STATIC BEHAVIOUR OF HIGH-VOLUME LANDFILL WASTE FILLED COMPOSITE RAILWAY SLEEPERS

A Thesis submitted by

Md Abdullah Al Mamun
BSc (Civil Eng)

For the award of

Master of Research

2024

ABSTRACT

The Australian railway industry has the sixth largest permanent railway track in the world. Every year the railway industry requires millions of railway sleepers. The traditional railway sleepers predominantly are made of timber, steel and concrete. These current sleeper materials have performance and environmental limitations regarding recycling, durability, and carbon emissions throughout their life cycle. In order to find a sustainable sleeper material, research studies have been conducted on composites as it has many advantages including high strength-to-weight ratio, excellent resistance against corrosion, moisture, and insects, thermal and electrical resistance, and environmental friendliness. The recent development of recycled plastic sleeper offers good environmental sustainability, but their strength and stiffness are significantly lower than traditional timber sleepers. On the other hand, some companies have developed fibre based composite sleepers and they are performing very similar to timber sleepers, but 5 to 10 times more expensive than traditional timber sleepers. Therefore, an alternative material to design for the development of railway sleeper is essential at this stage. In this research, an attempt has been made to develop an alternative materials railway sleeper that can replace traditional timber with an added advantage of environmental sustainability. To achieve this, a concept of composite railway sleeper consisting of high-performance Glass Fibre Reinforced Polymer (GFRP) and low-cost waste materials such as waste-based composite woods and recycled plastic panels is investigated. This study examines the bond behaviour of GFRP profiles, composite wood and plastic panels with cement grouts that have varying grout materials and surface treatments. A variety of composite sleeper combinations are tested under the three-point bending to determine their load carrying capacity and failure behaviour. Based on the findings of this study, it appears that surface coating of GFRP profiles with epoxy resin mixed with glass sand can improve the bonding performance significantly. Cement grout can be a suitable material for bonding composite woods and plastic panels when used as an infill material for hollow GFRP tubes. While the exterior GFRP profile of the composite sleeper dominates its behaviour, the interior infill material helps maximise load carrying capacity and protect against premature failure of the profile. The strength and stiffness obtained from the proposed concept of railway sleeper concept indicate that it can meet basic structural performance requirements.

CERTIFICATION OF THESIS

I Md Abdullah Al Mamun declare that the Master of Research Thesis entitled *Static behaviour of high-volume landfill waste filled composite railway sleepers* is not more than 40,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

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

Date: 8 July 2024

Endorsed by:

Dr Wahid Ferdous
Principal Supervisor

Professor Allan Manalo
Associate Supervisor

Dr Sourish Banerjee
Associate Supervisor

Student and supervisors' signatures of endorsement are held at the University.

STATEMENT OF CONTRIBUTION

Paper 1:

Mamun Abdullah, Wahid Ferdous, Sourish Banerjee, and Allan Manalo (2024). Bond behaviour of smooth surface GFRP pultruded profiles with cement grout, ***Case Studies in Construction Materials***, Volume 20, e02891

DOI: https://doi.org/10.1016/j.cscm.2024.e02891

The overall contribution of **Mamun Abdullah** was 55% to the Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Validation, Writing- Original draft preparation, **Wahid Ferdous** contributed to 25% in Conceptualization, Methodology, Supervision, Writing - Review & Editing, **Sourish Banerjee** contributed to 10% in Supervision, Writing - Review & Editing, and **Allan Manalo** contributed to 10% in Supervision, Writing - Review & Editing.

Paper 2:

Mamun Abdullah, Wahid Ferdous, Sourish Banerjee, Ali Mohammed and Allan Manalo (2024). Waste-based panels with cement grout as an infill material for composite railway sleepers, ***Results in Engineering***, Volume 24, 102924

DOI: https://doi.org/10.1016/j.rineng.2024.102924

The overall contribution of **Mamun Abdullah** was 60% to the Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Validation, Writing- Original draft preparation, **Wahid Ferdous** contributed to 25% in Conceptualization, Methodology, Supervision, Writing - Review & Editing, **Sourish Banerjee** contributed to 5% in Supervision, Writing - Review & Editing, **Ali Mohammed** contributed to 5% in Supervision, Writing - Review & Editing, and **Allan Manalo** contributed to 5% in Supervision, Writing - Review & Editing.

ACKNOWLEDGEMENTS

This thesis could not have been accomplished without the support and assistance of numerous individuals, some of whom I would like to acknowledge specifically here.

- The author extends sincere gratitude to his supervisors **Dr Wahid Ferdous, Prof Allan Manalo** and **Dr Sourish Banerjee** for providing the opportunity to pursue the Master of research program at the University of Southern Queensland (UniSQ-Toowoomba). Their encouragement, insightful guidance, valuable suggestions, extensive feedback, and constructive review throughout the various phases of this research are deeply appreciated. The author also values the accessible and supportive approach of their supervisors.
- **Dr Ali Mohammed,** Technical Lead, Wagners CFT, Wellcamp, QLD, who also provided significant contribution in providing technical specifications and product data sheet and in procurement of GFRP profiles.
- **Dr Choman Salih**, the technical officer (former) in engineering laboratory-UniSQ Toowoomba, who have shown exceptional kindness and patience during the experimental program.
- The author expresses gratitude to his colleague **Mr Ashiqul Islam** for his valuable suggestions, willingness to share knowledge, and collaborative spirit, which significantly contributed to this work.
- I am deeply grateful to my beloved wife and mother of my two adorable daughters, **Ananna Ahlam Mustofa**, for her unwavering love, boundless patience, and constant support throughout both the joyful and challenging

moments. Her comforting presence and words of encouragement have been invaluable to me.

- Thank you to Enviro Sand Pty Ltd and Wagners Pty Ltd for supplying materials in kind.
- Finally, I would like to acknowledge the financial support I have received from the Research Training Program (RTP) Fees Offset scheme, which covers the cost of tuition for my Higher Degree by Research program. The financial support received from Advance Queensland Industry Research Fellowship (AQIRF 098-2021RD4) is also acknowledged.

DEDICATION

This thesis is dedicated to my family

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

Abbreviation	***Elaboration***
CAGR	Compound annual growth rate
FFU	Fibre-reinforced Foamed Urethane
GFRP	Glass fibre reinforced polymer
KLP	Kunststof Lankhorst Product
MTS	Materials test systems
NGL	Natural Ground level

CHAPTER 1: INTRODUCTION

1.1. Background and motivation

Railway network over the world is an essential mode of transport and vastly contributed towards the social and economic growth of a country. It plays very important role carrying bulk quantity of goods and passengers with providing comparatively cheaper option due to less energy consumption than road network. Over the world, there is about 1.4 million kms of railway track installed [1] for transporting goods and passengers. This length of track (kms) is gradually increasing every year. The sleeper is one of the essential components of railway track shown in Figure 1. It offers the stability of the ballasted track by carrying the load from the rails pad and transferring the load to ballast and maintaining uniform gauge of railway track preventing derailment. Railway industry in Australia has a one of the longest rail networks which requires millions of sleepers every year for expansion of rail route and upgradation of existing railway track. In fact, the requirement for sleepers to replace the old one and for the new railway track is very high on demand.

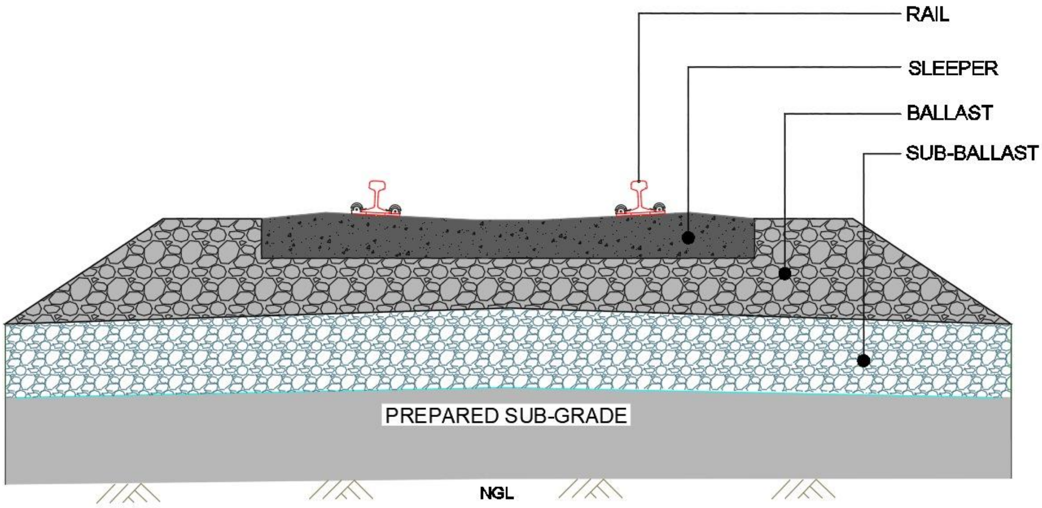


Figure 1: Basic components of typical railway track

Traditionally, railway sleepers worldwide are made from timber, steel, and predominantly concrete. These materials have design lifespans of 20, 30, and 50 years, respectively (Ferdous & Manalo, 2014; Manalo et al., 2010). Timber, the oldest material has been using, offered excellent dynamic, electrical, and sound-insulating properties. However, due to environmental concerns, timber scarcity, and issues such as rotting, splitting, and insect damage, steel and concrete sleeper thought to be a potential replacement of timber. Chemical treatments, such as creosote or copper-chrome-arsenic (CCA), improve their resistance to environmental factors but raise environmental concerns due to potential toxicity. Yet, steel sleepers face challenges such as corrosion, high electrical conductivity, and fatigue cracking.

In recent decades, the railway industry shifted its focus to concrete sleepers. Mono-block pre-stressed concrete sleepers becomes widely used globally for heavy haul and high-speed rail tracks. Concrete sleepers excel in load distribution, handling heavy axle loads effectively and maintaining track geometry under dynamic forces. While offering greater durability than timber and steel, concrete sleepers pose issues such as heavy weight, high initial costs, low impact resistance, susceptibility to chemical attack, and deterioration (Ferdous et al., 2015). Concrete sleepers require significant energy and raw materials during manufacturing, while steel sleepers are recyclable but involve mining and smelting activities. Additionally, the steel and cement industries emitted significant amounts of carbon dioxide during production. These challenges motivated researchers to seek new and effective alternative sleeper materials for the railway industry.

Consequently, over the growing concern of environment regarding carbon emission and to reduce high end maintenance cost of existing traditional sleeper, railway industry in Australia like the many other manufacturing industry is also focusing on using sustainable materials to construct the new track and facilitate the existing rail networks (UniSQ, 2023). Composite materials receive research attention globally to manufacture a sustainable railway sleeper. The global demand for composite sleepers has experienced a significant growth in recent times, driven by several key advantages associated with this material. These advantages include a high strength-to-weight ratio, which ensures strength without excessive weight, as well as high resistance to corrosion, moisture, and insect damage. Additionally, composite sleepers display favourable thermal and electrical conductivity properties.

One of the notable features of composite materials is their adaptability to specific requirements. This means that composite sleepers can be suited to meet the diverse needs of railway infrastructure projects. As a result, there is growing anticipation that composite railway sleepers will emerge as practical alternatives to traditional sleepers, suitable for deployment in both mainline and heavy haul rail networks. This shift towards composite sleepers represents a significant step forward in enhancing the efficiency, durability, and environmental sustainability of railway infrastructure worldwide.

To prevent the problems associated with traditional railway sleeper, researchers apply different composite materials and technologies to manufacture an alternative of traditional sleeper. For example, the recent development of recycled plastic sleeper by a Melbourne base company (AuManufacturing, 2021) offers good environmental sustainability and comparatively cheaper, but their performance regarding strength and stiffness are significantly lower than traditional timber sleepers. On the other hand, a company in Japan has developed fibre based composite sleepers and they perform very similar to timber sleepers and meet the performance criteria, but these sleepers are five times more expensive than traditional timber sleepers (Van Erp & Mckay, 2013). Therefore, an alternative composite material and design for the development of railway sleeper is essential to oppose the cost and performance challenges. Future developments in materials science and recycling technologies will likely enhance the performance and sustainability of railway sleepers, supporting the growing demand for efficient and reliable railway infrastructure.

1.2. Objectives

The aim of this study is to develop a sustainable railway sleeper using waste-based materials with consideration of cost effectiveness, and performance. The objective of this research is to explore a sustainable sleeper using high performance fibre-based GFRP tube bonded with high-volume low-cost waste-based materials that is expected to meet the performance and cost criteria. This concept was experimentally investigated with two different studies. The main objectives of this study are:

a) Understanding how well GFRP profiles bond to cement grout.
b) Understanding the static behaviour of railway sleepers made from GFRP profiles filled with high volume wastes.

1.3. Scope and limitations

The main materials employed to develop a railway sleeper in this study are Glass Fibre Reinforced Polymer (GFRP) pultruded profile, waste-based composite panels, and different cementitious materials. This study focuses on investigation of the composite materials to develop a sustainable sleeper material combination with the below scope:

a) A background study of traditional railway sleeper.
b) Detailed discussion of specific problems associated with the traditional railway sleeper material.
c) Discussion on composite sleeper development as an alternative of traditional sleeper and research scope.
d) A detailed plan statement and design procedure to understand bond behaviour of smooth surface GFRP profiles.
e) Laboratory testing using MTS equipment capable of handling 100kN of compression load and evaluation of the experimental results with graphical presentation of the data as received from GFRP profile bond testing.
f) Design and development of procedures and use of Taguchi design of experiments method to investigate the bond behaviour of waste-based composite panels, such as composite wood and plastic panels.
g) Laboratory testing with MTS equipment, results comparison depicting bond strength impact factors, and discussion of bond behaviour of waste-based composite panels.
h) Plan, design, procure materials, and prepare four composite sleeper specimen samples using GFRP Profiles, composite panels, and cement grout.
i) Conduct the three-point bending tests to understand the flexural behaviour with different sleeper specimens.
j) Results discussion and comparison of different composite sleepers.
k) Conclusion highlighting important findings and future recommendations and acknowledgement.

Although a comprehensive study of materials employed in this research were investigated, however, the following studies were excluded from the scope of research due to time limitations.

a) Dynamic behaviour of composite sleepers.
b) Study of screw pull-out behaviour as required for functional railway sleeper.
c) Electrical insulation and thermal behaviour of composite sleepers.
d) Environmental impacts and the durability.
e) Finite element modelling.

1.4. Thesis organisation

The dissertation consists of an introduction highlighting the research theme, an extensive literature review, two major studies, and a conclusion summarising the findings and contributions. Below are two high quality journal articles that were produced as a result of this research:

- **Article I**

  Mamun Abdullah, Wahid Ferdous, Sourish Banerjee, Allan Manalo (2024). "Bond behaviour of smooth surface GFRP pultruded profiles with cement grout", ***Case Studies in Construction Materials***, Volume 20, July 2024, e02891 (Q1 ranked journal).

  DOI: https://doi.org/10.1016/j.cscm.2024.e02891

- **Article II**

  Mamun Abdullah, Wahid Ferdous, Sourish Banerjee, Ali Mohammed, Allan Manalo. "Waste-based panels with cement grout as an infill material for composite railway sleepers", ***Results in Engineering***, Volume 24, December 2024, 102924 (Q1 ranked journal).

  DOI: https://doi.org/10.1016/j.rineng.2024.102924

The major findings of this study have been presented at reputed conference, as detailed in Appendix A.

The ***first objective*** of this study is to understand the bond behaviour of GFRP profiles and cementitious grouts, which is addressed in ***Article-I***. GFRP pultruded profiles have smooth surfaces when bonded to concrete, which can be a challenge. Article-I examined four different approaches to improving the bond performance between GFRP pultruded profiles and concrete surfaces to address this challenge. Among the approaches used are the addition of glass sand to cement grout, varying the size of the sand particles, preparing the bond surface of GFRP profiles for use with cement, and using various cement characteristics. In terms of improving the bond strength between the GFRP profiles and the concrete surface, the results of the experiment indicate that the surface preparation of the GFRP profiles is the most effective method of achieving this. While the bond behaviour of GFRP with cementitious materials was studied, the bonding between waste panels and cementitious grout as well as the overall structural behaviour of railway sleepers were uncertain. These issues were discussed in the second objective.

The ***second objective*** of this study is to investigate the static behaviour of railway sleepers made from GFRP profiles filled with waste materials of high volume which is addressed in ***Article-II***. A concept for a railway sleeper based on high-performance fibre composites and low-cost waste-based materials is presented. In this concept, thin hollow composite tubes are filled with high volume waste-based panels and bonded together with cement grout. A study was conducted to examine the impact of cement grout, grout thickness, panel types, and panel surface preparation on the bond behaviour between panels and cement grout. Several factors are investigated in order to understand the behaviour of railway sleepers, including the effects of filling hollow tubes, the orientation of the infill panels, as well as the type of material used for those panels. Based on the results, the proposed concept has a high potential for developing high performance and eco-friendly composite railway sleepers at an affordable cost.

1.5. Summary

Research into composite materials as alternatives to traditional railway sleeper materials has become a promising area of study. Several attempts have been made to develop a sustainable railway sleeper material. However, none of these studies have identified an alternative material that can replace timber while meeting performance, cost, and sustainability requirements. As a result, there is a need for research to develop sustainable materials for composite railway sleepers that can eliminate the problems associated with traditional railway sleepers. This study focuses primarily on this issue.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Railway sleepers are commonly manufactured using timber, steel, and concrete as the primary materials. Traditionally, timber has been used as a railway sleeper due to its excellent dynamic, electrical, and sound insulating properties. Due to several factors, including environmental concerns, limited supplies of timber, rotting problems, end splitting, and insect infestation (Figure 2), steel was considered to be a viable alternative to timber (Manalo et al., 2010). However, sleepers made of steel are highly susceptible to corrosion, electrical conductivity, and fatigue cracking. In recent decades, the railway industry has shifted its focus from timber and steel sleepers to concrete sleepers. Consequently, mono-block pre-stressed concrete sleepers have been widely used in heavy haul and high-speed rail systems worldwide. Despite greater durability of pre-stress concrete sleeper than timber and steel, their heavy weight, high initial cost, low impact resistance and susceptibility to chemical attack as well as deterioration of concrete remain major concerns (Ferdous & Manalo, 2014). In addition, the steel and cement industries emit a large amount of carbon-dioxide into the atmosphere during the production process. The problems raised by all the above have motivated researchers to explore and develop new alternatives to sleeper materials for the railway industry.

(a) (b) (c)

Figure 2: Premature failure of traditional sleepers (Ferdous & Manalo, 2014; Manalo et al., 2010): (a) timber (b) steel and (c) concrete

A new sleeper technology should be developed in a way that requires less maintenance, performs similarly to timber, reduces carbon emissions, and is affordable. A composite sleeper is becoming an increasingly popular alternative to traditional concrete, steel, and timber sleepers due to its many advantages, including its high strength-to-weight ratio, excellent resistance to corrosion, moisture, and insects, and low thermal and electrical conductivity (Ferdous et al., 2015). Globally, researchers are working on the development of composite sleepers that will minimise the challenges associated with traditional sleepers.

2.2. Existing Composite Sleepers

Global composites market value is expected to reach AUD 250 billion by 2030, growing at a compound annual growth rate (CAGR) of 7.2% (Advanced-Materials, 2024). Different countries have experimented with different composite technologies and developed composite railway sleepers. Two primary materials are used in the manufacture of these sleepers: recycled plastic and fibre composites as shown in Figure 3 (Ferdous et al., 2015).

A number of companies have developed recycled plastic sleepers that are available on the market. Australian company Integrated Recycling has developed recycled plastic composite railway sleepers from mixed waste plastic (AuManufacturing, 2021). An American company named TieTek developed a composite railway sleeper containing 85% recycled materials such as waste fibreglass, mineral fillers, recycled plastic bottles, bags, and scrapped vehicle tyres (TieTek). Additionally, a Dutch company KLP (Siahkouhi et al., 2021), British company Sicut (Sicut, 2023) and I-Plas based in Halifax (Adam, 2009), and a US company Axion manufacture composite sleepers made from 100% recycled plastic, including cups, bags, milk jugs, bottles, and many other household and industrial wastes (Nunez, 2013). Despite the fact that these sleepers are made from low-cost waste base recycled materials, they have experienced serious performance issues (such as low screw-holding capacity, low bending stiffness, crack formation due to low bending strength, high thermal expansion, low-dimensional stability at elevated in-service temperatures, plastic deformation causing loosening of fasteners, low fire resistance and inferior track-bed stability due to their lightweight nature (Ferdous et al., 2021)) and have not met their design life expectations.

As an alternative, Sekisui Chemical Co Ltd developed a fibre composite sleeper from synthetic wood called FFU (Fibre-reinforced Foamed Urethane), which consists of rigid urethane resin foam reinforced with long glass fibres (Koller, 2015; Sekisui-Chemical, 2010). With its light weight, good resistance to water absorption, heat, corrosion, and good weatherability, this sleeper offers the advantages of both wood and plastic. In terms of dynamic and acoustic performance, this sleeper is very similar to a timber sleeper. However, the cost of producing this fibre-based sleeper is too high (5-10 times of timber), and it is currently used in limited quantities in turnouts and steel-girder bridges and tunnels (Van Erp & Mckay, 2013). In Table 1, the performance of recycled plastic and fibre composite sleepers is compared to that of timber sleepers.

(a) Fibre composite sleepers

(b) Recycled plastic sleepers

Figure 3: Different type of composite sleepers (Ferdous et al., 2015; Koller, 2015)

Table 1: Performance comparison of composite and timber sleepers (Ferdous et al., 2015; Kaewunruen, 2013; McConnell, 2008; Pattamaprom et al., 2005)

Criteria	Properties	Softwood timber sleeper	Recycled plastic sleeper	Fibre composite sleeper
Performance	Density, (kg/m^3)	855	850-1153	670-820
	Modulus of elasticity, (GPa)	7.4	1.5-1.8	8.1
	Modulus of rupture, (MPa)	49.3	17.2-20.6	142
	Shear strength, (MPa)	4	4	10
	Rail seat compression, (MPa)	3	15.2-20.6	28
	Screw withdrawal, (kN)	13.3	31.6-35.6	65
Cost	Per sleeper (AUD)	$80-100	$120-150	$400-800

Despite having a similar density and shear strength to timber sleepers, recycled plastic sleepers perform poorly on key performance indicators, for example, modulus of elasticity and modulus of rupture. On the other hand, fibre composite sleeper shows better performance compared to timber sleeper. For instances, the fibre composite sleeper has higher value of modulus of elasticity, modulus of rupture, shear strength and rail seat compression. However, the production cost of fibre composite sleeper 5 to 10 times greater than traditional timber sleeper. In order to make composite sleepers widely available, this represents a significant challenge.

2.3. Research gap

There have been a number of developments in composite sleeper technology in different parts of the world, but their commercial application in the railway industry is limited. Low strength and stiffness of recycled plastic sleepers pose one of the greatest obstacles to their widespread application in railway track construction. In contrast, fibre-based sleepers have superior structural performance; however, their cost is five to ten times higher than timber sleepers. Consequently, none of the composite sleepers currently available can meet the performance and cost requirements to replace traditional timber sleepers. Therefore, there is an opportunity to address this challenge.

2.4. Hypothesis and novelty

In order to overcome the challenges with performance and cost associated with composite sleepers, a new concept of composite sleeper must be developed. As a matter of fact, it is imperative that fibres meet performance criteria while waste products are suitable for minimising costs. It is therefore hypothesised that if high volume waste can be incorporated into low volume fibre composites, the current challenges can be overcome. The novel aspect of this study is the concept of creating composite sleepers from thin composite shells filled with high-volume waste-based materials to meet cost, performance, and environmental criteria.

2.5. Summary

The literature review indicates that composite railway sleepers are in demand on the market. The existing composite sleeper technology, however, is not suitable to replace timber sleepers, either due to its high cost or its poor performance. The potential growth of the composite sleeper market could be unlocked by research and development that reduces costs without compromising performance.

CHAPTER 3: PAPER 1 – BOND BEHAVIOUR OF SMOOTH SURFACE GFRP PULTRUDED PROFILES WITH CEMENT GROUT

3.1. Preamble

The use of pultruded GFRP profiles in concrete structures presents a number of challenges. A smooth profile surface makes the profiles difficult to bond to concrete. In particular, this is important when railway sleepers are constructed from pultruded FRP profiles filled with waste materials and bonded with cement grout that may lead to failures in the bond under bending loading conditions. In fact, the prediction of bond behaviour between composite materials is a complex engineering problem. There are a number of factors that can influence the bonding performance, including the surface treatment and matrix behaviour. A comprehensive model capable of capturing these multifaceted interactions remains a challenging task due to the need for extensive experimental data and sophisticated computations. In this study, four potential methods were identified for improving the bond strength between GFRP profiles and low-cost cement grout. A suitable theoretical model was developed to predict bond strength within the scope of this study.

3.2. Published paper

Case Studies in Construction Materials 20 (2024) e02891

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Bond behaviour of smooth surface GFRP pultruded profiles with cement grout

Mamun Abdullah, Wahid Ferdous *, Sourish Banerjee, Allan Manalo

University of Southern Queensland, Centre for Future Materials (CFM), School of Engineering, QLD 4350, Australia

ARTICLE INFO

Keywords:
Bond behaviour
GFRP
Cement grout
Glass sand
Analytical model

ABSTRACT

The advantages of glass fibre reinforced polymer (GFRP) pultruded composite profiles, such as their high strength-to-weight ratio, corrosion resistance, and low maintenance costs, have attracted the attention of researchers and end users in structural applications. In spite of this, one of the challenges associated with using GFRP pultruded profiles is their smooth surfaces when bonded with concrete. To address this challenge, this study investigated four different approaches that can be used to improve the bond performance between GFRP pultruded profiles and concrete surfaces. These approaches are the incorporation of glass sand into cement grout, the variation in the size of the sand particles in the grout, the surface preparation of GFRP profiles, and the use of various cement characteristics. The experimental results show that the surface preparation of the GFRP profiles is the most effective method of improving the bond strength between the GFRP profiles and the concrete surface. Additionally, a theoretical model is developed to predict the bond behaviour, and it is observed that the linear elastic theory with the inclusion of the bond surface roughness coefficient is capable of predicting bond behaviour. The overall outcome of the study will assist design engineers and end users in the application of smooth surface GFRP profiles in concrete structures.

1. Introduction

In recent years, pultruded GFRP profiles have grown in popularity due to the increasing demand for lightweight, durable, corrosion-resistant materials across a variety of industries as well as advancements in manufacturing techniques and material formulations [1–3]. GFRP pultruded composite profiles are widely applied in civil engineering for infrastructure enhancement, performing an important role in retrofitting and strengthening existing structures such as bridges, buildings, and historical structures [4–10]. In order to meet the evolving demands for sustainable and resilient urban development, they can be designed in a variety of ways with a range of flexibility.

Pultruded GFRP profiles have been considered as an application for the development of composite railway sleepers. A study was conducted by Ferdous et al. [11] involving pultruded hollow GFRP profiles filled with rubberised cement concrete, and the beams were embedded in softer polymer concrete in order to manufacture composite railway sleepers. It was found that the railway sleeper concept was able to create a good bond between polymer concrete and GFRP profiles in this study. However, resin-based polymer concrete is a

* Correspondence to: University of Southern Queensland, Centre for Future Materials (CFM), School of Engineering, Toowoomba, QLD 4350, Australia.

E-mail addresses: Mamun.AlMamun@unisq.edu.au (M. Abdullah), Wahid.Ferdous@unisq.edu.au (W. Ferdous), Sourish.Banerjee@unisq.edu.au (S. Banerjee), Allan.Manalo@unisq.edu.au (A. Manalo).

https://doi.org/10.1016/j.cscm.2024.e02891
Received 1 October 2023; Received in revised form 8 December 2023; Accepted 15 January 2024
Available online 17 January 2024
2214-5095/

Nomenclature

t_o	thickness of the outer panel.
t_i	thickness of the inner panel.
t_m	thickness of the cement grout (i.e., matrix).
H	depth of the outer panel.
h	depth of the inner panel.
A_o	cross-sectional area of the outer GFRP profile.
A_i	cross-sectional area of the inner GFRP profile.
L_1	top unbonded length of inner panel.
L_2	length of overlap segment.
ΔL_1	reduction of length L_1 due to compression load.
ΔL_2	reduction of length L_2 due to compression load.
Δs_m	shear deformation of the cement grout.
Δ	total displacement of the specimen.
P	applied load.
E_o	compression modulus of elasticity of outer GFRP profile.
E_i	compression modulus of elasticity of inner GFRP profile.
G_m	shear modulus of elasticity of cement grout.

very expensive material. Therefore, a low-cost binder is needed in order to make railway sleepers cost competitive. A cement grout is one such binder. Fig. 1 illustrates how cement grout is conceptualised to create a bond between the waste-based filler and the pultruded GFRP profiles of the composite railway sleeper.

In concrete structures, the use of pultruded GFRP profiles poses a number of challenges. Due to the smoothness of the profile surfaces, the profiles do not bond well to the concrete [12]. Several studies [13–16] have investigated the mechanical properties of beams and columns using pultruded FRP profiles as external reinforcement elements to improve compressive, flexural, and shear capacities. According to these studies, the interfacial bond between the FRP and concrete plays a critical role in the reinforcement effectiveness of FRP-concrete beams, as the stress transfers from the concrete to the FRP component at this interface and vice versa. In order to overcome this challenge, the surface roughness of the profile needs to be improved. Lu et al. [17] studied the bond performance of sand coated GFRP bars in high-performance concrete. In this study, it was concluded that the coating of sand on reinforcing bars could increase the bond strength between concrete and reinforcing bars. Yuan et al. [18] studied the GFRP pultruded I-section coated with sand to investigate the influence of sand coating on bond behaviour when embedded in concrete. The findings of this study indicate that sand coatings improve the bond strength significantly. In another study, Yuan et al. [19] examined the bond strength between GFRP pultruded profiles and concrete using self-compacting concrete and normal concrete. In this study, it was found that the type of concrete material can have an impact on bond performance.

Predicting the bond behaviour of composite materials is an engineering challenge. There are a number of factors that influence bonding performance, such as surface treatment and matrix behaviour. Developing comprehensive models that can capture these multifaceted interactions remains a challenging task due to the need for extensive experimental data and sophisticated computational techniques. While researchers have attempted to predict the bond behaviour using complex computer simulations [20] or artificial neural networks [21], a simple theoretical model has always attracted the attention of researchers.

While the studies cited above highlighted the challenges associated with bonding FRP to concrete, they did not describe how to overcome these challenges. Based on the findings in the literature, this study identified four potential methods for improving bond strength between GFRP profiles and low-cost cement grout. These methods consist of a) adding angular sand in different proportions to

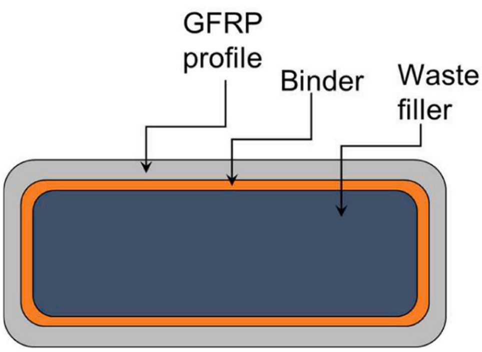


Fig. 1. Concept of cement grout as a binder between GFRP profile and waste filler for railway sleeper.

cement grout, b) adding different sizes of angular sand to cement grout, c) increasing the roughness of the bond surface of GFRP profiles, and d) using different types of cements in grout preparation. To test this hypothesis, a comprehensive experimental study was conducted. In order to predict the bond strength within the scope of this study, a suitable theoretical model was developed. In general, the outcome of this study will be beneficial to civil engineers when designing reinforced concrete structures using pultruded GFRP profiles.

2. Experimental program

2.1. Materials

2.1.1. Glass sand

Recycled glass waste is used to make glass sand made from 100 % recycled glass. The waste glass is screened, crushed into smaller pieces, and washed methodically before being graded into a product similar to natural sand. Three sizes of glass sand (coarse, medium, and fine) were used in this study. The reason for using three sizes of sand is the variation in surface area which determines the bonding characteristics. Unlike sea sand, these glass sands have an angular shape, which ensures greater bonding due to their rough surface. Enviro Sand, a supplier based in Australia, has provided this glass sand. Table 1 provides the particle size and density of three different types of glass sand.

2.1.2. Cement

This study used three types of cement (shrinkage compensating cement, expanding cement, general purpose cement). Three types of cement are used due to their unique bonding characteristics. As the name suggests, shrinkage compensating cement is a mixture of Portland cement, carefully selected and graded aggregates, and admixtures that can be used to compensate for shrinkage in cementitious grouts. A similar appearance to concrete is achieved with this product, which contains no chlorides or corrosion-causing agents. In contrast, expanding cement balances drying shrinkage, causing it to tightly grip embedded items and surrounding materials. This type of cement, which is more expensive than traditional cements, was chosen because of its expansion characteristics. General purpose cement, however, is a highly reliable, economical, and high-quality building material. Due to its versatility and consistency, GP cement is ideal for virtually all construction applications. The densities of these cements are listed in Table 1.

2.1.3. GFRP hollow tubes

The GFRP square hollow sections that Wagners Pty Ltd. supplied were made using the pultrusion process. This structural profile is made from vinyl ester resin and glass fibre reinforcements. Two different sizes of pultruded profiles were used in this study. Nominal dimensions of the section were 125 mm (depth) × 125 mm (width) × 6.40 mm (thick) and 100 mm (depth) × 100 mm (width) × 5.20 mm (thick), with a gross sectional area of 2970 mm^2 and 1905 mm^2 and mass of 6.07 kg/m and 3.85 kg/m, respectively. The properties were determined according to the technical data sheet provided by the manufacturer (Wagners Pty Ltd [22]). In addition to being lightweight, highly durable, and virtually maintenance-free, fibreglass tubes offer a variety of advantages. This type of profile is currently used in a number of structural applications, including piles, crossarms for power poles, decking, handrails, boardwalks, and many other applications.

2.2. Methods

2.2.1. Design of experiments

This study aims at understanding the impact of different influential parameters on the bond behaviour of GFRP tubes in order to determine the effectiveness of various bonding methods. The bond performance may be affected by several factors, including grout properties, grout materials, and the surface characteristics of the GFRP tube. This study examines the volume (0–20 % by volume) and size of sands (fine to course) in grout, GFRP surface treatment (no treatment, pre-coating and sanding) and different cementitious materials (shrinkage compensating, expanding cement and GP cement) to understand the effect of such critical parameters. The range of these parameters were selected to create surface roughness without significantly affecting the bonding properties of the grout. Experiments were designed to minimise specimen numbers while still investigating the effect of critical parameters. A total of 9 cases were studied, each with three samples. A detailed description of these 9 cases can be found in Table 2. Cases number 1 to 3 represent the effect of the different percentages of glass volume in the grout mix, whereas case numbers 3 to 5 represent the effect of glass sizes,

Table 1
Properties of glass sand and cement (Provided by the supplier of the material).

Materials	Particle size	Density (g/cm^3)
Coarse glass sand	1.7–3.35 mm	2.18
Medium glass sand	1.0–1.7 mm	2.10
Fine glass sand	0.5–1.0 mm	2.00
Shrinkage compensating cement	3–30 μm	1.87
Expanding cement	3–30 μm	1.48
General purpose cement	3–30 μm	1.54

case numbers 5 to 7 demonstrate the effect of surface treatment on GFRP tubes and cases 5, 8 and 9 demonstrate the effect of binder type. To investigate the effect of each parameter, this study ensures that the other design parameters are to remain the same within each study group.

2.2.2. Sample preparation and testing

The specimen was prepared by inserting a smaller tube (100 mm × 100 mm) into a larger tube (125 mm × 125 mm) and filling the small gap between the tubes with cementitious grout. To facilitate casting and testing, the external tube (125 mm × 125 mm) was cut by 100 mm and the internal tube (100 mm × 100 mm) by 125 mm. The bottoms of the tubes were level and sealed with plastic wrap to prevent the grout from flowing off. Some specimens were then precoated (Case 6) and sanded (Case 7) on their external and internal surfaces. Polyester resin and glass sands were used to precoat the bonded surfaces of both profiles, i.e., the internal surfaces of the larger profile and the external surfaces of the smaller profile. Pre-coated GFRP profiles were kept at room temperature for 24 h to dry. Similarly, sanding was performed on the bonding surfaces using sandpaper. All other samples were prepared without any surface treatment. Fig. 2(a) shows that 27 specimens (i.e., 9 cases with three samples each) were prepared for bond testing.

MTS equipment capable of handling 100 kN of compression load was used for the testing. In order to allow movement of the interior profile under applied load, a 25 mm long GFRP profile with the same cross-sectional dimensions as the external profile was placed at the bottom of the specimen (Fig. 2b). All the specimens failed in shear, and a representation of the failure mode is presented in Fig. 2(c). Testing of all the samples was conducted in the same way where the load on the panel was gradually increased until the bond failed.

3. Results and discussion

The results of specimens 1, 2 and 3 with a total of 9 cases are outlined in Table 3. The effect of glass sand volume, glass size, surface treatment and binder types were critically analysed and discussed in the following sections. The bond strength in Table 3 was calculated based on the failure load divided by the bond surface area. The standard deviation of the bond properties is affected by the complex shear behaviour of the non-homogenous binding materials.

3.1. Effect of glass sands

The effect of the percentage of glass sand volume is shown in Fig. 3. Load-displacement behaviour was slightly nonlinear at the beginning of the experiment, but linear behaviour was observed in the second half. Perhaps this is due to the initial settlement of the specimens. After the specimen was settled and compacted, a linear load-displacement relationship was observed (Fig. 3a). In general, the percentage of glass sand volume in binding material has only a small impact on the average bond strength (Fig. 3b). A difference of less than 5 kPa in average bond strength was observed when the percentage of glass sand in cement grout increased from 0 to 20 %. Based on the results, this small variation may be due to the fact that the cementitious grout was used only to cover the bond surface of the GFRP profiles, while the sand did not increase the roughness of the surface.

3.2. Effect of glass sand size

The bond strength of three different sizes of glass sand in binding materials can be seen in Fig. 4. Glass sand of fine or medium size offers similar bond strength, while glass sand of coarse size offers lower bond strength. In Fig. 4(a), there was a similar nature of load-displacement behaviour to that observed in Fig. 3(a), where a linear increase in load-displacement behaviour was seen after the initial settlement. The average bond strength for the fine and medium sands was 159 kPa and 171 kPa, respectively, while the coarse sand provided only 128 kPa. Perhaps the decrease in bond strength with coarse sand may be attributed to the fact that the bond surface area of the GFRP profile was partially covered by the larger particles of glass sand. This resulted in a reduction in the effective bonding surface area for cement grout, which is primarily responsible for creating the bond strength.

Table 2
Design of experiments.

Case number	Sample number	glass content	glass size	surface treatment	Binder types	Remarks
1	1–3	0 %	Medium	No treatment	Shrinkage compensating	Effect of glass sand content
2	4–6	10 % by vol	Medium	No treatment	Shrinkage compensating	Case 1–Case 3
3	7–9	20 % by vol	Medium	No treatment	Shrinkage compensating	
4	10–12	20 % by vol	Coarse	No treatment	Shrinkage compensating	Effect of glass size
5	13–15	20 % by vol	Fine	No treatment	Shrinkage compensating	Case 3–Case 5
6	16–18	20 % by vol	Fine	Pre-coating	Shrinkage compensating	Effect of surface treatment
7	19–21	20 % by vol	Fine	Sanding	Shrinkage compensating	Case 5–Case 7
8	22–24	20 % by vol	Fine	No treatment	Expanding Cement	Effect of binder types
9	25–27	20 % by vol	Fine	No treatment	GP cement	Case 5, 8 and 9

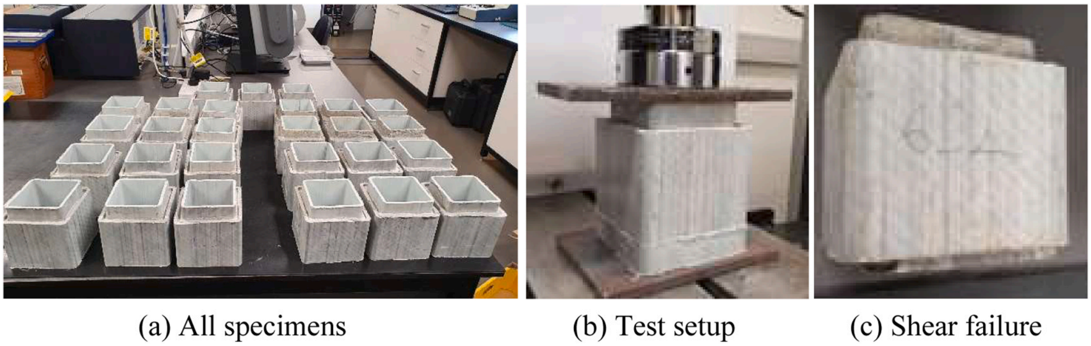


Fig. 2. Specimens, test set-up and failure mode.

Table 3
Test results of all specimens.

Bond strength (kPa)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Specimen 1	201	223	83	130	149	536	261	173	133
Specimen 2	200	145	202	131	150	716	201	101	190
Specimen 3	113	155	229	123	177	572	238	137	156
Average	171	174	171	128	159	608	233	137	160
Standard dev.	50.44	42.49	77.61	4.17	16.23	95.33	30.27	36.18	28.71

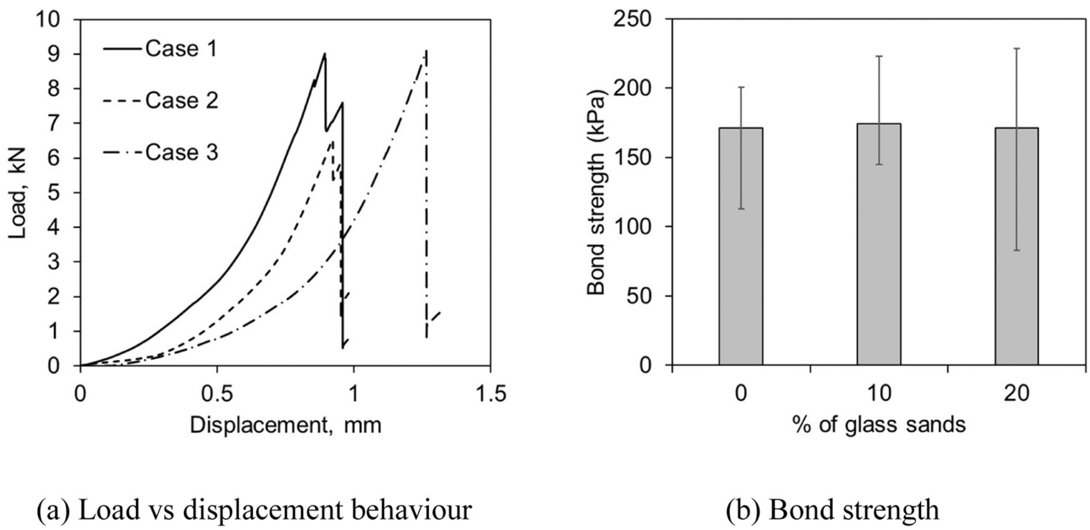


Fig. 3. Variation of bond strength with the increase of sand content.

3.3. Effect of surface treatment

In order to evaluate the effect of surface treatment, it is necessary to analyse the behaviour of specimens for Case 5, Case 6 and Case 7 since the surfaces of the GFRP profile in these three specimens were treated differently. In Case 5, the surface of the GFRP profile was left as it was (i.e., no treatment) while in Case 6, a resin and glass sand mixture was applied to the surface of the GFRP profiles (i.e., pre-coating). Before preparing the specimens for Case 7, a rough bond surface was created on the GFRP profile by sanding. There was a significant variation in bond strength as a result of the variation in surface treatment. There was a bond strength of 159 kPa, 608 kPa, and 233 kPa for specimens without treatment, pre-coating, and sanding, respectively (Fig. 5). The pre-coating of the bond surface increased the bond strength by 3.8 times compared with the bond surface that was not treated. On the other hand, the sanding of the bond surface increased the bond strength by 1.5 times compared to no surface treatment. It is therefore implied that precoating creates a highly rough bond surface, which enhances bond strength. The sanding method also produced a rough surface, but its roughness was not as high as that produced by the pre-coating method.

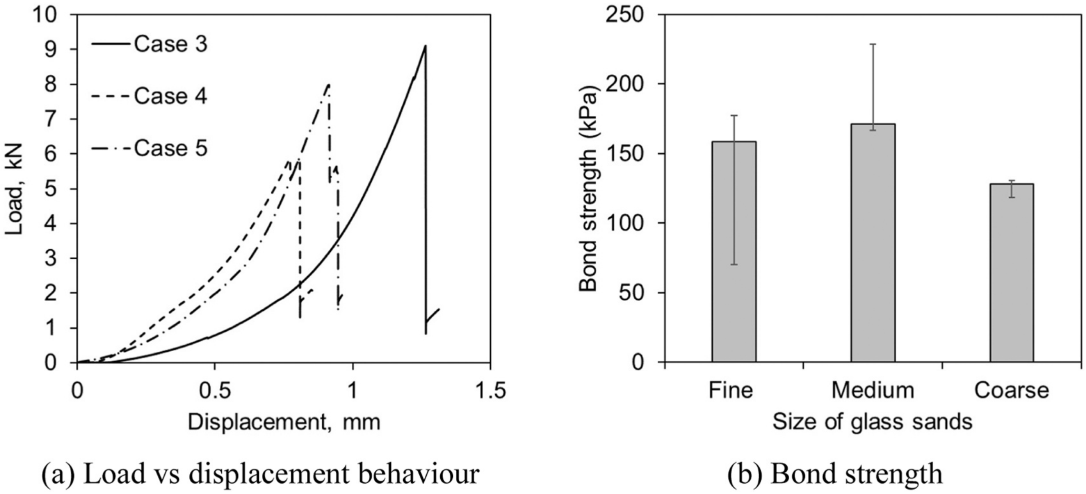


Fig. 4. Variation of bond strength with the increase of sand size.

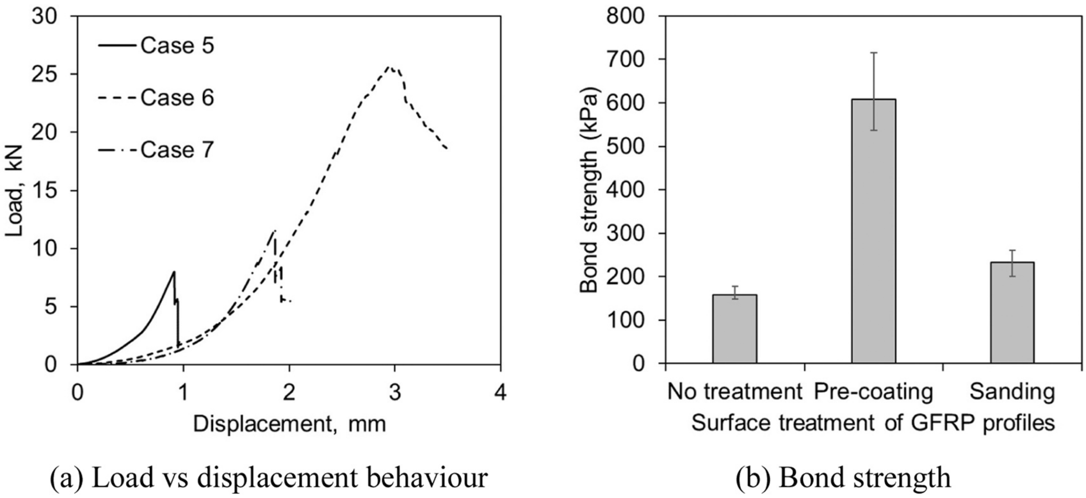


Fig. 5. Variation of bond strength with surface treatment of GFRP profiles.

3.4. Effect of binder types

The effect of the binder type can be studied by analysing the results of Case 5, Case 8 and Case 9 where shrinkage compensating, expanding cement and GP cement were used in the binder, respectively. The shrinkage compensating cement aims to offset the contraction of binder due to drying shrinkage by expanding the volume during the hardening process. Expanding cement generally expands the binder when hardened. GP cement, however, does not exhibit this type of binder movement. A purpose of introducing different types of cement is to understand how cement expansion characteristics influence bond strength. The results indicated that the average bond strengths of the binder with shrinkage compensating cement, expanding cement and GP cement were 159 kPa, 137 kPa, and 160 kPa, respectively (Fig. 6). Surprisingly, expanding cement binder provided the lowest bond strength compared to the other two cement binders. This is an interesting finding as it was expected that the expansion characteristics of expanding cement would improve the bond strength. It is possible that the lower bond strength of expanding cement binder is due to the movement of matrix as a result of the gradual expansion, which weakens the bond between the GFRP profile and the cement binder. Shrinkage compensating cement and GP cement binder did not move as much as expanding cement binder, which creates a stronger bond with the surface of GFRP profiles.

This study found that the volume of glass sand, the size of glass sand, the surface treatment of GFRP profiles, and the type of binder can affect the bond strength by 2 %, 34 %, 282 %, and 17 %, respectively. The results indicate that surface treatment is the most effective method for improving bond strength followed by variation of glass sand size, different types of binder, and adding glass sand to grout.

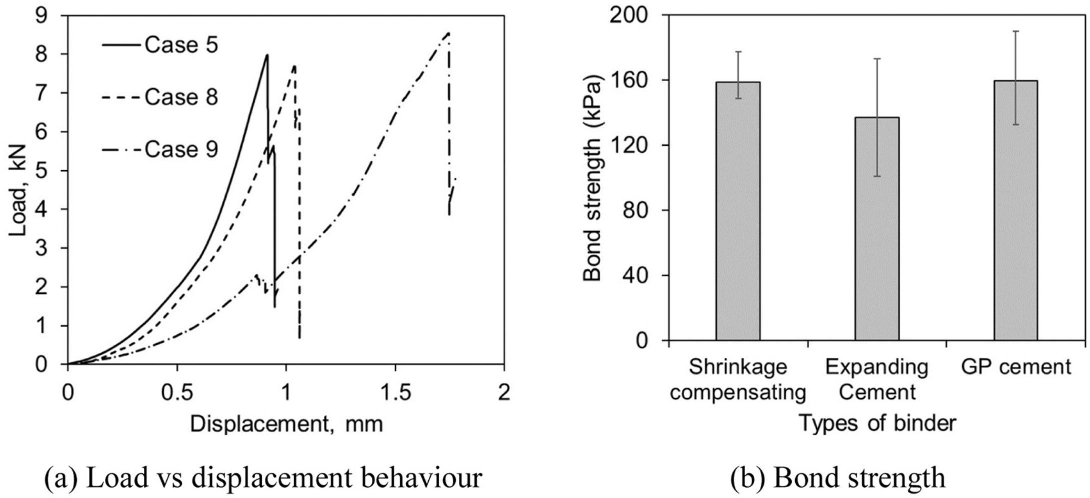


Fig. 6. Variation of bond strength with the types of binder.

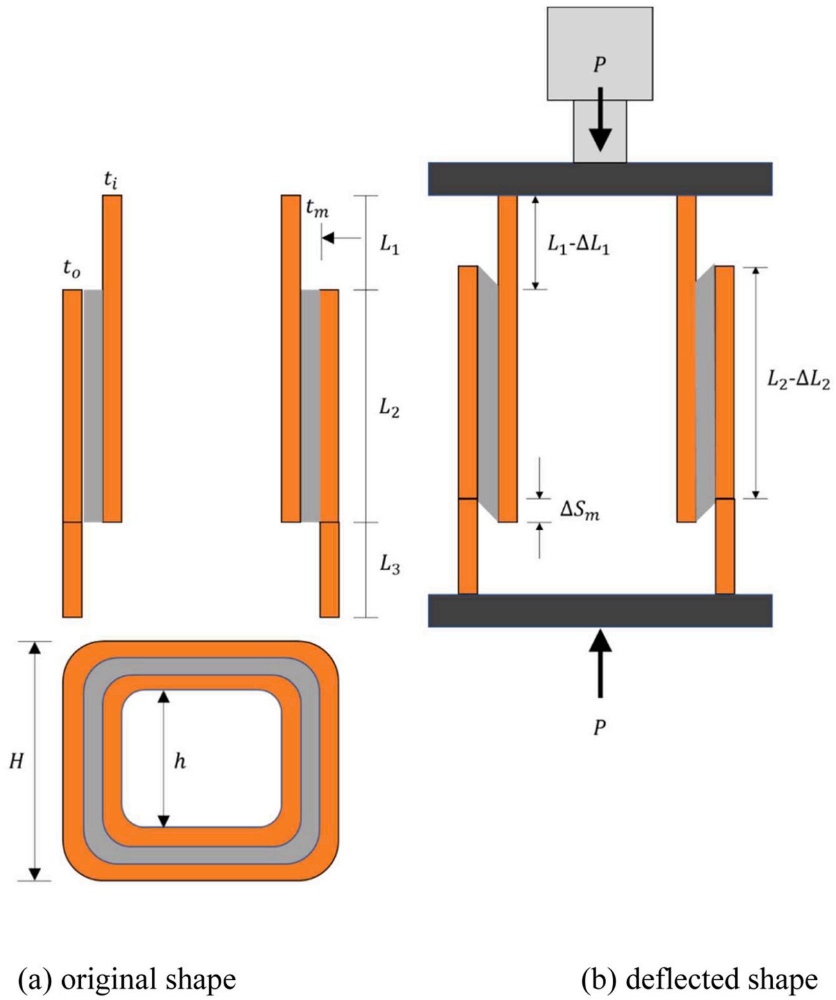


Fig. 7. Schematic diagram of the specimen for analytical solution.

4. Theoretical modelling

4.1. Model development

A theoretical model has been developed to predict bond strength. Model parameters include the dimensions and surface roughness of GFRP profiles, as well as the properties of GFRP profiles and cement binder. A schematic diagram of the section of specimen is shown in Fig. 7. In order to develop the model, linear elastic properties of materials were taken into consideration. This can be justified by the linear elastic load-displacement behaviour of the specimens after initial settlement under loads (Fig. 3 to Fig. 6).

From Fig. 1,

$$A_iE_i = 4t_i(h + t_i)E_i \tag{1}$$

$$A_oE_o = 4t_o(H - t_o)E_o \tag{2}$$

The properties of the GFRP material were obtained from the supplier's technical data sheet [22].

(a) Deflection in unbonded segment (length L_1 and L_3).

In unbonded segment, P load is acting on the cross-section A_i, and therefore,

$$\text{Compressive stress}, \sigma_1 = \frac{P}{A_i} \tag{3}$$

$$\text{Compressive strain}, \varepsilon_1 = \frac{\sigma_1}{E_i} = \frac{P}{A_iE_i} \tag{4}$$

The axial displacement of the inner-panel segment can be derived as

$$\Delta L_1 = \varepsilon_1 \times L_1 \tag{5}$$

Using Eqs. (1), (4) and (5).

$$\Delta L_1 = \frac{PL_1}{4t_i(h + t_i)E_i} \tag{6}$$

Similarly,

$$\Delta L_3 = \frac{PL_3}{4t_o(H - t_o)E_o} \tag{7}$$

(b) Deflection in overlap segment (length L_2).

The total deflection of the overlap segment is the sum of the axial deflection in outer-panel and the shear deflection in the cement grout.

In this segment, half of the reaction force P is transferred in the outer panel and the axial deformation is calculated as

$$\Delta L_2 = \frac{PL_2}{4t_o(H - t_o)E_of_r} \tag{8}$$

In Eq. (8), f_r represents roughness factor of the GFRP profile. Since the surface of the GFRP profiles was very smooth, it was assumed the roughness factor to be very similar to general steel pipes (i.e., $f_r = 0.015$ [23]). However, the roughness factors were increased to 0.020 and 0.018 when the GFRP profiles were pre-coated and sanded, respectively.

In the linear elastic range, the axial displacement of the cement grout due to the shear deformation would be the same whether it is calculated from an exact stress distribution or from the average shear stress of the matrix.

$$\text{Average shear stress}, \tau_{ave} = \frac{P}{(H - 2t_o - t_m)t_mf_r} \tag{9}$$

$$\text{Shear strain}, \gamma = \frac{\tau_{ave}}{G_m} \tag{10}$$

The axial displacement due to shear deformation of cement grout is

$$\Delta s_m = t_m\gamma \tag{11}$$

Using Eqs. (9), (10) and (11).

$$\Delta s_m = \frac{P}{(H - 2t_o - t_m)G_mf_r} \tag{12}$$

(c) Global axial displacement.

The global axial displacement is the sum of all displacement.

$$\Delta = \Delta L_1 + \Delta L_2 + \Delta L_3 + \Delta s_m$$

$$\Delta = \frac{PL_1}{4t_i(h+t_i)E_i} + \frac{PL_2}{4t_o(H-t_o)E_of_r} + \frac{PL_3}{4t_o(H-t_o)E_o} + \frac{P}{(H-2t_o-t_m)G_mf_r}$$

$$P = \frac{\Delta}{\left[\frac{L_1}{4t_i(h+t_i)E_i} + \frac{L_2}{4t_o(H-t_o)E_of_r} + \frac{L_3}{4t_o(H-t_o)E_o} + \frac{1}{(H-2t_o-t_m)G_mf_r}\right]} \tag{13}$$

Eq. (13) represents the theoretical load.

4.2. Model validation

The theoretical load can be calculated by using Eq. (13) when the deflection is known. The experimental deflection was taken into account in Eq. (13) in order to verify the model. A comparison was made between the load calculated from Eq. (13) and the experimental failure load shown in Table 4. It can be seen that the linear elastic models are reasonably able to predict the bond behaviour of the specimen.

Composites behave very differently from isotropic materials due to their unpredictable nature. As a result, the standard deviation of composite materials is expected to be higher than that of isotropic materials. It was found that the theoretical prediction was close to the average values of the experimental results. This theoretical model has the main contribution of allowing the bond behaviour of full composite panels to be predicted for a wide variety of composite panels bonded with a variety of cement grouts when their properties are known.

5. Conclusion

This study investigated the bond behaviour of cement matrix with GFRP profiles. Four different methods were studied to improve the bond behaviour. The effect of adding different percentages of glass sand in cement grout, the size of glass sand, surface treatment of GFRP profiles and the types of cement to prepare binder were investigated. A theoretical model was also developed to predict the bond behaviour. The findings of this study are provided below:

- The addition of glass sand up to 20 % does not appear to have a significant impact on the overall bonding behaviour (only 2 % variation). GFRP profiles are bonded primarily by cement paste and glass sand cannot increase surface roughness when added to the binder.
- The size of the glass sand can have a significant impact on the bond strength (up to 34 % variation). Based on the results of this study, an increase in the size of sand particles reduces the bond strength as a result of the reduction of the effective bond surface area due to the presence of sand particles. The larger the sand particles, the smaller the effective bond area.
- This study found that increasing surface roughness on the bonded area is the most effective method of improving bond strength (up to 282 % variation). A pre-coating of the bond surface with resin and glass sand mix creates a highly rough surface which increases bond strength by 3.8 times when compared to an untreated bond surface. In contrast, sanding the bond surface is not as effective as pre-coating, but it can increase bond strength by 1.5 times over untreated surfaces.
- Bond strength is affected by the characteristics of the cement binder (up to 17 % variation). The expansion and contraction characteristics of cement make it less effective for bonding. Internal movement of binder caused by the expansion and contraction of binder volume during the hardening process can weaken the bond strength.
- A linear elastic model can be used to predict the bond behaviour. The properties of the GFRP profile and cement binder are the key parameters that affect bond behaviour. It is, however, necessary to take into account the bond surface roughness coefficient when predicting the bond strength.

The results of this study have provided new insight into how to improve the bond behaviour between smooth surfaces of GFRP profiles and a low-cost binder. For an economic solution, it is important to determine the benefit-cost ratio of different methods. The findings of this study will be of value to design engineers and end users seeking to bond GFRP profiles to low-cost materials in end use

Table 4
Variation between experimental and theoretical failure load.

Case No.	Experimental *P* (kN)	Theoretical *P* (kN)
1	7.71 ± 2.3	5.59
2	7.84 ± 1.9	6.69
3	7.72 ± 3.5	9.36
4	5.77 ± 0.2	6.04
5	7.14 ± 0.7	6.12
6	27.36 ± 4.3	26.55
7	10.49 ± 1.4	14.69
8	6.17 ± 1.6	7.10
9	7.18 ± 1.3	11.38

applications.

CRediT authorship contribution statement

Mamun Abdullah: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Ferdous Wahid:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Banerjee Sourish:** Supervision, Writing – review & editing. **Manalo Allan:** Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge Enviro Sand Pty Ltd and Wagners Pty Ltd for their generous in-kind contributions to supply materials. The first and second authors would like to acknowledge the financial support they received from the Advance Queensland Industry Research Fellowship (AQIRF 098-2021RD4) program.

References

[1] T. Liu, X. Liu, P. Feng, A comprehensive review on mechanical properties of pultruded FRP composites subjected to long-term environmental effects, Compos. Part B: Eng. 191 (2020) 107958.
[2] A.K. Gand, T.-M. Chan, J.T. Mottram, Civil and structural engineering applications, recent trends, research and developments on pultruded fiber reinforced polymer closed sections: a review, Front. Struct. Civ. Eng. 7 (2013) 227–244.
[3] C.E. Bakis, et al., Fiber-reinforced polymer composites for construction—state-of-the-art review, J. Compos. Constr. 6 (2) (2002) 73–87.
[4] J.R. Correia, Y. Bai, T. Keller, A review of the fire behaviour of pultruded GFRP structural profiles for civil engineering applications, Compos. Struct. 127 (2015) 267–287.
[5] X. Zou, H. Lin, P. Feng, Y. Bao, J. Wang, A review on FRP-concrete hybrid sections for bridge applications, Compos. Struct. 262 (2021) 113336.
[6] Y.M. Amran, R. Alyousef, R.S. Rashid, H. Alabduljabbar, C.-C. Hung, Properties and applications of FRP in strengthening RC structures: a review, Structures 16 (2018) 208–238 (Elsevier).
[7] A. Sharda, et al., Axial compression behaviour of all-composite modular wall system, Compos. Struct. 268 (2021) 113986.
[8] W. Ferdous, A.D. Almutairi, Y. Huang, Y. Bai, Short-term flexural behaviour of concrete filled pultruded GFRP cellular and tubular sections with pin-eye connections for modular retaining wall construction, Compos. Struct. 206 (2018) 1–10.
[9] E. Guades, T. Aravinthan, M. Islam, A. Manalo, A review on the driving performance of FRP composite piles, Compos. Struct. 94 (6) (2012) 1932–1942.
[10] A.A. Mohammed, et al., Effectiveness of a novel composite jacket in repairing damaged reinforced concrete structures subject to flexural loads, Compos. Struct. 233 (2020) 111634.
[11] W. Ferdous, et al., Static behaviour of glass fibre reinforced novel composite sleepers for mainline railway track,", Eng. Struct. vol. 229 (2021) 111627.
[12] A.M. Ali, L. Dieng, R. Masmoudi, "Experimental, analytical and numerical assessment of the bond-slip behaviour in concrete-filled-FRP tubes,", Eng. Struct. vol. 225 (2020) 111254.
[13] Z. Guo, X. Xue, M. Ye, Y. Chen, Z. Li, Experimental research on pultruded concrete-filled GFRP tubular short columns externally strengthened with CFRP, Compos. Struct. 255 (2021) 112943.
[14] Y. Qasrawi, P.J. Heffernan, A. Fam, Performance of concrete-filled FRP tubes under field close-in blast loading, J. Compos. Constr. 19 (4) (2015) 04014067.
[15] T. Vincent, T. Ozbakkaloglu, Influence of fiber orientation and specimen end condition on axial compressive behavior of FRP-confined concrete, Constr. Build. Mater. 47 (2013) 814–826.
[16] T. Ozbakkaloglu, T. Xie, Geopolymer concrete-filled FRP tubes: behavior of circular and square columns under axial compression, Compos. Part B: Eng. 96 (2016) 215–230.
[17] J. Lu, H.M. Afefy, H. Azimi, K. Sennah, M. Sayed-Ahmed, Bond performance of sand-coated and ribbed-surface glass fiber reinforced polymer bars in high-performance concrete, Structures 34 (2021) 10–19 (Elsevier).
[18] J.S. Yuan, M.N. Hadi, Bond-slip behaviour between GFRP I-section and concrete, Compos. Part B: Eng. 130 (2017) 76–89.
[19] J.S. Yuan, M.N. Hadi, Friction coefficient between FRP pultruded profiles and concrete, Mater. Struct. 51 (5) (2018) 120.
[20] H. Yin, K. Shirai, W. Teo, Numerical model for predicting the structural response of composite UHPC–concrete members considering the bond strength at the interface, Compos. Struct. 215 (2019) 185–197.
[21] A. Cascardi, F. Micelli, ANN-based model for the prediction of the bond strength between FRP and concrete, Fibers 9 (7) (2021) 46.
[22] Wagners, "Composite Fibre Technologies - Product guide," Wagners CFT Manufacturing Pty Ltd, 2021, vol. 5.
[23] Engineering-tools. "Surface roughness of common materials (myengineeringtools.com)." (accessed 22/07/2023.

3.3. Links and implications

Based on the findings of Chapter 3 (Paper 1), smooth surface GFRP profiles can be bonded with cement grout. It is possible to improve the bond strength by coating the bond surface. The bond behaviour can be predicted using a linear elastic model. The results of these studies formed the basis for Chapter 4 (Paper 2), which examined the bond behaviour of waste panels and the structural behaviour of GFRP tubes filled with waste panels. The findings of this study will generally assist civil engineers in designing reinforced concrete structures using pultruded GFRP profiles.

CHAPTER 4: PAPER 2 – WASTE-BASED PANELS WITH CEMENT GROUT AS AN INFILL MATERIAL FOR COMPOSITE RAILWAY SLEEPERS

4.1. Preamble

Composite materials have been explored as substitutes for traditional timber in manufacturing sustainable railway sleepers. However, these composite sleepers tend to be either uneconomically expensive or fail to meet the required performance standards to replace timber sleepers. This chapter presents a concept for a new composite railway sleeper that uses a Glass Fibre Reinforced Polymer (GFRP) tube filled with waste-based panel materials and bonded with cement grout. GFRP tubes are expected to provide structural strength, infill waste panels will increase the sectional modulus, and cement grout will enable the beam to act as a composite. A proper understanding of how cement grout interacts with waste-based panels is essential to understanding the overall behaviour of railway sleepers. Consequently, this study investigates the bond behaviour between cement grout and panels, the orientation and type of infill panels, and the bending behaviour of railway sleepers. This study will provide guidelines for the design and manufacture of railway sleepers made from waste-based materials and composite fibres.

4.2. Submitted paper

Results in Engineering 24 (2024) 102924

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Waste-based panels with cement grout as an infill material for composite railway sleepers

Mamun Abdullah [a], Wahid Ferdous [a,*], Sourish Banerjee [a], Ali Mohammed [b], Allan Manalo [a]

[a] University of Southern Queensland, Centre for Future Materials (CFM), School of Engineering, QLD, 4350, Australia
[b] Technical Lead, Wagners CFT, Wellcamp, QLD, 4350, Australia

ARTICLE INFO

Keywords:
Composite railway sleepers
Bond behaviour
Sleeper bending strength
Wood composites
Recycled plastics

ABSTRACT

The development of high performance and eco-friendly composite railway sleepers at a reasonable price is a great challenge for composite railway sleeper manufacturers. The study proposed a railway sleeper concept based on high-performance fibre composites and low-cost waste-based materials to overcome this challenge. In this concept, thin hollow composite tubes are filled with high volume waste-based panels, which are bonded together with cement grout. This study examined the effect of cement grout, grout thickness, panel types, and surface preparation of the panels on the bond behaviour between the panels and cement grout. It also investigated the bending behaviour of manufactured railway sleepers by evaluating the effects of filling hollow tubes, the orientation of the infill panels, and the types of infill materials. Results indicate that the proposed concept has a high potential for development of high performance and eco-friendly composite railway sleepers at a competitive price due to the incorporation of high volume of waste materials. The results of the study will serve as a guide to the manufacture and design of composite railway sleepers.

1. Introduction

Railway sleepers are traditionally made of timber, steel and concrete. There are several challenges facing these sleeper materials. The decaying, splitting, and insect-attacking characteristics of timber, as well as its scarcity, posed new challenges. The corrosive nature, high electrical conductivity, and fatigue cracking of steel sleepers in the rail-seat region, as well as the difficulty of packing with ballast, make steel sleepers a less preferred material for use in sleepers. Contrary to timber and steel, prestressed concrete sleepers are heavy, have a high initial cost, have limited impact resistance, and are susceptible to chemical attack [1]. Heavy weights result in higher transportation costs, are difficult to handle, and require costly, specialised equipment to be installed. Concrete and steel sleepers require specific fasteners and cannot be substituted for timber sleepers in an existing track due to their incompatibility [2]. Traditional sleeper materials create several environmental problems from a sustainable perspective; for example, countless trees must be cut down to produce timber sleepers, while the cement and steel industries release a large amount of carbon dioxide during production. In response to the issues, researchers around the world have developed and investigated alternative sleeper technologies.

The strength, lightweight characteristics, superior workmanship, and design versatility of composite materials make them ideal for use as structural components in a wide range of engineering applications [3–5]. Researchers have examined composites as an alternative to traditional materials for developing sustainable railway sleepers. Typically, composite railway sleepers are made from either fibre composites or recycled plastics [6,7]. Recently, the authors examined several concepts for composite railway sleepers, including design concepts with internal and external reinforcements [7–9]. These sleepers, however, were made of resin-based polymer concrete, which is relatively more expensive than traditional railway sleeper materials. Fibre composite sleepers, particularly fibre-reinforced foamed urethane (FFU) [10], are exceedingly costly (five to ten times more expensive than timber sleepers [11]), have low shear resistance due to the absence of transverse reinforcements, and have caused concern about compliance with Occupational Health, Safety, and Environment (OHSE) guidelines due to the generation of polyurethane dust during drilling [12]. Recycled plastic sleepers [13,14] can be manufactured at a comparable price to timber sleepers, but their low screw-holding capacity, low stiffness, crack formation due to low bending strength, high thermal expansion, poor dimensional stability at elevated in-service temperatures, plastic

* Corresponding author.
E-mail addresses: Mamun.AlMamun@unisq.edu.au (M. Abdullah), Wahid.Ferdous@unisq.edu.au (W. Ferdous), Sourish.Banerjee@unisq.edu.au (S. Banerjee), ali.mohammed@wagner.com.au (A. Mohammed), Allan.Manalo@unisq.edu.au (A. Manalo).

https://doi.org/10.1016/j.rineng.2024.102924
Received 29 June 2024; Received in revised form 8 September 2024; Accepted 16 September 2024
Available online 17 September 2024

deformation that loosens fasteners, low fire resistance, and lack of track-bed stability due to their low weight have limited their use [6,15]. It is therefore necessary to develop a composite railway sleeper that is cost-effective, environmentally friendly, and can meet performance criteria. Integration of waste-based materials with fibre composites is one strategy to achieve this goal. An example of such a concept is shown in Fig. 1.

The proposed concept uses a Glass Fibre Reinforced Polymer (GFRP) tube filled with waste-based panel materials and bonded with cement grout. It is expected that the GFRP tube will provide structural strength to the beam, infill waste panels will increase the sectional modulus, and cement grout will enable the beam to act as a composite unit. To understand the overall behaviour of railway sleepers, it is necessary to understand the proper design of cement grout and how it interacts with waste-based panels. Therefore, this study investigates the bonding behaviour between cement grout and panels, the orientation and type of infill panels, and the bending behaviour of railway sleepers. This study is expected to provide guidelines for designing and manufacturing of railway sleepers made from waste-based materials and fibre composites.

2. Materials and methods

2.1. Materials

This study utilised waste-based composite wood and recycled plastic panels, cement grout mixed with waste glass sand, and GFRP hollow composite tubes. Waste-based panels were placed in GFRP hollow tubes and bonded with cement grout to manufacture composite beams.

2.1.1. Waste-based panels

Railway sleepers are manufactured using two distinct segments of composite material, consisting of wood and recycled plastic (Fig. 2). This engineered wood product is manufactured by Coen Composite Woods, which replaces traditional wood with an environmentally friendly alternative. It is composed of 60 % recycled wood flour, 30 % recycled High-density polyethylene (HDPE) plastic, and 10 % bonding agent [16]. Replas, on the other hand, supplies recycled plastic panels consisting of 100 % recycled HDPE and Polypropylene (PP), which offer a viable alternative to timber, which is susceptible to termites and moisture damage [17]. The densities of wood composite and recycled plastic panels are 1300 kg/m^3 and 900 kg/m^3, respectively.

2.1.2. Cement grout

General purpose cement (GP cement) and water were mixed with or without waste glass sand to prepare cement grout. Water-cement ratios of 0.35, 0.40 and 0.45 were used to maintain a good balance between bond strength and workability. Cement grout blended with glass sand provides sustainability and improved material properties, making it a viable option for environmentally conscious and high-performance building applications.

2.1.3. Fibre composite tubes

In order to understand composite beam behaviour, Wagners Pty Ltd [18] supplied pultruded GFRP hollow tubes. The dimensions of the rectangular hollow section (RHS) of GFRP were 1.60 m long, 250 mm wide, and 100 mm deep, with a wall thickness of 8.1 mm. Hollow rectangular profiles enhance structural efficiency while reducing material consumption, making them cost effective. Moreover, their non-conductive nature makes them ideal for applications requiring low electrical conductivity. The innovative GFRP sections redefine the possibilities in modern construction, providing solutions that contribute to the sustainability of infrastructure projects in addition to being durable and efficient. The properties of fibre composite tubes are presented in Table 1.

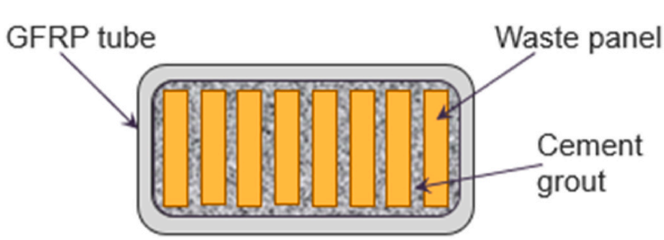


Fig. 1. Concept of composite railway sleepers.

2.2. Design of experiments using Taguchi method

The multiple levels and variables involved in the process can make it both time-consuming and costly. In order to reduce the number of necessary experiments, the Taguchi method [19] maintains an understanding of the influence each variable has on the outcome. In this method, the best results are obtained when there are a moderate number of variables (3–50), minimal interactions between them, and only a few variables have significant influence on the entire process. In the Taguchi experimentation, the following steps should be followed: deciding the design parameters and determining the number of levels for each level; choosing the optimal orthogonal array and placing it based on the parameters and levels; conducting experiments based on this arrangement; and analysing the results using Analysis of Variance (ANOVA) and signal-to-noise ratios (SNR). Table 2 shows four variables and three levels considered in the study. The most important parameters influencing the behaviour of bonds were identified systematically. To fully understand bond behaviour, the traditional approach requires 81 experiments (i.e., 3^4). By employing the Taguchi design of experiments, the number of experiments was reduced to nine without compromising understanding of each parameter.

2.2.1. Design parameters and levels selection

Different parameters influence bond strength, including grout properties, bond length, bond thickness, bond width, panel types, surface roughness, and curing temperature, method, and time. This study considers grout properties (water-to-cement ratio), bond thickness, panel type and surface coating, all of which have three levels, as shown in Table 2. Based on the results of a preliminary investigation [20], the levels for parameters A and B were determined, while for parameters C and D they were set based on the expected outcomes of the final application. A cement grout with a water-to-cement ratio of 0.35–0.45 is suitable for coating and binding panels. It has been reported by Ferdous et al. [20] that the effective bond thickness for FRP-to-polymer bonds is 5 mm. In a similar study, concrete and FRP were bonded with non-porous glue materials [21]. This type of bond produces a very thin bond (generally less than 1 mm), which is incompatible with cement grout as it contains a porous filler material. Further, glue laminated bonds are applied using a brush, whereas cement grout bonds require a wider gap between the adherents. Therefore, bond thicknesses of 3 mm–10 mm were considered reasonable. A consideration of sustainability and availability was made when choosing panel types. The findings of Abdullah et al. [22] indicated that the surface coatings have a significant impact on bond behaviour, and this has been taken into account when designing this study.

To calculate the number of experiments that will be required, orthogonal arrays are used (Table 3), which are the most compact matrix of combinations that involve simultaneous changes to all selected design parameters. An orthogonal array has a certain number of degrees of freedom (DOF) that represents the number of levels considered for each parameter. This quantity can be calculated using Eq. (1).

$$DOF = L - 1 \quad (1)$$

There must not be a lower degree of freedom (DOF) in the orthogonal array than in the total degree of freedom (DOF). The four design parameters, A, B, C, and D, each had three levels with two degrees of

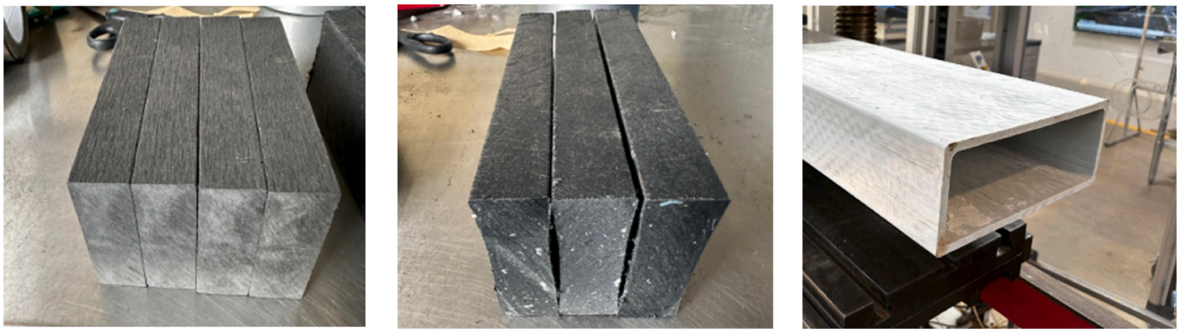


Fig. 2. Materials used in specimen preparation.

Table 1
Properties of fibre composite tube.

Properties	Fibre composite tube
Density (kg/m^3)	2030
Tensile strength (MPa)	610
Tensile modulus (GPa)	36
Poisson's ratio	0.28
Compressive strength (MPa)	485
Compressive modulus (GPa)	33
In-plane shear strength (MPa)	84
In-plane shear modulus (GPa)	4.28

Table 2
Design Parameters and Levels of selected parameters.

Design Parameters, P_d	Levels		
	1	2	3
A Water/cement ratio	0.35	0.4	0.45
B Bond thickness, T	3	5	10
C Panel types	Wood	Plastic	Combination
D Surface coating	Plain	Sanding	Sand coating

Table 3
$L_9(3^4)$ Designing experiments with orthogonal arrays.

Expt. No.	w/c ratio	Bond thickness, mm	Panel types	Surface coating
E−1	0.35	3	Wood	Plain
E−2	0.35	5	Plastic	Sanding
E−3	0.35	10	Combination	Sand coating
E−4	0.4	3	Plastic	Sand coating
E−5	0.4	5	Combination	Plain
E−6	0.4	10	Wood	Sanding
E−7	0.45	3	Combination	Sanding
E−8	0.45	5	Wood	Sand coating
E−9	0.45	10	Plastic	Plain

freedom each, making the total degree of freedom (DOF) eight in this study. Consequently, Taguchi $L_9(3^4)$ arrays could be used, which offer the same degree of freedom. Conversely, Eq (2) provides a method for determining the minimum number of experiments (N) required based on the design parameters (Pd) and level (L).

$$N = 1 + (L-1)P_d \tag{2}$$

2.2.2. Signal-to-noise ratio (SNR) and analysis of variance (ANOVA)

The deviation between the experimental and desired values is determined by using a loss function to determine the influence of design parameters. In the Taguchi method, the loss function is further transformed into the SNR, which represents the expected outcome in a logarithmic manner. Taguchi's method relies on three different models [23] of the SNR to achieve the following objectives: (a) nominally the best - achieve the highest response with the least deviation; (b) larger the better - achieve the highest response; and (c) smaller the better - achieve the lowest response. Eqs. (3)–(5) can be used to express each of these models.

$$\text{Nominal the best}, SNR = 10\log\left(\frac{\bar{y}_i^2}{\sigma_i^2}\right) \tag{3}$$

$$\text{Larger the better}, SNR = -10\log\left(\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y_j^2}\right) \tag{4}$$

$$\text{Smaller the better}, SNR = -10\log\left(\frac{1}{n}\sum_{j=1}^{n}y_j^2\right) \tag{5}$$

where,

$$\bar{y}_i = \frac{1}{n}\sum_{j=1}^{n}y_{i,j} \tag{6}$$

$$\sigma_i^2 = \frac{1}{n-1}\sum_{j=1}^{n}\left(y_{i,j}-\bar{y}_i\right)^2 \tag{7}$$

In Eqs. (6) and (7), n denotes the number of trials, i is the number of experiments, j the number of trials, $\bar{y}_i$ the mean value of the observed data, and σ_i^2 the variance of the observed data.

While the SNR analysis can rank the design parameters according to their influence on the final output, it cannot quantify the extent to which each parameter has an effect. This can be accomplished using ANOVA, a statistical technique used for interpreting experimental data and making decisions. The total variability can be separated from the SNR in order to determine the relative contribution of each parameter. In most cases, the relative significance of an effect is determined by the F value, which is a ratio between the mean of squared deviations and the mean of squared errors, where a higher value indicates a larger effect. As a result of overfitted designs, residual sums of squares have zero degrees of freedom; therefore, the percentage contribution of each parameter can be determined directly using equations (8)–(10).

$$\text{Contribution percentages of each parameter} = \frac{SS_k}{SS_T} \times 100 \tag{8}$$

where SS_T the total sum of squares of all parameters and SS_k denotes the sum of squares for the k th parameter.

$$SS_k = \sum_{j=1}^{L} n\left[(SNR)_{kj} - SNR_T\right]^2 \tag{9}$$

where n is the number of trials for each experiment at level j of parameter k, SNR_T the overall mean of the SNR, L is the level numbers and N is the number of total experiments.

$$SS_T = \sum_{i=1}^{N} \left[(SNR)_i - SNR_T \right]^2 \tag{10}$$

2.3. Specimen preparation and test setup

2.3.1. Bond specimen preparation and testing

The use of a double-leg specimen configuration was designed to examine the effects of the design parameters on the bond behaviour (Fig. 3). It is necessary to understand the bond behaviour of composite wood and recycled plastic panels before performing the full-scale composite beams. In this study, nine different specimens were prepared using Taguchi's design of experiment (3 replicates per specimen). Composite wood panels measuring 75 mm wide by 25 mm thick and recycled plastic panels measuring 70 mm wide by 20 mm thick were cut to 150 mm lengths. The middle panel was 25 mm larger than the side panels to facilitate load application. The composite panels (wood composites and recycled plastics) were attached with cement grouts of various thicknesses (3 mm, 5 mm and 10 mm) and surface conditions (plain, sanding and sand coating). Loads were applied in compression mode on the extended portion of the middle panel, which resulted in the specimens failing in shear mode. An investigation of the bond between composite wood and plastic panels was conducted, and the results revealed how composite panels will behave inside GFRP tubes if composite beams are manufactured.

2.3.2. Manufacturing of composite beams and testing

GFRP pultruded rectangular hollow sections were filled with composite wood and recycled plastic panels, which were bonded together with cement grout to manufacture the composite beams. The beam concepts are illustrated in Fig. 4. The rectangular hollow section (RHS) of GFRP considered was 1.60 m long, 250 mm wide, and 100 mm deep, with a wall thickness of 8.1 mm. Inside hollow GFRP profiles, composite wood and plastic profiles were placed flatwise (horizontally) and edgewise (vertically), and the results were compared with hollow profiles. The gap was filled with cementitious grout, which binds the panels together.

Four beams were tested (Fig. 4) in this study: (a) a hollow GFRP profile, (b) a GFRP profile filled with recycled plastic panels in edgewise orientation, (c) a GFRP profile filled with recycled plastic panels in flatwise orientation, and (d) a GFRP profile filled with composite wood in edgewise orientation. The hollow sections were used to study the effect of filling, but they were not considered sleeper concepts since they were unable to support screws for rail fastenings and collapsed under train wheel loads.

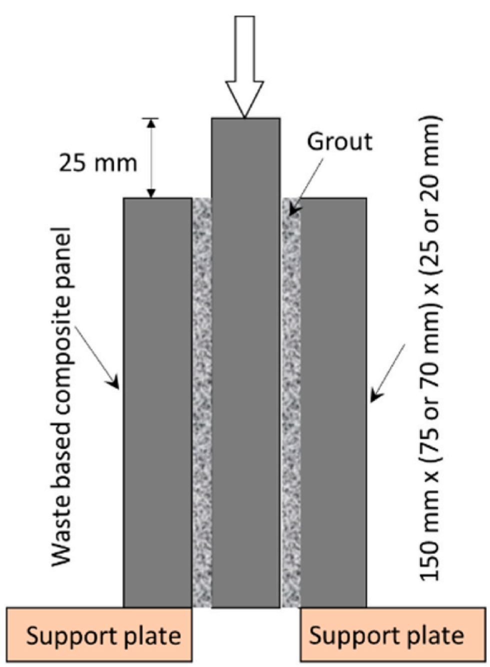
The beams were tested using the 400 kN capacity testing equipment under different span lengths (L), including 400 mm, 800 mm, and 1200 mm. To understand the effects of the span-to-depth ratios of the beam, non-destructive tests were conducted at spans of 400 mm and 800 mm. The beam was destructively tested to determine its ultimate load-bearing capacity under three-point bending over a span of 1200 mm. Two strain gauges were attached at the midspan of each beam to investigate compression and tensile strain behaviour. The top strain gauge was slightly off-centre of the beam to provide sufficient space for the loading plate. The bottom strain gauge was attached at the centre of the beam where there was the greatest deflection. Testing was conducted carefully to ensure that the strain gauges would not be damaged during the movement of the beam for testing at different span lengths. A stress and strain diagram were plotted accordingly. The failure characteristics of the beam were examined and identified during the tests.

3. Results and discussion

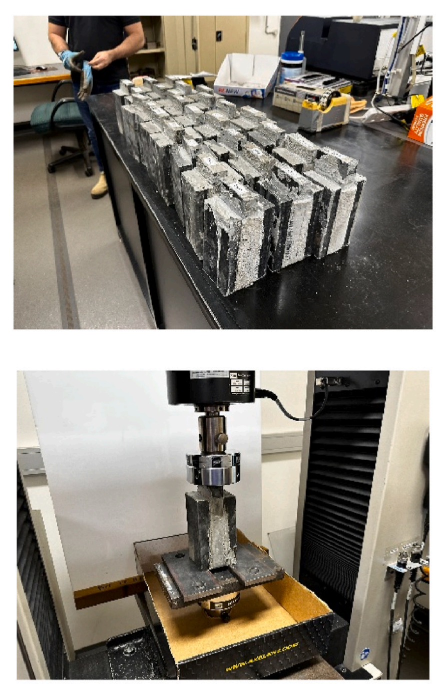
3.1. Bond behaviour of panels

3.1.1. Bond failure behaviour of panels

Testing was conducted under compression loading to determine bond failure behaviour. In this test method, the load is evenly distributed across two separate legs so that the bonded interface is subjected to a shearing force parallel to the adhesion plane. The force needed to separate the adherends provides valuable insight into the effectiveness of the bonding agent and the quality of surface preparation. It is important to note that a high shear bond strength indicates that there is a



(a) Schematic diagram of bond test



(b) Bond specimens and testing

Fig. 3. Bond behaviour investigation of Waste-based Panels.

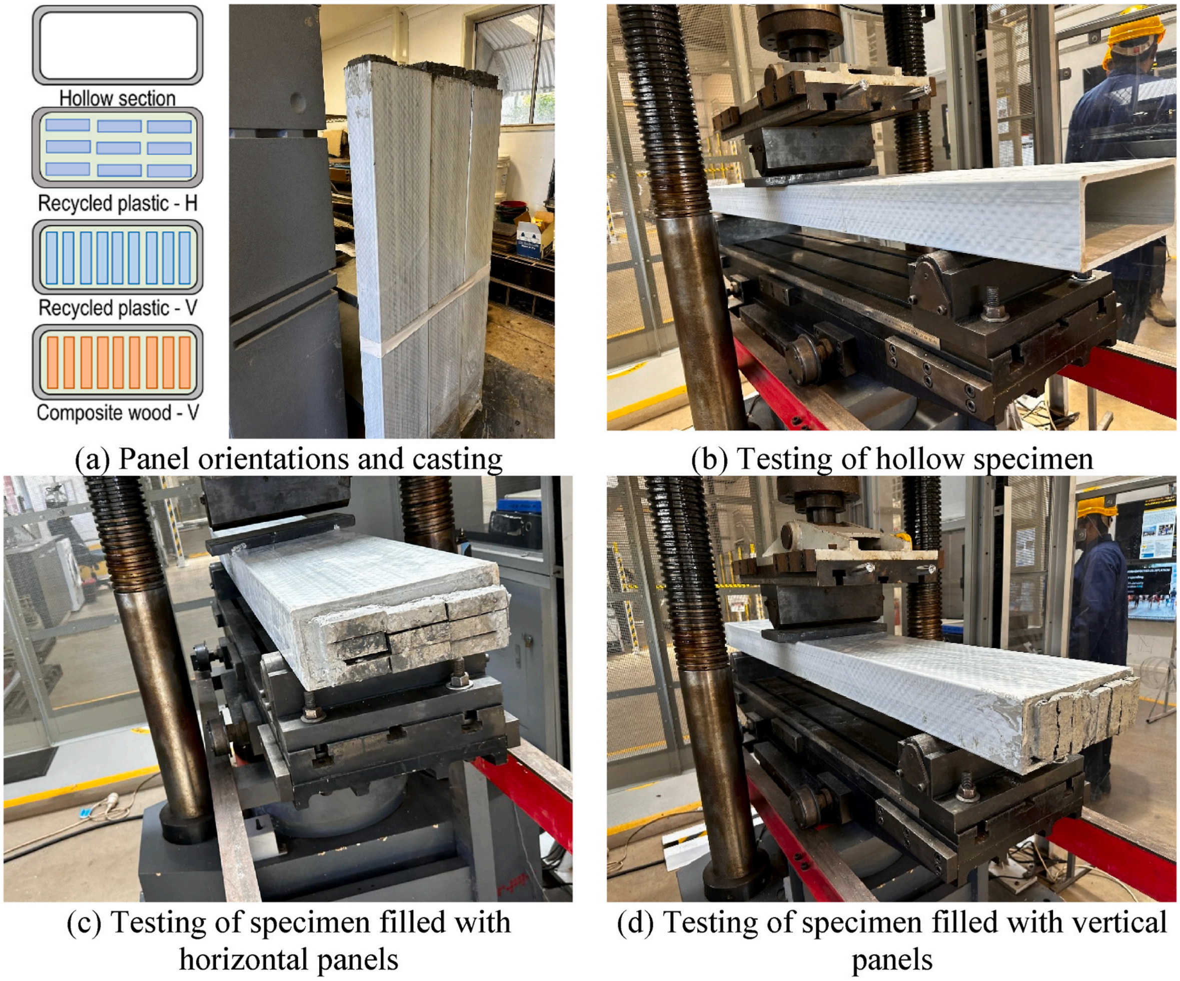


Fig. 4. Casting and testing of specimens.

robust adhesion and cohesive integrity in the bond, which ensures structural stability. Visual inspection of the samples was conducted, and failure behaviour was noted. Surface conditions and bond thickness both contributed to failures of both cohesive and adhesive bonds. Rough surfaces demonstrate more strength than smooth surfaces when it comes to bonding. Plastic material, for example, exhibits adhesive failure because of their relatively smooth surfaces. On the other hand, wood panels have a rough surface, and the failure pattern is cohesive, as illustrated in Fig. 5.

During compression loading, the specimens experienced shear stress in the joint area, as measured by Eq. (11) and presented in Fig. 5(c). It is evident that the bond strength varies between specimens. This is due to the variation in the design parameters. A large variation in bond strength from one sample to another indicates that the selected design

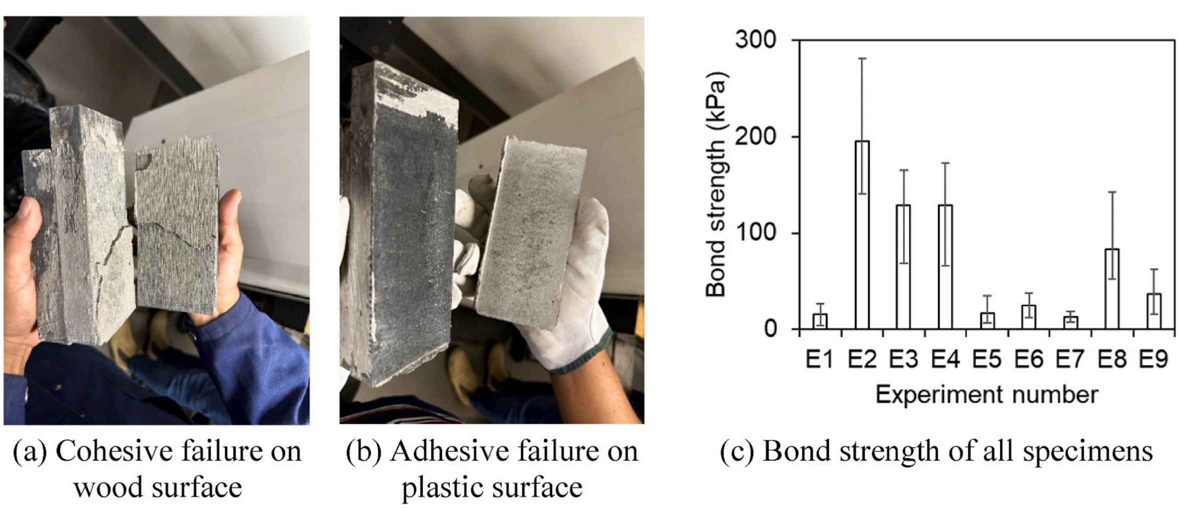


Fig. 5. Failure and strength behaviour of wood composite and recycled plastic panels.

parameters have a significant impact on bond strength. Furthermore, replicate specimens within the same group of samples showed a high degree of variation. Perhaps this is due to the complex nature of the bond specimen's shear behaviour, which has also been observed in previous studies [20].

$$\textit{Shear bond strength} = \frac{\textit{Failure load}}{2(\textit{Bond length} \times \textit{Bond width})} \tag{11}$$

3.1.2. Analysis of experimental variables

The mean of signal to noise ratio (SNR) was plotted against the different parameters that affected bond strengths, including water-cement ratio, bond thickness, panel type, and surface coating (Fig. 6). The results from nine experiments, including failure loads, strengths, standard deviations, signal-to-noise ratios (SNRs), and the overall average of SNRs, are investigated. In light of the fact that the purpose of this study was to know the bond strength between composite panels and cement grout, it follows that the quality characteristic specified in Eq. (4) is a "larger-the-better" criterion, indicating greater bond strength.

3.1.3. Effect of water-cement ratio on bond strength

The effect of the water-cement ratio on bond strength is shown in Fig. 6 (a) in relation to the mean SNR. In general, the SNR value decreases as the water-cement ratio increases. In the case of a water-cement ratio of 0.35, the SNR value was 34, while it decreased to approximately 28 in the case of a water-cement ratio of 0.40 and 0.45. Cement grout strength can have a significant impact on bond strength. It is well known that grout strength deteriorates with an increase in the water-to-cement ratio. Furthermore, excess water in the grout can increase porosity, decrease density, and make it more susceptible to cracking and degradation. In the presence of voids, the effective bond surface is reduced, resulting in bond failure at lower loads. Therefore, a water-to-cement ratio of 0.35 was selected for the manufacturing of composite beams.

3.1.4. Effect of bond thickness on bond strength

Fig. 6(b) illustrates the relationship between bond thickness and bond strength as expressed by the mean signal-to-noise ratio (SNR). For a bond thickness of 3 mm, the SNR was 26.09, whereas it increased to 33.34 for a bond thickness of 5 mm, and then decreased to 30.96 for a bond thickness of 10 mm. Strength and integrity of bonded materials are determined by the thickness of the bond layer. Excessively thick bond layers (e.g., 10 mm) may result in stress concentrations and reduced performance. On the other hand, thin bond layers may exhibit a lower bond strength due to their proneness to failure under load. The findings are also consistent with the effect of polymer bond thickness on sandwich panels in a previous study [20]. The proper thickness of a bonded assembly is therefore essential for maximising bond strength and ensuring its long-term performance and durability. The study determined that a 5 mm thick bond is more appropriate than others.

3.1.5. Effect of panel types on bond strength

The impact of panel types on bond strength displaying the average signal-to-noise ratio (SNR) is illustrated in Fig. 6(c). The composite panel types were chosen wood, plastic and a combination of wood and plastic. The plastic panel shows a greater SNR value (37.46) comparing to wood panels (26.14) and combination of plastic-wood panels (26.80). The variation of bond strength is due to the different types of failure for different panels. The bond on the wood surface fails cohesively while the bond on the plastic surface fails adhesively. This is because the surfaces of the plastic panels were smoother than those of the wooden panels. This can be attributed to the fact that wood composites and recycled plastic panels are derived from different ingredients (60 % wood powder with 30 % HDPE and 10 % additives for wood composites, and 100 % recycled HDPE and PP for recycled plastic panels) and are manufactured (pressure-temperature extrusion for wood composites, and injection moulding for recycled plastic panels) differently. It is interesting to note that the SNR values for wood and combination samples are similar. This occurred because of the cohesive failure of wood panels in both cases. In

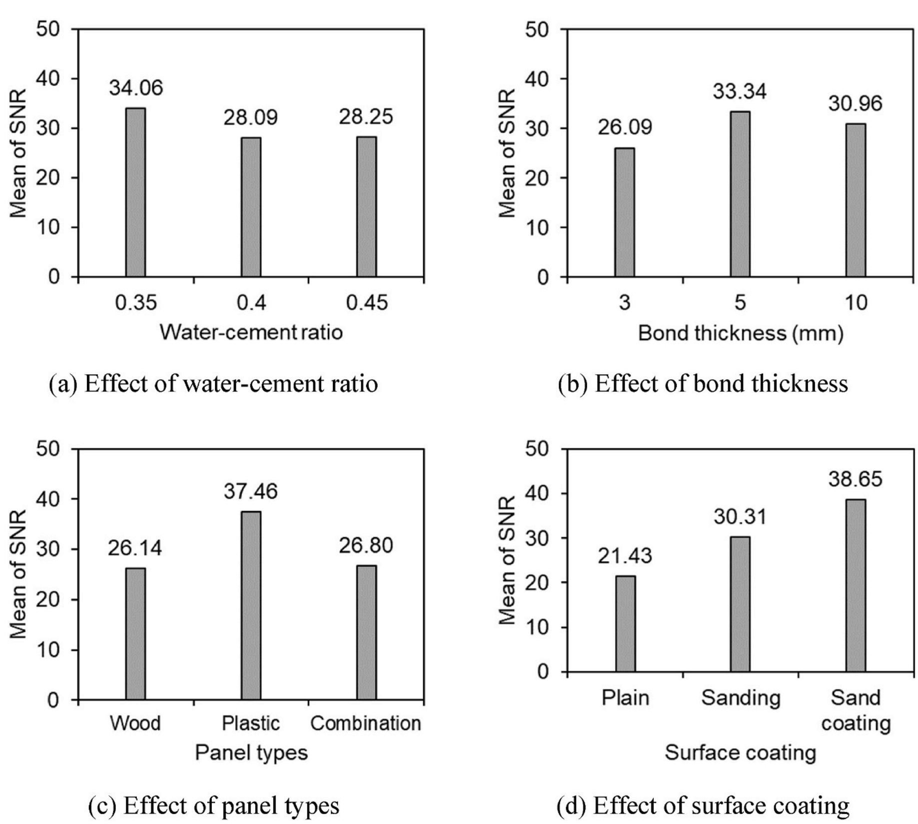


Fig. 6. Effect of different design parameters on bond strength.

this regard, it can be concluded that the combination of different panels does not necessarily improve the bond properties.

3.1.6. Effect of surface coating on bond strength

Treatment of smooth surfaces by sand coating and sanding has a significant effect on bond strength which has shown Fig. 6(d). Plain surfaces without treatment also investigated along with experiment to know the difference between with or without surface treatment. Among all these samples, the specimens with sand coating (38.65) have a greater SNR value comparing sanding (30.31) and plain surfaces (21.43). There is a reasonable expectation that surface roughness will affect the bonding behaviour. The level of surface treatment depends on the application and the cost of construction, which must be taken into consideration during the design process. The interesting finding is that the bond strength can be increased almost twice with an inexpensive method of sand coating in comparison with plane surfaces.

3.1.7. Contributions of design parameters to bond strength

Although the SNR analysis provides a ranking of design parameters based on their influence on bond strength, it does not offer insight into the specific contribution of each parameter to the development of bond strength. This contribution can be determined through ANOVA, which investigates the extent to which each parameter contributes to bond strength by partitioning the total variability of the SNR. The sum of squares for each design parameter (SS_k) and the total sum of squares for all parameters (SS_T) are calculated using Eq. (9) and Eq. (10) respectively, and then the percentage contribution of each parameter is determined using Eq. (8), as provided in Table 4.

In Tables 4 and it can be seen that surface coatings make the greatest contribution to bond strength development, accounting for 53 % of the development. The properties of the panel types and the bond thickness are the next two influential parameters, each contributing 29 % and 10 %. In contrast, the water-to-cement ratio has the least impact on bond strength development, contributing only 8 %. This is due to the contribution of sand coating to increasing surface roughness, whereas the other methods do not contribute to the increase in roughness. According to these results, the surface coating and panel type are the two most critical parameters for designing a cement grout-bonded structure.

3.2. Flexural behaviour of beams

3.2.1. Failure mode of beams

Different kinds of damages were noticed with the increase in displacement of GFRP profiles under loading, which varied depending on the types of infilled materials. The subsequent section elaborates on the failure patterns of GFRP profiles observed in laboratory experiments, as depicted in Fig. 7.

- Bending failure: A tensile rupture occurred on the bottom surface of the GFRP beam, followed by damage to the top surface of GFRP profile (Fig. 7(b)) and internal panels of the composite beam. Despite the tensile strength (610 MPa) of the GFRP profile being greater than its compressive strength (485 MPa), the tensile failure occurred before the compressive failure due to the loading plate located in the compression zone, which distributed stresses over a wider area. A loud noise just prior to ultimate failure confirmed that the internal panels had been damaged. The ultimate failure of the exterior GFRP profile occurred immediately following the tensile bending failure at the bottom. The bending failure was observed in hollow beams and in beams with vertically filled panels.
- Shear failure: A horizontal shear crack was observed on the vertical faces of the GFRP profile when it was filled with horizontal panels (Fig. 7(c)). This type of failure occurs when the beam fails horizontally rather than by bending due to a shear stress exceeding the material's shear strength.
- Exterior GFRP compression and fibre buckling: The GFRP profiles were damaged due to the compression at the top. This type of damage occurred in both hollow and filled profiles with vertical panels. The excessive deformation of beams, however, results in skin separation and buckling on the top surface of the beams (Fig. 7(d)).

3.2.2. Load-strain behaviour of beams

Load versus strain plots have been generated for the four specimens illustrated in Fig. 8. The linear load-displacement behaviour was observed across all spans, including 400 mm, 800 mm, and 1200 mm indicating the structural behaviour was mostly dominated by exterior GFRP tube. Spans were selected based on the shear span-to-depth ratio (i.e., a/d) which determines how the beams behave. Among the test specimens, the a/d ratio was 2, 4, and 6, which indicates a wide range of characteristics ranging from shear to bending. The failure strain of the beam specimens was found to be lower than the ultimate strain of the GFRP material (0.015). These results indicate that the beam specimens did not fail as a result of pure bending. The failure was caused by a combination of bending, shear, and damage to the infilled panels.

3.2.3. Effect of filling hollow tubes

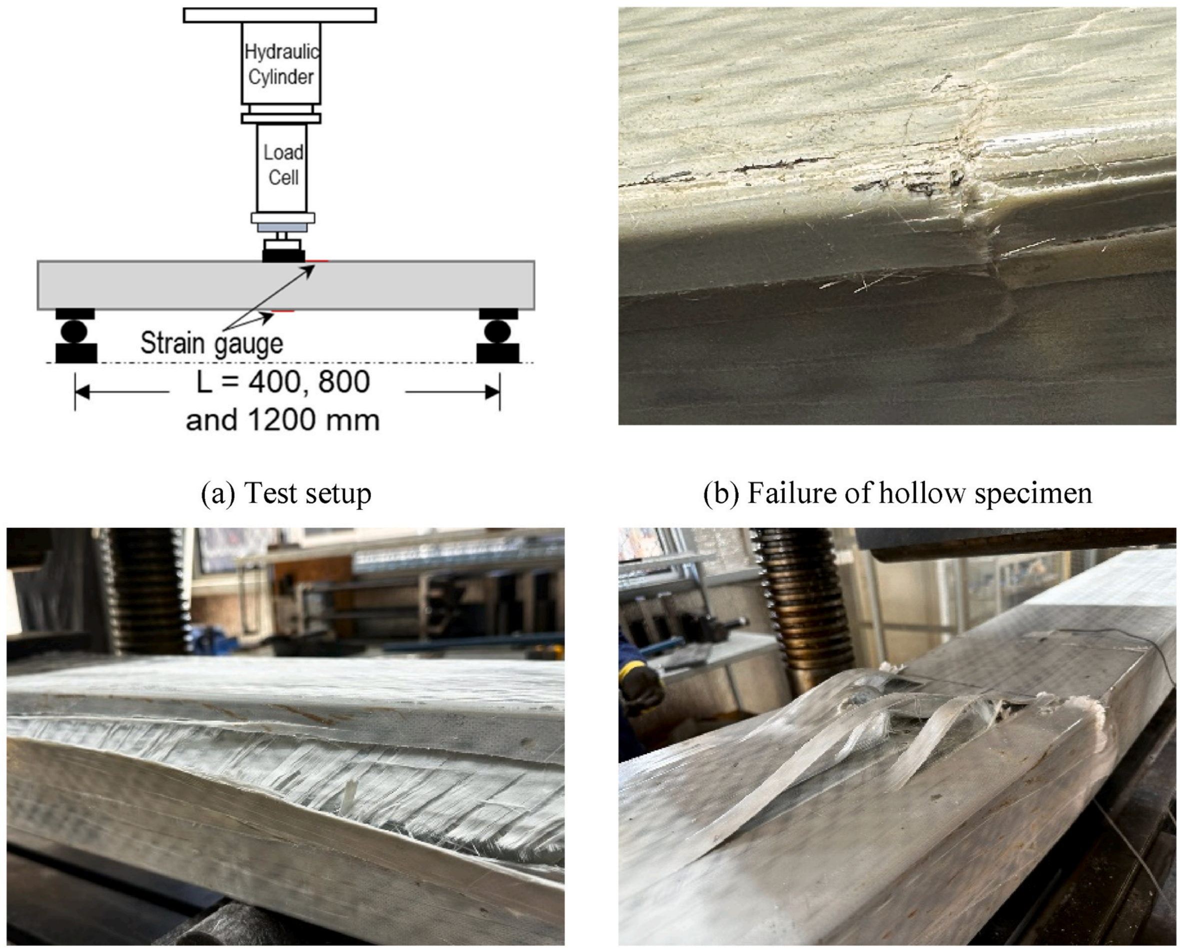
The effect of filling hollow tubes was studied by comparing the behaviour of hollow tube with tube that has been filled (Fig. 9). Filling hollow tubes increases the beam's strength and stiffness. It was observed that the strength of the beam increased by 2.3 times and the stiffness increased by 25 % when the hollow tube was filled with recycled plastic panels, as shown in Fig. 9(b). Infill panels contribute more to strength than stiffness by preventing premature failure of the beam. Performance was improved due to the increase in internal resistance to bending and the enhancement of overall structural integrity, which prevented premature local failure of the beam. It was found that the failure strength and strain of the filler (i.e., recycled plastic material) were 27 MPa and 0.035, respectively, which indicates that the confinement effect created by the external GFRP tube was highly influential on the overall structural performance. A filled tube demonstrated a slight nonlinear behaviour in the compression side of the beam just prior to failure, while a hollow tube failed suddenly at the peak load. In real-life applications, this nonlinearity of the filled tube could be interpreted as a warning of the ultimate failure of the beam.

3.2.4. Effect of infill panel orientations

The effect of infill panel orientations, flatwise (i.e., horizontal) and edgewise (i.e., vertical) orientations within the GFRP tubes were

Table 4
Percentage contribution of each parameter.

Parameter	DOF		Sum of squares		F-Value	% Contribution
	$L-1$	$N-1$	SS_k	SS_T		$(\frac{SS_k}{SS_T} \times 100)$
Water/cement ratio	2	8	70	839	–	8
Bond thickness	2		82		–	10
Panel types	2		242		–	29
Surface coating	2		445		–	53
Error	–		–			–



(a) Test setup

(b) Failure of hollow specimen

(c) Failure of specimen filled with horizontal panels

(d) Failure of specimen filled with vertical panels

Fig. 7. Failure of beam specimens for different orientations of panels.

compared (Fig. 10). The GFRP profiles filled with recycled plastic panels with horizontal orientation (RP-H) and vertical orientation (RP-V) behave almost identically in terms of strength (163 MPa and 156 MPa) and stiffness (26.8 GPa and 26.4 GPa). This can be explained by the volume of infill materials and the properties of those materials. The internal panels were oriented horizontally as well as vertically, occupying the same volume space, and their properties did not affect the beam behaviour due to their homogeneous material properties. The slight variation can be attributed to the higher deflected capacity of horizontal panels when compared to vertical panels, which can be observed in the compression side of the stress-strain graph prior to failure (Fig. 10(a)). The horizontal panel shows a 50 % drop of load, while the vertical panel shows an 80 % drop at ultimate failure. Perhaps the horizontal panels failed due to horizontal shear failure of the cement grout, whereas the vertical panels failed due to bending cracks. This statement is also in agreement with the previous investigation where layered sandwich panels failed by bending cracks in the vertical direction, and horizontal panels failed by horizontal shear cracks [24].

3.2.5. *Effect of infill panel material types*

The effects of infill panel materials were studied by comparing the behaviour of recycled plastic filled GFRP tubes with composite wood filled GFRP tubes (Fig. 11). The composite wood and plastic panels were placed vertically in the GFRP profile to determine the strength and stiffness of the beam. While infill panel types with composite wood and plastic panels resulted in similar strength (156 MPa vs 161 MPa), stiffness behaviour differed (26.4 GPa vs 29.3 GPa). It is believed that this is due to the characteristics of the infill material. In terms of bending strength, recycled plastic and composite wood were 27 MPa and 28 MPa, respectively, while bending modulus was 1 GPa and 2.75 GPa. This explains why both beams have a similar strength, but a slight difference in stiffness. It is interesting to note that while infilled wood composites exhibit 2.75 times greater stiffness than recycled plastics, this does not translate into a difference in beam performance. This is primarily due to the lower stiffness of the infill panels compared to the GFRP profiles (36 GPa) as well as confinement effect.

Based on the results of this study, the performance of the high-volume waste filled GFRP tubes can provide strength and stiffness of at least 156 MPa and 26.4 GPa, respectively. In comparison, this performance is superior to the strength and stiffness characteristics of timber railway sleepers, which are respectively 50 MPa and 7 GPa [6]. It is therefore evident from the initial findings of the study that it may be possible to replicate the behaviour of timber railway sleepers. It is, however, necessary to conduct a detailed investigation to determine how the beam will perform under screw pull-out and dynamic loading conditions, as these factors are extremely important when it comes to railway sleepers.

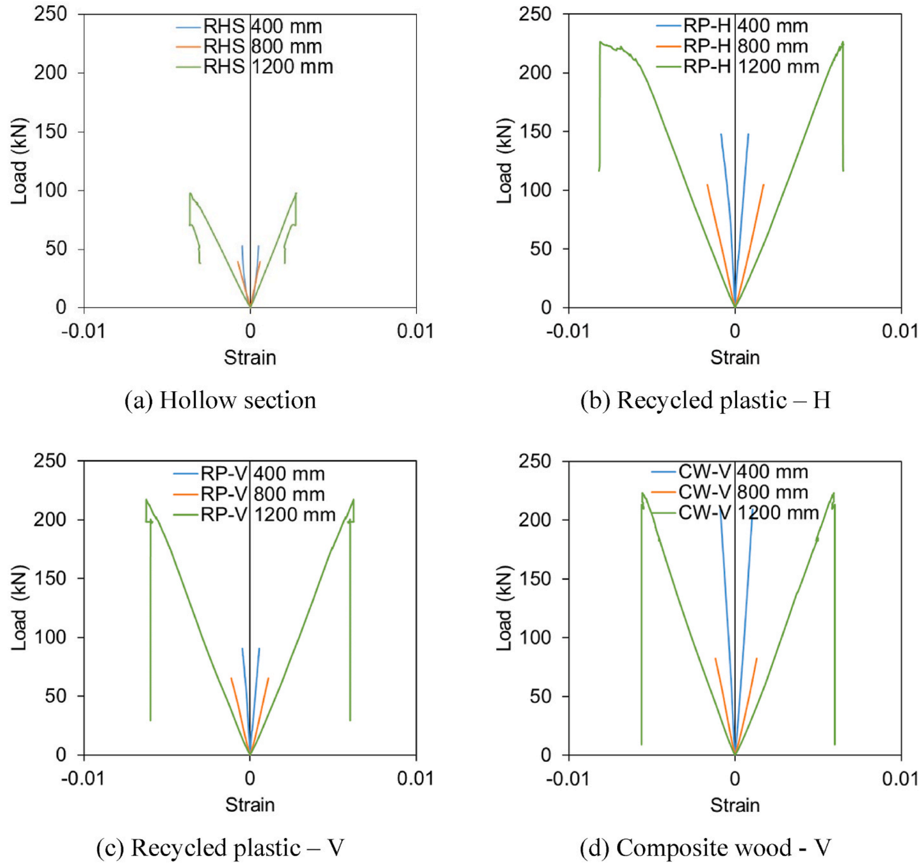


Fig. 8. Load-strain behaviour of different composite beams.

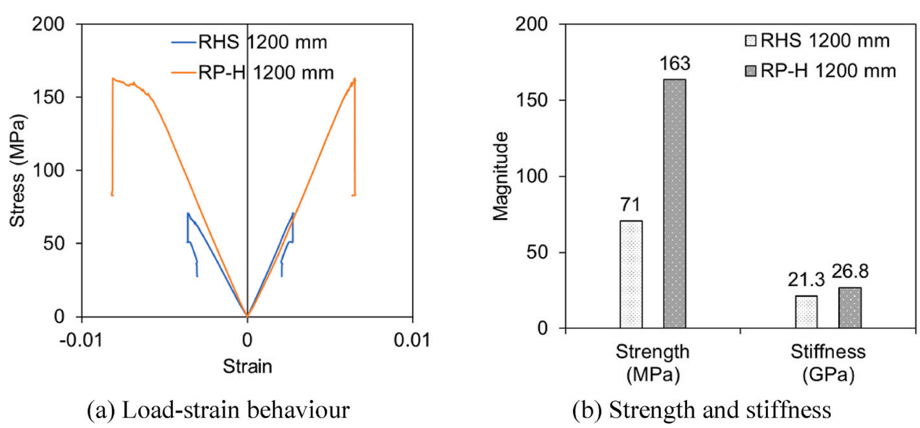
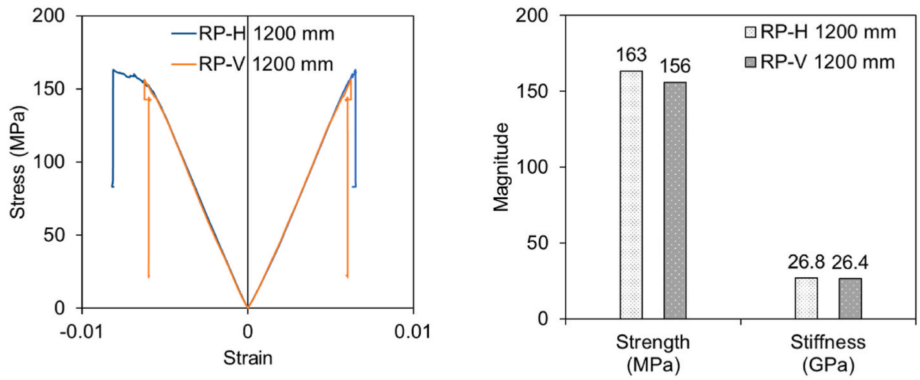


Fig. 9. Effect of filling hollow tubes.

4. Conclusions

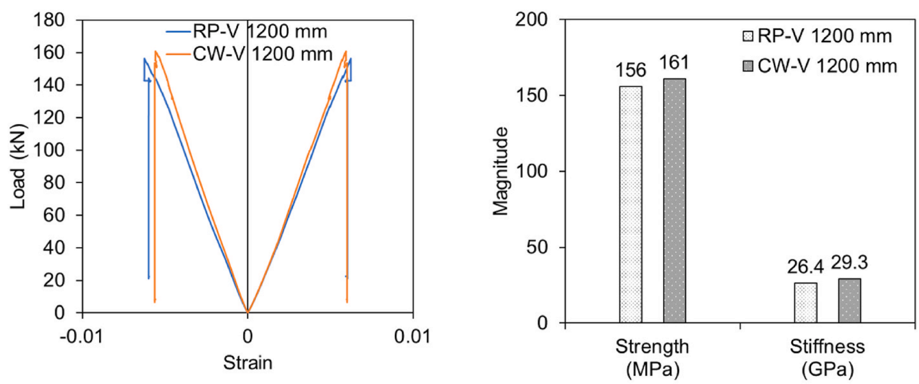
This study investigated the bonding properties of composite wood and recycled plastic materials with cement grout and utilised them as an infill material of GFRP tubes to manufacture a composite railway sleeper. The effect of cement grout properties (water-to-cement ratio), bond thickness, panel type, and surface coating were examined to understand the bond behaviour. Moreover, the effect of filling hollow tubes, the orientation of the infill panels, and the material types of the infill panels were studied to determine whether composite beams are suitable for use as railway sleepers. The following conclusions are drawn from this study.

- Wood composites and recycled plastic panels can be bonded using simple cement grout when used as infill materials, eliminating the need for expensive resin systems for many traditional structures. The bond thickness is a significant factor in determining how the bond will fail. An excessively thick bond layer (e.g., 10 mm) may result in stress concentrations and decreased bond performance. Conversely, thin cement grout bond layers (e.g., 3 mm) have a lower bond strength due to their tendency to fail under load. A bond thickness of 5 mm is found to be most suitable.
- Wood surface bonds fail cohesively, whereas the plastic surface bonds fail adhesively, due to the smoother surfaces of the plastic panels compared to the wood surfaces. An interesting finding is that the bond strength can be increased almost twice with an inexpensive



(a) Load-strain behaviour (b) Strength and stiffness

Fig. 10. Effect of in-fill panel orientations.



(a) Load-strain behaviour (b) Strength and stiffness

Fig. 11. Effect of in-fill panel material types.

method of sand coating in comparison with plane surfaces. In terms of improving bond strength, the surface coating is the most influential parameter, followed by the type of panel, the bond thickness, and the grout properties.

- When a hollow tube is filled with waste-based material, the strength of the tube increases significantly, while the stiffness properties are not greatly affected. Local buckling is prevented by infill materials, which enhances the structural strength of the beam. If the stiffness of the outer profile is greater than the stiffness of the infill materials, then the overall stiffness of the beam with or without infill materials is not different, since the stiffness characteristics of the beam are largely determined by the stiffness characteristics of the outer profile.
- Orientation of the infill panels flatwise or edgewise does not affect the strength or stiffness properties of the beam, provided that the infill volume remains the same and the infill material is homogenous. However, flatwise orientation of the infill panels may result in a greater residual capacity of the beam after ultimate failure than edgewise orientation.

A summary of the major conclusions from this study is that cement grout can be considered as a suitable adhesive for bonding panels together. It is possible to significantly increase bond strength by treating the bond surface, and infill panels can prevent premature tube failure, but their orientations and properties do not significantly affect the beam's behaviour. The purpose of this study was to investigate the feasibility of manufacturing composite railway sleepers using GFRP tubes filled with high volumes of waste materials. Findings indicate that the proposed concept has a high potential for replacing traditional timber railway sleepers. It is recommended that a detail investigation on the environmental impact assessment of the proposed sleeper concept should be conducted to understand the environmental sustainability.

CRediT authorship contribution statement

Mamun Abdullah: Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Wahid Ferdous:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Sourish Banerjee:** Writing – review & editing, Supervision. **Ali Mohammed:** Writing – review & editing. **Allan Manalo:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge Wagners Pty Ltd for their generous in-kind contributions to supply GFRP tubes. The second author would like to acknowledge the financial support he received from the Advance Queensland Industry Research Fellowship (AQIRF 098-

2021RD4) program.

References

[1] W. Ferdous, A. Manalo, Failures of mainline railway sleepers and suggested remedies – review of current practice, Eng. Fail. Anal. 44 (2014) 17–35.
[2] A. Manalo, T. Aravinthan, W. Karunasena, A. Ticoalu, A review of alternative materials for replacing existing timber sleepers, Compos. Struct. 92 (3) (2010) 603–611.
[3] C.E. Bakis, et al., Fiber-reinforced polymer composites for construction — state-of-the-art review, J. Compos. Construct. 6 (2) (2002) 73–87.
[4] S.M. Harle, Durability and long-term performance of fiber reinforced polymer (FRP) composites: a review, in: Structures, vol. 60, Elsevier, 2024 105881.
[5] L.C. Bank, Composites for Construction : Structural Design with FRP Materials, John Wiley & Sons, Inc, New Jersey, 2006.
[6] W. Ferdous, A. Manalo, G. Van Erp, T. Aravinthan, S. Kaewunruen, A. Remennikov, Composite railway sleepers–Recent developments, challenges and future prospects, Compos. Struct. 134 (2015) 158–168.
[7] W. Ferdous, A. Manalo, G. Van Erp, T. Aravinthan, K. Ghabraie, Evaluation of an innovative composite railway sleeper for a narrow-gauge track under static load, J. Compos. Construct. 22 (2) (2018) 1–13.
[8] W. Ferdous, et al., Static behaviour of glass fibre reinforced novel composite sleepers for mainline railway track, Eng. Struct. 229 (2021) 111627.
[9] W. Ferdous, et al., Behaviour of polymer filled composites for novel polymer railway sleepers, Polymers 13 (8) (2021) 1324.
[10] G. Koller, FFU synthetic sleeper – projects in Europe, Construct. Build. Mater. 92 (2015) 43–50.
[11] G. Van Erp, M. Mckay, Recent Australian developments in fibre composite railway sleepers, Electron. J. Struct. Eng. 13 (1) (2013) 62–66.
[12] P. Sengsri, C. Ngamkhanong, A.L. O.d. Melo, M. Papaelias, S. Kaewunruen, Damage detection in fiber-reinforced foamed urethane composite railway bearers using acoustic emissions, Infrastructures 5 (6) (2020).
[13] M.H. Esmaeili, H. Norouzi, F. Niazi, Evaluation of mechanical and performance characteristics of a new composite railway sleeper made from recycled plastics, mineral fillers and industrial wastes, Compos. B Eng. 254 (2023) 110581.
[14] AuManufacturing. Australian first: railway sleepers made of recycled plastic get type approval by Victorian operators, 2021. Aust. Now.: aumanufacturing.com.au 20 May.
[15] A. Bednarczyk, New composite sleeper set to undergo live trials, Int. Railw. J. 28 (Feb) (2019).
[16] COEN, COEN composite wood - building a better environment, Australia, www.coen.com.au, 2024.
[17] Replas, Turning problem plastic, into useful products, Australia, www.replas.com.au, 2024.
[18] Wagners, Composite Fibre Technologies - Product Guide, vol. 5, Wagners CFT Manufacturing Pty Ltd, 2021.
[19] G. Taguchi, Y. Yokoyama, Taguchi Methods: Design of Experiments, ASI Press, USA, 1993.
[20] W. Ferdous, A. Manalo, T. Aravinthan, Bond behaviour of composite sandwich panel and epoxy polymer matrix: Taguchi design of experiments and theoretical predictions, Construct. Build. Mater. 145 (2017) 76–87.
[21] A. Hosseini, D. Mostofinejad, Effective bond length of FRP-to-concrete adhesively-bonded joints: experimental evaluation of existing models, Int. J. Adhesion Adhes. 48 (2014) 150–158.
[22] M. Abdullah, W. Ferdous, S. Banerjee, A. Manalo, Bond behaviour of smooth surface GFRP pultruded profiles with cement grout, Case Stud. Constr. Mater. 20 (2024) e02891.
[23] R.S. Kumar, K. Sureshkumar, R. Velraj, Optimization of biodiesel production from Manilkara zapota (L.) seed oil using Taguchi method, Fuel 140 (2015) 90–96.
[24] W. Ferdous, A. Manalo, T. Aravinthan, A. Fam, Flexural and shear behaviour of layered sandwich beams, Construct. Build. Mater. 173 (2018) 429–442.

4.3. Links and implications

This study focused on investigating the feasibility of manufacturing composite railway sleepers using GFRP tubes filled with waste materials. Based on the results of the study, the proposed concept has a high potential for replacing traditional timber railway sleepers. The results of this study will be of interest to design engineers and end users of composite structures.

CHAPTER 5: DISCUSSION AND CONCLUSION

5.1. Discussion

5.1.1. Bond behaviour of GFRP profile with cement grout

GFRP profiles possess many advantages over traditional materials, such as steel and timber. These advantages include corrosion resistance, low maintenance costs, and high strength-to-weight ratios, but they are also characterised by a smooth surface, preventing good bonding with concrete. In order to overcome this challenge, the main objective of this part of the study was to improve the bond performance between GFRP tubes and concrete surfaces. Therefore, cement grout was used to bond GFRP tubes to smooth surfaces and their behaviour was examined. The bond performance of cement grout was evaluated using four different methodologies, which included surface treatment of GFRP tubes, adding glass sand to cement grout, varying the particle size of sand particles in the grout, and using a variety of binding materials during grout preparation. A sand coating of the GFRP tubes was found to be the most effective method of improving bond strength. The surface roughness of the GFRP tubes can be increased by this method, resulting in a better bond.

5.1.2. Materials and structural behaviour of composite sleepers

A sustainable railway sleeper is developed with performance, cost, and eco-friendliness in mind by using high-performance composite GFRP tubes infilled with low-cost waste-based composite materials in high volumes. There has been a study conducted to examine the bond behaviour of in-filled panels with different grout materials, grout thickness, panel types, and surface preparations. This study investigated the structural performance of the composite beam with different in-filled panel materials and orientations and studied the effects of filling hollow tubes. To gain a better understanding of the structural performance of sleepers, this study examined the bending behaviour of sleeper beams under static loads. The strength and stiffness of the beam are examined to determine whether they are suitable for use as composite railway sleepers. Based on the experimental results, it is evident that the proposed concept has a high potential for developing a sustainable sleeper which will serve as a guide for the development of composite railway sleepers for commercial use.

5.2. Conclusion

This study aims to develop a concept for composite railway sleepers that can replace traditional timber sleepers. In order to achieve this goal, it was proposed to use GFRP tubes filled with high volume waste-based materials and bonded with cement grout. Firstly, this study explored how GFRP tubes with smooth surfaces can be bonded to cement grout effectively. The incorporation of glass sand into cement grout, the variation in sand particle size in the grout, the surface preparation of GFRP profiles, and the use of various cement characteristics are studied for this purpose. Secondly, this study examined how the beam can be designed in such a way as to mimic the behaviour of timber sleepers. For this purpose, this study examined the effect of cement grout, grout thickness, panel types, and surface preparation of the panels on the bond behaviour between the panels and cement grout followed by the bending behaviour of manufactured railway sleepers by examining the effects of filling hollow tubes, orienting the infill panels, and choosing the types of infill materials. The major findings are provided below:

5.2.1. Bond behaviour of GFRP profile with cement grout

The findings of this part of research indicate that the addition of glass sand with cement grout up to 20% does not appear to have a significant impact (only 2%) on the overall bond behaviour. This is because GFRP profiles are primarily bonded by cement paste and glass sand cannot increase surface roughness when added to the binder. However, the size of the glass sand can have a significant impact (up to 34%) on the bond strength because the larger glass sand particles can significantly reduce the effective bond surface area. According to this study, increasing the surface roughness of the bonded area is the most effective method of improving bond strength (up to 282% variation). By pre-coating the bond surface with resin and glass sand mix, a highly rough surface is created, which increases bond strength by 3.8 times compared to an untreated bond surface. As opposed to pre-coating, sanding the bond surface can increase bond strength by 1.5 times over untreated surfaces. The bond strength is also affected by the characteristics of the cement binder (up to 17%). The expansion and contraction characteristics of cement make it less effective for bonding. Bond strength can be weakened by internal movements of the binder caused by expansion and contraction of the binder volume during the hardening process. The bond behaviour can be predicted using a linear elastic model. Properties of the GFRP profile and cement binder play a significant role in determining how well the bond will perform. When predicting the bond strength, it is necessary to take into account the bond surface roughness coefficient.

5.2.2. Materials and structural behaviour of composite sleepers

Composite wood and recycled plastic panels can be bonded with cement grout with a water-to-cement ratio of 0.35. Bond thickness is a significant factor in bond failure. Thick cement grout bond layers (e.g., 10mm) may result in stress concentrations and decreased bond performance while thin cement grout bond layers (e.g., 3mm) have a lower bond strength. Bond thickness of 5mm is recommended. Wood surface bonds fail cohesively, whereas plastic surface bonds fail adhesively because plastic panels have smoother surfaces than wood. An interesting finding is that sand coating can almost double bond strength compared with plane surfaces. Surface coating is the most influential parameter in improving bond strength, followed by panel type, bond thickness, and grout properties.

Hollow tubes filled with waste-based material increase strength and stiffness. Infill panels improve strength more than stiffness. Adding infill material increases internal resistance to bending and improves overall structural integrity, preventing premature failure of the beam. Orienting the infill panels flatwise or edgewise does not affect the strength or stiffness of the beam, provided the infill volume remains the same and the infill material is homogeneous. Infill panels oriented flatwise have a greater residual capacity than those oriented edgewise. When the infill material has a lower strength and stiffness than the external tube, its properties do not significantly affect the overall performance of the beam. Variation in material properties between the external tube and the infill material strongly influences beam behaviour.

This research provided an in-depth understanding of the structural integrity and composite action of GFRP profiles and composite panels, and the findings will provide a guide to future design and manufacture of a sustainable composite railway sleeper.

5.3. Future recommendations

Despite the fact that this dissertation covers a considerable area of research, the following area of research is still needed to be conducted in future as these are beyond the scope of the presented study:

5.3.1. Dynamic fatigue behaviour of composite sleepers

The dynamic load test of manufactured sleepers is necessary due to the repeated wheel loads transferred from the rail to the sleeper, which can result in fatigue. Due to the bonding between different materials in composite sleepers, they are more critical in fatigue cycles as they can become de-bonded as a result of fatigue.

5.3.2. Screw pull-out behaviour of composite sleepers

Rails on ballasted railway tracks are held in place by means of a variety of attachments, including pandrol clips with steel rail seats as commonly used on concrete sleepers and screw spikes in timber sleepers. In order to understand the pull-out capacity of composite sleepers, a suitable arrangement for holding the rail into position must be designed and tested.

5.3.3. In-track performance investigation of composite sleepers

The proposed sleeper should also be placed under the operating railway track so that the key performance of the composite sleeper can be investigated, which could provide an elaborate insight to the researcher about how to develop and find a sustainable composite sleeper.

REFERENCES

Adam, D. (2009). Network Rail to recycle rubbish into sleepers. *The Guardian*. www.theguardian.com

Advanced-Materials. (2024). *Composites market size, share & trends analysis report by product type (carbon fiber, glass fiber), by manufacturing process (layup, filament, injection molding, pultrusion), by end-use, by region and segment forecasts, 2023 - 2030*.

AuManufacturing. (2021). *Australian first: Railway sleepers made of recycled plastic get type approval by Victorian operators*

Ferdous, W., & Manalo, A. (2014). Failures of mainline railway sleepers and suggested remedies – Review of current practice. *Engineering Failure Analysis*, *44*, 17–35.

Ferdous, W., Manalo, A., AlAjarmeh, O., Mohammed, A. A., Salih, C., Yu, P., Khotbehsara, M. M., & Schubel, P. (2021). Static behaviour of glass fibre reinforced novel composite sleepers for mainline railway track. *Engineering Structures*, *229*, 111627.

Ferdous, W., Manalo, A., Van Erp, G., Aravinthan, T., Kaewunruen, S., & Remennikov, A. (2015). Composite railway sleepers–Recent developments, challenges and future prospects. *Composite Structures*, *134*, 158-168.

Kaewunruen, S. (2013). Acoustic and dynamic characteristics of a complex urban turnout using fibre-reinforced foamed urethane (FFU) bearers. International Workshop on Railway Noise 2013,

Koller, G. (2015). FFU synthetic sleeper – Projects in Europe. *Construction and Building Materials*, *92*, 43–50.

Manalo, A., Aravinthan, T., Karunasena, W., & Ticoalu, A. (2010). A review of alternative materials for replacing existing timber sleepers. *Composite Structures*, *92*(3), 603-611.

McConnell, V. P. (2008). Rail – an evolving market for FRP components. *Reinforced Plastics*, *52*(11), 24-29.

Nunez, J. (2013). *Axion: Ecotrax product and performance standards advance*.

Pattamaprom, C., Dechojarassri, D., Sirisinha, C., & Kanok-Nukulchai, W. (2005). *Natural rubber composites for railway sleepers: a feasibility study* www.rtg.ait.ac.th

Sekisui-Chemical. (2010). *FFU synthetic sleeper- Railway technology*

Siahkouhi, M., Li, X., Markine, V., & Jing, G. (2021). Experimental and numerical study on the mechanical behavior of Kunststof Lankhorst Product (KLP) sleepers. *Scientia Iranica, Transactions A: Civil Engineering*, *28*(5), 2568-2581.

Sicut. (2023). *Network Rail terminates procurement of hardwood sleepers and replaces with Sicut composite sleepers*.

TieTek. *Increase productive track time and reduce costs with TieTek™ composite ties, Access Date: 29 June 2024, Available from: www.tietek.net*.

UniSQ. (2023). *Future proofing Australian infrastructure*

Van Erp, G., & Mckay, M. (2013). Recent Australian developments in fibre composite railway sleepers. *Electronic Journal of Structural Engineering*, *13*(1), 62-66.

APPENDIX – A

Conference Paper

Mamun Abdullah, Wahid Ferdous, Sourish Banerjee, and Allan Manalo (2023). Flexural behaviour of pultruded GFRP profiles filled with layered composite panels for railway sleepers, ***26th Australasian Conference on Mechanics of Structures and Materials (ACMSM26)***, Edited by N. Chouw and T. Larkin, Auckland, New Zealand, 3 – 6 December 3, 2023

Abstract: This study focused on the flexural behaviour of a new type of composite beam, consisting of pultruded glass fibre reinforced polymer (GFRP) profiles filled with waste-based composite panels. Recycled plastic and wood composite panels are placed inside the GFRP rectangular hollow section with vertical and horizontal orientations, then gaps inside the panels are filled with cementitious grout. A total of four composite beam samples (e.g., three filled and one hollow) are tested under three-point bending at a shear span-to-depth ratio of 6. According to the test results, filling hollow tubes with waste-based layered composite panels increases the load carrying capacity by 2.3 times, while stiffness increases by 36%. Panels oriented horizontally inside hollow tubes show slightly greater load carrying capacity than panels oriented vertically, but panel orientation does not affect stiffness properties. When wood composite panels are used instead of recycled plastic panels, the beam stiffness increases by 7% but it does not affect the load carrying capacity. This study indicates that the filler materials do not need to be very high quality as the overall behaviour of the beam is governed by the confinement effect of the exterior GFRP panel. Moreover, the proposed concept of the beam can lead to the development of a highly sustainable railway sleeper. In addition, this development is consistent with the goal of Australian government for achieving net zero carbon emissions by 2050 through the encouragement of circular economies.

APPENDIX – B

Additional information

Table B1: Properties of the composite wood and recycled plastic panels (Paper 2)

Materials	Density (kg/m^3)	Bending strength (MPa)	Bending modulus (GPa)
Composite wood	1300	28	2.8
Recycled plastic	900	28	1

Table B2: Typical properties of cement grout (Paper 2)

W/C ratio	Density (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)
0.35	1600	40	4
0.40	1580	37	3.5
0.45	1560	35	3.2

Notes:

- In Charter 4: Paper 2, only one beam was tested in each category because this was a large-scale specimen.