



# **BEHAVIOUR OF COMPOSITE SANDWICH PANELS BONDED WITH EPOXY POLYMER MATRIX FOR RAILWAY SLEEPERS**

A thesis submitted in fulfilment of the requirements of the degree of  
**Doctor of Philosophy**

Submitted by

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## Abstract

The Australian railway industry spends millions of dollars every year in replacing poor condition railway sleepers in order to maintain the track quality and ensure a safe track operation. It is estimated that more than 2.5 million timber sleepers per year are required for railway track maintenance. Over the last decade, it has been increasingly difficult to get suitable quality hardwood to keep up with the demand for railway maintenance. Moreover, the global environmental impact due to felling huge number of trees for manufacturing timber sleepers is a major concern. In recent years, significant efforts have been provided towards the development of polymer composite sleeper alternatives to replace deteriorating timber sleepers. Despite their potential, the uptake of polymer composite sleepers has been extremely limited because of the high production cost of these technologies. An improved understanding of composite sleeper technology such that improved designs and effective material usage needs to be developed to reduce the overall cost of production.

This study focused on investigating the behaviour of a fibre composite railway sleeper manufactured from composite sandwich panels and the panels are bonded together with epoxy polymer matrix. An intensive characterisation of the epoxy polymer matrix and composite sandwich panels was conducted to determine the effective usage of these materials for railway sleepers. The effect of resin-to-filler ratio on the thermal, physical, mechanical and durability properties of the epoxy polymer matrix were evaluated. Filler materials composed of fire retardant filler, hollow microsphere and fly ash were increased from 0% to 60% in the epoxy based matrix. The results showed that epoxy-based polymer mixes containing 30% to 50% fillers by volume provided a good balance of thermal, physical, mechanical, and durability properties suitable for coating the composite railway sleepers. The capacity of single composite sandwich beam in resisting bending and shear forces were then determined by testing them in horizontal and vertical orientations and with a shear span-to-depth ratio varying between 0.5 and 12. The results showed that the horizontal sandwich beams performed better under bending while vertical sandwich beams were more effective in resisting shear. It was also found that the beam orientation has more influence on the load carrying capacity and stiffness properties than changing the shear span-to-depth ratio.

The structural integrity and composite action between the sandwich panels and epoxy polymer matrix were investigated. The effects of binder properties, bond length, bond thickness

and bond width were investigated to evaluate the bond behaviour of a composite sandwich panel and epoxy polymer matrix. The results indicated that the bond thickness has the greatest influence on the bond strength followed by the properties of polymer matrix, bond length and bond width. A bond thickness of 5 mm, bond length of 70 mm and using polymer matrix with 40% filler and 60% resin (by volume) can eliminate failure in the glue line and promote failure in the sandwich panels. Using these bond parameters, full-scale layered sandwich beams were manufactured and their structural behaviour was evaluated under four-point bending and asymmetrical beam shear tests. Results showed that the binding of sandwich panels using epoxy polymer matrix can prevent the wrinkling and buckling of the fibre composite skins as well as the indentation in the phenolic core. This concept increased the bending and the shear strength of the vertically oriented beams by as much as 25% and 100%, respectively, compared to single sandwich beams. Using the same amount of material, the vertically layered beams exhibited similar bending strength and 50% higher shear strength but only 7% lower effective modulus of elasticity compared to horizontally layered beams. More importantly, the layered sandwich beams were found to have strength and stiffness similar to the hardwood timber.

The optimal design of layered sandwich beams for railway sleepers and the performance evaluation under static loads were conducted as the last study. The optimal shape of sleeper under quasi-static load was obtained using topology optimisation. The optimal sleeper shape requires only 50% volume of materials compared to a rectangular timber sleeper. Moreover, the rail seat and centre bending moments, shear strength, screw holding capacity, and electrical resistance of optimised composite sleeper are higher than the traditional hardwood timber and exceed considerably the performance requirements for a railway sleeper. The handling, installing and fastening system of this composite sleeper were similar to timber and require the same equipment and machineries. A total of 50 sleepers have been installed on a trial basis in the Southern line rail track at Nobby, Queensland, which are performing very well and are expected to outperform its design life.

An in-depth understanding of the behaviour of a new type of composite sleepers made from layered sandwich panels bonded by epoxy polymer matrix was the significant outcome of this study. The experimental data, simplified theoretical models and finite element simulations derived from this study can be used as important tools for a safe design of composite railway sleepers. The optimal sleeper shape proposed in this study can provide a cost-effective alternative to timber sleepers in a mainline track to decrease railway track maintenance, and provide a totally recyclable and sustainable sleeper technology.

## Certification of Thesis

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

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

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## Statements of Contributions

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

- **Article I:** Wahid Ferdous and Allan Manalo, (2014). "Failures of mainline railway sleepers and suggested remedies – Review of current practice" *Engineering Failure Analysis*, vol. 44, pp. 17–35. (Top 10% journal; Impact Factor: 1.676 and SNIP: 1.681). DOI: <http://dx.doi.org/10.1016/j.engfailanal.2014.04.020>

The overall contribution of *Wahid Ferdous* was 60% to the concept development, analysis, drafting and revising the final submission; *Allan Manalo* contributed the other 40% to concept development, analysis, editing and providing important technical inputs.

- **Article II:** Wahid Ferdous, Allan Manalo, Gerard Van Erp, Thiru Aravinthan, Sakdirat Kaewunruen, and Alex Remennikov, (2015). "Composite railway sleepers – recent developments, challenges and future prospects" *Composite Structures*, vol. 134, pp. 158–168. (Top 10% journal; Impact Factor: 3.858 and SNIP: 2.033) DOI: <http://dx.doi.org/10.1016/j.compstruct.2015.08.058>

The overall contribution of *Wahid Ferdous* was 60% to the concept development, analysis, drafting and revising the final submission; *Allan Manalo*, *Gerard Van Erp*, *Thiru Aravinthan*, *Sakdirat Kaewunruen* and *Alex Remennikov* were contributed to the concept development, analysis, editing and providing important technical inputs by 20%, 5%, 5%, 5% and 5%, respectively.

- **Article III:** Wahid Ferdous, Allan Manalo, Thiru Aravinthan and Gerard Van Erp, (2016). "Properties of epoxy polymer concrete matrix: Effect of resin-to-filler ratio and determination of optimal mix for composite railway sleepers" *Construction and Building Materials*, vol. 124, pp. 287–300. (Top 10% journal; Impact Factor: 3.169 and SNIP: 2.339). DOI: <http://dx.doi.org/10.1016/j.conbuildmat.2016.07.111>

The overall contribution of **Wahid Ferdous** was 70% to the concept development, design of experiments, experimental works, analysis and interpretation of data, drafting and revising the final submission; **Allan Manalo**, **Thiru Aravinthan** and **Gerard Van Erp** were contributed to the concept development, design of experiments, analysis and interpretation of data, editing and providing important technical inputs by 20%, 5%, and 5%, respectively.

- **Article IV:** Wahid Ferdous, Allan Manalo and Thiru Aravinthan, (2017). "Effect of beam orientation on the static behaviour of phenolic core sandwich composites with different shear span-to-depth ratios" *Composite Structures*, vol. 168, pp. 292–304. (Top 10% journal; Impact Factor: 3.858 and SNIP: 2.033).  
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- **Article V:** Wahid Ferdous, Allan Manalo and Thiru Aravinthan. "Bond behaviour of composite sandwich panel and epoxy polymer matrix: Taguchi design of experiments and theoretical predictions" *Construction & Building Materials*. vol. 145, pp. 76–87. (Top 10% journal; Impact Factor: 3.169 and SNIP: 2.339).  
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- **Article VI:** Wahid Ferdous, Allan Manalo, Thiru Aravinthan and Amir Fam. "Flexural and shear behaviour of layered sandwich beams" *Composite Structures*. Elsevier (Under review, Submitted on 21 March 2017). (Top 10% journal; Impact Factor: 3.858 and SNIP: 2.033).  
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- **Article VII:** Wahid Ferdous, Allan Manalo, Gerard Van Erp, Thiru Aravinthan and Kazem Ghabraie. "Evaluation of an innovative composite railway sleeper for a narrow gauge track under static load" *Journal of Composites for Construction*. ASCE (Under review, Submitted on 25 March 2017). (Top 10% journal; Impact Factor: 2.648 and SNIP: 1.834).  
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# Introduction

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## Background and motivation

Australia has one of the longest railway networks in the world with millions of sleepers manufactured every year to satisfy demand for network expansions and line upgrades. The railway sleepers, which are the beams laid underneath the rails to support a track, have traditionally been made from timber, steel and concrete. A detail track structure component including sleeper are presented in Figure 1. The main functions of a sleeper are to transfer wheel loads from the rails to the track ballast and subgrade, and hold the rails to the correct gauge (Selig and Waters, 1994).

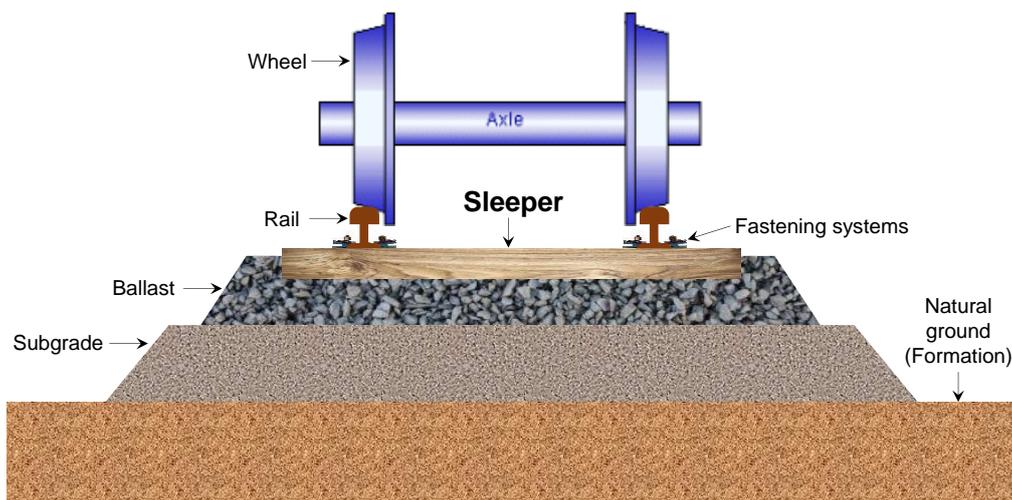


Fig. 1: Track structure components

Hardwood timber is the preferred material for railway sleepers. Timber sleepers are adaptable and have excellent electrical and sound-insulating properties. Approximately 15 million timber sleepers are needed every year around the world for maintaining the current demand (FIB, 2006). The low durability of timber increases the maintenance cost significantly. It has been reported that over 12 million timber sleepers are replaced every year in the USA due to in-service damage resulting in splitting and excessive wearing at a cost of around \$500 million (Qiao et al., 1998). In Australia, nearly 2.5 million timber sleepers are required per year for maintaining the Australian railway lines that equates an annual cost of \$150 million. Moreover, approximately 470 mature hardwood trees need to be cut down for each kilometre of timber track construction. The felling of huge numbers of trees for timber sleepers has a negative impact on the environment. In addition, the high-quality hardwood timber is becoming

scarcer as the harvested areas for quality hardwood trees are reducing. In order to address these issues, the Queensland Railway (QR) of Australia has adopted a strategy of replacing timber sleepers by the alternative sleepers on a substantial basis to meet demands. Recently, the QR has expressed their interest to purchase up to 130,000 (115 mm depth) alternative sleepers, per annum from 2018 to 2023. This strategic plan is not only taken by the QR but also it is the current approach for sleeper maintenance all over the world.

Several sleeper technologies have been developed as a potential alternative to timber sleepers. These sleepers are manufactured either from recycled plastic materials without fibre (Figure 2a) or from polymer materials with high volume of fibres (Figure 2b). The innovative design of KLP recycled plastic sleeper in Figure 2(a) reduced 35% volume of materials from the traditional rectangular shaped sleeper. While the recycled plastic sleeper technologies are offering environmentally friendly products with a reasonable price, they have gained limited acceptance by the railway industry due to their limited strength and stiffness. Moreover, the light weight of plastic sleepers and low resistance to the mechanical connection are two major concerns for maintaining the track stability (Kaewunruen, 2010). Research and development have now focused on fibre reinforced polymers to engineer the strength and stiffness properties suitable for railway sleeper application.

The University of Southern Queensland has a long history of fibre composite sleeper development research started in early 2000. Manalo and Aravinthan (Manalo and Aravinthan, 2012) investigated the behaviour of composite sleepers from glued sandwich panels for railway turnout applications. Figure 2(b) shows one of the earliest technologies of such developments (Van Erp and Mckay, 2013, Van Erp, 2015). These technologies were developed with the depth, stiffness and weight similar to the hardwood timber sleepers (Van Erp, 2015, Manalo, 2011). They are made of polymer concrete with glass fibre reinforcement, tailored the weight to 61 kg, have superior electrical resistance, excellent design flexibility, good flexural and shear strength, easy drilling, good fire performance (due to the presence of fire retardant filler in polymer coating) and can be fitted with standard fasteners. The revolutionary shape provides excellent resistance against lateral movement that increase the track stability. Trial installation of these sleepers in tracks showed satisfactory performance under actual service conditions. However, the variable section of the sleeper makes the manufacturing process more complex which outweighs the cost reduction due to material savings. There is a continuous need therefore to further engineer the composite sleepers to achieve reasonably priced sleepers without compromising their structural performance.



(a) recycled plastic sleeper



(b) fibre reinforced polymer sleeper

Fig. 2: Recently developed composite sleeper technology

It is yet not fully understood how the optimal composite sleeper will perform under vertical wheel load. This study investigated the behaviour of an innovative fibre composite railway sleeper manufactured from composite sandwich panels bonded with epoxy polymer matrix under static loading condition. This alternative sleeper technology aims to replace the existing timber sleepers by maintaining the depth, stiffness and weight similar to the hardwood timber. To achieve this objective, this study focused on designing a suitable epoxy polymer matrix, characterising the properties of sandwich panels, investigating the bond behaviour between the epoxy polymer matrix and sandwich panels, and structural performance of the bonded sandwich beams. Numerical and experimental studies are also implemented to assess the performance of the optimal composite railway sleepers.

## Objectives

The aim of this study is to investigate the behaviour of an alternative composite sleeper made by combining sandwich panels and epoxy-based polymer matrix. Understanding the behaviour of constituent materials and structural performance of this innovative railway sleeper are essential before their application in rail-track. The four specific objectives of this study are:

1. Review and understand the failure mechanisms and challenges of the existing materials for railway sleepers;
2. Design a suitable polymer matrix for binding and coating structural sandwich panels, and evaluate the mechanical behaviour of sandwich panels in vertical and horizontal orientations at different shear span-to-depth ratio;
3. Investigate the bond behaviour between sandwich panels and polymer matrix, and examine flexural and shear behaviour of beams manufactured from these materials; and
4. Evaluate the performance of an optimal composite sleeper for a narrow-gauge rail track.

## Scope and limitations

To achieve these objectives, the work has been subdivided into a number of discrete tasks and the scope of the study are summarised as follows:

- a) The failure mechanisms of timber, steel and concrete railway sleepers are exhaustively reviewed and possible solutions are suggested for minimising the premature failure of traditional sleepers. The recent development of existing alternative sleeper technologies are also reviewed comprehensively and the critical barriers to their widespread acceptance and applications are identified. Design approaches for overcoming the challenges in the utilisation and acceptance of composite sleeper technologies are suggested.
- b) The limited information on the design of epoxy polymer matrix for coating and binding sandwich panels suggested an investigation required for a suitable mix proportion. The effect of the resin-to-filler ratio on the thermal, physical, mechanical and durability properties of polymer matrices composed with epoxy resin and light weight filler materials are investigated, although some of the information such as the name and mixing ratio of fillers and resins are not provided in details due to the commercial-in-confidence. The optimal mix is selected using Analytic Hierarchy Process (AHP) based on the performance requirements of coating and sleepers as there is no standard guidelines for selecting coating materials of sleeper. Moreover, understanding the behaviour of sandwich panels in different orientations and at different shear span-to-depth ratios are necessary for their effective utilisation as the panels are the main structural component for railway sleepers. The static behaviour of phenolic cored sandwich beams with glass fibre skins are investigated under 4-point bending in the horizontal and vertical orientations at shear span-to-depth ratios between 0.5 and 12. The mid-span displacement is determined using experimental results in beam theory due to the limited space underneath the beam that not allowed to installed displacement transducer. The average value of elastic modulus in both horizontal and vertical orientations (termed as horizontal and vertical average) are determined to have a comparative evaluation on the effect of orientations on the flexural stiffness of the sandwich beams. The failure loads are estimated theoretically.
- c) The bond behaviour between sandwich panels and epoxy polymer matrix is important to understand their structural integrity and composite action when bonded together. An investigation into the effects of the matrix properties, bond length, bond thickness, and

bond width on the bond behaviour between a sandwich panel and polymer matrix is implemented. The effect of these parameters on bond behaviour is not fully understood as some study observed an inverse relationship between shear bond strength and bond length due to the greater moment development while others observed a different behaviour. To keep the original properties of sandwich panels, a dust free and non-abraded samples are used to prepare the bond specimens. The experimental program is designed by Taguchi method while the influence of each parameter is determined by the Analysis of Variance (ANOVA). A theoretical model is proposed for predicting the failure load and failure mode of the bonded sandwich panels considering some assumptions, particularly, ignoring the effect of bending moment at joint which may have an influence on thicker bond. To simplify the theoretical model, the slight non-linear variation of the experimental results is considered a linear variation. The validity of the model is specified with the limit based on the range of investigated parameters. After this, an investigation on the Layered Sandwich Beams (LSB) is important to determine the suitability of this novel beam concept. The flexural and shear behaviour of LSB are investigated in horizontal and vertical orientations under 4-point bending and asymmetrical beam shear tests. The fundamental behaviour of the LSB are predicted by the Finite Element Analysis (FEA).

- d) The performance of an innovative and optimal composite railway sleeper for a narrow-gauge railway track is evaluated. The vertical deflection and sleeper-ballast contact pressure of the optimised sleeper are checked by finite element simulation and compared with a traditional timber sleeper. The performance of optimal sleeper including rail-seat vertical load capacity, centre bending, shear capacity, screw holding capability and electrical resistance are evaluated experimentally and the sleepers are installed in rail-track for a trial.

Although a number of composite sleepers have been installed in the rail-track for a trial and in-track performance evaluation, however, the following investigations that are necessary for their widespread acceptance but beyond the scope of this study due to the time limitations are:

- Dynamic impact and fatigue behaviour;
- Durability and environmental aspects;
- Life cycle cost analysis; and
- In-track performance investigation over the years.

## Thesis organisation

This thesis is composed of an introduction that highlights the research theme, extensive review of literature that addressed the first objective, five major studies that cover the other three objectives, and a conclusion that summarises the findings and contributions of this study. A total of seven high quality journal articles produced from this research are presented below:

### Articles from study 1:

- **Article I**

Wahid Ferdous and Allan Manalo, (2014). "Failures of mainline railway sleepers and suggested remedies – Review of current practice" *Engineering Failure Analysis*, vol. 44, pp. 17–35. (Top 10% journal; IF: 1.676 and SNIP: 1.681).

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- **Article II**

Wahid Ferdous, Allan Manalo, Gerard Van Erp, Thiru Aravinthan, Sakdirat Kaewunruen, and Alex Remennikov, (2015). "Composite railway sleepers – recent developments, challenges and future prospects" *Composite Structures*, vol. 134, pp. 158–168. (Top 10% journal; IF: 3.858 and SNIP: 2.033).

DOI: <http://dx.doi.org/10.1016/j.compstruct.2015.08.058>

### Articles from study 2:

- **Article III**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan and Gerard Van Erp, (2016). "Properties of epoxy polymer concrete matrix: Effect of resin-to-filler ratio and determination of optimal mix for composite railway sleepers" *Construction and Building Materials*, vol. 124, pp. 287–300. (Top 10% journal; IF: 3.169 and SNIP: 2.339).

DOI: <http://dx.doi.org/10.1016/j.conbuildmat.2016.07.111>

- **Article IV**

Wahid Ferdous, Allan Manalo and Thiru Aravinthan, (2017). "Effect of beam orientation on the static behaviour of phenolic core sandwich composites with different shear span-to-depth ratios" *Composite Structures*, vol. 168, pp. 292–304. (Top 10% journal; IF: 3.858 and SNIP: 2.033).

DOI: <http://dx.doi.org/10.1016/j.compstruct.2017.02.061>

### Articles from study 3:

- **Article V**

Wahid Ferdous, Allan Manalo and Thiru Aravinthan. "Bond behaviour of composite sandwich panel and epoxy polymer matrix: Taguchi design of experiments and theoretical predictions" *Construction & Building Materials*, vol. 145, pp. 76–87. (Top 10% journal; IF: 3.169 and SNIP: 2.339).

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- **Article VI**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan and Amir Fam. "Flexural and shear behaviour of layered sandwich beams" *Composite Structures*. Elsevier (Under review, Submitted on 21 March 2017; Top 10% journal; IF: 3.858 and SNIP: 2.033).

Ref. No.: COST\_2017\_822

### Article from study 4:

- **Article VII**

Wahid Ferdous, Allan Manalo, Gerard Van Erp, Thiru Aravinthan and Kazem Ghabraie. "Evaluation of an innovative composite railway sleeper for a narrow-gauge track under static load" *Journal of Composites for Construction*. ASCE (Under review, Submitted on 25 March 2017; Top 10% journal; IF: 2.648 and SNIP: 1.834).

Ref. No.: CCENG-2161

In addition, the performance of heavy-duty sleeper manufactured from sandwich panels bonded with polymer matrix is provided in *Appendix A*. The major findings of this study are presented in several national and international reputed conferences, which are summarised in *Appendix B*. Where necessary, the supporting information of figures are provided in *Appendix C*. The copyright information of the published articles are given in *Appendix D*.

The *first objective* of this study is to review and understand the failure mechanisms and challenges of the existing materials for railway sleepers are presented in *Article I* and *Article II*. The failure mechanisms for traditional timber, concrete and steel sleepers are reviewed and several approaches to minimise these failures are suggested in *Article I*. This article concluded that the composite sleepers can be an alternative technology to replace the existing timber sleepers. Therefore, *Article II* reviewed the recent developments, challenges and future prospects of the composite sleeper technology. This review article found that a high performance fibre composite sleeper can be manufactured from a number of sandwich panels

bonded together with a suitable binder. Moreover, a more effective usage of fibre composites can minimise the cost of production. Addressing these research gaps have been the main motivation of this study.

The *second objective* of this study is to design a suitable polymer matrix for binding and coating structural sandwich panels, and to evaluate the mechanical behaviour of sandwich panels in vertical and horizontal orientations at different shear span-to-depth ratios which are addressed in *Article III* and *Article IV*, respectively. The epoxy polymer matrix appear to offer possibilities for meeting the binding requirements of sandwich panels with certain mixing proportions. The results from the investigation of sandwich panel has suggested that the composite sandwich panel has the potential to meet the performance requirements of railway sleeper if several layers of panel are bonded together. The question now arises how effective the polymer matrix is as a binder of sandwich panels. It is addressed in third objective.

The *third objective* of this study is to investigate the bond behaviour between sandwich panels and epoxy polymer matrix, and to examine the flexural and shear behaviour of layered sandwich beams that are presented in *Article V* and *Article VI*, respectively. The recommended polymer matrices obtained from Article III are used in Article V. Moreover, Article V recommended the most suitable bond thickness that are used in Article VI for manufacturing beams. The investigation on horizontal and vertical orientations of layered sandwich beams (Article VI) found a particular orientation is more suitable for railway sleeper, and that specific orientation is considered for designing railway sleepers in Article VII.

The last and *fourth objective* of this study is to evaluate the performance of a new composite railway sleeper for a narrow-gauge railway track which is addressed in *Article VII*. Matlab optimisation code is implemented to determine the optimal sleeper shape under quasi-static load and its behaviour is evaluated using finite element simulation. The performances of the innovative railway sleeper are evaluated experimentally and from which the conclusions are made on whether or not the composite railway sleeper manufactured from sandwich panels bonded with epoxy polymer matrix a suitable replacement for existing timber sleepers.

For better understanding the link among the studies and articles, the flow of the thesis is graphically presented in Figure 3.

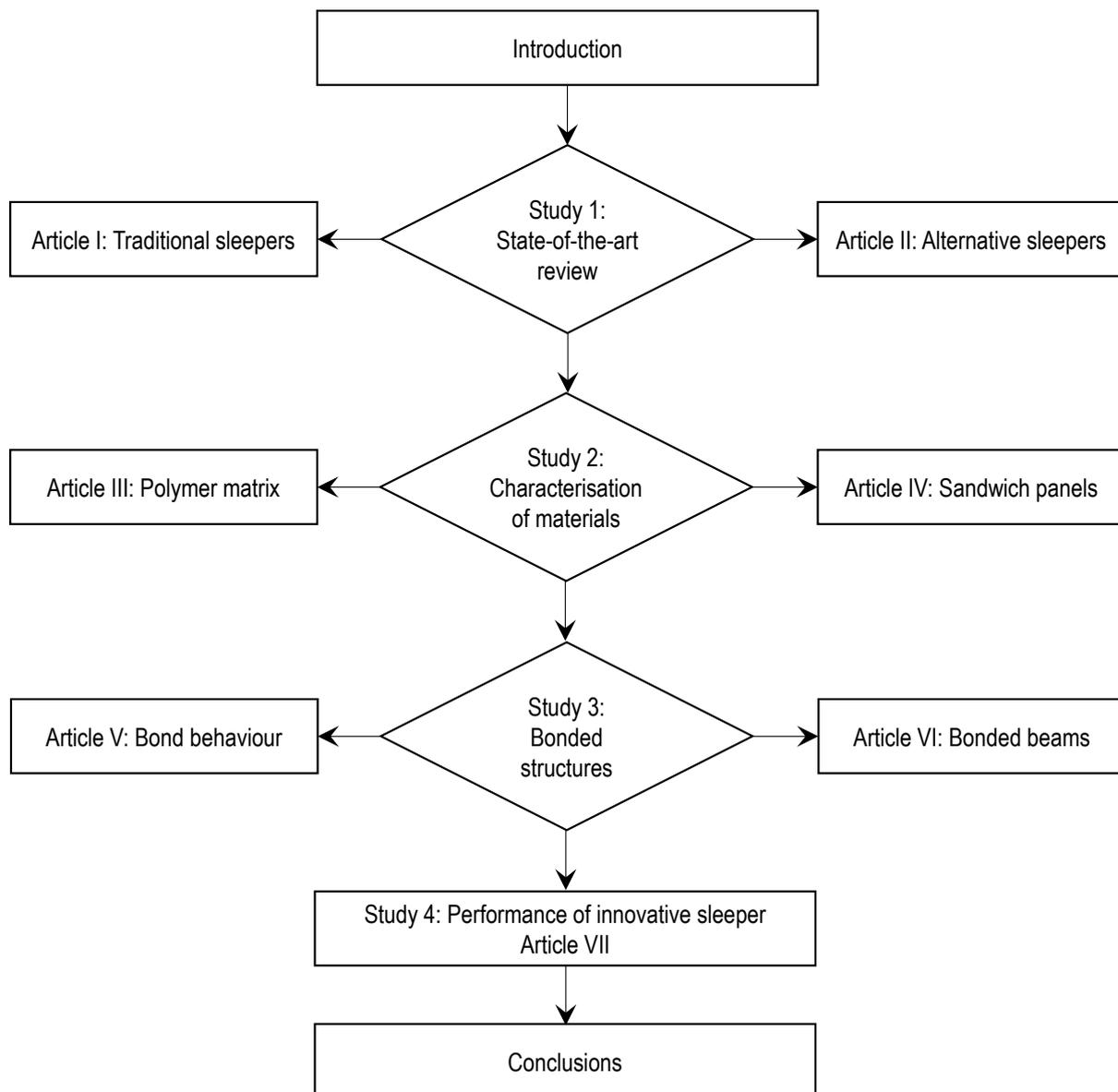


Fig. 3: Flow diagram of the thesis

## Summary

The premature failures of traditional timber sleepers significantly increase the track maintenance costs. The railway industry is now looking for alternative sleepers for replacing existing timber. The application of glued fibre composite sandwich panels in a structural beam has inspired the use of these materials for railway sleepers. Although a number of composite sleeper technologies have been developed in different parts of the world, their uptake in the market is extremely slow due to either limited structural performance or prohibitive cost. Overcoming these challenges is the main objective of this study to promote the widespread acceptance and use of composite sleepers.

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## *Study 1*

### *Challenges in available sleeper materials – A critical review*

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#### **Article I: Failures of mainline railway sleepers and suggested remedies – Review of current practice**

Sleeper replacement is majority of the track maintenance cost due to frequent failing of currently available sleeper materials. *Article I* provided a critical review of literature to identify the different causes of premature failures of traditional sleeper materials, i.e. timber, steel and concrete. This extensive review of literature also identified different protective methods to prevent premature sleeper failures and minimise track maintenance cost. Moreover, it provided an overview of the research and development on alternative sleeper materials, particularly on fibre composites alternatives and their potential to solve many problems of traditional sleeper materials. From this review, it was identified that a more rigorous examination focusing on fibre composite sleepers is necessary to gain a better understanding on the different challenges in using this new and emerging sleeper technology and to identify effective options for its wider acceptance in the railway industry.

#### **Article II: Composite railway sleepers – Recent developments, challenges and future prospects**

Significant efforts have been provided towards the development of fibre composite sleeper alternatives for replacing timber sleepers. *Article II* rigorously reviewed these recent developments to identify the challenges and to recommend innovative solutions for the widespread applications. Recycled plastic sleepers (photos are provided in Appendix C.1) are low cost but their limited strength, stiffness and dynamic properties are incompatible with those of hardwood timber for railway applications. On the other hand, the prohibitive cost and limited understanding of structural performance of fibre reinforced polymer sleepers were identified as the major challenges. The many advantages of sandwich structures bonded with a suitable binder favour its application to railway sleepers. A detailed understanding on the behaviour of novel sandwich structures and the polymer matrix and their contributions in carrying the load are needed to further optimise their usage in a cost-effective composite sleeper technology. This has been the main motivation of this study as were addressed in Studies 2 to 4.



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## Review

# Failures of mainline railway sleepers and suggested remedies – Review of current practice



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## ABSTRACT

Over the last two decades, the premature failures of traditional railway sleepers have significantly increased the track maintenance costs. The primary obstacle to minimising this problem is the lack of understanding of the mechanism of sleeper degradation. This paper discusses the different deterioration mechanisms for traditional timber, concrete and steel sleepers and the potential protective measures to minimise these problems. This paper exhaustively reviews the failure mechanisms of these three commonly used sleeper materials with suggested solutions. Fungal decay, end splitting and termite attacks has been identified as the principal causes of timber sleeper failures. On the other hand, concrete sleepers are vulnerable to rail-seat deterioration, cracking and damaging under different loading conditions and adverse environments. Steel's risk of corrosion and fatigue cracking makes it an inferior-quality material for sleeper. Solution approaches are recommended and provided in this paper in order to the best utilise these different railway sleeper materials. New materials are also introduced as effective alternative to replace the traditional railway sleepers.

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## 1. Introduction and motivation

The Australian railway transport industry may realise a potential savings of \$A80 million per annum in its operating cost if further improvements could be made in its railway operation and maintenance [1]. The premature deterioration of railway sleepers has become of great concern over the last two decades even the sleeper perfectly supported by the underlying ballast. For many years, timber, concrete and steel, which have targeted life spans of 20, 50 and 50 years, respectively have been used as sleeper materials. However, under certain circumstances and in particular environments, these traditional sleepers have not satisfactorily met the performance requirements due to their unexpected early failures. It has been reported that over 12 million timber sleepers are replaced every year in the USA due to in-service damage resulting in splitting and excessive wearing at a cost of around 500 million dollars [2] while another report indicates that the cost of sleeper renewal is about 12% of the total maintenance-of-way cost, that is, approximately twice that of the rail renewal [3], which has forced researchers and railway industry to think of effective ways of minimising this problem.

The demand for sleepers has been increasing over time, as the railways plays a significant role in the transport systems. In 2006, the International Federation for Structural Concrete [4] conducted a worldwide survey of annual demands for traditional sleepers in rail networks and is presented in Table 1.

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**Table 1**  
Sleepers in world's railway networks.

Country	Total sleepers in track ( $\times 1000$ )	Demands per year ( $\times 1000$ )		
		Concrete	Steel	Timber
Argentina	–	60	–	–
Australia	600,000	–	150	200
Austria	9000	200	70	100
Belgium	9912	400	2	20
Brazil	50,000	500	60	300
Chile	5300	200	–	–
China	115,000	3000	–	–
Colombia	5080	–	–	–
Czech Rep.	17,000	250	–	3
Denmark	–	150	–	–
France	60,000	800	0	400
Germany	70,000	1400	100	100
Greece	6150	30	5	3
Hungary	20,388	–	–	–
India	163,500	4640	–	–
Italy	40,000	2000	–	–
Japan	34,000	400	–	–
Malaysia	3000	–	–	–
Morocco	5000	–	–	–
Netherlands	8500	400	–	–
Norway	3000	60	–	–
Romania	16,000	12	–	–
Russia	150,000	3500	–	–
S. Africa	43,000	305	0	0
Spain	30,000	1200	0	30
Sweden	19,500	400	–	8
Switzerland	17,000	150	–	–
Taiwan	4000	120	0	12
USA	600,000	1000	10	13,000
UK	45,000	500	400	100
Venezuela	1225	–	–	–

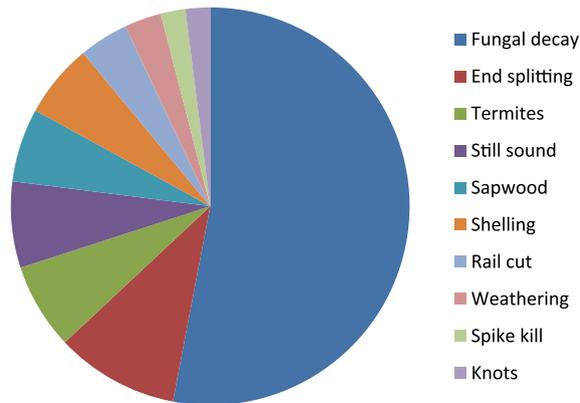
This survey illustrates that concrete is the dominant material for sleepers in many countries except in the USA where there is a major demand for timber sleepers. It is estimated that, there are currently approximately three billion sleepers in the world's railway networks. Over 400 million of these sleepers are made from concrete and 2–5% of them requires replacement every year due to their premature failure [5]. Similarly, Australia has one of the largest rail networks in the world where approximately 13% are made from steel [6]. A sleeper's ability to resist cracking, oxidation, chemical degradation, delamination and wear damage for a specified period of time, under appropriate load conditions and specified environmental conditions, has become of great concern. Research and innovation are now focusing on the durability of sleepers as the lack of understanding of sleeper degradation mechanisms is a great concern [7]. This paper aims to present these failure mechanisms and provide suggestions for minimising them to provide useful information to engineers, designers as well as asset owners.

## 2. Failure of timber sleeper

Proper investigation of the causes of premature failures of sleepers to minimise the cost of track maintenance and to improve the track efficiency, is necessary. The Railway of Australia (ROA) [8] surveyed several states in Australia in order to understand the causes and modes of failure of timber sleepers. For this purpose, it examined 2200 timber sleepers in Queensland railway tracks and found different reasons for the sleeper damage including fungal decay, end splitting, termites, still sound, sapwood, shelling, rail cut, weathering, spike kill and knots (Fig. 1). Of those failure types, fungal decay (53%), end splitting (10%) and termite attacks (7%) were found to be the principal causes of timber sleeper failure.

### 2.1. Fungal decay

Fungal decay is the predominant mode of timber sleeper failure as timber is susceptible to bio-deterioration from many micro-organisms because timber is an organic material. A fungus can lie dormant in timber until it obtains at suitable environment containing moisture, oxygen and nutrients. Railway sleepers can absorb moisture, especially in rainy seasons, that makes fungi reactive and when they are in timber, can spread from one sleeper to another across non-nutritional surfaces that adversely affect a track's structural integrity [9,10]. Fig. 2 presents the fungal decay of a timber sleeper in a railroad track.



**Fig. 1.** Common causes of timber sleeper failure.

## 2.2. End splitting

The failure of a timber sleeper due to splitting at its end is another common failure mode which arises when the sleeper is subjected to large transverse shear loading [6,11]. Also the rail is connected to each sleeper by a proper fastening system which includes a rail fastening clip, sleeper plate and screw-spike. During insertion of the screw-spike, a sleeper may split over time (Fig. 3).

## 2.3. Termite attacks

Termite attacks in timber sleepers have been identified as another significant cause of sleeper damage and it has been reported that the worldwide cost of repairing structures and preventing these attacks is approximately one billion dollars annually [12]. When a termite attacks timber, it consumes all the cellulose-containing materials and causes permanent damage [13]. Invasions of termites have been found in a cracked sleeper's pocket even after it was treated with creosote (Fig. 4).

## 3. Failure of concrete sleeper

The many advantages of concrete technology led to its use for sleepers in the 1950s. Nowadays, approximately 500 million railway sleepers in the world's railway networks are made from prestressed concrete and, every year, the demand for them constitutes more than 50% of total demand [4,5]. In Australia, the majority of modern railway sleepers are made from mono-block prestressed concrete which was first used in 1970 [15]. Over the last three decades, researchers in different parts of the world have been investigating the failures of concrete sleepers and looking for sustainable solutions. Dyk et al. [16] ranked the most common causes of concrete sleeper failures using the results obtained from their North American and worldwide surveys (Fig. 5). They indicated that the most critical cause of failure in concrete sleeper is rail-seat



**Fig. 2.** Failure of timber sleeper due to fungal decay [6].



Fig. 3. End splitting of timber sleeper.



Fig. 4. Termite attacks in timber sleeper [14].

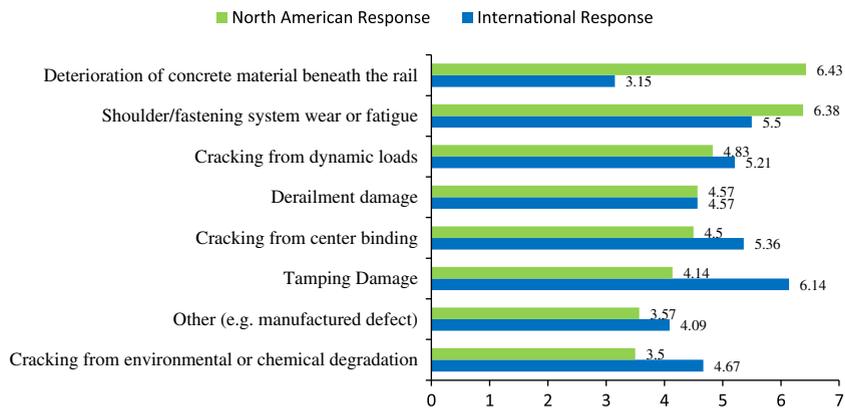


Fig. 5. Most critical concrete sleeper failures.

deterioration in the North America and the installation or tamping damage globally. However, these failure modes can vary from country to country as geometry and operation practices are different.

### 3.1. Rail-seat deterioration

The most common mode of failure for modern prestressed concrete sleepers in different parts of the world, particularly in western Canada and the northern United States, is the rail-seat deterioration. This failure is caused either by rail-seat

abrasion, hydro abrasive erosion, hydraulic pressure cracking, freeze thaw cracking or chemical deterioration [17] of which rail-seat abrasion is the most critical. Rail-seat abrasion occurs due to the relative movements between the rail pad and concrete rail seat which subsequently resulting in the gradual wearing away of the cement paste from the concrete by frictional forces as the abrasive fine particles and the water penetrates the rail-seat pad interface creating an ideal situation for abrasion. Zeman et al. [18] and Kernes et al. [19] have investigated the mechanism of rail-seat abrasion and found that, when the wheels transfer loads from the pad to sleepers through the rail, a shear force acts on the rail-pad interface. Once the shear force exceeds the static frictional force between the bottom of the pad and rail seat, slip occurs and the strain is transferred to the concrete. After a certain period when this strain overcomes the fatigue limit of concrete, deterioration starts and after many loading cycles, a significant amount of particles are torn from the rail-seat position which results in an uneven concrete surface underneath the sleeper pad. Several factors are responsible for the rail-seat abrasion, including the presence of water, heavy axle loads, the failure of fasteners, shoulders or sleeper pads, steep track gradients, and particularly track curves greater than two degrees [20,21]. Fig. 6 shows an abraded rail-seat area in a concrete sleeper. In 2010, the deterioration due to hydraulic-pressure cracking was investigated by Zeman et al. [22] and their results showed that a certain combination of dynamic rail-seat loads, sufficient moisture and sleeper-pad surface generates the high pressure responsible for rail-seat deterioration.

### 3.2. Centre-bound damage

The tensile fracture of a prestressed concrete sleeper may occur in a heavy-duty railway track. González-Nicieza et al. [24] investigated the failure analysis of a railway track used to transport heavy industrial freight with the aim of offering guidance to forensic engineers regarding the failure of railway track foundations. They observed vertical cracks on a damaged sleeper due to a tensile fracture in its upper central segment (Fig. 7a) which later propagated throughout its central segment and formed an 'X' shape before clearly fracturing (Fig. 7b).

A recent study by Rezaie et al. [25] found severe damage in a sleeper caused by longitudinal cracking which was observed even before the sleeper was mounted in a railway track (Fig. 8a). It originated from the rawlplug location due to the pre-tension forces which induce remarkable tensile stress around the rawlplug hole in the transverse direction. During its service



Fig. 6. Failure of concrete sleeper due to rail-seat abrasion [23].

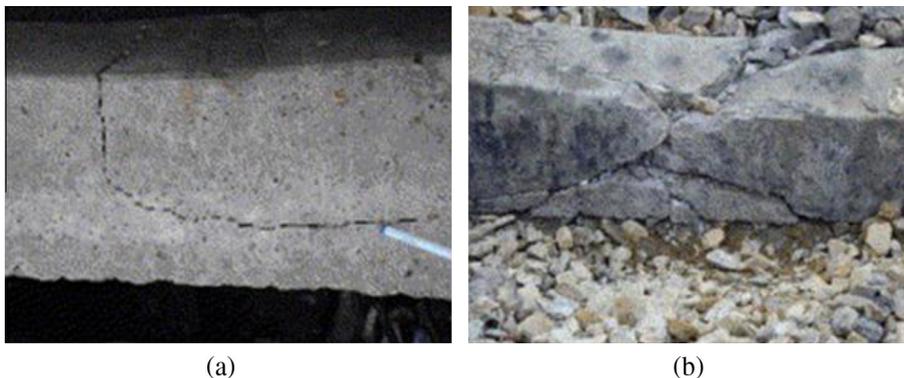
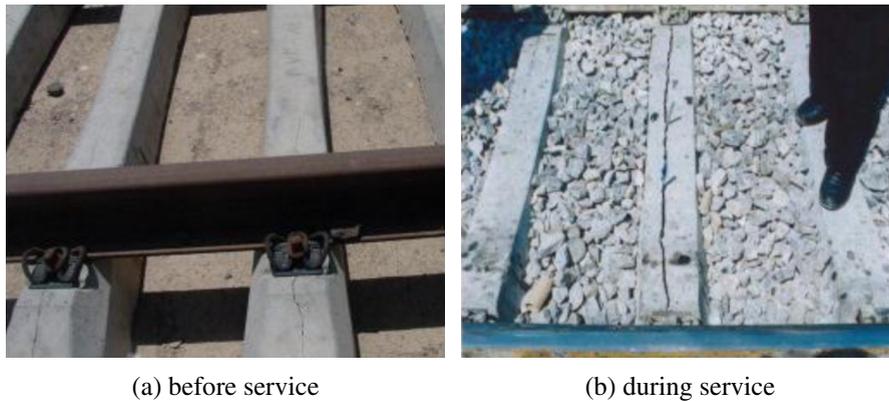


Fig. 7. Concrete sleeper damage due to tensile fracture [24].



(a) before service

(b) during service

**Fig. 8.** Longitudinal cracking due to tensile stress between rawlplugs [25].

life, additional effects such as water freezing and the existence of fine rocks within its rawlplugs can lead to increases in the transverse tensile stress in a sleeper and cause longitudinal cracks to appear (Fig. 8b). Their simulation results also showed that the maximum tensile stress between the two rawlplugs in a fastening system is responsible for the longitudinal cracking. Similar conclusions were drawn by Ma et al. [26] who found that the high shearing tensile stress on the edge of the bolt hole is the main cause of longitudinal cracks in a sleeper.

### 3.3. Derailment

Defects in sleepers, which occur mainly during the operational stage because of manpower faults and existing imperceptible defects in tracks, are considered the ultimate failure as they can cause derailments and render the relevant track inoperable. In 2012, Zakeri and Rezvani [27] observed derailment failures in concrete B70 sleepers in Iranian railways (Fig. 9). The sleepers that are damaged due to derailment need to be replaced which increases the track maintenance costs. The primary causes of derailment failures they identified are due to manpower fault and existing impermissible defects in track.

### 3.4. High-impact loading

The bending cracks in a concrete sleeper are often detected at its mid-span and eventually reduce the sleeper's flexural stiffness. Many railway organisations have observed cracks in concrete sleepers during field inspections, with the primary cause identified as an infrequent but high-magnitude wheel load of short duration, as reported by Murray et al. in 1998 [28,29]. They indicated that this is normally produced by either wheel or rail abnormalities, such as flat wheels and dipped rails, for example, an approximately 400 kN force per rail seat could be generated in 1–10 ms due to 'wheel flats'. Existing design guidelines for a prestressed concrete sleeper are based on only static and quasi-static loading conditions and do not take into account high-magnitude impact loads [30]. A field investigation into passenger lines as well as coal/mine transport in the Wollongong railway's suburban network confirmed that a crack in a sleeper occurred because of the effect of impact



**Fig. 9.** Derailment failure of concrete sleepers [27].

loading (Fig. 10). Recently, a collapsed sleeper was found in another rail track designed for a 30-ton axle load train providing services to the outer city and interstate passenger trains, freight bogies and heavy-haul coal wagons [33]. It was damaged in the rail-seat area and during the failure investigation, a dipped rail joint was found just in front of the sleeper's location. The local track maintenance engineers estimated that there was a 15–25 mm gap in the rail joint at the time of failure which could produce a high-impact load on the sleeper. Fig. 11a illustrates the collapsed railway sleeper and Fig. 11b the joint conditions after the track was repaired. The experimental investigation performed by Kaewunruen and Remennikov [34] determined the ultimate impact capacity of a prestressed concrete sleeper under impact loading which failed due to splitting (Fig. 12a). A similar failure pattern was found during a field investigation which demonstrated the domination of impact loading on sleeper failure (Fig. 12b).

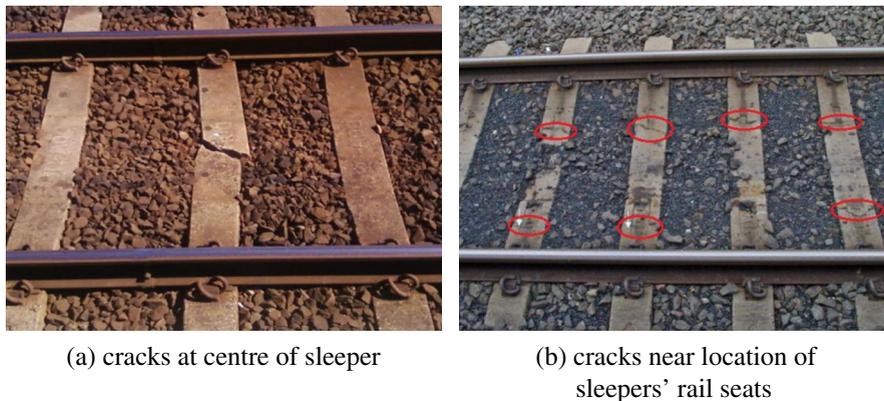


Fig. 10. Cracks in concrete sleepers due to impact loading [31,32].

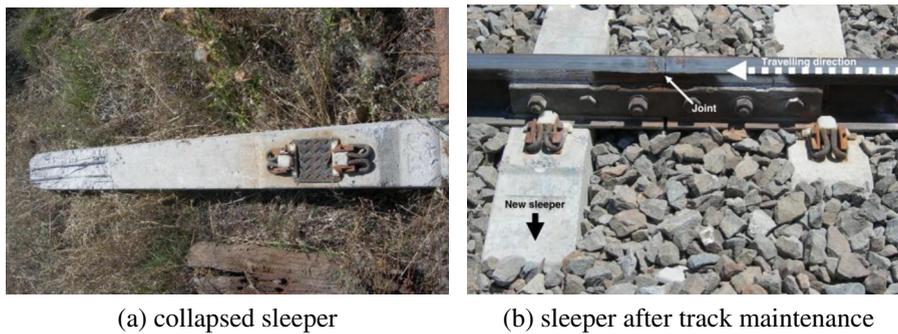


Fig. 11. Impact damage to sleeper due to rail irregularities [33].

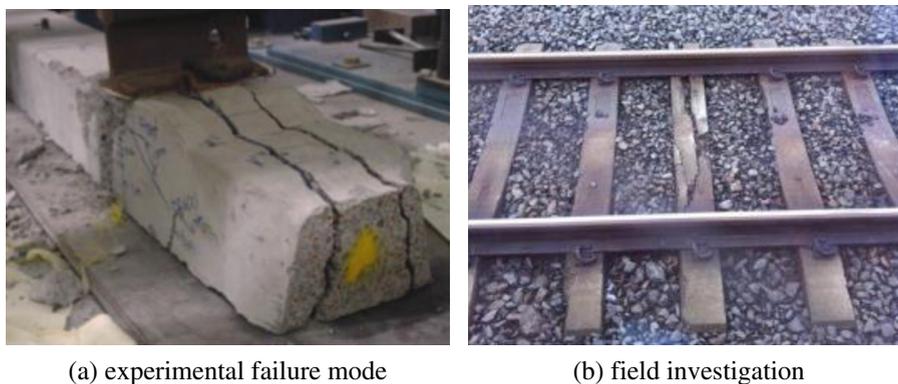


Fig. 12. Splitting failure of concrete sleeper caused by impact loading [34].

### 3.5. Delayed ettringite formation (DEF)

Soil, groundwater and sometimes aggregates may contain sulfates of sodium, potassium, magnesium and calcium which, when present in a solution, react with the tricalcium aluminate or calcium hydroxide components of the cement paste. Such reactions cause expansion which leads to cracking and, finally, deterioration of the concrete [35,36] as depicted in Fig. 13.

DEF caused by an internal sulphate attack can deteriorate concrete sleepers. The earliest observation of it was reported by Tepponen and Eriksson [38] who noted the damage that occurred in concrete sleeper in Finland within 10 years after its manufacture due to the formation of microcracks resulting from the heat treatment applied (75–80 °C for 2.5–4 h) during the pre-casting process. Also, Heinz and Ludwig [39] reported that the deterioration due to DEF does not occur at steam-curing temperatures below 75 °C even if the process takes 16 h. Hime's [40] investigation confirmed that the cracking of prestressed concrete sleepers due to DEF may come after they have been in service for several years (Fig. 14). According to him, in non-air-entrained concrete, the occurrence of DEF depends on the heat-curing temperature (above 60 °C) and the clinkers' sulphate levels. Similarly, Sahu and Thaulow [41] in 2004, found that premature deterioration occurred in a Swedish concrete sleeper within 7 years of its manufacture due to DEF leading to concrete cracks. However, in their research, they mentioned that DEF is dependent not only on the heat of the concrete's curing temperature but also on the composition (alkalis,  $C_3S$ ,  $C_3A$ ,  $SO_3$  and  $MgO$ ) and fineness of the cement, and may occur at temperatures lower than 60 °C if there are unfavourable combinations of these parameters.

### 3.6. Alkali–aggregate reaction (AAR)

The difference between sulphate and alkali attacks is that the reactive substance in the former is cement while, in the latter, it is aggregates [37]. Although the main source of alkalis in concrete is portland cement, sometimes, an additional one is unwashed sand containing sodium chloride while admixtures (super-plasticisers) and mixing water are also

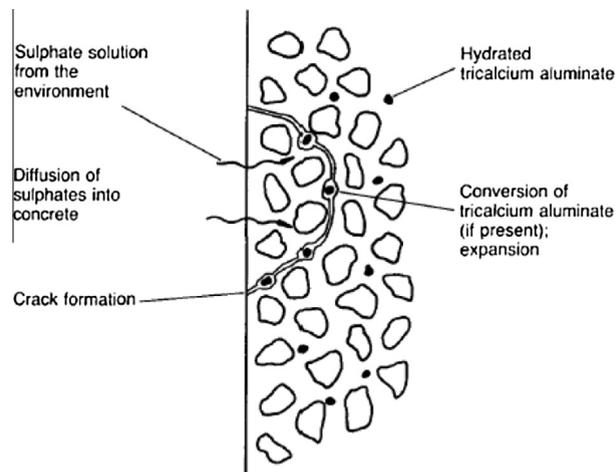


Fig. 13. Effect of sulphate attack [37].



Fig. 14. Cracking of prestressed concrete sleeper due to DEF [40].

considered internal sources [36]. Silica-containing aggregates (e.g., chert, quartzite, opal, strained quartz crystals) could be affected by hydroxyl ions in alkaline cement solutions which may lead to destructive expansion (Fig. 15) as follows:

- Reactive silica + Alkali → Alkali–silica gel
- $\text{SiO}_2 + \text{Ca}(\text{OH})_2 + \text{H}_2\text{O} \rightarrow \text{CaH}_2\text{SiO}_4 \cdot 2\text{H}_2\text{O}$  (Alkali–silica gel)
- Alkali–silica gel + water = expansion, which is responsible for cracking

Shayan and Quick [42] investigated the causes of parallel longitudinal cracking on the top surfaces and map cracking at the ends of prestressed concrete sleepers by examining both cracked and uncracked sleepers which showed that the alkali–aggregate reaction is responsible for sleeper failures. This was also identified by another investigation in China [43] which studied an affected concrete sleeper in the Shanghai region and through its Scanning Electron Microscope/Energy Dispersive X-ray (SEM/EDAX) analysis they found the presence of potentially reactive silica in the concrete sleeper that promoted cracking. Fig. 16 presents the failure of a sleeper due to AAR.

### 3.7. Acid attack in concrete

Concrete containing portland cement is not resistant to attack by strong acids [36,45,46] and the most vulnerable cement hydrate is  $\text{Ca}(\text{OH})_2$  which converts to calcium salts when it comes into contact with an acid [35,37]. Also, calcium silicate

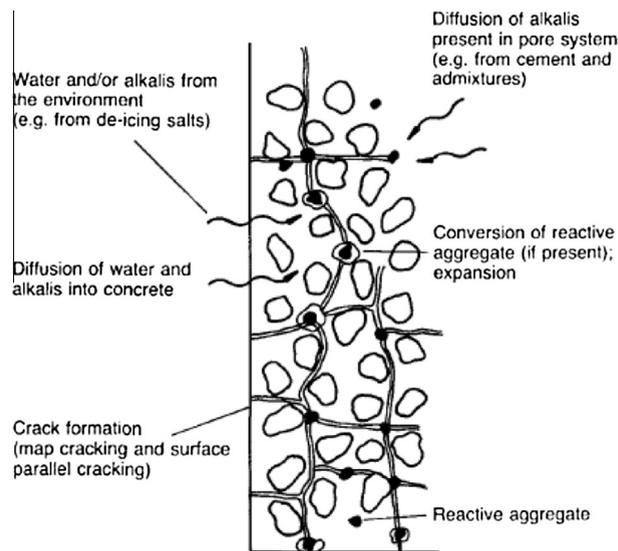


Fig. 15. Effect of AAR [37].



Fig. 16. Cracking in concrete sleeper due to AAR [44].

hydrate (C–S–H) and calcium aluminate hydrate can be attacked by acids [36,37] and due to this reaction, the structure of the hardened cement is destroyed (Fig. 17).

Industries and vehicles emit huge amounts of sulphur dioxide and nitrogen oxide into the atmosphere which are the primary causes of acid rain. This falls not only in areas of high industrial activity and transportation loads but also a long way away as a result of wind action and may harm concrete railway sleepers.

### 3.8. Bar corrosion

The deterioration of a concrete sleeper as a result of an adverse environment was studied by Mohammadzadeh and Vahabi [47] who focused on the impact of the penetration of chloride ion on the reliability index of a B70 prestressed concrete sleeper. Although most studies of sleeper failure have concentrated on damage at the rail-seat location, their research concluded that the mid-span of the sleeper is more vulnerable than its rail seat and the failure is more likely to happen at this

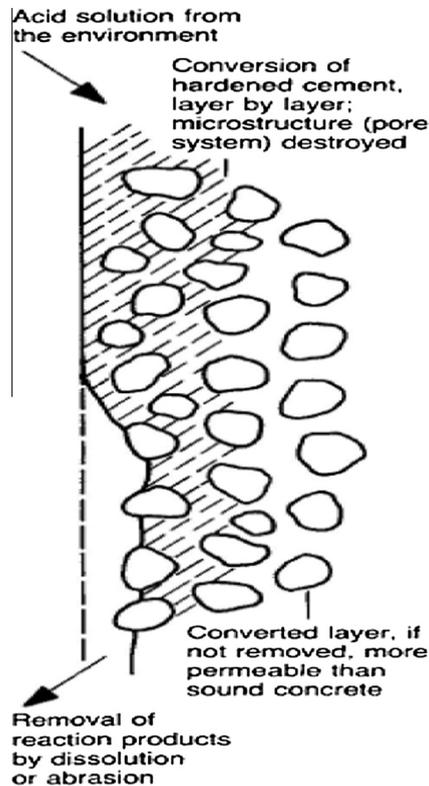


Fig. 17. Effect of acid attack [37].



Fig. 18. Failure of concrete sleeper as result of bar corrosion [47].

point. A large amount of fine-graded soil was found in the area of the sleeper examined and the relative humidity was measured as 30% which is a suitable environment for soils to be spread over sleepers by the wind. Over time, moisture and rain can provide favourable conditions for bar corrosion in concrete, and their observations indicate that the presence of chloride ions which ingress into the concrete and break down the protective iron oxide film is the main factor for the failure of a sleeper from bar corrosion (Fig. 18).

### 3.9. Ice forming in sleeper

Failures of concrete sleepers in a slab track system were studied by Zi et al. [48] who found that 0.22% of sleepers (approximately 1 sleeper in every 300 m of rail track), were damaged in the Kyengbu railway in Korea which was designed for high-speed train transport. According to their field observations, a crack was initiated from the bottom of a sleeper near the fastening bolt and formed a conical shape (Fig. 19). From the results of their experimental and numerical investigations, they concluded that failures occur due to freezing of the water leaking into sleepers which creates an ice pressure of 40 MPa that corresponds to 72–88 kN depending on the area of applied pressure.

## 4. Failures of steel sleepers

A very few studies of steel sleeper failure have been conducted. However, several researchers reported that the steel's risk of corrosion, high electrical conductivity, fatigue cracking in the rail-seat region and the difficulty of packing it with ballast has made it an inferior material for sleepers. Thus, a proper investigation into the reasons for its failure is essential.

### 4.1. Corrosion in steel

Steel sleepers suffer from corrosion in the areas where the supporting soil or ballast is rich in salty elements. The risk of corrosion is much higher than rail although both are made from steel as a sleeper establishes intimate contact with the



Fig. 19. Conical crack due to ice forming in slab track [48].



Fig. 20. Corrosion in steel sleeper [50].

ballast and subgrade materials. Sleepers may come into contact with different salts from soil, groundwater or aggregates which can react with steel, leading to sleeper failure due to corrosion (Fig. 20). Also, other reasons, including metallic slag-based ballast, a continually moist environment and the existence of corrosive materials, can enhance corrosion in a steel sleeper [49].

#### 4.2. Fatigue cracking

Fatigue failure occurs in a railway sleeper because of the repeated stress imposed by cyclic loading and the rail-seat location is subjected to heavy shear that is vulnerable to fatigue cracking. When a train is running over rails, as a sleeper experiences both longitudinal and transverse stresses, a diagonal stress originates its rail-seat location which is usually on its top surface but can also occur in the reverse direction depending on the train's movement and, over time results in fatigue cracking [51].

### 5. Approaches to minimise sleeper failure

Several studies aimed at minimising the problems of railway sleepers have been conducted and some of them already implemented. Some researchers have focused on taking special care of traditional sleepers while others have introduced relatively new materials. In this section the most appropriate method and best practice in reducing sleeper failure in service and in the maintenance work are discussed to provide guidelines for scientific researchers and practicing engineers.

#### 5.1. Timber sleeper

The traditional timber sleepers could be saved from premature deterioration if some special treatments were performed. Thus, several researchers have suggested methods to prevent timber sleeper failure which are presented in the next sections.

##### 5.1.1. Fungal decay and termite attacks

Timber protection methods for controlling fungus and termite attacks in timber structures are quite similar [52] and, over time, several have been studied with impregnation with synthetic chemicals and biological protection techniques the most common. Usually, toxic chemicals which can destroy harmful organisms in timber were used for more than two hundred years because of their relatively low cost. However, environmental agencies have now become concerned about the application of chemical preservatives in timber sleepers and their proper disposal when the sleepers are removed [53]. Recently, Verma et al. [52] and Susi et al. [54] have been emphasising the use of biological wood protection methods in order to address public concerns and conform with new environmental regulations regarding the use of chemicals. These methods involve placing micro-organisms in materials which prevent attacks by species but do not affect the materials' properties. Experimental investigation by Susi et al. [54] found that, biological control of timber degradation can be as effective as chemical protection and has the additional benefit of environmental safety. Fig. 21 is a diagrammatic representation of termite control measures in timber structures.

##### 5.1.2. Controlling end splitting

Splitting at the end of a timber sleeper separates one part of the timber from the other, and plates can be fixed at its ends to minimise separation [10,55]. However this technique only works when the splitting width and length is small, usually no more than 20 mm and 250 mm, respectively. For unseasoned and seasoned sleepers, the accepted limits for the splitting width are 3 mm and 6 mm and, for length 100 mm and the width of the sleeper respectively. Therefore, sleepers which are beyond their acceptance limits but not more than 20 mm in width and 250 mm in length could be saved by providing end-plates. Fig. 22 illustrates salvageable (Fig. 22a) and non-salvageable (Fig. 22b) situations of a timber sleeper.

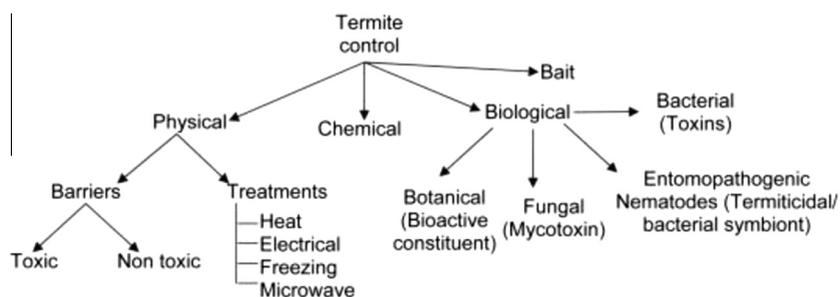


Fig. 21. Termite control measures in timber structures [52].

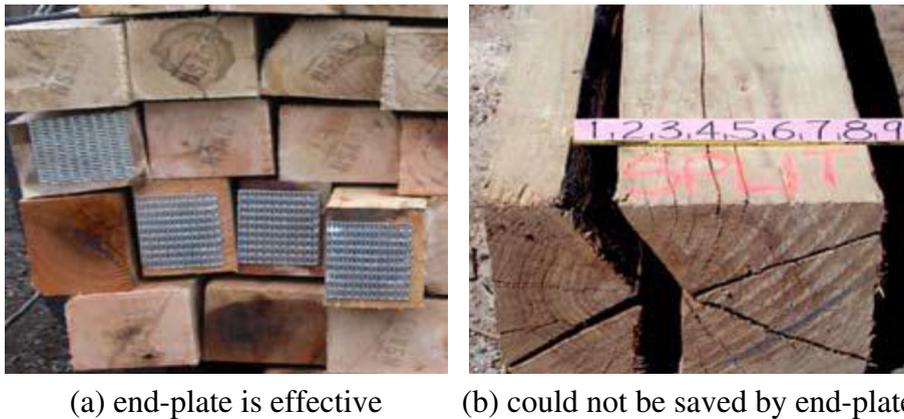


Fig. 22. End-splitting failure minimisation technique [10].

## 5.2. Concrete sleeper

Rail-seat deterioration and concrete cracking were considered as the most critical failure modes for concrete sleeper and several methods to minimise and prevent these types of failure are discussed in the following sections.

### 5.2.1. Preventing rail-seat abrasion

Many studies have focused on minimising or preventing rail-seat deterioration which is identified as the most critical problem for concrete railway sleepers in the North America. In 2003, Peters and Mattson [56] attempted to minimise abrasion using cast-in-place steel plates that covered the rail-seat area. The completion of their experimental program of fatigue testing, which ran for 10 million cycles at a rate of 2.5 cycles per second showed no rail-seat abrasion occurred (Fig. 23). However, this additional steel plate could significantly increase the manufacturing costs of sleepers and the water intrusion below it may deteriorate the concrete in the rail-seat area. This issue should be carefully considered when adopting this approach.

Another approach for preventing abrasion was studied by Peters [57] in which the researcher applied an epoxy coating over the rail-seat region. However, it is not a very convincing option as it is labour intensive, requires track closures during the application and curing of the epoxy, and there is a possibility that the epoxy will wear away over time. Alternative preventive measures considered by researchers include: the addition of fly ash and silica fume to the concrete in the rail-seat area [58]; the introduction of steel fibre-reinforced grout in the rail-seat region during manufacturing [56,59]; the application of multi-layer abrasion-resistant pad assembly [56]; and placing metallic aggregates in the rail-seat area [60]. In 2002, Atis [61] showed that concrete with a high-volume of fly ash has better abrasion-resistant properties and suggested using it in areas where highly abrasion-resistant concrete is required. The concept of improving concrete materials in the rail-seat area aims to restrict the cracking and concrete's permeability that allows water to intrude through a cracked channel into the void structure of the cement paste underneath the sleeper pad. However, although upgrading the concrete materials in the rail-seat region can increase the compressive and tensile strengths of the concrete, its effectiveness against abrasion is unwarranted and better alternative solutions should also be considered [20,58].



Fig. 23. Steel plate covering rail-seat after 10 million cycles [56].

### 5.2.2. Controlling longitudinal crack

The high shearing tensile stress around the rawplug/bolt hole is identified as the main cause of longitudinal cracking and, to minimise it, Ma et al. [26] suggested redistributing it by the use of a special expansive concrete in the inner and ordinary concrete in the outer parts of the bolt-hole area which will produce a radial nested stress on the interface between the two parts through expansion of the inner part and, finally, achieve a significant reduction of the shearing tensile stress. Another method for controlling longitudinal cracks suggested by Rezaie et al. [25] is to place transverse reinforcing bars in a sleeper, especially around the rawplug hole to strengthen the sleeper transversely and sustain more inducing pressure which can change the directions of the cracks and cracking planes.

### 5.3. Steel sleeper

A very limited study has been conducted so far to minimise the problems of steel sleeper. Some studies provide suggestions for controlling steel corrosion, among them the Australian Rail Track Corporation (ARTC) has suggested avoiding the use of steel sleepers in locations where the ballast is made from slag, there is high salinity, such as coastal regions, continually moist areas and areas with corrosive materials, such as coal, minerals, mud, clay and dirt [49]. Hernandez et al. [50] found that the presence of salt has the very detrimental effect on steel of accelerating corrosion which supports the ARTC recommendation to avoid placing steel sleepers in areas of high salinity. In its report, the ARTC also suggested that placing zinc (Zn) coating over steel is a useful method to create a protective layer that prevents corrosion. The Transit Cooperative Research Program (TCRP) stated that the use of metallic slags as ballast can enhance corrosion in steel and is not recommended for use in railroad tracks with steel sleepers [62].

## 6. New materials for railway sleepers

The many advantages of geopolymer concrete and composite materials have recently motivated researchers and railway industry to consider using them in sleeper construction, as highlighted in this section.

### 6.1. Geopolymer concrete sleeper

Many studies have shown that ordinary cement concrete sleepers can deteriorate because of alkali–silica reactions [42,43,63]. It has been claimed that fly ash-based geopolymer concrete is beneficial for reducing this reaction due to the chemical reaction between alkalis and the amorphous component in the fly ash which produces cementitious binders that increase the density of the concrete, decrease its permeability and reduce the mobility of its aggressive agent. Therefore, there is a lower possibility of an alkali–silica reaction because there are insufficient alkalis available to react with the reactive silica [64]. Kupwade-Patil and Allouche [65] reported that fly ash-based geopolymer concrete is significantly less vulnerable to an alkali–silica reaction than cement-based concrete, and García-Lodeiro et al. [66] drew similar conclusions, observing that the expansive character of the gel depends largely on the calcium oxide (CaO) content. Alkali-activated fly ash cement has a very high alkaline (Na) content but is low in calcium (Ca) while fly ash itself contains alkalis but, as only one-sixth of them are potentially reactive [36], if an alkali–silica reaction takes place, it will have a much less expansive character than that normally produced in cement.

Some recent investigations [40–42,67] have indicated the failure of concrete sleepers due to DEF which is a special case of sulphate attack. In cement concrete, sulphate ions may react with calcium hydroxide to form gypsum or with calcium aluminate hydrate to form calcium sulfoaluminate or ettringite both of which result in expansion, cracking and spalling in the concrete [36]. Fly ash-based geopolymer concrete has an excellent resistance to sulphate attack as it has no significant calcium aluminate hydrate reactant [68].

The resistances of geopolymer and ordinary cement concrete in acidic media were well studied by Bakharev [69] in 2005, with the results confirming that the former exhibits superior performance in terms of resisting acid attack. Although experiments by Song et al. [70] proved that, after a sulphuric acid attack, a geopolymer concrete matrix remains identical to that of an unaffected matrix. Wallah et al. [68] concluded that geopolymer concrete may be affected by acid depending on the concentration of the acidic solution. These superior performances of fly ash-based geopolymer concrete over traditional cement-based concrete have motivated concrete researchers to apply them in railway sleepers.

Rocla, the Australia's leading concrete sleeper supplier, has adopted the conventional prestressing process to develop geopolymer prestressed concrete sleepers for the mainline railway tracks since 2002. They have proven through inspections that presented geopolymer concrete sleeper perform well without presenting any problems (Fig. 24) [46,71].

In 2007, Palomo et al. [5] investigated the use of alkali-activated fly ash concrete in railway sleepers and suggested that it could be a suitable material for them, although their study did not provide adequate information regarding performance. In 2010, Uehara [72] proposed an environmentally friendly geopolymer prestressed concrete sleeper, manufactured using fly ash as the binder in the concrete (Fig. 25), which satisfied the static performance requirements of the standard they used, JIS E 1202. Palomo and Fernández-Jiménez [73] manufactured alkali-activated fly ash mono-block prestressed concrete sleepers for an industrial trial in 2011 and their experimental results met the requirements of both the Spanish and European codes.



Fig. 24. Geopolymer concrete sleeper in mainline tracks [71].



Fig. 25. Ordinary and geopolymer prestressed concrete sleepers [72].

Ferdous et al. [74] investigated a geopolymer concrete-filled pultruded composite beam as a replacement for a timber sleeper (Fig. 26). Their study found that the composite beam satisfies the minimum flexural requirements for composite railway sleepers as stated in the AREMA standards and shows satisfactory performance when compared with those of existing railway sleepers.

## 6.2. Composites as materials for sleeper

TieTek developed new composite sleepers using recycled plastic, old tyres, waste fibreglass and structural mineral fillers which it claimed have beneficial properties over timber sleepers because they resist rail-seat abrasion and spike pull, and are



Fig. 26. Geopolymer concrete-filled pultruded composite sleeper [74].



Fig. 27. FFU sleepers [78].

not damaged by moisture, insects or fungi [75,76]. However, they cost about twice as much as concrete sleepers [77]. Fibre-reinforced Foamed Urethane (FFU) synthetic sleepers made from hard polyurethane foam and glass fibres, with physical properties similar to those of timber sleepers and designed for more than 60 years of service, have been used in Japan while RailCorp is the first company in Australia to have used them as trial turnout sleepers (Fig. 27). According to the manufacturer, FFU does not need to be impregnated with environmentally harmful chemical which is essential for timber sleeper to protect them from biological degradation [78]. Moreover, they claim their sleeper is durable enough to provide resistance against the damaging effect of acids, alkalines and saltwater [79]. The use of these sleepers is increasing in situations in which maintenance and replacement are difficult [15].

In 2002, recycled plastic composite sleepers manufactured from recycled plastic bottles combined with glass fibre reinforcement were introduced in the USA as replacements for timber sleepers. Although the manufacturer claims that they are able to solve many drawbacks of timber sleepers, their performances in real tracks are only now being investigated [76]. Chow [80] conducted a series of tests on the static bending properties, compressive modulus of elasticity, surface hardness and three spike-resistant properties of IntegriCo composite sleepers made from composite plastics and oak with their test results satisfying the minimum requirements of the AREMA standard. This sleeper claims longer service life, immune to insect infestation, good resistance against fungus attack, and greater prevention of rail plate cutting which reflects their superior performance over timber sleeper [81]. Another research study, in which the team investigated an alternative sleeper material made from glass fibre composite skins and modified phenolic foam, was conducted at the University of Southern Queensland [82,83]. Their experimental investigation on composite sandwich beam in edgewise position showed higher shear capacity which can prevent the undesired failure due to end splitting. As the composite material has good resistance against corrosion, these proposed sleepers have the ability to overcome corrosion problems. In fact, the Queensland Rail has

**Table 2**

Summary form of sleeper failures and causes throughout world.

Sleeper	Failure mode	Causes of failure	Country	Study	Ref.
Timber	Decay	Fungus attack	Australia	1991	[8]
	End splitting	Trans. shear loading	USA	2008	[10]
	Damage	Termite attack	USA	2003	[14]
Concrete	Rail-seat deterioration	Shear force	Canada	1997	[17]
	'X'-shaped fracture	Tensile stress	USA	2011	[19]
			Spain	2008	[24]
	Longitudinal cracking	Derailment	China	2010	[26]
			Iran	2012	[25]
	Damage	High impact loading	Australia	1998	[28]
	Cracking	DEF	Finland	1987	[38]
	Micro-cracking	AAR	USA	1996	[40]
			Sweden	2004	[41]
	Cracking	Bar corrosion	Australia	1992	[42]
	Mid-span damage	Ice expansion	China	1996	[43]
	Conical cracking		Iran	2011	[47]
	Steel	Destruction of sleeper	Corrosion	Korea	2012
USA				2007	[50]
Cracking at rail seat		Fatigue	Canada Mexico Australia	1983	[51]

**Table 3**

Summary form of sleeper failures minimisation techniques.

Sleeper	Failure mode	Minimisation techniques	Ref.
Timber	Fungal decay and termite attacks	Impregnation with synthetic chemicals/biological treatment	[52]
	End splitting	Providing end plates	[54] [10]
Concrete	Rail-seat deterioration	Steel plate/epoxy coating/addition of fly ash and silica fume in concrete/steel fibre reinforced grout multilayer abrasion resistant pad assembly and metallic aggregate in the rail-seat region	[56]
			[57] [58] [60]
	Longitudinal cracking	Providing special expansive concrete/transverse reinforcing bar around bolt hole area	[26] [25] [66]
		Geopolymer concrete sleeper	[49]
Steel	Corrosion	Avoiding steel sleeper from the locations having slag ballast/high salinity/moist and corrosive materials; zinc coating can be alternative solution	[62] [75]
		Composite railway sleeper	[75]

installed the first 50 sleepers made from laminated sandwich beams in the maintenance of their existing railway lines to determine the in-service performance of this new sleeper material. However, the composite sleeper discussed here addresses some solutions of the specific problems of traditional sleeper and more investigation is required to check the other application issues particularly, their performance against impact and fatigue.

## 7. Discussions

Several causes of sleeper deterioration around the world over the last two decades are summarised in Table 2.

This study found that the big problem inherent in timber sleepers is their susceptibility to mechanical and biological degradation, including decaying, splitting and insect infestation which leads to their failure. Mono-block prestressed concrete sleepers are the most commonly used sleepers throughout the world due to their greater durability in adverse environments and, in Australia, the majority of modern railway sleepers are of this type. However, the low impact resistance and susceptibility to chemical attack (DEF, AAR etc.) of mono-block prestressed concrete sleepers are major problems. On the other hand, the worrying aspect associated with steel sleeper is their fatigue cracking at the rail seat region, which leads to failure and their acceptance is decreasing due to the risks of corrosion and other chemical attacks. To protect the sleepers from those unfavourable circumstances researchers have investigated their mitigation techniques as tabulated in Table 3.

The remedial measures discussed above are effective to protect sleepers from its early deterioration, but the cost associated with it, is a great concern. However, research and development are now focussed on new materials for manufacturing sleeper, particularly composites which have the potential to solve many problems of traditional timber, concrete and steel sleeper.

## 8. Conclusions

The unexpected deterioration of traditional railway sleepers and the lack of understanding of their degradation mechanisms are the main drivers behind this research which aims to provide guidelines for structural designers, engineers, researchers as well as asset owners. Several causes of sleeper deterioration are identified and some best practices for minimising sleeper problems provided by different researchers and organizations are presented, from which the following conclusions are drawn.

- *Timber sleeper failure:* The most predominant and two other major modes of timber sleeper failure are fungal decay, end splitting and termite attacks. They are responsible for 53%, 10% and 7% respectively of the total premature failures. *Protective measures:* Impregnation with synthetic chemicals and biological treatment protects sleeper from fungal decay and termite attacks. Biological protection methods are now being promoted to lessen the impact of chemical protection on environment. The use of end-plates on the cracked ends is a common practice to control the end splitting of timber sleeper.
- *Concrete sleeper failure:* The two major modes of failure for concrete sleeper are rail-seat deterioration and longitudinal cracking. *Protective measures:* The rail-seat deterioration can be minimised by (a) using cast-in-place steel plates that cover the rail-seat area, (b) applying epoxy coating over the rail-seat region, (c) adding fly ash and silica fume to the concrete in the rail-seat, (d) introducing steel fibre-reinforced grout in the rail-seat region during manufacturing, and (e)

applying a multilayer abrasion-resistant pad assembly and metallic aggregates in the rail-seat area. The longitudinal cracking of a concrete sleeper can be controlled by introducing a special expansive concrete around the bolt-hole area while transverse reinforcing bars can be placed in it, especially around the bolt hole, to strengthen it transversely.

- *Steel sleeper failure*: Corrosion in steel sleepers is considered the principal cause of its early failures. The factors responsible for steel corrosion are (a) salts which can come into contact with sleepers from soil, groundwater and aggregates, (b) metallic slag-based ballast, (c) a constantly moist environment around sleepers, and (d) corrosive materials in the track. *Protective measures*: Steel sleepers are suggested not to be used in locations where (a) the ballast is made from slag, (b) there is high salinity, including in coastal regions, (c) the area is continually moist, or (d) there are corrosive materials, such as coal, minerals, mud, clay and dirt. If these situations cannot be prevented, zinc (Zn) coating should be applied to steel sleepers as a protective layer for precautionary measure.
- *New materials for sleepers*: The deterioration of concrete sleepers due to DEF and AAR could be minimised by replacing cement concrete with geopolymer concrete as the latter material exhibits excellent engineering properties which provide protection against chemical degradation. On the other hand, the composite properties of resistance to corrosion, high-impact loading and fatigue, as well as their durability, make them efficient sleeper materials. Continued efforts are still needed towards the better understanding of these new materials for their more economical exploitation in mainline railway sleepers.

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## Review

# Composite railway sleepers – Recent developments, challenges and future prospects



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## ABSTRACT

A number of composite railway sleeper technologies have been developed but their applications in rail tracks are still limited. This paper rigorously reviews the recent developments on composite sleepers and identifies the critical barriers to their widespread acceptance and applications. Currently the composite sleeper technologies that are available ranges from sleepers made with recycle plastic materials which contains short or no fibre to the sleepers that containing high volume of fibres. While recycled plastic sleepers are low cost, the major challenges of using this type of sleepers are their limited strength, stiffness and dynamic properties which in most cases, are incompatible with those of timber. On the other hand, the prohibitive cost of high fibre containing sleepers limit their widespread application. Moreover, limited knowledge on the historical long-term performance of these new and alternative materials restricts their application. Potential design approaches for overcoming the challenges in the utilisation and acceptance of composite sleeper technologies are also presented in this paper.

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## 1. Introduction

The traditional materials used to manufacture railway sleepers are timber, concrete and in some cases steel, which are generally designed for 20, 50 and 50 years, respectively [1–3]. Timber was the earliest material used and more than 2.5 billion timber components have been installed worldwide [4]. They are adaptable and have excellent dynamic, electrical and sound-insulating properties. Around the 1880s, due to the scarcity of timber and the sensitivity to its use, steel railway sleepers were introduced as an alternative to timber. As their design has evolved, the original ones are now being replaced by modern ‘Y’ shaped steel ones. During the last few decades, the railway industry has focused on a cement-based concrete rather than timber and steel sleepers. Mono-block prestressed concrete sleepers were first applied in 1943 and are now used in heavy haul and high speed rail track constructions throughout the world [5].

This leads to the question on why the railway industry uses a variety of sleeper materials rather than a particular one? Undoubtedly, the main reason is that none of the existing materials (timber, steel and concrete) does satisfactorily meet all the requirements of a sleeper. The review by Manalo et al. [6] on alternative materials to timber indicated the high demand for new sleeper materials. A recent study on the potential causes of failures of railway sleepers [7] showed that the traditional materials have not satisfactorily met the demand requirements to resist mechanical, biological and chemical degradation (Fig. 1).

The problems of timber rotting, splitting and insect attack, as well as its scarcity introduced a new challenge. Steel’s risk of corrosion, high electrical conductivity, and fatigue cracking in the rail-seat region, and the difficulty of them packing within the ballast made steel sleepers an inferior material for use in sleepers. On the other hand, prestressed concrete sleepers, which offer greater durability than timber and steel, suffer from being heavy and having a high initial cost, low impact resistance and susceptibility to chemical attack. Due to the heavy weights, their transportation costs are significantly higher, they are difficult to handle and require expensive and extensive equipment for installation [8].

Moreover, concrete and steel sleepers require special fasteners and cannot replace timber ones in an existing track because of their incompatible behaviour [6]. From an environmental point of view, the production of traditional sleeper materials create several problems; for example, many trees need to be cut down to make timber sleepers while the cement and steel industries emit huge amount of carbon dioxide into the atmosphere during their production. All the aforementioned issues have motivated researchers around the world to develop and investigate new and effective alternative sleeper technologies for railway industry.

Nowadays, the global market for composites is rapidly increasing because of the many advantages including high strength-to-weight ratio, excellent resistance against corrosion, moisture and insects, and thermal and electrical non-conductivity [9]. This material can be engineered according to the specific requirements of railway sleepers [10]. Therefore, it is believe that the composite railway sleepers can be a suitable alternative for existing concrete, steel and, particularly, timber ones in both mainline and heavy haul rail networks. Moreover, composites demonstrate the material for the future generation sleeper. This paper provides an overview of recent developments of composite railway sleepers and their limitations, and suggests a solution which overcomes the challenges inherent in their utilisation and acceptance.

## 2. Recent developments on composite sleepers

Several composite sleeper technologies have been developed in different parts of the world. These technologies have emerged as a potential alternative to timber sleepers. Different from steel and concrete, composite sleepers can be designed to mimic timber behaviour (an essential requirement for timber track maintenance), are almost maintenance free, and are more sustainable from an environmental perspective. This section discusses the different classifications based on the amount, length and orientation of fibres in composite railway sleepers that are currently available and including technologies that are still in the research and development stage.



Fig. 1. Example of diverse failure modes of sleepers during service life [6,7].

### 2.1. Sleepers with short or no fibre reinforcements (Type-1)

Sleepers that consist of recycled plastic (plastic bags, scrapped vehicle tyres, plastic coffee cups, milk jugs, laundry detergent bottles, etc.) or bitumen with fillers (sand, gravel, recycled glass or short glass fibres < 20 mm) falls under the category of Type-1 sleepers. The structural behaviour of these sleepers is mainly polymer driven. While some of these technologies introduced short glass fibre to increase the stiffness and/or resist crack, they do not have major reinforcing effect to improve the structural performance required for heavy duty railway sleeper application. The high demand for alternative sleeper materials has resulted in some railway maintenance companies to adopt and trial the usage of these materials. As a sleeper material, Type-1 sleepers offer a range of benefits including ease of drill and cut, good durability, consumption of waste materials, reasonable price, and tough. However, it suffers from low strength and stiffness, limited design flexibility, temperature and creep sensitivity, and low resistance to fire. The notable sleepers in this category are TieTek [11,12], Axion [13,14], IntegriCo [15,16], I-Plas [17,18], Tufflex [19,20], Natural rubber [21,22], Kunststof Lankhorst Product (KLP) [23,24], Mixed Plastic Waste (MPW) [25] and Wood-core [26]. Table 1 provided a summary of technologies falling under the Type-1 sleeper.

### 2.2. Sleepers with long fibre reinforcement in the longitudinal direction (Type-2)

Type-2 sleepers are sleeper technologies reinforced with long continuous glass fibre reinforcement in the longitudinal direction and no or very short random fibre in the transverse direction. The strength and stiffness in the longitudinal direction is primarily governed by long glass fibre while it is dominated by polymer in the transverse direction. These sleepers are primarily suitable for ballasted rail track where the stresses in sleepers are governed by flexural loading, but less than ideal in bridge applications (e.g., transoms) where the sleepers are subjected to high level of combined flexural and shear forces. Easy to drill and cut, good durability, superior flexural strength and modulus of elasticity are the advantages of the sleeper in this category. However, low shear strength and shear modulus, limited design flexibility, marginal fire resistance and high price are some of the challenging issues associated with this sleeper. The FFU (Fibre-reinforced Foamed Urethane) synthetic sleeper [27–29] is classified in this sleeper category. The key features of this material include its light weight, good resistance to water absorption, heat and corrosion, its ease of drilling, and its more than 50 years of design life. FFU material has been used in railway industry as plain-track sleepers, bridge

**Table 1**  
Available Type-1 sleeper technologies.

Name	Materials	Country	Applications	Designed shape	Ref.
TieTek	85% recycled plastic (tyres, waste fibreglass)	USA	Mainline sleeper, turnout bearers and bridge transoms		[11]
Axion	100% recycled plastic (plastic bag, bottles etc.)	USA	Mainline sleeper, turnout bearers and bridge transoms		[14]
IntegriCo	Landfill-bound 100% recycled plastic materials	USA	Commuter, industrial and mining		[16]
I-Plas	100% domestic and industrial recycled plastic	UK	Timber replacement		[18]
Tufflex	Mix of recycled polypropylene and polyethylene	S. Africa	Underground rail track and narrow gauge line		[20]
Natural rubber	Natural rubber	Thailand	Narrow gauge line		[22]
KLP	100% recycled plastic materials	Netherland	Mainline sleeper, turnout bearers and bridge transoms		[24]
MPW	Polymer, mixed plastic and glass fibre waste	Germany	Timber replacement		[25]
Wood core	Plastic reinforced with wooden beam	USA	Timber replacement		[26]

transoms, and turnout bearers with a wide range of sleeper height from 100 mm to 450 mm. An investigation of the acoustic and dynamic characteristics of a FFU turnout bearers showed that its performance is equivalent to that of a hard-wood bearers [28]. In 2011, the Railway Technical Research Institute (RTRI) in Japan investigated 30 years old FFU sleepers that were used in the track under regular train operation and reported that it can still use for the next 20 years [30]. To date, this material has been installed (Fig. 2) in more than 1300 kms of track (approximately 2 million sleepers) with its main application in turnouts, open steel girder structures and tunnels [31]. Apart from Japan, Sekisui FFU components have been installed in Germany, Austria, Taiwan, Netherland, USA and Australia. Their applicability is also now investigated for a long span rail bridge in Chongqing city, China [32].

2.3. Sleepers with fibre reinforcement in longitudinal and transverse directions (Type-3)

Type-3 sleepers have long reinforcement fibres in both longitudinal and transverse directions and consequently both the flexural and shear behaviour are dominated by fibres. The structural performance of this sleeper can be engineered through the adjustment of the fibre reinforcements in each direction according to the specified performance requirements. In some cases, the disadvantage of a non-ductile behaviour of glass fibre reinforced polymer sleeper can be overcome by including some steel reinforcement bars. The ductile property is particularly important when the sleepers are installed in bridge, where sufficient warning before failure is expected. The excellent design flexibility, good flexural and shear strength, easy drilling and good fire performance are the key benefits of this sleeper. However, the production process of composite sleeper technologies under this category is quite slow which may increase the manufacturing cost. The sandwich polymer sleeper [10,33] and the hybrid composite [34] sleeper wherein fibres are

oriented in the two directions to resist flexural stresses as well as shear forces falls under this category. A brief description of these sleeper technologies are provided in Table 2.

3. Challenges of using composite sleeper

Despite many advantages of the newly developed composite sleepers, to date, they have gained a very limited acceptance by railway industry. This section presents the common challenges encountered in using composite sleeper.

3.1. Inferior strength and stiffness properties compared to timber sleeper

Most of the composite sleeper technologies have been developed to replace existing timber sleepers, as there is a high need for an alternative materials in this approach. It has been reported that, every year, the US railroad industry replaces 14 million timber sleepers [35], with another report indicating that, about 5% of sleepers are replaced in the US and Canada annually [36]. In Australia, approximately 1.5 million timber sleepers are required per year for maintaining rail track [37]. Even with this high demand for sleeper alternatives, there still limited usage and application of composite sleeper technologies. This is expected as most of the composite sleeper falls under Type-1 category that has strength and stiffness significantly lower than traditional timber sleeper. For comparison, the performances of composite sleeper technologies are summarised in Table 3.

The sleepers under Type-1 category showed low structural performance when compared with Type-2 and Type-3. This is due to mainly only short or sometimes no fibre in Type-1 sleepers. In contrast, Type-2 and Type-3 have long fibres, which provide significant reinforcing effect to increase strength and stiffness. A recent investigation of the modulus of elasticity (MOE) of a fibre composite

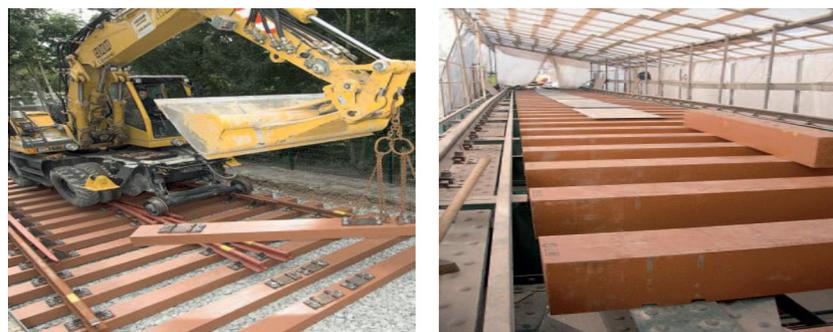


Fig. 2. Sekisui FFU synthetic sleeper [31].

Table 2  
Type-3 sleepers.

Name	Materials	Country	Applications	Designed shape	Ref.
Sandwich	Glue laminated sandwich composite	Australia	Mainline sleeper, turnout bearers and bridge transoms		[33]
Hybrid	Geopolymer concrete filled pultruded composite	Australia	Mainline sleeper, turnout bearers and bridge transoms		[34]

**Table 3**  
Performance comparison of different types of composite sleeper.

Performance measurement	AREMA specification			Type-1	Type-2	Type-3
	Oak	Softwood	Glue Lam			
Density (kg/m <sup>3</sup> )	1096	855	960	850–1150	740	1040–2000
Modulus of elasticity (GPa)	8.4	7.4	12.0	1.5–1.8	8.1	5.0–8.0
Modulus of rupture (MPa)	57.9	49.3	66.9	17.2–20.6	142	70–120
Shear strength (MPa)	5	4	4	4	10	15–20
Rail seat compression (MPa)	4.6	3	3.9	15.2–20.6	28	40
Screw withdrawal (kN)	22.2	13.3	N/A	31.6–35.6	65	>60

sleeper has showed that the optimal one can be as low as 4 GPa for a turnout application to maintain both the sleeper-ballast contact pressure and the maximum vertical static deflection within the limit [38]. Moreover, the modulus of rupture (MOR) of a new Australian hardwood timber sleepers was experimentally determined under various conditions and provided a wide range of strengths from 47 to 110 MPa [39] whereas most existing composite sleepers exhibit low strength and stiffness particularly Type-1. It has been reported that it is difficult to maintain track safety when replacing a timber by a recycled plastic composite sleeper (Type-1), as indicated by the failure modes presented in Fig. 3 [40], as fracture failures can occur both during installation and under operational conditions, particularly heavy dynamic loading. Moreover, railroad users have reported some failures of plastic composite sleepers occurring after several years in tracks [41] and a high percentage of TieTek sleepers have been rejected in the field due to their quality control issues.

The incorporation of longitudinal fibre makes the Type-2 sleeper stronger than Type-1 to resist flexural loading but its capacity to resist shear force is still moderate as no reinforcements are provided in transverse direction. The capacity of sleeper to resist shear force is particularly important for bridge application (transoms) where the sleepers are subjected to high shear force due to the position of rails and support beams which are generally off-set by approximately 250 mm in Australia [10]. The high shear capacity of Type-3 sleepers are achieved by placing reinforcement in both longitudinal and transverse direction.

### 3.2. Price of composite sleeper

The prohibitive costs of most composite sleeper technologies is one of the main reasons identified for their slow uptake in the market. Recycled Technologies International (RTI) stated that their costs range from 85 to 105 USD per sleeper (Type-1), a price not including installation which represents a significant value and can range from 70 to 200 USD per sleeper [36]. Van Erp and Mckay [10] indicated that the price of high fibre containing composite

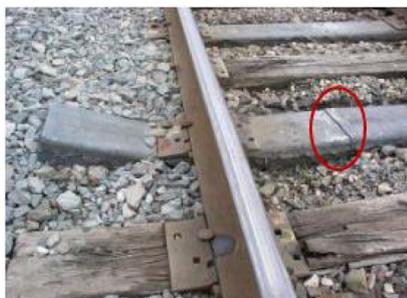
sleeper technologies (Type-2 and Type-3) is approximately 5–10 times higher than that of a standard timber sleeper. However, its lower life cycle cost is anticipated to offset its high initial cost [14,16,36] which to attract the attention of the railway industry, needs to be similar to, or insignificantly higher than, that of traditional ones. Similarly, optimising the manufacturing process and material usage would result in a more cost competitive sleeper product.

### 3.3. Low anchorage capability

A screw spike is primarily used to hold down the baseplates that attach rails to sleepers and prevent vertical and lateral movements between them. A hardwood timber sleeper has a screw-spike resistance of 40 kN [28,42] whilst at least 60 kN is required for the modern design of prestressed concrete sleepers supporting heavier and faster trains [43]. The low anchorage capacity of holding screw (Table 3) is another problem for Type-1 composite sleeper. It has been reported that the modified compound of a natural rubber composite sleeper (Type-1) showed a very stiff and inelastic performance when holding the spike for a fastening system [21]. This is due to the nature of plastic materials that cannot grip the screw firmly like concrete, especially under dynamic loading conditions. When using composite sleepers, the loosening of a fastener over time makes a track unstable due to stress relaxation [40] which has been considered the most likely reason for the derailment failures of track systems constructed with composite sleepers [44,45]. However, the anchorage capacity has been improved in Type-2 and Type-3 sleepers due to the usage of more quality and high performing materials.

### 3.4. Formation of material voids

During the manufacturing process for a plastic composite sleeper (Type-1), the raw materials are mixed, melted and compounded to create a homogeneous mixture which is later extruded into moulds. Once the moulds are filled, the cooling pro-



(a) local settlement due to cracking



(b) crackling at fasteners

**Fig. 3.** Failures of recycled plastic sleeper [40].

cess starts, and during this period, there is a high possibility of voids being formed inside the materials. It has been reported that, composite sleepers in the rail-seat region have sunk into their bodies when in-service [46]. Moreover, voids can break and transfer stresses from one part to others which creates a stress concentration and later leads to local failure of a sleeper before the end of its design life. This problem can be obtained during the production of any material depending on their manufacturing techniques but not for timber which comes from natural trees.

### 3.5. Creep deformation

The long-term performances of plastic sleepers (Type-1) are becoming a critical issue as their continuous service over time has a significant effect on their mechanical properties. It has been reported that, under sustained loads, a composite sleeper may be subjected to permanent deformation due to creep [40,47,48], the rate of which depends on the magnitude and duration of the stress and the temperature at which the load is applied. Because of the effect of creep and the subsequent stress relaxation, the fastening system tends to become loose, particularly in a curved track, which has an adverse effect on gauge holding [48]. These effects may reduce the service life of a plastic sleeper which the manufacturing companies have estimated to be approximately 50 years. Of all traditional sleeper materials, concrete and steel are prone to creep. In addition, it has been reported that fly-ash based geopolymer concrete tends to have significant problem with creep and shortening effect due to prestressing because fly-ash retards the hardening process of concrete [5]. However, sufficient information have not been found on the creep deformation for Type-2 and Type-3 sleepers, and more research need to be conducted to investigate their behaviour under permanent rail track loads.

### 3.6. Limited information on long-term performance

Although most composite sleeper manufacturers have evaluated the static performances of their products, the long-term performances in terms of aspects such as dynamic properties, impact resistance, fatigue and durability of all sleeper types are still unknown. Critical systemic design review suggests that it is essential to investigate these issues before installation as a sleeper is often subjected to dynamic, impact and fatigue loading, as well as critical weathering action as discussed in the following subsections.

#### 3.6.1. Impact loading

A good rail track is expected to have a smooth running surface on the rail and, for comfortable movement, a train's wheels should

be perfectly round. A moving vehicle usually generates low-frequency forces (below 20 Hz) when both the wheel and rail are free from any abnormalities. In this case, the rail track is subjected to static wheel load and the effect of static load at speed which jointly referred as 'quasi-static' loads. Over time, significant abnormalities can arise in either a rail track or train wheels (such as wheel flat or dipped rail) which produce higher frequency and, consequently, higher magnitude forces than a quasi-static load due to their additional dynamic effects, and called 'dynamic wheel/rail' or 'impact' forces [49,50]. In other words, the wheel/rail contact force will be similar to a static wheel load when both the wheel's tread and rail's surface are in perfect condition. However, in turnout applications, bearers are subjected to large forces from crossing impact that is more vulnerable than dynamic wheel/rail. Traditional timber sleeper exhibits high resistance to impact which is opposite in case of concrete and the performance of steel sleeper is classified in between the former two [6]. Response to impact loads and failure modes of prestressed concrete sleepers have been investigated by Remennikov and Kaewunruen [51,52] as shown in Fig. 4a. A composite laminate is prone to impact damage which leads to delamination and matrix cracking and, as its behaviour under a high-impact load is much different from that under normal loading conditions, that is, its strength and stiffness can reduce significantly, this requires a careful design approach [53,54]. Of all the composite sleepers, an impact test has been reported for only the FFU synthetic sleeper (Fig. 4b) developed by Sekisui Chemical Co. Ltd. in Japan. As the conditions on railway tracks often induce high-magnitude impact loads, the impact resistance of composite materials is inevitably required to define safety- and reliability-based design of the composite material.

#### 3.6.2. Fatigue loading

The purpose of fatigue testing is to establish how sleepers would behave when subjected to repeated loads. Although the traditional timber, concrete and steel sleepers rarely fail as a result of fatigue [55] this is more complicated in the case of composites because of their non-homogeneous and anisotropic nature, and they can fail by fibre cracking, de-bonding, de-lamination and matrix cracking [56]. While a thermosetting or thermoplastic materials subjected to cyclic loading, the imposed external work (stress) converts into heat that increase the temperature drastically and leads to failure of plastic structures [57]. Some fatigue tests of composite sleepers for between 2 and 3 million cycles have been conducted [14,16,58]. Those of a FFU synthetic sleeper were carried out between the lower and upper load limits of 10–140 kN respectively with a load application frequency of 3 Hz (Fig. 5a). The deflection of the rail relative to the sleeper was shown to be within the admissible range after 2.5 million load cycles at

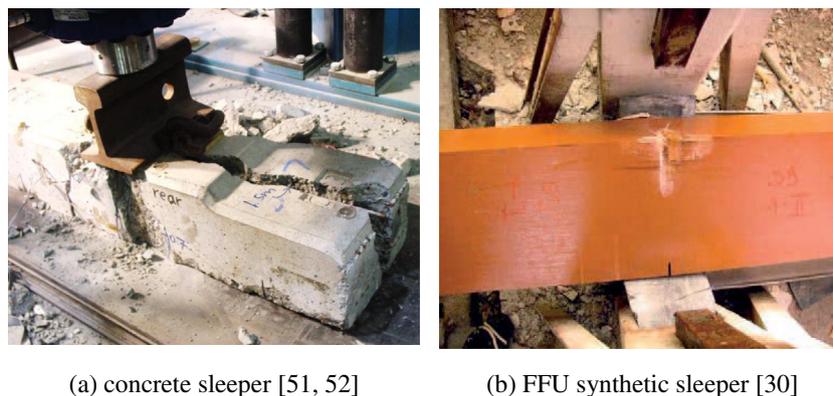


Fig. 4. Impact damage.

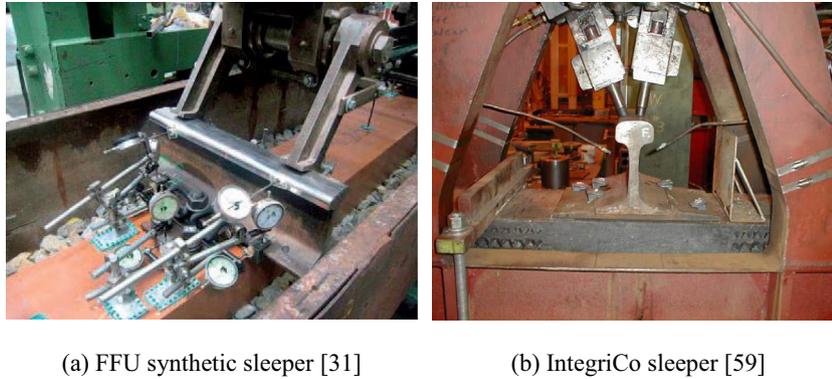


Fig. 5. Fatigue test set-up for railway sleeper.

the ambient temperature [31]. On the other hand, an IntegriCo sleeper was subjected to 21,000 lb (93.41 kN) loads on the field and gauge sides one after another to make one cycle (Fig. 5b). A total of 2 million load cycles, equivalent to 9000 passes of a 110-car train, was applied at a rate of approximately 220 cycles per minute (3.67 Hz), with the sleeper showing normal wear and abrasion in the sleeper plate area but no cracks or abnormalities found [59]. The Axion EcoTrax sleeper followed the same test procedure described for the IntegriCo sleeper but with a higher load cycle of 3 million which also did not find any cracking in the rail-seat area [14]. Apart from those tests of three sleepers, a very few reports have been found in the literature of fatigue testing of other composite sleepers. Although there were a number of fatigue tests for composite materials, there exists no relationship between operational loads and material fatigue performance. As a result, there is a clear opportunity to investigate the importance of stress thresholds, support conditions and load patterns on the fatigue failure modes of composite bearers/sleepers.

### 3.6.3. UV radiation

Outdoor applications of railway sleepers are routinely exposed to the ultraviolet (UV) radiation generated by the sun which has sufficient energy to break the molecular bonds of a structure. The lignin of timber can be affected by UV [60] whereas in a fibre reinforced polymer composite, the matrix is often considered the weak part as it undergoes physical damage and chemical degradation during exposure to the environment and stress applications [61]. In case of plastic materials, its chemical structure is affected by UV [62] as are its mechanical properties which results in embrittlement, discolouration and an overall reduction in its physical and electrical properties [63], a phenomenon that can significantly reduce the service life of a sleeper [40]. Unfortunately, to date, the potential damage to composite sleepers under UV radiation has not been examined.

### 3.6.4. Moisture

Railway components are generally exposed to the effects of moisture from rain, frost, snow, hail and dew which significantly contribute to the degradation of a polymer composite as the ingress of moisture can weaken not only its polymer resin but also its reinforcing fibres. This absorption can react with the polymer matrix or impose internal stress which causes reductions in a composite's overall mechanical properties [40,64,65]. It has been reported that the absorption of moisture can also reduce the mechanical properties of timber [66] and concrete [67], and a possibility of corrosion in steel structures when connected with salty environment. Therefore, the performance of a composite sleeper in a moist environment needs to be investigated.

### 3.6.5. Aqueous solution

Soil, groundwater and, sometimes, the ballast may contain sulphates of sodium, potassium, magnesium and calcium which, when coming in contact with water, can create an aqueous solution, a harsh environment that can reduce the mechanical properties of glass fibre reinforced plastic composites [68,69]. Amaro et al. [70] found that there is a significant effect on the flexural strength and flexural modulus of a glass fibre/epoxy composite after its immersion in hydrochloric acid (HCl) and sodium hydroxide (NaOH), with the latter more detrimental than the former. In aqueous environments, the degradation of concrete and the risk of corrosion in steel are quite known. The possibility of composite sleepers degrading in aqueous environments cannot be ignored, unfortunately, this has not yet been investigated.

### 3.6.6. Elevated temperature

Railway components are often subjected to high environmental temperatures, particularly in the summer season. A sleeper made from polymeric materials can demonstrate two different mechanical behaviours at below and above its glass transition temperature ( $T_g$ ). At a temperature well below its  $T_g$ , a polymeric material exhibits a high modulus and behaves like a glassy material whereas, its modulus drops dramatically and it behaves in a rubbery fashion when subjected to a temperature above its  $T_g$ . Shamsuddoha et al. [71] obtained the variations of  $T_g$  for polymer epoxy grouts ranges between 60 and 90 °C when determining it using DMA method. The  $T_g$  of a polymeric composite can also be affected by moisture and becomes low when water is absorbed [72]. The effect of temperature is more significant in case of turnout bearers that has a long length greater than 5.5 m each. However, as significant dimensional changes can occur in a plastic sleeper due to temperature variations [47], the performances of composite sleepers at different temperatures need to be investigated.

### 3.6.7. Fire

Railway sleepers should have sufficient resistance against fire as sometimes the thermite welding of joints adjacent to them can create a fire in them, as reported by Lampo [40]. Generally timber sleepers are combustible and some composite sleeper exhibits similar behaviour, TieTek in particular (Type-1). However, the toxic residues from the combustion should not exceed regulatory limit. Existing plastic sleepers are composed of thermoplastic materials which can be softened by heating and rehardened when cooled, a reversible process that can change the physical properties of plastics [73]. Although fire performance and incombustibility of FFU material has been reported [28], the studies of the performance of other composite sleeper under fires have not been found in the literature.

### 3.6.8. Lateral track stability

Lateral track stability measures the capability of sleepers to resist movement perpendicular to the rail. Sleepers are subjected to lateral forces during the movement of a vehicle over a rail and rail expansion due to temperature fluctuation, particularly in a curved track, and the inadequate frictional interaction between a sleeper and ballast does not indicate the failure of the individual sleeper but of the whole track system. An experimental investigation by Zakeri et al. [74] showed that the frictional concrete sleeper can improve the lateral resistance by 64% than the standard concrete sleeper which is comparable with their field investigation results of 68%. However, it is important to note that Australian sleepers have been designed to accommodate soffit roughness to improve the frictional capability [43]. Unlike the uniform shape of timber sleeper, some plastic sleepers have textured the bottom and two vertical sides to improve lateral stability (Fig. 6) [11,13,75]. Recently, it was reported that the railway industry is concerned to maintain track stability due to the light weight of the Sekisui FFU synthetic composite sleeper (Type-2) [5]. Special lateral resistance methodology was designed to aid FFU bearers in turnout systems [28]. The lack of relevant knowledge of composite sleepers restricts their extensive application.

### 3.7. Design guidelines for composite sleeper

Guidelines for the designs are well established for traditional timber, steel and concrete sleepers. In Australia, the standard ones are provided in AS 3818.2 [76] and RailCorp SPC 231 [77] for timber, AS 1085.17 [78] and ARTC ETA-02-03 [79] for steel, and AS 1085.14 [43] and RailCorp SPC 232 [2] for prestressed concrete sleepers. In addition, Jeffs and Tew [39] prepared the railway track design guidelines for timber, steel and concrete sleepers in 1991 which is also being used by the railway engineers and researchers in Australia. It is important to note that, the design guidelines for mainline sleepers and turnout bearers are different and the latter is generally design for higher load conditions. However, although relevant standard provisions containing specifications for composite sleepers are provided by the American Railway Engineering and Maintenance-of-way Association (AREMA), Chicago Transit Authority (CTA) and Union Pacific Railroad (UPRR), there are no recognised standard guidelines (such as load factors) for the design of sleeper. At present, the design philosophy for composite sleepers is based on the permissible stress concept resulting from quasi-static wheel loads which could be more realistic if it incorporated both dynamic and static design requirements. Excluding any unusual conditions (such as super-elevation), a quasi-static wheel load is approximately 1.4–1.6 times greater than a static wheel load [49]. Currently, the load factor is considered to be 1.5 for calculating rail-seat loads which clearly indicates that current design method does not consider the dynamic effect. Therefore, it is logical that the dynamic effect of a sleeper needs to be investigated and should be incorporated in sleeper design guidelines.



Fig. 6. Textured plastic sleeper [75,11].

## 4. Future prospects

The major challenges of using Type-1 composite railway sleepers are their limited strength, stiffness and dynamic properties which, in most cases, are not compatible with those of timber. The limitations of low structural performance in Type-1 sleeper has been overcome in Type-2 and Type-3 but their high prices compared to standard sleeper materials are still remaining a big challenge. Moreover, the lack of knowledge on their long-term performances and the unavailability of design guidelines restricts their widespread applications and utilisations. A comparison of the performance of three different types of composite sleeper are summarised in Table 4.

To address the limitations of existing composite sleepers, more significant research needs to be conducted. The following approaches are proposed to overcome the current limitations of composite sleepers.

### 4.1. Improving structural performance

Recycled plastic sleeper (Type-1) shows incompatible structural performance with timber. The Sekisui FFU synthetic composite sleeper (Type-2) provides better strength and stiffness than Type-1 composite sleepers due to inclusion of long reinforcement fibres but it is currently quite expensive and its usage is primarily limited to turnout applications. As the strength and stiffness of the recycled plastic sleepers (Type-1) are significantly lower than those of traditional timber, it is suggested that fibre reinforcements be used to improve these properties. However, a significant research is required to develop the techniques how the fibres will work with thermoplastic polymer. In terms of the concept of the wood-core plastic sleeper, the suitability of bonding between plastic and wood could be a critical issue and, moreover, it was developed at a time when researchers were looking for an alternative material to timber due to environmental sensitivities, with the replacement of wood by a suitable composite desirable. The initial results for a glue laminated sandwich sleeper (Type-3) showed that it performs much better than recycled plastic (Type-1) because of the high strength fibre composite skins in both the longitudinal and transverse direction of the sandwich panel results in this type of sleepers to meet the stiffness requirements of 4 GPa [38] for a safe and reliable track.

Table 4  
Comparison of different types of composite sleeper.

Properties and performances	Type-1	Type-2	Type-3
Flexural strength and stiffness	Low	Good	Good
Shear strength	Low	Medium	Good
Anchorage capacity	Low	Good	Good
Drilling and cutting	Easy	Easy	Moderately easy
Price	Low	High	High

#### 4.2. Optimal material usage and improve manufacturing techniques

The cost of Type-2 and Type-3 composite sleepers which is approximately 5–10 times higher than a standard timber sleeper as mentioned earlier, have been considered one of the primary obstacles to their widespread application in rail tracks. Nosker et al. [48] and Bank [80] recommended optimising the structural dimensions to avoid material wastage which can lead to minimising the cost. Awad et al. [81] suggested an optimisation methodology for a fibre composite structure based on different design aspects such as an experimental material test, FE analysis, design codes and standards, and optimisation methods that is useful to achieve the required structural performance within the optimal cost. The materials of a composite sleeper have been optimised in developments of KLP plastic sleepers (Type-1), with the optimised design reducing the plastic volume by 35% compared with that of a traditionally shaped solid sleeper. Unlike timber, the shape of steel and concrete sleeper has been optimised at the middle which is relatively smaller than its rail-seat section. The optimisation of sleeper is not only advantageous from economic point of view but also improves the lateral stability of rail track because of their non-uniform shape [82].

In addition, the costs is also associated in track construction that can vary depending on the types of sleepers used; for example, the depth of ballast required for a concrete sleeper is almost double that for a timber sleeper. This is due to the poor dynamic properties and high stiffness of concrete which results in large bending moments and require a foundation with moderate stiffness support. The installation of rail pad increases the track manufacturing cost as well as decreases the speed of construction although it is necessary for electrical and vibration isolation, noise management, etc. Therefore, the focus should be on developing a composite sleeper technology with improved dynamic properties that can work with low-depth ballast support and without any rail pad.

As a sleeper generally transfers the wheel load through the rail-seat region at a 45° angle as illustrated in Fig. 7, this region is the most critical section while other parts of a sleeper do not require the same strength. As the material cost is significant in the case of a composite, any reduction in the volume of materials can contribute to cost minimisation. A superior design of a sleeper can be achieved by decreasing its section thickness or lowering the quality of materials in those regions where the stress is insignificant, a technique which may be useful for developing a cost-effective composite railway sleeper. This technique has already been implemented in prestressed concrete sleepers wherein B70 concrete sleepers have been optimised based on the distribution of wheel loads [83].

In the optimisation of sleeper design, the stress distribution along the composite sleeper can be used as an indication of the efficient material usage. An iterative and intuitive approach using finite element simulation can be performed to determine the locations where stress levels are high and where fibre composites

needs to be provided. Similarly, this approach can provide information on areas where stress levels are low and materials can be removed. This can be done until the amount of polymer material and the efficient arrangement of fibre reinforcements in a composite sleeper is determined such that the overall cost becomes commercially viable and satisfy both strength and serviceability requirements.

#### 4.3. Short- and long-term performance evaluation

In addition to operational load requirements, the performance of the composite material is determined by durability and ability to withstand environmental loads from UV radiation, high pH, high and low temperatures, moisture, and so on. As composite railway sleepers are a relatively new technology, the performance histories of these new materials are relatively short in railway industry compared with those of more conventional sleeper materials such as hardwood, concrete and steel. Thus, short- and long-term investigation of the behaviour of composite sleepers are essential to develop the market and increase confidence in using these alternative materials. Also performance evaluation should be continuously monitored to ensure that they can carry the required loads to solve their installation and maintenance issues. Moreover, field performances of sleepers should be assessed routinely as this information is very important for providing the necessary guidelines for their effective design and utilisation in actual railway lines.

#### 4.4. Design recommendations and standards

As there is currently no widely recognised standard for composite sleepers (particularly Type-3), that for existing sleeper materials is used to design a composite railway sleeper. While the AREMA (2013) provides the minimum physical and mechanical performance requirements for an engineered composite sleeper (Type-1) and, FFU (Type-2) using JIS Z2101 [27] and DIN EN standard [30], these are limited to a standard gauge railway track. Design recommendations for composite railway sleepers should be developed so that their true capabilities can be exploited to achieve a satisfactory level of structural reliability. The development of national and international standards will further encourage the adoption of these new sleeper technologies as an alternative to conventional railway sleeper materials. The design standard for prestressed concrete sleeper AS 1085.14 [43] is based on the permissible stress design concept which provides less effective and less economic outcomes compared to the limit state design method, has proven through extensive research [84,85]. The limit state design equations needs to be established for composite railway sleepers with the values of partial load factors and capacity reduction factors.

## 5. Conclusion

The high maintenance costs and environmental problems of timber, concrete and steel sleepers have motivated researchers, engineers and end-users to think about alternative sleepers made from composite materials. Recently, several have been developed in different parts of the world but their uptake in the market has been extremely slow. The primary obstacles to the widespread application of recycled plastic sleepers are their low strength and stiffness, low anchorage capability of holding screws, formation of voids in the body of the sleeper, permanent deformation due to creep and temperature variations, and insufficient lateral resistance. On the other hand, the prohibitive cost of high fibre containing sleepers (long fibres either in longitudinal direction only or in both longitudinal and transverse directions) are restricted their

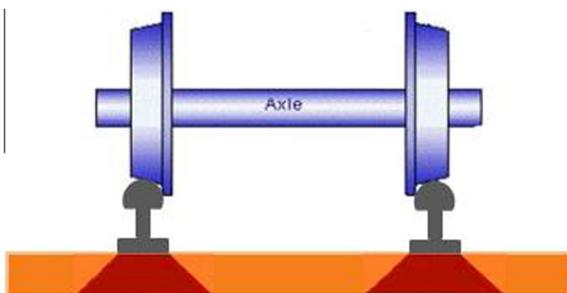


Fig. 7. Typical pattern of wheel load distribution.

applications in rail track. Moreover, the long term performances and durability of a composite sleeper are unknown. It is necessary to investigate the behaviour of a sleeper under dynamic impact and fatigue loadings, and its performances in different environmental conditions, such as UV radiation, moisture, high pH and elevated temperatures before installing it in a rail track. Currently, the design of a composite sleeper considers quasi-static loading that needs to be modified to incorporate dynamic effects in order to ensure a safe and reliable rail track.

This study suggested some potential approaches to overcome the current challenges of using composite sleepers. The strength and stiffness of the recycled plastic sleepers can be improved by incorporating fibre reinforcement while the cost of high fibre containing sleepers can be minimised by optimising the material usage and improving manufacturing process. The optimisation of sleeper is not only advantageous in terms of cost reduction but also improves the lateral stability of rail track. The design guidelines for composite sleeper is essential to establish for their widespread acceptance to the structural designers and end users.

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## Study 2

### *Behaviour of polymer matrix and composite sandwich panels*

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The high potential of sandwich panels bonded with a suitable binder as reviewed from *Study 1* was the key motivation of this study in manufacturing a composite railway sleeper. The materials behaviour of this innovative sleeper concept need to be investigated for designing sleepers. *Study 2* investigated the behaviour of epoxy polymer matrix and sandwich panels.

#### **Article III: Properties of epoxy polymer concrete matrix: Effect of resin-to-filler ratio and determination of optimal mix for composite railway sleepers**

A structural beam section can be manufactured by binding several sandwich panels together. *Article III* examined the optimal mix design for epoxy-based polymer matrix. The filler was increased from 0% to 60% in the matrix with a gradual increment of 10%. The results showed that increase in the filler in matrix improved the matrices thermal and durability properties as well as reduced its cost but decreased its physical and mechanical properties. Epoxy-based polymer mixes containing 30% to 50% fillers by volume provided a good balance of thermal, physical, mechanical, and durability properties suitable for composite railway sleepers. Along with epoxy polymer matrix, the investigation of the behaviour of sandwich panels under load is important as they are the main structural components in a railway sleeper.

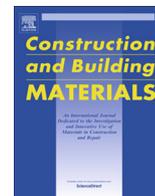
#### **Article IV: Effect of beam orientation on the static behaviour of phenolic core sandwich composites with different shear span-to-depth ratios**

Railway sleepers are subjected to high shear and flexural forces due to the wheel loads caused by a passing train. *Article IV* investigated the effective usage of composite sandwich beams made up of phenolic resin (good fire resisting capacity and cheaper than vinyl ester resin) based GFRP skins and core in resisting bending and shear forces. The shear span-to-depth ratio ( $a/d$ ) varying between 0.5 and 12 and tested under 4-point bending in the horizontal and vertical orientations. The results showed that the horizontal sandwich beams performed better under bending while vertical one was more effective in resisting shear. Moreover, the beam orientation has more influence on the load carrying capacity and stiffness properties than  $a/d$ .



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## Properties of epoxy polymer concrete matrix: Effect of resin-to-filler ratio and determination of optimal mix for composite railway sleepers



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### HIGHLIGHTS

- Study on the effect of resin-to-filler ratio on the properties of polymer matrix.
- Thermal, physical, mechanical and durability properties of epoxy based matrix.
- Mixes containing 30–50% filler are found suitable mix for coating sleepers.
- Analytic Hierarchy Process is conducted to select the best mix in different cases.

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Optimal mix

### ABSTRACT

The lack of knowledge of the behaviour of an epoxy polymer matrix has become a challenging issue for the design of a serviceable, durable and economic matrix. This study investigated the effect of the resin-to-filler ratio on the thermal, physical, mechanical and durability properties of polymer matrices composed with epoxy resin and light weight filler materials. This ratio was considered the experimental variable on which the properties of a polymer matrix are primarily dependent. The control mix was composed of 100% resin to which an amount of filler material of up to 60% of its volume was added in increment of 10%. No mix with more than 60% filler (that is, one containing 40% resin) was considered because it would not be a workable mix when prepared. A matrix's fundamental properties, including its generation of heat during mixing and glass transition temperature (thermal), density and porosity (physical), flexural and compressive behaviour (mechanical) and the effect of ultraviolet radiation (durability) were investigated. The results showed that, although adding a filler to the resin could improve the matrices thermal and durability properties as well as reduces its cost, there was a consequent decrease in its physical and mechanical properties. In maintaining a good balance among thermal, physical, mechanical and durability properties and cost, it was observed that mixes containing fillers from 30% to 50% could meet the requirements for coating of composite railway sleepers. Therefore, to select the most suitable one from the range of acceptable mixes an Analytic Hierarchy Process (AHP) was applied. The results from AHP showed that the 30% filler mix was the optimal one when priority was to obtain mechanical properties. However, if the cost of the matrix was considered the most important criterion for selecting the optimal mix, the mix containing 50% filler was the best choice. If durability was the priority, it was suggested that either a 30% or 50% filler mix be used depending on the relative importance of the mechanical properties and cost factors.

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### 1. Introduction

The weakness of an Ordinary Portland Cement (OPC) mortar in terms of its tensile strength, modulus and strain, rapid strength

development, drying shrinkage and resistance to chemical attacks has led to the utilisation of polymer matrices for bridge decks, concrete crack repairs, the coating and binding of composite panels, pavement overlays, hazardous waste containers, waste-water pipes, decorative construction panels and other structures in aggressive environmental conditions [1–4]. Unlike an OPC mortar, a polymer matrix consists of a thermoset resin with filler materials. The chemistry behind the development of polymer matrix is

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governed by the chemical reaction between resin and hardener. Generally, this reaction is exothermic (i.e., generated heat) and forms long polymer chains during the curing process which create the matrix's flexibility and strength. The properties of a polymer matrix depends largely on the type and amount of resin, type of filler and curing conditions used [5,6].

Different types of thermoset resins are available in the market. The choice of a particular one depends mainly on its tensile and compressive properties, glass transition temperature, durability, material availability, ease of processing, cost and specific user demand. In the past, researchers have investigated different resin systems in polymer concrete with the most commonly used resins epoxy [7], polyester [8] and vinyl-ester [2]. Despite the cost benefits of vinyl-ester and polyester compared with epoxy, they are not suitable if excellent mechanical and thermal properties, superior resistance to humidity, low shrinkage and high elongation are required in order to produce a durable and flexible polymer matrix [9]. Moreover, epoxy can provide a unique balance of chemical and mechanical properties combined with extreme processing versatility. Because of its superior mechanical, durability and thermal properties compared with those of other types of resins, this study examined whether epoxy is a suitable material in a polymer matrix for a coating of civil infrastructure. However, its high cost is identified as the primary obstacle.

To minimise the cost of an epoxy polymer matrix, light weight filler materials can be added to the resin. Research on the effects of different filler materials such as fly ash [6,10,11] and silica fume [6], on the polymer concrete have been investigated by several researchers, with the use of the former shown to improve the mechanical, chemical and durability properties of polymer concrete [11]. A comparative study of the performances of fly ash and silica fume with epoxy resin reported that a combination of fly ash and epoxy can provide higher mechanical strength than one of epoxy and silica fume [6]. The addition of a filler can also improve a matrix's compressive and tensile properties although its flexural strength may decrease [6]. However, Lokuge and Aravinthan [2] found that the addition of fly ash showed trends of increasing compressive strength but decreasing tensile and flexural strengths. In contrast to the traditional concept of using fly ash as a filler, this study incorporated two other filler materials, a fire retardant filler and hollow microsphere to improve fire and shrinkage performances respectively which are two important properties required for coating materials.

The fibre composites are the load carrying components of the existing and emerging composite sleeper technologies. Research and development projects on composite railway sleepers are now looking for an effective coating material to protect the load-carrying components of a sleeper against unfavourable weather conditions, particularly from ultraviolet (UV) radiation. The outdoor application of railway sleepers are routinely exposed to the UV radiation that can degrade the performance and needs a suitable coating to protect the fibre reinforcement [12]. Although the superior properties of an epoxy polymer matrix support its use as a coating material, a procedure for its mix design is not well established. In a previous study, the mix proportions of polymer concrete were arbitrarily selected and significant research carried out to investigate their behaviours [2]. For an economical design of a polymer concrete matrix, it has been recommended that minimum amount of resin is used to minimise the cost [2], and therefore, it is important to optimise the mix proportions. However, the effect on the properties of a polymer matrix due to an introduction of filler is still unknown. This study investigated the effects of different resin-to-filler ratios on the thermal, physical, mechanical and durability properties of a polymer matrix and determined an optimal one for coating of composite railway sleepers.

## 2. Materials and method

### 2.1. Materials

The materials employed in this investigation were an epoxy resin and light-weight filler.

#### 2.1.1. Resin

In this study, two main components of the resin systems were DGEBA type epoxy resin (Part-A) and an amine-based curing agent (Part-B). Epoxy resins are blended, filled, or modified with reactive and nonreactive components. The resin producer furnished an Epoxy Equivalent Weight (EEW) of 190 g for Part-A and Amine Hydrogen Equivalent Weight (AHEW) of 60 g for Part-B. To make the resin mix reactive, one equivalent weight quantity of the amine curative required one equivalent weight quantity of DGEBA epoxy resin. Therefore, 100 g of Part-A are required to mix with 32 g of Part-B to maintain the mixing ratio.

#### 2.1.2. Filler

Three different filler materials, as Fire Retardant Filler (FRF), Hollow Microsphere (HM) and Fly Ash (FA), were mixed together in approximate percentages to obtain an effective filler mix. The FRF used was non-toxic and had low abrasiveness, acid resistance, chemical inertness, smoke suppression and electric arc resistance. The HM was added to reduce the weight, control shrinkage and increase the thermal insulation of a polymer matrix while the FA could improve its performance in terms of resisting UV and reducing the permeability of water and aggressive chemicals.

### 2.2. Preparation of polymer matrices

Filler amounts of up to 60% of a matrix's volume were added in 10% increments as a mix with more than 60% filler was found unworkable. Seven mixes with different amounts of filler were prepared, and the mixes with no filler considered the control sample. The mixes were denoted according to their volumes of filler, e.g., F<sub>30</sub> indicates a mix containing 30% filler and 70% resin, as detailed in Table 1.

All the specimens were prepared in two different moulds: (a) plastic cups – suitable for measuring the heat generation, glass transition temperature, porosity, flexural strength and UV resistance, and (b) sealed-bottom cylindrical plastic pipes – suitable for measuring the density and compressive strength. All specimens were cured at room temperature for up to 24 h (Fig. 1). It was observed that the increase in the amount of filler increased the darkness of the samples as the fly ash was grey in colour.

### 2.3. Thermal behaviour

#### 2.3.1. Heat generation

During the preparation of specimens at room temperature, the resin (Part-A) and hardener (Part-B) created an exothermic reaction when mixed. The mixes produced heat, and the generated temperature was measured by a temperature gun at approximately 10-min intervals for 240 min after casting.

**Table 1**  
Mix proportions of polymer matrices.

Acronym of the mix		F <sub>0</sub>	F <sub>10</sub>	F <sub>20</sub>	F <sub>30</sub>	F <sub>40</sub>	F <sub>50</sub>	F <sub>60</sub>
% Resin/Filler (by volume)		100/0	90/10	80/20	70/30	60/40	50/50	40/60
Resin	Part-A (g)	124	112	100	87	75	62	50
	Part-B (g)	40	36	32	28	24	20	16
Filler (g)		0	30	59	89	119	148	178

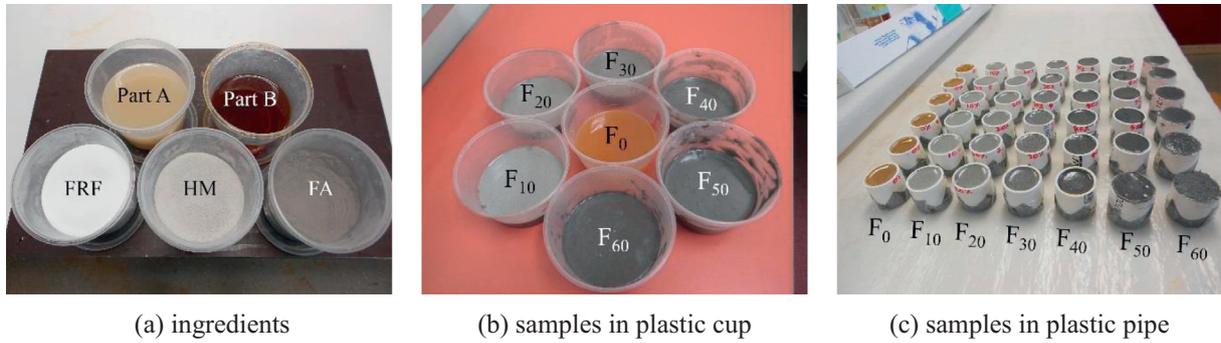


Fig. 1. Polymer matrix ingredients and sample preparation.

2.3.2. Glass transition temperature

The glass transition temperature ( $T_g$ ) is one of the most important thermal properties for designs of polymeric composite materials [13]. It is the temperature at which a polymeric material changes from a hard, rigid or glassy state to a more soft, compliant or rubbery state. Each specimen was cast in a plastic cup from which it could be de-moulded quite easily, with the resultant solid polymer matrix then cut to the specified dimensions using a cutting machine, and the dynamic mechanical tests was conducted in accordance with ASTM D7028 [14]. The machine was a Q800 type of TA instruments of which the motor applied a force and displacement sensors recorded the strain, force and amplitude in the form of raw signals. The test mode was the DMA multi-frequency-strain and the samples clamped using a dual-cantilever system. The temperature was set to between 30 °C and 120 °C, with increments of 5 °C during temperature scans. Two specimens (nominal dimensions of 60 mm × 14 mm × 4 mm) in each category were tested to determine the  $T_g$  of a polymer matrix, as shown in Fig. 2. The surfaces of the specimens were prepared as flat, clean, straight and dry to prevent them slipping from the dual-cantilever grips and suffering any effects due to moisture.

2.4. Physical behaviour

2.4.1. Density

The densities of the ingredients and solid specimen were measured using an electronic balance and helium pycnometer, with testing conducted according to the methodology specified in ASTM C905 [15].

2.4.2. Porosity

The porosity of a polymer matrix was determined by image analysis using the “TBitmap” software with measurements conducted on cut slices of 80 × 10 mm surface. A total of 35 images,

5 from each sample were taken for analysis using an optical microscope. They were saved in a manner that was workable with the software, whereby all the voids on the surface of a specimen appeared in black while the solid parts are red in colour.

2.5. Mechanical behaviour

2.5.1. Flexural strength

Each solid specimen was removed from its plastic mould and cut to nominal dimensions of 80 mm × 10 mm × 10 mm. Three specimens from each mix were prepared for flexural testing under three-point bending in accordance with ASTM C580 [16] using a 10 kN capacity testing machine with a span length of 64 mm and a test speed of 2 mm/min. During testing, frictionless papers were placed at the load and support points to facilitate smooth rotation and minimise membrane stresses.

2.5.2. Compressive strength

Each cylindrical sample was cast in a PVC pipe, with nominal dimensions of 25 mm in diameter and 25 mm high, stored at room temperature for 24 h, and then extracted from the mould and stored again at room temperature for another 6 days. Before testing, a smooth surface was prepared for the cylindrical specimens to facilitate the uniform distribution of load. The compressive strengths of the samples were determined following the test procedure prescribed in ASTM C579 [17], by the universal testing machine with a capacity of 100 kN.

2.6. Durability

In this study, the effect of UV radiation was determined by accelerated laboratory testing using a sun-test instrument, with specimens subjected to 2000 h of UV radiation by a Xenon 2200-watt air-cooled lamp in a sunset XLS chamber. This arc lamp was

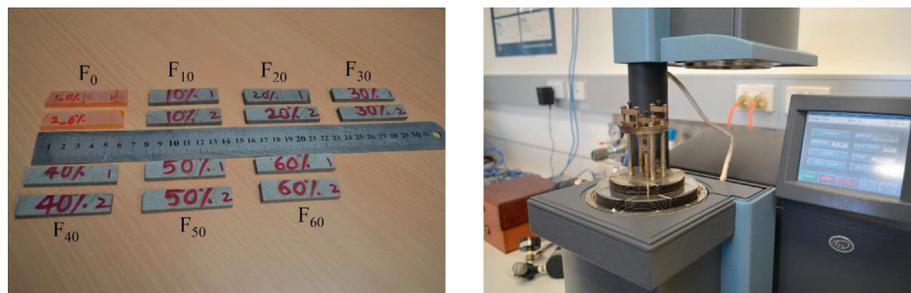


Fig. 2. Samples and the instrument for DMA.

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selected as it is the widely used UV source for photo-degrading materials and can emit a similar type of harmful radiation [18]. After the specified time, the specimens were taken out of the UV chamber and subsequently weighed, microscopically examined and mechanically tested using three-point bending.

### 3. Results and discussion

#### 3.1. Effects on thermal behaviour

##### 3.1.1. Heat generation

The temperature generated while mixing together the epoxy resin (Part-A) and hardener (Part-B) was measured by a

temperature gun at 10-min intervals. The maximum temperature recorded was 75 °C for the mix containing 100% resin, that is, 0% filler (F<sub>0</sub>). However, the peak temperature decreased in succeeding mixes with gradual increases in the amount of filler up to 60%, as shown in Fig. 3.

Fig. 3(a) demonstrates that, for the mix with 0% filler, the peak temperature was obtained at 150 min after starting the mix and gradually decreased to 90 min for the mix with 60% filler. This indicated that the exothermic reaction between the resin and hardener was completed within this time period, and the mixes started to lose plasticity. A decreasing trend of the peak temperature (Fig. 3b) with increase in the amount of filler could be explained by the heat absorption capacity of the filler [19]. The heat could

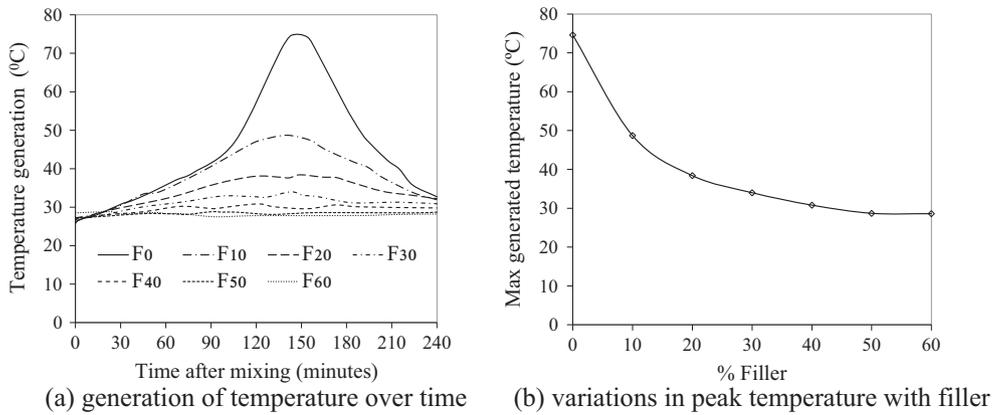


Fig. 3. Effects of volume of filler on heat generation.

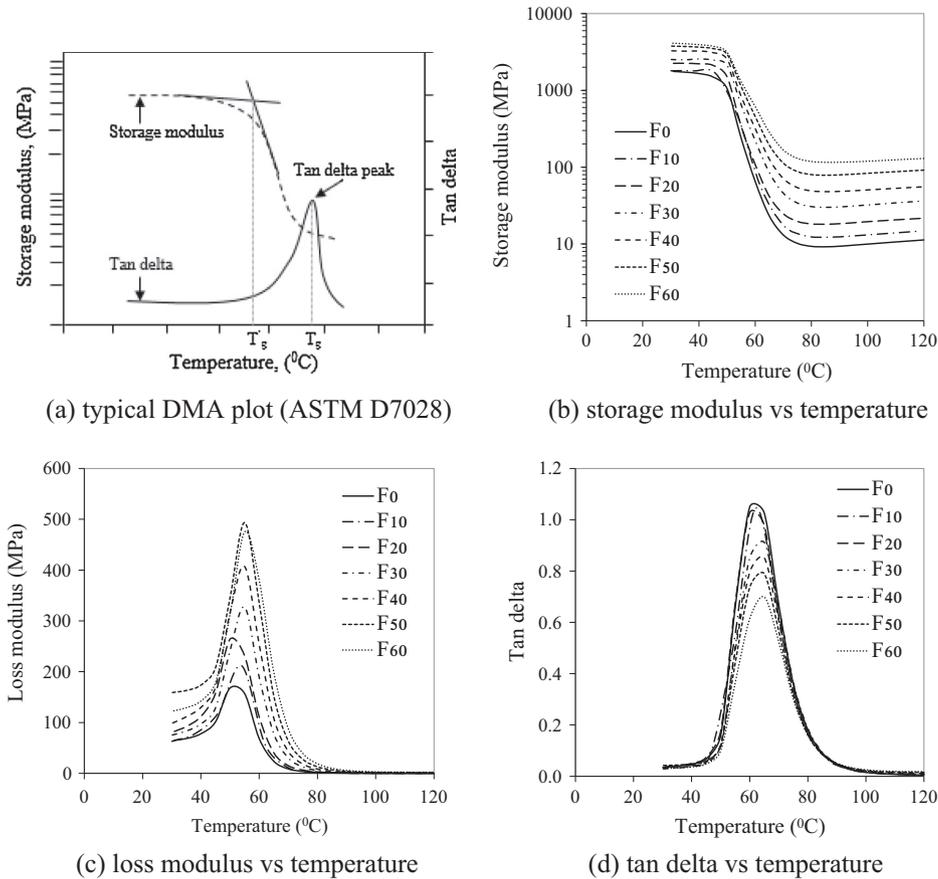


Fig. 4. Variations in dynamic mechanical properties with temperature.

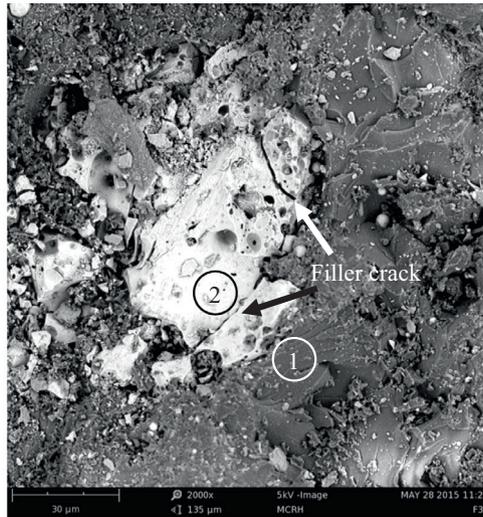
be absorbed by filler and the generated temperature reduced to a comfortable range when 30% or more filler was added to the mix. With the addition of 30–60% fillers, the temperatures of the mixes varied between 34 °C and 29 °C, which is a comfortable range of working temperature.

3.1.2. Glass transition temperature

Fig. 4(a) illustrated a typical DMA plot in accordance with ASTM D7028 [14]. Variations in the storage modulus, loss modulus and tan delta with respect to temperature are presented in Fig. 4(b–d). The temperature corresponding to the intersection of the two tangential lines in the storage modulus curve is the glass transition temperature, with the first tangent at the point where the glass transition started and the second between the inflection point and approximate mid-point of the storage modulus drop. The magnitude of  $T_g$  measured from the storage modulus curve was slightly lower than that measured from the peak of the tan delta curve. Test standard ASTM D7028 [14] suggests reporting both these magnitudes of  $T_g$  when using DMA. Although Li et al. [20], Goertzen and Kessler [21], and Shamsuddoha et al. [22] measured  $T_g$  from the peak of the tan delta curve, the standard practice, ASTM

D4065 [23], recommends measuring it from the peak of the loss modulus curve.

In all seven mixes, the magnitudes of  $T_g$  ranged from 50 °C to 55 °C using the storage modulus or loss modulus curve and from 60 °C to 65 °C using the tan delta curve. This indicated that adding 0–60% of filler to the polymer matrix could increase the glass transition temperature by only 5 °C. The  $T_g$  of the polymer mixes depended primarily on the resin system, where the type of resin was same for all mixes. Similar observation was noticed by Shamsuddoha et al. [22] where the increase of aggregates slightly enhanced the glass transition temperature. However as, in the present study, the samples were cured at room temperature, the post-curing/heat-curing system for a polymer matrix could have enhanced the  $T_g$  compare to the room-temperature curing system. Moreover, the addition of a filler could increase the storage modulus (Fig. 4b), indicating that the filler improved the capability of a polymer matrix to store energy under high temperatures. On the other hand, its capability to dissipate energy also increased with increases in the amount of filler (Fig. 4c). The magnitude of the peak of the tan delta decreased from 1.04 to 0.7 with increases in the volume of filler from 0% to 60% (Fig. 4d). This indicated that



(a) cracking of filler represents strong bond between resin and filler

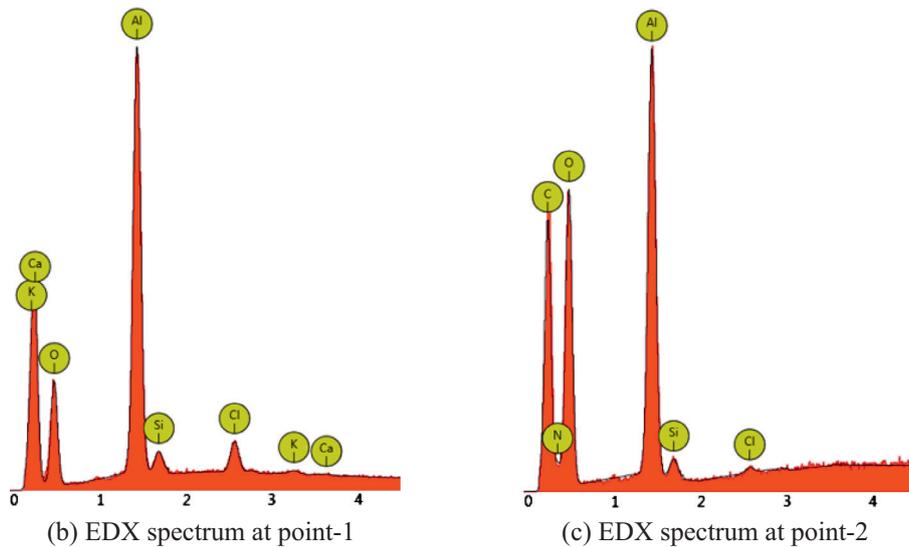


Fig. 5. SEM and EDX analysis.

the 0% filler mix (tan delta peak 1.04) had more potential for energy dissipation than any other mix under the application of load as tan delta represents the ratio of the dissipated energy (loss modulus) to the energy stored (storage modulus) per cycle of sample deformation.

At the end of the dynamic mechanical analysis, the microstructure of the specimen was observed using Scanning Electron Microscope (SEM) as shown in Fig. 5(a). It was found that, under the application of loads, the filler has been cracked before the failure occurred at the contact surface of resin and filler which represents a strong bond in between them. This phenomenon can also be observed if low strength filler materials are used, however, the filler materials employed in this study are frequently used in different structural applications that ensure their adequate strength and suitability. Point-1 and Point-2 indicate the resin and filler respectively that comes from different source materials and have different compositions, which are verified by the Energy Dispersive X-ray Spectroscopy (EDX) as shown in Fig. 5(b–c).

### 3.2. Effects on physical behaviour

#### 3.2.1. Density

In order to better understand the amounts of voids in the solid samples, the densities of the polymer matrix ingredients were measured (Table 2). The densities of the solid specimens were gradually increased from 1.093 g/cm<sup>3</sup> to 1.458 g/cm<sup>3</sup> with increases from 0% to 60% filler volumes and from 1.094 g/cm<sup>3</sup> to 1.623 g/cm<sup>3</sup> when the combined densities of the ingredients were measured. The increase of density was expected with the increase of filler as the density of filler was higher than that of the resin system. Based on the experimental results, it was observed (Fig. 6a) that variations in the measured densities of the solid samples and calculated densities based on the amounts of ingredients increased with increases in the filler loading. These discrepancies were due to gradual increases in the number of voids with increases in the amount of filler which was one of the key factors in optimising the mix proportion [24]. These variations were small for mixes containing 0–30% filler but significant (up to 10%) for

those with 40–60%, as shown in Fig. 6(b). This indicated that the mixes containing 0–30% filler volumes were resin-rich or flowable which allowed the easy escape of voids whereas the addition of 40% or more basically produced filler-dominated mixes in which air bubbles usually became stuck.

#### 3.2.2. Porosity

Fig. 7(a–e) shows the surfaces of the specimens containing different filler volume, where the black spots represent void areas and the red solid surfaces. The porosities of the specimens increased from 0.02% to 4.37% with increases in filler volumes from 0% to 60%, with higher ones producing less workable matrices which led to the generate of pores in the solid specimens. These formations were very small for up to 30% filler but relatively high for 40% and greater. The addition of fillers increased not only the porosity but also the pore sizes which is less than acceptable in an ideal polymer matrix. These findings were in agreement with the variations in density in Fig. 6, where differences between the densities of the ingredients and solid samples were higher in mixes containing 40% or more filler. It is important to note that the porosities were measured on a two-dimensional plane (Fig. 7) whereas the differences in densities in Fig. 6(b) were determined from volumetric measurements. The relative porosity measured from the image analysis was used to evaluate requirements for the coating material. Sometimes, in practice, a small percentage of pores is allowed in the design of concrete structures to prevent crack propagation.

### 3.3. Effects on mechanical behaviour

#### 3.3.1. Flexural strength

The specimens were tested under three-point bending, with sudden failure observed at their mid-spans, as shown in Fig. 8(a–b). The flexural behaviours of the polymer matrices under three-point bending are presented in Fig. 8(c–d). It can be seen that the behaviour of a polymer matrix changed from flexible to relatively rigid with gradual increases in the filler volume. For the 0% filler mix, slightly non-linear stress-strain behaviour was observed due to its nature of rubber-like material, but this non-linearity gradually decreased with increases in the filler content and became almost linear for the 60% filler mix (Fig. 8c).

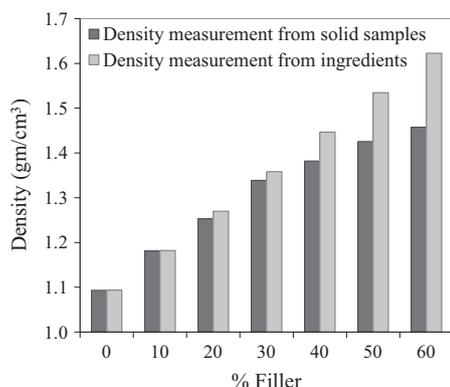
A decreasing trend in flexural strength was noticed with increases in the filler loading. The highest flexural strength obtained was 98 MPa when the mix contained no filler and the lowest 30 MPa with 60% filler (Fig. 8d). This phenomenon could be attributed to decreases in the resin content on which the strength of a polymer matrix primarily depends. Although the

**Table 2**  
Densities of the ingredients in polymer matrix.

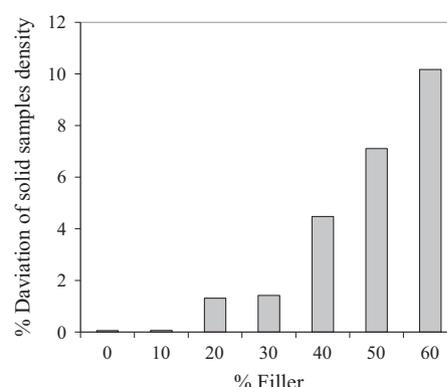
Ingredients	Resin		Filler		
	Part-A	Part-B	FRF	HM	FA
Components					
Density (g/cm <sup>3</sup> )	1.068	1.183	2.411	0.752	2.006

Part-A: epoxy resin, Part-B: hardener.

FRF: fire retardant filler, HM: hollow microsphere, FA: fly ash.



(a) variations in density with filler volume



(b) deviations in density due to voids

**Fig. 6.** Effect of filler volume on density of polymer matrix.

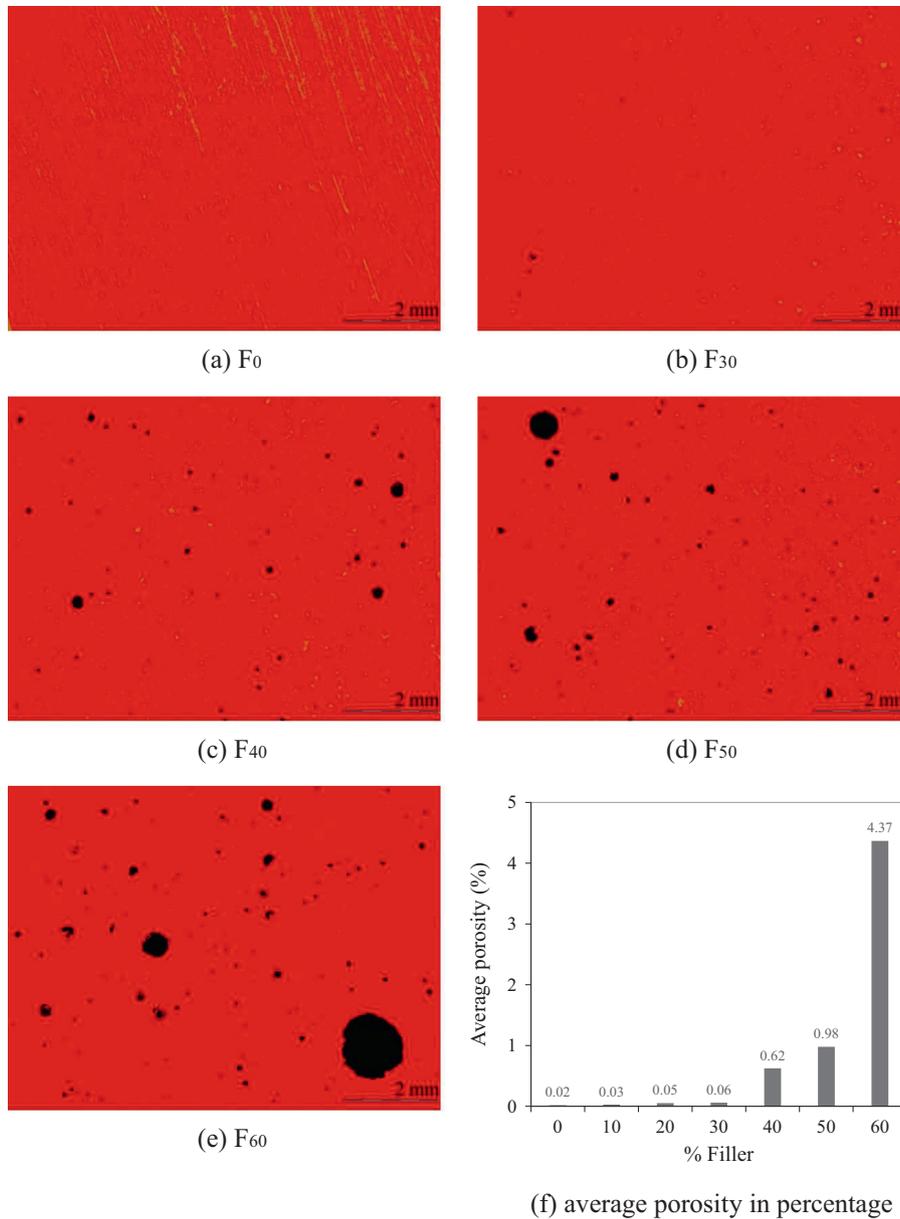


Fig. 7. Effect of filler content on the porosity of polymer matrix.

resin itself had good tensile properties, the addition of filler materials reduced the tensile capacity of the polymer matrices and, subsequently, lower flexural tensile strengths were achieved. In contrast to the flexural strength, with increases in the filler volume, the flexural modulus of elasticity increased in the range from 1.65 GPa to 4.83 GPa (Fig. 8d). An increase in the filler amount and consequent larger surface area could create a rigid bond with the resin which demonstrated an inflexible polymer matrix with the compound exhibiting a lower failure strain. This formation enhanced the stiffness properties and explained why the flexural modulus increased with increases in the filler loading. It is important to mention that a higher modulus of elasticity did not indicate high strength because the specimens failed quickly due to the deficiency of the resin and became less flexible.

### 3.3.2. Compressive strength

Unlike the traditional cement-based specimen, the resin-rich ( $F_0$  to  $F_{30}$ ) cylindrical polymer matrices were deformed without

crushing under compression, as shown in Fig. 9(a). The specimen is behaving like an elastic material as it resumed its original shape once the load was released. The failure modes of the different polymer matrices after compression testing are shown in Fig. 9(b) in which each picture was selected randomly from one of the six specimens in a batch. The specimens containing up to 30% filler did not exhibit any visible cracks under compression even after reaching their ultimate strengths. However, noticeable failures at the ultimate strength were observed for specimens containing 40–60% filler.

The compressive stress-strain behaviours of the polymer matrices are plotted in Fig. 9(c). The initial slope of each stress-strain curve representing the compressive modulus increased with increasing filler volumes due to gradual increases in the amounts of higher-modulus filler materials. No significant variations in strength (59.10–57.75 MPa) were observed for mixes containing 0–30% filler, as shown in Fig. 9(d). This was probably due to the similar failure behaviour of mixes containing relatively high

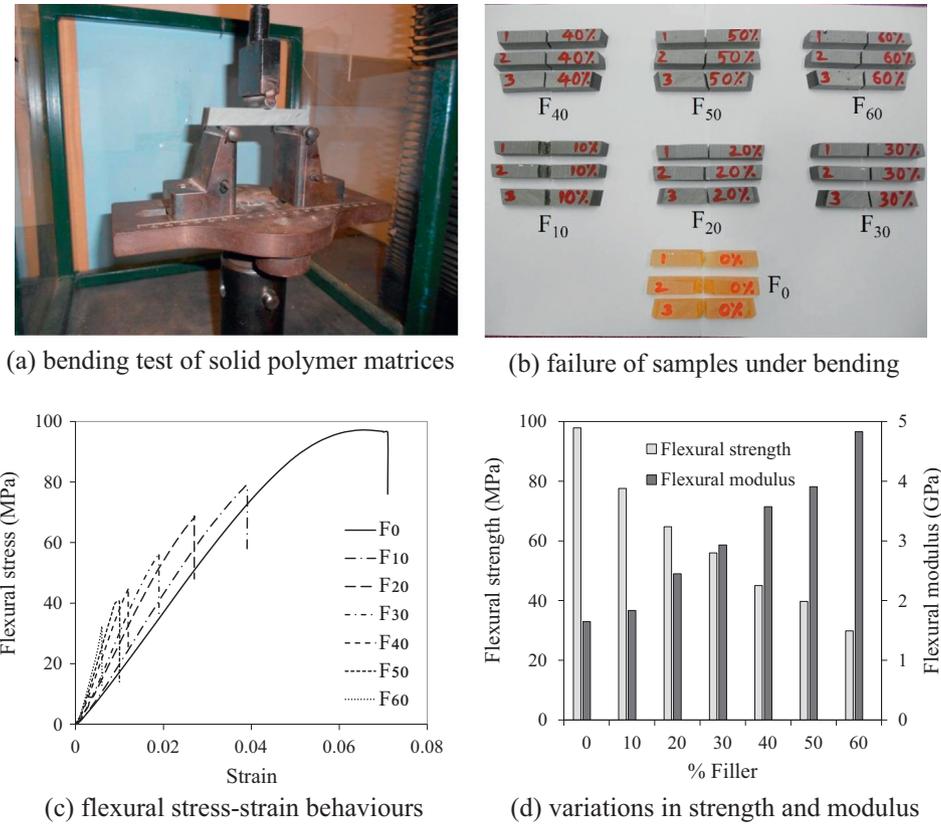


Fig. 8. Effects of filler content on flexural properties of polymer matrix.

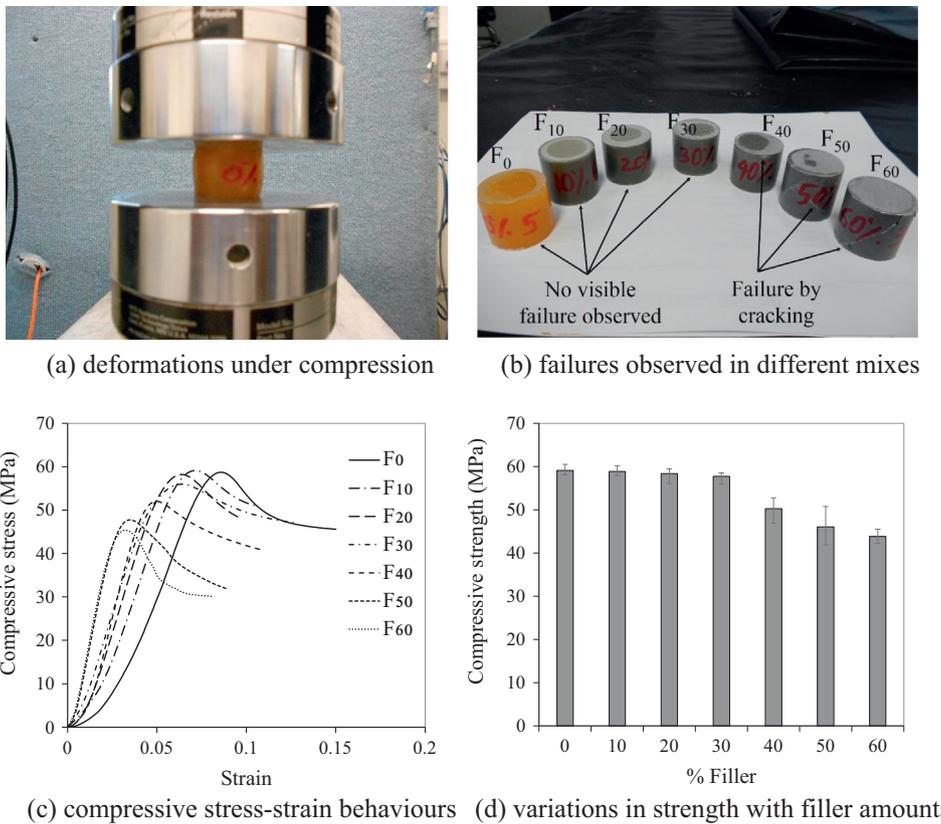


Fig. 9. Effects of filler content on compressive properties of polymer matrix.

volumes of resin which behaved like an elastic material under compression. However, a sudden drop in compressive strength (50.28 MPa) was noticed for the 40% filler mix which gradually decreased to 43.84 MPa for the 60% filler mix. This was due to the failure of the matrix at the ultimate load which more likely became brittle under compression.

3.4. Effects of UV radiation

Microscopic observations on the surfaces of the samples before and after UV exposure are illustrated in Fig. 10(a–g). The mixes containing relatively high resin, that is, low filler ( $F_0$  to  $F_{20}$ ) volumes were severely affected by UV, with surface degradation in the form of discolouration observed (Fig. 10a–c). This discolouration was due to interactions between the epoxy molecules on the exposed surface and photons from UV radiations which resulted in photo-oxidative reactions that altered the chemical structure [25]. No significant changes in colour were noticed for the mixes with 30% or more filler (Fig. 10d–g) while mix  $F_0$ , which contained 100% resin, was more transparent than the others. This transparency was due to the physical properties of the resin and the fact that the addition of filler could increase the darkness of the specimen as the colour of fly ash was grey. Significantly greater variations in colour were observed in the 30% filler mix ( $F_{30}$ ) than in mixes containing less than 30% filler ( $F_0$  to  $F_{20}$ ). Therefore, in general, it can be concluded that the mix containing a filler of less than

30% was prone to UV radiation. No significant variations were observed in the mixes containing 30–60% fillers ( $F_{30}$  to  $F_{60}$ ) because the darkness of the filler could block the UV rays and protect the samples from physical and mechanical degradation. However, minor changes in the surface roughness of all the UV-exposed specimens were visible.

The weights of the specimens were measured immediately after they were taken out of the UV chamber. As the UV lamp was focused on the specimens from the top, their top surfaces were the most affected by the UV light [26]. The loss of a specimen's weight per unit of UV-exposed area (only the top surface) was determined and it was found that it followed a decreasing trend with an increase in the filler volume in the mix (Fig. 11a). The highest loss of weight was  $50 \text{ g/m}^2$  for the 0% filler mix ( $F_0$ ) which decreased to  $27 \text{ g/m}^2$  for the 60% filler one ( $F_{60}$ ). Greater losses were found for the mixes containing 0–20% fillers which suddenly decreased from  $45 \text{ g/m}^2$  to  $35 \text{ g/m}^2$  when the filler increased from 20% to 30%. However, the rate of improvement between the 30% and 60% filler mixes was quite slow. The percentage losses of weight comparing with the initial weights of the specimens (before UV exposure) are shown in Fig. 11(b). It was also found that the loss of weight decreased from 0.37% to 0.15% with increases in filler volumes from 0% to 60%, a somewhat comparable result to that obtained for the loss of weight of carbon fibre-reinforced epoxy composites after 500 h of UV exposure by Kumar et al.[25] who found an average loss of 0.27%. This decrease in weight loss was

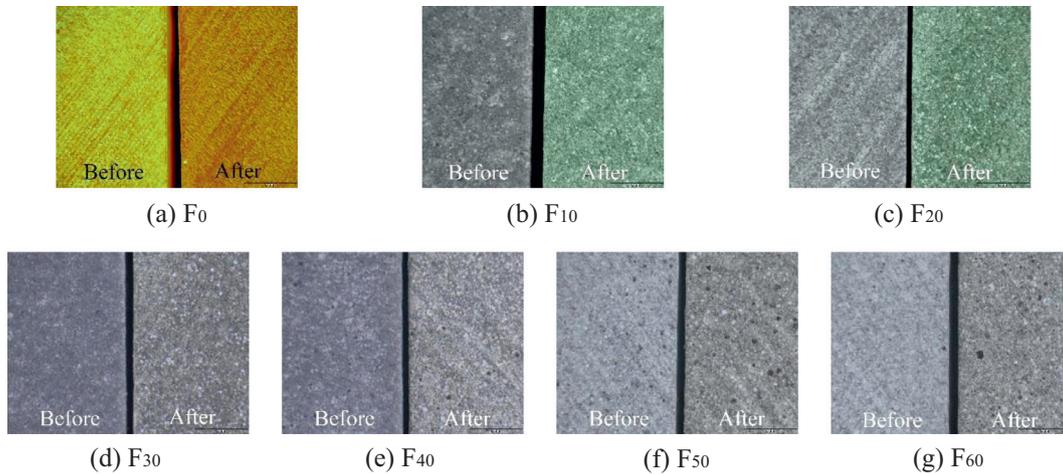


Fig. 10. Discolouration of UV affected samples after 2000 h of UV exposure.

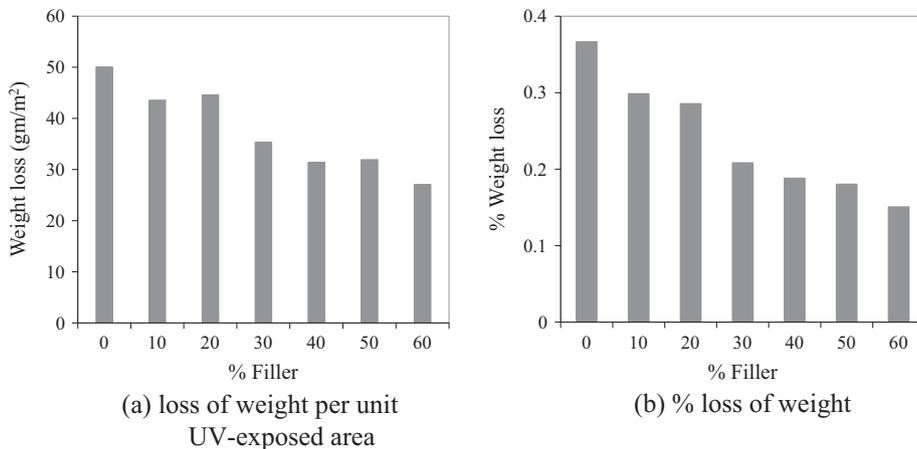


Fig. 11. Loss of weight of polymer matrix after 2000 h of UV exposure.

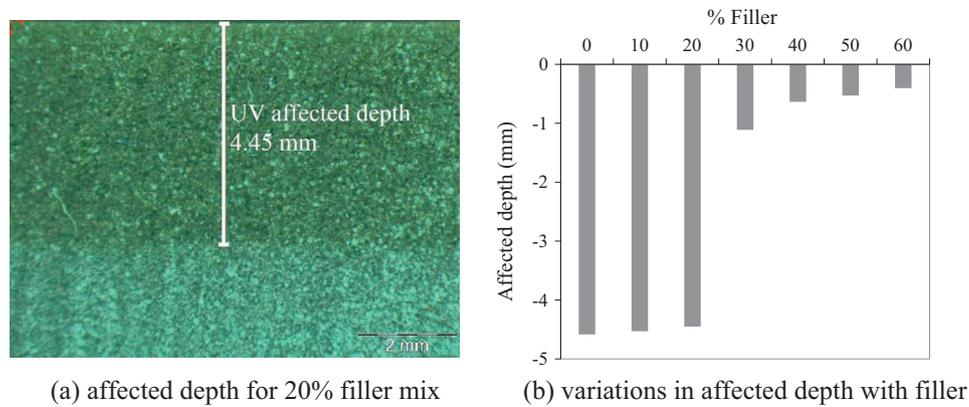


Fig. 12. Depths of samples affected by UV light after 2000 h of UV exposure.

due to the gradual improvement in UV-resistant properties with increases in the amount of filler which could protect samples from deterioration.

The depths of the specimens affected by the UV light were measured using an electronic microscope. There were clear distinctions in colour between the affected and unaffected layers (Fig. 12a), with the affected depths found to be higher for mixes containing fillers of up to 20%. The maximum was 4.58 mm for a 0% filler mix and slightly lower, 4.45 mm, for a 20% one but there was a sudden decrease for a 30% one (Fig. 12b). This indicated that the transitional polymer matrices with superior resistance to UV radiation contained fillers of between 20% and 30%, the expulsion of moisture was less in the latter, which explained why there was a sudden drop in weight loss in Fig. 11 when the filler increased from 20% to 30%. The affected depth gradually decreased from 1.11 mm to 0.40 mm for the mixes with fillers from 30% to 60%. Overall, the addition of filler to an epoxy polymer matrix could have increased resistance to UV radiation because, as the fillers blocked the penetration of UV, only the resin near the surface was affected.

The flexural strengths of the UV-unaffected specimens were measured before placing an identical second batch in the UV chamber and measuring them after 2000 h of UV exposure using a similar bending test. To assess the effect of UV on flexural strength, the specimens were placed in the testing machine in such a way that their UV-affected sides were subjected to tension in bending. The results were compared with those for the unaffected samples, and significant reductions in the flexural strength of up to 48%

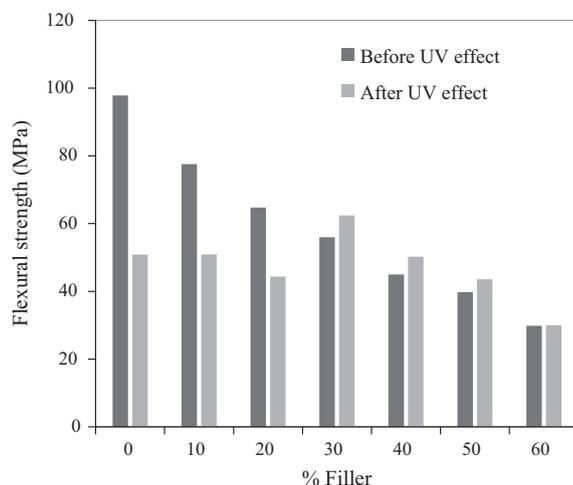


Fig. 13. Effects of UV radiation on flexural strengths of polymer matrix.

for a 0% filler mix ( $F_0$ ) and, 34% and 32% for mixes containing filler volumes of 10% and 20% respectively ( $F_{10}$  and  $F_{20}$ ) were observed. These reductions correlated with the affected depths of 46%, 45% and 44% (the total depth of the samples was 10 mm) for  $F_0$ ,  $F_{10}$  and  $F_{20}$  respectively which indicated that the loads were carried mainly by the unaffected depths. However, no reductions in flexural strength were noticed for mixes with higher filler volumes which stated that the fillers could have helped to preserve structural performance by absorbing or blocking UV radiation before it reached the chromophores in the polymer matrices (Fig. 13).

Surprisingly, slight increases in flexural strength were found in the UV-affected mixes containing filler volumes from 30% to 60%. It is mentioned previously, the effect of UV was only significant for mixes with fillers of less than 30% and no major changes in colour were observed for those containing 30–60% fillers (Fig. 10). Therefore, these slight increases in strength were probably due to the post curing during UV exposure and ages which were at least 2000 h (the in-chamber period) longer than those of unaffected samples.

#### 4. Evaluation of polymer mix for railway sleepers

Research and development of fibre composite railway sleepers are now looking for a suitable coating material to protect their load carrying components against adverse environments [12,27]. The superior mechanical, thermal and durability properties of a polymer matrix composed of epoxy resin and light-weight filler materials demonstrated a suitable and effective coating material. The main focus of this part of the study is to evaluate a suitable polymer matrix for the coating of composite railway sleepers based on their thermal, physical, mechanical, durability properties and cost factors. The performance requirements of the polymer matrix as a coating material is judged based on the issues associated with a sleeper.

- A polymer matrix generates heat during the mixing of the resin and hardener, and less than 35 °C can be considered a comfortable temperature with which to work [28].
- In India, one of the world's largest rail networks, variations in the rail temperature have been recorded to a maximum of 60 °C [29] which, in Australia is approximately 65 °C [30] and even lower in the colder regions. However, the rail is made of steel that can be heated up quite easily and most of the parts of sleeper are generally covered by ballast, and the temperature cannot reach to that high. Therefore, a glass transition temperature of 60 °C is considered sufficient for sleeper coating materials.

- Generally, the density of a timber sleeper varies between 1.05 g/cm<sup>3</sup> and 1.12 g/cm<sup>3</sup> [31] and that of a concrete one approximately 2.4 g/cm<sup>3</sup> as it is quite heavy and requires special machinery for its installation in a rail track [32]. Therefore, a sleeper with a density of between 1 g/cm<sup>3</sup> and 1.5 g/cm<sup>3</sup> would be a preferable choice.
- The porosity of concrete can reduce a solid material's mechanical properties as an increase in it indicates a decrease in the load-carrying capability of the material. It has been noted that an increase in the porosity of 1% can reduce the compressive and flexural strengths of concrete by approximately 10% over those of non-porous concrete [33]. As the general performance requirements of a composite sleeper stipulate that its properties should not be affected by more than 10% by adverse conditions [34], the allowable porosity of a polymer matrix can be up to a maximum of 1%.
- The average flexural strength of a new timber sleeper was found by Westrail to be approximately 40 MPa [35] while Humphreys and Francey [36] measured the flexural failure strain of a traditional timber sleeper to be around 1%. To avoid failure of the main structural component of a polymer railway sleeper, its coating materials should be more flexible than main structural component and the flexural failure strain greater than 1% is expected.
- A polymer matrix with vertical compressive strength greater than 40 MPa is sufficient to carry track loads [31].
- As it is mentioned, the properties of sleeper should not be affected by more than 10% by the adverse environments; it is therefore considered as an allowable limit for the reduction of strength due to UV radiation.

These target values for fulfilling the requirements of a polymer matrix as coating for a railway sleeper are presented in Table 3 and compared with the properties of the seven different polymer matrices investigated in this study.

Based on the target performance requirements presented in Table 3, it is shown that only the mixes containing filler from 30% to 50% are fulfilling all the requirements. A challenge still remains to select the most suitable one from the shortlisted (F<sub>30</sub>, F<sub>40</sub> and F<sub>50</sub>) polymer mixes as some of the required properties are dominated by F<sub>30</sub> and others by F<sub>50</sub>. To select the optimal one from these three, Analytic Hierarchy Process is applied and discussed next.

**Table 3**  
Comparison of performance requirements for polymer matrix.

Performance measurements	F <sub>0</sub>	F <sub>10</sub>	F <sub>20</sub>	F <sub>30</sub>	F <sub>40</sub>	F <sub>50</sub>	F <sub>60</sub>	Target
Heat generation (°C)	75	49	38	34	31	29	29	<35
Glass transition temp. (°C)	60	60	62	63	64	65	65	>60
Density (g/cm <sup>3</sup> )	1.09	1.18	1.25	1.34	1.38	1.43	1.46	1–1.5
% Porosity	0.02	0.03	0.05	0.06	0.62	0.98	4.37	<1
Flexural strength (MPa)	98	78	65	56	45	40	30	>40
% Failure strain in flexure	7.1	3.9	2.7	1.9	1.2	1.0	0.6	>1
Compressive strength (MPa)	59	59	58	58	50	46	44	>40
% Strength reduction by UV	48	34	31	0	0	0	0	<10
Relative cost comparison	100	94	88	83	77	71	65	As low as

### 5. Determination of optimal mix for railway sleepers

An optimal mix is one which can satisfy the requirements of a particular application in the best possible way. The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method that derives ratio scales from paired comparisons based on mathematics and psychology. The relative importance of each attribute can be expressed by the fundamental scale of AHP proposed by Saaty and Vargas [37]. The main advantage of this method is its capability to check and reduce inconsistencies in judgement, with a small one of less than 10% usually acceptable. The numbers 1, 3, 5, 7 and 9 represent the verbal judgments 'equal importance', 'moderate importance', 'strong importance', 'very strong importance' and 'extreme importance' respectively while 2, 4, 6 and 8 express intermediate behaviours. A relative importance matrix can be constructed for *n* attributes, where the relative importance of attribute *i* with respect to attribute *j* is represented by *a<sub>ij</sub>*. As a strong attribute always needs to be compared with weight scale 1 for a weak attribute, all the diagonal entries in the *n*-order square matrix are equal to 1. A typical relative importance matrix  $A = [a_{ij}]_{n \times n}$  can be expressed by Eq. (1) which has reciprocal properties where  $a_{ji} = 1/a_{ij}$  and  $a_{nn} = 1$ .

$$A = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ 1/a_{1n} & \dots & a_{nn} \end{bmatrix} \tag{1}$$

The normalised Eigen vector of matrix *A* represents the relative weights of the attributes and is called the priority matrix. The Eigen vector of matrix *A* can be determined manually or by using the Matlab program and then be normalised by dividing the sum of all its elements that can be expressed by Eq. (2).

$$a_{ij}^* = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \tag{2}$$

where *a<sub>ij</sub>* is an element of the Eigen vector.

To ensure consistent relative weights among the attributes, the Consistency Ratio (*CR*) needs to be checked. If  $CR \geq 0.1$ , the values are generally considered inconsistent in a pair-wise comparison and need to be revised. The *CR* can be expressed by Eq. (3).

$$CR = \frac{CI}{RI} \tag{3}$$

where *CI* is the Consistency Index, expressed by Eq. (4), and *RI* the Random Index, the average values of which with respect to *n* are given in Table 4 [37].

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

where  $\lambda_{max}$  is the Eigen value and *n* the number of comparisons.

The hierarchy of the analysis was divided into criteria, sub-criteria and alternatives, with the key factors, such as thermal, physical, mechanical, durability properties and cost, the main drivers in terms of criteria. These criteria were then sub-divided into more specific sub-criteria of properties, e.g., heat generation and glass transition temperature (thermal), density and porosity (physical), flexural strength, failure strain and compressive strength

**Table 4**  
Average values of *RI*.

<i>n</i>	1	2	3	4	5	6	7	8	9	10
<i>RI</i>	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

(mechanical) and UV resistance (durability), with each having three alternative polymer mixes (F<sub>30</sub>, F<sub>40</sub> and F<sub>50</sub>).

5.1. Relative intensities of criteria

The criteria were the main drivers for selection of the optimal mix. In this stage, a small change in intensity had a significant effect on the final output, and the priorities of the properties depended on the design requirements. Therefore, six cases were studied by interchanging the highest priorities of mechanical properties, cost and durability which are dominant properties in most engineering applications. Thermal and physical, the other two properties were provided fourth and fifth priorities respectively, in all six cases. In Case-1 (C1), the highest priority was given to the mechanical properties followed by the cost, durability, thermal and physical ones, with cost and durability also given the highest priorities in the other cases. The relative importance and intensities of the different properties are provided in Table 5.

5.2. Relative intensities of sub-criteria

Of the sub-criteria: for thermal properties, the glass transition temperature was strongly preferred over heat generation as it measures the quality of a product; for physical properties, porosity was slightly more important than density; and, for mechanical properties, the failure strain was more important than the flexural or compressive strength because, when a polymer matrix is used as a coating, it should have sufficient flexibility which depends on its failure strain. However, the flexural strength was considered slightly more important than the compressive strength for coating a polymer railway sleeper. Table 6 shows the relative weights of the sub-criteria.

5.3. Relative intensities of alternatives

The relative weightings of the alternative mixes were calculated based on their performances presented in Table 3. As previously mentioned, because no mix beyond F<sub>60</sub> could be produced, the best and the worst possible results previously obtained for either F<sub>0</sub> or F<sub>60</sub>. The intensity of the worst mix (either F<sub>0</sub> or F<sub>60</sub>) in the particular investigation presented in Table 3 was given 1 and that of the best 9. Using this concept, the normalised relative intensities of the shortlisted mixes were determined and are shown in Table 7.

5.4. Determination of priorities for mixes

The priorities of the alternatives with respect to the sub-criteria, those of the sub-criteria with respect to the criteria and those of the criteria with respect to the goal were calculated and are

**Table 6**  
Pair-wise comparison of sub-criteria.

Criteria	Sub-criteria		Importance	Intensity
	A	B		
Thermal	Heat generation	Glass transition temperature	B	5
Physical	Density	Porosity	B	2
Mechanical	Flexural strength	Failure strain	B	2
	Flexural strength	Compressive strength	A	2
	Failure strain	Compressive strength	A	3

**Table 7**  
Normalised relative intensities of alternative mixes.

Measuring criteria	F <sub>30</sub> vs F <sub>40</sub>		F <sub>30</sub> vs F <sub>50</sub>		F <sub>40</sub> vs F <sub>50</sub>	
	F <sub>30</sub>	F <sub>40</sub>	F <sub>30</sub>	F <sub>50</sub>	F <sub>40</sub>	F <sub>50</sub>
Heat generation	1	1.06	1	1.11	1	1.04
Glass transition temperature	1	1.28	1	1.55	1	1.22
Density	1.32	1	2.18	1	1.66	1
Porosity	1.13	1	1.23	1	1.09	1
Flexural strength	1.47	1	1.86	1	1.27	1
Failure strain in flexure	1.50	1	1.74	1	1.16	1
Compressive strength	2.02	1	4.10	1	2.03	1
Strength reduction by UV	1	1	1	1	1	1
Cost	1	1.28	1	1.56	1	1.22

presented in Fig. 14. The global priority of each mix was determined by multiplying its corresponding local priorities and summing them, and expressed as

$$\text{Global priority of the mix} = \sum [Priority_{\text{alternative}} \times Priority_{\text{sub-criteria}} \times Priority_{\text{criteria}}]$$

An example for Case-1 is given in Table 8.

Based on the relative importance of each attribute with respect to the goal, Table 9 presents the global priorities and optimal mixes for all six cases.

It is apparent from Table 9 that selection of the optimal polymer matrix depended on the priorities of its properties; for example, in Case-1 (C1), the mechanical properties were given the highest priority followed by cost and durability, with the highest priority of the best polymer matrix obtained for F<sub>30</sub> (38.17%) followed by F<sub>40</sub> (31.56%) and F<sub>50</sub> (30.27%). Depending on applications, if a designer or end user designated mechanical properties as the highest priority mix F<sub>30</sub> could be the best choice. On the other hand, if the cost of material was the dominant factor, mix F<sub>50</sub> would be preferable, while requiring durability might lead to either F<sub>30</sub> or

**Table 5**  
Pair-wise comparison of criteria.

Criteria		Importance						Intensity						
		A	B	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5
Thermal	Physical	A	A	A	A	A	A	A	3	3	3	3	3	3
Thermal	Mechanical	B	B	B	B	B	B	B	7	7	5	3	5	3
Thermal	Durability	B	B	B	B	B	B	B	3	5	3	5	7	7
Thermal	Cost	B	B	B	B	B	B	B	5	3	7	7	3	5
Physical	Mechanical	B	B	B	B	B	B	B	9	9	7	5	7	5
Physical	Durability	B	B	B	B	B	B	B	5	7	5	7	9	9
Physical	Cost	B	B	B	B	B	B	B	7	5	9	9	5	7
Mechanical	Durability	A	A	A	A	B	B	B	5	3	3	3	3	5
Mechanical	Cost	A	A	B	B	A	B	B	3	5	3	5	3	3
Durability	Cost	B	A	B	B	A	A	A	3	3	5	3	5	3

C1 to C6 represents Case-1 to Case-6.

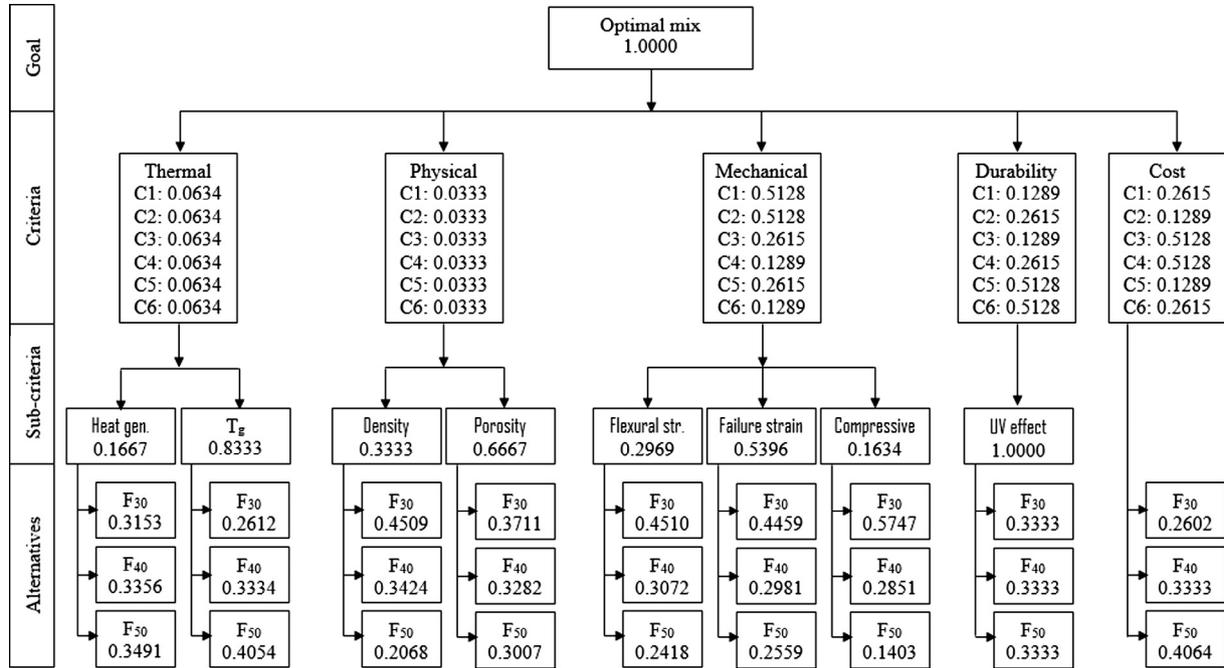


Fig. 14. Summary of local priorities.

Table 8  
Details of global priority for Case-1 (C1).

	Heat gen.	T <sub>g</sub>	Density	Porosity	Flexural strength	Failure strain	Compres. strength	UV effect	Cost	Total
F <sub>30</sub>	0.0033	0.0138	0.0050	0.0082	0.0687	0.1234	0.0482	0.0430	0.0681	0.3817
F <sub>40</sub>	0.0035	0.0176	0.0038	0.0073	0.0468	0.0825	0.0239	0.0430	0.0872	0.3156
F <sub>50</sub>	0.0037	0.0214	0.0023	0.0067	0.0368	0.0708	0.0118	0.0430	0.1062	0.3027
Sum	0.0106	0.0528	0.0111	0.0222	0.1523	0.2767	0.0838	0.1289	0.2615	1.0000

Table 9  
Global priorities and optimal mixes.

Case	Order of priority of properties			% Priority of matrix			Optimal mix
	1st	2nd	3rd	F <sub>30</sub>	F <sub>40</sub>	F <sub>50</sub>	
C1	Mechanical	Cost	Durability	38.17	31.56	30.27	F <sub>30</sub>
C2	Mechanical	Durability	Cost	39.14	31.56	29.30	F <sub>30</sub>
C3	Cost	Mechanical	Durability	32.93	32.43	34.64	F <sub>50</sub>
C4	Cost	Durability	Mechanical	31.14	32.89	35.97	F <sub>50</sub>
C5	Durability	Mechanical	Cost	35.74	32.43	31.83	F <sub>30</sub>
C6	Durability	Cost	Mechanical	32.98	32.89	34.13	F <sub>50</sub>

F<sub>50</sub> depending on the relative importance of the mechanical properties and cost.

6. Conclusion

This study experimentally investigated the thermal, physical, mechanical and durability properties of epoxy-based polymer matrices containing different resin-to-filler ratios from which the optimal mix was selected and the following conclusions drawn.

- The exothermic reaction between the resin (Part-A) and hardener (Part-B) could generate temperatures up to 75 °C which were uncomfortable to handle and difficult to work with. The addition of a filler to the resin resulted in a temperature within a comfortable working range. The mixes containing filler volumes of more than 60% were not able to produce a workable polymer matrix.

- At room-temperature curing, the addition of filler had no significant effect on the glass transition temperature which was found to be between 60 °C and 65 °C for all mixes.
- The density of a polymer matrix increased from 1.09 g/cm<sup>3</sup> to 1.46 g/cm<sup>3</sup> with an increase in the filler content from 0% to 60% which resulted in more and bigger voids in the matrix.
- The porosity of a mix was generally low (≤0.06%) when its filler was less than 30% but increased to 4.37% for a 60% filler mix.
- An increase in the amount of filler from 0% to 60% reduced the flexural strength by 70% (from 98 MPa to 30 MPa). However, the same addition could increase the flexural modulus from 1.6 GPa to 4.8 GPa and reduce the failure strain from 7.1% to 0.6%. This was due to the behaviours of the ingredients whereby the resin dominated the strength and the filler the stiffness.
- The mixes containing filler volumes of up to 30% did not exhibit any visible failure under compression even when they reached their ultimate strengths of around 58 MPa. However, noticeable

failures were observed for mixes containing fillers from 40% to 60%, the strengths of which reduced from 50 MPa to 44 MPa. The compressive modulus of elasticity increased with an increase in the amount of filler.

- UV radiation for 2000 h reduced the flexural properties of a polymer matrix by 48% for the mix with 0% filler. It also resulted in embrittlement, discolouration and an overall reduction in weight. Therefore, the addition of a filler could help to preserve structural performance by absorbing or blocking UV radiation before it reaches the chromophores on which the colour of a polymer matrix is dependent.
- The polymer matrices containing fillers from 30% to 50% could satisfactorily meet the requirements for coating of composite railway sleepers. If the mechanical properties of a matrix were the highest priority, the mix with a 30% filler would be the most suitable while that with a 50% filler would be the best choice if the material cost played a vital role. If durability (UV radiation) was paramount, the choice could be either a 30% or 50% filler mix depending on the relative priorities of the mechanical properties and cost factors. Finally, the AHP could be further implemented to assist a designer or end-user to select the optimal mix for other applications of epoxy polymer concrete.

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# Effect of beam orientation on the static behaviour of phenolic core sandwich composites with different shear span-to-depth ratios



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## ABSTRACT

This study thoroughly investigated the flexural behaviour of phenolic cored sandwich beams with glass fibre composite skins in the horizontal and vertical positions. The beams have a shear span-to-depth ratio ( $a/d$ ) varying between 0.5 and 12, and tested under 4-point static bending. Their failure load are then predicted theoretically. The results showed that changing the beam orientation from horizontal to vertical changes the failure mode from brittle to progressive. The sandwich beam's high bending stiffness can be efficiently utilised by placing them vertically. The  $a/d$  ratio played a major role on the load capacity and failure mode. In both orientations, the load capacity decreased with the increased of  $a/d$ . The beam failed in shear, a combined shear and bending, and bending for  $a/d \leq 2$ ,  $2 < a/d < 6$ , and  $a/d \geq 6$ , respectively. These failure mechanisms can be correlated to the shear-to-bending stress ratio while the failure load can be reasonably predicted using the available theoretical models. The two-way analysis of variance showed that the beam orientation is a more influential parameter than the  $a/d$  ratio. From this study, the horizontal beams are preferable for flexural dominated structures while the vertical beams are desirable for shear dominated structures.

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## 1. Introduction

The applications of fibre composite sandwich systems are rapidly increasing in civil infrastructure and construction due to their excellent durability, design flexibility, cost effectiveness, and high strength-to-weight and stiffness-to-weight ratios [1]. In these applications, composite sandwich panels are oriented either in the horizontal or vertical directions to effectively resist the design loading. In particular, sandwich panels in horizontal orientation are widely used for structural roofs [2], floors [3], walls [4] and bridge decks [2]. In this orientation, the strong and stiff fibre composite skins are located at the top and bottom surfaces of the panels. On the other hand, the panels are used in the vertical orientation for bridge girders [3], railway sleepers [5,6], or similar beam applications wherein the fibre composite skins are located at both sides of the core material.

Several studies have been conducted to investigate the behaviour of sandwich panels at horizontal orientation [7–13] while very limited studies have been reported on the behaviour at verti-

cal position. Manalo et al. [14] are probably the only researchers who evaluated the behaviour of 20 mm × 50 mm sandwich beams in both horizontal and vertical orientations. The results of their experimental investigation showed that the sandwich beams in the vertical position failed at a higher load with less deflection compared to beams in the horizontal position. Similarly, the beams in the vertical orientation failed progressively while the beams in the horizontal orientation exhibited a brittle failure. Their study however was limited to sandwich beams with a particular shear span resulting to beams with different shear span-to-depth ratios making the direct comparison of their behaviour inadequate. Many researchers [15–17] indicated that shear span-to-depth ratio has a strong influence on the failure behaviour and structural performance of the sandwich beams. Manalo [18] investigated the behaviour of phenolic-core sandwich beams in horizontal orientation with different shear span-to-depth ratios. His study found that with increase of shear span-to-depth ratio, the failure load of the sandwich beam decreases due to the increase of deflection. Recently, Mathieson and Fam [19] studied the bending and failure mechanism of sandwich beams with low-density polyurethane core and glass fibre-reinforced polymer skins in vertical orientation with varying shear span-to-depth ratios in the application of walls and supporting beams. They observed the increase of shear

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span-to-depth ratio can significantly reduce the moment capacity of the sandwich panel due to the occurrence of the skin wrinkling in compression.

Clearly, there are significant variations in the behaviour of sandwich beams due to the change of orientation and shear span-to-depth ratio. However, the reported studies are limited to the investigation of sandwich beams' behaviour either in the horizontal or vertical orientation making a comparison study necessary and significant. This study investigated the effect of beam orientation on the static behaviour of fibre composite sandwich structure made up of phenolic core and glass fibre composite skins. A total of 30 different specimens with 20 mm × 20 mm, 20 mm × 40 mm and 20 mm × 80 mm sectional dimensions were tested under static bending in horizontal and vertical orientations at different shear span-to-depth (a/d) ratios. The failure behaviour, strength and stiffness properties of the sandwich beams were evaluated. Prediction equations for the failure load of the sandwich beams in different orientations and a/d ratios were also presented and compared with the experimental results. The outcomes of this study provided an indication on how to effectively utilize the composite sandwich beams in carrying loads required in different civil engineering applications.

## 2. Materials and methods

### 2.1. Materials

The structural composite sandwich beams tested in this study consisted of glass fibre reinforced polymer (GFRP) composite layers (skins) bonded to a phenolic core. The fibres of each skin were laid up in 0° (4 layers), 90° (2 layers) and ±45° (2 layers in each) along the longitudinal direction of the sandwich beam to provide strength and stiffness in all directions. Each skin was 1.8 mm thick with a fibre volume ratio of 45%. The phenolic core material came from natural plant (non-food) products derived from vegetable oils and plant extracts and was chemically bonded with the polymer resin. The density of sandwich panel is approximately 990 kg/m<sup>3</sup> which is comparable to the hardwood red gum timber [20]. The properties of the GFRP skins and phenolic core were determined by the second author and are provided in Table 1.

### 2.2. Specimen details and test setup

The bending test for sandwich beams was conducted in accordance with ASTM C393 [21]. In the horizontal position, the skins

were located at top and bottom while the skins were at both side of phenolic core in vertical position. The specimens were prepared by cutting the panels into the required dimensions using a water jet cutter. The load was applied through a spreader beam with a loading rate of 3 mm/min using the MTS 100 kN testing machine. Three replicates were tested for each specimen type until the ultimate failure. Fig. 1(a) and (b) illustrated the horizontal and vertical positions of the beam section, respectively with the necessary dimensions while Fig. 1(c) shows the typical test setup.

In Fig. 1, the  $t_s$ ,  $t_c$ ,  $b$ , and  $d$  refer to the thickness of skin, thickness of core, beam width and beam depth, respectively. The other parameters  $P$ ,  $a$ , and  $L$  represent the applied load, shear span and span of the tested beam, respectively. In this study,  $t_s$  and core  $t_c$  were same for all 30 specimens. Therefore, the change of beam dimension indicates either the change of width ( $b$ ) or depth ( $d$ ). Depending on the test set-up, beam dimension and orientation, the a/d ratios were varying between 0.5 and 12. The variation of a/d ratio was ensured by changing the beam orientation and shear span while maintaining the span of the beams. The details of the 30 different types of sandwich beam specimens are summarised in Table 2.

## 3. Results and discussion

### 3.1. Failure mode

The typical failure modes of the sandwich beams made of GFRP skins and phenolic core are provided in Fig. 2(a) to (h). These failure modes can be classified into four broad categories, i.e. (a) shear failure, (b) combined shear and bending failure, (c) bending failure, and (d) indentation failure. The following presents a brief description of the different failure modes:

- **Shear failure:** Shear failure of the sandwich beam is illustrated by the diagonal cracks observed either in the phenolic core or GFRP skins between the loading point and the support. This type of failure occurred when the shear stress exceeded the shear strength either of the core or the skins. The specimens (e.g., A<sub>40</sub>D<sub>20</sub>W<sub>20</sub>H, A<sub>40</sub>D<sub>20</sub>W<sub>40</sub>H and A<sub>40</sub>D<sub>20</sub>W<sub>80</sub>H) at horizontal orientation (Fig. 2(a)) failed instantly due to core shear (CS) at the point of load application. On the other hand, the failure of the specimens at vertical orientation (Fig. 2(b)) was governed by skin shear (SS). With the increase of load, a number of diagonal cracks appeared progressively at the skins in the shear span which resulted in gradual decrease of stiffness (e.g., A<sub>40</sub>D<sub>20</sub>W<sub>20</sub>V, A<sub>40</sub>D<sub>40</sub>W<sub>20</sub>V and A<sub>80</sub>D<sub>40</sub>W<sub>20</sub>V).

**Table 1**  
Properties of GFRP skin and phenolic core materials.

Test	Properties	GFRP skin		Phenolic core
		Longitudinal	Transverse	
Flexure	Elastic modulus (GPa)	14.28	3.66	1.33
	Peak stress (MPa)	450.39	135.05	14.32
	Strain at peak (%)	2.29	5.26	1.22
Tensile	Elastic modulus (GPa)	15.38	12.63	1.03
	Peak stress (MPa)	291.20	216.27	5.97
	Strain at peak (%)	1.61	2.37	0.61
	Poisson's ratio	0.25	0.13	–
	Compressive	Elastic modulus (GPa)	16.10	9.95
Compressive	Peak stress (MPa)	238.04	124.23	21.35
	Strain at peak (%)	1.24	1.25	4.04
	Poisson's ratio	–	–	0.29
	Shear	Shear modulus (GPa)	2.47	2.17
Peak stress (MPa)		23.19	21.81	4.25
Strain at peak (%)		3.08	2.38	0.81

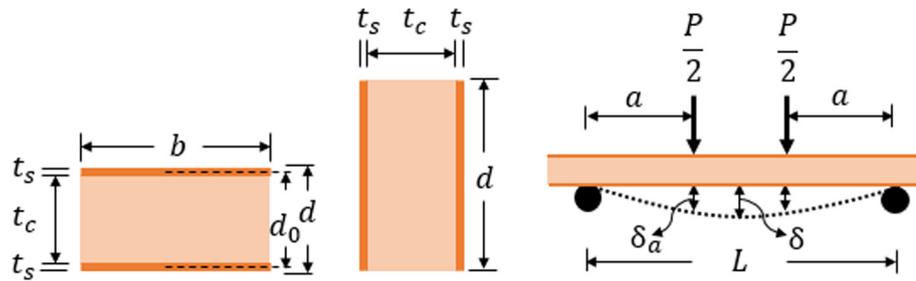


Fig. 1. Sectional dimension, orientation and test setup.

Table 2  
Details of the specimen.

Specimen ID	L (mm)	a (mm)	d (mm)	b (mm)	a/d	Beam orientation	Failure loads (N)			Failure mode
							Expt.	Theo.	%Diff.	
A <sub>40</sub> D <sub>20</sub> W <sub>20</sub> H	480	40	20	20	2	Horizontal	3375	2954	-12	CS
A <sub>40</sub> D <sub>20</sub> W <sub>20</sub> V	480	40	20	20	2	Vertical	2237	2905	30	SS
A <sub>40</sub> D <sub>20</sub> W <sub>40</sub> H	480	40	20	40	2	Horizontal	6582	5907	-10	CS
A <sub>40</sub> D <sub>40</sub> W <sub>20</sub> V	480	40	40	20	1	Vertical	5924	5811	-2	SS
A <sub>40</sub> D <sub>20</sub> W <sub>80</sub> H	480	40	20	80	2	Horizontal	12262	11814	-4	CS
A <sub>40</sub> D <sub>80</sub> W <sub>20</sub> V	480	40	80	20	0.5	Vertical	12903	7147	-45	I
A <sub>80</sub> D <sub>20</sub> W <sub>20</sub> H	480	80	20	20	4	Horizontal	2367	1672	-29	CS + D
A <sub>80</sub> D <sub>20</sub> W <sub>20</sub> V	480	80	20	20	4	Vertical	1309	1135	-13	SS + SC
A <sub>80</sub> D <sub>20</sub> W <sub>40</sub> H	480	80	20	40	4	Horizontal	4525	3344	-26	CS + D
A <sub>80</sub> D <sub>40</sub> W <sub>20</sub> V	480	80	40	20	2	Vertical	4417	5811	32	SS
A <sub>80</sub> D <sub>20</sub> W <sub>80</sub> H	480	80	20	80	4	Horizontal	9014	6687	-26	CS + D
A <sub>80</sub> D <sub>80</sub> W <sub>20</sub> V	480	80	80	20	1	Vertical	9572	7147	-25	I
A <sub>120</sub> D <sub>20</sub> W <sub>20</sub> H	480	120	20	20	6	Horizontal	2075	2568	24	SC + D
A <sub>120</sub> D <sub>20</sub> W <sub>20</sub> V	480	120	20	20	6	Vertical	1087	1242	14	SC + B
A <sub>120</sub> D <sub>20</sub> W <sub>40</sub> H	480	120	20	40	6	Horizontal	4072	5136	26	SC + D
A <sub>120</sub> D <sub>40</sub> W <sub>20</sub> V	480	120	40	20	3	Vertical	3354	2679	-20	SS + SC
A <sub>120</sub> D <sub>20</sub> W <sub>80</sub> H	480	120	20	80	6	Horizontal	8309	10272	24	SC + D
A <sub>120</sub> D <sub>80</sub> W <sub>20</sub> V	480	120	80	20	1.5	Vertical	8494	7147	-16	I
A <sub>160</sub> D <sub>20</sub> W <sub>20</sub> H	480	160	20	20	8	Horizontal	1571	1926	23	SC + D
A <sub>160</sub> D <sub>20</sub> W <sub>20</sub> V	480	160	20	20	8	Vertical	815	932	14	SC + B
A <sub>160</sub> D <sub>20</sub> W <sub>40</sub> H	480	160	20	40	8	Horizontal	3241	3852	19	SC + D
A <sub>160</sub> D <sub>40</sub> W <sub>20</sub> V	480	160	40	20	4	Vertical	2524	2271	-10	SS + SC
A <sub>160</sub> D <sub>20</sub> W <sub>80</sub> H	480	160	20	80	8	Horizontal	6533	7704	18	SC + D
A <sub>160</sub> D <sub>80</sub> W <sub>20</sub> V	480	160	80	20	2	Vertical	7228	7147	-1	I
A <sub>240</sub> D <sub>20</sub> W <sub>20</sub> H	480	240	20	20	12	Horizontal	1072	1284	20	SC + D
A <sub>240</sub> D <sub>20</sub> W <sub>20</sub> V	480	240	20	20	12	Vertical	545	621	14	SC + B
A <sub>240</sub> D <sub>20</sub> W <sub>40</sub> H	480	240	20	40	12	Horizontal	2222	2568	16	SC + D
A <sub>240</sub> D <sub>40</sub> W <sub>20</sub> V	480	240	40	20	6	Vertical	1950	2485	27	SC + B
A <sub>240</sub> D <sub>20</sub> W <sub>80</sub> H	480	240	20	80	12	Horizontal	4594	5136	12	SC + D
A <sub>240</sub> D <sub>80</sub> W <sub>20</sub> V	480	240	80	20	3	Vertical	5393	5358	-1	SS + SC

CS: Core shear.

CS+D: Core shear and debonding.

SC+D: Skin compression and debonding.

SS: Skin shear.

I: Indentation.

SS+SC: Skin shear and skin compression.

SC+B: Skin compression and buckling.

- **Combined shear and bending failure:** This kind of failure occurred when the sandwich beam specimens were subjected to significant amount of combined shear and bending stress. In horizontal orientation (Fig. 2(c)), the specimens failed in core shear followed by the propagation of cracks towards the edge of the specimen and debonding (CS + D) between skin and core (e.g., A<sub>80</sub>D<sub>20</sub>W<sub>20</sub>H, A<sub>80</sub>D<sub>20</sub>W<sub>40</sub>H and A<sub>80</sub>D<sub>20</sub>W<sub>80</sub>H). In vertical orientation (Fig. 2(d)), the failure was initiated by core cracking and then a number of small shear cracks progressively appeared before the crushing of the skin at top due to compression (SS + SC) followed by the skin splintering at bottom due to tension. The beam lost its load carrying capacity once it was failed by skin compression (e.g., A<sub>80</sub>D<sub>20</sub>W<sub>20</sub>V, A<sub>120</sub>D<sub>40</sub>W<sub>20</sub>V, A<sub>160</sub>D<sub>40</sub>W<sub>20</sub>V and A<sub>240</sub>D<sub>80</sub>W<sub>20</sub>V).

- **Bending failure:** In horizontal orientation (Fig. 2(e)), bending failure was observed between the loading points and initiated by the compressive failure of the top skin followed by debonding (SC + D) between the skin and the core. The core compression simultaneously occurred with debonding which started from the loading point (e.g., A<sub>120</sub>D<sub>20</sub>W<sub>20</sub>H, A<sub>120</sub>D<sub>20</sub>W<sub>40</sub>H, A<sub>120</sub>D<sub>20</sub>W<sub>80</sub>H, A<sub>160</sub>D<sub>20</sub>W<sub>20</sub>H, A<sub>160</sub>D<sub>20</sub>W<sub>40</sub>H, A<sub>160</sub>D<sub>20</sub>W<sub>80</sub>H, A<sub>240</sub>D<sub>20</sub>W<sub>20</sub>H, A<sub>240</sub>D<sub>20</sub>W<sub>40</sub>H and A<sub>240</sub>D<sub>20</sub>W<sub>80</sub>H). In vertical orientation (Fig. 2(f)), the bending failure was initiated by core cracking at the bottom surface under the loading point. The load continued to increase until failure of skins due to the combined effect of skin compression and buckling (SC + B) followed by the skin tension (e.g., A<sub>120</sub>D<sub>20</sub>W<sub>20</sub>V, A<sub>160</sub>D<sub>20</sub>W<sub>20</sub>V, A<sub>240</sub>D<sub>20</sub>W<sub>20</sub>V and A<sub>240</sub>D<sub>40</sub>W<sub>20</sub>V).

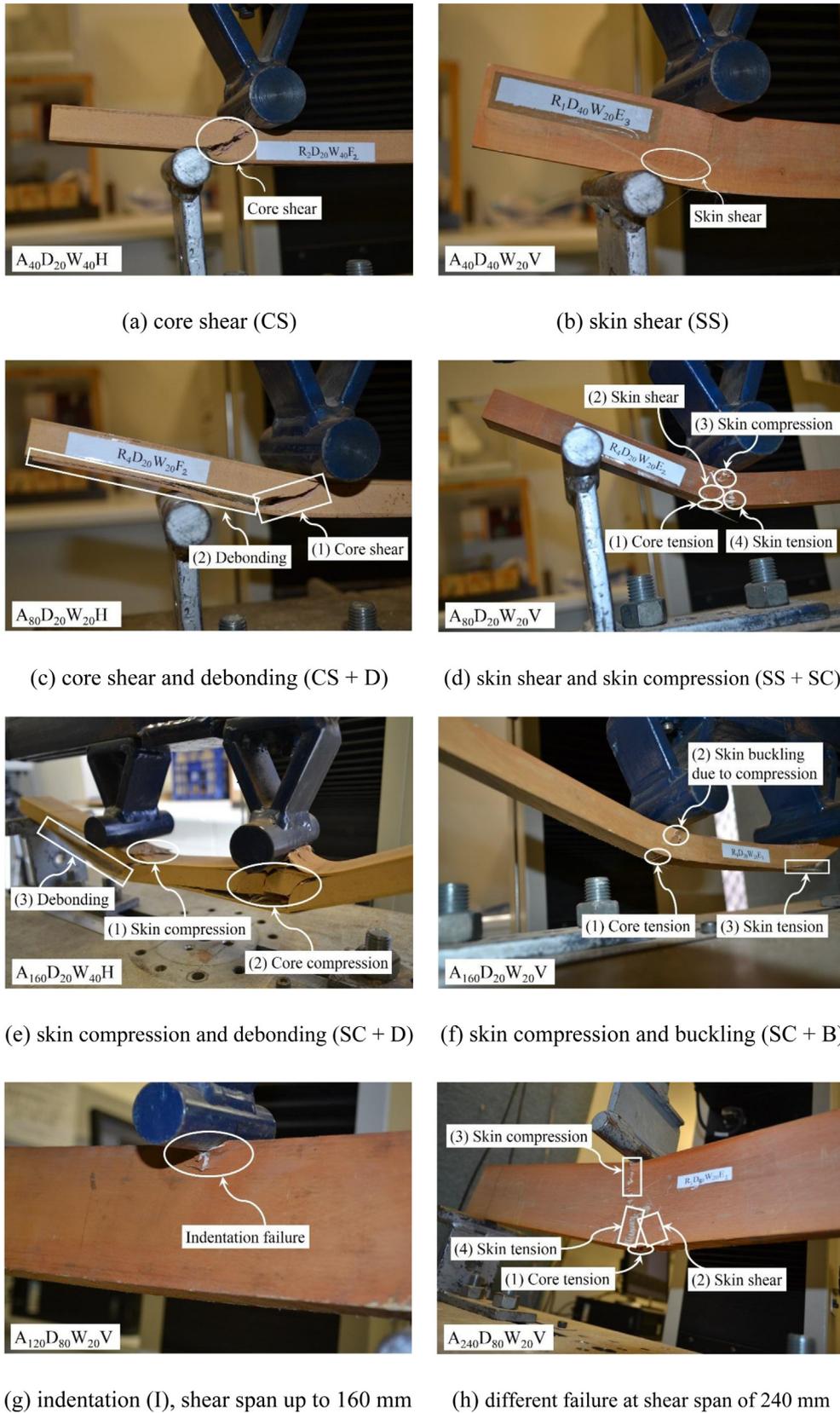


Fig. 2. Failure modes of the composite sandwich beam.

• **Indentation failure:** Indentation occurred due to the high local stress of the sandwich beams in vertical orientation which under four-point bending behaves a specimen under compression and local load transfers from the indenter to the beam, par-

ticularly at short shear spans (e.g.,  $A_{40}D_{80}W_{20}V$ ,  $A_{80}D_{80}W_{20}V$ ,  $A_{120}D_{80}W_{20}V$  and  $A_{160}D_{80}W_{20}V$ ). The load was transferred to supports through compressive stresses that created the local compression at load points and the initiation of the indentation

(1) process started (Fig. 2g). However, the same beam (20 mm × 80 mm) with a shear span of 240 mm (e.g., A<sub>240</sub>D<sub>80</sub>W<sub>20</sub>V) failed due to bending (Fig. 2h).

### 3.2. Load-displacement behaviour

The applied load and corresponding displacement at the loading point ( $\delta_a$ ) were recorded using a data logger. From the measured  $\delta_a$ , the mid-span displacement ( $\delta$ ) was calculated following the relation given in Eq. (1). The load and mid-span displacement behaviour of the sandwich beams in the horizontal orientation are presented in Fig. 3(a), (c) and (e) while the beams in the vertical orientation are shown in Fig. 3(b), (d) and (f).

$$\delta = \frac{\delta_a}{4} \left( \frac{3L^2 - 4a^2}{3La - 4a^2} \right) \quad (1)$$

At 40 mm shear span, a significant drop in load was observed in the horizontal beams before the final failure as shown in Fig. 3(a), (c) and (e). The first drop of the load was observed due to the core shear at one end between the loading point and the support. However, the load increase again with almost same stiffness prior to the first core shear failure. At almost the same load before the first load drop, the second and ultimate drop of the load was observed due to the core shear failure at the other end of the beam. On the other hand, the specimens in vertical orientation with 40 mm shear span showed different behaviour as shown in Fig. 3(b), (d) and (f). A linear elastic behaviour was observed at the early application of the load. Thereafter, a slight drop of load was observed but the beam specimens continued to carry the load due to the effect of core shear compression. A nonlinear load deflection behaviour was further observed prior to failure due to the progressive developments of either shear cracks in the skin or indentation (Fig. 2b and g).

At 80 mm and 120 mm shear spans with horizontal orientation (Fig. 3a, c and e), the initiation of debonding between top skin and core occurred at the loading points in several stages that causes staggering pattern in the load-displacement curve. However, this behaviour was gradually transformed into the single stage failure mode when shear span was 160 mm and 240 mm (Fig. 3a, c and e). On the other side, at 80 mm, 120 mm, 160 mm and 240 mm shear spans with vertical orientation (Fig. 3b, d and f), the load-displacement behaviour was linear up to a certain point and then it showed a non-linear behaviour. This nonlinearity was initiated by the tensile cracking of the phenolic core followed by compressive failure of the skin. However, the failure of the core in tension does not indicate the ultimate failure of the beam as the vertical skins continue to carry the loads. One obvious difference between horizontal and vertical orientation is that the load dropped suddenly at horizontal orientation whereas the load gradually decreased for vertical beams.

For 20 mm × 20 mm beam section (Fig. 3a and b), the higher displacement was noticed in vertical than horizontal orientation at a certain magnitude of loads. However, the horizontal orientation provided the greater displacement for 20 mm × 40 mm (Fig. 3c and d) and 20 mm × 80 mm (Fig. 3e and f) beam. Moreover, for the same orientation and dimension, it is observed that the increase of shear span decreases the load carrying capacity of the specimens. In addition, at the same level of loads, the specimens with greater shear span deflected more than the specimens with smaller shear span.

### 3.3. Bending and shear stiffness

The bending and shear stiffness of the beams were determined using the simultaneous method [22]. Bank [23] indicated that the total deflection of composite structures is the sum of the deflection

due to bending and shear deformations. This applies to the composite sandwich beams due to the relatively low shear stiffness of the core compared to the GFRP skins. As a result, each of the sandwich beams tested in this study exhibited a load-displacement behaviour with two unknowns,  $EI$  and  $kGA$  as presented in Eq. (2) with  $(3L^2 - 4a^2/48)$  being the independent variable while  $(\delta/Pa)$  being the dependent variable. Fig. 4(a) and (b) depict the graphical presentation of Eq. (2) for horizontal and vertical orientations with different beam dimensions and shear spans. The bending stiffness ( $EI$ ) and shear stiffness ( $kGA$ ) is determined from the slope and intercept of the fitted line, respectively.

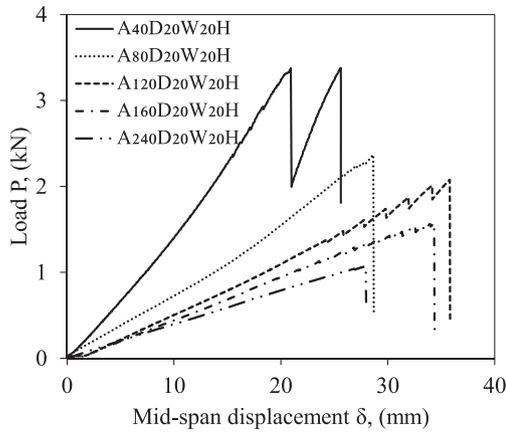
$$\frac{\delta}{Pa} = \frac{1}{EI} \left( \frac{3L^2 - 4a^2}{48} \right) + \frac{1}{2kGA} \quad (2)$$

Fig. 4 shows the variation of  $(\delta/Pa)$  with respect to  $(3L^2 - 4a^2/48)$  for shear spans of  $L/2$ ,  $L/3$  and  $L/4$ . The effective bending modulus ( $E_{eff}$ ) and effective shear modulus ( $G_{eff}$ ) are evaluated by dividing with the equivalent moment of inertia and area of a rectangular section assuming that the sandwich beams are made up of a homogeneous material. The shear correction factor  $k = 1$  is considered and  $G$  and  $A$  are the shear modulus and cross sectional area, respectively. The effective elastic properties of the sandwich beams are tabulated in Table 3.

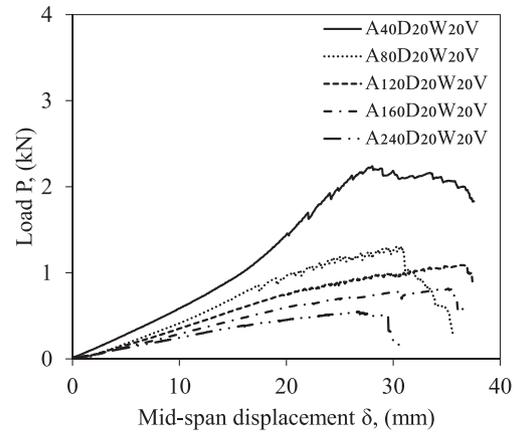
In the horizontal orientation, Table 3 shows that the magnitude of  $EI$  and  $kGA$  are increasing almost proportionally with the increase of beam dimension. On the other hand, in vertical orientation, the increase of beam dimension exponentially increase the  $EI$  but proportionally increase the  $kGA$ . The average magnitude of  $E_{eff}$  is higher in horizontal orientation (6.88 GPa) than the vertical position (3.98 GPa). This is due to the separation of skins with respect to major axis of bending which contributed in improving the bending modulus of the beam at horizontal orientation but the separation does not contribute at vertical orientation. However, the magnitude of  $G_{eff}$  are similar regardless of beam orientation due to the equal area of the beam resisting the shear deformation.

### 3.4. Effect of beam orientation

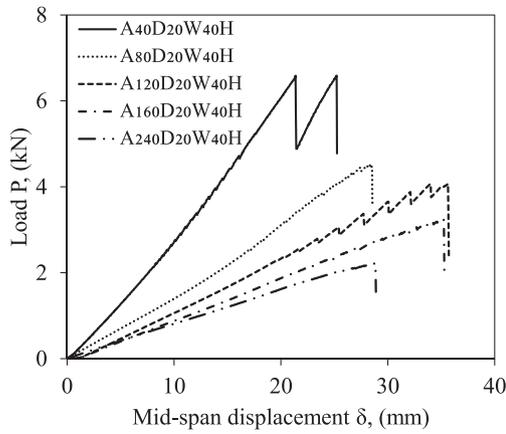
The change of beam orientation from horizontal to vertical changes the mode of failure of the sandwich beams. The sandwich specimens failed in brittle manner at horizontal orientation while the failure is progressive at vertical orientation. The load-displacement behaviour in Fig. 3 has shown a sudden drop of load in horizontal orientation indicating a brittle nature of failure. The brittle failure occurred due to the core shear when specimen fails in shear, and combined shear and bending whereas this happened at bending failure due to core compression. On the other side, the gradual decline of load with the increase of displacement demonstrated the progressive failure of the skins due to shear, compression and tension. This failure behaviour indicates that the structure constructed with vertical sandwich beams will provide sufficient warning before the ultimate failure which is an important characteristics in civil engineering design. However, the load carrying behaviour in horizontal and vertical orientation depends on the sectional dimension of the beam. At a particular shear span, Fig. 5 shows that the horizontal orientation carried higher loads than the vertical orientation for 20 mm × 20 mm and 20 mm × 40 mm beams whereas the vertical orientation carried greater magnitude of loads than the horizontal position for 20 mm × 80 mm sectional beam. This is due to the effective utilisation of skin's strength at horizontal orientation for 20 mm × 20 mm and 20 mm × 40 mm section where separation of skins with respect to the major axis of bending are more effective in carrying loads than the vertical orientation of skins. On the other hand, the effect of skin depth in vertical orientation become more effective



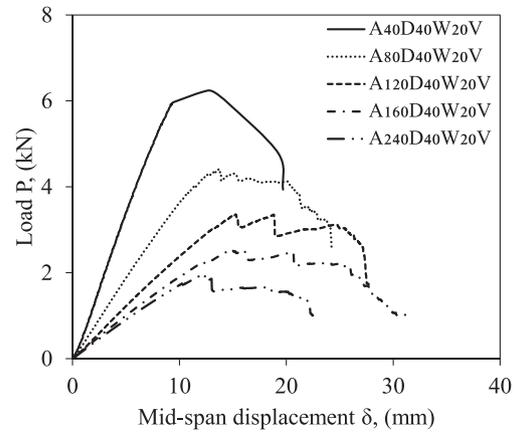
(a) 20 × 20 mm at horizontal orientation



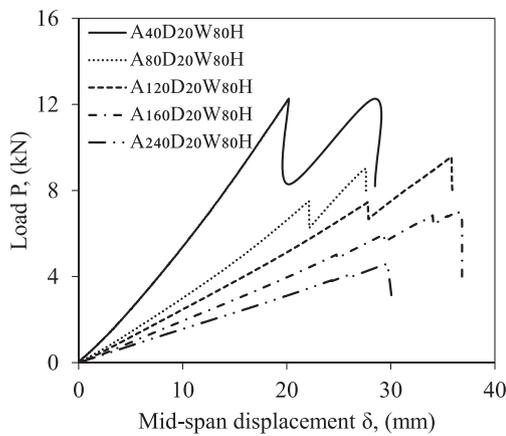
(b) 20 × 20 mm at vertical orientation



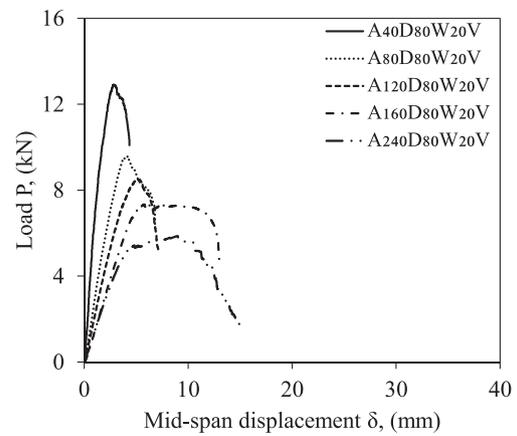
(c) 20 × 40 mm at horizontal orientation



(d) 20 × 40 mm at vertical orientation



(e) 20 × 80 mm at horizontal orientation



(f) 20 × 80 mm at vertical orientation

Fig. 3. Load-displacement behaviour of sandwich beams.

than the skin separation in horizontal orientation for 20 mm × 80 mm section. The gradual increase of beam dimension exponentially increase the load carrying capacity at vertical orientation while the increase of load capacity is only linear at horizontal ori-

entation with the increase of beam dimension. Glenn and Francis [24] indicated that the load-carrying capacity of a beam can greatly increase by its depth. Moreover, the increase of depth increased the shear dominance on the vertical beams and the higher load carry-

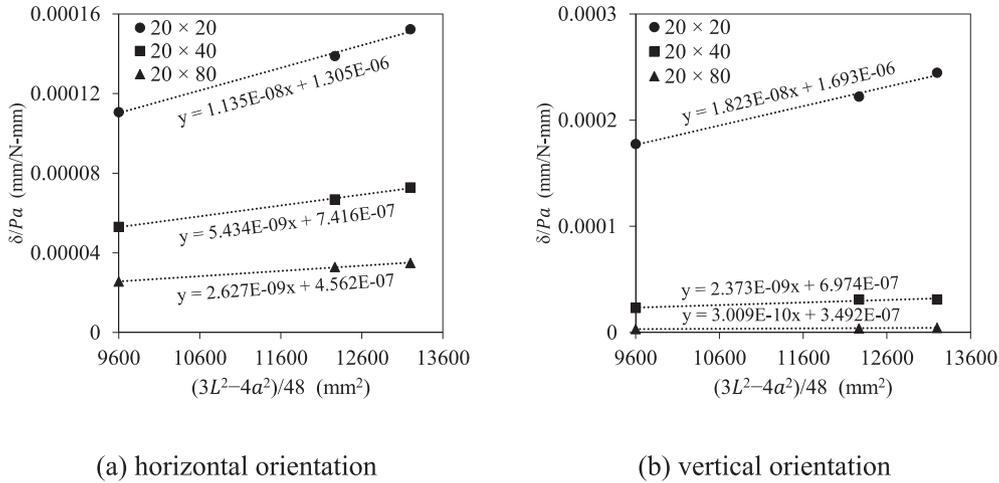


Fig. 4. Graphical presentation for determining bending and shear stiffness.

Table 3  
Stiffness properties of sandwich beams.

Orientation	Beam section	EI (MPa-mm <sup>4</sup> )	kGA (MPa-mm <sup>2</sup> )	E <sub>eff</sub> (GPa)	C <sub>eff</sub> (GPa)
Horizontal	20 × 20	88 × 10 <sup>6</sup>	383 × 10 <sup>3</sup>	6.61	0.96
	20 × 40	184 × 10 <sup>6</sup>	674 × 10 <sup>3</sup>	6.90	0.84
	20 × 80	381 × 10 <sup>6</sup>	1096 × 10 <sup>3</sup>	7.14	0.69
Horizontal average=				6.88	0.83
Vertical	20 × 20	55 × 10 <sup>6</sup>	295 × 10 <sup>3</sup>	4.11	0.74
	20 × 40	421 × 10 <sup>6</sup>	717 × 10 <sup>3</sup>	3.95	0.90
	20 × 80	3323 × 10 <sup>6</sup>	1432 × 10 <sup>3</sup>	3.89	0.89
Vertical average=				3.98	0.84

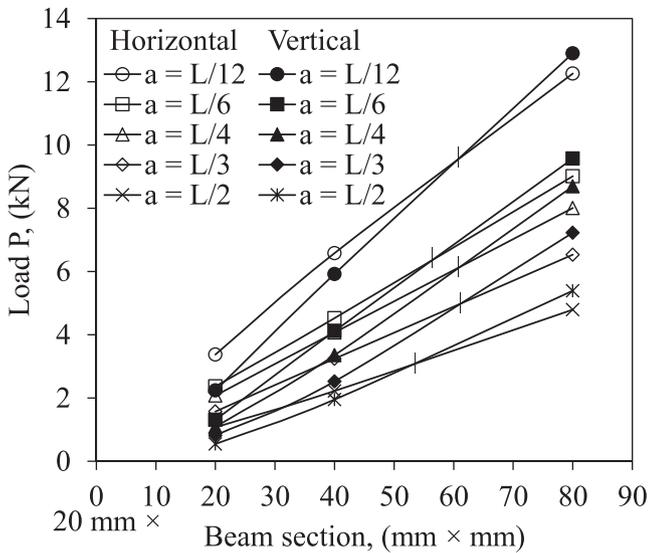


Fig. 5. Load carrying capacity at horizontal and vertical orientation.

ing capacity of the vertical beams at larger section (20 mm × 80 mm) indicating the vertical orientation is preferable against shear. Fig. 5 shows that, for any shear span, the horizontal and vertical curves intersects in the range between 50 mm and 60 mm. Results indicated that the transitional sectional dimension is between 50 mm and 60 mm with an average of 55 mm, below which the horizontal and above which the vertical orientation can carry higher load.

Table 3 shows that the bending stiffness of sandwich beam is greatly influenced by the orientation. For 20 mm × 20 mm beam, the bending stiffness of beams at the vertical orientation is only 63% of beams at the horizontal orientation. This is expected for the square cross sectional beam where the separation of skins contributed more to the bending stiffness at horizontal orientation than the vertical position. The bending stiffness at vertical orientation increased 2.29 and 8.73 times than the horizontal orientation for 20 mm × 40 mm and 20 mm × 80 mm beams, respectively. This result suggests that the larger the sectional dimension, the sandwich beams are more effective when positioned vertically than horizontally to minimise the amount of total deflection. This efficiency is due to the increase of skin depth at vertical orientation which significantly contributed to the increase of bending stiffness. For any sectional dimension, the contribution of core is 8% and 23% for horizontal and vertical orientations respectively, indicating both core and skin significantly contributed to the bending stiffness at vertical orientation. Therefore, the bending stiffness of the sandwich beam with fibre composite skins and high strength core primarily depends on the modulus of elasticity, sectional dimension and orientation of the constituent materials. Chakraborty et al. [25] indicated the low stiffness of fibre composite structure is a great concern and can only be addressed through innovative design. Thus, the high bending stiffness of the sandwich structure can be efficiently utilised by placing the beams at vertical orientation, particularly when the depth-to-width ratio is 2 or more (e.g., 20 mm × 40 mm and 20 mm × 80 mm beam).

3.5. Effect of shear span-to-depth ratio

The variation of failure mode of the specimens at horizontal and vertical orientation with different shear span-to-depth (a/d) ratios

are plotted in Fig. 6(a) and (b), respectively. These figures suggested that a/d ratio has strong influence on the failure mode of the sandwich beams. Generally, the beams failed in shear when  $a/d \leq 2$ , specifically, the horizontal beams failed in core shear (Fig. 2a) and vertical beams failed by skin shear (Fig. 2b). However, an exception was observed in 80 mm depth beam at vertical orientation which failed by indentation due to the high local compression (Fig. 2g). With the increase of a/d ratio, the shear dominance on the beam decreases and the bending effect increases. The sandwich beams failed due to the combined effect of shear and bending for  $2 < a/d < 6$ . Within this a/d range, the horizontal specimens failed in core shear followed by debonding between the core and the top skin due to the effect of bending (Fig. 2c). In vertical orientation, the diagonal cracks in vertical skins arose from shear effect, and the compressive and tensile failure of the skins were developed due to the bending effect (Fig. 2d and h). From an experimental investigation of the sandwich beams at horizontal orientation, Manalo [18] observed a transitional zone for a/d ratios between 3 and 6, where the specimens experienced both shear and bending. In the present study when  $a/d \geq 6$ , the bending failure was observed for the specimens. The bending failure of horizontal beams was confirmed with the skin compression followed by core compression and debonding (Fig. 2e). The buckling of the skins due to compression, and tensile fracture of the skins are the indication of bending failure in vertical orientation for  $a/d \geq 6$  (Fig. 2f). In contrast, Mathieson and Fam [19] observed the buckling failure of the skin at a/d ratios between 1.33 and 4.67 for soft core sandwich beam. This suggests the better stability of the vertical skins due to the high strength phenolic core compared to the soft core material which can provide only a low tensile bond strength between the core and the skin.

The bending stress of the extreme fibres in both horizontal and vertical orientations can be calculated by Eq. (3).

$$\sigma_s = \frac{M(d/2)}{EI} E_s \quad (3)$$

where,  $\sigma_s$ ,  $M$ ,  $d$ ,  $E_s$ , and  $EI$  represent the bending stress of the skin, bending moment at failure load, depth of the beam, elastic modulus of the skin, and bending stiffness (Table 3) of the beam, respectively. When the average shear stress in the core is determined, the skin is transformed into an equivalent core using the shear modular ratio. On the other hand, the core was transformed into an equivalent skin area if the average shear stress is determined for skin [14]. The average shear stress in core ( $\tau_c$ ) at horizontal orientation and the average shear stress in skin ( $\tau_s$ ) at vertical orientation are calculated

using Eqs. (4) and (5), respectively. Where,  $G_c$  and  $G_s$  represents the shear modulus of core and skin respectively.

$$\tau_c = \frac{(P/2)}{[t_c + 2t_s(G_s/G_c)]b} \quad (4)$$

$$\tau_s = \frac{(P/2)}{[2t_s + t_c(G_c/G_s)]d} \quad (5)$$

The variation of bending and shear stress with respect to the a/d ratio for both horizontal and vertical orientations are shown in Fig. 7. The bending stress increases with the increase of a/d ratio from 2 to 6 and gradually become constant when  $a/d > 6$ . This is due to the similar mode of failure for all specimens at horizontal (i.e., skin compression and debonding) or vertical orientations (i.e., skin compression and buckling) when  $a/d > 6$  as shown in Fig. 6(a) and (b). From Fig. 7(a), it can be seen that the bending stress at horizontal orientation is higher than the vertical position when the beam fails in bending. The maximum compressive bending stress in the skin was 237 MPa at horizontal orientation which is close to the average compressive strength of skin determined from the test of coupons as reported in Table 1. However, the vertical beams failed only at 220 MPa compressive bending stress. This can be attributed to the failure mode of the vertical beams due to a combined skin compression and buckling. The buckling failure is exhibited in the form of debonding of the skins from the core as shown in Fig. 2(f). Mathieson and Fam [19] observed that the buckling of skin in the sandwich beam arises before the skin reaches to its ultimate compressive strength due to the low tensile bond between the core and the skins. This explains why the beams in vertical orientation failed at lower bending stress for  $a/d \geq 6$  and indicating the preference of horizontal orientation for the design of bending dominated structures. It is important to note that the load at which buckling failure of the vertical skins occurred was almost 92% of the maximum compressive stress of the fibre composites. In contrast, the buckling of the skin for sandwich beams with a soft core investigated by Mathieson and Fam [19] is only at 50%. This result further suggest the suitability of a phenolic core in providing stability to the vertical skins.

Fig. 7(b) shows that the shear stress decreases with the increase of a/d ratio. Dai and Hahn [26] and Awad et al. [27] indicated that the sandwich beams with shorter shear span exhibited higher shear stress than the longer shear span. However, there is a clear distinction of shear stress level between horizontal and vertical orientations (Fig. 7b). At horizontal orientation, the core is mainly carrying the shear force whereas the shear force is carried by both the core and the skins at vertical orientation. As a result, for the

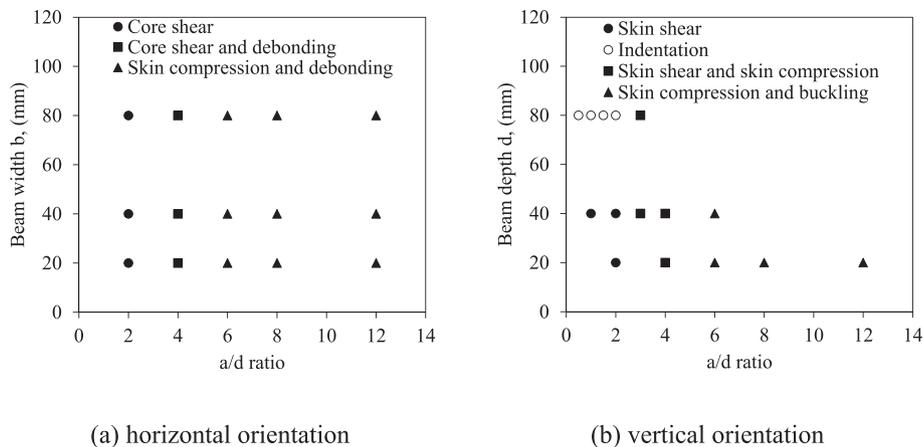


Fig. 6. Failure of the beam at different shear span-to-depth ratios.

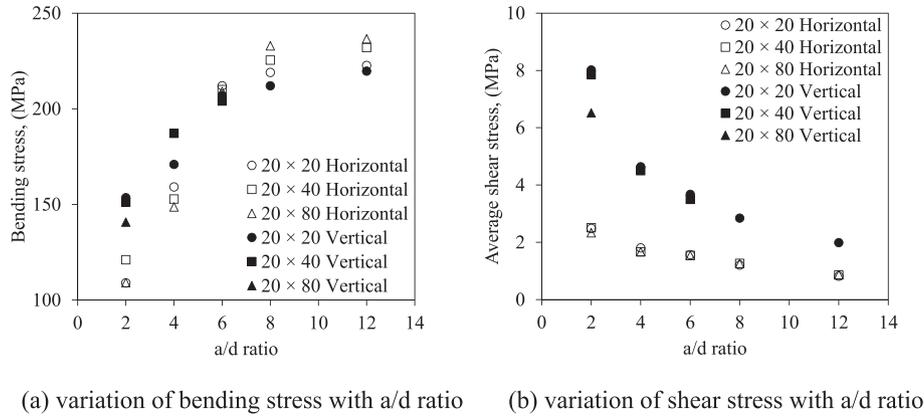


Fig. 7. Effect of a/d ratio on bending and shear stress at different orientations.

same a/d ratio, the shear stress at failure is significantly higher at vertical orientation than the horizontal position. This indicates that the sandwich structure is more effective in carrying shear if they are to be applied in the vertical orientation.

Manalo [18] indicated that the different failure modes observed for the sandwich beams with different a/d ratios can be explained by the shear-to-bending stress ratio. Thus, the variation of shear-to-bending stress ( $\tau/\sigma$ ) with a/d ratio at horizontal and vertical orientations are plotted in Fig. 8(a) and (b), respectively. Based on the failure mechanism, in horizontal orientation the  $\tau/\sigma$  ratio was calculated as the ratio of the actual shear stress in the core and the bending stress of the skin while this ratio was determined as the ratio of the actual shear and bending stress of the skin at vertical orientation. Fig. 8 shows that the  $\tau/\sigma$  ratio decreases due to the decrease of shear effect and increase of bending influence with the increase of a/d ratio. Yoshihara and Furushima [28] indicated that when the actual  $\tau/\sigma$  ratio is larger than the allowable  $\tau/\sigma$  ratio, the timber specimen would fail in shear. In horizontal orientation, the upper bound allowable stress ratio (0.014) is calculated as the ratio of shear strength of core to the tensile strength of skin while the lower bound (0.009) is the ratio of shear strength of core to the bending strength of skin. Similarly, in vertical orientation, the upper bound allowable stress ratio (0.079) is calculated as the ratio of shear strength of skin to the tensile strength of skin while the lower bound (0.051) is the ratio of shear strength of skin to the bending strength of skin. This is due to the core shear failure at horizontal orientation and skin shear failure at vertical orientation as mentioned earlier. During shear failure, the actual bending stress in the skin is lower than the skins' maximum bending

strength and thus the tensile strength of skin is considered for determining the upper bound stress ratio. The upper and lower bound allowable stress ratio is particularly important in determining the zone of shear and bending failure. When the actual  $\tau/\sigma$  ratio is higher than the upper bound allowable  $\tau/\sigma$  ratio, the sandwich beams are expected to fail in shear. On the other hand, the sandwich specimens are expected to fail in bending if the actual  $\tau/\sigma$  ratio is lower than the lower bound allowable  $\tau/\sigma$  ratio. Moreover, if the actual  $\tau/\sigma$  ratio falls between the upper and lower bound allowable limit, the sandwich beams are expected to fail in combined shear and bending. Fig. 8(a) shows that the stress ratio concept can accurately predict the mode of failure of the sandwich beams at horizontal orientation. However, at vertical orientation, the upper and lower bound allowable stress ratio is slightly higher than the expectation. This may be attributed to the progressive nature of failure of the beams at vertical orientation which provided several load drops at different displacements. This result also indicate that the vertical beams are superior in shear performance and prediction of failure behaviour is more complex than the horizontal orientation.

3.6. Determination of the influence of the variables

The influence of beam orientation and a/d ratio on the load carrying capacity and stiffness properties of the sandwich beam was evaluated by a two-way Analysis of Variance (ANOVA) using SPSS - a statistical analysis software [29]. As it is mentioned, the change of failure modes from shear to bending occur when a/d ratio changes from 2 to 6 in both horizontal and vertical orientations, therefore,

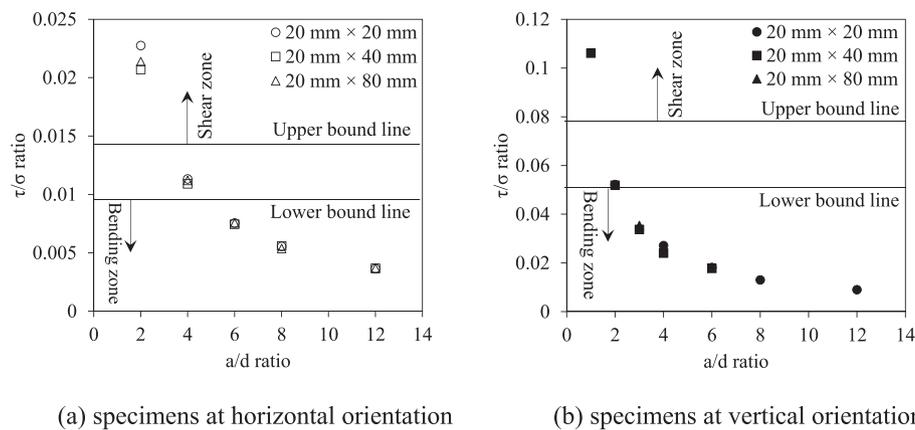


Fig. 8. Effect of a/d ratio on shear-to-bending stress ratio.

the variation of a/d is considered in that range for this analysis. The results of two-way ANOVA are shown in Table 4.

Table 4 indicates that the variation of failure loads and bending stiffness for different test setup are not statistically significant ( $p > \alpha$ ) with 95% confidence interval ( $\alpha = 0.05$ ) due to the change of orientation and a/d ratio. However, the influence of orientation and a/d ratio on the failure loads and bending stiffness are not same which is represented by  $\eta_p^2$ . The result of the analysis shows that 28.3% of the variability of failure loads is being accounted by orientation while a/d ratio is responsible for 21% variation. On the other hand, 20.3% of the variability of bending stiffness is being accounted by orientation while a/d ratio has no influence on the bending stiffness. This concludes that the orientation of the sandwich beam is a more influential parameter than the a/d ratio. The distance between the skins at horizontal orientation plays significant role on load carrying capacity while the separation of skins at vertical orientation does not have significant effect that makes the beam orientation an influential parameter. Moreover, the bending stiffness of the beam affected by its orientation but does not depends on the loading position.

#### 4. Theoretical analysis

##### 4.1. Estimation of failure loads

This section discussed the theoretical estimation of failure loads for different configuration of sandwich beams. The experimentally observed failure modes, i.e. bending failure, shear failure, combined shear and bending failure, and indentation failure were considered as the criterion to estimate the load capacity of the sandwich beams.

##### 4.1.1. Bending failure

The sandwich beam is expected to fail in bending when the bending stress of the skin ( $\sigma_s$ ) reaches to the allowable compressive bending stress of the skin ( $\sigma_{s(all)}$ ). Simplifying Eq. (3), the ultimate failure load due to bending ( $P_b$ ) of sandwich beams with horizontal and vertical orientations can be determined by Eq. (6).

$$P_b = \frac{4(EI)\sigma_{s(all)}}{adE_s} \quad (6)$$

The theoretical bending stiffness  $EI$  in horizontal and vertical orientations can be calculated by Eqs. (7) and (8), respectively.

In horizontal orientation,

$$EI = \frac{bt_c^3}{12}E_c + \frac{bt_s}{2} \left( \frac{t_s^2}{3} + d_0^2 \right) E_s \quad (7)$$

In vertical orientation,

$$EI = \frac{t_c d^3}{12} E_c + \frac{t_s d^2}{6} E_s \quad (8)$$

##### 4.1.2. Shear failure

The shear stress at different levels of the sandwich beam section can be determined by accounting the constituent materials of the

cross section [30]. In horizontal orientation, the sandwich beam is expected to fail in shear when the shear stress of the phenolic core reaches its allowable shear strength ( $\tau_{c(all)}$ ). In vertical position, shear failure occurs when the shear stress in the skin exceeds the allowable shear strength of the skin ( $\tau_{s(all)}$ ) [14]. The shear failure load ( $P_s$ ) in horizontal and vertical orientations of the beam can be determined by Eqs. (9) and (10), respectively [14].

In horizontal orientation,

$$P_s = \frac{16(EI)\tau_{c(all)}}{4E_s t_s d_0 + E_c t_c^2} \quad (9)$$

In vertical orientation,

$$P_s = \frac{4d\tau_{s(all)}}{3} \left( 2t_s + t_c \frac{E_c}{E_s} \right) \quad (10)$$

The bending stiffness  $EI$  in Eq. (9) can be calculated by Eq. (7).

##### 4.1.3. Combined shear and bending failure

When shear span-to-depth ratios are between 2 and 6, the failure of the sandwich beam occurs due to the combined action of shear and bending. Bank [23] indicated that, when a beam is subjected to high shear forces and high bending moment, a combined shear and bending action will govern. Under this circumstances, the maximum stress criterion can be used in predicting failure loads. The failure is expected when the sum of the ratios of actual shear stress ( $\tau_{act}$ ) to allowable shear stress ( $\tau_{all}$ ) and actual bending stress ( $\sigma_{act}$ ) to allowable bending stress ( $\sigma_{all}$ ) approaches unity. The linear failure criterion can be expressed as:

$$\frac{\tau_{act}}{\tau_{all}} + \frac{\sigma_{act}}{\sigma_{all}} = 1 \quad (11)$$

Simplifying Eq. (11) using Eqs. (610), the failure loads can be calculated as:

In horizontal orientation,

$$P_{s-b} = \frac{1}{\left[ \frac{4E_s t_s d_0 + E_c t_c^2}{16(EI)\tau_{c(all)}} + \frac{adE_s}{4(EI)\sigma_{s(all)}} \right]} \quad (12)$$

In vertical orientation,

$$P_{s-b} = \frac{1}{\left[ \frac{3E_s}{4d(2t_s E_s + t_c E_c)\tau_{s(all)}} + \frac{adE_s}{4(EI)\sigma_{s(all)}} \right]} \quad (13)$$

In Eqs. (12) and (13),  $P_{s-b}$  is the failure load due to combined action of shear and bending,  $\tau_{c(all)}$  and  $\tau_{s(all)}$  are the allowable shear stress in core and skin, respectively and  $\sigma_{s(all)}$  is the allowable compressive stress of skin. The bending stiffness in horizontal and vertical orientations can be determined by Eqs. (7) and (8), respectively.

##### 4.1.4. Indentation failure

The theoretical model for predicting indentation failure loads of foam-core sandwich beams at horizontal orientation have been studied by several researchers [31–35]. However, there is a lack of research for estimating indentation failure loads at vertical orientation. The present study proposed a theoretical model for esti-

**Table 4**  
Two-way ANOVA results

Dependent variable	Independent variable	F-value	p-value	Partial eta squared ( $\eta_p^2$ )
Failure loads	Orientation	3.941	0.075	0.283
	a/d ratio	1.333	0.307	0.210
Bending stiffness	Orientation	3.066	0.105	0.203
	a/d ratio	0.000	1.000	0.000

mating indentation failure loads at vertical orientation based on the principle of contact mechanics theory [36]. Two assumptions have been considered for indentation modelling; (a) the beam is supported on rigid plastic foundation [31], and (b) the indentation failure occurs when the stress in skins under the indenter attains to the transverse compressive strength of the skin. The mechanism of transferring loads from the indenter to the sandwich beam through a line contact at the early stage of load application and the contact area increase with the increase of applied loads as shown in Fig. 9.

According to contact theory, when indentation occurs, the half width of the contact zone can be expressed by Eq. (14).

$$b_h = K_b \sqrt{\frac{P_i}{2}} \quad (14)$$

In Eq. (14),  $b_h$  and  $P_i$  represents the half width of the contact zone and the applied load at which indentation failure occurs, respectively. The other parameter  $K_b$  can be expressed by Eq. (15).

$$K_b = \sqrt{\frac{2}{\pi b} \frac{\left(\frac{1-\nu_i^2}{E_i} + \frac{1-\nu_b^2}{E_b}\right)}{\left(\frac{1}{d_i} + \frac{1}{d_b}\right)}} \quad (15)$$

In Eq. (15),  $b$  is the beam width (contact length),  $\nu_i, E_i$  and  $d_i$  are the poisson's ratio, elastic modulus and diameter of the indenter, respectively. Similarly,  $\nu_b, E_b$  and  $d_b$  are the poisson's ratio, elastic modulus and diameter of the sandwich beam, respectively. The effective elastic modulus of the 20 mm × 80 mm beam at vertical orientation is determined in Table 3. As the contact zone of the sandwich beam is a plane surface, the diameter of the beam is considered infinite. The indentation failure loads,  $P_i$  can be determined by Eq. (16).

$$P_i = (\pi b_h b) \sigma_{tcs} \quad (16)$$

In Eq. (16),  $\sigma_{tcs}$  is the transverse compressive strength of the skin as provided in Table 1.

#### 4.1.5. Comparison between calculated and actual failure load

The calculated failure loads from the appropriate theoretical model presented in Eqs. (6), (9), (10), (12), (13) and (16) are provided in Table 2 and compared it with the actual failure loads of

the beam. Shear based equation (Eqs. (9) and (10)) can reliably predict the failure load for  $a/d$  ratio up to 2. On the other hand, bending equation (Eq. (6)) can estimate the failure loads when  $a/d$  ratio is equal to or  $>6$ . However, when  $a/d$  ratio is between 2 and 6, the combined shear and bending equations (Eqs. (12) and (13)) are the most reliable. The indentation failure model in Eq. (16) can reliably estimate the failure loads for 80 mm deep vertical sandwich beams with  $a/d$  ratio of 2. The loads calculated from Eq. (16) represents the initiation of the indentation, and with the gradual decrease of  $a/d$  ratio the effect of shear compression increase and the ultimate failure occurs at higher loads even the early initiation of indentation (Fig. 2g). However, a combined shear and bending failure was observed for  $a/d$  of 3 and Eq. (13) provided a reliable estimation.

From the percentage differences (% Diff.) between experimental and theoretical failure loads in Table 2, it can be seen that the theoretical model mostly underestimates the ultimate load when the sandwich beam fails in shear. On the other hand, the bending failure equation overestimates the failure load due to the initiation of debonding between the skin and the core. It is important to note that in the considered theoretical analyses, the skin is assumed perfectly bonded to the core. This separation from the core resulted in the thin fibre composite to buckle in both beam orientation. In most cases, the traditional theoretical models estimated the shear failure loads within 30%, combined shear and bending failure loads within 25%, and bending failure loads within 20% of the experimental failure loads. This indicates the classical failure models can estimate the bending failure loads more reliably than the shear failure loads. Moreover, the greater variation between predicted and actual failure loads was obtained at vertical orientation than the horizontal position. This is due to the more complex behaviour of vertical beams than the horizontal one as explained in Fig. 8. The proposed indentation failure model for vertical orientation satisfactorily measures the initiation of the indentation failure loads. However, this model cannot describe how the shear span affected the load carrying capacity which seems an important effect during indentation. The high actual indentation load compared to the predicted value for vertical beams with  $a/d < 2$  is due to the effect of shear compression which have allowed the beam to continuously carry the load. This failure mechanism needs further investigation. In many circumstances, researchers have found the differences between experimental and theoretical failure loads of sandwich beams up to 20% [19], 21% [31], 30% [37], 34% [18], and even up to 100% [7]. Therefore, further investigation is necessary to establish better theoretical models that can capture the insight into the response of the sandwich beams.

#### 4.2. Theoretical evaluation of bending and shear stiffness

Experimentally, the bending stiffness ( $EI$ ) and shear stiffness ( $kGA$ ) are evaluated from the load-displacement relationship and presented in Table 3. Theoretically, the bending stiffness of sandwich beams in horizontal and vertical orientations can be estimated using Eqs. (7) and (8), respectively, by assuming the skins and core are perfectly bonded [38]. However, for a particular sandwich beam, theoretically the shear stiffness in horizontal and vertical orientations can be estimated by Eq. (17).

$$kGA = k[G_s A_s + G_c A_c] \quad (17)$$

where,  $G_s, A_s, G_c$  and  $A_c$  are the shear modulus and cross sectional area of skins and core for the beam section, and the shear correction factor  $k = 1$  as mentioned earlier. A comparison between the experimental and theoretical stiffness are depicted in Fig. 10. Results shows that the analytical equations can satisfactorily estimate the actual bending stiffness of the sandwich beams.

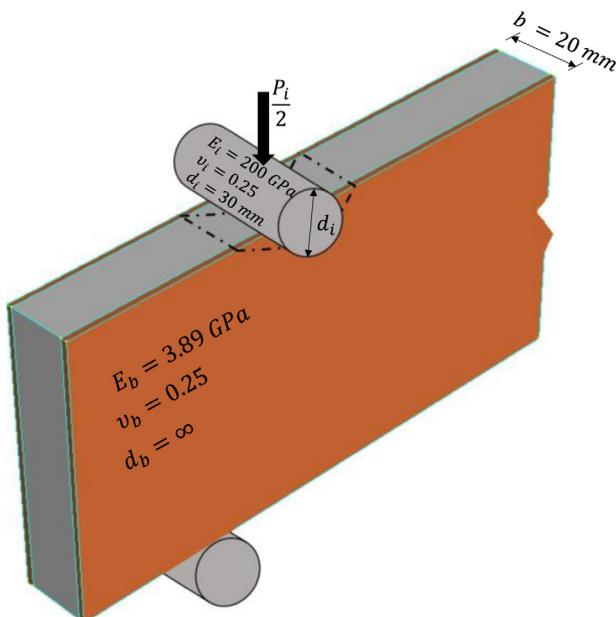


Fig. 9. Indentation failure modelling using contact mechanics theory.

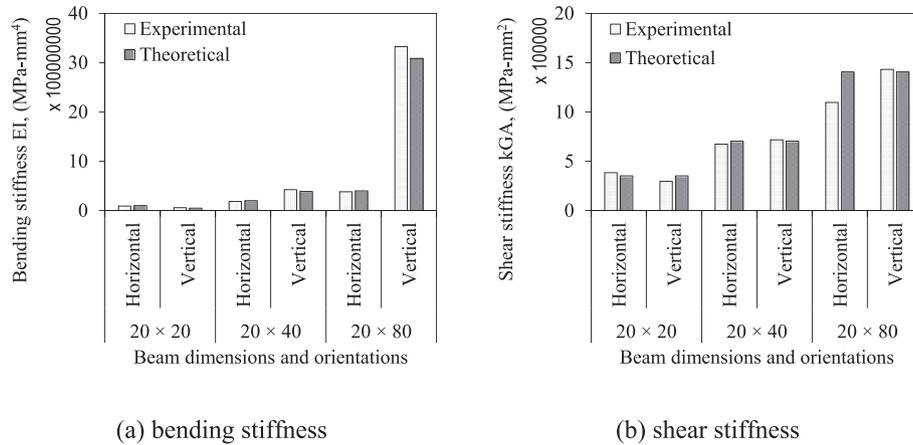


Fig. 10. Comparison between experimental and theoretical stiffness.

## 5. Conclusions

A series of experimental tests were carried out on 30 specimens to evaluate the properties and to understand the flexural and shear behaviour of phenolic core sandwich beams at different orientations. The load-displacement behaviour, failure mode, strength and stiffness of beams were systematically investigated. The findings of the present study can be summarised as follows:

- The sandwich beam fails in brittle manner at horizontal orientation while the failure is progressive at vertical orientation. With the increase of sectional dimension but same shear span, the sandwich beam fails in similar mode at horizontal orientation but fails differently at vertical orientation.
- The transitional sectional dimension of the beam is approximately 20 mm × 55 mm, below which the horizontal orientation and above which the vertical orientation carried higher loads.
- The bending stiffness of the sandwich beam is greatly influenced by its orientation and can be efficiently utilised by placing the beams vertically, particularly when the beam depth-to-width ratio is 2 or more.
- Generally, the sandwich beam fails in shear, a combined shear and bending, and bending for shear span-to-depth ratios of 2 or less, between 2 and 6, and 6 or more, respectively. The possibility of indentation failure is higher at vertical orientation than the horizontal position.
- Sandwich beams in the horizontal orientation is preferable for designing bending dominated structure while vertical orientation is a superior choice for shear dominated structure.
- The beams are expected to fail in shear when the actual shear-to-bending stress ratio is higher than the allowable shear-to-tensile stress ratio while the beams are more likely to fail in bending when the actual shear-to-bending stress ratio is lower than the allowable shear-to-bending stress ratio. In between these ratios, a combined shear and bending failure is expected.
- The two-way Analysis of Variance showed that the beam orientation has more influence on the load carrying capacity and stiffness properties than changing the shear span-to-depth ratio.
- The existing theoretical models can estimate more reliably the failure loads in bending than in shear. The proposed indentation failure model reliably estimated the initiation of indentation in the vertical orientation. These moderate variation of failure loads predicted by existing models suggested a further investigation to establish better theoretical models that can capture

other critical behaviour such as the initiation of skin debonding and the shear compression failure of the very short vertical sandwich beams.

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### *Behaviour of bonded sandwich beams*

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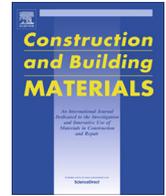
After investigating the materials in *Study 2*, the question now arises how effective is the epoxy polymer matrix as a binder of sandwich panel? Therefore, understanding the behaviour of sandwich panels bonded with epoxy polymer matrix is critical to evaluate the effectiveness of this structural beam concept for a railway sleeper, which is the focus of *Study 3*.

#### **Article V: Bond behaviour of composite sandwich panel and epoxy polymer matrix: Taguchi design of experiments and theoretical predictions**

A very good adhesion between the layers of composite sandwich panels has to be ensured for a better performance of the bonded sandwich beams. *Article V* studied the effect of matrix properties, bond length, bond thickness and bond width on the bond behaviour between a composite sandwich panel and epoxy polymer matrix (more information is provided in Appendix C.2). Results indicated that the bond thickness has the greatest influence on the bond strength followed by the properties of polymer matrix, bond length and bond width. A polymer matrix with 40% filler and 60% resin (by volume) was found optimal for binding sandwich panels together. Moreover, a bond thickness of 5 mm was the most suitable to utilise the strength of sandwich panels effectively. Using these bond parameters, full-scale beams were manufactured and their structural behaviour was evaluated.

#### **Article VI: Flexural and shear behaviour of layered sandwich beams**

An innovative beam concept termed “layered sandwich beams (LSB)”, which is made by combining layers of sandwich panels and binding them with epoxy polymer matrix was developed. *Article VI* investigated the behaviour of the LSBs’ under 4-point bending and asymmetrical beam shear tests. Results showed that the binding of panels using polymer matrix can prevent the wrinkling, buckling and indentation failure (Photos in Appendix C.3). This concept increased the bending and shear strength of the vertically oriented beams by 25% and 100%, respectively, compared to single sandwich beams. Using the same amount of material, the vertically layered beams exhibited similar bending strength and 50% higher shear strength but only 7% lower modulus of elasticity compared to horizontally layered beams. Therefore, the vertical orientation of panel was used for designing railway sleepers with an optimal shape.



# Bond behaviour of composite sandwich panel and epoxy polymer matrix: Taguchi design of experiments and theoretical predictions



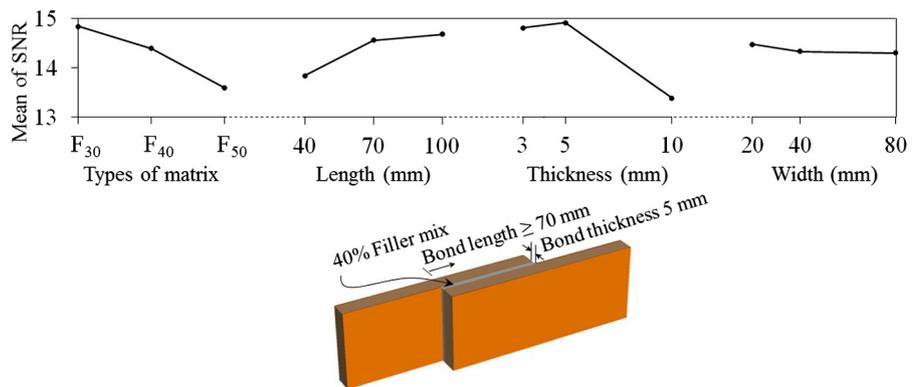
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## HIGHLIGHTS

- Structural bond between sandwich panel and epoxy polymer matrix is investigated.
- Polymer matrix with 40% filler and 60% resin has optimal bond properties.
- A thickness of 5 mm and length of 70 mm provides a satisfactory bond performance.
- Bond thickness has the greatest influence on bond performance.
- The developed theoretical model can reliably predict the bond behaviour.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Structural sandwich panels made of glass fibre reinforced polymer (GFRP) and a phenolic core are used to manufacture a new type of composite railway sleeper. As these sandwich panels are produced in limited thicknesses for production efficiency, they are bonded together by an epoxy-based polymer matrix with structural filler to manufacture the composite railway sleepers. In this paper, an investigation into the effects of the matrix properties, bond length, bond thickness and bond width on the bond behaviour between a composite sandwich panel and polymer matrix is discussed. The experimental program was designed by Taguchi method to minimise the number of required experiments, and the percentage contribution of each variable on the bond strength was evaluated using the analysis of variance (ANOVA). The results indicated that a polymer matrix with 40% filler and 60% resin (by volume) is optimal to satisfactorily bind the sandwich panels together. A bond length of at least 70 mm and bond thickness of 5 mm are necessary to effectively utilise the strength of the composite sandwich panel. The ANOVA showed that the bond thickness has the greatest influence, contributing 51% to the bond strength, while the properties of the polymer matrix, bond length and bond width contribute 33%, 15% and 1%, respectively. The proposed theoretical equations can reliably predict the failure load and failure mode of the bonded joints.

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## 1. Introduction

In recent years, a composite sandwich structure has become an effective alternative structural element for industrial applications due to its excellent design flexibility and good balance between rigidity and lightness [1–4]. This type of composite system is also now being explored to develop cost-effective composite railway sleepers [5,6]. As sandwich panels are generally produced with limited thicknesses for production efficiency, a number of panels can be joined together using mechanical fastener or bonded together with a polymer matrix to achieve the desired cross-section for a railway sleeper. However, the major difference between mechanical fastener and adhesive bonding is the bonded area which is larger in later case that minimise the stress concentration by uniformly distributing the loads. Because of the effect of stress concentration, the mechanically fastened structures often fractured at the fasteners at a load well below the ultimate strength of material. This makes the bonded joint more fatigue resistant and lighter due to the absence of fastener hardware [7]. Given the preference to adhesive bonding, the structural integrity and composite action of both the panels and matrix used are important in terms of transferring the load from one panel to another through the bond as de-bonding between a sandwich panel and binder interface can lead to premature failure of a railway sleeper. It has been reported that approximately 70% of the failure of structures is initiated from joints [8]. Thus, understanding the bond behaviour is essential to ensure the safety of joints in structures and to develop a full composite interaction between the panels.

Manalo and Aravinthan [9] investigated the glue-laminated sandwich composite beams, consisting of several layers of sandwich panels glued together with epoxy resin, to manufacture a composite railway sleeper. This process however requires applying and maintaining pressure to the panels until the resin hardened and then removing the excess glue-lines, which is a labour-intensive process. A cost-effective manufacturing technology for this type of sleeper is to cast the sandwich panels together and simultaneously coat them with a polymer matrix. This concept is relatively simple than the gluing process and similar to the casting of a reinforced concrete beam, as shown in Fig. 1. However, it is important to ensure the quality of the bond between the sandwich panels by using an appropriate polymer matrix and providing sufficient space between the panels into which to properly pour it.

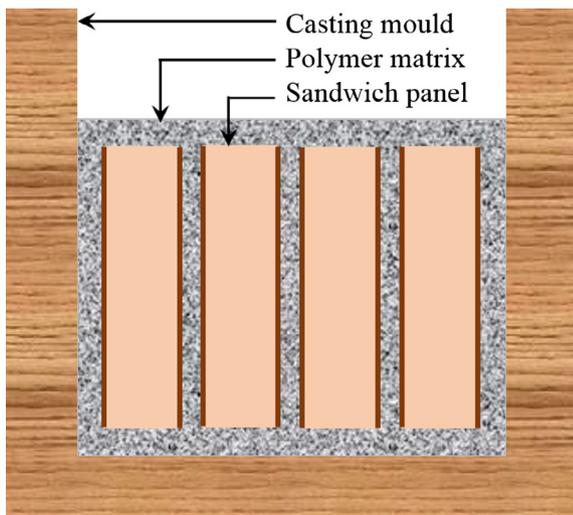


Fig. 1. Proposed casting method and typical cross section of composite railway sleeper.

The authors [10] have investigated the properties of epoxy polymer matrix and found an excellent mechanical, durability and thermal properties. Therefore, this study used further this epoxy polymer matrix and examined whether such a matrix is suitable for binding composite sandwich panels.

Studies conducted on using externally bonded FRP-steel plates to rehabilitate existing structures [11–13] have found that the properties of the adhesive materials, and the bond length, thickness and width are some of the parameters that influence bond behaviour. Prolongo et al. [14] investigated the adhesive behaviours of different epoxy resins through lap shear testing and found that an epoxy-amine combination could provide higher adhesive strength than homo-polymerised epoxy resins. Button's [15] study of fibre-fibre bond strength found a very strong influence of the bond length on the shear bond strength which decreased with an increase in the bond length. However, for externally bonded structures, researchers [11,16] have observed a trend of increasing bond strength with an increasing bond length up to a certain level. Arenas et al. [17] studied the effect of the adhesive thickness on the shear bond strength of lap joints and concluded that the bond strength could increase with a decrease in the bond thickness. Similar outcomes were noted by Xiong et al. [18] and Miller et al. [19]. The effect of the bond width on the interfacial behaviour of FRP-bonded concrete was studied by Woo and Lee [20] who observed a decrease in the failure stress with an increase in the bond width of a FRP plate.

However, those studies were conducted for the specific purpose of retrofitting existing structures where the FRP was bonded with concrete by a very thin layer of resin (<1 mm) [17,21] which was applied on the surface of concrete before placing FRP sheets. In the present study of a sandwich panel bonded with an epoxy polymer matrix, the properties and thickness of the matrix and casting method are different, which can affect the bond performance, the findings from retrofitting studies may not be applicable. Therefore, the main motivation of this study was to determine how the matrix properties, and bond length, thickness and width affect the bond behaviour between a composite sandwich panel and epoxy polymer matrix. Moreover, simple theoretical equations were developed to reliably describe the bond behaviour between these two materials.

## 2. Materials and methods

### 2.1. Materials

Two constituent materials employed in this investigation were (a) composite sandwich panel and (b) epoxy polymer matrix, the properties of which are presented in the following subsections.

#### 2.1.1. Sandwich panel

The composite sandwich panel consists of GFRP composite layers (skins) bonded to a phenolic core (Fig. 2a). The fibres of each skin were laid up in longitudinal (4 layers), transverse (2 layers) and  $\pm 45^\circ$  angular (2 layers in each) directions to obtain the strength and stiffness in all directions. The top and bottom skins were 1.8 mm thick with a fibre volume ratio of 45%. The phenolic foam core material came from natural plant (non-food) products derived from vegetable oils and plant extracts and was chemically bonded with the polymer resin. The density of sandwich panel is approximately  $990 \text{ kg/m}^3$  which is comparable to the hardwood red gum timber [22]. The properties of the GFRP skins and phenolic core determined by the second author and are provided in Table 1 [23]. The flexural, tensile, compressive and shear properties of the skins were determined by three-point bending, unidirectional tensile, unidirectional compressive, and V-notch shear tests of GFRP strips, respectively. On the other hand, the flexural, tensile, compressive and shear properties of the core were determined by three-point bending, dog-bone tensile, cylinder compression and V-notch shear test of phenolic core, respectively [24].

#### 2.1.2. Polymer matrix

Polymer matrix was prepared by mixing resin and filler. Fillers were added from 30% to 50% (by volume) with the resin in increments of 10% as, from a previous study by the authors [10], mixes in that range were found to be the most suitable.

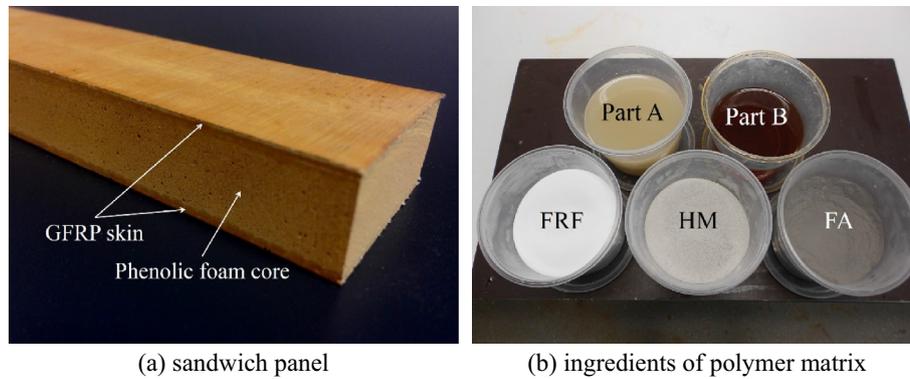


Fig. 2. Materials employed in bond test.

**Table 1**  
Properties of GFRP skin and phenolic core materials.

Test	Properties	GFRP skin		Phenolic core
		Longitudinal	Transverse	
Flexure	Elastic modulus (GPa)	14.28	3.66	1.33
	Peak stress (MPa)	450.39	135.05	14.32
	Strain at peak (%)	2.29	5.26	1.22
Tensile	Elastic modulus (GPa)	15.38	12.63	1.03
	Peak stress (MPa)	291.20	216.27	5.97
	Strain at peak (%)	1.61	2.37	0.61
	Poisson's ratio	0.25	0.13	–
Compressive	Elastic modulus (GPa)	16.10	9.95	1.33
	Peak stress (MPa)	238.04	124.23	21.35
	Strain at peak (%)	1.24	1.25	4.04
	Poisson's ratio	–	–	0.29
Shear	Shear modulus (GPa)	2.47	2.17	0.53
	Peak stress (MPa)	23.19	21.81	4.25
	Strain at peak (%)	3.08	2.38	0.81

The two main components of these resin systems were a DGEBA type epoxy resin (Part-A) and amine-based curing agent (Part-B), as shown in Fig. 2(b), with three different filler materials a Fire Retardant Filler (FRF), Hollow Microsphere (HM) and Fly Ash (FA). The fillers were round in shape with the diameter of 75 to 95  $\mu\text{m}$  for FRF, 20 to 300  $\mu\text{m}$  for HM, and 0.1 to 30  $\mu\text{m}$  for FA. The properties of the three mixes are provided in Table 2 and a detailed investigation of them can be found in [10].

## 2.2. Design of experiments using Taguchi method

Due to the wide range of variables that affect the bond strength, it is necessary to carefully design the experimental procedure. Usually, in a traditional concept, a series of tests is conducted to determine the variables from which a meaningful conclusion can be drawn; for example, if an experiment is required to investigate four variables, each of which has three levels, at least 81 (i.e.,  $3^4$ ) experimental combinations need to be carefully performed to understand the effects of each variable. This is certainly a time-consuming and expensive process, particularly when there

are many variables and levels. The Taguchi method [25] is an effective tool for the design of experiments that can significantly reduce the number of tests required while retaining the effects of each variable on the final output. It is very effective for a nominal number of variables (3–50) with few interactions between them and only when a few variables contribute significantly. The steps in the Taguchi experimental design are: selection of the design parameters and the number of levels for each; determination of the appropriate orthogonal array and its arrangement with the selected design parameters and levels; the conduct of experiments according to this arrangement; and analysis of the experimental results using the signal-to-noise ratio (SNR) and ANOVA [26,27].

### 2.2.1. Selection of design parameters and their levels

Among the different parameters influencing bond strength such as matrix properties, bond length, bond thickness, bond width, surface roughness, and curing temperature, method and time, this study primarily focuses on the matrix properties and influence of bond dimensions on bond behaviour. Therefore, the design parameters considered in this study are the matrix properties, and bond length, thickness and width, each with three levels are shown in Table 3. The levels for parameter A were chosen based on the results from a preliminary investigation [10] while, those for B, C, and D were according to the expected possible outcomes of the final application. For a FRP-to-concrete bond, Hosseini and Mostofinejad [16] determined the effective bond length as being from 40 mm to 70 mm and Bizindavvi and Neale [28] from 55 mm to 100 mm. In a similar study, a FRP and concrete were bonded with non-porous glue materials and in most cases, the bond was too thin (generally <1 mm) which is not a suitable thickness for a polymer matrix as it creates porous matrix similar to cement grout while hardening due to the use of filler materials. Moreover, the methods of gluing the sandwich beams together and bonding with epoxy polymer matrix are different as the former is applied and spread with brush then clamped together to introduce the pressure while the later one is similar to concrete casting which requires greater opening between adherends to ensure better flow of the matrix between the panels. Therefore, it was decided that a sensible choice of bond thickness was from 3 mm to 10 mm. The bond width has less influence on bond strength of adhesively bonded joints [29] thus, the common widths of the bond were considered that elsewhere varied from 25 mm to 80 mm [11].

**Table 2**  
Properties of epoxy polymer matrices.

Properties investigated	Comparison of properties of polymer matrices		
	30% Filler mix (F <sub>30</sub> )	40% Filler mix (F <sub>40</sub> )	50% Filler mix (F <sub>50</sub> )
Glass transition temperature ( $^{\circ}\text{C}$ )	63	64	65
Density ( $\text{gm}/\text{cm}^3$ )	1.34	1.38	1.43
% Porosity	0.06	0.62	0.98
Flexural strength (MPa)	56	45	40
% Failure strain in flexure	1.9	1.2	1.0
Compressive strength (MPa)	58	50	46
Shear modulus (MPa)	533	664	800

**Table 3**  
Selected design parameters and their levels.

Parameters ( $P_d$ )	Levels ( $L$ )		
	1	2	3
A % Filler in epoxy polymer matrix (by volume)	30	40	50
B Bond length (mm)	40	70	100
C Bond thickness (mm)	3	5	10
D Bond width (mm)	20	40	80

The required number of experiment depends on the orthogonal arrays that is the shortest possible matrix of combination in which all the chosen design parameters are varied at the same time. For selecting the orthogonal array, the total degrees of freedom (DOF) has a great importance as it indicates the number of levels considered for each parameter which can be calculated using Eq. (1).

$$DOF = n - 1 \tag{1}$$

The orthogonal array's DOF should not be smaller than the total DOF [30]. In this research, as each of the four design parameters, A, B, C and D, has three levels and a DOF of 2, the total DOF was 8 which made using the Taguchi  $L_9(3^4)$  array possible because the  $L_9$  orthogonal array has the same DOF.

On the other hand, the minimum number of experiments ( $N$ ) that needs to be conducted can be expressed by Eq. (2) in terms of the design parameters ( $P_d$ ) and levels ( $L$ ) [31].

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

Also, as four independent design parameters, each with three levels that have no interactions with each other require a minimum of 9 experiments instead of 81 as used in the traditional factorial experimental design, an  $L_9(3^4)$  orthogonal array should be the best choice. The 9 experiments selected based on this array are shown in Table 4 [32,33].

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

The influence of the design parameters on the final output depends on the loss function which measures the deviation between the experimental and desired values. In the Taguchi approach, the loss function is further converted into the SNR which is the log function of the expected outcomes. Depending on the objectives of the problem, three models of the SNR [34] used in the Taguchi method are: (a) nominal the best – to achieve the target with minimum deviation; (b) larger the better – to maximise the response; and (c) smaller the better – to minimise the response. These three models can be expressed by Eqs. (3)–(5).

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

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

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

where

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

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

**Table 4**  
 $L_9(3^4)$ orthogonal array used for experimental design.

Experiment No.	% Filler in matrix	Length (mm)	Thickness (mm)	Width (mm)
E-1	30	40	3	20
E-2	30	70	5	40
E-3	30	100	10	80
E-4	40	40	5	80
E-5	40	70	10	20
E-6	40	100	3	40
E-7	50	40	10	40
E-8	50	70	3	80
E-9	50	100	5	20

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

Although a SNR analysis can rank the design parameters according to their influence on the final output, it is incapable of identifying how much influence each has. However, this can be achieved by the ANOVA which is a statistical technique utilised to interpret experimental data and make necessary decisions. The relative contribution of each parameter can be determined by separating the total variability from the SNR. This relative significance usually represented through the  $F$  value which is a ratio of the mean of squared deviations to the mean of squared errors, with the larger its value the greater the effect of the parameter. However, in cases in which the residual sums of squares have zero DOFs due to over-fitted designs, the percentage contribution of each parameter can be determined directly using Eqs. (8–10).

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

where  $SS_k$  is the sum of squares of the  $k$ th parameter and  $SS_T$  the total sum of squares of all parameters.

$$SS_k = \sum_{j=1}^3 n [(SNR)_{kj} - SNR_T]^2 \tag{9}$$

where  $n$  is the number of experiments at level  $j$  of parameter  $k$  and  $SNR_T$  the overall mean of the SNR.

$$SS_T = \sum_{i=1}^9 [(SNR)_i - SNR_T]^2 \tag{10}$$

**2.3. Specimen preparation and test setup**

In order to investigate the effects of different parameters on bond behaviour, a special specimen configuration was designed to perform bond tests [35,36]. After their surfaces were cleaned, the specimens were cast in special moulds which were made of plywood with smooth surfaces to provide their relatively easy removal and provided the specified bond thickness between them into which to pour the polymer matrix (Fig. 3a). The samples were cured at 23 °C with 50% relative humidity, removed from the moulds after 3 days of casting (Fig. 3b) and tested after 7 days. MTS Insight 100 kN capacity twin-column testing machine was used that can reliably perform standard tests such as peel, tear, shear, tensile, compression, and flexure. The bond between a sandwich panel and polymer matrix was investigated by a direct compression test in accordance with the most relevant test standard ASTM D905 [37] at a speed of 1.2 mm/min (Fig. 3c). Under compression loading, the sandwich panels transferred stresses to the matrix from two opposite directions that generated a shear stress in the polymer matrix. Three specimens in each category were tested in order to obtain reliable results. To avoid the slenderness effect, only panel dimensions of 25 mm beyond the bond length (later defined as  $l_1$  and  $l_2$ ) were used for all specimens.

**3. Results and discussion**

**3.1. Shear bond strength**

Under compression loading the specimens were subjected to high shear stress in the joint area calculated by Eq. (11).

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

The load and cross-head displacement relationships for all specimens are plotted in Fig. 4(a). Apart from the initial portions of the load-displacement curves, the behaviour of the specimens were fairly linear. The slight nonlinearity at the beginning was probably due to the initial settlements of the loaded surfaces of the specimens which were not perfectly smooth and level. A close inspection of the load-displacement behaviour (Fig. 4a) obtained from experiments E-3, E-6 and E-9 shows that these specimens failed in a different manner and took longer time (indicating greater displacement) than those in experiments E-1, E-4 and E-7 while, the experiments E-2, E-5 and E-8 showed the displacement in between previous two sets of experiments. Fig. 4(b) presents the average shear bond strengths of the specimens which varied between 4.15 MPa and 5.96 MPa. The strengths of the replicate samples in each group from E-1 to E-6 were more consistent comparing with E-7 to E-9.

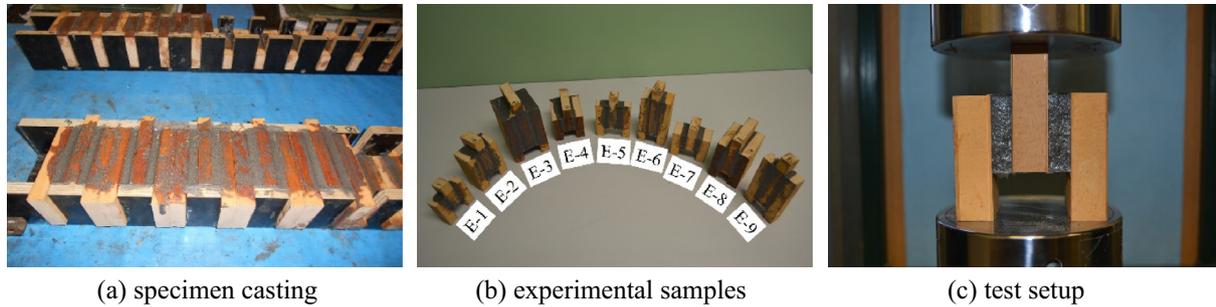


Fig. 3. Preparation of specimens and test setup.

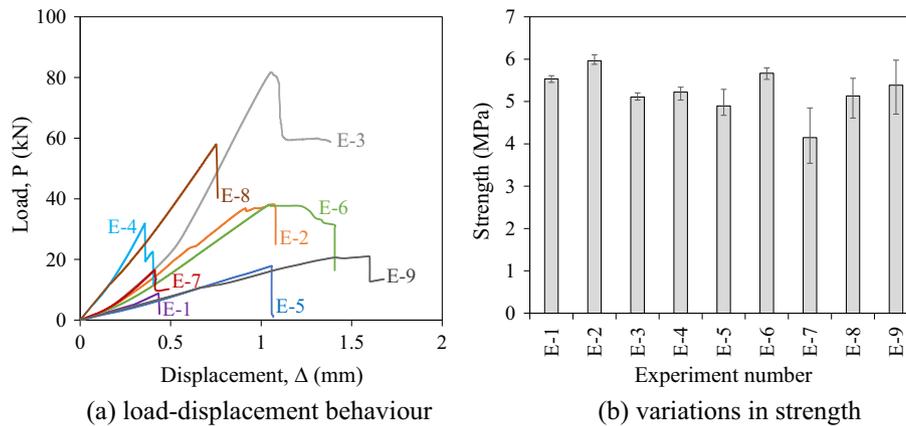


Fig. 4. Bond behaviours of sandwich panel and polymer matrix.

### 3.2. Failure behaviour

Three types of failure observed for the specimens under compression loading were: (a) adhesive failure, where the bond failed at the interface between the polymer matrix and sandwich panel; (b) cohesive failure, where the polymer matrix fractured; and (c) panel failure, where the sandwich panel failed (Fig. 5). An adhesive failure was observed for the specimens in E-1, E-6 and E-8 (Fig. 5 (a), (f) and (h)) whereas the cohesive failure were noticed in E-3, E-5 and E-7 (Fig. 5(c), (e) and (g)). The other mode of failure was the failure of sandwich panel which was observed for the specimens in E-2, E-4 and E-9 (Fig. 5(b), (d) and (i)).

The chemical bond formed at the interface between a polymer matrix and sandwich panel at the time the matrix was cured played an important role in failure behaviour. Adhesion failures occurred in E-1, E-6 and E-8 which indicated that a weak chemical bond formed at the interface, a kind of failure not desirable when a good bond is expected. On the other hand, the cohesion failures observed in E-3, E-5 and E-7 indicated strong chemical bond at the interface of a sandwich panel and polymer matrix. However, this type of failure does not ensure effective use of the full strength capacity of sandwich panel which is the main structural component. Therefore, the effective utilisation of sandwich panel in the structural application deserve a failure in it which was observed in E-2, E-4 and E-9. The skin delamination followed by core tension failure of a sandwich panel not only ensures utilisation of the full capacity of the panel but also represents a very strong bond between panel and the matrix. An interesting observation in Fig. 5 is that the failure mode was strongly dominated by the bond thickness as, regardless of the other design parameters, specimens with the same bond thickness failed in a similar manner. Therefore, for design purposes, it is important to understand the order of

influence of the design parameters on bond performance. To identify the rank of influencing parameters on bond strength, it is necessary to determine the effect of each individual one which can be done by analysing SNR.

### 3.3. Analysis of experimental variables

The failure loads and strengths obtained from the nine sets of experiments, their standard deviations, SNRs and overall mean of SNRs are presented in Table 5. As the bond strength between a sandwich panel and polymer matrix is a positive value and maximising it is the objective of the present work, this signified the larger-the-better type of quality characteristics given in Eq. (4) thereby indicating better bond strength.

The results show that the highest mean bond strength of 5.96 MPa is obtained from E-2 while E-7 provided the lowest strength of 4.15 MPa. The high bond strength of specimens failing in the panel (e.g., E-2) indicated a strong bond was developed between the panel and the matrix while the cohesive failure (e.g., E-7) represents a weaker bond than the panel failure. Although E-2 showed superior performance to the others, this does not indicate the optimum set of parameters. Using the SNR values presented in Table 5, it is possible to determine the effect of individual parameters at different levels. The SNR of a particular design parameter at a specified level is calculated and termed the level mean SNR, with that of design parameter A at level 1 found to be 14.84 using the average values of the SNR (14.86, 15.50 and 14.16) taken from E-1, E-2 and E-3. Similarly, the level mean SNR of design parameter B at level 1 is 13.79 from E-1, E-4 and E-7. The level mean SNRs of each design parameter at different levels that are the representative values of bond strength are given in Table 6.

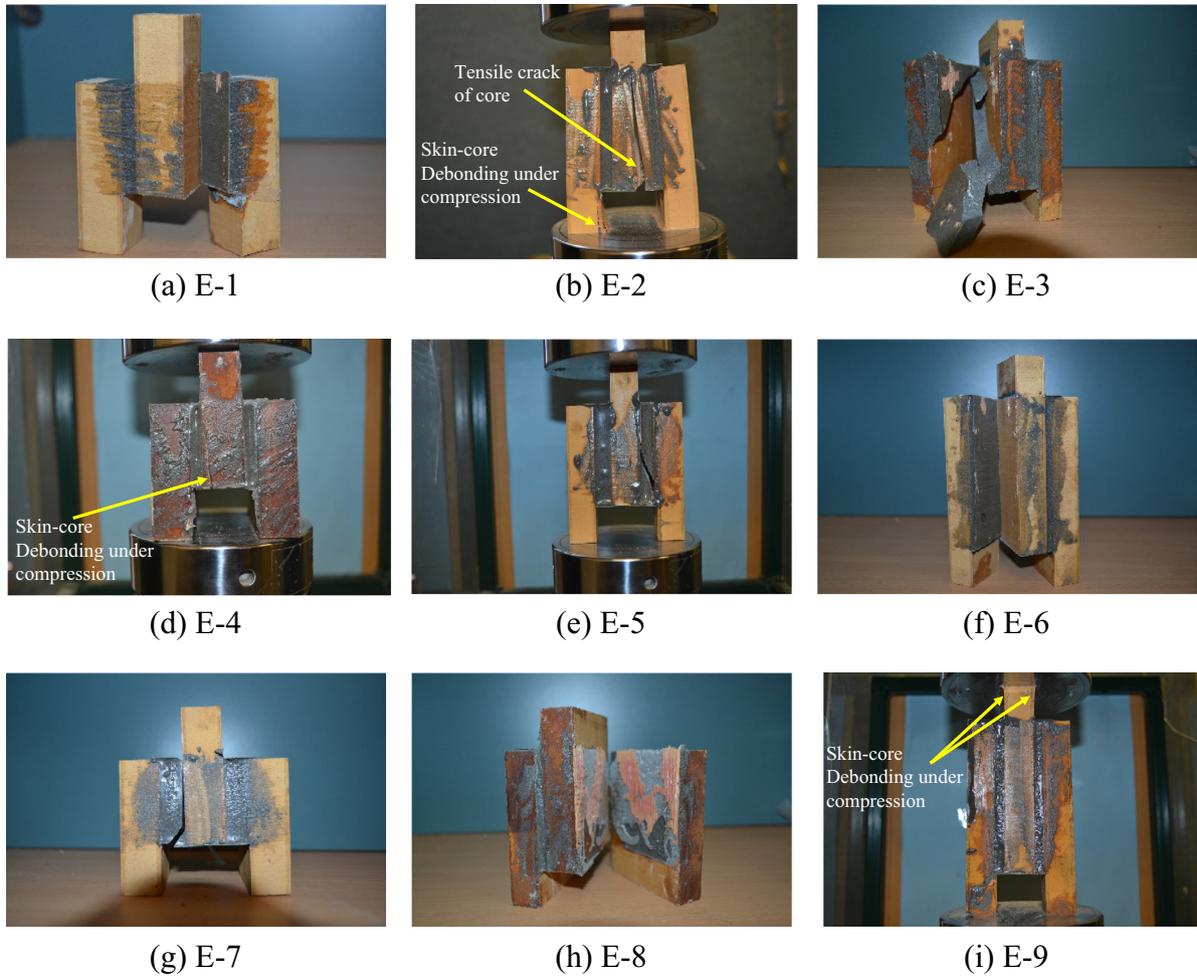


Fig. 5. Failure modes of specimens.

Table 5  
Average failure loads, strengths, standard deviations (SDs) and SNRs of experiments.

Expt. No.	Average failure (kN)			Failure strength (MPa)					SNR
	Load	SD	Mode	T-1	T-2	T-3	Mean	SD	
E-1	8.86	0.13	Adhesive	5.61	5.54	5.45	5.54	0.08	14.86
E-2	33.39	0.70	Panel	5.88	6.11	5.90	5.96	0.12	15.50
E-3	81.68	1.43	Cohesive	5.08	5.21	5.03	5.11	0.09	14.16
E-4	33.43	1.07	Panel	5.30	5.34	5.03	5.22	0.17	14.35
E-5	13.71	0.96	Cohesive	5.29	4.73	4.68	4.90	0.34	13.76
E-6	45.35	1.08	Adhesive	5.79	5.69	5.52	5.67	0.14	15.07
E-7	13.28	2.11	Cohesive	4.85	3.54	4.05	4.15	0.66	12.15
E-8	57.48	5.36	Adhesive	4.61	5.24	5.55	5.13	0.48	14.13
E-9	21.54	2.56	Panel	5.98	5.47	4.71	5.39	0.64	14.50
Overall mean of signal-to-noise ratio (SNR <sub>T</sub> )=									14.27

Note. T-1 to T-3 indicate Test-1 to Test-3 of replicate samples.

Table 6  
Level mean SNR of each design parameter at different levels.

Level	Level mean SNRs			
	SNR <sub>(Matrix)</sub>	SNR <sub>(Bond length)</sub>	SNR <sub>(Bond thickness)</sub>	SNR <sub>(Bond width)</sub>
1	14.84	13.79	14.68	14.37
2	14.39	14.46	14.78	14.24
3	13.59	14.57	13.35	14.21
Max	14.84	14.57	14.78	14.37
Min	13.59	13.79	13.35	14.21
ΔSNR	1.25	0.79	1.43	0.16
Rank	2	3	1	4

The difference between the maximum and minimum level mean SNR (i.e., ΔSNR) and ranks, which indicated the order of the influence of the four design parameters on bond strength, are calculated (Table 6). The highest ΔSNR value, which is assigned rank 1, indicated that the bond thickness has the greatest influence on bond strength, with the properties of the polymer matrix and bond length ranked second and third, respectively, followed by the bond width. The variation of level mean SNR are plotted in Fig. 6. The maximum value in each plot specifies the optimal level of that particular parameter. Therefore, the optimal bond strength can be obtained from the combination of 100 mm length and 20 mm width, bonded with 5 mm thick bond using F<sub>30</sub> matrix.

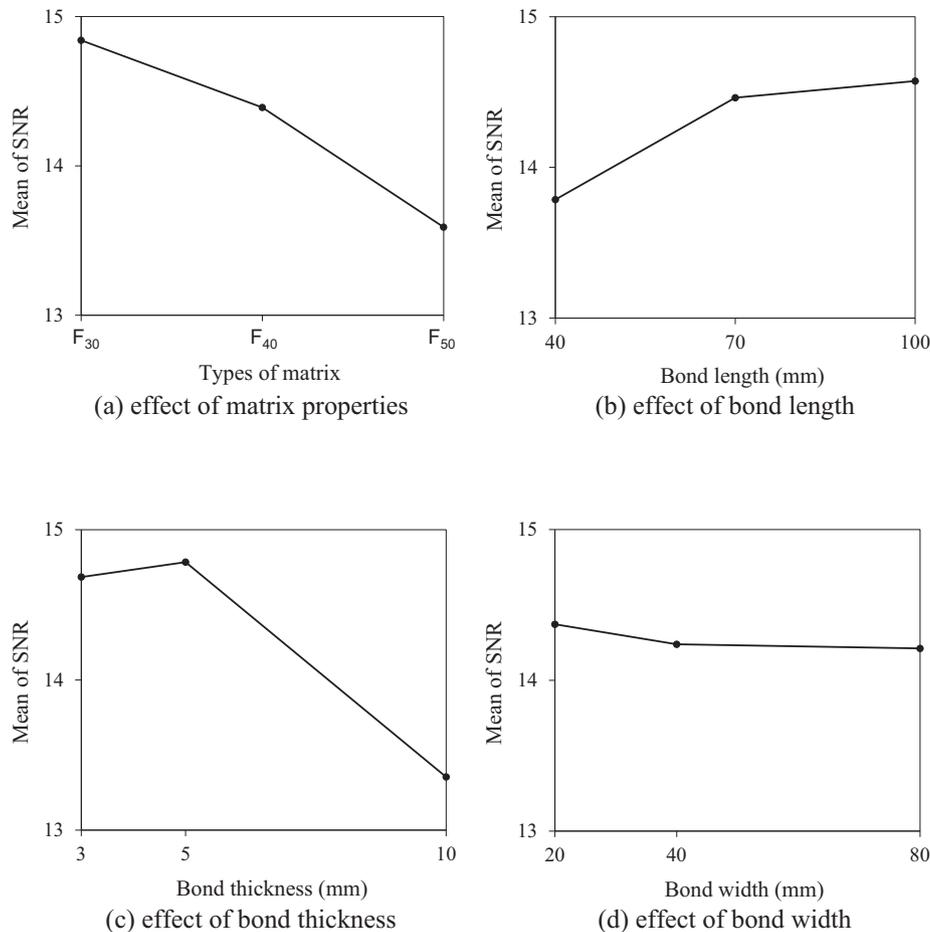


Fig. 6. Effect of design parameters at different levels (Larger the better).

### 3.4. Effect of matrix properties

The properties of a polymer matrix depend greatly on the resin-to-filler ratio. Previous investigation by the authors [10] has shown that adding 30% to 50% of filler (by volume of resin) can satisfy the requirements for coating and binding sandwich panels for the manufacture of composite railway sleepers. It can be observed in Fig. 6(a) that increasing the filler content from 30% to 50% gradually decreased the SNR response which meant that an increase in the amount of filler gradually weakened the bond between a sandwich panel and polymer matrix. Fig. 5 indicates that the failure modes of the specimens were not dominated by the properties of the polymer matrix because all three mode of failures were observed for the same matrix. The adhesive properties of the polymer matrix depended primarily on the amount of resin which gradually decreased with increases in the filler content, similar to the tensile or flexural properties of the polymer matrices provided in Table 2. An increase in the amount of filler made the polymer matrix more brittle and less workable due to the consequent decrease in resin, gradually creating an inflexible polymer matrix. The flow-ability of the matrix has an effect on the quality of the bond; for example, E-7, E-8 and E-9 produced relatively inconsistent results (a large standard deviation in Table 5) due to the increase of porosity in F<sub>50</sub> matrix (Table 2) as explained in [10] that has less workability and promoted to create voids while flowing. As the other two matrices (F<sub>30</sub> and F<sub>40</sub>) produced quite consistent results, they are preferable for use in the final application. However, as the economical design of a polymer matrix suggests an optimal use of resin, a matrix composed of 40% filler and 60% resin (F<sub>40</sub>) is the preferred choice.

### 3.5. Effect of bond length

Compression of the sandwich panel is transferred to the polymer matrix through shear stresses along the bond length. Results showing an increase in failure strength when the bond length increased from 40 mm to 70 mm while an insignificant variation is observed between 70 mm and 100 mm as depicted in Fig. 6(b). This led to an important aspect of effective bond length beyond which an extension of the bond length cannot increase the ultimate bond strength. The effective bond length could vary from one specimen to another depending on the properties, geometry and surface preparation of the specimens. From the present study, it can be concluded that the experimentally evaluated effective bond length for a sandwich panel and polymer matrix is approximately 70 mm. In other words, a bond length beyond 70 mm would make no further significant contribution to the bond strength. This phenomenon of the effective bond length has been confirmed by other researchers [13,16,38]. However, the results in Fig. 4(a) show that the ductility of the failure process (displacement) may have improved with a longer bond length whereas a shorter bond length would have provided little warning before final failure. The crack can propagate immediately after its initiation for the shorter bond length (e.g., 40 mm) specimens that causes a lower bond strength among the groups of similarly failed specimens, e.g., the specimens E-1, E-4 and E-7 have a tendency to provide the lowest bond strength in their respective failure group due to shorter bond length (Table 5). The specimens E-3, E-6 and E-9 (Fig. 4a) with bond lengths of 100 mm exhibited nonlinear behaviour before final failure and took longer time to fail (higher displacements) than other specimens.

3.6. Effect of bond thickness

Increasing the bond thickness from 3 mm to 5 mm slightly increased the bond strength but, from 5 mm to 10 mm, decreased it, as is evident in Fig. 6(c). Previous research [17–19] found an inverse relationship between the bond thickness and bond strength, with an increase in the former generally decreasing the latter. The slightly higher bond strength at 5 mm than 3 mm bond thickness is due to the different nature of failures of the specimen. Unlike adhesive failure at 3 mm bond thickness, the specimens with 5 mm thickness were failed in panel that ensures better bond strength. A close inspection of the failure modes of the specimens presented in Fig. 5 and Table 5 indicates that the bond thickness has a very strong influence on the failure behaviour. Regardless of all the other design parameters, adhesive failure occurred at the interface between a sandwich panel and polymer matrix when the bond thickness was 3 mm (E-1, E-6 and E-8). For a 5 mm thickness (E-2, E-4 and E-9), failure occurred in the sandwich panel while, for a 10 mm thickness (E-3, E-5 and E-7), there was cohesion failure in the polymer matrix. Hart-Smith [39] indicated that the shear load capacity of an adhesively bonded joint is proportional to the square root of the thickness of the adhesive (matrix). An observation of the failure modes of thicker bond specimens (E-3, E-5 and E-7) indicates that the failure path of the polymer matrix was not vertical but rather angular. A decrease in failure strength due to a thicker bond could be attributed to the greater eccentricity of the load path. Similarly, thinner bond specimens (E-1, E-6 and E-8) exhibited less eccentricity of the load path, the primary cause of adhesion bond failure. The failure of a sandwich panel with a 5 mm bond thickness represented the desired failure mode and a strong bond between the two components as the panel limit the joint strength. In this condition, the bond strength is higher than the tensile strength of the sandwich core and only the panels need to be tested to demonstrate structural integrity.

In a structural application, the function of a polymer matrix is to bind the sandwich panels together and protect them from adverse environments. The structure should be designed in such a way that ultimate failure will occur in the primary load-carrying component and that is sandwich panel as shown in Fig. 1. Therefore, a bond thickness of 5 mm is required to promote failure in the sandwich panels.

3.7. Effect of bond width

The effect of the bond width on failure strength is investigated using three different widths of 20 mm, 40 mm and 80 mm. The responses from the analysis showed that an increase in the bond width slightly decreased the ultimate failure strength, i.e., the utilisation efficiency of the combined action of a sandwich panel and polymer matrix marginally reduced. However, variations among the responses of the three different widths are insignificant (Fig. 6(d)) compared with those of the other variables in this study. Consequently, an increase in bond width could increase the load-carrying capacity but its effect on the ultimate failure strength is

minimal which indicated that a wider sandwich structure bonded with a polymer matrix could be designed for a unit width. Similar experimental findings have been noted in the behaviour of externally bonded carbon fibre reinforced plastic (CFRP) used to strengthen reinforced concrete structures whereby the failure stress decreased with an increase in the bond width of a CFRP plate due to a decrease in the strengthening effectiveness of the plate [20]. However, the study conducted by Song and Lim [29] of adhesively bonded joints concluded that the bond strength is not affected by the bond width.

3.8. Contributions of variables to bond strength

Although the SNR analysis could rank the design parameters according to their influence on bond strength, it is however, not possible to understand the contribution of each parameter on the development of bond strength which can be determined by ANOVA. The ANOVA was implemented to investigate how much each parameter contributed to the bond strength. This is accomplished by separating the total variability of the SNR. The sum of squares for each design parameter ( $SS_k$ ) and 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 determined using Eq. (8) [26,31] and provided in Table 7.

In Table 7, it can be observed that the bond thickness made the highest contribution of 51% to the development of bond strength between a sandwich panel and polymer matrix. The properties of the polymer matrix and bond length are the next two influencing parameters contributing 33% and 15% respectively. The bond width has the lowest influence on the development of bond strength and its contribution is only 1%. Structures that bonded with thin layer of epoxy glue, the bond length plays an important role for the development of plastic zones in the adhesive that can increase the strength of the joint to the adherend material’s ultimate strength [7]. However, instead of epoxy glue, the present study used epoxy polymer matrix that has higher shear modulus with greater bond-line thickness. Because of the higher shear modulus, a lower shear strain is developed at the joint and the bond length does not play such an important role. On the other hand, the function of bond width is to distribute applied loads and its contribution towards the development of bond strength is minimal as expected. These results suggest that the bond thickness and matrix properties are the two most critical parameters for the design of a sandwich structure bonded with a polymer matrix.

4. Theoretical analysis

4.1. Stress analysis and prediction of failure load

The stress analysis was performed to effectively identify the key parameters affecting the bond strength. This analysis was conducted using classical elasticity theory following the concept of Volkersen [40] analysis and de-Bruyne [41] solution. The original shape, deflected shape and free body diagram of an infinitesimal

Table 7  
Percentage contribution of each design parameter.

Parameter	DOF		Sum of squares		F-Value	% Contribution ( $\frac{SS_k}{SS_T} \times 100$ )
	L-1	N-1	$SS_k$	$SS_T$		
Matrix properties	2	8	2.41	7.37	-	33
Bond length	2		1.09		-	15
Bond thickness	2		3.83		-	51
Bond width	2		0.04		-	1
Error	-		-		-	-

element are shown in Fig. 7(a), (b) and (c) respectively. Where,  $t_s$ ,  $t_c$  and  $t_m$  are the thickness of the skin, core and matrix;  $l_1$ ,  $l$  and  $l_2$  are the length of single-leg, overlap and double-leg segment;  $\Delta l_1$ ,  $\Delta l$  and  $\Delta l_2$  are the reduction of length  $l_1$ ,  $l$  and  $l_2$  due to compression load, respectively. The width  $b$ , shear deformation of the matrix  $\Delta s_m$ , and  $P$  is the applied load.

The following assumptions are considered for the stress analysis:

- a) The behaviour of the sandwich panel is assumed to be linear elastic
- b) The shear stresses in the polymer matrix do not vary through the thickness
- c) The effect of bending moment developed by the applied forces in the joint is ignored

In Fig. 7(c), the equilibrium condition provides

$$\frac{dF_o}{dx} = \tau b \tag{12}$$

$$\frac{dF_i}{dx} = 2\tau b \tag{13}$$

In Eq. (12) and Eq. (13),  $F_o$  and  $F_i$  are the axial compression of the outer and inner panel, respectively and  $\tau$  is the shear stress in the polymer matrix. The longitudinal strain can be presented by the ratio of stress and modulus as shown in Eq. (14) and Eq. (15).

$$\frac{du_o}{dx} = \frac{F_o}{b(2E_s t_s + E_c t_c)} \tag{14}$$

$$\frac{du_i}{dx} = \frac{F_i}{b(2E_s t_s + E_c t_c)} \tag{15}$$

where  $u_o$  and  $u_i$  represents longitudinal displacement of the outer and inner panel, respectively. Shear stress of the polymer matrix can be calculated as

$$\tau = G_m \left( \frac{u_o - u_i}{t_m} \right) \tag{16}$$

From Eq. (12) and Eq. (16),

$$\frac{d^2 F_o}{dx^2} = \frac{b G_m}{t_m} \left( \frac{du_o}{dx} - \frac{du_i}{dx} \right) \tag{17}$$

From Eq. (14), Eq. (15) and Eq. (17),

$$\frac{d^2 F_o}{dx^2} = \frac{G_m}{t_m} \left( \frac{F_o - F_i}{2E_s t_s + E_c t_c} \right) \tag{18}$$

For equilibrium condition, the sum of the axial forces in inner and outer panels is equal to the applied force  $P$ , i.e.

$$P = F_i + 2F_o \tag{19}$$

From Eq. (18) and Eq. (19),

$$\frac{d^2 F_o}{dx^2} - \frac{G_m}{t_m} \left( \frac{3}{2E_s t_s + E_c t_c} \right) F_o + \frac{G_m}{t_m} \left( \frac{P}{2E_s t_s + E_c t_c} \right) = 0 \tag{20}$$

Taking,  $\frac{G_m}{t_m} \left( \frac{3}{2E_s t_s + E_c t_c} \right) = \lambda^2$  (21)

From Eq. (20) and Eq. (21),

$$\frac{d^2 F_o}{dx^2} - \lambda^2 F_o + \lambda^2 \left( \frac{P}{3} \right) = 0 \tag{22}$$

The solution of Eq. (22) is

$$F_o = A \sinh(\lambda x) + B \cosh(\lambda x) + \frac{P}{3} \tag{23}$$

The integration constants  $A$  and  $B$  can be determined by applying the boundary conditions-

$$F_o = 0, \text{ at } x = \frac{l}{2}$$

$$F_o = \frac{P}{2}, \text{ at } x = -\frac{l}{2}$$

Putting the integration constants  $A$  and  $B$  into Eq. (23) and using Eq. (19), the Eq. (24) and Eq. (25) can be obtained.

$$F_o = P \left[ \frac{1}{3} - \frac{\sinh(\lambda x)}{4 \sinh(\frac{\lambda l}{2})} - \frac{\cosh(\lambda x)}{12 \cosh(\frac{\lambda l}{2})} \right] \tag{24}$$

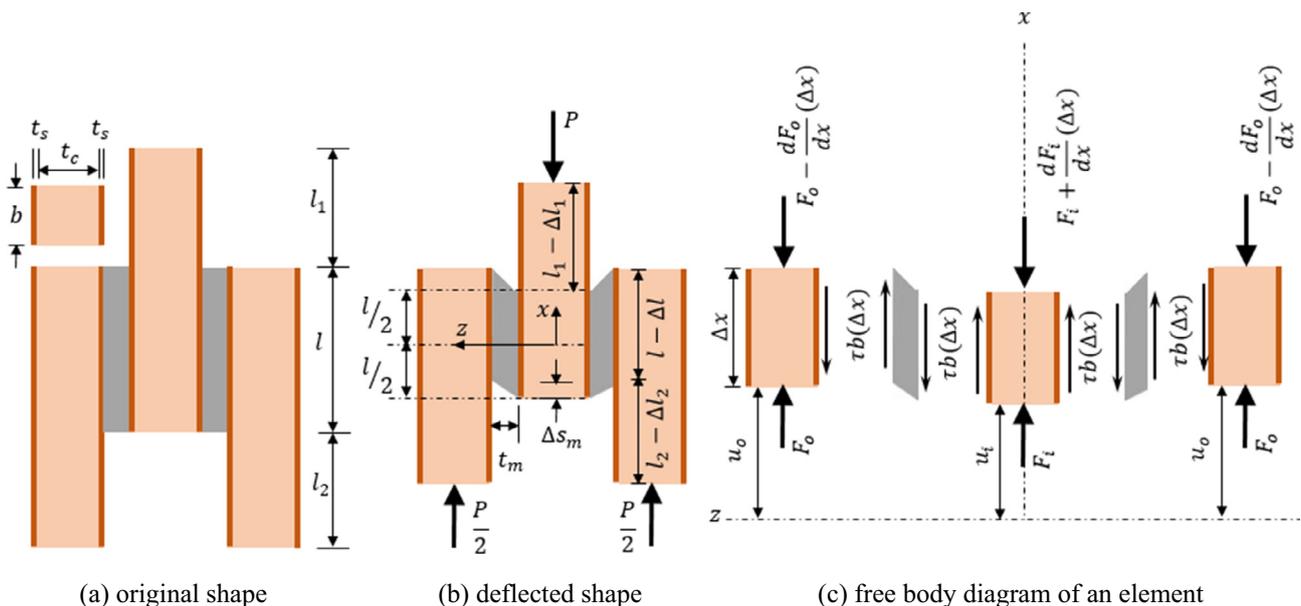


Fig. 7. Schematic diagram of the specimen for stress analysis.

$$F_i = P \left[ \frac{1}{3} + \frac{\sinh(\lambda x)}{2\sinh(\frac{\lambda l}{2})} + \frac{\cosh(\lambda x)}{6\cosh(\frac{\lambda l}{2})} \right] \quad (25)$$

Using Eq. (13) and Eq. (25), the shear stress between polymer matrix and panel can be determined by Eq. (26).

$$\tau = \frac{\lambda P}{4b} \left[ \frac{\cosh(\lambda x)}{\sinh(\frac{\lambda l}{2})} + \frac{\sinh(\lambda x)}{3\cosh(\frac{\lambda l}{2})} \right] \quad (26)$$

Eq. (26) can determine the shear stress of matrix at any distance between  $-l/2$  and  $+l/2$ . The average shear bond stress ( $\tau_{ave}$ ) can be represented by Eq. (27).

$$\tau_{ave} = \frac{1}{l} \int_{-l/2}^{l/2} (\tau) dx \quad (27)$$

It is highlighted in Section 3.3 that the optimal bond strength can be obtained from the combination of 100 mm length and 20 mm width, bonded with 5 mm thick bond using F<sub>30</sub> matrix. The bond thickness and matrix properties are the two most influential design parameters jointly contributes 84% towards the development of bond strength as shown in Table 7. Therefore, the specimen prepared with 5 mm bond thickness using F<sub>30</sub> matrix should have the highest bond strength among the tested specimens and can be close to the optimal bond strength. In this study, the specimen E-2 cast with 5 mm bond thickness and F<sub>30</sub> matrix that provided the maximum average bond strength of 5.96 MPa (Table 5) and assuming an optimal bond strength. With the variation of design parameters, the average bond strength at any combination can be determined from the optimal bond strength by incorporating the influence of design parameters. Simplifying Eq. (27) and including influence of design parameters, the failure loads of the specimen at any combination of the design parameters can be calculated by Eq. (28).

$$P = 2bl(\tau_{ao} \cdot K_m \cdot K_l \cdot K_t) \quad (28)$$

In Eq. (28),  $\tau_{ao}$  is the average bond strength from optimal design.  $K_m$ ,  $K_l$  and  $K_t$  are the factors introduced to consider the influence of matrix properties, bond length and bond thickness, respectively with a maximum value of 1 for optimal design. As the change in bond width was found to have insignificant contribution to the development of bond strength, there was no modification factor applied to consider this parameter in Eq. (28). After a little modification, the influence factor of design parameters can be defined from Fig. 6 using the ratio of SNR at a particular level to the maximum SNR, and expressed as Eq. (29), Eq. (30) and Eq. (31). However, the proposed model did not account the surface roughness of the materials which may affect the bond strength. Moreover, it was developed based on the novel sandwich panels

and a particular polymer epoxy and may not be suitable for other types of sandwich panels and polymer matrix. Further studies are therefore suggested to verify the applicability of these proposed model for other material types.

$$K_m = 1 - 0.004(\%Filler - 30) \quad \text{for } 30 \leq \%Filler \leq 50 \quad (29)$$

$$K_l = \begin{cases} 0.95 + 0.0017(l - 40) & \text{for } l < 70 \text{ mm} \\ 1 & \text{for } l \geq 70 \text{ mm} \end{cases} \quad (30)$$

$$K_t = \begin{cases} 1 & \text{for } t < 5 \text{ mm} \\ 1 - 0.02(t - 5) & \text{for } 5 \text{ mm} \leq t \leq 10 \text{ mm} \end{cases} \quad (31)$$

4.2. Prediction of failure mode

By examining the contribution of variables on bond strength, the bond thickness (51%) and matrix properties (33%) are found the key influential parameters in Table 7. A function that combines these two parameters is  $\lambda^2$  given in Eq. (21). Therefore,  $\lambda^2$  must have a significant influence on bond behaviour. The variation of average shear bond stress with  $\lambda^2$  is shown in Fig. 8(a). It can be seen that the failure mode of the specimen is strongly depends on the parameter  $\lambda^2$ . The specimens with similar mode of failure are separated from others and the transitional  $\lambda^2$  where the specimen changes the failure mode, can be obtained from Fig. 8(a). Using the magnitude of transitional  $\lambda^2$ , the transitional thickness of the bond for different polymer matrix can be determined by Eq. (21) as shown in Fig. 8(b).

Fig. 8(b) shows that the transitional thickness of the bond depends on the properties of matrix, particularly, shear modulus. The specimen will fail in adhesion for the bond thickness up to 3.16 mm, 3.93 mm and 4.74 mm, and cohesion for the bond thickness above 5.73 mm, 7.13 mm and 8.60 mm when using F<sub>30</sub>, F<sub>40</sub> and F<sub>50</sub> type matrix, respectively. At any other bond thickness between the adhesion and cohesion failure, the specimen will fail in panel. The increase of shear modulus of the matrix (from F<sub>30</sub> towards F<sub>50</sub>) can promote the adhesive failure with larger bond thickness (from 3.16 mm to 4.74 mm). This can be attributed by the reduction of resin in the F<sub>50</sub> matrix which provided lower adhesive strength even with greater bond thickness.

4.3. Comparison between experimental and theoretical results

The comparison between experimental and theoretical results in terms of the failure load with percentage difference, and the mode of failure are provided in Table 8. Result showed that the

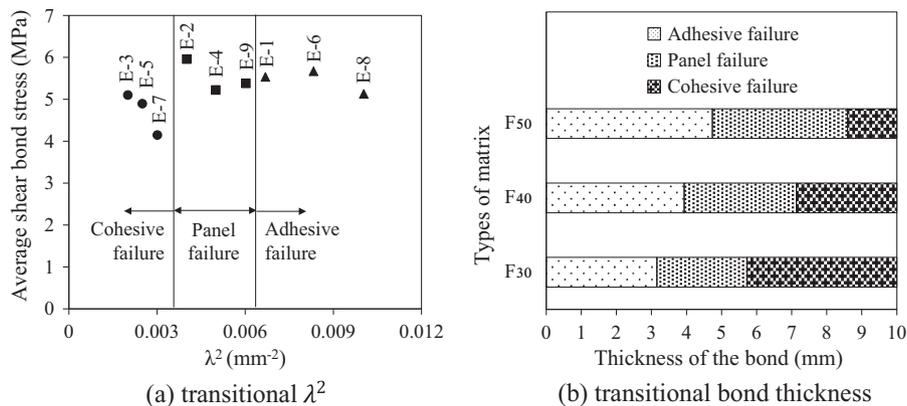


Fig. 8. Failure map of the specimens.

**Table 8**  
Comparison between the experimental and theoretical results.

Sample ID	Failure load, $P$ (kN)			Failure mode	
	Experimental	Theoretical	% Difference	Experimental	Theoretical
E-1	8.86	9.06	2.3	Adhesive	Adhesive
E-2	33.39	33.39	0.0	Panel	Panel
E-3	81.68	85.85	5.1	Cohesive	Cohesive
E-4	33.43	34.80	4.1	Panel	Panel
E-5	13.71	14.42	5.2	Cohesive	Cohesive
E-6	45.35	45.79	1.0	Adhesive	Adhesive
E-7	13.28	15.01	13.0	Cohesive	Cohesive
E-8	57.48	61.43	6.9	Adhesive	Adhesive
E-9	21.54	21.94	1.9	Panel	Panel

theoretical model can predict the failure loads within 13% of the experimental value indicating a good agreement between the experimental results and theoretical analysis. Moreover, the failure map can accurately predict the failure modes at any combination of the design parameters. The small variation between experimental and theoretical results for failure loads is due to the assumption considered for the prediction equations. The specimen E-2 does not show any variation between the experimental and theoretical failure load as the shear bond strength of this specimen was considered an optimal strength.

## 5. Conclusion

In this study, the Taguchi design of experiments was implemented to investigate the effects of four independent parameters, the binder properties, bond length, bond thickness and bond width on the bond behaviour of a composite sandwich panel and epoxy polymer matrix. The results were analysed using ANOVA and the theoretical analysis were performed from which the following conclusions are drawn:

- The Taguchi design of experiments and ANOVA can be used to reliably evaluate the effects of several critical parameters on the bond between a composite sandwich panel and epoxy polymer matrix with a minimal number of experiments.
- The bond strength between a sandwich panel and epoxy polymer matrix decreases with an increase in the amount of filler due to the reduced adhesive properties of the matrix. The polymer matrix with 50% filler promoted to create voids at the joint due to its higher porosity and lesser workability than the 30% and 40% filler mixes. Therefore, to avoid voids in the joints and ensure that the matrix is economical, a polymer matrix with 40% filler and 60% resin is identified as the preferred one.
- For the specific design parameters in this study, the bond strength is improved by increasing the bond length up to 70 mm, beyond which the extension of the bond length cannot increase the bond strength significantly. However, ductility is improved by a longer bond length while a shorter one provides little warning before ultimate failure.
- The thickness of the polymer matrix has the greatest influence on the bond performance and failure mode. Regardless of other parameters, failure occurs due to adhesion, panel and cohesion for bond thicknesses of 3 mm, 5 mm and 10 mm, respectively. The greater eccentricity of the load path for 10 mm thicker bond emphasized cohesive failure while a thinner bond with thickness of 3 mm exhibited less eccentricity of the load path and causes adhesive failure. As the failure of a sandwich panel with a 5 mm bond thickness indicates a very strong bond between the panel and matrix, which is the desired mode of failure for the effective utilisation of panels, this study suggests using this thickness to bind sandwich panels.

- The bond width has no significant influence on bond behaviour which indicates that an epoxy polymer matrix-bonded sandwich panel can be designed for a unit strip of width for wider sandwich structure.
- The results from the ANOVA show that the bond thickness has the greatest influence (51%) on the development of bond strength between a sandwich panel and polymer matrix, followed by the properties of the polymer matrix (33%), bond length (15%) and bond width (1%).
- The developed simplified theoretical equations can reliably describe the failure loads and failure modes of the sandwich panel bonded with epoxy polymer matrix. The results showed that the specimen will fail in adhesion for a bond thickness up to 3.16 mm, 3.93 mm and 4.74 mm, and cohesion for a bond thickness above 5.73 mm, 7.13 mm and 8.60 mm when using 30%, 40% and 50% filler in the matrix, respectively. At any other bond thickness between the adhesion and cohesion failure, the specimen will fail in panel.

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# Flexural and shear behaviour of layered sandwich beams

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## Abstract

A new type of composite beam, referred to as Layered Sandwich Beam (LSB) is introduced in this study. The sandwich system consists of Glass Fiber Reinforced Polymer (GFRP) skins and Phenolic cores, and several layers of sandwich panels are bonded together with epoxy polymer matrix for manufacturing beams. To explore the suitability of this novel concept for structural applications, the flexural and shear behaviour of LSB have been investigated. Eight LSB, with four having layers horizontally oriented and the other four vertically oriented, have been tested under four-point bending and asymmetrical beam shear. A three-dimensional finite element model was developed using Strand7 to further understand the fundamental behaviour of the LSB. The results showed that the LSB has an increased sectional stability by preventing wrinkling and buckling of the composite skins and indentation failure. This improved the bending and shear strengths of the vertical LSB by 25% and 100%, respectively, compared with single sandwich beams. While horizontal LSB provide a higher bending stiffness, the vertical beams exhibited higher shear strength due to the orientation of the skins. The finite element model can reliably predict the fundamental behaviour of the LSB in different orientations and loading configurations, within -10% to +14%.

**Keywords:** Composite beam, Orientation of sandwich panel, Shear span-to-depth ratio, Flexure, Shear, Finite element analysis.

## 1. Introduction

Composite sandwich panels are widely used in automotive and aircraft applications. The structural sandwich panels are generally composed of two thin but stiff skins that carry the majority of flexural loads, and are separated by a thick lightweight core that increases the shear capacity and moment of inertia of the section. These engineered composite systems are now receiving wider acceptance in the characteristically conservative infrastructure construction industry (Bakis et al., 2002) due to their excellent durability, high strength-to-weight ratio, cost effectiveness, excellent fatigue and corrosion resistance, good impact resistance and design flexibility. Their current applications include structural roofs (Keller, 2007), floors (Van Erp and Rogers, 2008), walls (Tomlinson and Fam, 2015) and bridge decks (Keller, 2007).

In the last few years, a significant amount of research has investigated the behaviour of a wide range of fibre composite sandwich panels (Manalo et al., 2010c, Manalo et al., 2016a, Mathieson and Fam, 2016, Ferdous et al., 2017), but despite having great potential, their application in developing sustainable composite beams is limited. Recently, some studies were conducted on glue-laminated sandwich panels aiming to develop a possible alternative to timber beams. Awad et al. (Awad et al., 2012) investigated the behaviour of horizontally layered glue-laminated glass fibre reinforced polymer composite sandwich beams, and their study found that the shear and bending capacity of the glue-laminated beams reduced marginally from the single sandwich beam due to debonding failure of the internal sandwich layers. Manalo and Aravinthan (Manalo and Aravinthan, 2012) studied the behaviour of horizontally and vertically layered sandwich panels glued together with epoxy resin, and they concluded that the glue-laminated composite sandwich structures have stiffness and strength properties comparable to that of structural timber. However, the manufacturing process of these layered beams required applying and maintaining pressure to the sandwich panels until the resin is hardened and later removing the excess glue-lines, which was a labour-intensive process. A cost-effective manufacturing technology for this type of beam is to cast and coat the sandwich panels together using polymer matrix without applying external pressure. This method is similar to the casting of traditional reinforced concrete beams and relatively easier than the gluing process. However, the structural integrity and composite action of the layered sandwich panels bonded with polymer matrix which is important to satisfy the structural requirements for civil engineering applications are not yet fully understood. Therefore, an investigation on the structural behaviour of layered sandwich panels bonded with the polymer matrix is necessary for its safe use and widespread application as a composite beam. The

outcome of this study aims at contributing to the scientific knowledge of understanding the behaviour of LSB in different sandwich orientations that can help to increase the confidence of this novel beam concept in civil engineering and construction application.

## **2. Experimental program**

This study investigated the structural behaviour of composite beams manufactured from layers of sandwich panels that are bonded together with the epoxy polymer matrix. The sandwich panels were bonded either in a horizontal or vertical orientation to compare the behaviour of LSB in the two orientations. Manalo and Aravinthan (Manalo and Aravinthan, 2012) indicated that the orientation of the sandwich laminations affects the structural behaviour of glued sandwich beams. On the other hand, the epoxy polymer matrix has excellent mechanical, thermal and durability properties (Ferdous et al., 2016c), and can be used as a suitable binder for LSB. Similarly, the LSB were tested with different shear span-to-depth ratios to investigate the flexural and shear behaviour as many researchers (Awad et al., 2012, El-Hacha et al., 2010, Kotsovos and Pavlović, 2004) have indicated that this design parameter plays a significant role in the sandwich beam's structural behaviour. A recent study (Ferdous et al., 2017) on the single sandwich panel has shown that the sandwich beam fails in shear, a combined effect of shear and bending, and bending for shear span-to-depth ratios of 2 or less, between 2 and 6, and 6 or more, respectively. Therefore, this study considered shear span-to-depth ratios of approximately between 1 and 6 to capture the behaviour of LSB transitioning from shear to flexure.

### **2.1. Materials**

The beams were manufactured using sandwich panels bonded with epoxy polymer matrix. The details of these materials are described in the succeeding sections.

#### **2.1.1. Sandwich panel**

The sandwich panels were made up of GFRP skins and phenolic core (Fig. 1a). The thickness of each skin was 1.8 mm with fibre volume fraction of 45% while the core was 16.4 mm thick. In each skin, the fibres were oriented in the longitudinal ( $[0^\circ]$ , 4 layers), transverse ( $[90^\circ]$ , 2 layers) and diagonal ( $[\pm 45^\circ]$ , 2 layers in each) directions according to the following stacking sequence  $[0/90/0/+45/-45/+45/-45/0/90/0]$ . The bio-based phenolic core came from non-food based natural plant products derived from vegetable oils and plant extracts (Manalo et al.,

2012b). The sandwich panel density was approximately  $990 \text{ kg/m}^3$  which is comparable to the hardwood red gum timber (Bootle, 2005). The properties of the GFRP skins and phenolic core (Ferdous et al., 2017) are provided in Table 1.

Table 1: Properties of GFRP skin and phenolic core materials

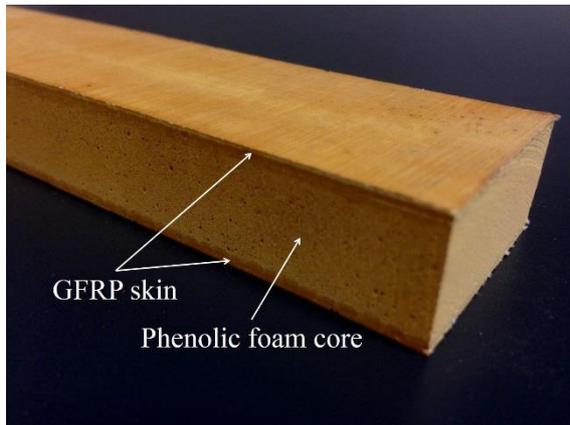
Test	Properties	GFRP skin		Phenolic core
		Longitudinal	Transverse	
Flexure	Elastic modulus (GPa)	14.28	3.66	1.33
	Peak stress (MPa)	450.39	135.05	14.32
	Strain at peak (mm/mm)	0.0229	0.0526	0.0122
Tensile	Elastic modulus (GPa)	15.38	12.63	1.03
	Peak stress (MPa)	291.20	216.27	5.97
	Strain at peak (mm/mm)	0.0161	0.0237	0.0061
	Poisson's ratio	0.25	0.13	-
Compressive	Elastic modulus (GPa)	16.10	9.95	1.33
	Peak stress (MPa)	238.04	124.23	21.35
	Strain at peak (mm/mm)	0.0124	0.0125	0.0404
	Poisson's ratio	-	-	0.29
Shear	Shear modulus (GPa)	2.47	2.17	0.53
	Peak stress (MPa)	23.19	21.81	4.25
	Strain at peak (mm/mm)	0.0308	0.0238	0.0081

### 2.1.2. Polymer matrix

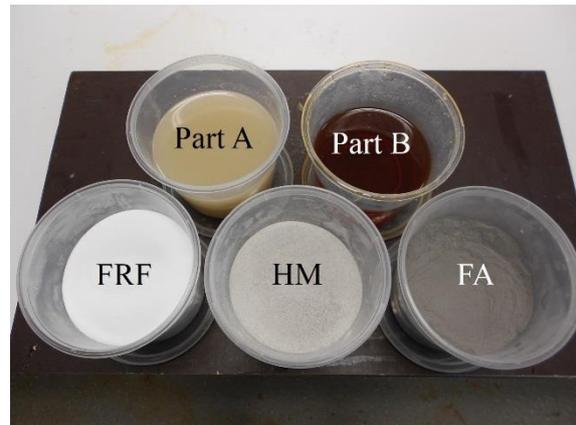
The polymer matrix was prepared by mixing resin and filler. A previous study by the authors (Ferdous et al., 2016a) has suggested that the optimal polymer matrix can be obtained by mixing 40% filler with 60% resin (by volume) when maintaining a good balance between performance and cost. The two main constituents of resin systems were a DGEBA type epoxy resin (Part-A) and amine-based curing agent (Part-B), as shown in Figure 1(b), with three different filler materials a Fire Retardant Filler (FRF), Hollow Microsphere (HM) and Fly Ash (FA). The diameters of the round shaped filler were 75 to 95 microns for FRF, 20 to 300 microns for HM, and 0.1 to 30 microns for FA. Some relevant properties of the polymer matrix are given in Table 2, and the detailed investigation can be found in (Ferdous et al., 2016c, Ferdous et al., 2016a).

Table 2: Properties of epoxy polymer matrix

Properties	Magnitude	Unit
Glass transition temperature	64	$^{\circ}\text{C}$
Density	1.38	$\text{gm}/\text{cm}^3$
Porosity	0.62	%
Flexural strength	45.09	MPa
Tensile strength	14.74	MPa
Compressive strength	65.46	MPa
Compressive elastic modulus	1656	MPa
Shear strength	4.90	MPa
Shear modulus	664	MPa



(a) sandwich panel



(b) ingredients of the polymer matrix

Fig. 1: Materials for manufacturing the beam

## 2.2. Specimen preparation

The sectional details of the LSB and casting method are provided in Figure 2. Two different sectional configurations were considered in this study. The fibre composite sandwich panels, which were the main reinforcing elements of the beam, were placed either horizontally (Fig. 2a) or vertically (Fig. 2b). The horizontal LSB were 90 mm wide, and 105 mm deep whereas the width and depth of the vertical LSB were 105 mm and 90 mm, respectively. The purpose of selecting this dimension is to make the depth and width of the section as equal as possible. While there is a dimensional variation between horizontal and vertical LSB due to the 5 mm gap between sandwich panels, the total amount of reinforcement remains the same (i.e. four

panels in both orientations). The 5 mm thick bond line and the coating were adopted to eliminate voids as determined in (Ferdous et al., 2016a).

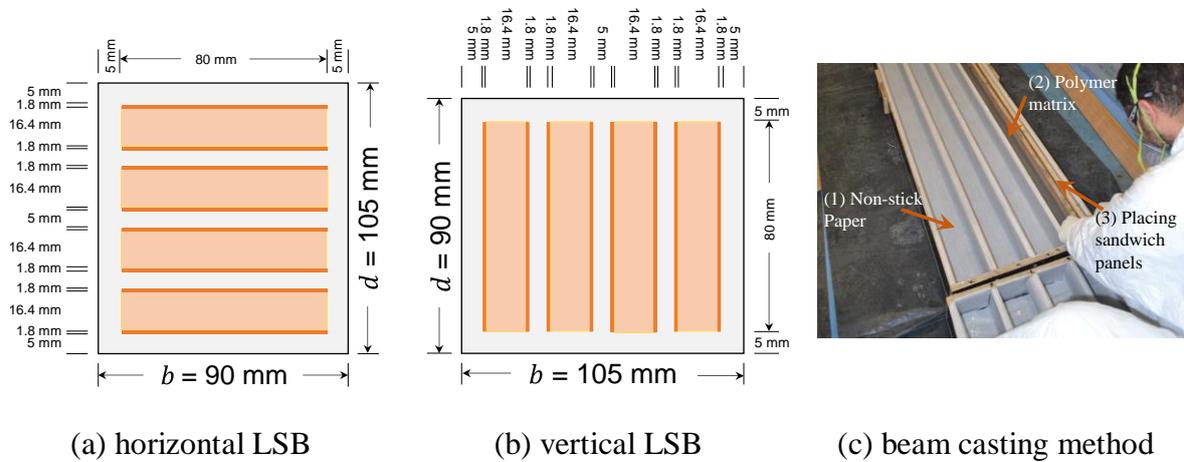


Fig. 2: Sectional details of the horizontal and vertical LSB, and casting method

The beams were cast in the plywood formwork, and non-stick papers were laid-up in the interior surface of the mould for easy removal of the hardened specimens (Fig. 2c). Small spacers made of composite materials with a thickness of 5 mm were attached inside the formwork to achieve the required cover and gap between the panels. They were placed at two ends of each beam in order to be outside of the test span. Approximately 30% of the volume of the formwork (estimated based on sectional dimensions) was filled with the polymer matrix before placing the sandwich panels in it. The sandwich panels were laid vertically into the matrix and consequently an upward flow of matrix filled up the empty space in the formwork. This casting method minimised the void formation as the air bubbles escape out during the upward flow of matrix. After placing the panels into the matrix, the two ends of the beam were repressed to ensure the vertical alignment and position of the panels. The beams were cured at normal room temperature with an approximate humidity of 50%, and the specimens were removed from the mould after 7 days of casting. Six beams were prepared for the four-point bending test and the other two for asymmetrical beam shear test. All eight beams have the same properties, however, the test set-up and the orientation of the beams were different for each.

### **2.3. Test setup and procedure**

A total of six LSB, three of which were horizontally layered and the other three vertically layered, were tested in simply supported condition under four-point bending (FPB) with a span of 1400 mm as shown in Figure 3(a). The load was applied at shear spans of 600 mm, 400 mm and 200 mm which provided shear span-to-depth ( $a/d$ ) ratios of approximately 6, 4 and 2, respectively. Two strain gauges were attached to top and bottom surface of the beam at mid-span while another three gauges were attached vertically, horizontally and diagonally on the 45° line drawn from the loading point as shown in Figure 3(a). Depending on the shear span, both flexural and shear failures were observed in the horizontal LSB, however, all three LSB in the vertical orientations failed in flexure with no observed shear failure. Therefore, the other two LSB were tested under asymmetrical beam shear (ABS) loading to generate a zero-bending point and ensure a shear failure of the specimens and have a better understanding of the shear behaviour of the horizontal and vertical LSB. The shear spans were fixed at 100 mm ( $a/d = 1$ , approximately). The beams under ABS test were eccentrically loaded at two trisected points, and the supports were applied at the other two points (Fig. 3b). Only three strain gauges were attached on the 45° line drawn from the load point at vertical, horizontal and diagonal directions to measure the shear strain as shown in Figure 3(b).

The load was applied through a spreader beam using a hydraulic jack. To prevent the occurrence of abrupt failure due to load fluctuation, based on recommendations from previous studies, a moderate loading speed of approximately 5 mm/min was considered for FPB test (Manalo and Aravinthan, 2012) and 1 mm/min for ABS tests (Manalo, 2013). The displacement of the beams under FPB test was measured at midspan with a laser sensor. The applied load and displacement were recorded continuously by a System-5000 data acquisition system. Only one specimen was tested for each case due to the large size of the beams. This is rational as shown by the previous studies (Ferdous et al., 2016c) that the properties of the materials are reasonably consistent and the beam manufactured with the same materials would give results within an acceptable margin of error. The details of the tested beams are provided in Table 3. In the specimen designation, the first letter indicates the orientation of the sandwich layer, i.e. 'H' or 'V' for horizontal and vertical orientation, respectively. The second letter 'F' or 'A' corresponds to the test configurations (FPB or ABS, respectively), and the third letter 'A' represents the shear span and the associated subscript number indicates the length of shear span in mm, i.e. A<sub>600</sub> means a shear span of 600 mm.

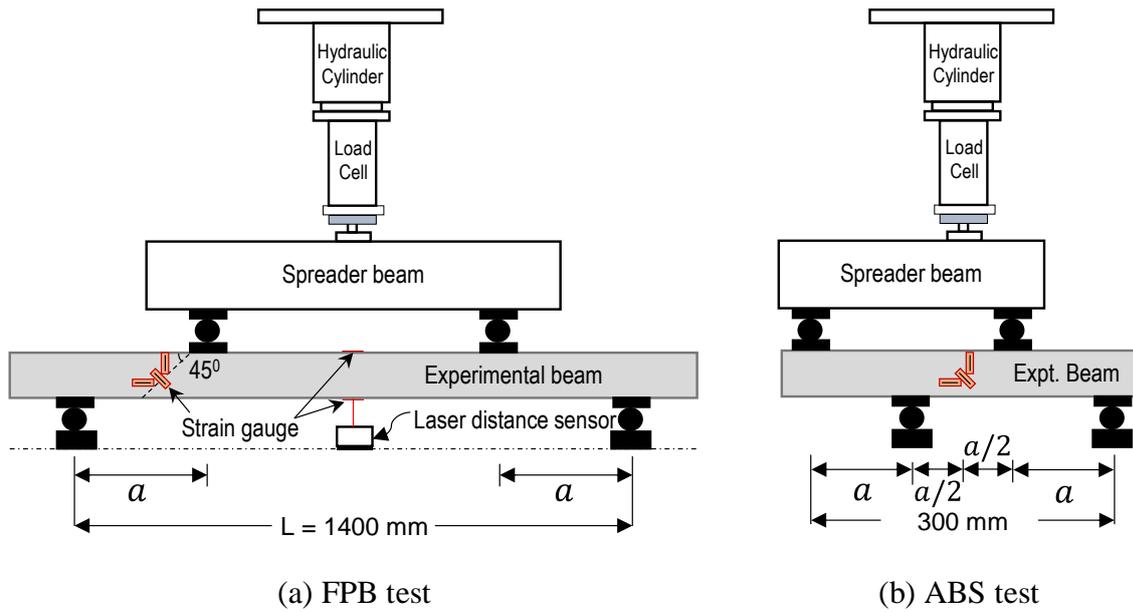


Fig. 3: Schematic diagram of the test set-up

Table 3: Details of the investigated beams

Beam identity	LSB orientation	Test type	$a$ mm	$b$ mm	$d$ mm	$a/d$ ratio	Failure load, P (kN)			Slope, $\Delta P/\Delta\delta$ (kN/mm)			Failure mode
							Expt	FEA	%Dif	Expt	FEA	% Dif	
HF-A <sub>600</sub>	Horizontal	FPB	600	90	105	5.71	28.3	32	13.1	0.44	0.45	2.3	ST+D
VF-A <sub>600</sub>	Vertical	FPB	600	105	90	6.67	28.8	26	-9.7	0.30	0.32	6.7	ST
HF-A <sub>400</sub>	Horizontal	FPB	400	90	105	3.81	50.9	53	4.1	0.54	0.56	3.7	CS+D
VF-A <sub>400</sub>	Vertical	FPB	400	105	90	4.44	40.1	38	-5.2	0.37	0.4	8.1	ST
HF-A <sub>200</sub>	Horizontal	FPB	200	90	105	1.90	90.8	85	-6.4	0.95	0.99	4.2	CS
VF-A <sub>200</sub>	Vertical	FPB	200	105	90	2.22	76.4	74	-3.1	0.64	0.7	9.4	ST
HA-A <sub>100</sub>	Horizontal	ABS	100	90	105	0.95	220	213	-3.2	61.3	65.3	6.5	CS
VA-A <sub>100</sub>	Vertical	ABS	100	105	90	1.11	315	305	-3.2	74.5	81.7	9.7	SS

Expt.: Experimental; FEA: Finite Element Analysis; Dif.: Difference

FPB: Four-point bending; ABS: Asymmetrical beam shear

ST+D: Skin tension and debonding

ST: Skin tension

CS+D: Core shear and debonding

SS: Skin shear

CS: Core shear

### 3. Results and observation

#### 3.1. Failure modes

Different types of failure were observed for the LSB depending on the test setup, shear spans and orientations as shown in Figure 4. The following presents a brief description of the failure modes:

- *Skin tension and debonding (ST+D)*: The horizontal LSB when loaded with a shear span of 600 mm (HF-A<sub>600</sub>) failed by the skin tension at the bottom fibre followed by debonding through bond-line of the bottommost sandwich layers as shown in Figure 4(a). The top skin between the loading points failed in compression immediately after debonding.
- *Core shear and debonding (CS+D)*: The horizontal LSB with a shear span of 400 mm (HF-A<sub>400</sub>) failed by core shear followed immediately by debonding between the skin and the core of the topmost and bottommost sandwich layers. The core shear occurred at approximately 45° from the loading point (Fig. 4b). This type of failure was abrupt, and the debonding occurred immediately after the core shear.
- *Core shear (CS)*: The core shear failure was observed in the horizontal LSB with a shear span of 200 mm (HF-A<sub>200</sub>) and 100 mm (HA-A<sub>100</sub>). In this type of failure, a diagonal crack in the phenolic core was observed between the loading point and support as shown in Figures 4(c) and 4(g). The failure occurred instantly without providing any warning and resulted in a significant drop of the load.
- *Skin tension (ST)*: The tensile rupture of the skin started from the bottom of the vertical LSB (VF-A<sub>600</sub>, VF-A<sub>400</sub> and VF-A<sub>200</sub>) in the FPB tests. This failure was progressive, and the ultimate failure occurred when the tensile failure of the skin reached to the mid-depth of the beam (Figs. 4d, 4e and 4f). The ultimate cracking of the polymer matrix happened immediately after the tensile failure of skins. The top fibres of the skins were compressed before the ultimate failure (Fig. 4d).
- *Skin shear (SS)*: The vertical LSB under ABS test (VA-A<sub>100</sub>) failed due to the diagonal shear cracking of skins between interior support and load points as shown in Figure 4(h). This failure was progressive and occurred when the shear stress of the skin reaches its ultimate shear capacity.

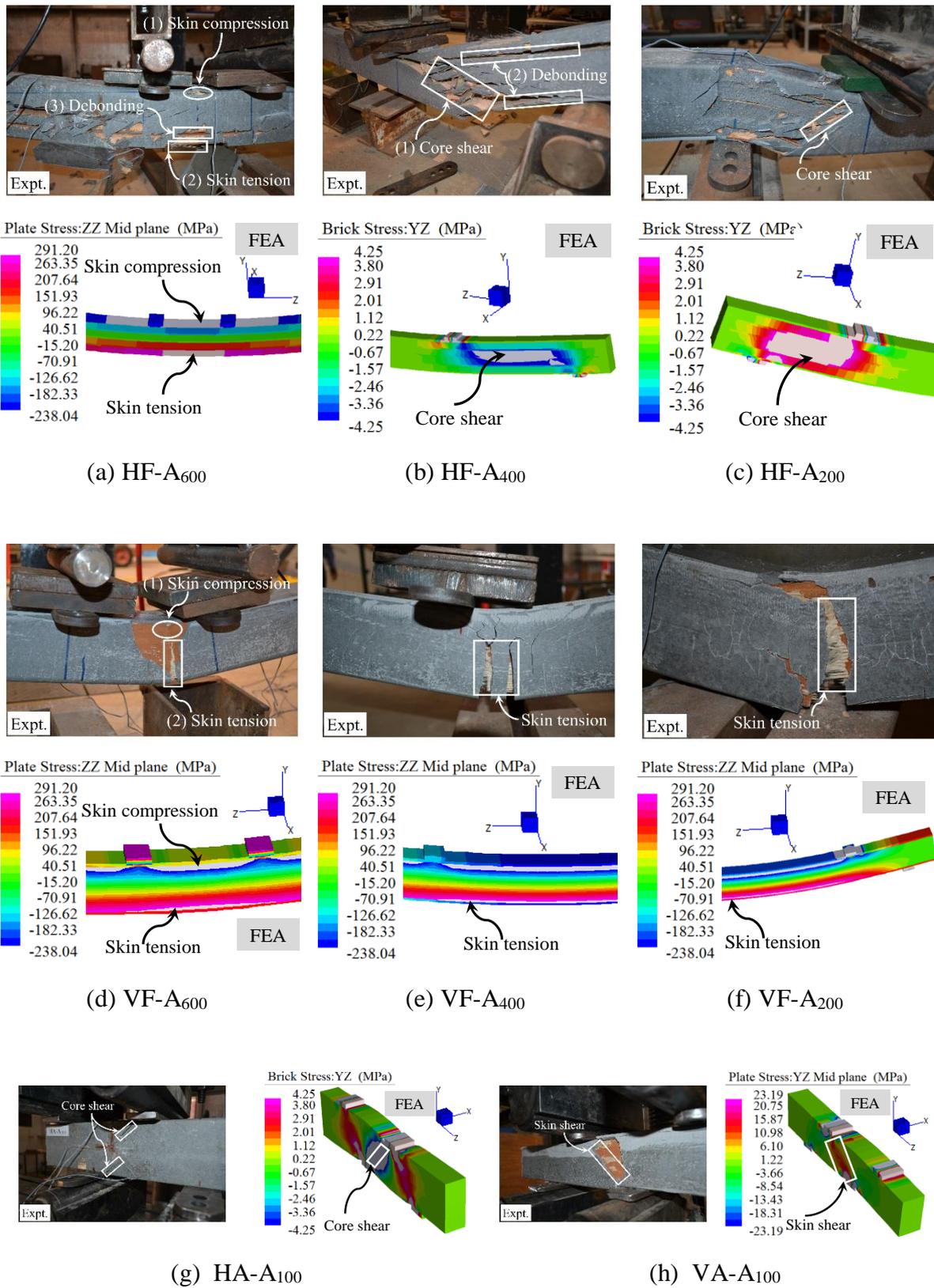


Fig. 4: Failure modes of the LSB

### 3.2. Load-displacement behaviour

The load-displacement relationship for different beams under FPB and ABS test configurations are illustrated in Figure 5(a) and Figure 5(b), respectively.

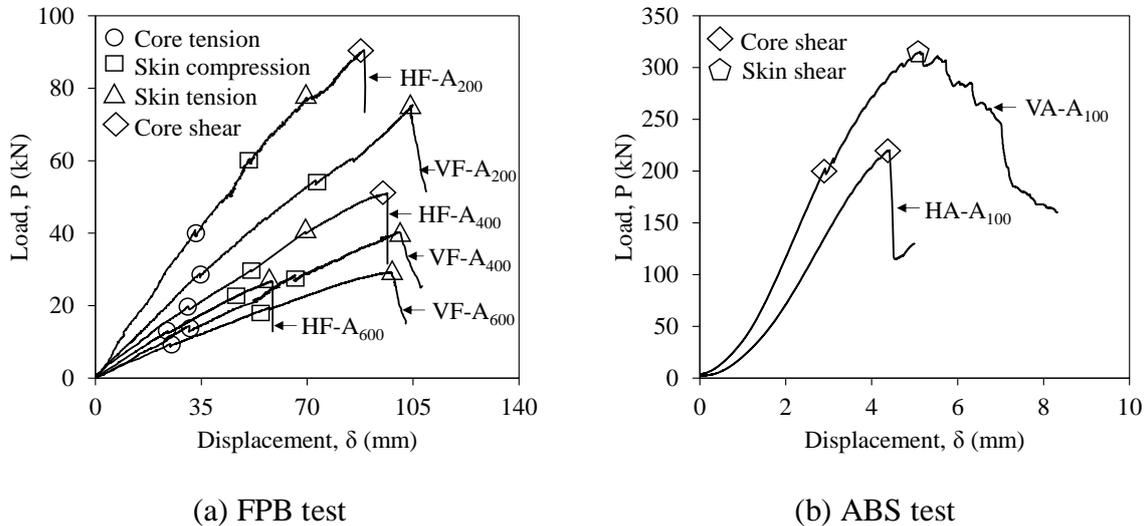


Fig. 5: Load-displacement relationship

Under FPB test condition (Fig. 5a), a slight non-linearity was observed in beams VF-A<sub>200</sub>, VF-A<sub>400</sub>, VF-A<sub>600</sub>, and HF-A<sub>600</sub> due to the small load drops caused by tensile cracking of the core followed by skin compression and finally due to skin rupture in tension and matrix cracks at the bottom. On the other hand, for HF-A<sub>200</sub> and HF-A<sub>400</sub> beams, the load-displacement curve extended with the same slope beyond the point of skin rupture in tension and ultimate drop of load observed when the core shear failure occurred. The progressive mode of failure was confirmed by the finite element simulation discussed in Section 4. The beams under FPB test as shown in Figure 5(a) demonstrated that the load at ultimate dropped suddenly for horizontal LSB (HF-A<sub>200</sub>, HF-A<sub>400</sub> and HF-A<sub>600</sub>) while for vertical LSB (VF-A<sub>200</sub>, VF-A<sub>400</sub> and VF-A<sub>600</sub>) it dropped progressively. The increase of shear span gradually decreases the load carrying capacity for both horizontal and vertical LSB. The horizontal LSB deflected less than the vertical LSB for a particular shear span at the same level of load. The lower deflection is due to the higher bending stiffness of the horizontal LSB than the vertical one due to the extreme top and bottom horizontal skins being more efficient in flexure. The HF-A<sub>600</sub> beam failed at a significantly lower displacement than the HF-A<sub>400</sub> and HF-A<sub>200</sub> beams due to the early debonding failure through the bond-line (Fig. 4a) for the former beam rather than core shear failure of the latter two beams. The inter-laminar shear stress of polymer matrix at failure was only 2.50 MPa (determined by stress analysis) for HF-A<sub>600</sub>. This indicates that the bond of

polymer matrix failed earlier than the expected failure load as the bond strength of polymer matrix and sandwich panel is 5 MPa (Ferdous et al., 2016a). On the other hand, the vertical beams VF-A<sub>600</sub>, VF-A<sub>400</sub> and VF-A<sub>200</sub> failed almost at the level of maximum displacement due to the similar mode of skin tension failure. At failure, the maximum tensile stress of the skin reaches to approximately 300 MPa (determined by stress analysis), which is consistent with the longitudinal tensile strength of the skin (Table 1).

Under ABS test (Fig. 5b), the stiffness of the vertical LSB marginally reduced after shear induced core cracking, however, the beam continued to carry the loads due to the undamaged vertical skins. When the peak load was reached, the load dropped gradually with the increase of displacement due to the progressive failure of the vertical skins (VA-A<sub>100</sub>). On the other hand, the horizontal LSB failed in a brittle manner due to the shear failure of the core (HA-A<sub>100</sub>). The vertical LSB carried 43% more load than the horizontal LSB confirming the higher load to fail the fibre composite skins in shear.

### **3.3. Load-strain behaviour**

The load-strain behaviour of the LSB are shown in Figures 6(a) to 6(h). Five strain gauges, three of them for measuring shear strain (named as vertical, horizontal and diagonal) and the other two for bending strain (named as top and bottom) were attached to the beam (Fig. 6i) under FPB test as the beams usually subjected to both shear and bending stress under this loading condition. On the other hand, only three strain gauges were attached to measure the shear strain under ABS test as shear failure is the expected failure mode under this test setup. Using the vertical, horizontal and diagonal strain readings, the actual shear strain can be determined by Eq. (1).

$$\gamma = 2\varepsilon_d - \varepsilon_v - \varepsilon_h \quad (1)$$

In Eq. (1),  $\gamma$  represents the shear strain while  $\varepsilon_d$ ,  $\varepsilon_v$  and  $\varepsilon_h$  are the measured strain in diagonal, vertical and horizontal directions, respectively. In Figure 6, Expt-C, Expt-T and Expt-S represent the experimental compressive, tensile and shear ( $\gamma$ ) strains while FEA-C, FEA-T and FEA-S represent the finite element analysis (discussed later) of compressive, tensile and shear strains, respectively.

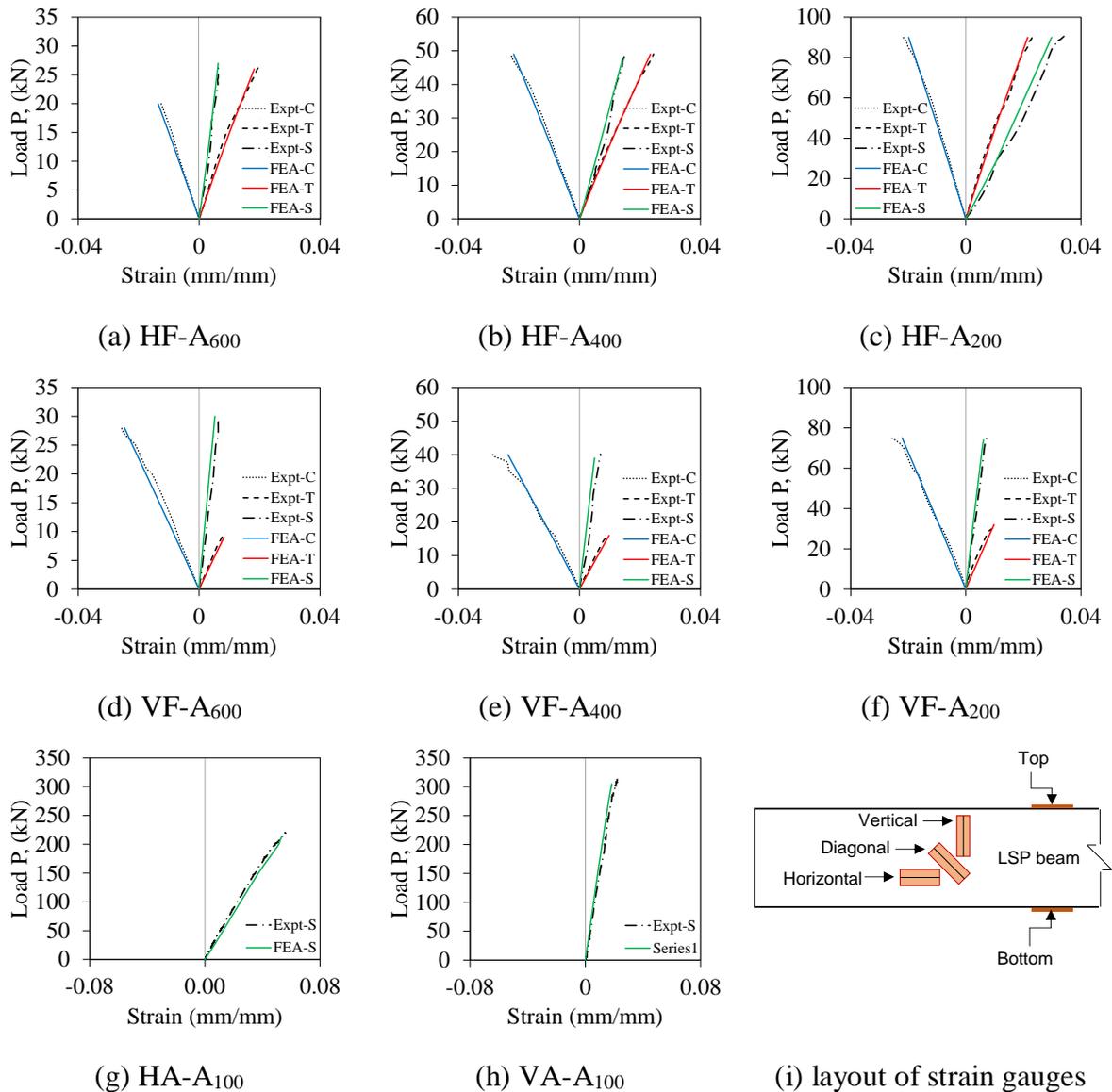


Fig. 6: Load vs. strain behaviour

Figures 6(a) to 6(f) show that all the load-strain relationship increases linearly up to approximately 40% of the ultimate load, and the behaviour becomes slightly nonlinear thereafter. At 40% level of ultimate load, the tensile strain (Expt-T) was approximately 0.007 mm/mm that indicates a strain of 0.006 mm/mm at the bottom of the core considering the 5 mm polymer matrix cover underneath. This level of strain is similar to the failure strain of the phenolic core in tension as reported in Table 1. The top strain gauge (Expt-C) was broken at around 20 kN load for HF-A<sub>600</sub> beam (Fig. 6a), however, all the strain gauges for HF-A<sub>400</sub> and HF-A<sub>200</sub> beams recorded the strain value up to the maximum load (Figs. 6b and 6c). At 20 kN load, the compressive strain at the top skin of HF-A<sub>600</sub> reached 0.011 mm/mm which is close to the failure strain of the skin compression (Table 1). The shear strain (Expt-S) of the outside

polymer matrix of HF-A<sub>400</sub> and HF-A<sub>200</sub> beams attained 0.014 mm/mm and 0.032 mm/mm respectively, that causes the shear failure of the inside core. On the other hand, all the bottom strain gauges (Expt-T) were broken at approximately 10 kN, 15 kN and 30 kN loads for VF-A<sub>600</sub>, VF-A<sub>400</sub> and VF-A<sub>200</sub> beams, respectively, due to the tensile cracking of the polymer coating (Figs. 6d, 6e and 6f). Figures 6(g) and 6(h) illustrate the shear strain for HA-A<sub>100</sub> and VA-A<sub>100</sub> beams under ABS loading configuration. The high failure load of HA-A<sub>100</sub> and VA-A<sub>100</sub> beams increases the ultimate shear strain. The fairly linear load-strain curve indicates that the behaviour of the LSB is mainly controlled by the high strength skins which behave linear elastic up to failure. However, the strain measured on the beam surface does not represent the actual strain of the inside sandwich panels. For a better understanding of the inside strain behaviour, the next section discusses the finite element analysis of the beams.

#### **4. Finite element analysis (FEA)**

Finite element analysis was conducted for a better understanding of the behaviour of LSB, particularly the behaviour inside the beam as the sandwich panels were not visible during loading due to the polymer coating. The FEA was implemented using the Strand7 commercial software (Strand7, 2010). The polymer matrix, phenolic core, loading plate and supports were modelled as three-dimensional eight-node brick element while the skins of the sandwich panel were created as plate element. Figure 7 shows the stress-strain model for the GFRP skin (Manalo et al., 2012b), phenolic core (Manalo et al., 2012b) and polymer matrix (Ferdous et al., 2016c) used in the FEA. The shear failure of the beam was considered when any component of the beam exceeds the ultimate shear strength. The different properties of GFRP skins in longitudinal and transverse directions suggested to consider an orthotropic material behaviour. A perfect bond between sandwich panel and polymer matrix was assumed in the model as no bond failure was observed during the experiment. The failure of the specimen was based on the maximum stress yield criterion. The selected stress limit help to understand the failure of the model once it exceeds the maximum allowable stresses. Figure 8 provides an overview of the horizontal and vertical LSB models under different loading conditions, together with the X, Y, and Z coordinate system. In order to reduce the computation time, a general size mesh for the element with an aspect ratio of 1 in Y-Z plane was adopted. Only half model was created (50% in the X-direction, i.e., Y-Z plane symmetry) for the FEA as the other half was symmetric. Therefore, symmetric boundary conditions were applied in Y-Z plane indicating all the nodes at the mid-plane section were restrained from translating in the X-direction and rotating in the Y- and Z- directions. To simulate the simply supported boundary condition, the

translational displacement of the supports were restrained in X- and Y-directions and the rotational displacement were restrained in Y- and Z-directions. The tensile and compressive strains were determined from the topmost and bottommost element in the direction of ZZ at the point of maximum displacement. On the other hand, the maximum shear strain was measured from the element located at 45° line drawn from the load point towards the support in YZ plane. The nonlinear analysis of the finite element model was implemented considering the material non-linearity. The feasibility and accuracy of the finite element model were verified by comparing the FEA predictions with the experimental results. This comparison was made on the failure mode, the initial slope of the load and displacement curve, ultimate load and the load-strain behaviour.

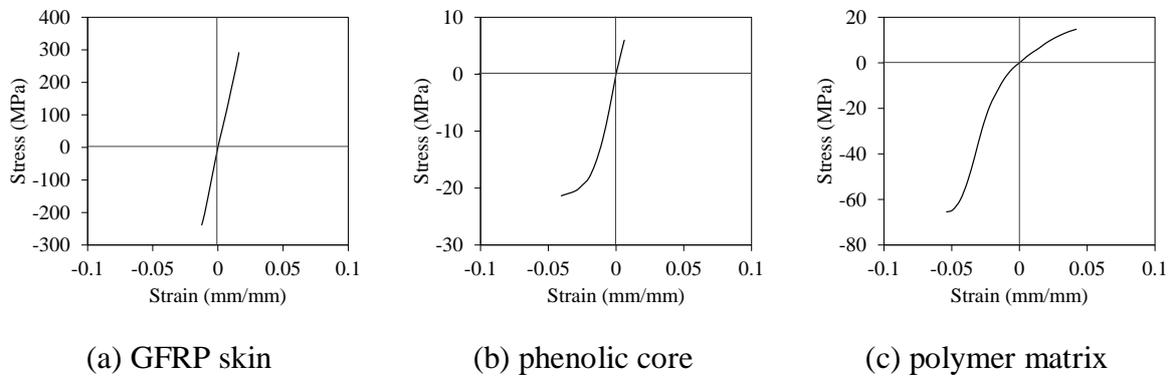


Fig. 7: Stress-strain behaviour of the constituent materials

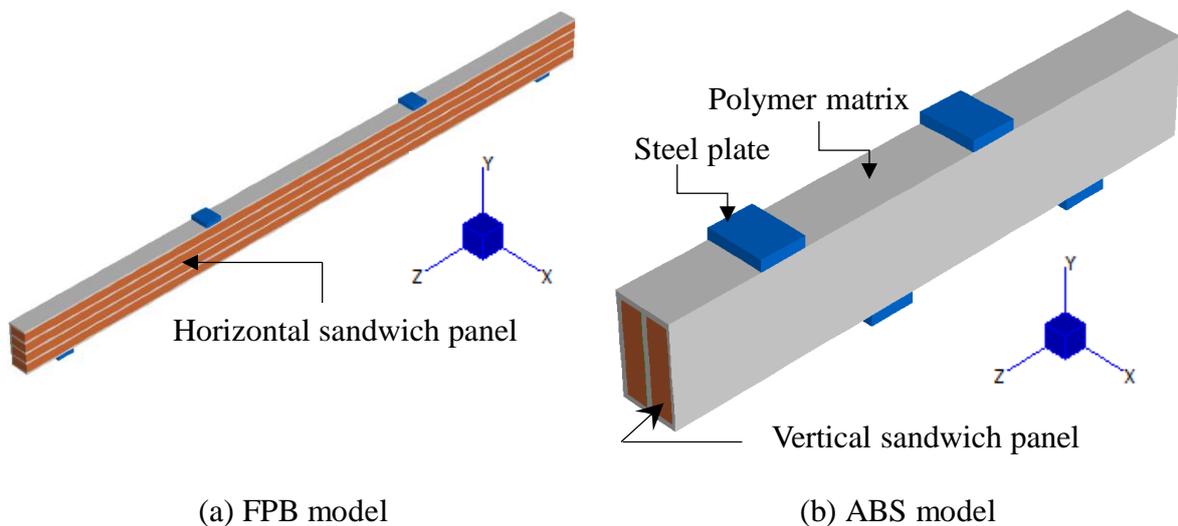
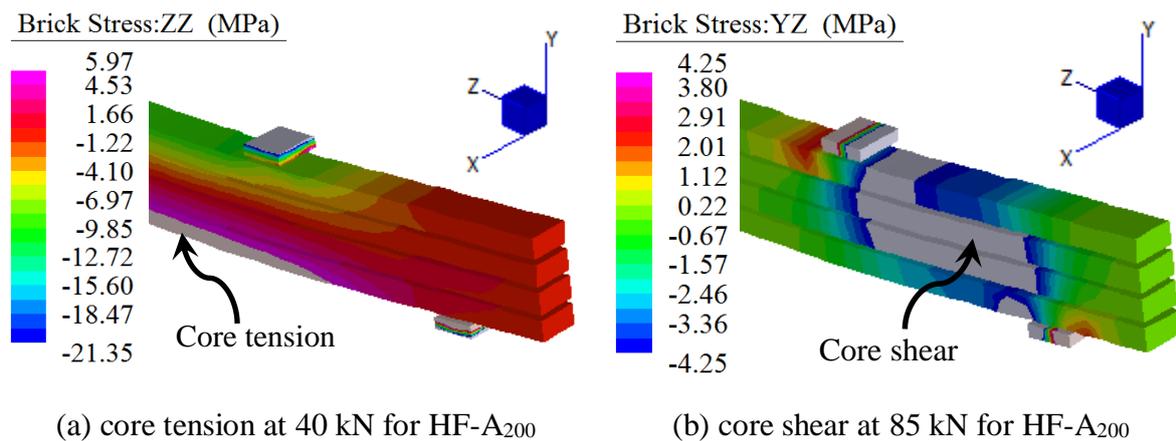
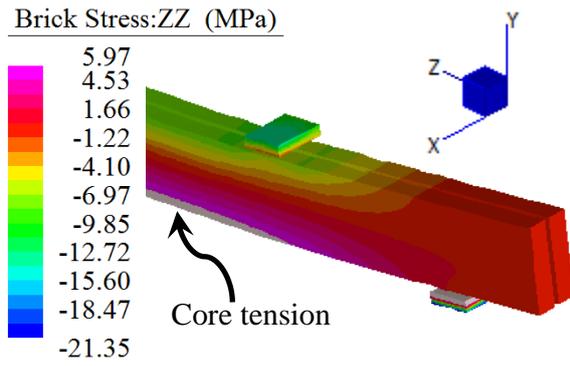


Fig. 8: Finite element model of the horizontal and vertical LSB (Half model)

#### 4.1. Behaviour of the sandwich core

The failure progression in the sandwich core was confirmed by the finite element simulation. Figure 9 shows the progression of sandwich core failure of the HF-A<sub>200</sub> and VF-A<sub>200</sub> beams. The comparison between the predicted and experimentally observed load and corresponding strain at which failure was observed in the core is provided in Table 4. The results of the finite element simulation show that the bottom of the core was cracked at 40 kN (Figs. 9a) and finally the ultimate failure due to core shear occur at 85 kN (Figs. 9b) for HF-A<sub>200</sub> beam. The tensile stress of the core attained to the allowable limit at 40 kN load (Fig. 9a) while the maximum tensile strain of the core at that level of load also reached to the allowable tensile strain limit of 0.0061 (Table 4). The shear stress (Fig. 9b) and shear strain (Table 4) of the core exceeded the allowable limit at 85 kN. The experimental investigation of the load-displacement behaviour on HF-A<sub>200</sub> beam (Fig. 5a) showed the drop of the load at 40 kN and 91 kN due to core tension and core shear, respectively. On the other hand, at 26 kN load, the tensile stress (Fig. 9c) and strain (Table 4) exceeded the allowable limit for VF-A<sub>200</sub> beam that is also reflected in Figure 5(a). The results in Table 4 showed that the failure modes and failure loads of the finite element prediction agrees well with the experimental observation. However, the debonding failure observed in some of the beams (Figs. 4a and 4b) was not captured in the finite element simulation as this type of failure is a consequence of the major failure in the beam. For example, the debonding in Figure 4(b) was observed immediately after the beam failed in core shear.





(c) core tension at 26 kN for VF-A<sub>200</sub>

Fig. 9: Sandwich core failure of HF-A<sub>200</sub> and VF-A<sub>200</sub> beams at different load levels

Table 4: Failure load and strain behaviour of the sandwich core

Beam identity	Core tension			Core shear		
	Expt.	FEA		Expt.	FEA	
	Load (kN)	Load (kN)	Strain (mm/mm)	Load (kN)	Load (kN)	Strain (mm/mm)
HF-A <sub>600</sub>	13	14	0.0065	-	-	-
VF-A <sub>600</sub>	9	10	0.0066	-	-	-
HF-A <sub>400</sub>	20	19	0.0062	51	53	0.0082
VF-A <sub>400</sub>	14	15	0.0063	-	-	-
HF-A <sub>200</sub>	40	40	0.0063	91	85	0.0083
VF-A <sub>200</sub>	28	26	0.0062	-	-	-
HA-A <sub>100</sub>	-	-	-	220	213	0.0085
VA-A <sub>100</sub>	-	-	-	205	200	0.0082

#### 4.2. Behaviour of the sandwich skins

The finite element model satisfactorily captured the skin compression (Figs. 4a and 4d), skin tension (Figs. 4a, 4d, 4e and 4f) and skin shear (Fig. 4h) failure as shown in Figure 10. The predicted and experimentally failure load of the skin for different beams are compared in Table 5, and the level of strain is also predicted at the skin failure load. The progression of the skin failure of HF-A<sub>200</sub> beam shows that the compressive stress (Fig. 10a) and strain (Table 5) exceeded the allowable limit at 63 kN load while the tensile stress (Fig. 10b) and strain (Table 5) attained to the allowable limit at 80 kN load. In vertical orientation, the skins of the VF-A<sub>200</sub> beam reached to the allowable compressive stress (Fig. 10c) and strain (Table 5) limit at 58

kN, and tensile stress (Fig. 10d) and strain (Table 5) limit at 74 kN load. The results in Table 5 shows that the finite element simulation reasonably predicts the experimental failure loads of the skin at compression, shear and tension. Moreover, the compressive and tensile strain of the skin attains to the allowable limit of 0.0124 mm/mm and 0.0161 mm/mm, respectively at the failure load. The predicted skin shear failure load of the VA-A<sub>100</sub> beam is close to the experimental skin shear failure load as shown in Figure 5(b), however, the shear strain predicted at this load level (Table 5) is lower than the ultimate shear strain of 0.0308 mm/mm. This is due to the nonlinear shear stress-strain relationship of skins (Manalo et al., 2012b) where the shear stress of skin can reach to the ultimate stress level even at a low shear strain. The strength and stiffness of the LSB are highly influenced by the skin properties. The beam stiffness determined from the slope of the linear elastic part of the load-displacement curve from the experimental results and finite element simulation are tabulated in Table 3. The formation of voids in the polymer matrix and the slight imperfection of the panel alignment during casting may cause the little variation between experimental results and finite element simulation. From Table 3, it can be seen that the finite element simulation predicted the experimental failure loads within the range of -3% to +14% and the slope within +2% to +10%.

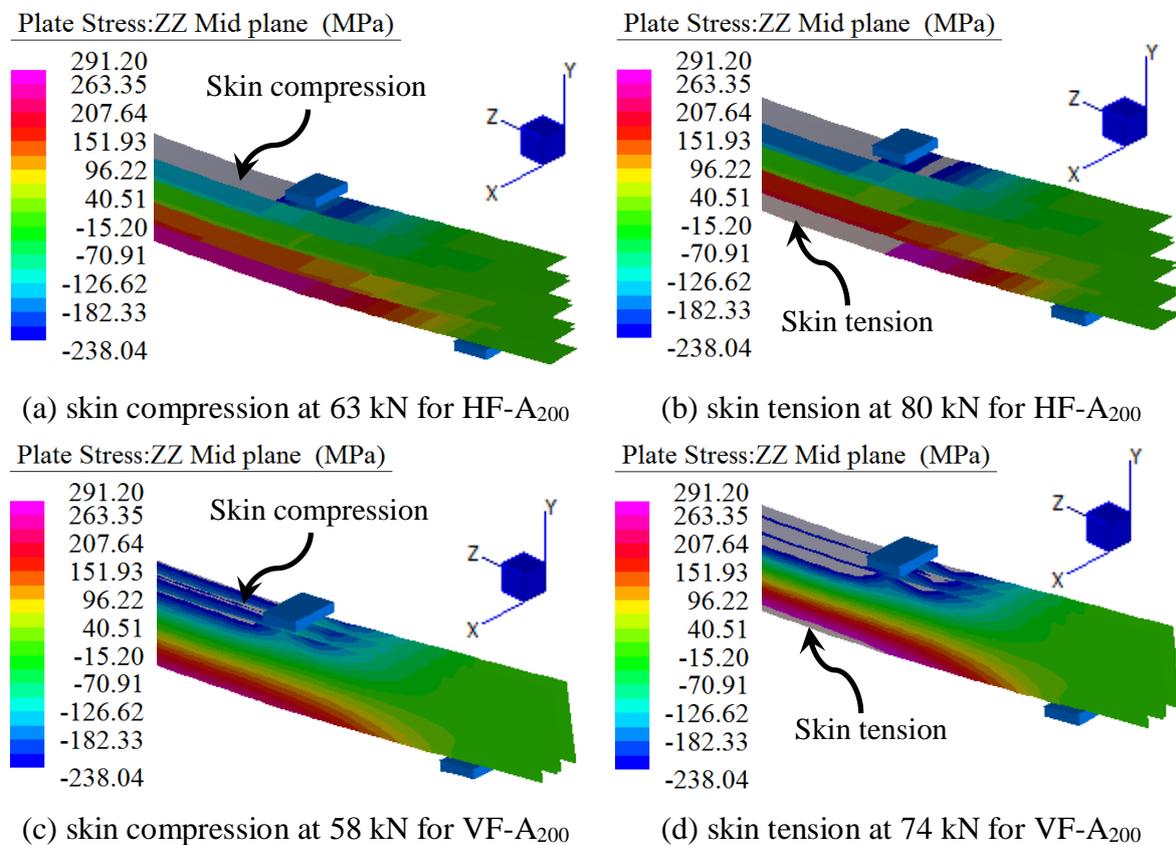


Fig. 10: Sandwich skin failure of HF-A<sub>200</sub> and VF-A<sub>200</sub> beams at different load levels

Table 5: Failure load and strain behaviour of the sandwich skins

Beam identity	Skin compression (kN)			Skin shear (kN)			Skin tension (kN)		
	Expt.	FEA		Expt.	FEA		Expt.	FEA	
	Load (kN)	Load (kN)	Strain	Load (kN)	Load (kN)	Strain	Load (kN)	Load (kN)	Strain
HF-A <sub>600</sub>	23	24	0.0138	-	-	-	28	32	0.0174
VF-A <sub>600</sub>	19	20	0.0128	-	-	-	29	26	0.0176
HF-A <sub>400</sub>	30	33	0.0133	-	-	-	40	46	0.0175
VF-A <sub>400</sub>	28	30	0.0131	-	-	-	40	38	0.0178
HF-A <sub>200</sub>	60	63	0.0135	-	-	-	77	80	0.0166
VF-A <sub>200</sub>	54	58	0.0127	-	-	-	76	74	0.0165
HA-A <sub>100</sub>	-	-	-	-	-	-	-	-	-
VA-A <sub>100</sub>	-	-	-	315	305	0.0189	-	-	-

### 4.3. Behaviour of the polymer matrix

The finite element simulation showed an interesting behaviour of the polymer matrix. At the experimental failure load of the LSB, the failure was observed in the polymer matrix coating. However, none of the polymer matrix coating failed in finite element simulation except HA-A<sub>100</sub>. This indicates that the observed failure of the matrix during the experiment is triggered by either the skin or core failure. At ultimate load, Figure 11(a) and 11(b) shows the bending and shear stress of the polymer matrix for horizontal beam (HF-A<sub>200</sub>) while the same for vertical beam are shown in Figure 11(c) and 11(d). The allowable tensile, compressive and shear strength of the polymer matrix are 14.74 MPa, 65.46 MPa and 4.90 MPa, respectively. The finite element results in Table 6 indicated that the tensile and compressive stresses of the polymer matrix at the ultimate failure load are well below than the allowable limit. In addition, the tensile and compressive strains at the failure load are lower than the allowable tensile and compressive strain limits of 0.0419 mm/mm and 0.0538 mm/mm, respectively. The shear stress of the polymer coating in HA-A<sub>100</sub> beam (Table 6) is only exceeded the shear strength which is reflected in Figure 4(g) as the diagonal shear crack appeared in polymer coating for this beam. Therefore, the failure of the polymer matrix in other experimental beams was due to the consequent of sandwich panel failure. This indicates the polymer matrix are flexible enough to ensure the failure in the main structural components for the efficient utilisation of the strength

of sandwich panels. Moreover, the intact polymer matrix can contribute to improve the structural performance of the LSB.

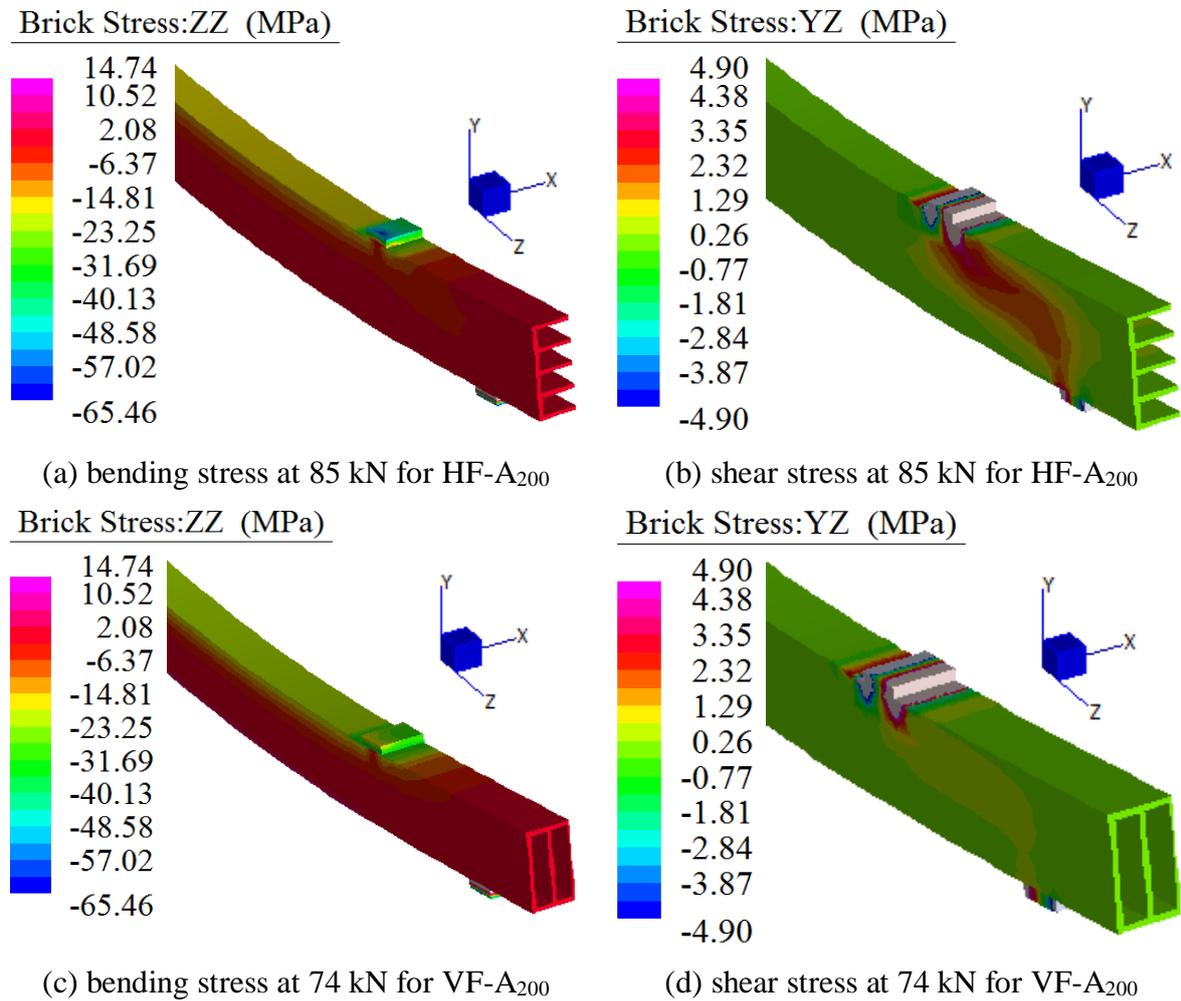


Fig. 11: Stresses in polymer matrix of HF-A<sub>200</sub> and VF-A<sub>200</sub> beams at ultimate failure load

Table 6: Stress and strain behaviour of the polymer matrix at ultimate failure load (FEA)

Beam identity	Ultimate failure load (kN)	Tensile behaviour		Compressive behaviour		Shear behaviour	
		Stress (MPa)	Strain	Stress (MPa)	Strain	Stress (MPa)	Strain
HF-A <sub>600</sub>	32	2.67	0.0227	19.55	0.0222	0.73	0.0072
VF-A <sub>600</sub>	26	3.99	0.0251	20.95	0.0229	1.23	0.0045
HF-A <sub>400</sub>	53	4.19	0.0255	21.93	0.0235	1.22	0.0151
VF-A <sub>400</sub>	38	3.59	0.0244	20.01	0.0224	1.26	0.0049
HF-A <sub>200</sub>	85	1.56	0.0202	15.23	0.0187	4.03	0.0270
VF-A <sub>200</sub>	74	2.83	0.0237	18.07	0.0218	1.47	0.0062
HA-A <sub>100</sub>	213	0.29	0.0106	21.11	0.0226	5.10	0.0535
VA-A <sub>100</sub>	305	0.30	0.0114	4.27	0.0077	2.35	0.0184

In general, it can be concluded that the developed finite element model is reliable in predicting the fundamental behaviour of the LSB at different orientations.

## 5. Discussion

### 5.1. Effect of shear span-to-depth ratio

The influence of  $a/d$  ratio on the bending stiffness, bending stress and shear stress of the horizontal and vertical LSB are presented in Figure 12 and determined by Eq. (2), Eq. (3) and Eq. (4), respectively.

$$EI = \frac{a}{48} (3L^2 - 4a^2) \left( \frac{\Delta P}{\Delta \delta} \right) \quad (2)$$

$$\sigma_s = \frac{M(d/2)}{EI} E_s \quad (3)$$

$$\tau = \frac{P/2}{A_{eq}} \quad (4)$$

In Eq. (2),  $EI$  is the bending stiffness of the beam. The shear span  $a$ , span of the beam  $L$ , and the slope of the load-displacement curve  $\Delta P/\Delta \delta$  are provided in Table 3 and Figure 3(a). In Eq. (3), the bending stress of the skin  $\sigma_s$ , bending moment  $M$ , depth of the beam  $d$  and  $E_s$  is the elastic modulus of the skin. In Eq. (4), the shear stress  $\tau$ , applied load  $P$ , and the equivalent shear area of the beam  $A_{eq}$ . The equivalent shear area for horizontal LSB is determined by transforming the skin and polymer matrix into an equivalent core using the shear moduli ratio. On the other hand, the core and polymer matrix was transformed into an equivalent skin area

for vertical LSB (Manalo et al., 2010c). This is because the shear stress is carried by the sandwich core for horizontal LSB while it is carried by the sandwich skins for vertical LSB.

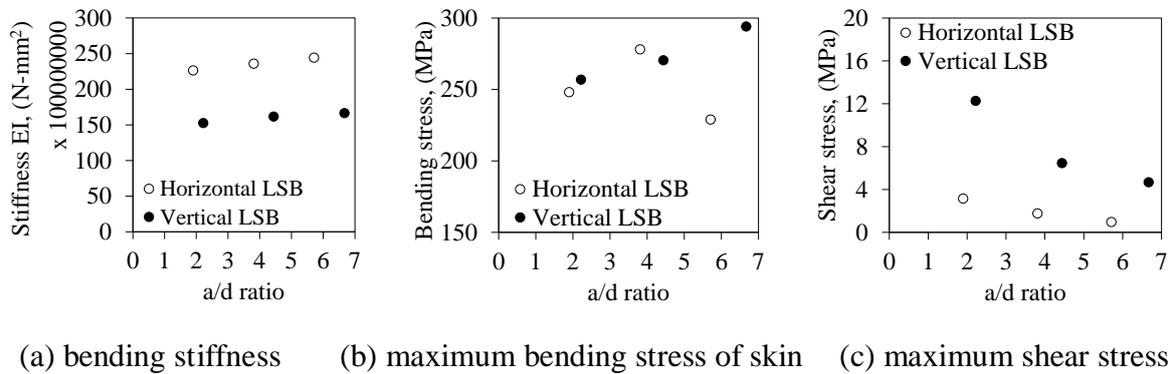


Fig. 12: Effect of  $a/d$  ratio on bending stiffness, bending stress and shear stress

Figure 12(a) shows the variation of bending stiffness calculated from Eq. (2) with the increase of  $a/d$  ratio for both horizontal and vertical LSB tested under FPB loading configuration. It is shown that the bending stiffness slightly increases with the increase of  $a/d$  ratio for a particular LSB orientation. The slight increase of bending stiffness with the increase of  $a/d$  ratio can be attributed to the lower shear deformation of the beam at higher  $a/d$  ratio. However, the shear deformation of the beam is only minor when  $a/d \geq 4$  as the beam is subjected to bending load. The experimental bending stiffness (Fig. 12a) determined from Eq. (2) is 10% lower than the theoretical bending stiffness estimated by Eq. (5). The slightly lower actual bending stiffness can be attributed to the unintentional manufacturing imperfections in maintaining the perfect panel orientations and the small voids in the polymer matrix.

$$EI = \sum(E_m I_m + E_s I_s + E_c I_c) \quad (5)$$

In Eq. (5),  $E_m$ ,  $E_s$  and  $E_c$  are the elastic modulus and  $I_m$ ,  $I_s$  and  $I_c$  are the second moment of inertia of the polymer matrix, skin and core of the sandwich panel, respectively.

The modes of failure are influenced by the  $a/d$  ratio. Table 3 shows that the horizontal LSB were failed in shear (core shear), a combined shear and bending (core shear and debonding), and bending (skin tension and debonding) for  $a/d \leq 2$ ,  $2 < a/d < 4$  and  $a/d \geq 4$ , respectively. On the other hand, the vertical LSB were failed in shear (skin shear), and bending (skin tension) for  $a/d \leq 1$ , and  $a/d \geq 2$ , respectively. In contrast, the investigation on the single sandwich panel has shown that the horizontal and vertical panels will fail in shear, a combined shear and bending, and bending for  $a/d \leq 2$ ,  $2 < a/d < 6$ , and  $a/d \geq 6$ , respectively (Ferdous et

al., 2017). This indicates that the binding of sandwich panels using polymer matrix improves the shear capacity that induced bending dominated failure comparing with single sandwich beams. The shear capacity of the LSB is improved by preventing skin wrinkling and skin buckling failure that was observed in single sandwich panels at  $a/d \geq 6$  (Ferdous et al., 2017). On the other hand, the unwanted indentation failure due to local compression in vertically oriented single sandwich panels at  $a/d \leq 2$  (Ferdous et al., 2017) can be eliminated using LSB concept. Gdoutos et al. (Gdoutos et al., 2002) indicated that the indentation failure is a serious problem in foam-core sandwich construction. This implies that the polymer coated LSB can distribute the local loads more uniformly and increase the sectional stability than the single sandwich panel. In glue laminated beams, Manalo et al. (Manalo et al., 2010b) observed the inner skins of sandwich panel failed at a higher load than the outer skins due to the lateral supports of the neighbouring panels. However, the early failure of the unprotected outer skins reduces the sectional stability in glue-laminated beams.

Figure 12(b) shows that the maximum bending stress of the skin for horizontal LSB is increased for  $a/d$  ratio up to 4 and significantly decreased at  $a/d$  of 6. The significant drop of maximum bending stress at  $a/d$  of 6 is due to the debonding failure of the polymer matrix. Awad et al. (Awad et al., 2012) also observed the reduction of bending and shear capacity of the horizontal glue-laminated beams comparing with single sandwich beams due to the debonding effect within the interim layers. This indicates that careful attention should be given during casting of the polymer matrix to prevent debonding failure of bond-line and ensure that full composite action is achieved for horizontal LSB. The thicker bond-line (5 mm) of polymer matrix has a greater influence on the failure behaviour of LSB than the thinner epoxy bond in glue-laminated beams. Therefore, the analysis of glue laminated beams may ignore the contribution of thinner glue-lines (Manalo and Aravinthan, 2012, Awad et al., 2012) while the contribution of thicker bond-lines cannot be ignored for LSB. On the other hand, the maximum bending stress increases with the increase of  $a/d$  ratio for vertical LSB indicating the uniform transfer of stress within the panels. The study conducted by Manalo and Aravinthan (Manalo and Aravinthan, 2012) on glue-laminated sandwich beams has shown that the vertically laminated sandwich specimens failed in skin buckling at  $a/d$  ratio of 5.33. Mathieson and Fam (Mathieson and Fam, 2016) observed that the buckling of skin in the sandwich beam arises before the skin reaches to its ultimate strength that reduced the sectional stability of the sandwich beams. However, the stress analysis of the vertical LSB at  $a/d$  ratio of 6.67 shows that (Fig. 12b) the maximum bending stress of the skins reaches to 294 MPa which is similar

to the tensile strength of the skin (Table 1) while the single sandwich beam achieved 210 MPa only (Ferdous et al., 2017). This implies the full strength of the skin can be utilised effectively in the LSB concept at a vertical orientation, indicating a better structural integrity that provided superior composite action.

Figure 12(c) shows the variation of maximum shear stress in vertical and horizontal LSB with the  $a/d$  ratio. The shear stress decreases with the increase of  $a/d$  ratio, and the vertical LSB provided better shear resistance than the horizontal one at a particular  $a/d$  ratio. The LSB concept utilised the shear strength of the constituent materials more efficiently than the single sandwich beam. For example, at  $a/d$  ratio of 2, the horizontal LSB utilised 74% of core shear strength and vertical LSB utilised 53% of the skin shear strength while the single sandwich beam (Ferdous et al., 2017) in horizontal and vertical orientations utilised only 59% and 35% of the corresponding strength, respectively. The polymer matrix in the LSB system plays an important role in improving shear capacity by preventing the premature skin wrinkling, skin buckling and indentation failure.

## **5.2. Effect of LSB orientation**

The failure modes of the horizontal LSB is brittle while that of the vertical LSB is progressive. The brittle and progressive nature of failure was also observed in single (Ferdous et al., 2017) and glue-laminated (Manalo and Aravinthan, 2012) sandwich beams, however, the polymer matrix of the LSB prevents the shear failure in vertical orientation under the same loading condition. Moreover, the polymer coating improves the load carrying capacity of the vertical LSB by utilising the full-strength capacity of the material and completely preventing the skin buckling failure which cannot be even prevented by wrapping the glue-laminated sandwich beams with one-layer of triaxial glass fibre composite wraps. The horizontal LSB under FPB test failed in bending (ST+D), combined shear and bending (CS+D), and shear (CS) while all the vertical LSB with the same test setup were failed in bending (ST) at shear spans of 600 mm, 400 mm and 200 mm, respectively. This indicates the vertical LSB is strong in shear due to the high shear strength of the fibre composite skins which prevented the shear failure of the core even at the low shear span. However, both horizontal (CS) and vertical (SS) LSB failed in shear under ABS test at the shear span of 100 mm.

From Figure 5(a), it can be seen that the horizontal LSB generally failed at higher loads than the vertical LSB at the same shear span when tested under bending. In horizontal LSB, the horizontal layer of skins provided greater resistance to bending due to the larger moment

arm of the skins from the neutral axis. Moreover, the horizontal LSB failed at 74%, 42% and 23% of the core shear strength while the vertical LSB failed at 53%, 28% and 20% of the skin shear strength for 200 mm, 400 mm and 600 mm shear span, respectively. Under ABS, the vertical LSB failed at higher loads than the horizontally layered panels (Fig. 5b) due to the higher shear resistance provided by the vertical skins than the phenolic core. For better understanding the effectiveness of polymer matrix in binding the sandwich panels, Figure 13 compares the strength and stiffness of the single, glue-laminated and LSB.

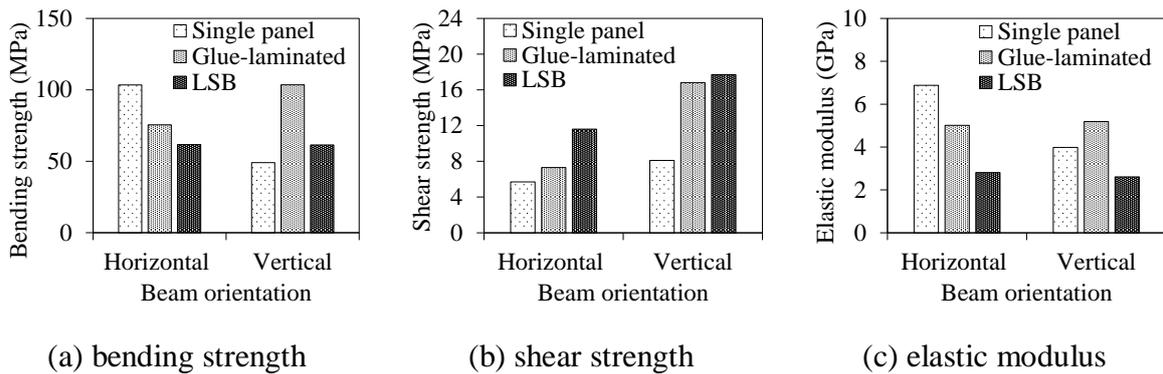


Fig. 13: Strength and stiffness of the single (Ferdous et al., 2017), glue-laminated (Manalo and Aravinthan, 2012) and LSB

Figure 13(a) shows the bending strength of the single sandwich, glue-laminated and LSB in both horizontal and vertical orientations. It can be seen that the bending strength of the LSB decreased by 40% from the strength of the single panel at a horizontal orientation. This is due to the bond failure of the bonded specimens under high bending that cannot utilise the full strength of the sandwich panels. However, in a vertical orientation, binding the sandwich panels using polymer matrix increased the bending strength by 25% from the strength of the single panel. Binding the panels together prevent the premature skin buckling failure under high bending that explains why the strength increased in vertical orientation. However, the glue-laminated beams provided greater bending strength than the LSB in both orientations. This indicates the thinner epoxy bond in the glue-laminated beam is more effective for structural integrity than the thicker polymer bond in LSB system under bending.

Figure 13(b) compares the shear strength of the single sandwich, glue-laminated and LSB in horizontal and vertical orientations. The shear strength of the LSB increased by 100% from the strength of the single panel in both orientations. The local compression in the single sandwich panel under high shear load causes indentation failure, particularly at vertical

orientation (Ferdous et al., 2017). Through an experimental investigation, Xie et al. (Xie et al., 2011) observed that the indentation significantly reduces the load bearing capacity of the sandwich beams. The glue-laminated beam minimised the unwanted indentation failure (Manalo and Aravinthan, 2012) while the LSB completely prevented it by distributing the local loads due to the presence of outside polymer coating. The polymer coating is not only better in distributing loads but also attractive from the architectural viewpoint and serve as a protective cover for sandwich panels. The latter one is particularly important for improving the durability of structures from the ingress of moisture, chemicals or other adverse weathering action such as ultraviolet radiation. However, the higher shear strength of the LSB compared to the glue-laminated one has suggested that the binding of sandwich panels with polymer matrix are more efficient if the structure is subjected to a high shear load. Using the same amount of material, the vertical orientation of the LSB increased the shear strength by 50% than the horizontal position.

Figure 13(c) compares the effective elastic modulus of the beams at different orientations. The effective elastic modulus of the LSB decreased by 60% in a horizontal orientation and by 35% in a vertical orientation from the modulus of the single sandwich beam. Moreover, the effective elastic modulus of the LSB is even lower than the glue-laminated beams. The reduction of the effective elastic modulus of LSB from the single and glue-laminated sandwich beams is due to the presence of low modulus polymer matrix. The effective elastic modulus of the horizontal and vertical LSB are 2.81 GPa and 2.61 GPa, respectively, calculated by assuming the LSB as a solid homogeneous section with perfect bonding (Manalo and Aravinthan, 2012), indicating that the vertical LSB provided 7% lower elastic modulus than the horizontal LSB. Figure 5(a) shows that the horizontal LSB deflected less than the vertical ones at the same level of load and same shear span due to the higher bending stiffness. The position of the skins plays an important role for the bending stiffness as the elastic modulus of the skin is significantly greater than the other components of the beam as reported in Table 1 and Table 2.

## 6. Conclusions

This paper investigated the flexural and shear behaviour of a new type of composite beams manufactured from sandwich panels and bonded together with epoxy polymer matrix. The effects of the panel orientations and shear span-to-depth ratios were examined. A finite element model was also developed to better understand the fundamental behaviour of the beams. The nature of the failure, load carrying capacity and deflection behaviour were systematically investigated from which the following conclusions are drawn:

- Careful consideration in the casting process is critical to achieve the full structural integrity and composite action of the LSB. Aside from the horizontally layered beam with a shear span-to-depth ratio of 5.71, there was no bond failure observed for all the tested LSB.
- The polymer coating prevented the wrinkling and buckling of the fibre composite skins of the sandwich layers. Similarly, indentation failure in the phenolic core for vertically layered beams was eliminated. This increased the bending strength and the shear strength of the vertical LSB by as much as 25% and 100%, respectively compared to single sandwich beams.
- The failure of the horizontal LSB is mostly governed by the shear strength of the core while for vertical LSB the failure is governed by the shear strength of the skin. The failure of the core and skin promoted the failure in the matrix.
- Using the same amount of material, the vertical LSB can maintain the same bending strength, increase the shear strength by 50% but decrease the effective modulus of elasticity by 7% than the horizontal LSB.
- Consideration of the material nonlinearity in the finite element model reliably predicts the fundamental behaviour of the LSB at different orientations and loading conditions. The failure modes, failure loads and strain behaviour from the finite element simulation are in good agreement with the experimental results.

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### *Performance of a novel railway sleeper*

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The satisfactory performance of layered sandwich beams in *Study 3* motivated to manufacture and evaluate the performance of railway sleeper using this concept. Therefore, the optimal design, analysis and performance of the innovative sleeper technology was investigated in *Study 4* to increase the confidence in practical application.

#### **Article VII: Evaluation of an innovative composite railway sleeper for a narrow-gauge track under static load**

The evaluation of the overall behaviour of new sleeper technology is crucial to its safe and efficient use for railway sleeper application. *Article VII* evaluated the performance of an innovative composite railway sleeper for a narrow-gauge railway track manufactured from sandwich panels bonded with epoxy polymer matrix. Moreover, the performance of heavy-duty sleepers is numerically evaluated in *Appendix A*. The optimal shape of sleeper under quasi-static load was obtained using topology optimisation and the performance was evaluated under low- and high-stiffness support conditions. The results showed that the optimal sleeper shape requires only 50% volume of materials compared to a standard rectangular timber sleeper. Moreover, regardless of the support conditions, the composite sleepers comply with the allowable vertical deflection of 6.35 mm and sleeper-ballast pressure of 750 kPa. The rail seat and centre bending moment, shear strength, screw holding capacity, and electrical resistance of these composite sleepers are higher than the traditional hardwood timber and exceed considerably the performance requirements for a railway sleeper. The handling, installing and fastening system of the composite sleeper is similar to timber and requires the same equipment and machineries. A total of 50 sleepers have been installed on a trial basis in the Southern line rail track at Nobby, Queensland to investigate the in-track performance of the innovative composite sleeper as a replacement of timber sleeper. The in-track sleepers are performing very well and are expected to outperform its design life. Future studies that will lead to the better understanding of the long-term behaviour of composite railway sleepers including fatigue as well as the development of design guidelines and specifications are recommended for a widespread application of the composite sandwich beam bonded with epoxy polymer matrix for railway sleeper applications.

# Evaluation of an innovative composite railway sleeper for a narrow-gauge track under static load

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## Abstract

This paper introduced an innovative composite railway sleeper with an optimal material usage for a narrow-gauge railway track under static loading condition. The composite sleeper is designed using sandwich panels which were bonded and coated with epoxy polymer matrix. The sleeper's optimised shape was obtained using topology optimisation. The vertical deflection and sleeper-ballast contact pressure of the optimised sleeper were analysed by finite element simulation and compared with a traditional timber sleeper. Prototype sleepers were then manufactured and their performance was evaluated experimentally. Results showed that the optimal sleeper shape only needs 50% volume of materials required for a standard rectangular timber sleeper. The performance of the optimal sleeper satisfactorily met the Australian standard requirements and was very similar to a timber sleeper indicating the high potential of this sleeper technology to replace the existing timber sleepers. This new sleeper is currently being trialled in the Queensland Rail network as part of their sleeper maintenance program.

**Keywords:** Composite railway sleepers, Optimal shape, Sandwich panels, Epoxy polymer, Finite element analysis, Performance of sleeper, Installation.

## Introduction

Australia has one of the longest railway networks in the world with millions of sleepers manufactured every year for network expansions and line upgrades. In Queensland, 57% of the railway tracks are constructed using timber sleepers that equates about 10 million in total and requires over 400,000 timber sleepers per year to maintain them (McCombe and Ryan, 2003). Approximately 100,000 mature hardwood trees need to be cut down to supply this sleeper demand which have a severe impact to the environment. Moreover, the supply of high quality hardwood for timber sleepers is becoming scarcer. In order to address these issues, the Queensland Railway (QR) has adopted a strategy of replacing timber sleepers by the alternative sleepers on a substantial basis to meet demands. This strategic plan is not only taken by the QR but it is also the current approach for sleeper maintenance all over the world.

The University of Southern Queensland has a long history of composite sleeper development which started in early 2000 to address the high demand for alternative timber sleeper replacements. The early developments produced an alternative sleeper with similar depth, stiffness and weight to that of the existing timber sleepers with the additional benefits of excellent durability, environmentally friendly and cost effectivity (Van Erp, 2005). This sleeper was produced from polymer concrete reinforced with fibre composite materials wherein the amount of resin in the polymer concrete was higher in the tension zones comparing with the other parts. The innovative polymer concrete was formulated by polymer resin mixed with hardener, an amount of light aggregate with a specific gravity less than that of the resin, and an amount of a heavy aggregate with a specific gravity larger than that of the resin (Van Erp, 2004, Ferdous et al., 2016c). The development of fibre composite beams has also led in their use for turnout railway sleepers (Manalo and Aravinthan, 2012, Manalo et al., 2016a). More recently, a sleeper technology was developed using fibre composite sandwich panels and polymer concrete as a binding material (Van Erp, 2015, Van Erp and Mckay, 2013). In addition to these novel composite sleepers, sleeper technologies made from recycled plastic materials are also available. The challenges of using these composite sleeper technologies are presented in (Ferdous et al., 2015b). This comprehensive review found that the recycled plastics are struggling to meet the minimum performance requirements for a railway sleeper although they have a reasonable price. On the other hand, the fibre reinforced polymer sleepers can meet the performance requirements satisfactorily, however, they are up to 10 times more expensive than the traditional timber sleepers. The inferior strength and stiffness properties of recycled plastic sleepers and the prohibitive cost of currently available fibre reinforced technologies have been

identified as the primary reasons for their slow uptake in the market. There is a continuous need therefore to further engineer the composite sleepers to achieve reasonably priced sleepers without compromising their structural performance.

This study introduced an innovative fibre composite railway sleeper manufactured from composite sandwich panels and bonded with epoxy polymer matrix. A topology optimisation technique was implemented to optimise the material usage in a narrow-gauge railway sleeper subjected to quasi-static load. The vertical deflection of the optimal composite sleeper and sleeper-ballast contact pressure in both low and high stiffness support foundations were then analysed by the finite element simulation using Strand7 and the results were compared with the traditional timber sleepers. The performance of optimal sleeper was then investigated experimentally and trialled in actual railway track. The results of these studies are presented in this paper to provide the railway industry useful information on the performance of a cost effective and alternative sleeper technology for replacing the deteriorated timber sleepers.

## **Evolution of shapes and materials in sleepers**

Approximately three billion railway sleepers are currently used in rail networks around the world (FIB, 2006) and their shapes have evolved since their initial development. The shape evolution of railway sleepers made from different materials is discussed in the following subsections.

### ***Timber sleepers***

Timber is the widely used material for railway sleepers due to its many advantages including relatively low cost, good resilience, ease of handling, adaptability to non-standard situations, and electrical insulation (Kaewunruen, 2010). At the early stage, round shaped log were used as sleepers to support the railway track. However, the problems of stress concentration and non-uniform distribution of wheel loads evolved them to a rectangular cross-sectional shape (Fig. 1). The rectangular timber sleeper was not further optimised because any further processing to change this shape would only add to the cost of the sleeper.



(a) round shaped timber sleepers



(b) rectangular shaped timber sleepers

Fig. 1: Evolution of timber sleepers

### ***Steel sleepers***

During the 1880s, due to the scarcity of timber and sensitivity towards its use, steel railway sleepers, which are much stronger than timber and less expensive than pre-stressed concrete ones, were introduced. In Australia, approximately 13% of sleepers used in tracks are manufactured from steel (Manalo et al., 2010a). The advantages of steel sleepers which have caught the attention of railway engineers are their light weight, ability to be stacked in compact bundles, requirement of a low volume of ballast for laying on tracks, and recyclability. The inverted trough profile of conventional steel sleepers however makes them difficult to satisfactorily pack with ballast as shown in Figure 2(a) (Bonnett, 2005). ‘Y’-shaped steel sleepers (Fig. 2b) are also being used as they offer better support for rails and considerable reduction in noise emission than traditional steel sleepers (Bajer and Bogacz, 2005).



(a) traditional shape



(b) modern ‘Y’ shape

Fig. 2: Evolution of steel sleepers

## Concrete sleepers

There are two types of concrete sleepers that are commercially available, i.e. twin-block reinforced concrete and mono-block prestressed concrete. A twin-block reinforced concrete sleeper shown in Figure 3(a) is made from two concrete blocks joined together by a steel tie bar cast into them and is widely used in Europe, particularly in France (Remennikov and Kaewunruen, 2005, Weiss, 2008). It weighs less than a mono-block concrete sleeper but is difficult to handle and place due to its high tendency to twist when lifted. In the early twentieth century, when concrete sleepers were first introduced into railway tracks, they failed within a few years due to brittle fracturing, cracking and low resistance to fatigue (Taherinezhad et al., 2013). To overcome these weaknesses, concrete sleepers were reinforced by steel bars (Profillidis, 2006). However, these ordinary reinforced concrete sleepers could not provide satisfactory service (Bonnett, 2005).



(a) twin-block reinforced concrete



(b) mono-block rectangular shape



(c) increased optimisation



(d) modern optimised shape

Fig. 3: Evolution of concrete sleepers

Despite twin-block reinforced concrete sleepers being more cost-effective, mono-block prestressed concrete sleepers (Fig. 3b) are the most commonly used sleepers throughout the world due to their greater durability in adverse environments and their resistance to twist

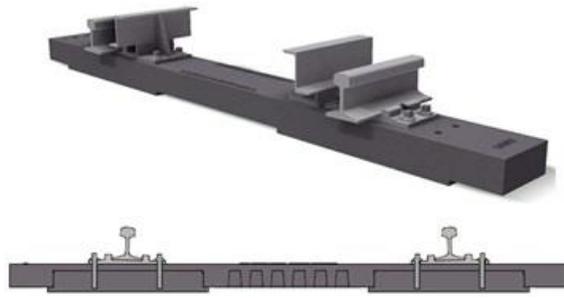
(Kaewunruen, 2010). However, the heavy weight and high initial cost in addition to the low impact resistance and susceptibility to chemical attack of a mono-block prestressed concrete sleeper are major problems (Hime, 1996, Shayan and Quick, 1992, Ferdous and Manalo, 2014). Therefore, the profile of the prestressed railway sleepers has evolved from a traditional rectangular shape to a more complex sleeper form to reduce weight and cost. Namura et al. (Namura et al., 2005), and Sadeghi and Babaei (Sadeghi and Babaei, 2006) presented an optimised design for prestressed concrete sleepers with reduced dimensions and number of reinforcing bars. An increased optimised shape is shown in Figure 3(c), while Figure 3(d) depicts the modern optimised shape of concrete sleeper (Van Erp, 2012). It can be seen that the modern sleepers are gradually refining the shape from a consistent rectangular shape to an optimized shape accounting for rail seats, less cost, reduced weight, and increased lateral support.

### ***Plastic sleepers***

Several plastic sleeper technologies have been developed in different parts of the world. Most of them are manufactured from recycled plastic materials which contains short or no fibres. An overview of the recent developments of composite railway sleepers, their major challenges and opportunities for their increased usage was presented in (Ferdous et al., 2015b). The shape of the plastic sleepers is now being optimised (Fig. 4) to reduce the volume of materials in manufacturing sleeper (Ferdous et al., 2015b). The KLP sleepers in Figure 4(a) showed a 35% reduced section at the middle and two ends. KLP sleepers with an optimised shape (Figure 4b) are also being used in bridge application (Van Belkom, 2015). While the plastic sleeper technologies are offering environmentally friendly products with a reasonable price, they have gained a very limited acceptance by the railway industry due to their limited strength and stiffness. Moreover, the light weight of plastic sleepers and low resistance to the mechanical connection are two major concerns for maintaining the track stability (Ferdous et al., 2015b, Kaewunruen, 2010).



(a) KLP plastic sleeper



(b) KLP bridge sleeper

Fig. 4: Evolution of plastic sleepers

### ***Fibre reinforced composite sleepers***

Research and development have now focused on fibre reinforced polymers to engineer the strength and stiffness properties suitable for railway sleeper application. The University of Southern Queensland has a long history of fibre reinforced composite sleeper development research started in early 2000. Figure 5 shows one of the earliest technologies of such developments (Van Erp and Mckay, 2013, Manalo et al., 2010a, Van Erp, 2015). These technologies were developed with the depth, stiffness and weight similar to the hardwood timber sleepers (Van Erp, 2015). They are made of polymer concrete with glass fibre reinforcement, tailored the weight to 61 kg, have excellent electrical resistance and can be fitted with standard fasteners. The revolutionary shape provides excellent resistance against lateral movement that increase the track stability. The installation of rail clips were trailed in a track to check the accuracy of the fastening systems which shown a satisfactory performance under actual service conditions. However, the variable section of the sleeper along its length makes it manufacturing process more complex which outweighs the cost reduction due to material savings. Further optimisation is therefore required to come-up with a more cost-effective composite sleeper section. Moreover, numerical and experimental studies should be conducted to demonstrate the structural performance of composite sleepers with optimal material usage and to provide railway engineers preliminary indications of the aptness of these new technologies for railway sleeper applications.



(a) optimised FRP sleeper



(b) timber replacement sleeper

Fig. 5: Recently developed fibre composite sleepers

## Design of composite sleepers

The prohibitive cost of composite sleeper technologies is identified as one of the main reasons for their slow uptake in the market (Ferdous et al., 2015b). Van Erp and Mckay (Van Erp and Mckay, 2013) reported that the price of high fibre containing composite sleeper technologies is approximately 5 to 10 times higher than a standard timber sleeper. Nosker et al. (Nosker et al., 1998) and Bank (Bank, 2006) suggested optimising the structural dimensions to avoid material wastage and to minimise the cost as any reduction in the volume of materials is significant for fibre composites. Therefore, an optimal section for a narrow-gauge railway sleeper with a reduced amount of composite materials was determined. It is important to note that the optimisation process in this study only considers the effect of quasi-static load due to the passing train. The rail seat region of the sleeper is the most critical as the sleeper generally transmit the wheel loads through this region at a  $45^\circ$  angle as shown in Figure 6. As a result, a high stress is developed at the rail-seat region while the other parts of sleeper are subjected to relatively low stress (Fig. 6). A superior design of a sleeper was achieved by decreasing the section thickness in regions where the stress is minimal but at the same time meets the minimum dimensional requirements. The design requirements provided by the QR for narrow gauge sleepers are tabulated in Table 1. The optimal shape of sleeper was obtained by applying the loading and boundary conditions in an optimisation algorithm using Matlab - R2015b (MatLab, 2016).

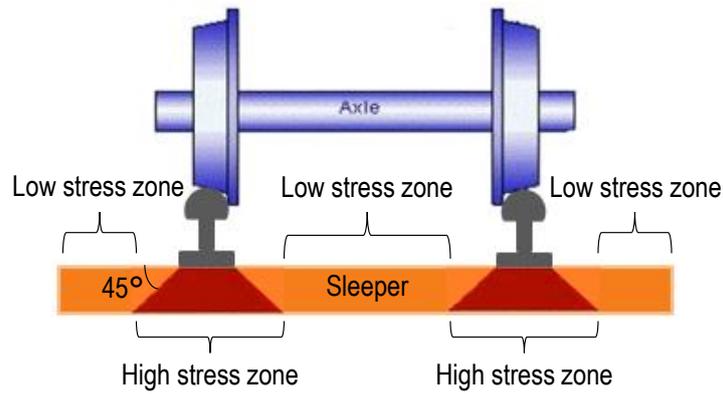


Fig. 6: Identifying the low and high stress zone of a sleeper

Table 1: Queensland Railway (QR) requirements for track design

Parameters	Requirements
Sleeper type	Timber-replacement sleeper
Most common rail type	AS41 (41 kg/m)
Track gauge length (Narrow gauge)	1067 mm
Distance between rail centres, ( $g$ )	1130 mm
Sleeper length, ( $l$ )	2125 – 2175 mm
Sleeper depth at rail seat	110 – 125 mm
Sleeper width at base	225 – 255 mm
Sleeper spacing	685 mm
Train speed	100 km/h
Design axle load	20 ton (i.e., 200 kN)
Nominal depth of ballast	150 – 250 mm
Maximum sleeper-ballast contact pressure	750 kPa

### ***Determination of an optimal sleeper shape using topology optimisation***

Topology optimisation can determine the optimal distribution of materials within a design domain satisfying the imposed constraints (Bendsoe and Sigmund, 2013). The topology optimisation algorithm used in this paper is known as the Solid Isotropic Materials with Penalisation (SIMP) method (Bendsøe, 1989, Rozvany et al., 1992). In this method, the relative densities of the elements are considered as design elements and are varied iteratively to obtain

an optimal solution. The optimisation problem considered here is a compliance minimisation problem with volume constraint defined as

$$\begin{aligned} & \min_{x_1, x_2, \dots, x_n} && \mathbf{f}^T \mathbf{u} \\ \text{such that} &&& \mathbf{K}\mathbf{u} = \mathbf{f} \\ \text{and} &&& V = \sum_{e=1}^n v_e x_e \leq \bar{V} \end{aligned}$$

where  $\mathbf{f}$  and  $\mathbf{u}$  represent the nodal force and displacement vectors,  $\mathbf{K}$  is the stiffness matrix of the system,  $v_e$  and  $x_e$  are the volume and relative density of element  $e$ ,  $n$  is the number of elements used in the finite element discretisation, and  $\bar{V}$  is a selected upper limit on the allowable material volume and that is 0.6. Minimising the mean compliance,  $\mathbf{f}^T \mathbf{u}$ , is equivalent to maximising the stiffness of the system.

The optimisation code originally proposed by Sigmund (Sigmund, 2001) was modified and implemented in this study with the necessary boundary conditions for achieving the optimal shape of sleepers. The initial shape of the composite sleeper is assumed a rectangular beam similar to the traditional timber sleepers. The material properties of the sleeper including elastic modulus and Poisson's ratio are incorporated in optimisation code with the aspect ratio of approximately 1 used in meshing to ensure the best results. The code works with two-dimensional plane stress problems, has two degrees of freedom, one corresponding to the horizontal displacement and the other for the vertical displacement. Consequently, a two-dimensional optimal shape was obtained from topology optimisation and further analysed using finite element software as a three dimensional model. In maintaining the track stability, manufacturing efficiency and holding rail-seats, the sleeper was designed as a single body structure. Therefore, the bottom half of the sleeper was restrained and the required conditions were applied in the optimisation code. The uniform shape of bottom part facilitates the ease of manufacturing the sleepers using composite sandwich panels comparing with the stepping shape section in Figure 5. This is important as cutting the sandwich panels to achieve the stepped shape will entail additional cutting process and results in material wastage. The design rail seat load is determined by Eq. (1).

$$R = \emptyset \times Q \times DF \tag{1}$$

In Eq. (1), the impact factor  $\emptyset = 1.5$  suggested by the American Railroad Engineering Association (AREA) (Jeffs and Tew, 1991), the static wheel load  $Q = 100$  kN which is half of the design axle load (Table 1), and the axle load distribution factor  $DF = 48\%$  for a sleeper

spacing of 685 mm (Jeffs and Tew, 1991). Thus, the design rail seat load  $R = 72$  kN and the optimisation process only considered the static load. A two-dimensional optimal shape obtained from the optimisation code is provided in Figure 7 for illustration purposes. The optimal shape in Figure 7(b) supports the stress distribution pattern of sleeper as shown in Figure 6. The higher the stress, the deeper the section is required, indicating the rail seat region is the most critical section while other parts of sleeper do not require the same strength.

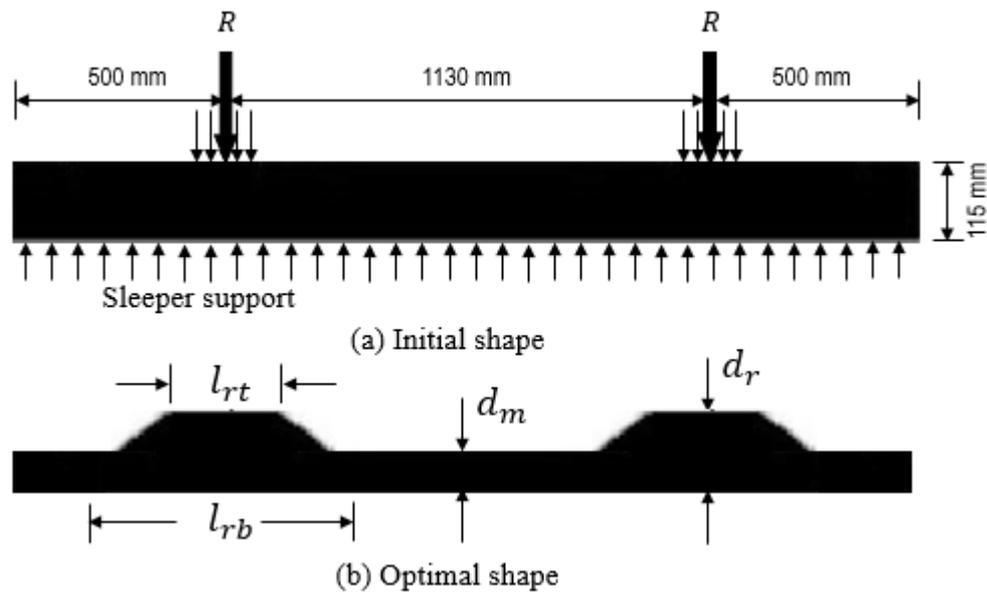


Fig. 7: Two dimensional optimal shape of sleeper obtained from topology optimisation

### ***Design shear force and bending moment***

The sleeper in Figure 7(a) is analysed based on the beams on elastic foundation theory to determine the design shear force and bending moment of the composite sleepers. The sleeper was created as a beam element supported on a continuous linear elastic foundation using Strand7 (R2.4.6) finite element software (Strand7, 2010). While an effective analysis method in preliminary design of sleepers (Manalo et al., 2012a), the beams on elastic foundation model do not consider the continuity and actual behaviour of the ballast and subgrade layers, longitudinal loads from thermal stresses, eccentricity of the vertical loads on the rail head, and track dynamic effects, such as inertial and damping forces which are known to affect the stresses and deflections in railroad track (Doyle, 1980). Based on the minimum dimensional requirements of sleeper provided in Table 1, a rectangular sleeper of dimension  $230 \text{ mm} \times 115 \text{ mm} \times 2000 \text{ mm}$  with elastic modulus of 7 GPa and Poisson's ratio of 0.25 is considered and supported by an elastic foundation with a support modulus of 30 MPa. The modulus of

elasticity of the rectangular sleeper is adopted from the timber's modulus of 7 GPa (Manalo et al., 2012a). When designing sleepers, the QR suggested to use the track modulus from the field measurements relevant for the application of the sleepers. The standard specification of the concrete sleepers has recommended the nominal track modulus of 30 MPa (Stead and Kerr, 2012) for medium duty sleepers indicating 30 N load is required per millimetre length of rail to depress the rail by 1 mm of depth. This level of track modulus represents a sound, crushed stone and free of mud ballast condition with average drainage of track (Foruria, 1988). The deflection, shear force and bending moment diagram of the traditional sleeper under distributed load over 150 mm (approximate base dimension of rail) at both rail-seat location (Fig. 7a) are presented in Figure 8. From these results, the maximum deflection and design shear force are 2.95 mm and 32.52 kN respectively at rail-seat section. Moreover, the design bending moments of the sleepers are 5.53 kN-m positive bending at rail-seat, and -3.04 kN-m negative bending at the mid-span.

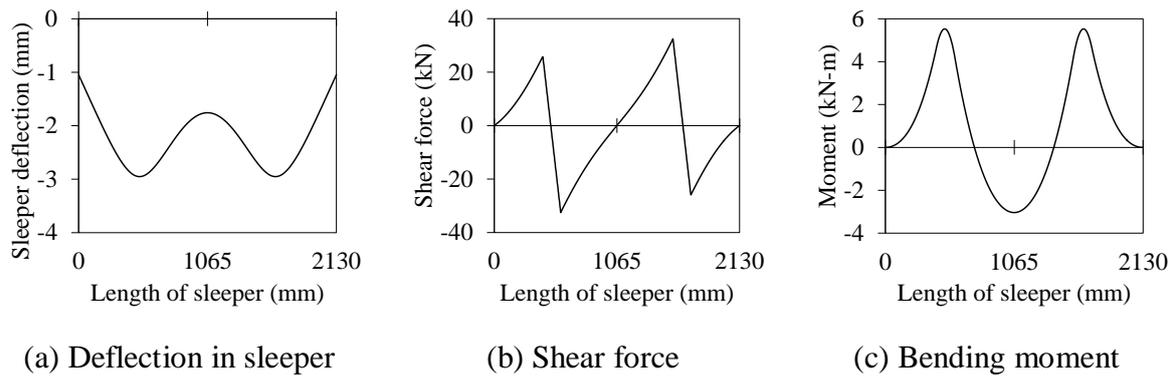


Fig. 8: Deflection, shear force and bending moment of sleeper

### ***Dimensional requirements of optimal sleeper***

Some of the dimensions of the sleepers are provided by the QR, such as the total length between 2125 – 2175 mm, distance between the rail centres of 1130 mm, sleeper depth at the rail seat between 110 – 125 mm, and sleeper width at the base between 225 – 255 mm. The sleeper length, depth at rail-seat ( $d_r$ ) and width at the base are selected as 2130 mm, 115 mm and 230 mm as the preliminary dimensions for the rectangular sleeper. The length of rail seat at top ( $l_{rt}$ ), length of the rail-seat at bottom ( $l_{rb}$ ) and the depth at the mid-span section ( $d_m$ ) of the optimal sleeper shape in Figure 7(b) are then determined to satisfy the performance requirements. The dimension of  $l_{rt}$  depends on the rail-types, rail-pad and fastening systems used in the track. The largest size of rail used by the QR is AS60 type that has a base dimension

of 146 mm. Rail pad are sometimes placed on the rail-seat to reduce noise and vibration, improve load distribution, reduce rail wear and fatigue failure and to transfer the dynamic forces from rails to the sleepers. The engineering specification of the concrete sleeper (Stead and Kerr, 2012) indicated the length of the rail pad is 180 mm to be used. To provide the sufficient space for the rail fastening system beyond the rail pad length, the length of  $l_{rt}$  is selected 320 mm. Figure 6 shows that the load is distributed at  $45^\circ$  angle which suggested a minimum dimension of 550 mm is required to transfer the load at the bottom of the rail-seat. For smooth transfer of loads, the length of  $l_{rb}$  is selected 600 mm. The depth  $d_m$  can be determined from the design moment at the mid-span section of the sleeper and the relationship is provided in Eq. (2).

$$b_m d_m^2 = \frac{6M}{\sigma} \quad (2)$$

In Eq. (2), the width at the mid-span section  $b_m$ , the design moment at the mid-span section  $M = 3.04$  kN-m, and the bending strength of the beam  $\sigma$ . The investigation on layered sandwich panels bonded with epoxy polymer matrix observed the first drop of load due to the tensile cracks of the phenolic core at 25 MPa bending stress (Ferdous et al., 2016b). The composite sleeper was designed in such a way that it will not crack under the rail-seat load. Therefore, the sectional dimension of the sleeper at mid-span section was determined based on the tensile cracking strength and thus  $\sigma = 25$  MPa. Taking,  $b_m/d_m = 1.5$  (close to timber sleeper's sectional ratio), the Eq. (2) gives  $b_m = 120$  mm and  $d_m = 80$  mm. Figure 9 shows the longitudinal and cross-sectional dimensions, and the full-scale optimal sleeper.

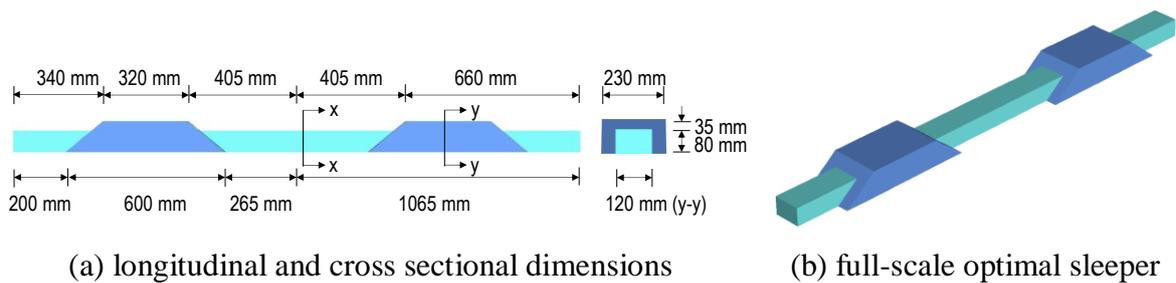


Fig. 9: Dimensions and optimal shape of sleepers

### ***Analysis and design of the optimal sleeper section***

The investigation on layered sandwich panels bonded with epoxy polymer matrix has suggested that the vertically oriented sandwich panels can maintain the same bending strength and provide 50% higher shear strength than the horizontally layered panels (Ferdous et al., 2016b). Therefore, vertically oriented panels are the preferred choice for achieving composite sleepers with a high shear strength. The sectional details of the sleeper section can be found in (Van Erp, 2015). A typical layout of the sandwich panels are given in Figure 10. Five sandwich panels of which the cross-section of each panel is 20 mm × 60 mm are vertically placed and bonded with epoxy polymer matrix to achieve the desired bending moment capacity of at least 3.04 kN-m. Two GFRP skins with 5 mm thickness of each are placed horizontally at the top and bottom of the vertical sandwich panels to increase the bending stiffness of the section. Without top and bottom skins, the effective elastic modulus of the sleeper at mid-span section is only 2.88 GPa while it is increased to 5.72 GPa after providing the skins. Manalo et al. (Manalo et al., 2012a) investigated the effect of elastic modulus on the behaviour of the fibre composite railway sleepers and they found that the elastic modulus should be at least 4 GPa to ensure that both the vertical deflection of rail track and sleeper-ballast contact pressure are within the allowable limits. For achieving better structural integrity and composite action, the inner middle part of the rail-seat section was kept the same as it is in the mid-span section. However, as the load is transferred through rail-seat region, this section requires greater strength and stiffness than the mid-span section of the sleeper. Two vertical and one horizontal sandwich panels are added with the horizontal skins one at top and two at bottom of the additional vertical panels. The additional sandwich panels increased the strength at rail-seat section while the horizontal skins improved the stiffness.

The properties of the sandwich panels and epoxy polymer matrix are given in Table 2. The detail investigation of these properties can be found in (Ferdous et al., 2017) for sandwich panels and (Ferdous et al., 2016c, Ferdous et al., 2016a) for epoxy polymer matrix.

Table 2: Properties of sandwich panels and epoxy polymer matrix

Test	Properties	Sandwich panels		Polymer matrix
		GFRP skin	Phenolic core	
Flexure	Elastic modulus (GPa)	14.28	1.33	-
	Peak stress (MPa)	450.39	14.32	45.09
	Strain at peak (%)	2.29	1.22	-
Tensile	Elastic modulus (GPa)	15.38	1.03	-
	Peak stress (MPa)	291.20	5.97	14.74
	Strain at peak (%)	1.61	0.61	-
	Poisson's ratio	0.25	-	-
Compressive	Elastic modulus (GPa)	16.10	1.33	1.66
	Peak stress (MPa)	238.04	21.35	65.56
	Strain at peak (%)	1.24	4.04	-
	Poisson's ratio	-	0.29	0.25
Shear	Shear modulus (GPa)	2.47	0.53	0.66
	Peak stress (MPa)	23.19	4.25	4.90
	Strain at peak (%)	3.08	0.81	-

Using the material properties provided in Table 2, the simplified sectional analysis (Ferdous et al., 2015a) gave a neutral axis location at 40 mm for mid-span section and 55.94 mm for rail-seat section, both measured from the bottom of the beam (Fig. 9a). The study on layered sandwich panels (Ferdous et al., 2016b) found that the cracking in polymer matrix is triggered by the core tension. Therefore, tensile strain of the core is considered the failure strain in sectional analysis to avoid the first crack in the composite sleepers. The design moments and sectional capacity of the sleepers are given in Table 3. From this Table it can be seen that the sleeper will not crack under the static wheel load of the train as the first cracking moment is approximately 4- and 2-times greater than the required design moment at rail-seat and centre section, respectively. The higher capacity of the section can also provide the resistance against dynamic impact load. The moment capacity and bending stiffness of the rail-seat section is approximately 4- and 5-times greater than the centre section, respectively as the load is transferred through rail-seat region, a greater strength and stiffness are required. For both sections, the effective modulus of elasticity is above 4 GPa which is the proposed minimum required elastic modulus for fibre composite sleepers (Manalo et al., 2012a). Careful

considerations are required for further optimisation based on the design capacity that would make the sleeper unsuitable for dimensional requirements.

Table 3: Theoretical analysis of design requirements and capacity of the section

Section of sleeper	Design moment of the sleeper	Design capacity of the section		
		Moment at first crack	Bending stiffness	Modulus of elasticity
	kN-m	kN-m	kN-m <sup>2</sup>	GPa
Rail-seat	5.53	23.38	157	5.39
Centre	3.04	6.42	29.29	5.72

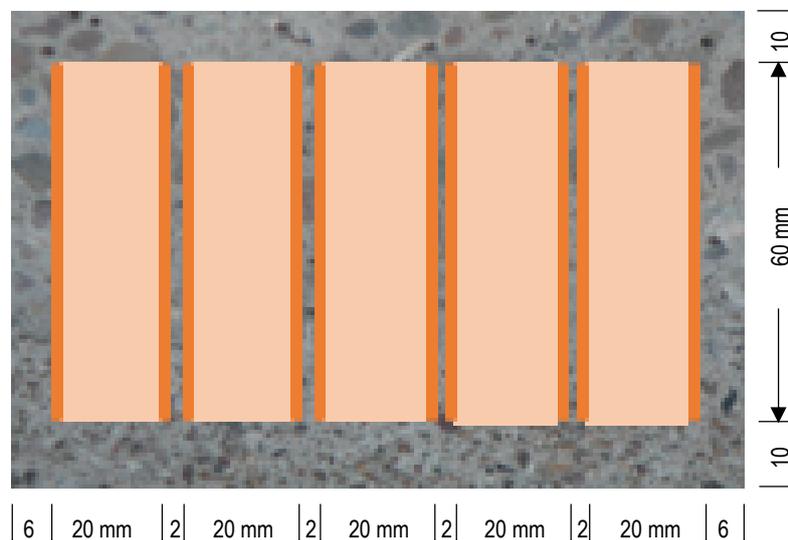


Fig. 10: A typical layout of the sandwich panels at centre of sleeper

### ***Evaluation of vertical deflection and sleeper-ballast contact pressure***

The vertical deflection and sleeper-ballast contact pressure should be within the allowable limit to satisfy the requirements for a railway sleeper. Strand7 finite element software was used to check these parameters for both composite and timber sleepers at low and high stiffness support conditions. The properties of support condition in Table 4, provided by QR were used for the finite element model. The difference between low and high stiffness support foundation is the sub-grade layer which does not exist in low stiffness support. Three-dimensional brick element (Hexa20 and Wedge15) in Strand7 was used to model the rail, ballast, subgrade and formation layers as shown in Figure 11(a). However, the fibre composite skins in the composite

sleeper were created as laminated plate element while the sandwich core and polymer matrix were modelled as brick element. To reduce the computational time required, only one quarter of the sleeper was modelled as, due to symmetry, the other three quarters would exhibit similar behaviour. The width of the ballast and formation layer was 685 mm which is mainly the spacing of a sleeper in Queensland rail track. All the nodes on the bottom surface of the formation layer were fixed while those on the vertical surfaces were restrained symmetrically with respect to that plane. Once the model was finalised with appropriate boundary conditions and loading, a linear static solution was performed to predict the behaviour.

Table 4: Properties of the low and high stiffness support foundation

Types of foundation layer	Low stiffness support foundation			High stiffness support foundation		
	Depth (mm)	Modulus (MPa)	Poisson's ratio	Depth (mm)	Modulus (MPa)	Poisson's ratio
Ballast	200	200	0.2	200	500	0.2
Sub-grade	-	-	-	200	120	0.3
Formation	2000	40	0.4	2000	91	0.4

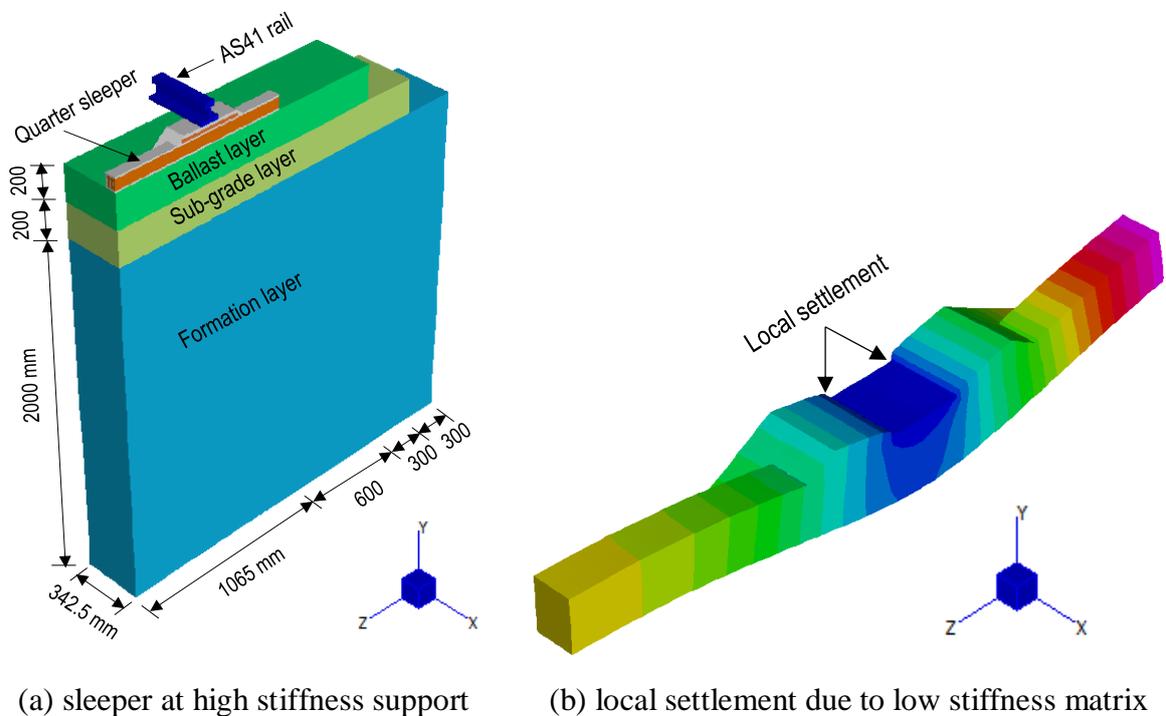


Fig. 11: Strand7 model for composite sleeper

Figure 11(b) shows that the top surface of the composite sleeper depressed locally at rail-seat load. This is due to the presence of low stiffness epoxy polymer matrix at top surface while the sleepers on elastic foundation also provide resistance against deflection. To avoid the local settlement that may affect the track stability by releasing the fastening system, a high modulus epoxy polymer concrete was introduced at the top surface of the sleeper as the stress concentration is higher in this region. The higher specific gravity of the coarse aggregate than the epoxy polymer matrix will promote them to settle at the top of the rail-seat region during casting as the sleepers were cast upside down. The following analysis considered the polymer concrete at the top half while the bottom half of the sleeper considered polymer matrix. The Modulus of Elasticity and Poisson's ratio of the polymer concrete are found to be 10 GPa and 0.2, respectively while the properties of polymer matrix are given in Table 2.

Figure 12 shows the deformed shape of the timber and composite sleepers due to vertical deflections in both low and high stiffness support foundations. The maximum vertical deflection is obtained at rail seat position and this parameter under rail seat is considered as a main criterion (Chrismer and Selig, 1993) in a railway track analysis and also a significant factor in track deterioration (Sadeghi and Akbari, 2006). Table 5 compares the results with the allowable limit. The deflection behaviour at low stiffness support foundation is similar to the deflection behaviour obtained from beams on elastic foundation theory as shown in Figure 8(a). It is observed from the numerical analysis that, at a 72 kN rail-seat load, the vertical deflection of the composite sleeper is only 15% higher than the timber ones at the same support condition. This can be attributed to the slightly lower modulus of elasticity of composite sleeper (average 5.5 GPa in Table 3) compared to the timber one (7 GPa). Moreover, the deflection in the high-stiffness support foundation is approximately 50% less than that in the low-stiffness foundation. However, both are well within the allowable limit of 6.35 mm (Table 5) (ARTC, 2013).

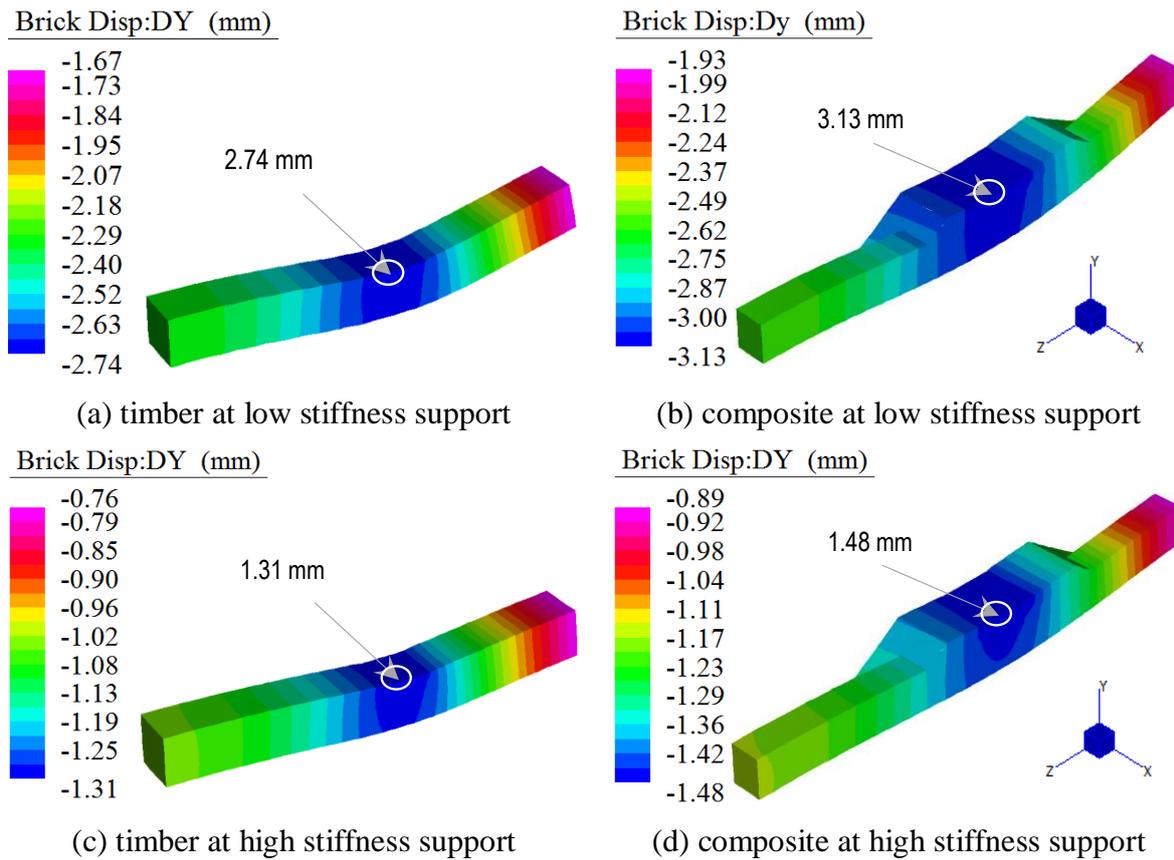


Fig. 12: Displacement behaviour of timber and composite sleepers at rail-seat load

Figure 13 shows the sleeper-ballast contact pressure for timber and composite sleepers at low and high stiffness support foundation. The sleeper-ballast contact pressure is one of the significant parameters considered in sleeper design. In a freshly tamped ballast track, the contact pressure between sleeper and ballast are mainly occurred under the rail seat positions which gradually distributed over the sleeper length under accumulated traffic loading (Zakeri and Sadeghi, 2007). The highest sleeper-ballast contact pressure is obtained at rail seat positions. Ignoring the stress concentration due to edge of the sleepers, the maximum sleeper-ballast contact pressure obtained at the location of rail-seat load. The vertical pressure generated on the ballast bed by the composite sleeper is approximately 10% lower than the timber sleeper at the same support condition, while the high stiffness support foundation created 40% higher pressure than the low stiffness foundation for the same sleepers. The numerical results support the basic principles of generating a higher sleeper-ballast contact pressure in a high-stiffness foundation and those obtained from this analysis in both support foundations are within the limit of the maximum allowable contact pressure of 750 kPa provided by QR as shown in Table 1.

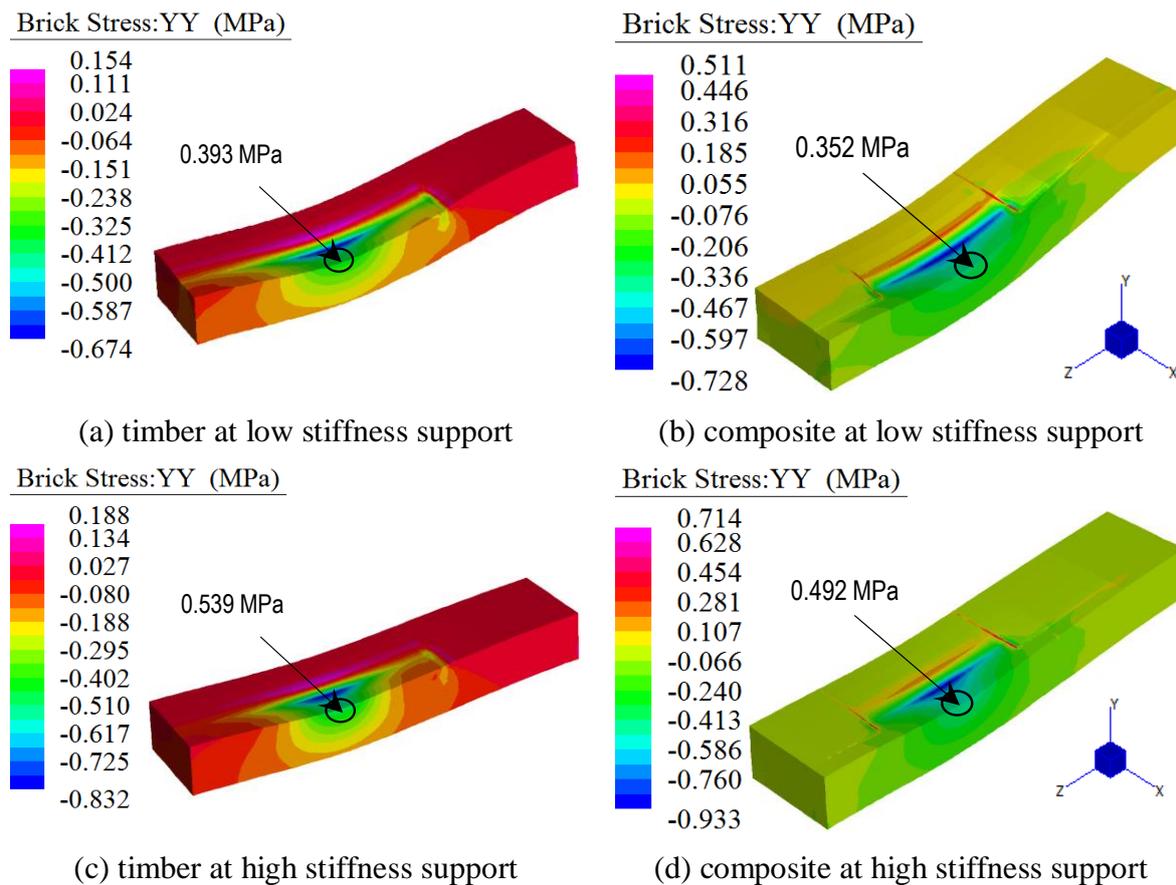


Fig. 13: Sleeper-ballast contact pressure at rail-seat load

Table 5: Comparison between timber and composite railway sleepers

Investigated parameters	Low stiffness support		High stiffness support		Allowable limit
	Timber	Composite	Timber	Composite	
Vertical deflection (mm)	2.74	3.13	1.31	1.48	6.35
Sleeper-ballast contact pressure (kPa)	393	352	539	492	750

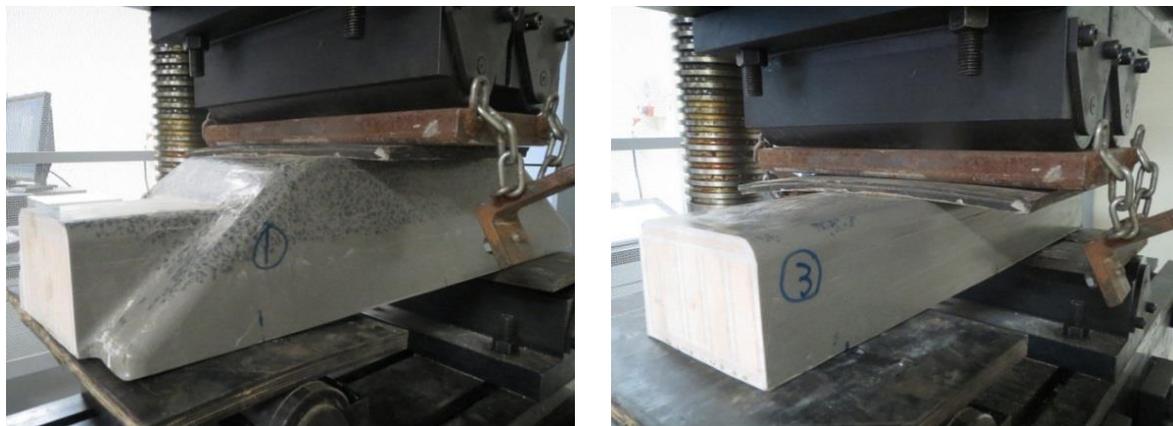
In general, the analyses showed that the new composite sleeper behaves very similar to the traditional timber sleepers. The volume of composite rectangular sleeper is  $0.066 \text{ m}^3$  while the volume of the optimal sleeper is  $0.033 \text{ m}^3$ . The reduced volume of composite sleepers indicates a material savings of 50% which is very important to reduce their manufacturing cost. The total weight of optimal sleeper is approximately 60 kg that is similar to the weight of a narrow-gauge timber sleeper. It is important to note that optimisation of the sleeper considered only the optimal usage of composite materials with only a minor consideration to the manufacture and installation of the sleepers. Moreover, the long-term performance due to fatigue and impact were beyond the scope of this study.

## Experimental evaluation of sleepers' performance

The strength and stiffness of the composite sleeper should be compatible with those of timber during railway maintenance works. This compatibility is necessary to avoid the differential settlement of rail track. Prototype sleepers with optimal section were manufactured and their structural performance was evaluated experimentally and compared with those timber and standard requirements. The results of which are presented in the following sub-sections.

### ***Rail seat vertical load and centre bending moment***

Rail seat vertical load and centre bending moment tests are some of the most important performance characteristics required for the approval of new sleeper technology. Figure 14 shows the set-up for the rail-seat vertical load and centre bending moment tests in accordance with AS 1085.14 (Standards-Australia, 2012). The experimental investigation was carried out in two rail seats and centre part of sleeper over 400 mm span at a load rate of 2 mm/min using 2000 kN capacity of SANS machine. Rubber pads were placed under loading and support points to prevent localised failure and then the experimental capacity of the sleeper was measured when the first crack occurred.



(a) vertical load test at rail seat

(b) centre bending moment test

Fig. 14: Flexural capacity tests at rail seat and centre position

The results of the test are summarised in Table 6. As indicated, the first cracking in the rail seat of composite sleeper occurred at an applied moment of 24.02 kN-m. The load at which the first sandwich core cracking occurs should be considered as a measure of the capacity of sleepers to avoid any cracks. However, it is worth noting that the section was still intact after initial crack and the sleeper continued to carry load up to an applied moment of 41.01 kN-m with a slight reduction of stiffness. The observed failures were due to compressive and shear

failure of the fibre composite sandwich panels, the main structural component of the composite sleeper promoted flexural tensile cracking in the polymer matrix. On the other hand, the first sign of structural cracking was observed at the centre of the sleeper at a bending moment of 5.37 kN-m. Similarly, the specimen continued to carry load and failed at an applied moment of 19.97 kN-m. The first cracking moment obtained from the experiment at the rail-seat and centre of the sleeper (Table 6) is similar to the predicted capacity at the first crack provided in Table 3. The developed bending moment at the rail-seat ( $M_r$ ) and the centre ( $M_c$ ) of the sleeper can be determined from the rail-seat load ( $R$ ), distance between rail centres ( $g$ ) and total sleeper length ( $l$ ) by Eq. (3) and Eq. (4), respectively (Doyle, 1980). These values are important to be compared with the experimental capacity of the sleeper and determined the suitability of the newly developed sleeper technology in carrying the applied wheel load. From Table 6 it can be seen that the first cracking moment capacity at the rail-seat and centre of the proposed composite sleepers are 3-times and 2-times higher than the developed bending moment of 9 kN-m and 2.34 kN-m at the respective sections.

$$M_r = R \frac{(l-g)}{8} \quad (3)$$

$$M_c = R \left[ \frac{g}{2} - \frac{l}{4} \right] \quad (4)$$

Table 6: Experimental results of rail seat vertical load and centre bending moment tests

Segment	Core cracking		Ultimate capacity		Developed bending Moment (kN-m)
	Load (kN)	Moment (kN-m)	Load (kN)	Moment (kN-m)	
Rail-seat	240.2	24.02	410.1	41.01	9
Centre	53.7	5.37	199.7	19.97	2.34

### **Shear strength**

The shear strength of the composite sleeper was evaluated by an asymmetrical beam shear test. The beams were eccentrically loaded at two trisected points and the supports were applied at the other two points with a shear span of 100 mm (Fig. 15a). This type of test method promotes shear failure of the specimen by reducing the bending effect. Figure 15(b) shows the shear crack of the tested beam at 305 kN load. As the position of load cell was above the mid-section of the sleeper, the maximum shear force experienced by the sleeper is only half of the failure load that is approximately 5 times greater than the maximum developed shear force of 32.52 kN (Fig. 8b). Therefore, the shear strength of 120 mm × 80 mm section was obtained 15.89

MPa which is significantly greater than the shear strength of the softwood timber of 4 MPa (Ferdous et al., 2015b). These results further show the effectiveness of using the sandwich panels in the vertical position to achieve a high shear strength sleeper.



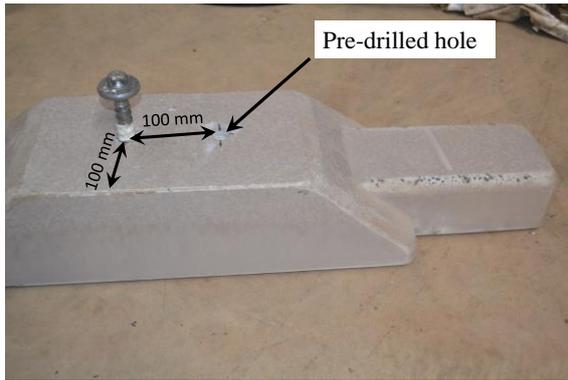
(a) asymmetrical beam shear test setup

(b) shear test of the beam

Fig. 15: Shear capacity test of the composite sleeper

### ***Screw holding capacity***

The low anchorage capacity of the fibre composite sleepers is identified a major challenge for their slow uptake in the market (Ferdous et al., 2015b). The screw is primarily used to hold down the baseplates that attach sleepers to the rails and prevent lateral and vertical movements between them. The screw holding capacity of the composite railway sleepers are evaluated through direct withdrawal test. The screw used in the fastening system has a diameter of 16 mm with 125 mm of length and can be inserted into a pre-drilled hole using petrol driven rattle-gun. Two screws were inserted in the rail-seat area at a distance of 100 mm from the edge and 100 mm between the two holes (Fig. 16a). A loading head and jig (Fig. 16b) was used to pull-out the screw from the sleepers using a 500 kN hydraulic jack at a rate of 2 mm/min and the maximum value of pulling force was determined. The average screw withdrawal resistance of the composite railway sleeper was found to be 74 kN and showed reasonably consistent results between two locations at rail-seat region with a maximum variation of 10%. This magnitude is well above 40 kN pulling force which is the minimum required screw holding capacity for timber sleepers according to AS1085.18 (Standards-Australia, 2013). Similarly, the consistent results indicate that the proximity of the holes will not affect the screw spike resistance. These results demonstrated that the innovative composite sleepers can overcome the limitations of low screw holding capacity of the most of existing plastic sleepers.



(a) Screw inserted at different locations



(b) direct pull-out test

Fig. 16: Pulling strength test of screw

### ***Electrical resistance***

The railway sleepers should have sufficient electrical resistance to minimise the problems for signalling, particularly in track-circuited areas. Resistance was measured in both dry and wet conditions of sleeper. The rain was simulated by sprinkling water on the sleepers as shown in Figure 17(a). Moreover, the sleepers were immersed in water for 6 hours to meet the composite sleeper specification (AREMA, 2013). After preparing the sleepers for testing, a 26 volts and 13 volts AC 50 Hertz potential was applied between the two screws at rail seat location (Fig. 17b). This range of voltage and frequency is within the limit of 10 to 40 volts AC at 50 Hertz according to AS 1085.19 (Standards-Australia, 2003). The magnitude of current flow was measured after 15 minutes of applying the voltage for getting a stable dial reading. The electrical impedance was determined from the applied voltage divided by the current flow through sleeper from one end to another as provided in Table 7. According to the American Railway Engineering and Maintenance-of-way Association (AREMA) specification, the minimum required impedance is 10 kilo-ohms when a wetted sleeper is subjected to 10 volts AC 60 Hz between two rails for a period of 15 minutes (AREMA, 2013). The impedance of dry and wet sleepers shall not be less than 1000 kilo-ohms and 4 kilo-ohms, respectively according to the Australian Standard AS 1085.19. This indicates the proposed composite sleeper satisfactorily meet the electrical impedance requirements.

Table 7: Electrical impedance determination in dry and wet conditions

Test condition	Performance of composite sleeper			Minimum requirements, k $\Omega$	
	Voltage, V	Current, $\mu$ A	Resistance, k $\Omega$	AS 1085.19	AREMA
Dry	26.00	4.6	5650	1000	-
	12.98	2.3	5640		
Wet	26.03	7.7	3380	4	10



(a) spraying water on the sleeper



(b) applying voltage between two rail-seats

Fig. 17: Electrical impedance test

### In-track installation and performance

A total of 50 sleepers have been installed on a trial basis in the Southern line rail track at Nobby, Queensland as shown in Figure 18 to investigate the in-track performance of the new composite sleeper. The existing track was constructed with timber and steel sleepers (Fig. 18a) where timber was only replaced by the alternative composite sleeper. The conventional machinery for timber sleepers were used (Fig. 18b). After removing the existing timber sleeper from the rail-track, the composite one was inserted below the rail using the installation machineries. The screw fastening system inserted into the sleeper at two opposite sides of the rail that can hold the rail and sleeper in correct gauge (Fig. 18c). The installation process and fastening systems of composite sleeper are similar to the installation of timber sleepers.



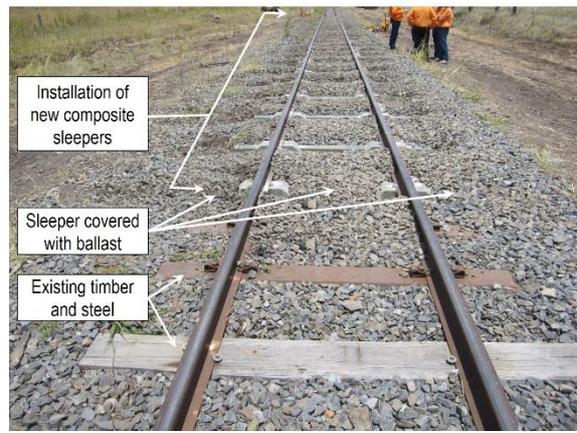
(a) existing track with timber and steel



(b) composite sleeper installation technique



(c) fastening system installation



(d) timber replaced by composite sleepers

Fig. 18: Installation of composite sleepers replacing existing timber

Report has been published on the derailment failures of sleeper and in this case the damaged sleepers need to be replaced which increases the track maintenance costs (Ferdous and Manalo, 2014). The low depth at the middle and end part of the optimal sleeper usually covered by the ballast layer when installed in the track as shown in Figure 18(d). This ballast cover not only protects the sleeper from the potential damage caused by derailment but also keeps lower the surface temperature from the extreme heat by sun. The exterior surface of the sleeper composed with polymer matrix that has a glass transition temperature above 60 °C, protects the interior sandwich panels from high temperature. Moreover, Manalo et al. (Manalo et al., 2016b) observed that the GFRP skin, phenolic core, and sandwich beams retained more than 80% of their mechanical properties at 80 °C. The non-uniform shape of composite sleepers increases the lateral stability of track by creating superior interlock between sleeper and ballast. However, the handling and installation of the sleeper requires careful attention due to this non-uniform shape. The long-term performance, particularly fatigue needs to be investigated to

increase the confidence of using this new technology. A high durability against the environment is expected due to its outer polymer coating which is able to resist moisture ingress, ultraviolet radiation and chemical attack investigated by the authors (Ferdous et al., 2016c). Moreover, it is also expected a high resistance against fire during welding of joints adjacent to sleeper due to the use of fire retardant filler in polymer concrete. As the new composite sleepers can maintain the standard performance requirements and showed a very similar behaviour to the timber, this technology could be a suitable replacement to the existing timber sleepers.

## **Conclusions**

This study designed and investigated an optimal composite railway sleeper manufactured from sandwich panels and bonded with epoxy polymer matrix for a narrow-gauge railway track. The optimal shape of sleeper under quasi-static load was obtained using topology optimisation and its behaviour was evaluated using finite element simulation. After evaluating and confirming the sleeper's performance experimentally, 50 sleepers were installed in Queensland rail track as part of their sleeper maintenance program. From the results of this study, the following conclusions are drawn:

- The optimal shape of new composite sleeper reduces 50% volume of materials of a standard rectangular sleeper that lead to minimise the cost. Most of the materials are provided in the rail seat region where bending and shear stresses are critical.
- The design of the composite sleepers is based on the tensile cracking of the phenolic core. The first cracking moment is approximately 3- and 2-times greater than the developed bending moment at rail-seat and centre section, respectively.
- The vertical deflection of the composite sleeper is 50% lower and the sleeper ballast pressure is 40% greater in high stiffness support foundation compared to the low stiffness support foundation. Regardless of the support conditions, the composite sleepers comply with the allowable vertical deflection of 6.35 mm and sleeper-ballast pressure of 750 kPa.
- Sandwich panels in vertical position and coated with epoxy-based polymer are suitable for timber replacement railway sleepers. The rail seat and centre bending moment, shear strength, screw holding capacity, and electrical resistance of these composite sleepers are higher than the traditional hardwood timber and exceed considerably the performance requirements for a railway sleeper.

- The handling, installing and fastening system of the composite sleeper is similar to timber and requires the same equipment and machineries. The in-track sleepers installed in the last 3 years are performing very well and are expected to outperform its design life.

It is to be noted that the conclusions obtained in this study are based on the particular loading conditions and considering only the quasi-static load. Moreover, the new sleeper shape considered only the optimal material usage. Refined studies are required to fully validate these preliminary conclusions and modifications and improvements are expected to take place based on the actual performance of the sleepers in the actual railway track.

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## *Conclusions*

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Research and development are now focused on fibre reinforced polymer composites as the most viable alternative material for replacing timber sleepers. Fibre reinforced composites have several features which make them attractive for railway sleeper applications including low weight, high strength, excellent durability, ease of transportation and installation, and low energy during manufacture. In the last 20 years, the Centre for Future Materials (CFM) at USQ has dedicated significant research effort developing innovative sleeper technologies based on polymer composite materials. Several polymer composites technologies have evolved from concept development to the construction and deployment of full scale prototypes for field trials. Despite this potential, the uptake of polymer composites for railway applications in Australia has been extremely limited because of the high production cost of these technologies. A better understanding on composite sleeper technology such as improved designs and effective material usage can be developed to reduce the overall cost of production. This study focused on investigating the behaviour of a fibre composite railway sleeper manufactured from composite sandwich panels and bonded with epoxy polymer matrix. It involved extensive experimental, theoretical and numerical studies to evaluate the characteristics of the constituent materials and when they are combined together to determine their potential as an alternative sleeper material. The major findings of this study are divided into four phases as follows:

- a) Analysis of the failure of traditional railway sleeper materials and the challenges of using currently available composite railway sleepers;
- b) Material characterisation of the epoxy based polymer matrix and composite sandwich panels made from glass fibre composite skins and phenolic core;
- c) Bond behaviour between composite sandwich panels and epoxy polymer matrix; and
- d) Performance evaluation of an optimal railway sleeper for narrow gauge rail-track under static load.

### **Reviewing the challenges in using available railway sleepers**

The failure mechanisms for traditional timber, concrete and steel sleepers and the potential protective measures to minimise these failures were reviewed. Moreover, the critical barriers of the recently developed composite sleepers for their widespread acceptance and applications were identified. The major findings from this critical review of literature are:

- Timber is the mostly used sleeper materials worldwide but is vulnerable to fungal decay, end splitting and termite attacks. They are responsible for 53%, 10% and 7% respectively of the total premature failures. These failures can be minimised by impregnating with synthetic chemicals and biological treatment for fungal decay and termite attacks, and providing end-plates on the cracked ends to control the end splitting.
- Concrete sleepers generally failed in rail-seat deterioration and exhibit longitudinal cracking. The rail-seat deterioration can be minimised by using either cast-in-place steel plates that cover the rail-seat area or applying superior materials at rail-seat area. The longitudinal cracking of a concrete sleeper can be controlled by either introducing a special expansive concrete around the bolt-hole area or providing transverse reinforcement.
- Steel sleepers are suffering from corrosion due to saline environment around them. The zinc coating can be applied to steel sleepers as a protective layer for precautionary measure.
- The high strength-to-weight ratio and excellent durability of composite materials can be a sustainable solution to prevent the premature failure of traditional timber, concrete and steel sleepers.
- Sleeper technologies made from recycled plastics are available but they are struggling to meet the minimum performance requirements for a railway sleeper. Railway sleepers reinforced with fibres perform well but their cost is approximately five times higher than a timber sleeper.
- Optimisation and effective usage of fibre reinforced composite materials can reduce the volume of materials and minimise the cost of railway sleepers but still complies with all strength and stiffness requirements of a timber sleeper.
- The development of a structural composite sandwich panels made of phenolic core and glass fibre composite skins and gluing them together were found suitable for railway sleeper application.

This study introduced an innovative fibre composite railway sleeper manufactured from composite sandwich panels and bonded with epoxy polymer matrix. The materials and structural behaviour of this innovative sleeper concept need to be investigated and their performance need to be evaluated for alternative timber sleeper replacement.

## Behaviour of epoxy polymer matrix and sandwich panels

The effect of filler increasing from 0% to 60% on the thermal, physical, mechanical and durability properties of polymer matrices composed of epoxy resin and light weight filler materials were studied from which the optimal range of mix was selected. Investigation of behaviour of phenolic core sandwich beams at horizontal and vertical orientations, and with varying shear span-to-depth ratios (between 0.5 and 12) was conducted to determine the effective usage of this composite material in resisting the flexural and shear loads. The following conclusions are drawn from extensive characterisation of constituent materials.

- Increasing the filler from 0 to 60% reduced the exothermic reaction between the resin and hardener making easy to handle and mix. This also maintained the glass transition temperature of the matrix between 60 °C and 65 °C. Polymer matrix mixes containing filler more than 60% by volume is found not workable.
- Increasing the filler from 0% to 60% increased the density from 1.09 g/cm<sup>3</sup> to 1.46 g/cm<sup>3</sup> and the porosity from 0.02% to 4.37%. This also reduced the flexural strength by 70% (from 98 MPa to 30 MPa) but increased the flexural modulus 3-times (from 1.6 GPa to 4.8 GPa). The mix also became brittle reducing the failure strain from 7.1% to 0.6%.
- The polymer matrices containing filler of up to 30% by volume did not exhibit any visible failure under compression even at ultimate strength (58 MPa). On the other hand, noticeable failures were observed for mixes containing fillers from 40% to 60% and the compressive strength decreased from 50 MPa to 44 MPa but with a slight increase in the compressive modulus.
- Exposure to ultraviolet radiation for 2000 hours reduced the flexural properties of polymer matrix by 48% for the mix with 0% filler. It resulted in embrittlement, discolouration and an overall reduction in weight. The increase of filler preserved the matrix properties effectively against ultraviolet radiation by absorbing or blocking UV radiation before it reaches the chromophores on which the colour of a polymer matrix is dependent.
- Based on the target performance requirements of thermal, physical, mechanical and durability properties, the polymer matrices containing fillers from 30% to 50% were found satisfactorily to meet the coating and binding requirements for composite railway sleepers.

- The composite sandwich beams failed in brittle manner at horizontal orientation, while the failure was progressive at vertical orientation. Generally, the sandwich beams failed in shear, a combined shear and bending, and bending for shear span-to-depth ratios of 2 or less, between 2 and 6, and 6 or more, respectively.
- Sandwich beams in the horizontal orientation exhibited better performance under bending while the sandwich beams in the vertical orientation was more effective in resisting shear. The higher bending stiffness of the sandwich beam can be efficiently utilised by placing the beams vertically than horizontally.
- The sandwich beams are expected to fail in shear when the actual shear-to-bending stress ratio is higher than the allowable shear-to-tensile stress ratio while the beams are more likely to fail in bending when the actual shear-to-bending stress ratio is lower than the allowable shear-to-bending stress ratio.
- The two-way Analysis of Variance showed that the beam orientation has more influence on the load carrying capacity and stiffness properties than changing the shear span-to-depth ratio. The result of the analysis shows that 28% of the variability of failure loads is being accounted by orientation while shear span-to-depth ratio is responsible for 21% variation. On the other hand, 20% of the variability of bending stiffness is being accounted by orientation while shear span-to-depth ratio has no influence on the bending stiffness.
- Indentation failure model was developed to reliably estimate the initiation of indentation in the vertical orientation. This proposed model assumed that the beam is supported on rigid plastic foundation, and the indentation failure occurs when the transverse compressive strength of the skin is exceeded. The predicted indentation failure load for vertically oriented sandwich beams agreed well with the experimental failure load.

The above studies determined the optimal mix design for the epoxy-based polymer matrix and provided information on how structural sandwich beams can effectively resist the bending and shear loads. As these sandwich panels are generally produced with limited thicknesses for production efficiency, they need to be joined together to form a larger section for railway sleeper application. The structural integrity and composite action between the sandwich panels and epoxy polymer matrix are therefore important to transfer the load from one panel to another through the bond.

## Behaviour of bonded sandwich panels

The effects of binder properties, bond length, bond thickness and bond width were investigated to evaluate the bond behaviour of a composite sandwich panel and epoxy polymer matrix. The polymer matrices considered are those with 30% to 50% filler by volume. Layered Sandwich Beams (LSB) were then manufactured and their flexural and shear behaviour were investigated. The effects of the panel orientations and shear span-to-depth ratios were examined. Finite element model was also developed to better understand the fundamental behaviour of the beams. The nature of failure, load carrying capacity and deflection behaviour were systematically investigated. The main findings of this study are as follows:

- The bond strength between sandwich panels and epoxy polymer matrix decreased by 8% with an increase in the amount of filler from 30% to 50% due to the reduced adhesive properties of the matrix. The polymer matrix with 50% filler had 60% higher porosity and lesser workability than the 40% filler mix. On the other hand, both of the matrices with 30% and 40% filler produced consistent results, and were preferable for use in the final application. However, the polymer matrix composed with 40% filler and 60% resin was identified as a practical choice to bond the sandwich panels together as it has reasonable bond strength, moderate cost and minimal voids.
- The bond width has no significant influence on bond behaviour. On the other hand, a bond length of 70 mm was found optimum, beyond which the extension of the bond length cannot increase the bond strength significantly. Similarly, a 5 mm bond thickness provided a very strong bond between the sandwich panel and polymer matrix. Using these bond parameters eliminated failure in the glue line and promoted failure in the sandwich panels.
- The results from the Analysis of Variance show that the bond thickness has the greatest influence (51%) on the development of bond strength between a sandwich panel and polymer matrix, followed by the properties of the polymer matrix (33%), bond length (15%) and bond width (1%).
- The failure loads and failure modes can be predicted reliably using a simplified theoretical model. This model assumed a linear elastic behaviour of sandwich panel and a constant shear stress in the polymer matrix through the thickness. Similarly, the effect of bending moment developed by the applied forces in the joint is ignored.

- Careful consideration in the casting process is critical to achieve the full structural integrity and composite action of the LSB. With the polymer coating, the wrinkling and buckling of the fibre composite skins as well as the indentation in the phenolic core for vertically layered beams were eliminated. This increased the bending strength and the shear strength of the vertical LSB by as much as 25% and 100%, respectively compared to single sandwich beams.
- The behaviour of the horizontal LSB was mostly governed by the shear failure of the core while for vertical LSB it was governed by the failure of the fibre composite skins. Using the same amount of material, the vertical LSB exhibited similar bending strength and 50% higher shear strength but only 7% lower effective modulus of elasticity compared to horizontal LSB.
- Consideration of the nonlinear properties of phenolic core and polymer matrix in the finite element model reliably predicts the fundamental behaviour of the LSB at different orientations and loading conditions. The failure modes, failure loads (up to 14% variation), stiffness (up to 10% variation) and strain behaviour from the finite element simulation were in good agreement with the experimental results.

The composite sandwich beams bonded and coated with epoxy based polymer matrix were found to have strength and stiffness similar to the hardwood timber. An optimal shape of LSB that satisfies the minimum requirements of a railway sleeper needs to be determined for effective material usage of fibre composite materials.

### **Performance evaluation of an innovative railway sleeper**

A composite railway sleeper manufactured from sandwich panels and bonded with epoxy polymer matrix for a narrow gauge railway track was designed and investigated. Topology optimisation was implemented to determine the optimal sleeper shape under quasi-static load. The behaviour of this optimal sleeper shape was then evaluated using finite element simulation and verified experimentally. Field trial was also conducted to evaluate the in-service performance of this new composite sleeper. From the results of this study, the following conclusions are drawn:

- The optimal shape of composite sleeper required only 50% volume of materials compared to a standard rectangular sleeper. This optimal sleeper shape has a greater section at rail-seat region to resist the high stress and ballast pressure due to train wheel

load and a reduced rectangular section in other parts to maintain the gauge width, carry the negative bending moments, and uniformly distribute the load to the ballast.

- The moment capacity of the optimal sleeper was approximately 3- and 2-times higher than the required design moment at rail-seat and centre section, respectively. The maximum vertical deflection of the optimal sleeper is 3.13 mm and the sleeper-ballast contact pressure of 492 kPa which are within the allowable limit of 6.35 mm and 750 kPa, respectively.
- The beams with sandwich panels in oriented vertically and bonded with epoxy polymer matrix are suitable for timber replacement railway sleepers. The rail seat and centre bending moment, shear strength, screw holding capacity, and electrical resistance of these composite sleepers are higher than the traditional hardwood timber and exceed considerably the performance requirements for a railway sleeper.
- The handling, installing and fastening system of the composite sleeper is similar to timber and requires the same equipment and machineries. The 50 sleepers installed by the Queensland Rail in their mainline track are performing very well and are expected to outperform its design life of 50 years.

## **Contribution of the study**

An in-depth understanding of the behaviour of a new type of composite sleepers made from sandwich panels bonded by epoxy polymer matrix was obtained. Through extensive material characterisation, an optimum resin-to-filler ratio for epoxy polymer matrix for bonding and coating sandwich panels was determined. Similarly, a better understanding on how the composite sandwich panels can effectively carry bending and shear loads was gained. This study also developed a new type of layered sandwich beams, which was found to have sufficient strength and stiffness similar to that of timber. The optimal sleeper shape proposed in this study effectively utilises the fibre composite materials for more cost-effective railway sleepers, which can provide an effective alternative to timber sleepers in a mainline track. The experimental data, proposed theoretical model and finite element simulation can be important tools for a safe design of fibre reinforced composite sleepers. With further evaluation of its in-track performance and dynamic behaviour, this timber replacement composite sleepers is expected to save approximately 470 mature trees for each kilometre of rail-track construction, reduce carbon footprint, decrease track maintenance, and provide a sustainable sleeper technology.

## Directions of future research

The manufacturing, handling and installation of the optimal composite sleeper requires careful attention due to this non-uniform shape. Furthermore, the following studies are proposed for future research to increase the confidence of using this innovative composite sleeper technology:

- *Dynamic impact and fatigue behaviour:* The optimal composite sleeper was found to perform satisfactorily under static load. However, abnormalities can arise in either a rail track or train wheels (such as wheel flat or dipped rail) which produce higher frequency and, consequently, higher magnitude forces than a quasi-static load due to their additional dynamic effects, and called impact forces. As the tracks often induce high-magnitude impact loads and million cycles repeated loads, the impact resistance and fatigue behaviour of composite sleepers are inevitably required to define safety and reliability based design. This investigation is particularly important for composites because of their non-homogeneous and anisotropic nature, and they can fail by fibre cracking, de-bonding, de-lamination and matrix cracking.
- *Long term performance:* The trialled sleepers in the Queensland Rail track are performing well. Continuous evaluation of its in-track performance will provide information on the creep deformation and lateral track resistance of this new sleeper technology. The effect of creep creates stress relaxation, and subsequently the fastening system tends to become loose, particularly in a curved track, which has an adverse effect on gauge holding. More research needs to be conducted to investigate their behaviour under permanent rail track loads.
- *Design guidelines for composite sleepers:* There is no recognised standard guideline for the design of composite sleeper. The results of the experimental investigation, theoretical evaluation and finite element simulation from this study could contribute to the development of design and specifications for fibre reinforced composite sleepers. At present, the design philosophy for composite sleepers is based on the permissible stress concept resulting from quasistatic wheel loads which could be more realistic if it incorporated both dynamic and static design requirements. Establishing design guidelines is important as it will provide instructions to the design engineers for a safe and reliable design of composite sleepers.

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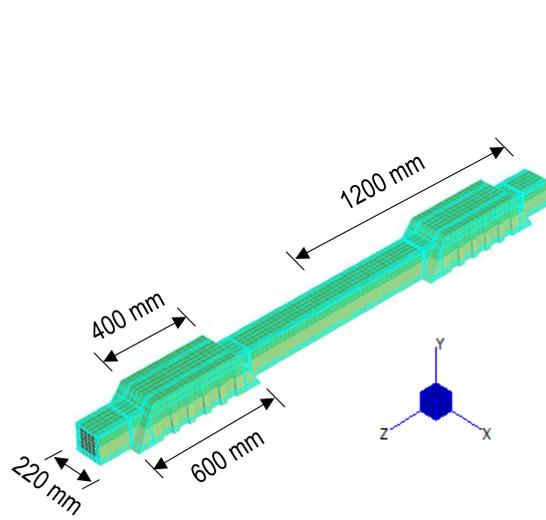
## *Appendix A: Additional study*

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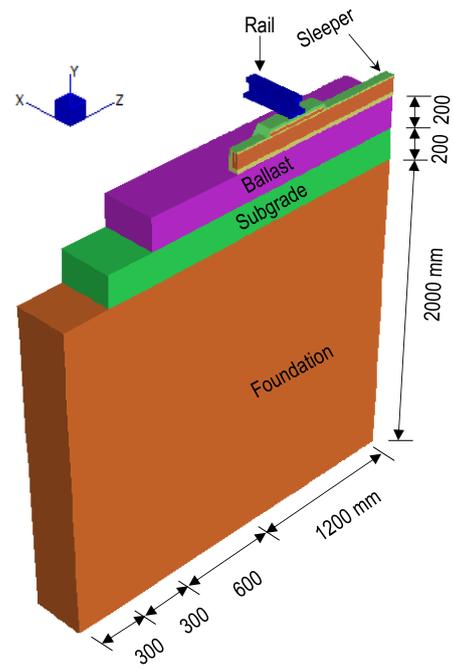
### **A.1: Heavy-duty composite railway sleepers**

Australia's railway industry have significant demands of heavy-haul railway sleepers due to their widespread mining facilities. Currently, prestressed concrete is the commonly used sleeper in heavy-haul rail network. However, they suffer degradation before the end of their design life by unexpected cracking due to chemical attack and rail-seat deterioration which increases the track maintenance cost. The environmental protection agency is also very concerned regarding the huge carbon emission from the cement industry which is the basic materials for manufacturing concrete sleeper. The need for improved performance of sleeper is becoming a new challenge as the freight axle loads are increasing in Australia. The environmentally friendly composite materials could be an alternative to concrete for manufacturing sleeper as composites have high resistance to chemical attack and have been used successfully in structural application. On the other hand, the epoxy based polymer concrete has the superior properties to prevent abrasion which is the primary causes for rail seat deterioration. This study investigated the performance of a sandwich composite railway sleeper coated with polymer concrete for the heavy-haul rail track. In contrast with the traditional shape of sleeper, the investigated sleeper has an innovative design which significantly reduces the volume of materials in the sleeper leading to reduced manufacturing cost.

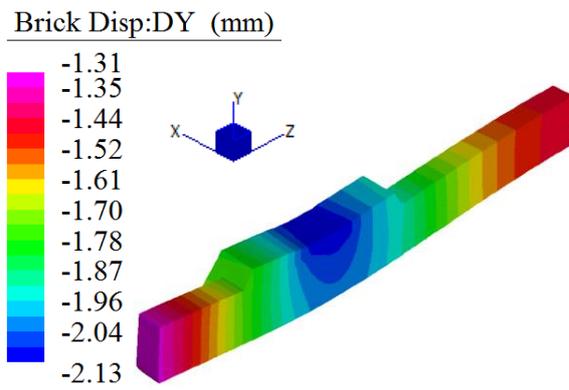
The dimensions of the sleeper in finite element model are provided in Figure A.1. The innovative design of sleeper satisfies the dimensional requirements of heavy-duty sleeper of length between 2390 – 2500 mm, width at base between 220 – 255 mm, depth at the centre of rail-seat within 230 mm, and the minimum rail-seat area of 28800 mm<sup>2</sup> according to the engineering specification of heavy-duty sleeper in Australia. The performance of heavy-duty composite sleeper in the high stiffness support foundation is evaluated numerically under 130 kN design rail-seat load. Only a quarter model is analysed as the other three quarter are symmetric. Results showed that the maximum vertical deflection and sleeper-ballast contact pressure are 2.13 mm and 674 kPa which are within the maximum allowable track deflection of 6.35 mm and sleeper-ballast contact pressure of 750 kPa, respectively. Therefore, the concept of sandwich panels bonded with epoxy polymer matrix could be a sustainable solution for heavy-duty railway sleeper application.



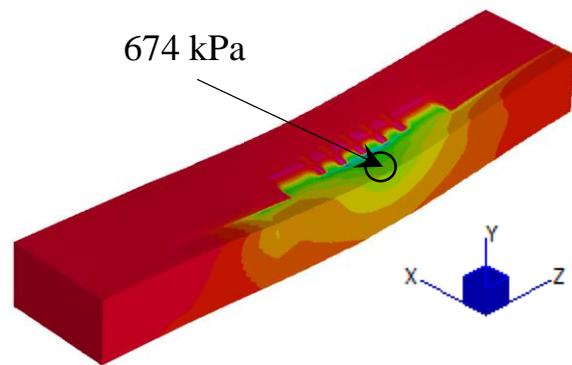
(a) Heavy-duty composite sleeper



(b) Sleepers' on high stiffness foundation



(c) Deflection behaviour



(d) Sleeper-ballast contact pressure

Fig. A.1: Analysis of heavy-duty composite railway sleeper

## *Appendix B: Conference presentations*

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The major outcomes of this study were presented for receiving feedback to improve the quality of this study in several national and international reputed conferences, including, *Conference on Fibre-Reinforced Polymer Composites in Civil Engineering (CICE)*, Joint conference of *Fibre Reinforced Polymers for Reinforced Concrete Structures (FRPRCS)* and *Asia-Pacific Conference on Fibre Reinforced Polymers in Structures (APFIS)*, *Australasian Conference on the Mechanics of Structures and Materials (ACMSM)*, *Biennial National Conference of the Concrete Institute of Australia (Concrete)*, *Australasian Structural Engineers Conference (ASEC)*, *Advanced Composites Innovation Conference (Composite Australia)*, *International Conference on Infrastructure Failures and Consequences (ICIFC)*, and the railway industry related conference of *International Heavy Haul Association Conference (IHHA)* and *Conference on Railway Excellence (CORE)*. A brief description of these conference presentations are provided below.

### **B.1: Review of failures of railway sleepers and its consequences**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Alex Remennikov, "Review of failures of railway sleepers and its consequences," *1st International Conference on Infrastructure Failures and Consequences (ICIFC)*, 16 – 20 July 2014, Melbourne, Australia.

**Abstract:** Railway sleeper is one of the important structure that having problems with high maintenance and replacement costs owing to its early failure. This paper presents the causes of failures of the traditional railway sleepers particularly timber, concrete and steel, and discussed its effect on the railway industry. The review of literature indicates fungal decay, end splitting and termite attack are the typical causes of timber sleeper failure. In case of concrete sleeper, deteriorations are observed because of rail seat abrasion, longitudinal cracking, high impact force and chemical attack. Failures in steel sleepers are mainly due to corrosion and fatigue cracking at the rail seat region. These unexpected failures of sleeper significantly increase the track maintenance costs. This paper also presents some recommendations to minimise sleeper failures for their safer usage.

## **B.2: Composite railway sleepers: New developments and opportunities**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, "Composite railway sleepers: new developments and opportunities," *11th International Heavy Haul Association Conference*. 21 - 24 Jun 2015, Perth, Australia.

**Abstract:** Composite sleeper is becoming a suitable alternative for replacing the existing concrete, steel and particularly timber sleeper in both mainline and heavy haul rail network. Composite sleeper technologies are already available in the last 20 years but they have gained limited acceptance by the railway industry. For better understanding of the reasons for their slow uptake in the market, a comparative study was conducted among the existing composite sleepers. Firstly, this paper accumulated information on the performance of commercially available composite sleepers. Secondly, issues on the application and developments of composite sleepers are identified. Thirdly, the ongoing research on the composite sleeper is presented for keeping update the sleeper researchers, engineers and end users. The potential of sandwich composite for overcoming the current limitations of composite sleeper is briefly discussed. Finally, this paper provided suggestions and recommended solutions to increase the market opportunities of composite sleepers.

## **B.3: Recent developments and applications of composite railway sleepers**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, "Recent developments and applications of composite railway sleepers," *Conference on Railway Excellence (CORE)*. 16 - 18 May 2016, Melbourne, Australia

**Abstract:** Several composite sleeper technologies have been developed in different parts of the world. These technologies have emerged as a potential alternative to timber sleepers. Different from steel and concrete, composite sleepers can be designed to mimic timber behaviour (an essential requirement for timber track maintenance), are almost maintenance free, and are more sustainable from an environmental perspective. This paper presents and compares the performance of currently available composite railway sleeper technologies with different amounts, length and orientation of fibres and including their application. The common challenges encountered in using composite sleepers are also discussed. Finally, potential

approaches are suggested to overcome the challenges in the utilisation and acceptance of composite sleeper technologies.

#### **B.4: Design of epoxy resin based polymer concrete matrix for composite railway sleeper**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, " Design of epoxy resin based polymer concrete matrix for composite railway sleeper," *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*, 9 - 12 Dec 2014, Byron Bay, Australia, pp. 137-142.

**Abstract:** A new type of railway sleeper made from composite materials is now being developed to replace deteriorating timber sleepers. To protect it from unfavorable environments and to increase the strength at rail-seat area, the sleeper is coated with epoxy based polymer concrete. This paper investigates the properties of the polymer concrete matrix with different percentages of epoxy resin binder and light-weight particulate filler. The mixing proportion of Particulate Filled Resin (PFR) was optimised while targeting a specific strength and workability. The content of epoxy resin was varied from 40 to 100% whereas the filler material ranged from 0 to 60%. The flexural performance of PFR was evaluated using three-point bending tests and the most suitable mix proportion is determined based on the experimental results.

#### **B.5: Effect of ultraviolet radiation on the physical and mechanical properties of polymer matrix**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, "Effect of ultraviolet radiation on the physical and mechanical properties of polymer matrix," *27th Biennial National Conference of the Concrete Institute of Australia (Concrete 2015) in conjunction with the 69th RILEM Week conference*. 30 Aug - 02 Sept 2015, Melbourne, Australia.

**Abstract:** In recent years, the use of polymer concrete have become a promising choice in outdoor applications such as repair concrete structures, beams and slabs of small cross section and coating of railway sleepers, is subjected to degradation caused by photochemical reactions from solar ultraviolet (UV) radiation. Any small damage in polymer matrix can be detrimental to the overall mechanical performance of the structure as it binds and transfers load to the

reinforcement. This paper deals with the effect of UV radiation on the physical and mechanical properties of epoxy resin based polymer matrix. Seven different mixes containing filler materials from 0 to 60% with an increment of 10% were exposed to UV radiation using accelerated laboratory testing. Specimens were subjected to 2000 hours of UV radiation by Xenon 2200-watt air cooled lamp in the sunset XLS chamber and subsequently weighed, examined by microscope and mechanically tested. Surface degradation in the form of discoloration were observed by microscopic observation. It was found that, the loss of specimen's weight decreased with the increase of filler materials in the mix. Significant decrease of flexural strength was observed in the mixes containing filler volume up to 20%. However, no reduction of flexural strength was noticed for the higher filler ( $\geq 30\%$  filler) containing mixes indicating the filler can help to preserve the structural performance by absorbing or blocking UV radiation before it reaching the chromophores in polymer matrix.

## **B.6: Thermo-mechanical behaviour of epoxy based polymer matrix**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, "Thermo-mechanical behaviour of epoxy based polymer matrix," *27th Biennial National Conference of the Concrete Institute of Australia (Concrete 2015) in conjunction with the 69th RILEM Week conference*. 30 Aug - 02 Sept 2015, Melbourne, Australia.

**Abstract:** This study revealed the dynamic mechanical behavior of polymer matrix having different percentage of filler contents. Epoxy resin based polymer matrix were prepared and characterized their dynamic mechanical properties such as storage (elastic) modulus, loss (viscous) modulus and tan delta (damping coefficient) as a function of temperature. The temperature was applied from 30 to 120 °C with 5 °C increment and the specimens were clamped for dual cantilever bending. A total of seven different mixes with a filler volume increment of 10% started from zero filler mix (100% resin) were casted and the glass transition temperature were evaluated for each of the specimens. Knowing this temperature is important for the polymer matrix as the mechanical properties of material can change dramatically when the specimens are subjected to a temperature beyond this point. Results showed that the gradual increase of filler materials in the polymer matrix can shift the state of materials progressively from viscous to elastic. However, a slight increase of glass transition temperature was obtained among all seven mixes which ranged from 50 to 55 °C when using storage modulus or loss modulus curve and 60 to 65 °C when using peak of tan delta. To evaluate the effect of

temperature and fatigue loading on specimens during the execution of Dynamic Mechanical Analysis (DMA), the flexural properties of the invaded samples were tested using three point bending once the specimens cool down to the normal temperature. It was found that the dual action of temperature and repeated loading can reduce flexural strength and modulus significantly.

## **B.7: Optimal polymer matrix coating for composite railway sleeper – Analytic hierarchy process**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, "Optimal polymer matrix coating for composite railway sleeper – Analytic Hierarchy Process," *The joint conference of 12th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-12) and 5th Asia-Pacific Conference on Fiber Reinforced Polymers in Structures (APFIS-2015)*. 14 - 16 Dec 2015, Nanjing, China.

**Abstract:** The deterioration of the mechanical properties due to environmental exposures is now becoming an issue in the use of fibre composite materials in civil infrastructure. In this study, seven polymer mixes with different percentages of epoxy resin-to-filler ratio has been considered as a coating material for composite railway sleepers. Selecting a particular one from the seven mixes has become a major challenge as the variation on the filler content enhanced some of the physical and mechanical properties of the polymer matrix but degrade some important properties at the same time. To obtain the most suitable polymer coating and to utilise its maximum benefits, the Analytic Hierarchy Process (AHP) was implemented to select the optimal polymer mix for coating of a composite railway sleeper. Initially, three suitable mixes were shortlisted out of total seven based on their satisfaction of the performance requirements of a timber replacement composite railway sleeper. The AHP method was then applied to select the best suited mix out of three alternatives based the thermal, physical, mechanical, durability and cost properties. The results of this analysis found the polymer mix with a resin-to-filler ratio of 70:30 is the most preferred coating when mechanical properties are given the highest priority followed by cost, durability, thermal and physical properties for composite sleeper application.

## **B.8: Behaviour of composite sandwich beams with different shear span-to-depth ratios**

Wahid Ferdous, Allan Manalo, and Thiru Aravinthan, "Behaviour of composite sandwich beams with different shear span-to-depth ratios," *24th Australasian Conference on the Mechanics of Structures and Materials (ACMSM24)*. 6 - 9 Dec 2016, Perth, Australia.

**Abstract:** A novel composite sandwich beam made up of glass fibre reinforced polymer (GFRP) skins and phenolic core material has been developed for use in civil infrastructure applications. To understand the shear and flexural behaviour of the sandwich systems, static bending test was conducted using beams in different orientations and with varying shear span-to-depth ( $a/d$ ) ratios. The beams were cut into 20 mm  $\times$  40 mm cross section and tested in both flatwise (GFRP skin in horizontal plane) and edgewise (GFRP skin in vertical plane) orientation with  $a/d$  ratios of 2, 4 and 6. The results showed that the  $a/d$  ratio has a significant influence on the development of bending and shear stresses affecting the mode of failure. In flatwise position, the observed failure modes were (a) core shear ( $a/d = 2$ ), (b) core shear followed by de-bonding between core and skin ( $a/d = 4$ ), and (c) skin compression followed by de-bonding between core and skin ( $a/d = 6$ ). In edgewise orientation, the failure was governed by (a) skin shear ( $a/d = 2$ ), and (b) core tension followed by skin shear and skin compression ( $a/d$  at 4), and (c) core tension followed by skin compression and buckling. The beams at edgewise orientation can provide 1.94 times higher bending stiffness and better ductile properties than the flatwise orientation with the same beam dimensions. The increase of shear span-to-depth ratio from 2 to 6 decrease the load carrying capacity of the beam and gradually changes the beam behaviour from shear to flexural dominance.

## **B.9: Bond behaviour of composite sandwich panel and epoxy polymer matrix**

Wahid Ferdous, Allan Manalo, and Thiru Aravinthan, "Bond behaviour of composite sandwich panel and epoxy polymer matrix," *8th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE)*. 14 - 16 Dec 2016, Hong Kong.

**Abstract:** Fibre composite sandwich panel made up with glass fibre reinforced polymer skins and phenolic foam core can be glued or cast together to produce a large structural beam section. To ensure the structural integrity and composite action, the sandwich panels should be

effectively bonded with polymer matrix. However, the bond behaviour between sandwich panel and polymer matrix is not well understood. This paper experimentally investigated the effect of epoxy polymer matrix properties, bond length, bond thickness, and bond width on the bond behaviour, and evaluated the optimal parameters for effective bonding. The experimental program was designed by Taguchi method to reduce the number of experiments. Results showed that the polymer matrix consist with 40% filler and 60% resin (by volume) is the optimal binder. A bond length of at least 70 mm and bond thickness of 5 mm were found effectively to utilise the strength of the composite sandwich panel. The bond width however has insignificant effect on the bond strength.

### **B.10: Evaluation on the structural performance of sandwich composite beams for railway sleepers**

Wahid Ferdous, Allan Manalo, and Thiru Aravinthan, "Evaluation on the structural performance of sandwich composite beams for railway sleepers," *Australasian Structural Engineers Conference (ASEC)*. 23 - 25 Nov 2016, Brisbane, Australia.

**Abstract:** Structural composite sandwich panels made up with glass fibre reinforced polymer skins and phenolic foam core have been developed for civil engineering and constructions. Several layers of panels can be cast together using epoxy polymer matrix (consisting of epoxy resin and filler materials) to carry higher loads. This paper investigated the behaviour of full-scale beams under four point bending with different sandwich orientations and shear span-to-depth ratios. The structural performance of the composite beam is then evaluated for suitability as an alternative sleeper material in a narrow-gauge railway track. Results showed that, the sandwich beams can satisfactorily meet the requirements of the composite sleepers.

### **B.11: Structural optimisation of composite railway sleeper**

Wahid Ferdous, Allan Manalo, and Gerard Van Erp, "Structural optimization of composite railway sleeper," *Composites Australia and CRC – ACS Conference*, 7 – 9 April 2014, Newcastle, Australia.

**Abstract:** Structural optimisation of composite railway sleeper is becoming an important area of research to effectively use composite materials and minimising their manufacturing costs. This study used the finite element approach to structurally optimise a composite sleeper for a

mainline railway track and evaluate their performance. Strand7 finite element simulation is executed to achieve this goal. This study presents the optimised shape of a sleeper which requires only one-third volume to that of a standard rectangular sleeper. The performance of the optimised sleeper is determined in a high and low stiffness support foundation and the results obtained from this analysis are compared with the behaviour of traditional timber sleeper. The new composite sleeper showed comparable behaviour with that of timber sleeper and performed within their allowable limit.

### **B.12: Performance of an innovative composite railway sleeper**

Wahid Ferdous, Allan Manalo, and Thiru Aravinthan, "Performance of an innovative composite railway sleeper," *Advanced Composites Innovation Conference*. 29 - 30 March 2017, Sanctuary Cove, Australia.

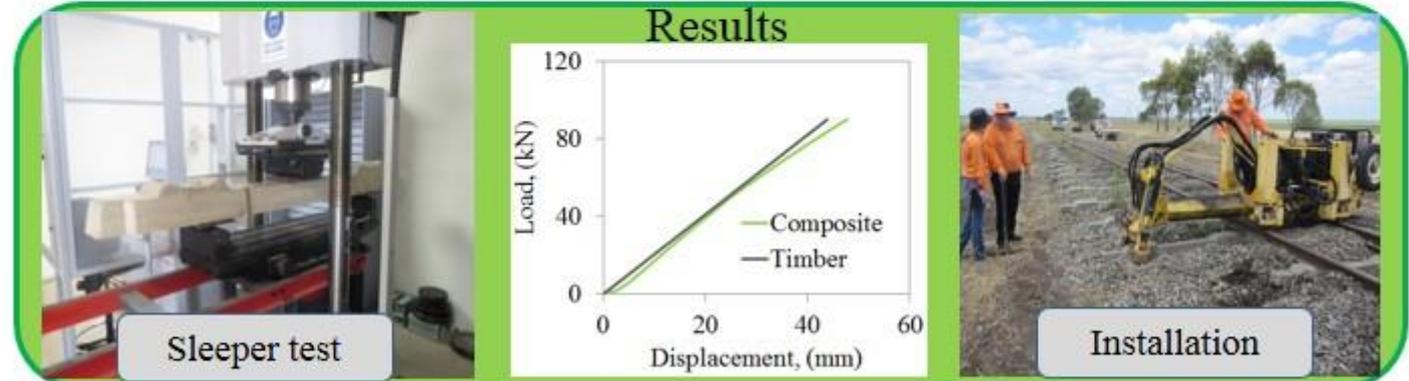
**Abstract:** The high maintenance cost and scarcity of the hardwood timber promote alternative technologies for replacing the timber railway sleepers. The advantages of composites in high strength-to-weight ratio, durability, reliability, longer life and less maintenance are of great interest for their application in railway sleepers. This study investigated the performance of an innovative composite railway sleeper manufactured from sandwich panels and bonded with the epoxy polymer matrix. The performance including rail-seat vertical load, centre bending moment, shear strength, screw holding capacity and electrical resistance have been investigated and compared with the timber sleepers. Results showed that the new composite sleeper can maintain the minimum performance requirements and showed a very similar behaviour to the timber ones. This innovative composite technology could be a suitable replacement to the existing timber sleepers.

### **B.13: Composite Railway Sleeper: A cost effective and eco-friendly alternative**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, "Composite railway sleeper: a cost effective and eco-friendly alternative," *Australia and New Zealand Student and Young Professionals Congress – (ANZSCON)*, 3 – 5 July 2014, Brisbane, Australia.

### **B.14: Structural performance of heavy duty composite railway sleeper**

Wahid Ferdous, Allan Manalo, Thiru Aravinthan, and Gerard Van Erp, "Structural performance of heavy duty composite railway sleeper," *11th International Heavy Haul Association Conference*. 21 - 24 Jun 2015, Perth, Australia.



### Conclusions:

- Optimised shape reduces two-third volume of materials
- Composite sleeper behaviour is comparable with timber



# Structural performance of heavy duty composite railway sleeper



Wahid Ferdous<sup>1</sup>, Allan Manalo<sup>1</sup>, Thiru Aravinthan<sup>1</sup>, Gerard Van Erp<sup>2</sup>

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 2. Former professor, CEEFC, University of Southern Queensland, Toowoomba, QLD 4350, Australia



## Introduction

- Heavy duty mono-block prestressed concrete sleeper currently suffers from rail-seat deterioration and unexpected cracking due to chemical attack.
- Early failure of sleeper increases the track maintenance cost.
- The production of cement for infrastructure (e.g., concrete sleeper) contributes to more than 5% of global carbon dioxide emission.
- Composites are now an emerging materials because they are environmentally friendly, have high strength and good resistance to chemical attack.



Fig. 1: Environmental and durability issues

Are composite materials a suitable alternative for heavy duty railway sleeper application?

## Objective

- To investigate the performance of sandwich composites coated with polymer concrete and determine their suitability for heavy duty sleeper application.

## Materials and method

### Composite railway sleeper concept



Fig. 2: Composite sleeper concept

### Optimization

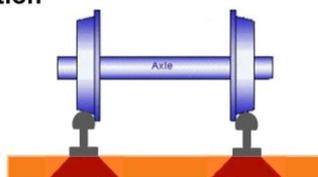


Fig. 3: Load distribution

## Analysis and results

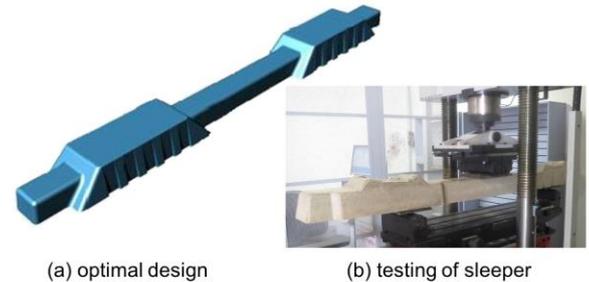


Fig. 4: Optimised composite sleeper

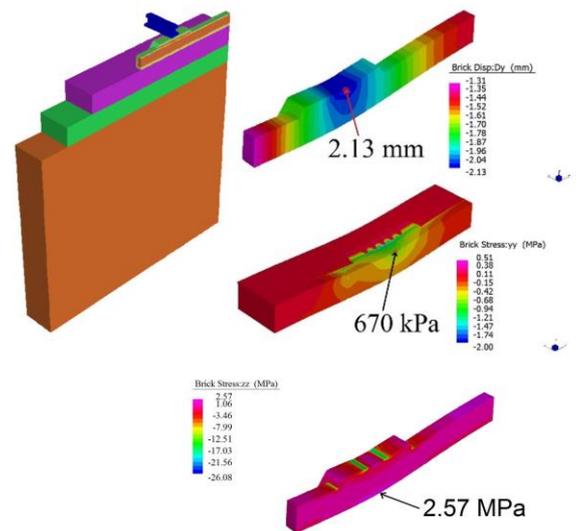


Fig. 5: Composite sleeper on high stiffness support foundation

Table 1: Performance of composite sleeper

Parameters	Results	Allowable limits
Deflection of sleeper, (mm)	2.13	6.35
Sleeper-ballast contact pressure, (kPa)	670	750
Tensile bending stress, (MPa)	2.57	5.5

## Conclusions

- Optimal composite sleeper design reduces approximately two-third volume of material usage.
- Structural performance of composite sleeper complies with the design requirements for heavy duty railway sleeper.

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## Appendix C: Supporting information

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### C.1: Recycled plastic sleepers



TieTek



Axion



IntegriCo



I-Plas



Tufflex



Natural rubber



KLP



MPW



Wood core

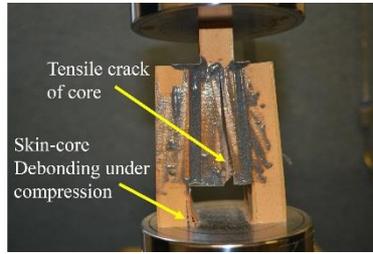
Fig. C.1: Photos in larger size extracted from Article II, Table 1

## C.2: Details of the bond specimens

The details of the bond specimens are provided in the subtitle of the photos for better understanding.



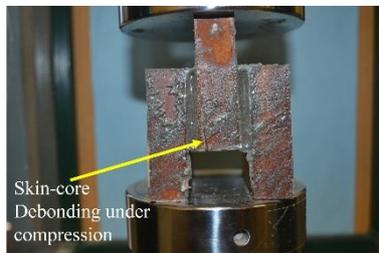
(a)  $F_{30}l_{40}t_{m3}b_{20}$  (Adhesive)



(b)  $F_{30}l_{70}t_{m5}b_{40}$  (Panel)



(c)  $F_{30}l_{100}t_{m10}b_{80}$  (Cohesive)



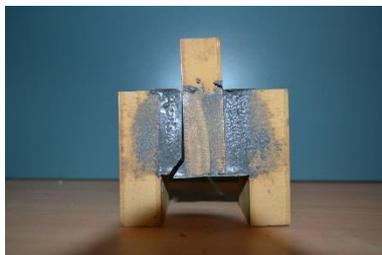
(d)  $F_{40}l_{40}t_{m5}b_{80}$  (Panel)



(e)  $F_{40}l_{70}t_{m10}b_{20}$  (Cohesive)



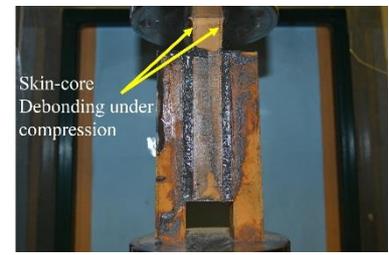
(f)  $F_{40}l_{100}t_{m3}b_{40}$  (Adhesive)



(g)  $F_{50}l_{40}t_{m10}b_{40}$  (Cohesive)



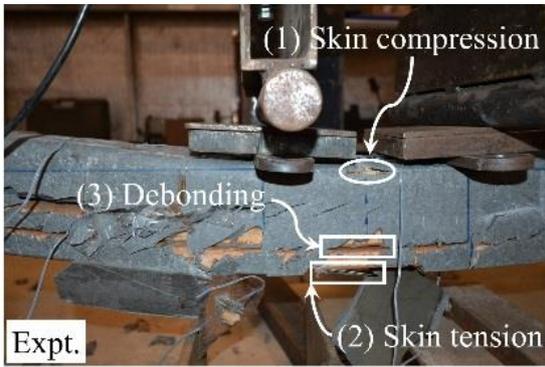
(h)  $F_{50}l_{70}t_{m3}b_{80}$  (Adhesive)



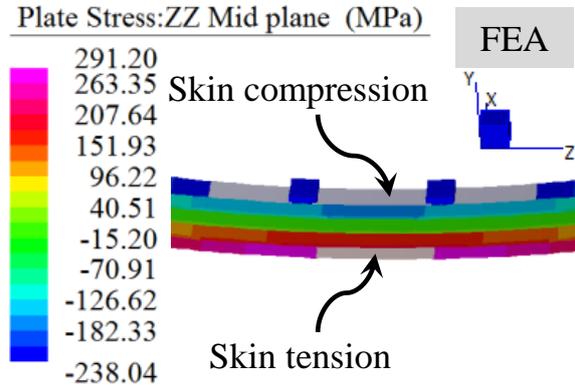
(i)  $F_{50}l_{100}t_{m5}b_{20}$  (Panel)

Fig. C.2: Details of Figure 5 in Article V

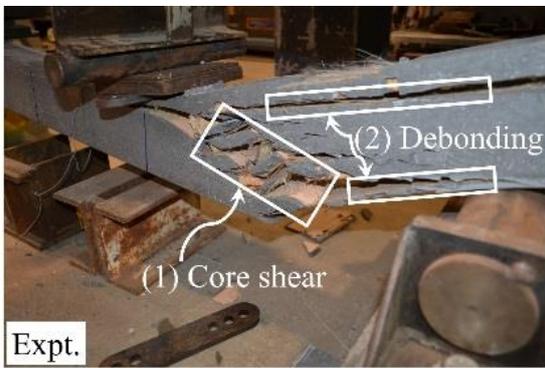
### C.3: Failure loads and failure modes of the LSB



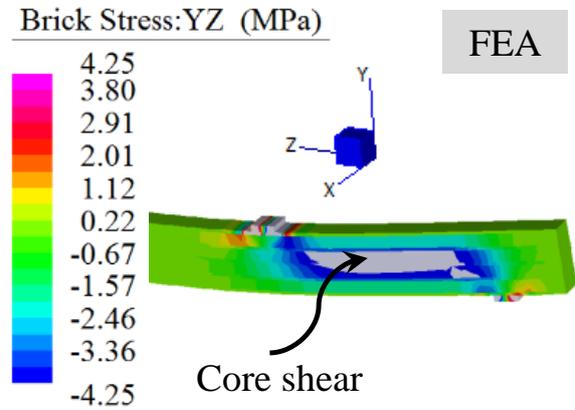
(a) HF-A<sub>600</sub> at 28.3 kN



HF-A<sub>600</sub> at 32 kN



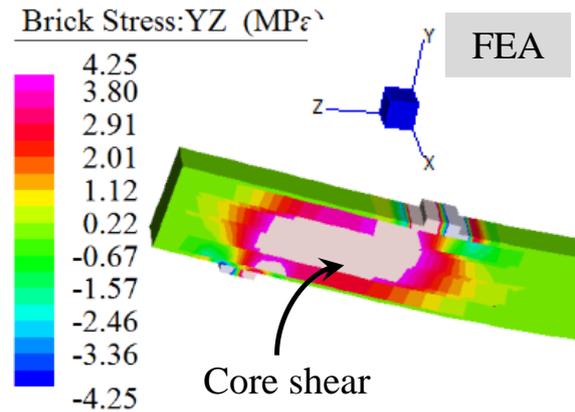
(b) HF-A<sub>400</sub> at 50.9 kN



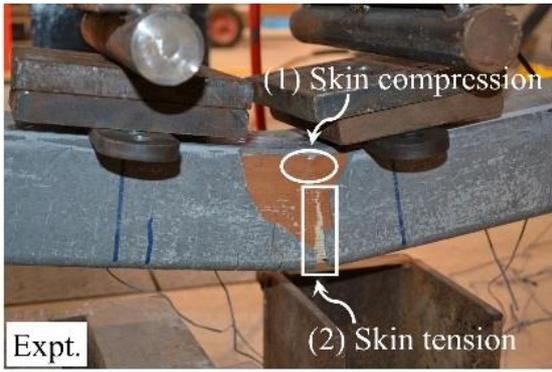
HF-A<sub>400</sub> at 53 kN



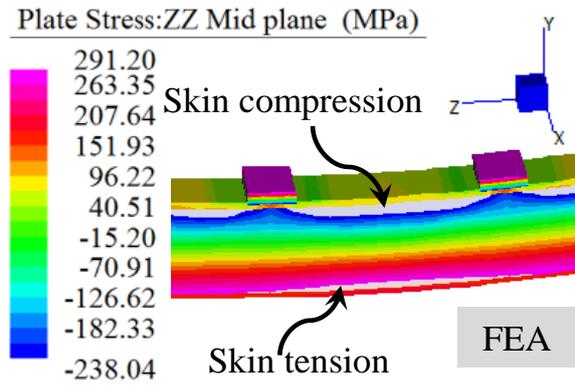
(c) HF-A<sub>200</sub> at 90.8 kN



HF-A<sub>200</sub> at 85 kN



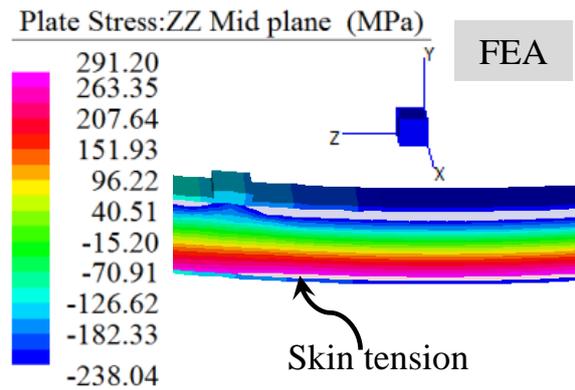
(d) VF-A<sub>600</sub> at 28.8 kN



VF-A<sub>600</sub> at 26 kN



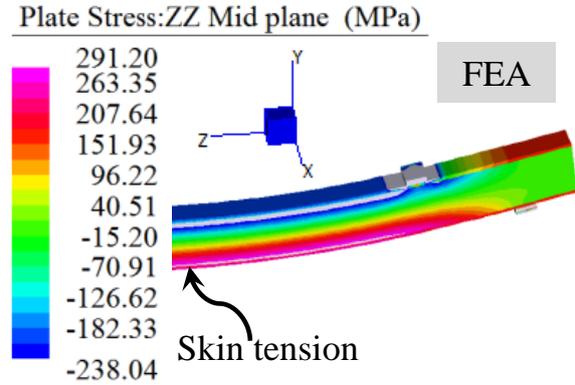
(e) VF-A<sub>400</sub> at 40.1 kN



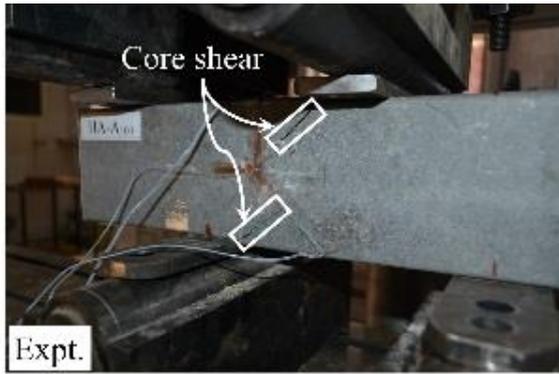
VF-A<sub>400</sub> at 38 kN



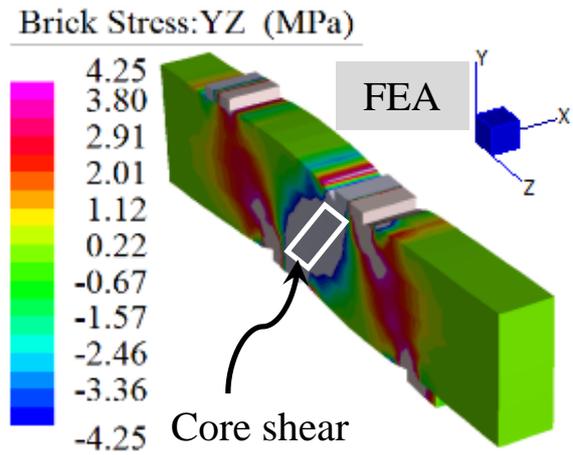
(f) VF-A<sub>200</sub> at 76.4 kN



VF-A<sub>200</sub> at 74 kN



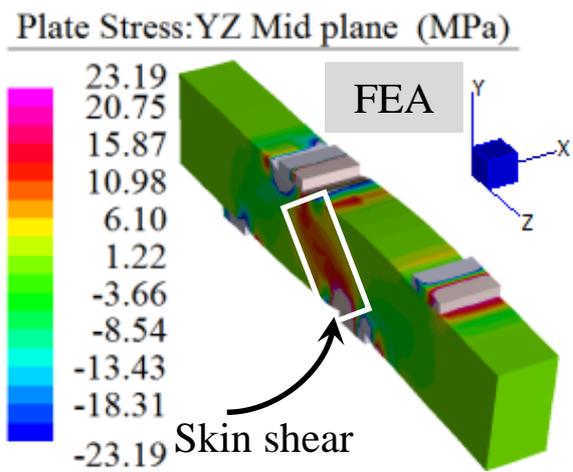
(g) HA-A<sub>100</sub> at 220 kN



HA-A<sub>100</sub> at 213 kN



(h) VA-A<sub>100</sub> at 315 kN



VA-A<sub>100</sub> at 305 kN

Fig. C.3: Detailed photos in larger size extracted from Article VI, Figure 4

## *Appendix D: Copyright information*

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### **D.1: Article I: Failures of mainline railway sleepers and suggested remedies – Review of current practice**

**Wahid Ferdous** and Allan Manalo, (2014). "Failures of mainline railway sleepers and suggested remedies – Review of current practice" *Engineering Failure Analysis*, vol. 44, pp. 17–35. (Top 10% journal; Impact Factor: 1.676 and SNIP: 1.681).

DOI: <http://dx.doi.org/10.1016/j.engfailanal.2014.04.020>

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## **D.2: Article II: Composite railway sleepers – recent developments, challenges and future prospects**

**Wahid Ferdous**, Allan Manalo, Gerard Van Erp, Thiru Aravinthan, Sakdirat Kaewunruen, and Alex Remennikov, (2015). "Composite railway sleepers – recent developments, challenges and future prospects" *Composite Structures*, vol. 134, pp. 158–168. (Top 10% journal; Impact Factor: 3.858 and SNIP: 2.033).

DOI: <http://dx.doi.org/10.1016/j.compstruct.2015.08.058>

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### **D.3: Article III: Properties of epoxy polymer concrete matrix: Effect of resin-to-filler ratio and determination of optimal mix for composite railway sleepers**

**Wahid Ferdous**, Allan Manalo, Thiru Aravinthan and Gerard Van Erp, (2016). "Properties of epoxy polymer concrete matrix: Effect of resin-to-filler ratio and determination of optimal mix for composite railway sleepers" *Construction and Building Materials*, vol. 124, pp. 287–300. (Top 10% journal; Impact Factor: 3.169 and SNIP: 2.339).

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**Wahid Ferdous**, Allan Manalo and Thiru Aravinthan, (2017). "Effect of beam orientation on the static behaviour of phenolic core sandwich composites with different shear span-to-depth ratios" *Composite Structures*, vol. 168, pp. 292–304. (Top 10% journal; Impact Factor: 3.858 and SNIP: 2.033).

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## **D.5: Article V: Bond behaviour of composite sandwich panel and epoxy polymer matrix: Taguchi design of experiments and theoretical predictions**

**Wahid Ferdous**, Allan Manalo and Thiru Aravinthan. "Bond behaviour of composite sandwich panel and epoxy polymer matrix: Taguchi design of experiments and theoretical predictions" *Construction & Building Materials*, vol. 145, pp. 76–87. (Top 10% journal; IF: 3.169 and SNIP: 2.339).

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