologies. The effect of these properties is reviewed in the next section. The different screw geometries for the three different types of sleepers are shown

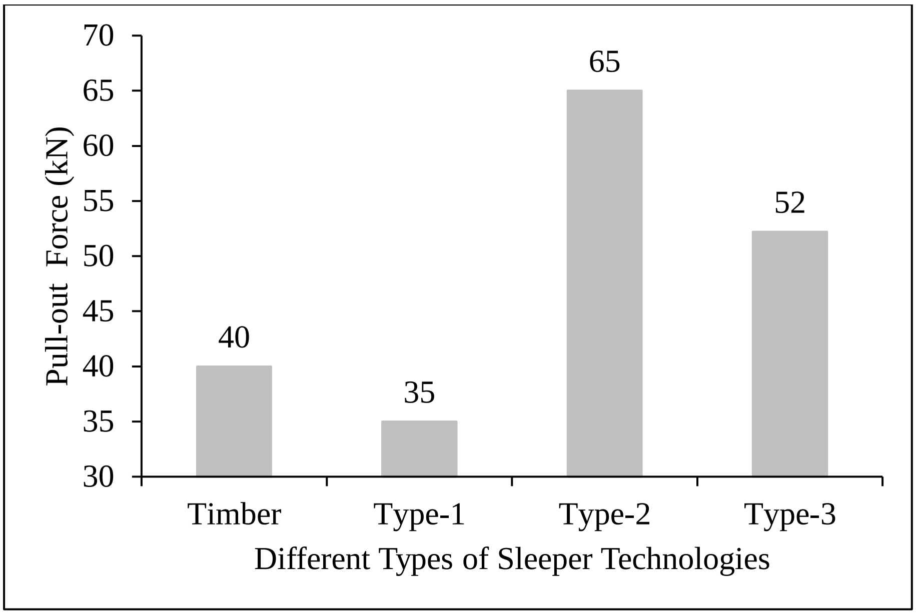

Figure 4: The screw pull-out performance of different types of sleepers (Ferdous at el. 2015)

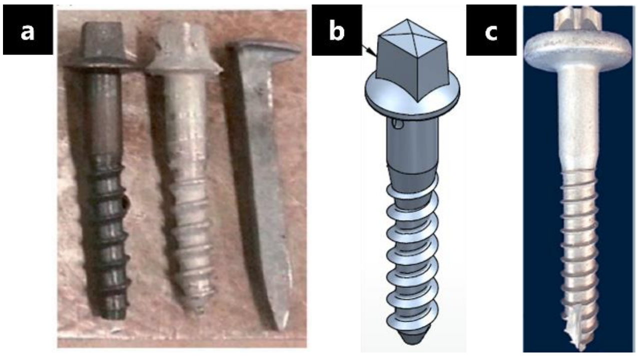

Figure 5: Rail screw used for a) Type-1 sleepers (Lotfy et al. 2017), SS8-140 screw for Type-2 sleepers (Freudenstein 2008), and GageLok-5 rail screw for Type-3 sleepers.

2.3. Screw pull-out performance of railway sleepers

The screw pull-out performance is often investigated with the properties of holding materials especially when fasteners show no damage or deformation after the ultimate force was reached. The material properties of sleepers dominate the overall screw withdrawal performance. In order to evaluate the effect of material properties, well-defined material characterisation plays a significant role in the research purpose. A large amount of research (Green et al. 1999; Sandhaas et al. 2012; Hassanieh et al. 2017; Bedon & Fragiacomo 2019) has been conducted to identify the material properties of different timber species while that of the currently available composite sleepers are rarely searchable (Yu et al. 2021). Consequently, it is worthwhile but difficult to investigate the influence of material properties on the screw holding capacity of timber-replacement polymer composites. Alternatively, fasteners in other applications (e.g., rock bolts (Kılıc et al. 2002), reinforcing bars (Maranan et al. 2015; Zhou et al. 2019), or biomedical screws (Zhang et al. 2004; Kubiak et al. 2019)) can provide helpful insights to understand the effect of different host materials' properties.

Based on the pull-out mechanism, the ultimate shear strength is regarded as an important parameter affecting the pull-out strength. Particularly, the relatively strong screw tends to shear the internal threads on the weak host materials during pull-out. In biomedical research, polyurethane foam is widely used as an alternative material for evaluating the pull-out resistance of synthetic bones considering their similar shear strength (Chapman et al. 1996). The predicted values showed a high correlation ($R^2 = 0.95$) with the pull-out force measured in the tests. This high correlation was further developed by Tsai et al. (Tsai et al. 2009) who modified the equation by re-calculating the shear strength of the squeezed synthetic bone. A more correlated result was reported by using the modified formula for pedicle screws. Yu et al. (Yu et al. 2021) conducted the screw pull-out test on timber and alternative composite railway sleepers in order to evaluate the effect of various material properties. Their statistical analysis shows the highest correlation of shear strength at 0.974 higher than other properties (e.g., compressive strength, modulus of elasticity, and density). More studies (Oberg et al. 1987; Kleeman et al. 1992; Shih et al. 2017; Du et al. 2019) are found to demonstrate the significance of material shear strength in predicting the pull-out strength.

The density of host material is believed to have a direct influence on the pull-out strength. Seebeck et al. (Seebeck et al. 2004) developed a linear regression model using the cancellous density to predict the axial pull-out forces. They pointed out that 98% of the variance of the pull-out strength can be explained by the material density. Ramaswamy et al. (Ramaswamy et al. 2010) applied polyurethane foam blocks of three different densities in the pull-out test and correlated the foam density to the mean pull-out results. Higher pull-out strength was observed in the foam block having higher density values. Cetin and Bircan (Çetin & Bircan 2021) also agreed that the pull-out strength of polyurethane foam increased with the increasing foam density, as a higher density facilitates a wider stress distribution. Despite the high correlation, predicting the pull-out strength of composite materials based on density can be challenging, as the polymer composites generally possess varied specific strengths.

Moreover, the effect of density seems to work well for isotropic rather than orthotropic materials. Particularly, even if the density remains the same, the orthotropic composite materials (timber or synthetic composites) have varied strengths in different directions which may significantly affect the pull-out strength.

Some researchers suggest the ultimate pull-out strength also demonstrates a high correlation with other material properties. Pujari-Palmer et al. (Pujari-Palmer et al. 2018) investigated the effect of cement porosity and compressive strength on the screw pull-out force. They concluded the correlation of cement compressive strength ($R^2 = 0.79$) was lower than that of total cement porosity ($R^2 = 0.89$), even though both material properties are able to accurately the pull-out resistance ($R^2 \geq 0.80$). Lorrain et al. (Lorrain et al. 2011) suggested assessing the compressive strength of structural concrete using the pull-out bond test considering the high correlation between these two parameters observed in their experiments. AI-Sabah et al. (Al-Sabah et al. 2021) also acknowledged this strength assessment method as the peak pull-out strength of the post-installed screw is largely correlated to the concrete compressive strength. In particular, the concrete compressive strength can be regarded as an indicator for the pull-out mechanism because the compressive stress of the concrete increases when the concrete hole increasingly bears the screw during pull-out. As a consequence of the compressive failure, the complete pull-out failure (cone failure) may occur. Apart from that, concrete tensile strength shows a correlation to the pull-out strength considering that the radial tension surrounding the bar is raised by the resultant bearing and friction forces (Mendis & French 2000). A splitting failure can be expected if the concrete tensile strength takes control.

2.4. Effect of screw geometry on the pull-out performance

Aside from the material properties, different screw geometrical parameters demonstrate a dramatic influence on the pull-out performance. However, various types of rail screws are currently used for railway sleepers while the international standards or specifications have different requirements. This fact leads to difficulties for local authorities in evaluating overseas composite sleeper products for local usage. A typical example is the introduction of Sekisui FFU sleepers (SEKISUI 2019) to the Queensland Railway (QR) tracks in Australia. Due to the different sizes of the screw (Ø24mm) used in the tests, the pull-out performance of a smaller diameter (Ø16mm) in FFU remains uncertain (Yu et al. 2021). It is necessary therefore to review the currently used test methods worldwide in order to produce a comparable solution.

The available literature and industry reports show composite sleepers are generally tested using a variety of rail screws. The Ø17.5mm rail screws and Ø14mm pre-drilled holes were adopted together in the pull-out test on Ecotrax composite sleepers (produced by Axion (2019)) using Ø25mm screws following ASTM D6117 (ASTM International 2018). In comparison, the AREMA (2013) specification is mostly applied to other recycled plastic sleepers (e.g., TieTek (2019) and IntegriTies (2019)) in the US market. However, AREMA sets no requirements for screw geometry as spikes are widely adopted in the US rail tracks than screws. As a result, the provided industry reports give no information on the dimensions of rail screws used in testing, which may decrease clients' confidence in choosing composite railway sleepers. Only limited information is found in the literature. The high-density polyethylene (HDPE) sleeper was tested with the Ø22mm screw having 133mm underhead length (76mm effective thread length) and 12.7mm pitch. Average pull-out strength of 44 kN was reported by Lotfy et al. (2017) who also investigated the effect of pre-drilling configuration, loading rate, and temperatures in their study but not the influence of screw geometry. Two different types of rail screws (Ø16mm and Ø19mm) were applied in the pull-out test of the recycled plastic sleepers under AS 1085.22 (Standards Australia International 2020). Qiu and Tew (2017) highlighted that the larger diameter screws facilitate a higher pull-out force of the plastic sleepers.

In countries other than the US, rail screws are generally used to fix the rail to the polymer composite sleepers. In the Japanese railway industry, the JIS E 1203 (Japanese Industrial Standard (Japanese Standards Association 2007)) recommends the rail screws with Ø24mm in major diameter (the diameter of an imaginary cylinder formed by the crest of all external threads on the screw) and specifies a minimum pull-out performance of 30 kN for synthetic sleepers made from FFU. The Sekisui FFU sleepers were tested in pull-out applying SS8-140 screws (Freudenstein 2008) in accordance with DIN EN 13481-2 (European Committee for Standardization 2017). An average of 65 kN was reported by Sekisui while only 29 kN in pull-out strength (Yu et al. 2021) was measured from the AGICO synthetic composite samples (*Plastic Sleeper* 2021) despite the similar fibre reinforcement and polymer matrix adopted. AGICO's relatively weak performance is possible due to the smaller size of screws

(Ø16mm in major diameter and 105mm underhead length (Cold Forge 2020)) than the SS8-140 screws (Ø24mm in major diameter and 140mm underhead length (Bemo Rail)). Although the Ø24mm screws are recommended for timber sleepers by AS1085.18 (Standards Australia International 2003a) and the alternative composite sleepers by AS1085.22 (Standards Australia International 2020), QR normally uses Ø16mm screws in the actual narrow gauge rail tracks (Murray 2006). The QR suggested screws were adopted in the pull-out test of the USQ innovative composite sleeper and superior pull-out strength of 74 kN was reached owing to the sleeper's excellent shear capacity (Ferdous et al. 2017). The above review shows that researchers and industries currently implement various test approaches, rail screw types, and screw geometries. As a consequence, predicting the pull-out resistance of polymer composite sleepers becomes complicated and reduces their uptake as timber replacement technologies.

The screw geometrical parameters, generally accompanied by material shear strength, are included in various prediction models of pull-out strength. The fundamental thread stripping (FTS) model is proposed from an assumption that the internal threads in the sleeper hole were stripped off by the external threads on the screw (Patel et al. 2010). The screw pull-out strength is calculated as a product of the shear strength of the host material and a cylindrical surface identified by the screw major diameter and embedded length. Another expression of this model can be used to estimate the average bond stress between the fastener and the surrounding material (Kılıc et al. 2002; Zhandarov & Mäder 2005; Maranan et al. 2015; Zhou et al. 2019). In addition, the Thread Shape Factor (TSF) was introduced to the FTS model in ASTM (FED-STD-H28/2B) (Interdepartmental Screw-Thread Committee 1990) to consider the effect of pitch and thread depth (Einafshar et al. 2021). TSF is a dimensionless value normally ranging from 0.70 to 0.87 indicated by Chapman et al. (Chapman et al. 1996) depending on the geometry of different bone screws. When TSF is introduced, the estimated pull-out strength is likely to decrease. Migliorati et al. (Migliorati et al. 2012) fitted univariate linear regression to investigate the correlation between the TSF and the pull-out force. They highlighted the statistical significance of TSF in demonstrating the mechanical competency of temporary anchorage devices (orthodontic mini-screws). Apart from the direct effect on the pull-out outcomes, the screw geometrical feature may also affect the expression of other parameters. For the conical thread pattern, Tsai et al. (Tsai et al. 2009) integrated the pull-out force along the axis of conical screws by calculating the squeezed bone strength in accordance with ASTM F1839 (American Society for Testing Materials 2008). Due to the conical shape of screws, the engaged area of host material reduced with the decreasing major diameter along the screw axis.

The thread bearing (TB) model features the thread bearing area and the interacted thread number (Juvinall & Marshek 2020). A relatively low result predicted by the TB model was reported by Shih et al. (Shih et al. 2017) compared to the outcome generated by the TSF equation. These researchers indicated that the size of the bearing area is dependent on the difference between the major and minor diameters or the number of engaged threads. Sivapathasundaram and Mahendran (Sivapathasundaram & Mahendran 2018) also demonstrated that the TB model failed to provide an accurate prediction of the pull-out force for the connections in the steel cladding system. It indicates that screw geometry should be carefully considered before applying this equation. In fact, most rail screws have a long shank (to resist the lateral movement of rail/rail plate) which limits the length of thread area and have a relatively large pitch which results in fewer thread numbers. Therefore, the TB model is likely to produce a comparably low pull-out result for railway sleepers. Even if the TSF and TB models are well studied, the failure modes of different composite sleepers vary from one another (e.g., matrix splitting of Type-2 sleepers and global shear cracking of Type-3 sleepers (Yu et al. 2021)). It is significant therefore to investigate the suitability of these existing prediction models and develop new equations to well describe the unique pull-out failure modes of different composite sleeper technologies.

2.5. Finite Element Analysis on the lateral restraint behaviour

The lateral force generated from the train movement is an important component in the sleeper design. Rail screws are fixed to the rail-seat region of sleepers to provide lateral restraint to the track and prevent gauge widening. Due to the repeated lateral forces, fastener fracture was observed in timber tracks and caused wide gauge and derailments (Roadcap et al. 2019; Stuart et al. 2019). The type of screw failure may appear at any stage of the entire life of the track without any visible signs on fasteners (Carrasco et al. 2012; Federal Railroad Administration 2016; Kerchof 2017). In addition, timber marks were found on the fracture surface of the screw indicating the sleeper hole was compressed dramatically during the lateral pushing process (Dersch et al. 2019). The lateral behaviour seems relatively complicated as both screw and sleeper exhibit permanent damages in this process compared to the screw pull-out behaviour. The screw was mainly subjected to bending while sleeper material was considerably affected by different stresses including compressive, tensile, in-plane shear and rolling shear stress.

Another issue is that screw lateral restraint behaviour is rarely investigated in industry tests or research and there is no clear requirement stated in current standards for lateral restraint force resisted by a single fastener. AREMA (2013) suggests lateral force being measured up to 5.1 mm lateral displacement in 1 minute, but no test criteria are defined. Specifically, the 5.1 mm is likely to be the maximum gauge widening accepted by AREMA without any risk of derailment. Similarly, the lack of test method or criteria is found in most current standards or design codes including AS 1085.19 (Standards Australia International 2003b), AS 1085.22 (Standards Australia International 2020), ARTC Code of Practice (2007), JIS E 1203 (Japanese Standards Association 2007), and ISO/DIS 12856-2 (International Organization for Standardization 2014). Nevertheless, the lateral strength requirement is in need to measure and regulate the performance of different composite sleeper technologies.

Finite Element Analysis (FEA) is regarded as an effective method to understand the complex lateral mechanism. Researchers applied FEA to show stress contribution in the fastener to sleeper connection and to identify the failure location. Dick et al. (Dick et al. 2007) expressed timber behaviour as an elastic foundation for which the stiffness can be adjusted. Nevertheless, it seems not an appropriate approach for 3D modelling owing to the orthotropy of timber materials. Timber's non-linear behaviour could not be realised as well, which may result in prediction errors when considering the plasticity of timber. Since the elastic foundation was used instead of a separate model for the timber sleeper sample, the screw model was de-featured by ignoring the threads. Thus, the relative movement between the sleeper and the screw was not simulated but has a significant influence on the stress development in the sleeper hole considering the normal stress on threads and friction occurred.

Different approaches were applied to realise the lateral behaviour of sleeper materials. Yu and Liu (Yu & Liu 2019) conducted an FEA to simulate the lateral bending failure of cut spikes in timber sleepers. An elastic model was initiated to simulate the timber behaviour but failed to demonstrate the post-elastic reaction. As an alternative approach, a user material subroutine (UMAT) originally developed for fibre-reinforced composites was modified to exhibit white oak properties including additional orthotropic strength limits and fracture energy prescriptions. The FEA results showed the damage initiation forces and locations in both the spike and the timber hole, which indicates the effectiveness of the modified UMAT in showing different properties in different directions of orthotropic materials. However, this model has a limitation to reveal the damage in the vertical direction while the vertical stress component continuously grows with the increasingly serious screw bending magnitude. Dersch et al. (Dersch et al. 2019) also used UMAT to create timber models for the lateral restraint simulation. A constitutive model was proposed as per continuum damage mechanics for different timber species they have a considerable effect on the rail fastener's behaviour. Specifically, the maximum stress and its location decreased with the increase of timber's mechanical properties, which revealed the importance of the proper definition of sleeper properties. Notwithstanding, the UMAT subroutine is not easy to apply due to the high level of programming skills required. The unique Fortran codes written in UMAT were not a common programme language that was generally adopted by most researchers and design engineers.

2.6. Research gaps

This chapter provides a state-of-the-art review on the alternative timber-replacement sleepers, their material composition and the performance under their rail-seat including pull-out strength of screw and lateral restraint behaviour. From the detailed review of literature, the following research gaps are identified:

- There is very limited information to date on the development of particulate filled resin (PFR) matrix mixed with flexible fillers or fibre reinforcement to address the challenge in drilling, chipping and pull-out performance of polymeric railway sleepers;
- There is limited understanding of how the composite sleeper materials affect the pull-out behaviour as most industry reports or literature rarely provide information of pull-out failure or microstructural analysis;

- It seems difficult to straightforwardly predict the pull-out resistance of composite-based sleepers due to the different test approaches and screw geometries implemented by different researchers and industries;
- Research or test rarely investigates the screw lateral restraint behaviour of composite sleeper while current standards show no clear specifications for single screw lateral restraint performance.

The above research gaps are addressed in this thesis by conducting extensive experimental studies supported by analytical and finite element analyses, the details of which and the significant findings are presented in Chapters 3 to 6.

CHAPTER 3: OPTIMISATION OF POLYMER MATRIX FOR RAILWAY SLEEPERS

Chapter 2 reviewed the rail-seat performance of current composite sleeper technologies and indicated the need for a suitable polymer core for an innovatively designed composite sleeper. **Manuscript 1** in Chapter 3 introduced crumb rubber and short fibres to the epoxy-based PFR matrix to reduce cost and improve mechanical properties and satisfactorily addressed the first objective of the thesis. The effect of new PFR ingredients on the physical and mechanical properties was investigated. A simplified prediction equation was developed to predict critical properties as a function of compressive strength while the Analytical Hierarchy Process was applied to identify the most suitable PFR mix for the development of a cost-effective and best performing composite railway sleeper.

The test results show that up to 10% short glass fibres in weight effectively improve all mechanical properties of the polymer mix. Additionally, the twisted polypropylene fibres addition enhanced the flexural and shear behaviour due to their uniform dispersion. The compressive strength was applied in the simplified equation to estimate other properties with a high coefficient of determination. The Analytical Hierarchy Process method suggested the optimal PFR mix for each specific condition. This newly formulated PFR was implemented in composite sleeper development and its screw spike and lateral resistance was evaluated in Chapters 4 to 6.

CHAPTER 4: PULL-OUT BEHAVIOUR OF POLYMER SLEEPERS

Chapter 2 highlighted the significance of material properties on the pull-out strength and failure behaviour of composite sleepers. Similarly, a new particulate filled resin (PFR) system for composite sleepers was developed in Chapter 3. In this chapter, **manuscript 2** measured the pull-out force of the sleepers with PFR and comparatively evaluate with hardwood timber recycled plastics, and synthetic composites. This study addressed the second objective of the thesis. The failure modes of different sleeper materials were observed in the hole cross-section under the microscope. The material properties were then correlated to the measured pull-out strength and analysed with the failure behaviour. A simplified equation was established to predict the pull-out resistance of railway sleepers using the most correlated property.

The results demonstrated a statistically significant difference in the pull-out strength among different sleeper types while the paired samples test showed the highest correlation occurred between the pull-out strength and the ultimate shear strength. Then, a linear regression model was developed to estimate the pull-out resistance of railway sleepers with a high coefficient of the determination being 0.97. The proposed equation provided a better alignment with the experimental results than an existing theoretical model regardless of different pull-out behaviour. A more detailed investigation on the pull-out resistance of different sleeper materials was conducted by evaluating the effect of the screw geometries and the results are presented in Chapter 5.

CHAPTER 5: NEW PREDICTION MODEL FOR THE SCREW PULL-OUT STRENGTH

The results of Chapter 4 showed that the material properties have a significant effect on the pull-out strength and failure behaviour of railway sleepers. Chapter 5 addressed the third objective of the thesis and evaluated the effect of the screw geometries (major diameter and thread embedded length) on the pull-out performance of timber, plastic, synthetic composite and PFR cored sleepers. The ultimate pull-out force was measured and the normalised stress on the screw was calculated to identify the influence of the major diameter and thread embedded length of the screws. A new analytical model is developed to predict the pull-out strength of railway sleepers and compared with existing theoretical models.

The results indicated that the increased thread embedded length significantly affect the pull-out strength due to the increase of thread engaging area while the screw major diameter has a considerable influence on timber rather than composite materials owing to timber's continuously high shear strength. The proposed model is found more than 50% more reliable than other existing models. The novel findings of this research are expected to eliminate the need for the costly and time-consuming repeated pull-out test, to improve the limited understanding of the effect of screw geometries on the pull-out behaviour, and to ensure the stability of railway track when alternative sleeper technologies are adopted for the maintenance strategy. As the fasteners in the rail seat of the sleepers are also subject to lateral forces due to the travelling train, an investigation of the screw lateral restraint behaviour was conducted, and the results are presented in Chapter 6.

New prediction model for the screw pull-out strength of polymer composite railway sleepers

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Abstract

Estimation of the screw pull-out strength of composite railway sleepers is a complex problem due to the wide variability of their material properties and the availability of different screw geometries used to fasten the rail track. This study investigated the effect of screw geometry (screw diameter and embedded length) and sleeper material (timber, synthetic composites, recycled plastics and particulate filled resins) on the pull-out strength and developed a new prediction model for polymer composite railway sleepers. The two-way analysis of variance showed that the material shear strength has a higher influence than the screw geometries on the pull-out strength. Increasing the thread embedded length has a significant effect on all tested sleeper types due to the increased thread engaging area while the screw major diameter affects timber rather than composites owing to timber's continuously high shear strength. Based on the failure behaviour and type of fibre reinforcement, an analytical model was developed to estimate the pull-out resistance and was also verified by the results from the available literature and reports. The proposed model is found over 50% more reliable than other existing theoretical models.

1 INTRODUCTION

The growth of the Australian national economy is sustained by its more than 40,000 km long rail track which transports a significant volume of passengers, agricultural, and mineral products. As one of the major states in Australia, Queensland has over 11,000 km rail network equating to a total of 16.5 million railway sleepers of which 57% are timber sleepers [1]. The simple installation and superior mechanical properties of timber have made it the most preferred material for railway sleepers for more than 150 years. Over 2.5 billion timber sleepers have been installed globally [2]. However, the increasing cost with diminishing availability [3], environmental deterioration [4], and frequent maintenance [2] are becoming a problem in using hardwood timber for railway sleeper application. In fact, UK spent $775 million on railway track maintenance during 2016-2017 while it cost India $2.08 billion [5]. Sleeper replacement costs accounted for 25-35% of the total operational costs per annum in Australia [6, 7]. Thus, rail track companies around the world are looking for cost-effective and highly durable timber-replacement technologies.

Composite railway sleepers have emerged as effective alternatives to timber sleepers owing to their superior durability, higher strength/weight ratio and lower environmental impact [8]. These new technologies are classified by Ferdous et al. [9] in three categories base on the amount, length and orientation of fibres. The Type-1 sleepers are generally made of recycled plastics with short (< 20mm) or no fibre reinforcement [10-12]. Although this category of sleepers is easy to drill, durable, eco-friendly and reasonably priced, the low anchorage capability is one of their major issues especially in dynamic loading conditions due to the inherently low strength of the plastic material. Pull-out strength of 40kN is required for the timber-replacement sleepers [13] while a relatively low pull-out resistance of 31.6-35.6kN was reported for the plastic sleepers [9]. The plastic-composite sleeper tested by the Institute of Railway Technology (IRT) of Monash University [14] exhibited the pull-out force meeting the requirement of 22.2kN specified by the American Railway Engineering and Maintenance-of-way Association (AREMA [15]) but failed to reach 40kN required for timber sleepers as suggested in AS1085.18 [13]. A strong screw holding capacity reaching 65kN was reported for the Type-2 sleepers with long fibre reinforcement in the longitudinal direction (represented by Fibre-reinforced Foamed Urethane, FFU) [16, 17]. The Type-3 sleepers reinforced by fibres in both the longitudinal and transverse directions also showed a superior pull-out capacity of over 60kN. The strong structural components of Type-3 sleepers can be due to the fibre-reinforced pultruded hollow section [18, 19] and phenolic core sandwich beam [20, 21] which are either provided confinement effect to the core material or contributed directly to the pull-out resistance. However, the pull-out performance of the above-mentioned sleeper technologies are difficult to compare directly as they were tested using different screws and geometries as required by current standards and specifications.

Various rail screws with different geometries were used in the pull-out test on composite sleepers according to the available literature and industry reports. The Ecotrax composite sleeper from Axion has a pull-out resistance of 31.6kN using the Ø17.5mm screw with the Ø14mm diameter pilot hole [10] in accordance with ASTM D6117 [22] which nominates the Ø25mm (in major diameter) screw. Other recycled plastic sleepers available in the US market mostly were tested following the AREMA specification [15]. Since spikes are extensively applied in the US railway industry rather than screws, the requirement for screw geometry is not stated in the test method. Lotfy et al. [23] measured the pull-out strength of the high-density polyethylene (HDPE) sleepers (44kN averagely) adopting the Ø22mm screw having 133mm underhead length (76mm effective thread length) and 12.7mm pitch. Their study highlighted the effect of pre-drilling configuration, loading rate, and temperatures, but the influence of screw geometry was not within the scope. Unlike the US, rail screws are widely adopted in other countries (e.g., Japan, Australia, and European countries). Japanese Industrial Standard (JIS E 1023 [24]) recommends a screw diameter of 24mm and a minimum pull-out strength of 30kN is specified. The SS 8-140 sleeper screws with the same major diameter were pulled out from the Japanese SEKISUI FFU sleepers following the European Standard (DIN

EN 13481-2 [25]) [26]. Even though Australian Standards recommends Ø24mm screws with the pitch of 12.5mm for timber sleepers (AS1085.18 [13]) and alternative material sleepers (AS1085.22 [27]), the Queensland Rail has been using the Ø16mm screw with 125mm of length in actual practice [28]. This type of screws was tested in an innovative composite railway sleeper developed by the University of Southern Queensland and an average of 74kN was achieved in the pull-out test [3]. Qiu et al. [14] used Ø16mm and Ø19mm screws in the pull-out test on plastic sleepers under Australian Standards and highlighted that a higher pull-out force was achieved by the larger diameter screws rather than the smaller diameter. Due to the different test approaches, types of screws and screw geometries implemented by different researchers and industries, it seems difficult to straightforwardly estimate the pull-out resistance of composite-based sleepers, contributing to the low confidence in their usage and their wide application as timber replacement in the maintenance of railway track.

The pull-out performance of sleepers can vary significantly depending on the screw geometry while the understanding of how the screw geometry affect the pull-out behaviour is very limited. Moreover, the analytical model to predict the pull-out strength for railway sleepers is not currently available. This is probably the main reason why most available literature and industry test reports are limited to information on the level of the pull-out load based on the investigated sleeper material and type of screw used. The ultimate shear strength of the sleeper material is also known to have an effect when the pull-out failure mainly occurs in the hole [29-31] and the screw can be considered as a rigid body [32]. As a result, a variety of prediction models adopted the ultimate shear strength of the host material to estimate the pull-out strength. The fundamental thread stripping (FTS) model is a function of material shear strength and a cylindrical surface defined by the screw major diameter and thread embedded length. This basic model is developed from the assumption that the external threads of screw shear off the internal threads along the line “A” shown in Figure 1 [33]. Alternatively, this function can also be transformed to express the average bond stress between the reinforcing bar [34, 35] or rock bolt [36] or single fibre [37] and the host material. Additionally, ASTM (FED-STD-H28/2B) [38, 39] modified the FTS model by considering the thread shape factor (TSF) which is the average product of pitch and thread depth [40]. Chapman et al. [30] indicated that TSF may decrease the predicted pull-out strength as this dimensionless value varied from 0.70 to 0.87 according to the type of the tested bone screws. The statistical significance of TSF was highlighted by Migliorati et al. [41] in defining the mechanical competency of orthodontic mini-screws. Tsai et al. [31] further modified the ASTM equation and focused on the integration of the pull-out force along the screw axis for conical and cylindrical screws. The Tsai's model describes the pull-out strength of bond screws as a function of squeezed bone strength, screw design, and pilot hole. In order to take these parameters into consideration, additional evaluation of the shear strength and material constant of the host material is required to conduct following ASTM F1839 [42], which seems to be necessary only for the conical thread pattern and meanwhile increases the practical efforts. On the other hand, the pull-out model due to thread bearing features the bearing area indicated as area 1-3 in Figure 1 on threads and the thread number within the interacted depth [43]. Shih et al. [44] highlighted that the predicted values of the thread bearing (TB) model were generally lower than that of above-mentioned thread stripping models. This is because the bearing area could be considerably smaller than the cylindrical shear area if the screw with certain geometry (a small difference between the major and minor diameters or a small number of threads) was fully embedded. Sivapathasundaram and Mahendran [45] adopted the ASTM model and the TB model to predict the screw pull-out force of the connections in steel cladding system. Neither of these two equations reported accurate prediction as their pull-out failure modes are not well corresponding to the failure of steel roof battens and purlins. Predicting the pull-out strength of sleepers may face a similar challenge due to the much complex failures [46] (e.g., matrix splitting of synthetic composites, longitudinal grain shearing of hardwood timber, and global shear cracking of fibre-reinforced polymer matrix). It can be concluded that an accurate prediction of pull-out strength is greatly dependant on the influence of screw geometrical parameters and the pull-out failure mode, but current models are not likely to describe the pull-out behaviour of sleeper materials properly.

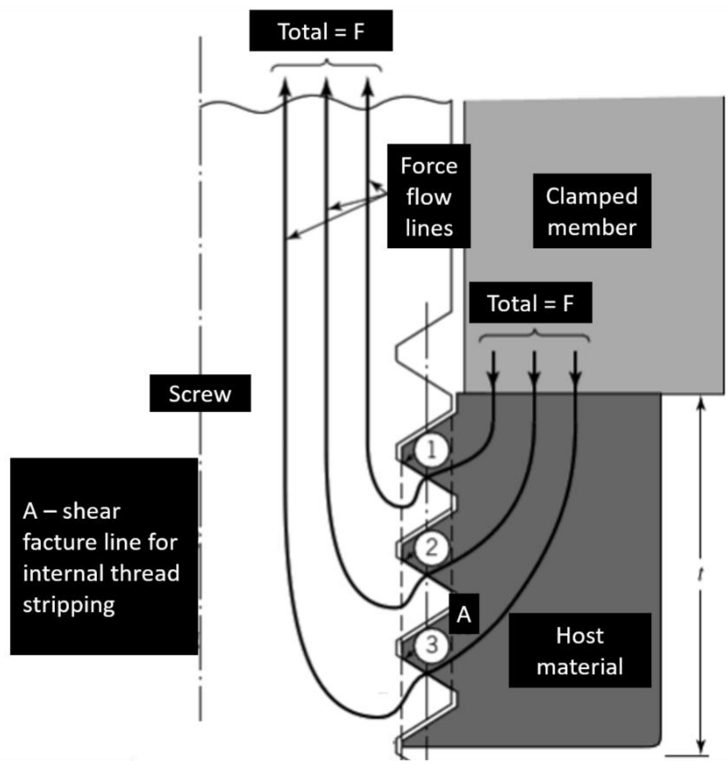


Figure 1: Force flow for a fastener in pull-out [43]

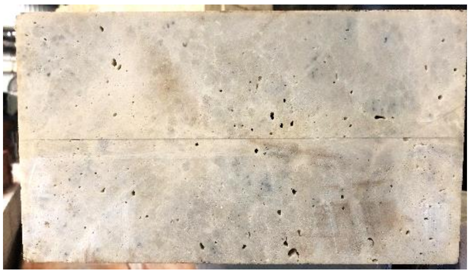
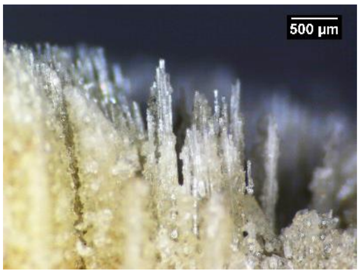
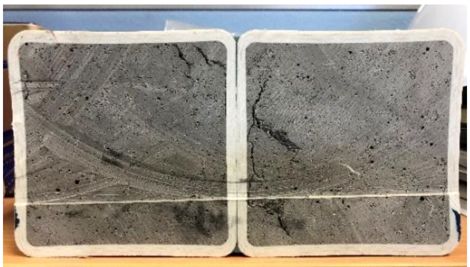
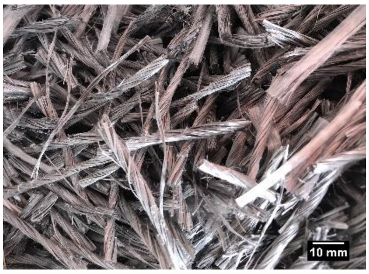
This study is the first to investigate the effect of screw geometry (diameter and embedment length) on the pull-out behaviour of timber and timber-alternative composite sleeper technologies. The ultimate pull-out strength of the referenced sleeper types was measured in the screw pull-out test and analysed with the variance of thread embedded length and screw major diameter. The normalised stress on the screw was calculated to further determine the effect of the two investigated parameters. The two-way analysis of variance (ANOVA) was conducted to evaluate the influence level of the material shear strength and screw geometries. Based on the statistic results and the distinct failure modes of the tested sleeper materials, an analytical model is proposed to predict the pull-out resistance of railway sleepers and further compared with other existing theoretical equations. The novel findings of this research are expected to eliminate the need for the costly and time-consuming repeated pull-out test, to improve the limited understanding on the effect of screw geometries on the pull-out performance of composite railway sleepers, and to ensure the stability of railway track when alternative sleeper technologies are adopted for the maintenance strategy.

2 METHODOLOGY

2.1 Material characterisation and screw geometry

This study investigated hardwood timber railway sleepers and three types of timber alternative sleeper technologies including synthetic composites (SC) made from hard polyurethane foam reinforced with continuous glass fibre in the longitudinal direction, Ultra High Molecular Weight Polyethylene (UHMWPE) plastic sleepers and Particulate-Filled Resin (PFR) cored sleeper. The PFR core is reinforced with randomly dispersed short fibres (54mm-long macro Polypropylene fibres) and inside the GFRP (Glass Fibre Reinforced Polymer) rectangular hollow pultruded sections. Table 1 presented the cross-sections, fibre reinforcement (if present), and the shear strength of the referenced sleeper materials. The ultimate shear strength is examined in this research owing to its highest correlation with the pull-out strength among other material properties [46]. In addition, the strength direction is perpendicular to grain/long fibre (directions defined in Figure 2 (e)) along the load direction as the sleeper hole is subjected to axial shear force due to the pull-out mechanism. The Asymmetrical Shear Beam test [47, 48] was adopted to obtain the shear strength of the four tested sleeper types. It should be noted that this study does not consider the shear capacity of the GFRP section of the PFR sleeper due to PFR's significant effect on resisting screw pull-out, although the laminates impose restraint on the core.

Table 1: The tested railway sleepers

Sleeper technology	Cross-section	Fibre reinforcement	Shear strength* (MPa)
Hardwood Timber		Timber grain in the longitudinal direction	9.0
UHMWPE Plastic		No fibre reinforcement	14.0
Synthetic Composite			7.0
PFR			10.6

*The shear strength is perpendicular to the grain/fibre direction along the load direction.

GageLok rail screws made of Grade U3 steel [13] with a minimum 250 MPa yield strength and minimum 410 MPa tensile strength [49] are the fasteners used in this study. These screws are the type of screws used by Queensland Rail in Australia to fix rail directly to timber or composite sleepers or with plates and to prevent lateral and vertical movements between them [3]. Table 2 presents the parameters of the tested GageLok rail screws which have a thread angle of 60°. Figure 2 (a) illustrates these parameters including major diameter, minor diameter, pitch and thread angle which determine the screw profile configuration. The major diameter is the diameter of an imaginary cylinder formed by the crest of all external threads on the screw while the minor diameter is the lowest diameter measured from the thread root. Figure 2 (b) shows the Ø17.5mm GageLok-11 rail screw. The shank of the screw can be noticed but its effect on the pull-out behaviour is not investigated in this study due to its main function of resisting the lateral shear force from the rail/plate rather than the uplift force. Thus, only the thread part was embedded in the sleeper material.

Table 2. Screw geometry of GageLok rail screws.

Screw	GageLok-5	GageLok-15	GageLok-13	GageLok-7
Major Diameter	16	16	17.5	19
Minor Diameter	12	12	13.5	14.5
Pitch	6	6	6	7
Thread Length	70	90	99	90
Pilot hole diameter	13	13	14	15

Dimensions are in mm.

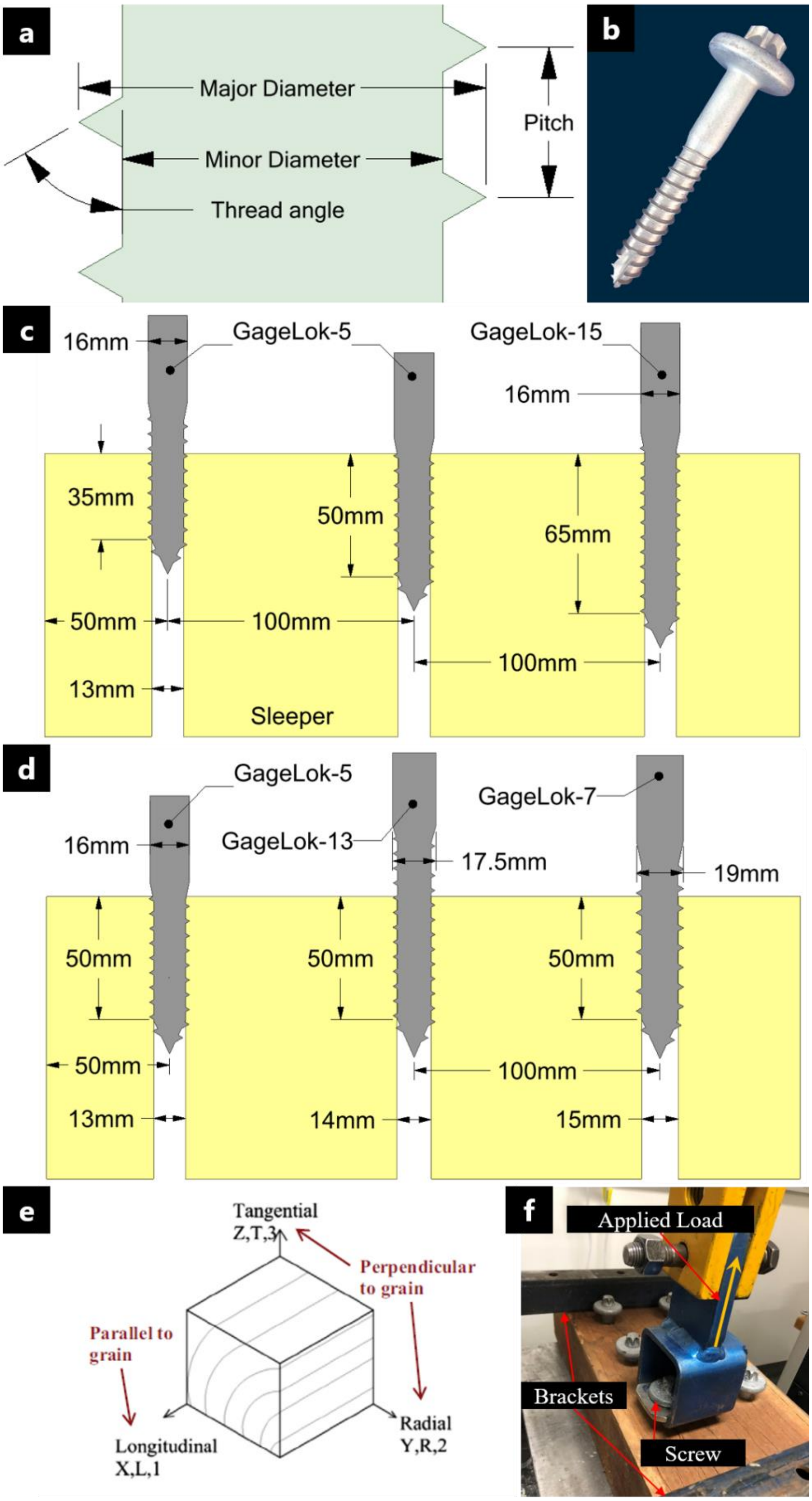


Figure 2. a) Terminology of the screw profile, b) the GageLok-11 rail screw, c) screw installation diagram with varied thread embedded length, and d) screw installation diagram with varied major diameter, e) definition of material directions of orthotropic material, f) screw pull-out test setup.

2.2 Screw pull-out test

Pilot holes were pre-drilled for screw installation to prepare the pull-out test. The size of the through-holes was close to 1.1 times the minor (root) diameter with no observation of timber splitting after installation complying with the requirements of AS1085.18 [13]. The timber-replacement sleepers were inserted in the holes of the same size. The last row of Table 2 presents the different sizes of pilot holes corresponding to the size of rail screws. The screws were then inserted in the rail-seat region of the sleeper at a distance of 100mm in between and 50mm from the edge using an 18V brushless impact wrench. In order to investigate the effect of the thread embedded length, the GageLok-5 and GageLok-15 with the identical thread form (Ø16mm) were inserted 35mm, 50mm and 65mm deep in the rail-seat region of the sleeper samples. As presented in Table 2, the GageLok-5 and GageLok-15 have the same thread configurations but have different lengths. On the other hand, the GageLok-5, GageLok-13 (Ø17.5mm) and GageLok-7 (Ø19mm) were driven in the rail-seat region to the same depth of 50mm to determine the effect of the major diameter of threads. Figure 2 (c) and (d) show the relevant screw installation diagrams. A universal test machine with 100kN capacity was used to conduct the pull-out test following the AREMA specifications [15]. The Australian Standards AS 1085.22 [27] was mostly followed with some modifications in which the test load is increased to the maximum to measure the ultimate strength and to analyse the failure modes of the different sleepers instead of maintaining the load for 3 minutes. This load-maintaining requirement of AS 1085.22 seems to be suitable for a qualification test but not to understand the pull-out behaviour of sleeper technologies. Figure 2 (f) depicts the screw being lifted upward from the rail seat by a loading head and jig at a rate of 2 mm/min until the maximum pull-out force was reached while the sleeper section was fixed to the test bench by two brackets at two ends.

2.3 Microscopic examination

The tested holes were cut in half to observe the cross-sections after the pull-out test. Both the longitudinal and transverse directions of the orthotropic sleepers including timber, SC and PFR are investigated. A Leica DMS 300 camera (Leica microsystems) was used to investigate the failure modes of different sleeper materials in terms of their pull-out behaviour. The microscopic photos were then analysed and the failure modes were used as the fundamental guide for predicting the pull-out behaviour in the development of the proposed new analytical models.

3 RESULTS AND DISCUSSION

3.1 Effects of the thread embedded length

Figure 3 depicts the effect of the thread embedded length by varying from 35mm to 65mm (with an increment of 15mm). The results showed that the pull-out load of all tested sleepers, i.e., hardwood timber (T), UHMWPE plastics (P), synthetic composites (SC), and PFR, increases linearly with increasing thread embedded length as illustrated in Figure 3 (a). This is due to the longer thread embedment length enabling more pitches of the screw engaging with the sleeper material and consequently generating higher pull-out resistance. Similarly, Cai et al. [50] reported better pull-out performance of rock bolts with increasing installing length as more rock mass were interacted and worked together. Maranan et al. [51] highlighted that the increased engaged surface generates higher mechanical interlock and greater friction resistance. Ren et al. [52] indicated the pull-out load continued to increase with the bond length even after the effective bond length was reached but at a slower rate. Nevertheless, different slopes are noticeable on the initial part of the pull-out load and embedment length relationship curve for different sleeper materials. By increasing embedded thread length from 35 to 65mm, the PFR sleepers had a dramatic enhancement from 33.5±1.1kN to 70.5±1.7kN, and similarly, the pull-out strength of UHMWPE plastics increased from 23.9±2.8kN to 56.2±0.4kN. In comparison, timber and synthetic composite sleepers saw relatively small increases in the pull-out strength. The stiffer slope of PFR and plastic sleepers can be corresponding to their high shear strength as reported in Table 1. As shown in the theoretical equations, material shear strength is the most important factor affecting the pull-out performance when the same screw geometry is adopted. It can be thus concluded that the embedded length has a stronger positive effect on sleepers with high shear strength while it has a less effect on low shear strength sleeper materials.

The effect of thread engaged length is further investigated when a constant stress distribution is assumed along the screw embedment during pull-out. Equation (1) is transformed from the FTS model [33] to calculate this normalised shear stress τ as demonstrated in Figure 3 (b).

$$\tau = \frac{F_{pull-out}}{\pi D_{major} L} \quad (1)$$

where $F_{pull-out}$ is the pull-out force, D_{major} is the major diameter of the screw, and L is the thread embedded length. It is observed that the normalised stress on each type of the tested sleepers is almost the same with increasing thread length. These experimental results were further analysed in section 3.4 using Tukey's honest significant difference (HSD) Post Hoc multiple comparisons. Table 3 presents the significance of difference ranging from 0.845 to 0.996 (with 95% confidence interval) which indicates a minor statistical difference of the normalised stress. The unnoticeable change in stress implies that the sleepers' shear strength was fully utilised as the failure generally occurred within the sleeper material rather than the screw. Thus, the normalised stress can correspond to sleepers' shear strength. Similarly, it is reported that the bond strength of rock bolts increases with the increasing shear strength of the grouting material during pull-out [36]. However, a distinct effect of embedded length was found in the research of composite reinforcing bar pull-out [34] that the shear stress decreases with the increasing length due to its nonlinear distribution (the stress gap between the loaded end and the unloaded end). Even though the nonlinear stress distribution was also proposed by Lotfy et al. [23] for the mechanics of rail screw pull-out, the stress gap seems relatively small, as the embedded length (35-65mm) of rail screws is much less than the rebar embedded length (63-300mm) [34].

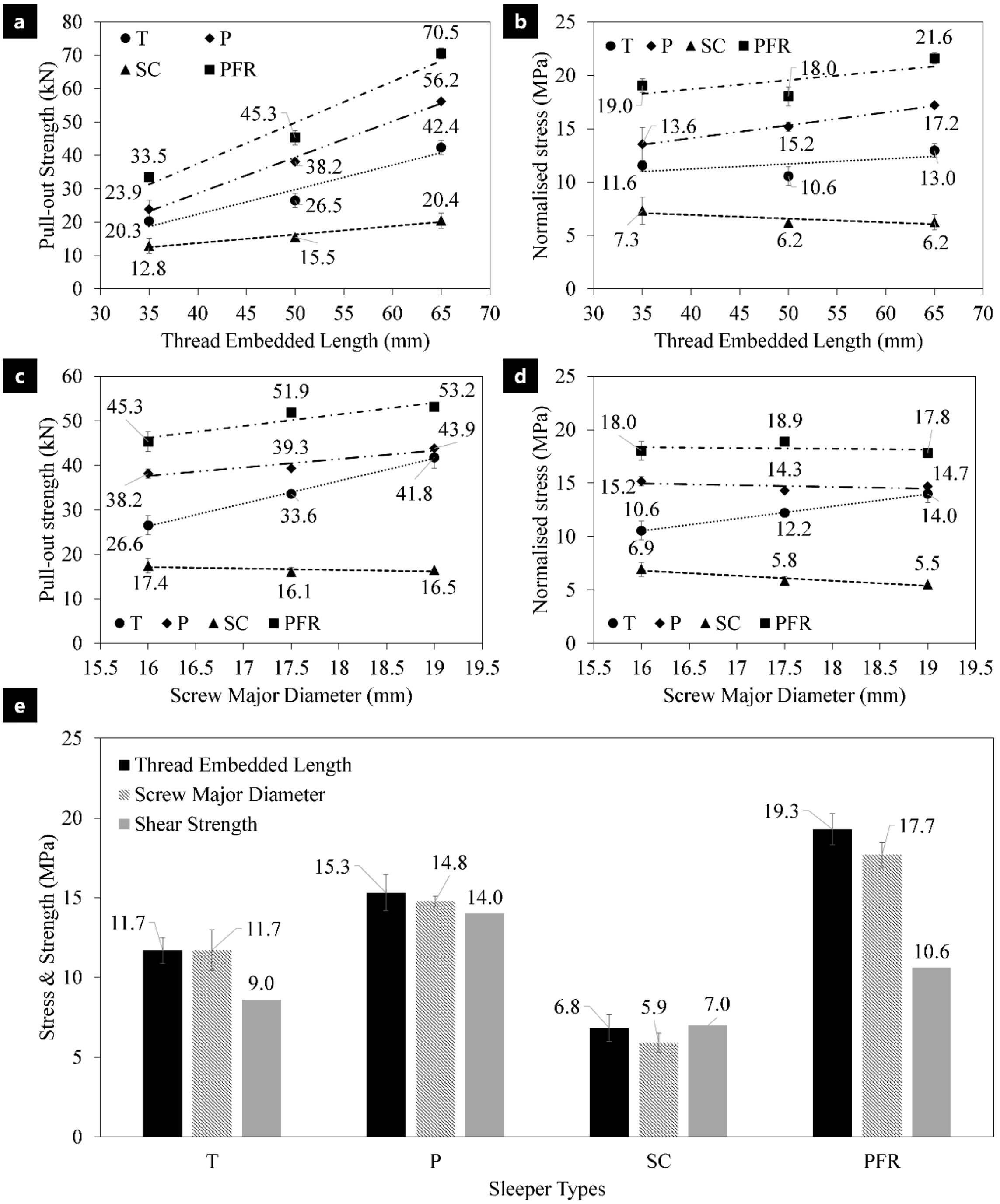


Figure 3: Increasing thread length (mm) plotted against a) pull-out strength (kN) and b) normalised stress (MPa); increasing screw major diameter (mm, discussed in Section 3.2) plotted against c) pull-out strength and d) normalised stress of timber (T), synthetic composites (SC), UHMWPE plastics (P), and PFR; e) average normalised stress compared to the sleepers' shear strength (MPa).

3.2 Effect of the thread major diameter

The major diameter of the screw is extensively regarded as one of the dominant factors of the predicted pull-out force [30, 32, 33, 53, 54] while the variation of the minor diameter did not show a statistically significant difference [55] nor the pitch [32]. Theoretically, it corresponds to the thread stripping failure in which the external threads on screws shear off the internal threads on the host material. However, Figure 3 (c) illustrates the minor effect of the increasing screw major diameter (16-19mm) on the pull-out performance of the tested sleepers except for the hardwood timber. In the pull-out mechanism, the increase in major diameter is able to interact with the sleeper material in a larger area but the total increment of 3mm (from 16mm to 19mm) in diameter seems limited compared to the ten times larger increase (30mm) of embedded length. To be specific, the 19% increment in diameter can be correlated to the improved pull-out strength of PFR (17%) and UHMWPE plastics (15%) while it did not affect the pull-out performance of SC sleepers due to its significantly low shear strength. The SC sleepers are weak in shear as subjected to in-plane shear cracking due to the matrix failure in the fibre direction [46]. On the other hand, the increase of major diameter immediately enlarges the thread bearing area (on thread surface) and strongly affects the pull-out strength of timber which has superior load-bearing capacity. This capacity is dependent on the continuously high shear strength of timber as a natural orthotropic material. In the authors' previous work [46], shear failure longitudinal to the grain direction and hole lifting was observed in the pull-out failure of the timber sleeper, which implies that the hardwood timber is strong in shear in the screw axial direction and continuously along the full length of the sleeper. Hence, its 57% increase in the pull-out strength can be explained.

Similar to the effect of embedded length, various researchers reported that increasing bar diameter decreases the bond stress due to non-linear stress distribution [34, 56, 57], Poisson effect [35], or shear lag effect [58]. However, Figure 3 (d) depicts that the normalised stress of the composite sleepers is hardly affected by the screw major diameter. In comparison to the bar's pull-out, the non-linear stress distribution can be ignored possibly owing to the relatively shorter embedded length of rail screws. Besides, it seems the Poisson's ratio or the shear lag showed no influence on the screw behaviour as the deformation on the screw can be neglected due to its considerably higher strength than the sleeper materials. Table 3 further verifies the minor significance of difference (>0.95) in the normalised stress of different major diameters using Tukey's HSD multiple comparisons. Additionally, the timber samples see a noticeable increase in normalised stress exceeding the material shear strength, which indicates Equation (1) is not suitable to predict the normalised stress in timber sleepers due to its different failure behaviour. Specifically, since the rail screw interacts with more timber material in thread bearing failure than thread stripping, the relevant stress area is larger as illustrated in Section 4.3. This is corresponding to the failure of the timber hole being lifted during screw pull-out [46]. Therefore, the stress area on threads mainly defined by the major diameter greatly affects the pull-out performance of timber.

3.3 Relationship between normalised stress and shear strength of sleepers

The pull-out failure generally occurs on sleeper materials instead of screws. This suggests that the normalised shear stress have a strong relationship with the sleepers' ultimate shear strength. Figure 3 (e) compares the shear strength of the tested sleeper technologies with the average normalised stress with varied embedded lengths and major diameters. Synthetic composites and UHMWPE plastics show a minor difference which implies the effectiveness of Equation (1) and the basic pull-out model [33] in predicting the pull-out strength of thread stripping failure. In this failure mode, the stress component equals the ultimate shear strength of the sleeper materials. In comparison, the shear strength of hardwood timber and PFR sleepers is noticeably lower than their normalised stress. This result implies that the theoretical model for thread stripping failure is not suitable to estimate the pull-out performance of these two types of railway sleepers as the screw geometrical parameters may have a distinct effect on the thread bearing failure of timber and global shear cracking of PFR observed in [46]. Timber sleeper showed grain longitudinal shearing accompanied by inclining shear cracking in the transverse direction while the global shear cracking due to the load transfer function of short fibres dominated the pull-out failure of the PFR sleeper. Compared to the simple thread stripping failure, these two complex failure modes indicate that more sleeper materials were engaged with screw uplifting, and therefore, the relevant stress area can be larger. Hence, a new analytical model is required to incorporate the effect of screw geometry on the pull-out capacity of different sleeper technologies.

3.4 Statistical analysis of pull-out results

The pull-out results were analysed with IBM Statistical Package for the Social Science (SPSS) Statistics 26 [59] to compare the significance of the difference at a 95% confidence interval. The one-way analysis of variance (ANOVA) [60-62] was conducted to determine whether there was any significant difference between the mean and the standard deviation of the calculated normalised stress. In Table 3, Tukey's honest significant difference (HSD) Post Hoc multiple comparisons show the minor difference of the normalised stress despite the increasing thread embedded length or screw major diameter. On the other hand, the univariate analysis of two-way ANOVA [63] was applied in

Table **4** to evaluate the influence of sleepers' shear strength, embedded length and major diameter over the pull-out performance of all the tested sleeper technologies while the effects of the last two parameters on each sleeper type were also investigated. The p-value represents the significance level and demonstrates that the pull-out strength is remarkably influenced by all the three parameters indicated by the p-value below 0.05 except the screw major diameter for the SC sleeper (0.979). The limited effect of major diameter indicates that SC failed immediately instead of bearing the axial pull-out force, which corresponds to the progressive load drops observed in both this study and in [46]. The partial eta squared reflects the influence level of different parameters on the pull-out strength.

Table **4** highlights that the shear strength (0.938) and embedded length (0.882) has approximately two times greater influence than the major diameter (0.463) for all tested sleeper types. In the conditions considering each sleeper technology separately, thread embedded length is more likely to affect the pull-out strength than major diameter. However, it is noticeable that the effect of major diameter is much higher on hardwood timber (0.739) than other sleeper types but minor on synthetic composites (0.003). The statistical results are discussed with different pull-out failure modes to develop a new analytical model for sleeper technologies.

Table 3: Tukey's HSD Post Hoc multiple comparisons on normalised stress (in MPa) of reference sleeper technologies

Multiple Comparisons – Tukey HSD							
Dependant Variable: Normalised Stress (MPa)							
Factor (I & J)	(I)	(J)	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Thread Embedded Length (mm)	35	50	.18000	2.07267	.996	-4.9133	5.2733
		65	-.99644	2.11925	.886	-6.2042	4.2113
	50	35	-1.8000	2.07267	.996	-5.2733	4.9133
		65	-1.17644	2.11925	.845	-6.3842	4.0313
	65	35	.99644	2.11925	.886	-4.2113	6.2042
		50	1.17644	2.11925	.845	-4.0313	6.3842
Screw Major Diameter (mm)	16	17.5	.60447	2.03446	.953	-4.3950	5.6039
		19	.09333	1.98974	.999	-4.7962	4.9829
	17.5	16	-.60447	2.03446	.953	-5.6039	4.3950
		19	-.51114	2.03446	.966	-5.5106	4.4883
	19	16	-.09333	1.98974	.999	-4.9829	4.7962
		17.5	.51114	2.03446	.966	-4.4883	5.5106

Table 4: Two-way ANOVA determining the influence effect of parameters

Dependant variable	Sleeper technologies	Independent variable	F-value	p-value	Partial eta squared
Pull-out strength	All	Shear Strength	237.2	.000	.938
		Embedded Length	175.4	.000	.882
		Major Diameter	20.3	.000	.463
	T	Embedded Length	31.1	.000	.827
		Major Diameter	18.4	.000	.739
	P	Embedded Length	121.2	.000	.949
		Major Diameter	5.1	.024	.438
	SC	Embedded Length	4.7	.030	.418
		Major Diameter	.02	.979	.003
	PFR	Embedded Length	137.4	.000	.955
		Major Diameter	9.9	.002	.603

4 ANALYTICAL MODELS FOR SCREW PULL-OUT STRENGTH BASED ON FAILURE MODES

The ultimate shear strength of sleeper materials is found to be the most significant parameter for the pull-out behaviour compared to the screw geometrical parameters. Likewise, screw diameter and embedded length show different levels of importance in the prediction equations of different failure modes. The thread embedded length has considerably greater influence in the thread stripping model while major diameter affects the thread bearing model more. According to the effects of the parameters discussed above, this section reviewed currently existing pull-out models and proposed a new analytical model based on the observed three failure modes to predict the pull-out strength of the railway sleepers.

4.1 Review of existing pull-out models

The fundamental thread stripping (FTS) model expressed in Equation (2) is extensively applied to formulate the pull-out strength in various research areas (e.g., rebar [34], rock bolt [36], bone screw [33] and single fibre pull-out [37]) when the internal thread/bond of host materials is stripped off.

$$F_{pull-out} = S\pi D_{major}L \quad (2)$$

where $F_{pull-out}$ is the pull-out strength, S is the material ultimate shear strength, D_{major} is the major diameter of the threads (mm), L is the thread embedded length (mm). Since the thread stripping failure is assumed, the pull-out strength is determined by the material shear strength (S) and cylindrical shear area ($\pi \times D_{major} \times L$) of the threads. Another pull-out model is the ASTM function [38] featuring the thread shape factor (TSF) as presented in Equation (3).

$$F_{pull-out} = S\pi D_{major}L \times TSF \quad (3)$$

TSF (dimensionless) is defined by $(0.5 + 0.57735 \times \frac{d}{p})$, where d is the thread depth ($(D_{major} - D_{minor})/2$, D_{minor} is the minor (root) diameter of the threads, all dimensions in mm) and p is the thread pitch (mm). Since Tsai's model [31] is more suitable for conical screws rather than cylindrical rail screws, it is not included in this section. The two pull-out models of thread stripping clearly explain the linear relationship between the embedded length/major diameter and the pull-out strength. These two parameters show positive contributions to the pull-out force, but their influence can be largely affected by the low shear strength of sleeper materials (e.g., the synthetic composite sleeper) especially when the increment of the parameter is small. This result suggests that the prediction equations developed based on the thread stripping failure seem to be suitable for the sleeper technologies exhibiting similar failures. On the other hand, Equation (4) shows the prediction equation for the thread bearing failure [43].

$$F_{pull-out} = S\frac{\pi}{4}({D_{major}}^2 - {D_{minor}}^2)\frac{L}{p} \quad (4)$$

where D_{minor} is the minor diameter (mm) of the screw. The pull-out force is a product of material shear strength, the number of threads, and the difference in the cross-sectional area of the major and minor diameter. It is noticeable that only two failure modes (thread stripping and thread bearing) are described in the existing models, but the timber and composite sleeper materials seem to have distinct pull-out failures. Hence, a new analytical model consisting of three equations is developed from the distinct pull-out failure mechanics in the following sections and each equation corresponds to a specific failure mode.

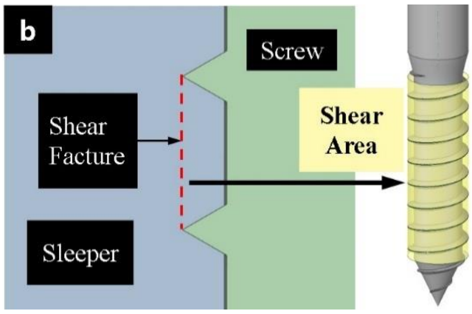
4.2 Prediction model for Failure Mode 1

Failure Mode 1 can be regarded as the traditional thread stripping failure in which the internal threads in the sleeper hole are sheared off due to the screw's axial shear force. This type of failure is common in the composite sleepers with no [23] or one-directional (normally longitudinal) fibre reinforcement [46] for which the matrix dominates the shear strength in the pull-out direction. Although synthetic composites and UHMWPE plastics exhibited noticeably different shear capacities as well as the pull-out performance, their failure modes are similar and categorized to the same failure mode in Table 5 (a). The localised failures were observed in the cross-sections of both sleeper types and the sleeper material between threads was partly stripped in the plastics while that in SC was mostly deformed due to abrasion. Due to the flexibility of the synthetic composite and plastic material, the internal threads were not completely stripped off similar to rock bolting failure [64] or bone chips peeling [31, 44]. However, this type of failure can be considered as the localised damage along the shear fracture line (shown in Table 5 (b)) same to the thread stripping. Therefore, Equation (2) is directly applied to predict the pull-out strength of SC and P based on the material shear strength and screw geometry. Table 5 (c) illustrates the pull-out strength of SC and P from experiments is plotted against the predicted values from Equation (2). The coefficient of determination (R^2) reaches 0.90 indicating the 90% of the total variation of the data can be explained by the model while the root mean square error (RMSE) has a value of 4.75 demonstrating the actual difference between the experimental results and the predicted values.

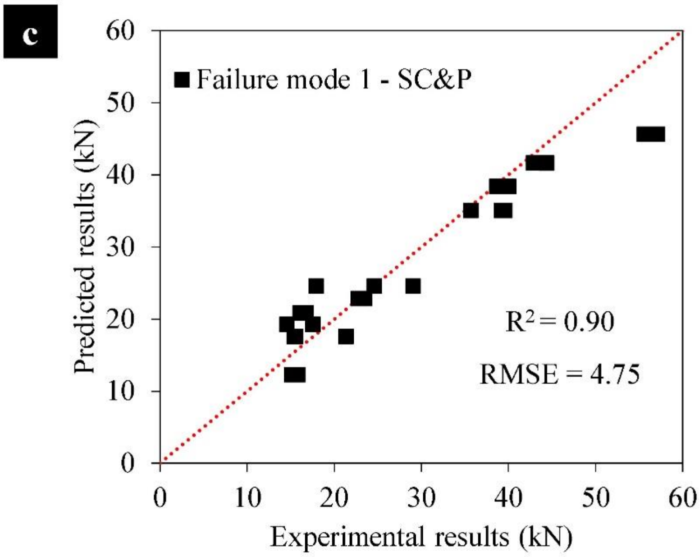
Table 5: Analytical models developed based on failure analysis

	Failure Mode	Failure Mechanism

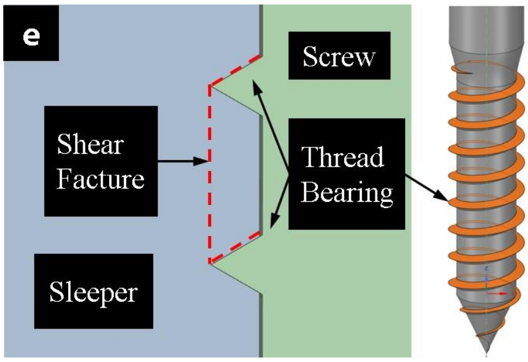
Failure Mode 1



$$F_{pull-out} = F_{stripping} = S\pi D_{major}L \qquad (2)$$

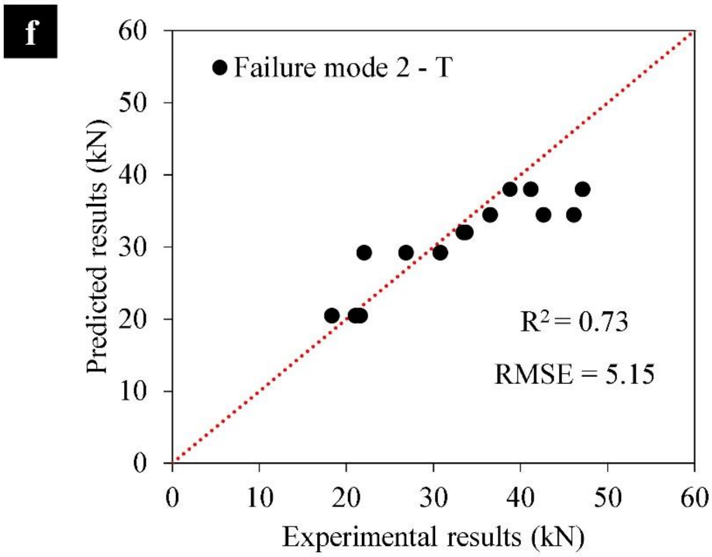


Failure Mode 2



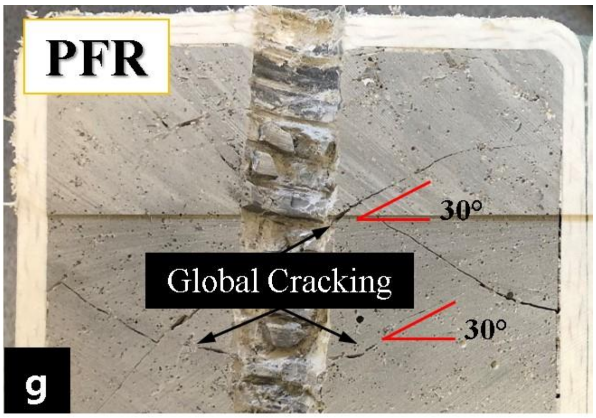
$$F_{pull-out} = F_{stripping} + F_{bearing} \quad (5)$$

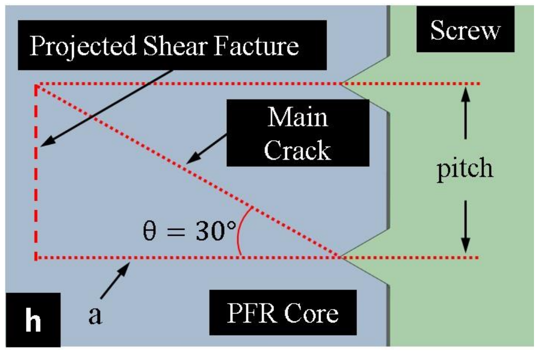
$$F_{pull-out} = S\pi D_{major}L + \frac{\pi}{4}\left(D_{major}{}^2 - D_{minor}{}^2\right)S\frac{L}{p} \quad (6)$$



Failure

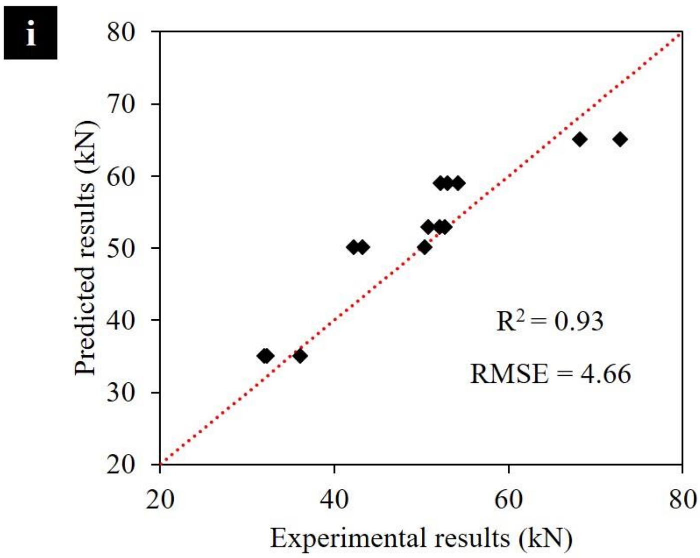
Mode 3





$$F_{pull-out} = S \times A_{projected} \qquad (7)$$

$$F_{pull-out} = S\pi(D_{major} + \frac{p}{\tan\theta})L \qquad (8)$$



4.3 Prediction model for Failure Mode 2

Failure Mode 2 features thread bearing in timber holes as shown in Table 5 (d). This unique type of failure is only observed in hardwood timber rather than other polymer composite sleepers [46] because timber has a strong shear capacity in the screw pull-out direction and continuously along the full length of the sleeper. As illustrated in Table 5 (d), the load-bearing capacity of hardwood timber is revealed by the grain longitudinal shearing during screw pull-out while the entire hole being lifted implies that timber's shear strength was fully utilised along the shear fracture line. Although brittle shear cracks were observed in [46], the grain shearing dominates the pull-out failure in timber sleepers. This is due to the hardwood material has a high shear strength (9MPa) perpendicular to grain along the load direction [65]. Additionally, the significant role of load-bearing is corresponding to the greater effect of thread major diameter on the pull-out strength of timber than other sleeper technologies. According to the pull-out mechanics of timber sleepers shown in Table 5 (e), Equation (4) for thread bearing is combined with Equation (2) for thread stripping to predict the pull-out strength of hardwood timber sleepers as presented in Equation (5). Equation (6) shows the proposed prediction equation, which matches reasonably well with the experimental pull-out strength having a coefficient of determination of 0.73 and the RMSE being 5.15 as depicted in Table 5 (f).

4.4 Prediction model for Failure Mode 3

Failure Mode 3 of the PFR sleepers is dominated by global shear cracking accompanied by thread partly stripping, as the sleeper material is reinforced by fibres in multi-directions. Table 5 (g) depicts that the inclined cracks occurred owing to fibres' load transferring function while the short fibres also bridged the cracking at thread root and prevented thread stripping. Hence, the existing theoretical models seem unsuitable to describe Failure Mode 3. As revealed in section 3 that the non-linear stress distribution has a minor effect on the screw pull-out mechanism despite the increasing major diameter, the normalised stress method is used to simplify the matrix global cracking by increasing the projected shear area. It is possible because the global shear cracking [46] in the core indicates more PFR material has radially interacted with the short fibres and thus generated a shear cylindrical area (formed by projected shear fractures shown in Table 5 (h)) larger than the thread stripping failure. The engaged area of sleeper material is assumed based on the observed crack path. As the mechanism of Failure Mode 3 demonstrated in Table 5(h), the main crack initiated from thread tips, propagated at approximately 30° (along the lower surface of external threads), and was assumed to stop at the horizontal level of the next thread tip. Hence, the diameter of the new projected shear area can be calculated as the sum of the screw's major diameter and the length of 'a' in the Failure Mode 3 mechanics in Table 5. The length of 'a' equals to $\tan\theta$ multiplied by the pitch of the screw. Equation (7) is modified from Equation (2) by adopting the new projected shear fracture line. Equation (8) presents the full prediction equation for Failure Mode 3. The relation between the experimental and predicted values are provided in Table 5 (i). The R squared value for the prediction model is 0.93 while the RMSE is 4.66.

4.5 Verification and comparison with other models

This section compares the proposed analytical model for three failure modes of railway sleeper technologies with other existing models. The predicted results for the tested sleeper types are plotted against the experimental results measured in this work. The diagonal line in red is also plotted to provide a good understanding of the accuracy of each prediction model. Figure 4 (a) depicts the overall performance of the proposed analytical model. It is noticeable that the plotted points are well aligned with the diagonal line showing an R-squared value of 0.89 and RMSE of 4.83. In Figure 4 (b), Equation (2) based on thread stripping failure did not show a good correlation with the experimental results, especially for timber and PFR. This is due to these two sleeper types have different pull-out failure modes other than thread stripping.

Adopting the thread stripping model generally neglects the fact that more sleeper materials of timber and PFR were engaged in the pull-out behaviour resulting in larger axial shear resistance. It is noticeable that neither Figure 4 (c) illustrates that the predicted values from Equation (3) are generally lower than the experimental results due to the effect of TSF (Thread Shape Factor). Rail screws generally have a low value of TSF due to relatively long pitch and thus a small number of threads [13, 23, 46]. In this study, the TSF ranges from 0.64 to 0.67 which largely decreases the predicted values, and thus, is not suitable for the prediction of rail screw pull-out. Compared to the prediction models discussed above, the thread bearing model (Equation 4) not only exhibits the lowest predicted results but also shows almost no difference between different sleeper technologies. This is due to the fact that this model considers the thread bearing area, which is dependent on the thread number, to be the dominant factor instead of thread embedded length. In comparison, Equation 4 seems to be more suitable for the prediction with a smaller pitch, hence a larger number of threads [33, 44, 45, 66]. It can be concluded that the existing theoretical models provide less accurate results as these equations only consider the individual contribution of either the shear strength of the sleeper materials or the geometry of the screw. It is noticeable that the overall performance of the new prediction model is over 50% more reliable than the existing models. This highlights the need for a new theoretical prediction equation that can appropriately describe the pull-out behaviour of railway sleeper materials.

The overall prediction performance of the proposed model is further verified by the pull-out results measured by other researchers to enhance its reliability and applicability. To apply the new analytical model, the failure mode of the target sleeper technology needs to be determined to select the most suitable prediction equation. As mentioned in the above sections, the failure modes of the referenced sleepers can be assumed according to their fibre reinforcement type based on the outcomes of [46]. This assumption was also verified by the failure photos available in the literature. Equation (1) was applied to predict the pull-out strength of the HDPE plastic and Sekisui FFU sleepers according to their fibre reinforcement as shown in Table 6. Lofty et al. [23] inserted the Ø22mm rail screw with an effective thread length of 76mm into the HDPE plastic sleeper having the shear strength of 8.1MPa while Sekisui tested the pull-out strength of their FFU sleepers (10MPa in shear) using the Ss 8-140 screw (24mm of major diameter and 70mm of thread embedded length) [39]. Additionally, Equation (8) was adopted to estimate the pull-out performance of the innovative composite sleeper developed by USQ [3] as the core material of this type of sleeper failed in a similar manner as the short-fibre-reinforced PFR. The inclining shear cracks were observed in the shear failure of both the phenolic sandwich beam [21] and the polymer bonding material [67]. The Ø16mm rail screws having 6mm pitch were installed in the rail-seat region with 60mm-long threads embedded. Figure 4 (f) illustrates that the predicted strength is well aligned with the measured results from the literature. The proposed model shows an R squared value of 0.81 and a low RMSE of 5.01, which demonstrates that the capability of this new model to estimate the screw pull-out performance of current fibre-reinforced composite sleeper technologies.

Table 6: referenced sleeper technologies

Sleeper Type	Fibre Reinforcement	Assumed Failure Mode	Shear Strength (MPa)	*Thread Embedded Length (mm)	Major Diameter (mm)
HDPE Plastic	No fibre	Failure Mode 1	8.1	76	22
Sekisui FFU	Longitudinally one-directional	Failure Mode 1	10.0	70	24
USQ	Multi-directional	Failure Mode 3	16.0	60	16

*The thread embedded length does not include the length of shank and conical area of the screw due to their minor contribution to pull-out.

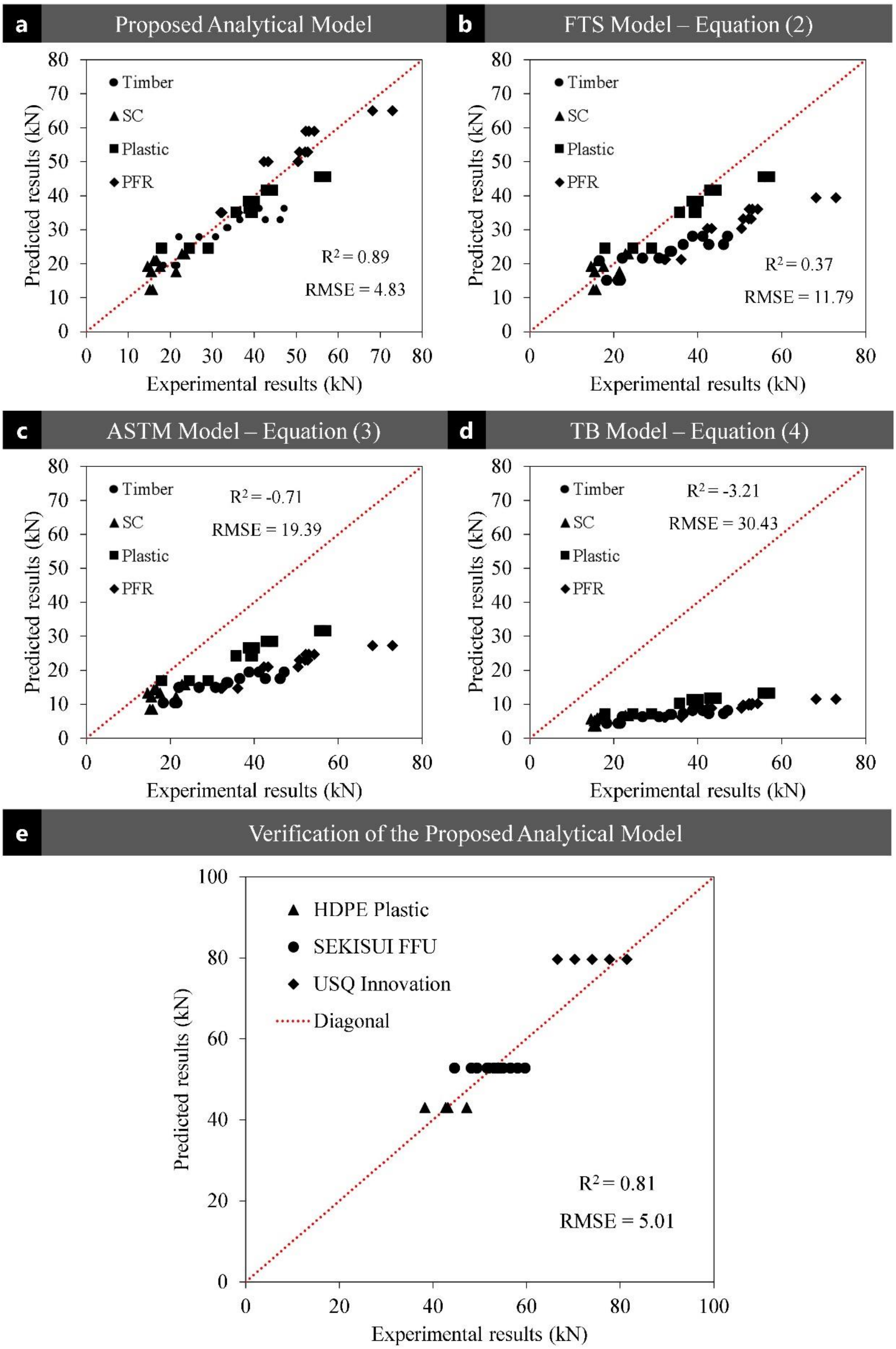


Figure 4: Comparison between the a) proposed model and b) - d) existing prediction models, e) verification with the data from literature

5 CONCLUSIONS

This study experimentally investigated the effect of screw geometry on the screw pull-out behaviour in the rail-seat region of timber and composite railway sleepers. An analytical model based on pull-out failure modes was proposed to well predict the pull-out strength of different sleeper materials. Based on the results, the following conclusions are made:

- Increasing thread embedded length has a significant effect on the pull-out strength of timber and timber alternative sleepers, but has a very minimal effect on the normalised stress on the screw. This result indicates the sleepers' shear strength is fully utilised during pull-out. The higher shear strength the sleeper material exhibits, the greater influence the embedded length has.
- The increase in major screw diameter has a greater effect on the pull-out performance of hardwood timber than other sleeper technologies, same to the normalised stress. This is due to the timber's high axial shear resistance on the thread surface accompanied by the hole being lifted. The size of thread surface defined mainly by the major diameter thus has an important influence on timber's pull-out capacity.
- The two-way ANOVA demonstrates the greatest influence of material shear strength in the screw pull-out behaviour, closely followed by the effect of thread embedded length which is approximately two times higher than that of thread major diameter. The influence level of the shear strength is at 0.938 while the embedded length is at 0.882. The influence level of the major diameter is generally low on the composite sleepers but relatively high on timber.
- New analytical models considering the material shear strength, thread embedded length, screw major diameter and the failure mode were developed to predict the screw pull-out resistance of railway sleepers. The proposed model shows a relatively well

agreement with the experimentally tested sleeper types (R^2 = 0.89, RMSE = 4.83) and the referenced sleeper technologies from literature (R^2 = 0.81, RMSE = 5.01).

The above conclusions are drawn from the investigation on the effect of screw geometry on the pull-out behaviour of timber and timber-replacement composite sleeper technologies of this study. Researchers and design engineers are encouraged to conduct finite element analysis for a particular type of sleeper without building different models. Nevertheless, the experimental results and proposed analytical model could improve the understanding of screw pull-out behaviour of timber and alternative composite sleepers to facilitate their wide adoption in the maintenance of deteriorating railway tracks.

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CHAPTER 6: SCREW LATERAL RESTRAINT BEHAVIOUR OF POLYMER SLEEPERS

Chapters 4 and 5 evaluated the effect of the material properties and screw geometries on the pull-out performance of polymer sleepers, respectively. The results of these studies showed that these parameters have a major influence on the pull-out strength and failure behaviour of sleepers. As the sleepers are also subject to lateral forces, their screw lateral restraint behaviour and failure modes were studied experimentally and analytically in Chapter 6. The results of this work addressed the fourth objective. In this study, the lateral forces of timber and composite sleepers were obtained in the lateral restraint test. FEA was also used to simulate the lateral restraint behaviour and to demonstrate the stress distribution in the screw body and the sleeper holes.

The results showed screw yielding and sleeper material hardening even before the first 5.1 mm displacement for all the tested sleeper samples. Specifically, timber and synthetic composites exhibited around half of the ultimate lateral strength of plastics' performance. The grain/fibre shear-out failure was observed from the orthotropic sleepers while the isotropic material (plastic) exhibited bearing as the main failure mode. The developed finite element models accurately described the screw deformation and the resultant stress in the timber and composite sleeper bodies. The new knowledge gained from this study are highlighted in the Conclusion and recommendations for further studies to completely understand the screw pull-out and lateral restraint behaviour of polymer sleepers are presented in Chapter 7.

CHAPTER 7: CONCLUSIONS

Polymer composite railway sleepers have emerged as a promising alternative technology to traditional timber sleepers. Fibre reinforcement is widely applied to engineer the mechanical properties in the desired direction and to be compatible with that of timber sleepers. Nevertheless, the limited understanding of their rail-seat performance limits the confidence of the railway industry in adopting these new technologies. Therefore, this study investigated the composite sleepers reinforced by different fibres experimentally and analytically in terms of their rail-seat behaviour and comparatively evaluated with hardwood timber. The major findings of this research are stated below:

State-of-the-art review on the rail-seat performance

This study reviewed the material composition and the rail-seat behaviour of the timber alternative composite sleepers. The challenges and opportunities in the rail-seat region were analysed in terms of the composite sleeper materials reinforced by different types of fibres. The major findings are drawn below:

- Polymer composite sleepers are categorised based on their fibre reinforcement types. Type-1 sleepers (e.g., the recycled plastic sleeper) without fibre reinforcement are more durable than timber but suffer low mechanical strength while Type-2 sleepers (e.g., the synthetic composite sleeper) demonstrate superior flexural performance but poor interlaminar shear capacity due to the continuous fibres only in the longitudinal direction. In addition, Type-3 sleepers (e.g., the Particulate Filled Resin (PFR) cored sleeper) having fibres in both longitudinal and transverse directions exhibit excellent mechanical properties but are generally more expensive and difficult to produce.
- Particulate-Filled Resin (PFR) with structural components seems to be a promising alternative to hardwood timber but suffers the chipping issue during handling and drilling owing to the brittleness of PFR. Further improvements (e.g., adding flexible fillers or short fibre reinforcement) is necessary to enhance its flexibility, mechanical strength, and resistance to crack.
- The screw pull-out performance is generally dominated by the material properties if the fastener shows no damage or permanent deformation.

Researchers reported high correlations between the pull-out force and different material properties including ultimate shear strength, density, compressive strength, and tensile strength. However, it is unclear how the pull-out behaviour is affected by the sleeper material properties.

- Screw geometry is an important factor affecting the pull-out behaviour. The thread stripping failure is influenced by screw major diameter and thread embedded length while the thread bearing failure features the thread bearing area and the interacted thread number. Due to the configuration of rail screws, necessary attention should be paid to the long shank and the resultant small thread area.
- The Finite Element Analysis (FEA) is an effective method to analyse the lateral restraint behaviour due to the combined effect of the screw and the sleeper material. Current modelling methods for composite sleepers can be simplified to accurately realise the behaviour of polymer composite materials.

This state-of-the-art review highlighted that polymer composites are an effective alternative to traditional hardwood timber sleepers due to their outstanding mechanical properties and excellent durability. In order to increase the uptake of this new type of sleepers in the railway industry, it is necessary to understand how their rail-seat behaviour including the failure behaviour is affected by the material properties and screw geometries.

Material optimisation of PFR core

In this study, the addition of crumb rubber and different types of short fibres was investigated in terms of their effect on the physical, mechanical properties and microstructure of the epoxy-based particulate filled resin (PFR). Based on the experimental results, a simplified model was developed to predict critical mechanical properties of PFR using its compressive property. In addition, Analytical Hierarchy Process (AHP) was adopted to identify an optimal mix for sleeper development. The following conclusions can be drawn out of this study:

- An increase of porosity of the PFR was observed for mix with more than 30% volume ratio of crumb rubber, accompanied by the decreases of the flow values and densities. The strength properties were reduced by the rubber addition, but the flexibility increased due to the relatively low modulus of rubber particles, their even dispersion, and good bond with the PFR matrix.

- The porosity and density increased after the addition of more than 15% by weight of short glass fibres. The 10% of glass fibres saw an effective improvement of all tested mechanical properties of PFR despite the fibre pull-out failure. The workability of the mix became unacceptable when the fibre content further increased accompanied by a high porosity which led to a sudden decrease of the compressive and shear strength.
- The twisted Polypropylene (PP) fibres enhanced the flexural and shear performance of the PFR mix due to their even dispersion in the matrix while the straight PP fibres rarely showed a reinforcing effect owing to the poor dispersion. Microscopic observation showed that the twisted fibres had a massive fibre fracture.
- Simplified equations were proposed to predict the critical properties of the polymer matrix containing varied contents of crumb rubber and short fibres. The compressive strength was then used as an independent variable to describe other properties with a coefficient of determination as high as 0.99.
- The optimal mix was selected using the AHP method which indicated that the PFR mix containing 1% twisted PP fibre in volume is chosen if mechanical properties are highly valued; the 5% glass fibre reinforced mix becomes optimal when the priority is given to physical properties; if cost control is preferred, 10% volume ratio of crumb rubber is the best option.

According to this study, further research was conducted to measure the rail-seat performance of the PFR core reinforced by 1% twisted PP fibre and 5% glass fibre. An innovative design of composite sleeper was proposed and made of GFRP (Glass Fibre Reinforced Polymer) rectangular hollow pultruded sections filled with the two types of PFR cores. Their screw pull-out performance was then investigated with the effect of material properties and screw geometries determined.

Effect of material properties on the pull-out behaviour

This study examined the effect of sleeper material properties on the screw pull-out behaviour in the rail-seat region. The pull-out strength of timber and alternative composite sleepers was measured in the pull-out test. Pull-out failures of these sleepers were observed in the hole cross-section of the failed samples. The one-way analysis of variance (ANOVA) was implemented to reveal the correlation between material properties and pull-out strength. Moreover, a linear regression model was developed to estimate the pull-out force of composite sleepers and the predicted results were compared with an existing theoretical model. The following conclusions can be found below:

- Timber sleeper exhibits a longitudinal grain shearing failure in the thread area due to its strong shear capacity in the longitudinal-transverse and longitudinal-radial plane. The pull-out behaviour is linear up to the ultimate load followed by a plateau segment.
- The polyurethane (PU) foam dominates the pull-out behaviour of the synthetic composite sleeper which observed a linear to non-linear transition. The low shear strength of PU foam caused load drops and loss of stiffness that occurred before 20 kN due to the formation of minor cracks conforming to the observed matrix longitudinal cracks from thread tips.
- The strong bond strength between the polymer matrix and the added short fibres resulted in the PFR cored sleeper achieving pull-out resistance greater than the timber sleeper, despite the sudden and significant load drop at failure.
- The ultimate shear strength of the sleeper materials along the load direction strongly affects the pull-out performance of the thread area while the compressive strength significantly influences that of the shank area owing to the resultant friction between the screw and the engaged sleeper material.
- The paired samples test revealed the highest correlation between the shear strength and the pull-out force among other material properties. A linear regression model was thus developed to consistently predict the pull-out performance of railway sleepers using their shear strength as an independent variable. A high coefficient of determination was achieved at 0.95 which is higher than that of the existing theoretical model.

Effect of screw geometry on the pull-out behaviour

Screw geometries were investigated in terms of the effect on the pull-out behaviour of timber and composite sleepers accompanied by the analysis of the normalised stress on the screw body. The influence level of the investigated parameters was evaluated in the two-way analysis of variance (ANOVA). Based on the experimental results, an analytical model was developed to express the pull-out strength of railway sleepers and then compared with other existing theoretical models.

- The pull-out force is positively affected by the increase of thread embedded length but the normalised stress on the screw body is rarely influenced, which suggests the full utilisation of the shear strength of sleeper materials. The stronger shear capacity the sleeper material has, the greater effect the thread embedded length demonstrates.
- The pull-out resistance of hardwood timber was highly influenced by the increasing screw diameter compared to other sleeper materials, same to the normalised stress. This is possible because timber shows high axial shear strength on the thread surface the size of which is mainly identified by the major diameter.
- The two-way ANOVA reveals that the material shear strength exhibits a stronger effect than the screw geometrical parameters. The thread embedded length has its effect two times higher than that of major diameter. The major diameter generally shows a minor effect on the composite sleepers but greatly affects timber.
- According to the three different failure modes, new analytical models were proposed to express the pull-out strength using the material shear strength, thread embedded length, and screw major diameter. The developed models provided a good alignment with the experimental results and available data from the literature.

Screw lateral restraint and failure behaviour

The screw lateral restraint behaviour and failure modes of timber and polymer composite sleepers were evaluated. The single screw lateral restraint test was conducted to obtain the lateral force of all tested sleeper types. Based on the failure modes observed, a damaging process was proposed to express the progressive failure of different sleeper materials. FEA was conducted to simulate the lateral restraint behaviour and illustrate the stress distribution in both the screw body and sleeper hole.

- No noticeable deformation nor crack was observed in the tested sleepers at 5.1 mm lateral displacement, but the screw exhibited slight deformation due to bending. The plastic sleeper showed higher strength owing to its higher shear strength in the load direction than timber and synthetic composites.

- Fibre shear-out was the dominant failure mode of timber and synthetic composites due to their low shear strength in the load direction while bearing failure with significant deformation and material whitening occurred in the plastic sleeper. The plastic sleeper exhibited its ultimate lateral strength twice higher than timber and synthetic composites because of its relatively strong shear in the load direction.
- The multi-linear isotropic hardening rule is an effective method to describe the lateral restraint behaviour of the plastic sleeper while Hill's criterion for timber and synthetic composites at a displacement of 5.1 mm or lower. The lateral strength and material deformation were well estimated, which is 83% of the experimental results.
- An extensive interaction of the sleeper material was realised to resist lateral forces in the plastic sleeper having a high shear capacity. Consequently, a wide stress propagation in the hole was observed. In comparison, the stress propagation in timber and synthetic composites was restricted in the longitudinal direction due to their orthotropy. The compressive stress seems to dominate the lateral restraint behaviour under 5.1 mm displacement.

Contribution of the study

The results gained from this study significantly increased the understanding of the rail-seat performance of polymer composite sleepers reinforced by different types of fibres. This research also generated useful experiment data and analytical tools for researchers and railway engineers to accurately express the pull-out and lateral resistance for a similar design of composite sleepers. The significant contributions of this research are shown below:

- Provided sufficient information to date on the development of PFR matrices with flexible fillers/fibre reinforcement and addressed the effect of crumb rubber and short fibres on the physical and mechanical properties of the polymer matrices.

- Understood the screw pull-out of timber and timber-alternative composite sleepers with different influential parameters including material properties of sleepers and screw geometries.
- Understood the lateral restraint behaviour and failure modes of the rail screw to sleeper connection in the rail-seat region of timber and polymer composite sleepers.
- Developed simple analytical tools to accurately express the pull-out and lateral performance of railway sleepers to increase the confidence of adopting composite sleepers as an alternative to timber sleepers.

New opportunities and future research

This thesis presented the promising performance in the rail-seat region of polymeric sleepers and increase the confidence in adopting this type of new technology as an effective replacement for the traditional timber sleepers in the railway industry. Based on the significant outcomes of this study, new opportunities and potential research areas are available to further understand the critical parameters that influence the screw pull-out and lateral restraint performance of polymer composite sleepers as follows:

- The effects of crumb rubber and short fibres were investigated in this study to improve the material properties (e.g., porosity, workability, compressive strength, shear strength, flexural strength and strain) of the PFR core while their influence on other properties (e.g., impact resistance or tensile strength) can be further evaluated to completely understand the rail-seat region of sleepers and to help increase the confidence in using these additives in the polymer matrix.
- More material properties and screw geometries can be included in further investigations to explore their effects on the pull-out behaviour. Additional research may be required to reveal the influence of tensile strength of sleeper materials considering the uplifting force from threads. The investigated screw geometry was limited to the GageLok screw configuration which led to the nonlinear increment of major diameter (16 to 17.5 to 19 mm). More rail screw types are recommended to be included in further research.

- Although an analytical model has been developed to predict the pull-out force of timber and composite sleepers, finite element analysis (FEA) of screw pull-out behaviour is suggested for researchers and engineers who intend to study a specific type of sleepers beyond those investigated in this thesis. In addition, the effect of screw geometry can be validated in FEA by simply adjusting the screw model.
- The lateral restraint models developed in this thesis can be further implemented to evaluate other polymeric sleepers or other types of rail screws. The screw geometry or sleeper structure can be changed to simulate the lateral restraint behaviour affected by other critical parameters.
- The fastening assembly repeated load test is recommended for further research on the fatigue performance of timber and timber-replacement composite sleepers. The results of single screw pull-out and lateral behaviour from this research can be used to understand the fatigue behaviour of the entire fastening system and the rail-seat region of different sleeper technologies.
- A comparative analysis can is recommended on the cost-effectiveness of traditional timber sleepers and the three types of polymer sleepers studied in this thesis. The results of the cost analysis can be used by researchers and design engineers to figure out the optimal design of railway sleepers.

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APPENDIX A: CONFERENCE PAPERS

1. APFIS2019-155-Gold Coast

EFFECT OF CRUMB RUBBER ON THE FLEXURAL BEHAVIOUR OF EPOXY POLYMER MATRIX FOR COMPOSITE RAILWAY SLEEPERS

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ABSTRACT:

In recent years, composite railway sleepers made from polymer matrix and reinforced with fibre composites have attracted significant attention to the railway industry. The manufacture of these sleepers requires a flexible polymer matrix to hold together the fibre reinforced composites and as an external coating to the sleepers. It is also a requirement that the polymer matrix does not crack under service load to protect the fibre composite from aggressive environments. Thus, crumbed rubber was introduced into the epoxy polymer matrix with the aim of improving its flexural behaviour. The specimens were prepared composed of 40-60% epoxy resin, 30% lightweight fillers and 10 – 30% of crumb rubber by volume, and were tested under three-point static bending. The experimental results show that the addition of crumb rubber up to 30% increased the flexibility of the polymer matrix by 55% but decreased the flexural strength. Based on this study, it is recommended to use crumb rubber to enhance the flexural properties of epoxy-based polymer matrix for manufacturing composite railway sleepers.

KEYWORDS: PFR, epoxy, crumb rubber, composite railway sleeper, flexural modulus of elasticity, flexibility.

2. AMST2021-Gold Coast

EVALUATION OF SCREW PULL-OUT RESISTANCE OF TIMBER-ALTERNATIVE COMPOSITE SLEEPER TECHNOLOGIES

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ABSTRACT:

Composite railway sleeper technologies are becoming effective alternatives to traditional timber sleepers due to their good mechanical properties and relatively high durability. However, the limited understanding of their screw pull-out behaviour restricts their wide adoption in railway track maintenance. This study evaluated the screw pull-out strength of different sleeper technologies including timber, synthetic composites, recycled plastics and Particulate Filled Resin (PFR) cored sleepers. The results of the evaluation tests showed that all composite sleeper technologies considered in this study, except the recycled plastics, met the minimum requirement for composite sleepers (22kN) suggested by the AREMA. On the other hand, the shear strength of the sleeper material dominated the thread area of the screw spikes in resisting the pull-out force. Statistical analyses of the results through one-way analysis of variance showed that the shear strength of the sleepers had the highest correlation with the measured pull-out strength among other material properties. Based on this highest correlation, a simplified prediction model was developed to predict the pull-out resistance for different railway sleeper technologies.

KEYWORDS: screw pull-out behaviour, polymer composite sleeper, shear strength, prediction model, failure mode.

3. Materials Oceania 2021 – Online

Properties and microstructure of epoxy-based polymers with short glass fibres

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ABSTRACT:

Polymer matrix and fibre composites are now increasingly used as materials in the development of timber alternative railway sleeper technologies. A cost-effective polymer matrix is usually used as the internal core material for composite sleepers to hold together the fibre composites and to drill and hold screws. At the same time, short glass fibre is found as a promising reinforcement to improve the mechanical properties and the resistance to cracking of brittle cementitious and polymer materials. In this study, 0-15% weight of 3mm-long glass fibre chopped strands are introduced into the epoxy polymer matrix with the aim of improving its mechanical performance. The physical and mechanical properties including the microstructure of the new polymer mixes were investigated. The results showed that the addition of 0-10% short glass fibres significantly enhanced the mechanical performance of the polymer matrix with acceptable physical properties observed. However, the 15% addition saw deterioration in both the physical and mechanical properties due to the high porosity in the matrix. The experimental results also showed a high correlation between the number of glass fibres and the engineering properties of the polymer mixes. A simplified prediction equation based on linear function was proposed to predict critical properties as a function of the compressive strength.

KEYWORDS: PFR, epoxy, crumb rubber, composite railway sleeper, flexural modulus of elasticity, flexibility.