

CRANFIELD UNIVERSITY

QIHONG JIANG

SUSTAINABLE SANDWICH COMPOSITES FOR AUTOMOTIVE
APPLICATIONS

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING
PhD IN MANUFACTURING

DOCTOR OF PHILOSOPHY
Academic Year: 2019 - 2022

Supervisor: Sameer Rahatekar
Associate Supervisor: Andrew Mills
October 2022

CRANFIELD UNIVERSITY

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING
PhD IN MANUFACTURING

DOCTOR OF PHILOSOPHY

Academic Year 2019 – 2022

QIHONG JIANG

SUSTAINABLE SANDWICH COMPOSITES FOR AUTOMOTIVE
APPLICATIONS

Supervisor: Sameer Rahatekar
Associate Supervisor: Andrew Mills
October 2022

This thesis is submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

© Cranfield University 2022. All rights reserved. No part of this
publication may be reproduced without the written permission of the
copyright owner.

ABSTRACT

The increasing regulation and demand are raising the pressure on manufacturing automotive components towards lighter weight and more recyclability. The commercial road transport industry, contributing a giant part of emissions, is still significantly utilising wood panels as trucks'/ lorries'/ vans'/ buses' floor or side walls (of boxes), which is cost-effective and used for a very long time. However, with the increasing pressure on lighter weight and more recyclability, the wood panels that could cause deforestation, become a bio-degradable landfill at the end of life and have a relatively high density are no longer the best-fit choice for the floor or side panels of such vehicles. The challenge is to have a floor panel design that could satisfy the increasing pressure and product requirements such as mechanical properties, price, and durability.

This research aimed to complete such a challenge by designing sandwich composite structures with fibre-reinforced plastics and foam materials (foam is used in case thermal resistance is needed, and honeycomb materials could be applied when thermal insulating is unnecessary). A fully recyclable sandwich composite achieved using recycled carbon fibre, polypropylene, and recycled PET foam underwent various tests to evaluate its applicability as a commercial transport vehicle floor or side panel. Single fibre tensile tests were operated to understand the behaviour of the RCF mats. Composite mechanical properties were estimated from tensile and three-point bending results, and impact behaviour was analysed after drop tower impact testing. Fibre embedding and sandwich bonding were verified under SEM, and the resulting sandwich composite product properties were also tested using three-point bending.

The novelty of such sandwich composite is using RCF with PP to achieve a fully recycled composite skin, while RCF were used mainly with thermoset resin (in the same ways as virgin carbon fibre fabrics). Also, thermoplastic materials such as PP were hard to process with fibre fabrics to form suitable composites due to their non-polar constitution and high viscosity. Fibre fabric would be squeezed together and create a layered structure with fibre rich zone at a very

high fibre volume fraction, while the intermedia zone mostly has resins. However, when RCF and PP are mixed, the randomly oriented fibre could also hinder the load from the viscose melt and reduce the amount of fabric pressed closely, forcing some of the melt to pass through inter-fibre areas to create a better filling. Different forms of PP (sheet, powder) were used, and their effect on the compression moulding process and the final product were studied in this research. A faster-pressing cycle was achieved, and a lower pressing pressure was needed for the powder PP process, but disadvantages came from the emission and cost side.

Keywords:

Recycled carbon fibre, polypropylene, PET foam, compression moulding, tensile, three-point bending.

ACKNOWLEDGEMENTS

Firstly, I am grateful for the financial support provided by my parents and the research opportunity from the composite centre at Cranfield University.

I am thankful to both of my supervisors, Sameer Rahatekar and Andrew Mills for the research opportunity and their continuous mentoring and teaching during my research. I would also like to thank them for being patient and guiding me through it and helping me to develop my knowledge and technical expertise during the difficult times (COVID-19) during my PhD.

I would like to thank all the technical staff at the composite centre and other facilities at Cranfield University who trained, helped, and supported me and my experimental work. Many thanks to David Ayre for their professional guidance on polymers and DSC training. Many thanks to Jim Hurley for the training in the central composite lab, including all the work of sample preparation, manufacturing, post-treatment and cutting. Thank you, Ben and Andrea, for training, guiding, and supporting all the mechanical testing. Thank you, Steve and Tracy, for the training and support on microscopies. And a brief thank you to the staff in the workshop for the introduction and assistance with sample cutting via CNC machines.

Thank you to the supportive and friendly research staff and PhD colleagues within the composite centre. Many of you have helped me during my PhD study through both social and technical conversations.

A special thanks to my wife for the constant support, advice, help, and motivation during my PhD, especially when we could not meet in person for more than one year due to COVID. She decided to move to the UK from China and stay together with me.

TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTS.....	iii
LIST OF FIGURES.....	vi
LIST OF TABLES	viii
LIST OF EQUATIONS.....	ix
LIST OF ABBREVIATIONS	x
1 Introduction.....	1
1.1 Background, Motivation, Challenge	1
1.2 Aim & Objectives.....	9
2 Literature Review	11
2.1 Sandwich Composite Design – Structures and Materials	11
2.1.1 Sandwich Composite for Automotive Application – Advantages and Disadvantages	11
2.1.2 Floor Panels	13
2.1.3 Fibres in Composite	14
2.1.4 Matrix Selection – Thermoplastic vs Thermoset.....	17
2.1.5 Sandwich Core	19
2.1.6 Summary	20
2.2 Manufacturing Process and Design	21
2.2.1 Manufacturing Techniques for Automotive Composites	21
2.2.1.1 Resin Transfer Moulding.....	22
2.2.1.2 Reaction Injection Moulding.....	24
2.2.1.3 Vacuum Assistant Resin Infusion	25
2.2.1.4 Compression Moulding	26
2.2.2 Manufacturing Techniques for PP Composite	28
2.2.3 Manufacturing Parameters	35
2.2.4 Combination Techniques with Sandwich Core	37
2.2.5 Summary.....	39
2.3 Testing and Standards.....	40
2.3.1 Calculations in Sandwich Composites.....	41
2.3.2 Three Point Bending Testing	43
2.3.3 Drop Tower Impact Testing	45
2.3.4 Microscopy Image	47
2.3.5 Summary	49
2.4 Composite Material Recycling	50
2.4.1 General Recycling Process of Fibre Composites	51
2.4.2 On Recycling: Thermoplastic vs Thermoset.....	55
2.4.3 Summary.....	59
2.5 Overall Research Gaps and Their Significance	60
3 Methodology.....	62

3.1 Design and Materials	63
3.2 Sample Manufacturing	66
3.2.1 Composite Skins Manufacturing.....	66
3.2.2 Sandwich Composite Manufacturing	69
3.3 Testing Techniques and Equations.....	70
3.3.1 Single Fibre Tensile Comparison	71
3.3.2 Tensile and Three Point Bending Test of Pure RCF Composites	73
3.3.3 Three Point Bending Test of Sandwich Composites	76
3.3.4 Drop Tower Impact Test.....	77
3.3.5 Formulas and Calculations.....	80
3.3.5.1 Calculating Tensile Properties, Single Fibres & RCF Composites.....	81
3.3.5.2 Mixing Rule for Composites.....	82
3.3.5.3 Calculations Related to Bending Results	83
3.3.5.4 Prediction and Simulation of Sandwich Bending.....	87
4 Results: Single Fibre Tensile Tests	89
4.1 Single Fibre Tensile Results	90
4.2 Discussion on Single Fibre Results.....	92
5 RCF/PP Composite Properties.....	94
5.1 Effective Modulus Calculation	94
5.2 Composite Skin Tensile Results	95
5.3 Three Point Bending Results	97
5.4 Controls of the RCF/PP Composite Manufacturing Process.....	101
5.5 Failure of Samples	107
6 Sandwich Composite Properties	109
6.1 Sandwich Bending Results	109
6.2 SEM Results of The Sandwich Composites.....	113
6.3 Failure of The Sandwich Samples	117
6.4 Impact Comparisons Between GFRP, RCF/PP Skins and The Sandwich Composite	119
7 Recyclable Sandwich Composite for Van Side Panels: A Case Study	126
8 Conclusion and Future Research	130
REFERENCES.....	134

LIST OF FIGURES

Figure 1. Vehicle electrification goals announced by different countries (1).....	1
Figure 2. Substituted components by composite materials in a vehicle (13).....	3
Figure 3. Current vehicles materials among 12 significant components and 42 significant products (21).....	5
Figure 4. Automotive material mixes of a typical vehicle in 2025 (22).....	5
Figure 5. Illustration of wood panels on a steel frame (chassis).....	7
Figure 6. DRIFT [™] process (87)	30
Figure 7. Manufacturing of unidirectional laminates by the film stacking (90) ..	32
Figure 8. Cost-effective material preforms for thermoplastic composites (93)..	33
Figure 9. Raw materials	63
Figure 10. DSC result example for PP sample with melting and recrystallisation peak.....	66
Figure 11. Mould plates and the compression machine	67
Figure 12. The schematic diagram for the stacking and compression process	68
Figure 13. The schematic diagram for composite join	69
Figure 14. (a) Fibre sample mounted in between two papers with a testing window; (b) Tensile testing equipment; (c) Monitoring of fibre under a microscope.	71
Figure 15. (a) tensile sample dimensions; (b) three-point bending setup; (c) tensile test setup with laser extensometer	74
Figure 16. Drop tower impact tester	78
Figure 17. Schematic diagram to illustrate effective core width.....	83
Figure 18. Loading state during the 3-point-bending test	85
Figure 19. Single fibre samples diameter examples and the distribution with average values and variations (a)i&ii, diameter distribution (b)i&ii, strength distribution (c)i&ii. modulus distribution	91
Figure 20. Example plot of PP/RCF composite (20% v.f.) tensile results and the table of overall results.....	95
Figure 21. (a) example of RCF composite sample bending result; (b) mechanical properties distribution of RCF composite samples: overall distribution of strength (i) and modulus (ii); (c) mechanical properties distribution of PP-sheet samples strength (i) and modulus (ii); (d)	

<i>mechanical properties distribution of PP-powder samples strength (i) and modulus (ii)</i>	<i>98</i>
<i>Figure 22. (a) RCF composite samples after the three-point bending test, (b) RCF composite samples after tensile test</i>	<i>107</i>
<i>Figure 23. Sandwich beam bending result example: (a) pure RCF skin samples, (b) mixed skin samples</i>	<i>110</i>
<i>Figure 24. (a)i SEM image of the sandwich bonding interface; (a)ii magnified interface region; (b)i SEM image of the flax composite region in the mixed skins; (b)ii magnified flax fibre agglomerate; (b)iii comparison of RCF carbon fibre gathering at the same magnification</i>	<i>114</i>
<i>Figure 25. (a) pure RCF skins sandwich foam core failure at three-point bending test, (b) mixed skins sandwich skin buckling failure</i>	<i>117</i>
<i>Figure 26. Results of impact energy against time from drop tower tester</i>	<i>120</i>
<i>Figure 27. Top and rear side image of GFRP samples after impact</i>	<i>121</i>
<i>Figure 28. Top and rear side image of RCF & powder PP samples after impact</i>	<i>122</i>
<i>Figure 29 Top and rear side image of RCF & powder PP sample 6 compared to RCF & sheet PP sample 7 after impact</i>	<i>123</i>
<i>Figure 30. (a) Schematic of a truck with grey side panels and blue supportive frames; (b) Wind load and supporting system illustration (c) Flexural behaviour prediction of truck panel with sustainable design</i>	<i>128</i>
<i>Figure 31. Specific flexural modulus vs Specific flexural strength to compare currently used truck panel materials with current sustainable design (Source: CES EduPack software)</i>	<i>128</i>

LIST OF TABLES

Table 1. The density of different thickness designs (skin fibre volume fraction at 20%) 65

Table 2: Materials properties used for FEA 88

Table 3: Sandwich composite properties..... 110

LIST OF EQUATIONS

<i>Equation 1: Composite mixing rule</i>	<i>82</i>
<i>Equation 2: Effective width for sandwich composites</i>	<i>83</i>
<i>Equation 3: Second moment of area after effective width conversion</i>	<i>83</i>
<i>Equation 4: Flexural strength.....</i>	<i>84</i>
<i>Equation 5: Strength for sandwich composite</i>	<i>85</i>
<i>Equation 6: Modulus for sandwich composite</i>	<i>86</i>
<i>Equation 7: Strength for RCF composite skin.....</i>	<i>86</i>
<i>Equation 8: Modulus for RCF composite skin.....</i>	<i>86</i>
<i>Equation 9 prediction of sandwich bending behaviour</i>	<i>87</i>

LIST OF ABBREVIATIONS

RCF	Recycled carbon fibre
PP	polypropylene
PU	polyurethane
PET	polyethylene terephthalate
PVC	polyvinyl chloride
CFRP	carbon fibre reinforced plastic
GFRP	glass fibre reinforced plastic
MAPP	maleic anhydride polypropylene

1 Introduction

1.1 Background, Motivation, Challenge

The European Union end-of-life vehicle directive requires all vehicles manufactured to be more than 95% recyclable and reusable at the end of their life. Many countries have announced their goal for vehicle electrification popularity around 2030-2050, as shown in Figure 1 (1).

Government	Target vehicle type	Target year	Target on new sales	Source
Canada ^a	Vehicles	2040	100% electric vehicles	Government document
China ^b	Vehicles	2025	25% electric vehicles	Draft government document
Costa Rica ^c	Light-duty vehicles	2050	100% electric vehicles	Government document
Denmark ^d	Passenger cars	2030	No gasoline or diesel vehicles	Government document
		2035	No gasoline, diesel, or plug-in hybrid electric vehicles	
France ^e	Passenger cars and light-duty commercial vehicles	2040	No vehicles using fossil fuels	Law
Germany ^f	Passenger vehicles	2050	100% electric vehicles	ZEV Alliance commitment
Iceland ^g	Passenger cars	2030	No gasoline or diesel vehicles	Government document
India ^h	Passenger cars	2030	30% electric vehicles	Speech of Transport Minister
Ireland ⁱ	Passenger cars	2030	No fossil fuel vehicles	Government document
Israel ^j	Passenger cars	2030	No gasoline or diesel vehicles	Speech of Energy Minister
Japan ^k	Passenger vehicles	2030	23%-33% electric vehicles	Government document
Netherlands ^l	Passenger cars	2030	100% electric vehicles	Government document
Norway ^m	Passenger vehicles	2025	100% electric vehicles	Government document
	Light-duty vans	2025	100% electric vehicles	
	Long-distance coaches	2030	75% electric vehicles	
	Trucks	2030	50% electric vehicles	
Portugal ⁿ	Passenger cars	2040	No vehicles with internal combustion engines	Speech of First Secretary of State for Mobility
Scotland ^o	Passenger cars and vans	2032	No gasoline or diesel vehicles	Government document
Singapore ^p	Vehicles	2040	No internal combustion engine vehicles	Speech of Deputy Prime Minister
Sri Lanka ^q	Vehicles	2040	100% electric or hybrid vehicles	Speech of Finance Minister
Slovenia ^r	Passenger cars and light-duty commercial vehicles	2030	100% vehicles with CO ₂ emissions up to 50 g/km	Government document
South Korea ^s	Passenger cars	2030	33% electric vehicles	Speech of President
Spain ^t	Passenger cars	2040	100% electric vehicles	Draft law
Sweden ^u	Passenger cars	2030	No gasoline or diesel vehicles	Government document
United Kingdom ^v	Passenger cars and vans	2035	No petrol, diesel, hybrid, or plug-in hybrid vehicles	Speech of Prime Minister

Figure 1. Vehicle electrification goals announced by different countries (1)

It is shown in a lot of research that the reduction in the vehicle weight could have long-term benefits on less emission for all types of vehicles and could provide more battery space/ weight for electrical/ hybrid vehicles, which enables them a more considerable travel distance and a longer charging cycle (2–8). Light weight could be achieved by a better structural design and a more suitable

material selection. However, in a balancing study between lighter-weight materials and total emission reduction for electrical vehicles, the author considered the cost and emission of manufacturing lighter raw materials and pointed out that regarding the emission only, the benefit from significantly lighter weight might be limited while a suitable balanced design would be the best (8). Thus, a balanced design to reduce vehicle weight is very important to help improve sustainability in automotive industries. Also, with a lighter weight, the electrical vehicles could have a longer travel distance and a more extended period between charging, which could facilitate public acceptance and help speed up the electrification (8). There are many other benefits of reducing the vehicle weight for special occasions, such as reducing the impact of energy during car accidents, which reduces the dangers (9) and reducing the weight of commercial vehicles like lorries or buses, allowing them to carry more items/passengers to improve efficiency.

The regulations on vehicle recyclability, electrification goals and the demand for lightweight vehicles aim to reduce overall emissions and generate a more sustainable environment. This direction has raised the pressure on manufacturing automotive components to be lighter and more recyclable. Carbon fibre reinforced plastic, with its extremely high mechanical properties and low density, is a widely researched topic for substituting heavy steel components in a vehicle to reduce the weight significantly (10–13), including the car body and chassis (10,11) and the wheels (12,13). Many other secondary structures in a vehicle which are not required to have an extremely high property could also be substituted by composite materials, as shown in Figure 2, to maximise the weight reduction (14,15). However, such modification may not bring the best sustainable solution, considering the cost and emission needed to manufacture such composite materials compared to simple metal alloys (15).

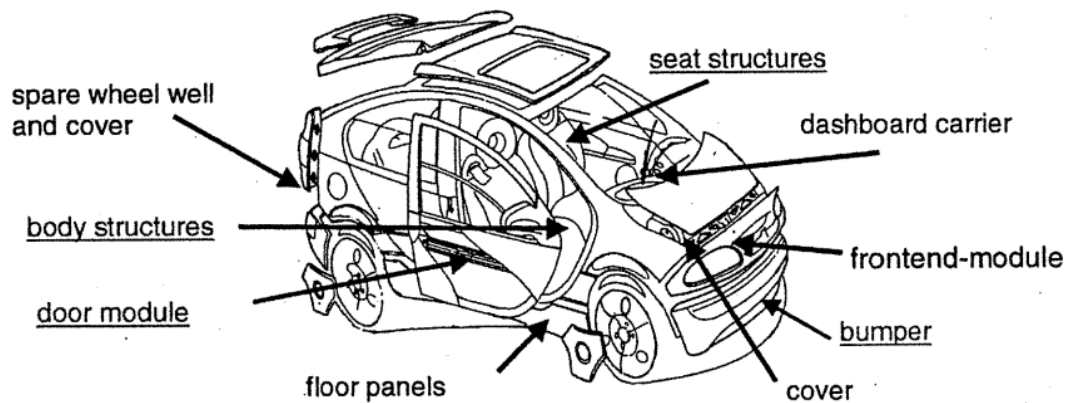


Figure 2. Substituted components by composite materials in a vehicle (13)

Some life cycle analysis studies show worries that lighter materials may have drawn back on sustainability. Although it is agreed in all research that the application of composite materials in vehicles could result in weight reduction and reduce fuel consumption and bring other side benefits, the extent of such benefits could be minimal when considering the emission generated during raw materials production and component manufacturing (16–19). The overall emissions could be reduced after a certain distance travelled by the vehicles depending on factors like the percentage of composite materials, driving conditions etc and a specific example showed the vehicle with CFRPs was more environmentally friendly once the total travel distance has over 132,000 km (17). However, such a threshold result from experimental prediction with a predicted average fuel/energy consumption which may differ under different traffic quality. Also, only some cars could survive until such mileage. Car accidents, owner's choice and habit, road quality (in different countries), system failure, or manufacturing/design defects could influence a car's mileage. Although the average mileage of a car travelled before being scrapped should exceed such distance (132,000 km), the level of exceedance and the long-term benefit after such a threshold could be pretty limited. The benefit of using highly lightweight materials, mainly CFRPs, is further limited since many secondary structure components in vehicles do not require such a high-performance CFRPs, and on the other hand, more effective recycling and reusing carbon fibres could significantly increase the overall emission reduction benefit (19) as

the CFRPs are not recognised as an environmentally friendly material by the EU end of life vehicle directive due to the energy consumption during recycling (19). Thus, such CFRPs (mostly epoxy and virgin carbon fibre) could help solve the lighter weight target but raise the difficulty on the recyclability and sustainability side.

A secondary energy absorption structure, bumper, was designed and manufactured using jute fibre composite, had less weight and showed more energy absorption than chromium-coated mild steel or aluminium (20). Using such natural fibre composites on secondary structure applications could have more benefits when considering emission reduction and weight reduction together than using CFRPs to replace heavy steel structures and will be further discussed in the following literature review chapter, “fibres in composites”.

Although composite design and application in vehicles within the prediction of life cycle analysis seem to help reduce the emission in long-term strategies by using these lighter-weight materials, the risk of being non-sustainable in real applications due to insufficient lifetime travel distance is still relatively high. This might be one of the reasons that why the market may not be willing to take such a risk to accept CFRPs materials as a more sustainable, lighter-weight choice. A statistical result published in June 2017 by a non-profit automotive research organisation ‘The Centre for Automotive Research for Innovation, Science and Economic Development Canada’ shows that 14 significant components among 42 mass-produced vehicles contain only 1% of CFRPs/GFRPs while different steel materials counted 86% in total and aluminium counted 12% as shown in Figure 3 (21).

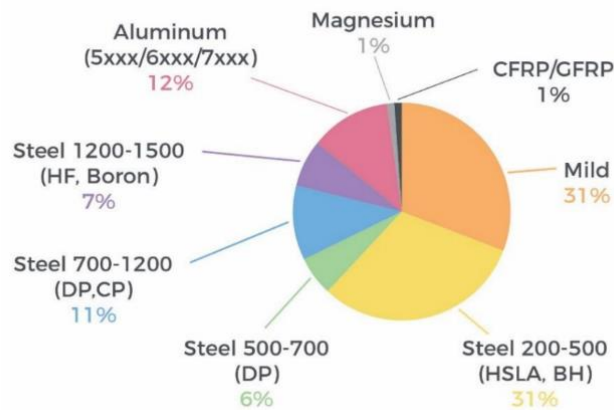


Figure 3. Current vehicles materials among 12 significant components and 42 significant products (21)

Figure 4 is a prediction of materials used constituting a vehicle in 2025 based on previous statistical data and trends from Statista (which can be accessed via this link: <https://www.statista.com/statistics/270252/material-use-in-car-production/> accessed on 21 May 2021).

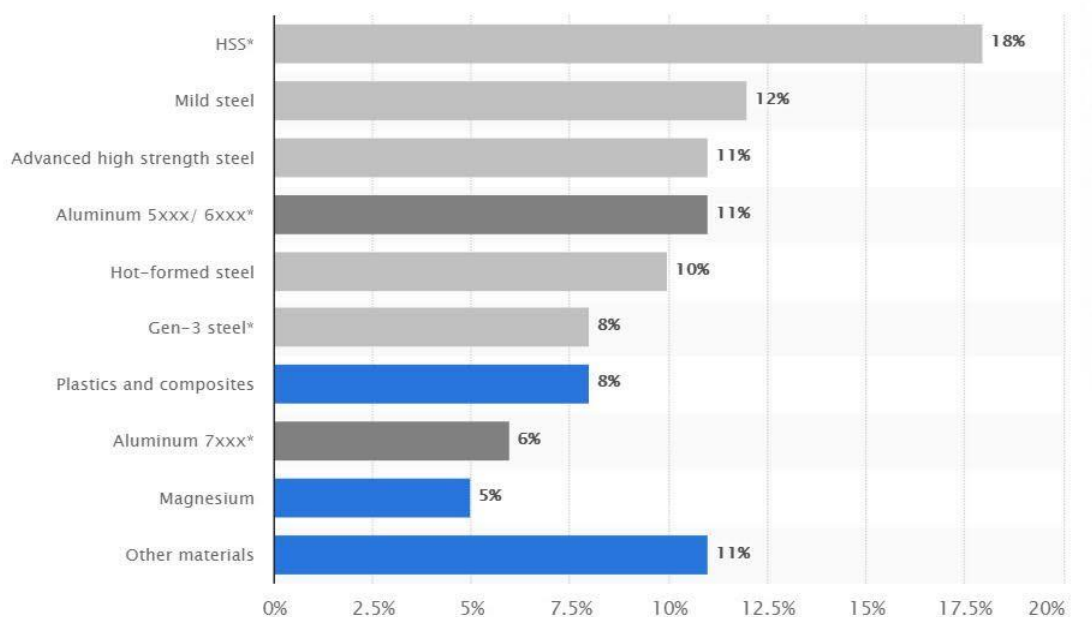


Figure 4. Automotive material mixes of a typical vehicle in 2025 (22)

All types of plastics and composite materials add up to only 8% of the composition in this prediction. It did show confidence in increasing using of

composite materials in vehicles in future compared to the 1% constitution in the statistic made in 2017 among old vehicles. However, to some extent, both statistical data indicated that the popularity of lighter-weight designs using CFRPs in vehicles in the actual application still needs to grow. Another possible reason for carbon fibre composites at such a low real application rate in automotive components may be due to the lack of high speed/volume and energy-efficient manufacturing process, and the high material cost stopped manufacturers from shifting towards such lighter material (23), even though they could significantly reduce the weight, thus saving fuel and reducing life cycle emissions.

Overall, weight reduction and recyclability are the most critical concerns for automotive component manufacturers. However, the effect of lighter-weight materials is quite limited for several reasons presented above; thus, a more practical design that could shift the real automotive applications towards lighter weight and more recyclability is needed.

Considering the effect of the global pandemic (COVID-19) during this research, which causes many countries to lock down for several periods, leads to significant emissions reduction during the pandemic (24). However, it is believed that such lockdowns are highly likely to cause rebounded travel and consumption, resulting in an increasing demand for commercial transportation for supply chain, goods, and passengers, which could lead to a significant increase in carbon emission during a short period (24–27). Besides the individual shopping and travel desire in the post-pandemic period, governments in many countries will also have different strategies to stimulate the economy's recovery (25,26). These activities would lead to rebounding emissions, but stopping any country's economic recovery during the post-pandemic period is impossible and unreasonable. Thus, reducing the effect of such rebounded emissions is more feasible via actions on reducing the emission of commercial transportation industries.

Currently, in most commercial vehicles such as lorries, buses and small vans, the floor used simple panel wood materials for many years due to cost

efficiency and accessibility. These panels act as a secondary supporting surface lying on primary steel frames, as shown in Figure 5.

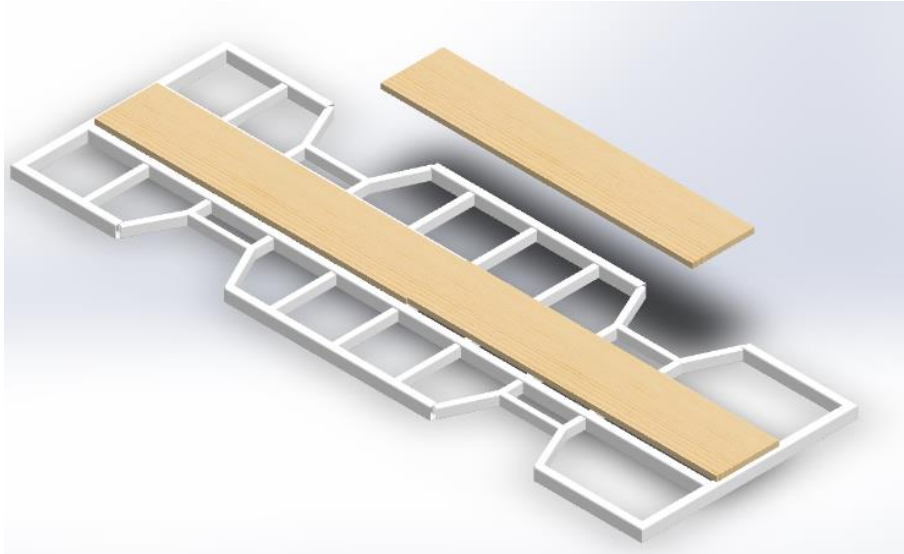


Figure 5. Illustration of wood panels on a steel frame (chassis)

These wood panels are cost-effectively, and their performance is enough to meet the needs of such secondary structure applications. However, using wood is easy to cause deforestation, and these woods can only become landfills at the end of their life, which is against the EU end end-of-life vehicle directive requirement. Also, wood panels are easily affected by moisture and corrosion; thus, the durability is limited, and new panels require frequent refit. The density of general wood panels is relatively high; though a thin panel around 10 mm could usually satisfy this floor application, the weight per area still needs to be higher.

Overall, considering the requirements in shifting automotive components towards lighter and recyclable to satisfy the market demand and regulation, as well as the feasibility and the space for improvements to reduce the emission from automotive in actual applications, the floor panels for commercial transportation (lorries/ buses/ vans) is selected in this research to be improved, reducing the weight to reduce total life cycle emission, and allowed recyclable instead of bio-degradable landfill. Compared with private cars, the frequency of commercial vehicles will be more stable, and the final mileage threshold will be

easier to reach. Although, according to the above statistics (21,22), it can be speculated that most manufacturers are unwilling to take risks to try new materials; the improvement of floor panels can increase the overall weight of goods carried by such vehicles at the same time, which may increase the acceptance for both manufacturers and customers.

1.2 Aim & Objectives

Current research about recycled carbon fibre (RCF) mats focused on composite skins but very few sandwich structures, most of which are related to thermoset resins by infusion process. Thus, this research aimed to manufacture fully sustainable sandwich composites using recycled/renewable fibres with thermoplastic polymers and identify potential applications for automotive industries to increase their sustainability.

The most challenging part of this research is to keep the balance between two aspects: one is the selection and properties of the recyclable material of such a designed panel, and the other is the weight such design could save and the cost as well as manufacture/ customer's interest for replacing traditional wood panels with such design. As discussed above, virgin carbon fibre is unsuitable for such application due to its superior properties needed as a secondary structure. Its life cycle emissions and price will increase the difficulty of achieving the aim of this project. On the other hand, recycled carbon fibre mats are suitable for their properties, random-oriented/ chopped fibres, and other unique characteristics. Rigid plastics are often used in vehicles to reduce weight, especially in structure designs with plastic honeycomb or foam materials (28). In this research, a sandwich structure that could improve mechanical properties and weight reduction by sacrificing the volumes is a good choice, as the vehicle restriction is mostly the maximum weight, not the spacing. Also, various core materials could provide different unique properties, such as a honeycomb core is extremely good at specific shear strength while foam cores could provide very low thermal conductivity, thus could help those vehicles which need heating/ cooling to maintain the temperature with the lowest energy consumption. PP was used as the matrix, and the RCF to manufacture the sandwich skins. It has an excellent specific mechanical property among thermoplastic materials, and its melting point is below 200 °C, making the manufacturing and recycling processes more manageable. One of the benefits of RCF in this application is that the process of cutting components into small pieces at the initial stage of recycling would not cause too many property changes in RCF because it is already a completely random distribution of tiny

fibres, while composites reinforced by RCF, compared to virgin carbon fibre ones, have about a quarter of the mechanical properties (29). This will be further discussed and compared in the following literature review chapter, “general recycling process of fibre composites”.

The objectives of this research are 1. Design the target sandwich composite and complete material/process selection through a literature review. 2. Study the recycled carbon fibre (RCF) mat and understand its characteristics through mechanical tests and comparison with virgin carbon fibres. 3. Comparison of the characteristics of composite skins based on RCF mats and different polypropylene forms (sheet and powder) through manufacturing process differences and mechanical testing, modifying and implanting the pultrusion process for manufacturing the RCF preform tapes. 4. Integrating RCF mats/ renewable fibres with polypropylene matrix and recycled PET foam core to manufacture the fully recyclable sandwich composite, characterising and testing such sandwich composite. 5. Property comparison with commercial and automotive materials and case study to evaluate the potential application of such recyclable sandwich composite.

In conclusion, this chapter introduced some background about the demand for low-weight vehicle components and the regulations for more recyclable vehicle designs. Pointed out that private cars are still mainly manufactured from metals, especially various steel products though research had posted the potential of lightweight composites in automotive applications. This shows the motivation and challenge in this research to design an automotive component that could satisfy those demands and regulations and have more reliable improvements, thus better accepting the real market.

2 Literature Review

2.1 Sandwich Composite Design – Structures and Materials

2.1.1 Sandwich Composite for Automotive Application – Advantages and Disadvantages

As discussed in the introduction, weight reduction for automotive components is a vital target to satisfy regulations and market demand (1–8). However, simply using lighter-weight materials like CFRPs in the actual application might not generate benefits as much as research simulated due to the fact that lightweight materials have higher costs and life cycle carbon emissions (8). Composite material would have relatively weaker stiffness, while overcoming by directly adding thickness would result in high costs and emissions. On the other hand, structural components like I-beam and sandwich structural could achieve the same bending stiffness with significant weight reduction (28,30,31) compared to thick composite bulk. All of such structural components are similar in that both contain a sheet surface (top and bottom) without homogeneously filling between them with the same materials as the surface. Usually, when the two surfaces are separated by a bar from the same materials, it could be both I-beam or C-beam, depending on the position of the supporting bar at the middle or edge. When different supports between the two surfaces become complicated, they could be called different core materials for a sandwich structure, including foams, honeycombs, X / Y cores, or corrugated cores (28). These sandwich structures could allow one skin under tension and the other under compression while the core is under shear deformation, which generates more stiffness when the load is applied to the sandwich component along with the thickness, and the bonding between skins and core is strong enough. In a static testing environment, the composite sandwich design could reduce weight by more than 50% while maintaining the same stiffness as the steel sheet component. The addition of a thin layer viscoelastic damping layer also shows much better efficiency when applied within a sandwich structure compared to simply adding onto the surface of the steel sheet component (30). The research compared four different structural designs (monolithic / stiffener bar reinforced / sandwich

insert-reinforced / sandwich plates) with different materials and also showed similar weight reduction at the same properties by using a sandwich plate. It also pointed out that using RCF or glass prepreg could achieve a 50% cost reduction compared to virgin carbon fibre products, and lignin-based carbon fibre or hemp fibre can provide more cost reduction but at relatively decreased mechanical properties (31).

In terms of lighter automotive components, the sandwich composite could provide sufficient bending properties via structural designs, though the disadvantages of lighter materials (8) could not be fully avoided as most of the sandwich skins are made from lightweight fibre reinforced composites, Sandwich composite made from metal skins could further reduce such issues, though it would reduce thermal and chemical resistance and damping properties compared to fibre-reinforced plastics (32). Another limitation sandwich composites have is that such superior specific stiffness/properties (in weight) are achieved by compensation of low specific properties (in volume). When maintaining the bending stiffness and reduction of more than 50% weight by using sandwich components having a total thickness of around 10-15.5 mm (0.1-0.2 mm skins), the targeted metal sheet was only around 0.5-1 mm thick (30). Thus, the application of sandwich composites in automotive also needs to consider whether the volume is an essential factor for such components and affects the whole vehicle design.

2.1.2 Floor Panels

(Ply)wood panels are widely used for lorries' flooring with a steel frame base to support the whole floor structure due to their cheap price, acceptable properties, and weight for such application (layout as shown in Figure 3 in Introduction) (30). Also, it has been shown in the "Handbook of finish plywood" that such timber product is not only a construction material but has been broadly used as a floor for commercial and mass transportation (33). However, there are advanced sandwich composite floor panels to reduce the weight in the market, such as CFRPs skin plywood sandwich, GFRPs skin polypropylene honeycomb, or steel skin high-density polyethylene foam composites (34). However, similar to the situation the private car industry in Canada faced (21), such advanced design still needs to be more popular among vehicle manufacturers and customers. The reason for it could be diverse, but more likely because of difficulty in maintaining the balance between the benefit from these designs against the cost and recycling regulations. Most of such advanced designs are still containing fibre reinforced thermoset plastics which could be recycled but energy intensively and resulting in products having lower properties (which will be discussed more in the following chapter, "composite material recycling") and, thus, not recognised by the EU end of life vehicle directive as an environmentally friendly selection (17). This means a fully recyclable design like the steel / high-density polyethylene foam sandwich could be more attractive and easier to popularise (34). However, steel skins in such applications, even with hot-dipped galvanising protection, might develop corrosion facing moisture or chemical contaminants.

2.1.3 Fibres in Composite

As discussed in previous chapters, balancing lower-weight design and recyclability or life cycle emissions is crucial for automotive components. Thus, selecting fibre materials has become the most critical topic for sandwich design. Carbon fibre-reinforced plastics are increasingly popular in aircraft, and Airbus A350-XWB contains about 52%, and Boeing 787 contains about 50% CFRPs, respectively. This is also because weight could be considered one of the dominant factors for aircraft design. However, as shown in the previous content, weight is just one essential factor that needs to be balanced in automotive component design. CFRPs have excellent specific weight properties, but it is widely used in racing cars or expensive sports cars only, which occupy a small proportion in a large number of private cars due to several reasons discussed in the above chapters, could hardly become popular for private vehicles. Glass fibres, on the other hand, are relatively too heavy which could influence the target to a lighter automotive component. Furthermore, the recycling process for both continuous CFRPs and GFRPs is not friendly in that after the cutting and chopping, short discontinuous random oriented fibre could cause resulted composite product from recycled fibre to have only about 1/4 mechanical properties of virgin fibre composite (which will be explained in “composite material recycling”).

Natural fibre could be a more environmentally friendly selection for general private vehicle components (35–40) and a comparable substitution for glass fibres, especially when environmental issues are counted (35,36). Also, it is mentioned in the previous chapter that a bumper made from Jute fibre composite could provide better energy absorption and damping than metal alloys while being much less costly than CFRPs (20). A sandwich structural research also shows that RCF or glass could reduce costs by about 50% compared to virgin CFRPs, and natural fibre could reduce even more (31). Generally, natural fibres could perform better when impact properties are required during the composite design as they have superior damping ability and, thus, are very suitable for applications such as bumpers or other sacrificial or impact-resistant structural (38,39). Low-velocity impact resistance is a

significant property for commercial or vehicle floors of mass transportation; thus, natural fibres could perform well in such applications (40). Natural fibre composite is already presented in some automotive components in manufacturing, and Germany is the leader in such area (41). However, this might be due to the strictest EU regulation that to have more sustainable and lighter components while manufacturers need to maintain the cost at an acceptable level at the same time, but not a result of technology development (41). Nevertheless, natural fibres do have the disadvantage that they can hardly be recycled and could only become a bio-degradable landfill, and the mechanical properties are highly dependent on fibre growth conditions and natural factors such as weather or geographical position (41–43). Resulting in a distribution range of natural fibre mechanical properties (e.g., Flax modulus ranges from 20GPa to 80GPa) and fibre size. Furthermore, natural fibre generally has poor moisture resistance, and thus vehicle applications, significantly those commonly using air conditions like refrigerated delivery cargo, could absorb a significant amount of condensed water that results in increasing weight and decreasing mechanical properties (44,45). Even though moisture absorption ability is different among different types of natural fibres, such an issue is more or less presented among all the natural fibres (45).

Recycled carbon fibre is another possible candidate for applications in automotive to satisfy the lighter weight, fully recyclable and cost requirements. Although most CFRPs are considered to have a long lifetime, with the increasing applications in aerospace industries, the CFRPs in use keep increasing, and up to some point, a large amount of end-of-life CFRPs would need to be handled (46). However, it is wasteful to landfill such superior materials, and the RCF can still be used to make products comparable to glass / natural fibre composites (47). Generally speaking, the energy required to extract RCF from end-of-life CFRPs is only about 10% of the energy required to manufacture virgin carbon fibre. At the same time, the carbon emission will be reduced correspondingly, but the reduction depends on the recycling process and the chemicals used (47). Composites made from randomly oriented RCF mat at a normalised 30% volume fraction have about 30% mechanical

properties compared to virgin carbon fibre products (0,90 oriented) (29), although the recycled single carbon fibres could maintain more than 90% of the mechanical properties, it could be the result of both randomly oriented fibres, and the fibre length reduced significantly after cutting and chopping during the recycling process, which will be explained more in the following chapter, “composite material recycling”. The manufacturing process and resin selection also affect the fibre volume fraction, resulting in different RCF composite properties (now, the maximum volume fraction of around 35% could be achieved from compression moulding)(29,48).

2.1.4 Matrix Selection – Thermoplastic vs Thermoset

The density, through-thickness mechanical properties, manufacturing technique and parameters such as temperature or pressure of composite material are primarily influenced by a matrix material. Furthermore, fully recyclable composite or partially recyclable is also controlled by matrix materials such as thermoplastic or thermoset resins (49). Thermoplastic composites are consistently recognised as recyclable materials as they can be heated to melt and extract/recycle the fibres inside and the matrix separately (49). Although the fibres extracted from both thermoset and thermoplastic resins could maintain more than 90% mechanical properties, the pyrolysis process is needed during the recycling of thermoset composites to burn off the resins, or intense use of chemicals determines such matrix non-environmentally (47).

The process parameters should also be considered when selecting the matrix. Thermosetting resin generally needs to be cured for a long time but at a relatively low temperature (below 150 °C). At the same time, the curing sequence of the localised position will also affect the performance uniformity of the finished products (50). Thermoset resin has good flowability before the curing process; thus, there is no apparent limitation for manufacturing techniques of such matrix. On the other hand, thermoplastic composites could be demoulded and completed manufacturing when the temperature is suitable without a curing cycle. However, most thermoplastic resins are more stringent for the manufacturing process, which usually requires higher processing temperatures depending on the melting point and associating with pressure to overcome the low melt flow rate. Research made a comparison of thermoplastic and thermoset resin with carbon fibre to manufacture composite material in different techniques for automotive floor pan showed that even with currently used machines such as thermoset RTM (resin transfer mould) process, and presser for forging metal sheets are enough for thermoplastic composites thus high-pressure requirements may not be a critical parameter to stop manufacturers to shifting towards thermoplastic matrix (48). The temperature, however, could be a barrier to fibre selection. Research showed that all-natural fibres could have a different level of decomposition or oxygen-associated

oxidation under a high temperature (51–55). Below 170 °C, the effect on the mechanical properties of natural fibres could be negligible, while significant properties change is observed after 170 °C (51). Most research pointed out a property loss at about 20-30% around 180 °C for a certain period of treatment and suggested manufacturing process related to natural fibre should not exceed 180 °C (53–55). Such property has primarily limited the matrix selection; even polypropylene, which generally has a melting point around 160-165 °C, could still be a risky combination. On the contrary, because thermoset resins do not require a high temperature of more than 150 °C to cure, they could be more suitable for reinforcement by natural fibre. Furthermore, natural fibres are hardly recycled but are bio-degradable; thus, combining a biodegradable resin such as polylactic acid could have a fully bio-degradable composite which is more environmentally friendly (56).

During composite manufacturing, a coupling agent could also help to improve the bonding between fibres and matrix. For example, when manufacturing carbon fibre / PP composite, due to the fully saturated poly-propylene chain, the composite is just in mechanical combination that almost no chemical bonding between the carbon fibre and PP could form. However, when adding the coupling agent to form MAPP, the maleic anhydride groups will be both grafted on the polypropylene and form hydrogen bonding/ester bonding with the carbon fibres (48). Further, compared to thermoset composites which generally require adhesive or metal joints for connection, thermoplastic composites could be joined together through welding/fusion bonding (57).

2.1.5 Sandwich Core

In a sandwich structure, the core material is vital to separate the two stiff skins, keep them apart, and provide sufficient shear strength for the whole structure during a through-thickness load applied, such as bending. Different sandwich cores are suitable for different applications; X and Y cores are often used in commercial vessels (58), honeycomb core is often used for applications which are sensitive to buckling or bending in the aerospace industry, while corrugated and foam cores or balsa wood has been commonly used in headliners, cabin floors and vehicle roofs (59). Core materials could also bring functional properties to the whole structure, such as thermal resistance via foam core or damping via viscoelastic addition layer/ cores (31)

The topic concerned in this research is a fully recyclable lighter-weight sandwich component for automotive applications. Thus, the core material density and recyclability are also critical. Furthermore, the density of the core material in a sandwich structure would influence the dynamic loading properties, which are counted and need to be considered for automotive component applications (60). Thus, thermoplastic foam, honeycomb, or metal honeycombs would be more suitable to satisfy such requirements. The foam core seems the best and only suitable choice when including the thermal insulation requirements for applications like a refrigerated lorry.

2.1.6 Summary

In conclusion, this chapter reviews the composite sandwich structure as a more suitable component than pure CFRPs, which do have superior density and properties but hardly balance the recyclability and cost at the same time, as an automotive application to complete the challenge posed in the introduction that to design a fully recyclable and lighter automotive component with a comparable property and cost; summarised the wood flooring widely used in commercial and mass-transportation vehicles and some advanced sandwich composite substitution, their respective characteristics, some disadvantages and the reason for hardly widespread usage; introduced different materials including fibres, matrix resin and core for sandwich composite with their characterisation and selection guidance.

Overall, virgin carbon fibre is a superior material but not suitable for such secondary structural design and the proposes of this research, while glass fibres may be applicable but could riskily add weight burden. Natural fibres and RCF could be suitable candidates for the aim of this research. However, natural fibres are fragile to high temperatures and could face moisture and non-recyclable issues, while RCF may face costly issues which need to consider during the panel design, respectively. Thermoplastic resins are much more suitable than thermoset ones in this research due to recyclability. Furthermore, they could generate a good combination as those randomly distributed short fibre RCF mats, thus simply melting and re-manufacturing new products. However, the higher processing temperature for most thermoplastics and their low melt flow rate needs to be handled well during manufacturing. Selection for core materials is relatively more straightforward as it just needs to base on their specific properties vs the cost since most core materials (those suitable for automotive applications) are recyclable. Also, additional care about functional properties such as thermal resistance could be a bonus.

2.2 Manufacturing Process and Design

2.2.1 Manufacturing Techniques for Automotive Composites

As shown in the introduction, Fibre-reinforced composites, especially those from carbon fibres, could significantly reduce weight for automotive components with similar mechanical performance. However, the applicability is limited by the balance between the life cycle benefits (overall energy/fuel saving and carbon reduction via the lighter weight) and the drawbacks, including recyclability and energy needed to manufacture raw materials and products. The balance in material selection has been discussed in previous chapters, so this chapter will focus on those manufacturing techniques that can modify into a suitable, rapid, and energy-efficient automotive manufacturing process. This chapter will not discuss composite manufacturing techniques with a slow manufacturing period, low energy, or cost efficiency (such as auto-clave). Four manufacturing techniques have been developed and used in recent decades to speed up the manufacturing cycle and reduce the manufacturing cost/energy consumption to successfully implant fibre-reinforced composite materials as automotive components. The customised design of some technologies will be a little in this chapter, and the customisation process for the favoured materials selected in this research will be discussed in the next chapter.

2.2.1.1 Resin Transfer Moulding

Resin transfer moulding is one of the most appropriate manufacturing techniques for automotive composite components and can produce complex geometries. A mould with a designed shape is used to stack up dry fibres, and the mould is closed before liquid resin is injected inside at certain pressure (generally up to 10-20 bar) or just vacuum. Once the resin is cured, the mould can be opened, and the component can be removed. This process could manufacture automotive components with low capital and operational cost (since the hydraulic pressure is very low) at a relatively low risky level (which generates significantly less volatile chemical vapours due to the closed chamber). Furthermore, as the mould could have a perfect surface finish via machining, the finished product could also have a good surface finish and a complex shape that needs no further treatment. High volume fraction composite material (from 60% to 65% v.f.) could be achieved via the pressure applied too (61). However, this process could only use to manufacture thermoset composite materials as the pressure included inside the injection process is not very high, and high viscose thermoplastic materials could hardly be fully injected through the fibre and arrive all over the mould due to a similar reason, the size of components could manufacture by these techniques are also limited to small or medium. Voids and different curing zone could also affect the quality of the product when relatively large components are manufactured via this technique, and the overall manufacturing cycle is relatively long (62).

On the other hand, high-pressure modifications (up to 150 bar) on the resin transfer mould process could solve those problems and are more suitable for some thermoplastic resins, which have a relatively higher melt flow rate (61). It could also slightly increase the product fibre content (up to 70% v.f.), significantly reducing the manufacturing cycle time and the possibility of defects such as voids. However, such modification with high pressure could damage the dry fibre before the resin has been impregnated, resulting in a high tooling and processing cost (63). Compression-associated resin transfer mould is another modification to reduce the cycle time and possibility of defects. In this modified process, the mould is not fully closed during the resin injection phase;

the gap between the mould and the un-pressed fibres reduces flow resistance, allowing less injection pressure. After the injection is finished, the mould is fully closed under compression, which behaviours more similar to the compression moulding and thus share similar disadvantages such as poor edge finish. This process could allow the resin to be evenly heated compared to the direct compression moulding. The fibres (when UD fabric is used) are unlikely to dislocate under pressure as more liquid state resin would be easier to flow without pushing fibres away. However, due to the low injection pressure, this modification is more suitable for producing thermoset composites (64–66).

Both commonly seen modified resin transfer moulding could overcome some of the disadvantages of the original process and manufacture thermoset automotive components at a relatively low cost and fast cycling. The suitable number of plant machines and modification techniques depend on the target composites and raw materials. However, there are more suitable techniques for producing thermoplastic components.

2.2.1.2 Reaction Injection Moulding

Reaction injection moulding, as the name shows, is a similar manufacturing process as the compression-associated resin transfer moulding but uses two or more very low viscosity liquids sources as the matrix at a specific ratio that could first be injected through the whole chamber, fill all dry fibres inside easier and mix well (after which would generally increase the viscosity before fully cured) and then curing or chemical reacting to form the composite component under compression when the mould is fully closed after the injection of liquid materials completed (67,68). Thermoset resin is generally used in this application, and a typical polyurethane (isocyanate and polyol based) is used in this process for structural automotive parts because of the fast reaction rate compared to other thermoset resins such as epoxies or thermoset polyesters which need a long curing cycle. However, such polyurethane has a relatively lower modulus and hardness (68).

Similar to the compression-associated resin transfer process, reaction injection moulding could provide evenly mixed/heated resin compared to direct compression moulding and avoid fibre dislocation; the manufacturing cycle and tooling/manufacturing costs are both suitable for automotive mass production applications. However, it is not suitable for most commonly used thermoplastic materials as most polymerisation process requires extremely high pressure or temperature. Some uniquely designed thermoplastic material/polymerisation processes which involve liquid state resources without high pressure or temperature could be more suitable for such processes. Such as, a new liquid Methyl Methacrylate (MMA) thermoplastic resin, named Elium ®, is claimed to be able to maintain a liquid state at room temperature but 'cured' as a thermoset resin while behaviours like a thermoplastic material (69).

2.2.1.3 Vacuum Assistant Resin Infusion

Vacuum-assisted resin infusion, always called vacuum bag infusion, is the most commonly used technique for manufacturing all different types of composite components at a relatively large size; it is like a more straightforward, cheaper version of resin transfer moulding. During this process, only a bottom mould is needed for placing dry fibres, and a flow-assistant medium is needed on the top of fibre stacks to facilitate the resin flow and a flexible plastic vacuum bag (sheet) to cover the whole mould with a rubbery substance to sealing the whole system (70). Commonly two channelling tubes are needed for resin input and vacuuming, respectively; thus, the resin would flow through the whole system and fill the fibres until reaching the vacuuming tube, and the component could be demoulded after curing. This process has very low tooling and manufacturing cost; the curing cycle could be completed while only occupying one single bottom mould, thus could be flexible and suitable for mass automotive components production.

However, the disadvantage of this technique is evident; defects such as dry spots and voids could be formed when leakage point, non-completely degassed resin or partially cured (too viscose resin) before the infusion is completed happened. The overall sample surface is good on the mould side but could be better on the bagging side, affecting the laminate thickness/geometry accuracy. Composites manufactured using this technique would have a lower fibre volume fraction (up to 40% v.f.) compared to both resin transfer mould and reaction injection mould, as the vacuum pressure which pushes the resin to flow in this process is lower. (71,72). When the component is large enough, the thickness of the infused composite will decrease from the input tube toward the vacuuming tube as the pressure could not be evenly distributed through the whole component with resistance from fabrics and location. Again, this process is suitable for low-cost, mass-produced large thermoset automotive components but not thermoplastic resins. Similar to reaction injection moulding, only customised designed liquid thermoplastic resin could be applied in this technique.

2.2.1.4 Compression Moulding

Compression moulding is one of the most adopted manufacturing technologies for the mass production of composite automotive components and a suitable technique for thermoplastic resins. During this process, dry fibres and resin materials are placed inside the mould and compressed/squeezed into a composite product with the assistance of heat and pressure. Solid form materials at room temperature, such as fibres and thermoplastics, would be easier to handle and more favourable in this process; in contrast, thermoset materials, mainly in the form of liquid form at room temperature, would require additional handlings, such as the assistance with resin transfer process or injection process (73,74). Additional fillers such as pigments, stabilisers or fire-retardant agents could be applied with the most negligible influence on the manufacturing process (parameters and cycle time) during compression moulding compared to other above mass production technologies, affecting the composite design, processing, and properties (75).

Generally, the manufacturing cycle time for compression moulding is swift for automotive manufacturers who could flexibly remove the mould from a separated chamber to heat, cool, or cure the component, while this process could take more time when the compression is mixed with other temperature-related stages that all in one machine. The typical compression time is only 1-3 minutes, while heating and cooling could largely depend on the mould size and heating/cooling methods (73–75). The size limit of components manufactured from this technique is similar to resin transfer or reaction injection moulding, at a relatively small or medium size, while the surface finish is similarly excellent and complex geometries could be achieved (75). The resulting product is similar to the compression-associated resin transfer moulding and could reach up to 60% v.f., while thermoset resins which usually have a better flowability, are used (64,65) but could reach up to only 40% weight fraction when thermoplastic glass fibre composite is manufactured directly using a press (76).

Compression moulding can manufacture automotive components rapidly and is more suitable for thermoplastic applications. However, the initial tooling cost is

most of all other automotive composite manufacturing techniques. Furthermore, the manufacturing cost and energy consumption would be more by using the hydraulic press (73–75). The viscose thermoplastic resin would provide giant resistance that would produce composites at a lower volume fraction and require hydraulic pressure than thermoset ones to embed the fibre into the resin.

2.2.2 Manufacturing Techniques for PP Composite

Polypropylene, one of the most commonly used thermoplastic materials nowadays, has a very low density of about 0.89-0.92 g/cm³ and is relatively strong with Young's modulus of about 1.3-1.8 GPa. It has relatively stable daily usage properties and a low melting point (about 160-170°C) to process. Facing the situation that PP is easy to decompose under ultraviolet light, stabilisers or simple anti-ultraviolet coatings can also be used to solve the problem (77). Thus, PP is selected as the most suitable matrix candidate in this research for manufacturing a fully recyclable lightweight composite for lorry floor panels.

Polypropylene is very tricky to deal with during the manufacturing of PP composites due to its high viscosity, rheological properties, semi-crystal, and thermo-oxidative degradation. Polypropylene has a very high viscosity after melting, showing rheological properties that its viscosity could significantly reduce with an increasing shear rate by stirring (78–80). The viscosity reduction could exceed more than 50% when the shear rate changes from 100 to 500 per second (78). This is why most polypropylene component manufacturing processes are related to extrusion, which could utilise the rheological property to facilitate the flow rate. Semi-crystalline is another particular property of polypropylene which could influence the manufacturing techniques mainly on the temperature and post-processing side. Pressure is needed to drive the PP flow, while with the pressure, even a normal air-cooling (slow) rate could lead to the generation of β -crystal, which would reduce the mechanical properties (79). Although such defects could be eliminated by annealing at 200 °C for 10 minutes, it may raise the other concern, thermo-oxidative degradation. Polypropylene would have thermal degradation initiated around 280 °C under a nitrogen-presented environment but could have degradation with the help of oxygen (air) initiated around 190-200°C (81). Thus, the processing temperature and environment need to be secured to avoid any degradation during the manufacturing process when processing PP composite.

Thermoplastic resins are primarily similar to PP resins, being a solid form at room temperature, request a critical environment to polymerise and are very

sticky (high viscosity / low melt flow rate) after melting; the currently used techniques to solve some problems on the manufacturer side for composite automotive components such as manufacturing cycle time and costs are more suitable for thermoset composite designs. The only suitable manufacturing technique, compression moulding, is also limited by the high tooling and operational cost, and the resulting thermoplastic composite has relatively lower fibre v.f. and mechanical properties. However, as shown in previous chapters, thermoplastic composite is becoming more and more popular for automotive component design due to its recyclability, satisfying the regulations, and bringing environmental benefits. Due to this reason, many customised manufacturing techniques to manufacture a perform state before applying compression moulding were developed to reduce the requirements on tooling and operational conditions.

As mentioned above, the extruder is the most common way to overcome the high viscosity and extremely low melt flow rate of thermoplastic materials, especially PP, which has a rheological property. Thus, the simplest way to manufacture thermoplastic composites is using injection moulding fed by an extruder or co-extruders (82–84). PP added with short wood fibres, or lignocellulosic particles, is injected into a mould to produce short fibre thermoplastic composites. However, such composites primarily rely on matrix properties due to a low fibre volume fraction and randomly oriented short fibres and would be more suitable as properties enhancing techniques for traditional plastic components. Research on manufacturing composite from RCF and polyamide 66 by injection moulding after the mixing in an extruder also showed that, reducing the fibre length could improve the overall flowability and reduce the difficulty during the manufacturing process and could provide a better quality product (85). Such benefits were only inside one recycling cycle and the reduction in fibre length could increase the difficulty in product design on suitable application for the next recycling cycle. Similar to the injection process, extruders could also be used to mix thermoplastics with relatively longer fibres (long discontinuous fibres can be recognised as (fibres at 12-38mm (84) and 3-25mm (86)) and extrude a molten charge as the raw material for compression

moulding. Compared to injection moulding, this process could allow the mixture to have a much lower viscosity, and be less restricted by flow rate as the molten charge needed to travel through any die.

The pultrusion process is another technique to rapidly manufacture continuous fibre-reinforced thermoplastic composite preforms, including, as the name shows, a pulling process of fibres with extrusion. A technique named DRIFT™ is used to manufacture composite pellets at a high production rate, as shown in Figure 6, by pulling continuous fibres through a molten resin die with a controlled resin rate to form impregnated fabrics which will be followed by a chilling and chopping process to produce reinforced composite pellets.

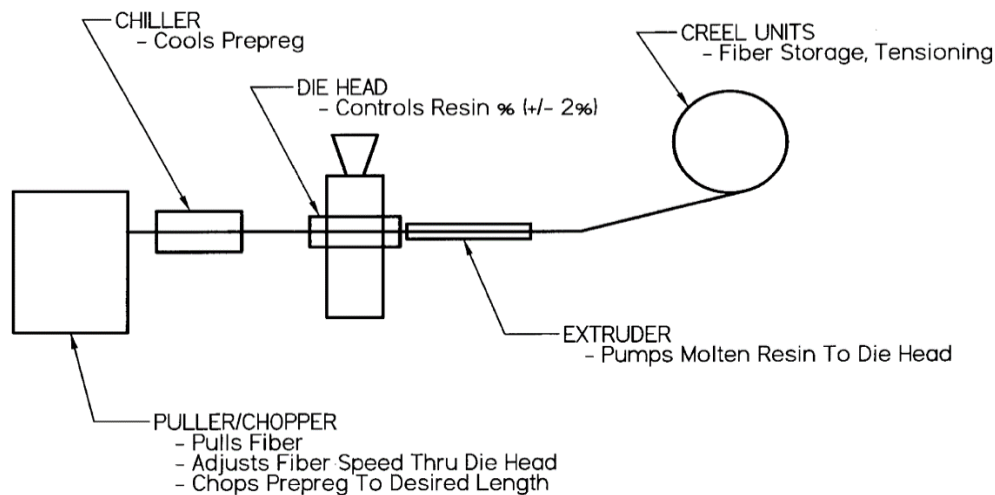


Figure 6. DRIFT™ process (87)

Such pellets could be then melted in a mould or extruder (which could provide homogeneous pressure and reduce the chance of thermo-oxidative degradation) and transferred into a compressor to be pressed into automotive components. This process could manufacture long fibre thermoplastic composites at a rapid rate for automotive industries when suitable system management and moulding units are utilised with the DRIFT process (87). Although the fibre used in this technique is still discontinuous and would be randomly oriented under pressure, the overall composite properties could be primarily enhanced compared to previous injection components. Also, due to the discontinuous and randomly oriented fibre, it is believed that the resulting product from this technique could be chopped again into small pellets after

being scrapped and go through melting and compression again to manufacture new products for recycling while maintaining most mechanical properties. However, the product mechanical property would reduce continuously through such a recycling process with the increase of the remanufacturing cycles due to thermoplastic characteristics which would be further discussed in chapter 2.4.2 On Recycling: Thermoplastic vs Thermoset. On the other hand, with proper settings, the extrusion process can produce composite materials containing continuous fibres, which pull the continuous fibre bundles through a resin bath and is followed by a hot roller or presser to manufacture thin-layer composites. Such layered thermoplastic product is often known as a thermoplastic composite tape which could be used similarly to thermoset prepregs as preforms for compression moulding to improve manufacturing efficiency for thermoplastic composite materials significantly. However, compared to manufacturing prepregs from thermoset resin which is low-viscosity liquid materials at room temperature before curing, the thermoplastic pultrusion process would be more challenging to impregnate fibres inside the resin (88,89).

Film stacking is another innovative way of manufacturing thermoplastic composites using continuous fibres (90). As shown in Figure 7, A mandrel with a release agent is used as a mould for glass fibres and thermoplastic film to be winded/stacked together layer by layer in this technique. The resulting preform would be moving into a hot press to manufacture the thermoplastic composite with continuous fibres. In this research, the resulting product is in elementary geometries as a panel, while with the help of mould design, this technique can manufacture geometries as complex as regular compression moulding products (90). In this study, the author also conducted a comparative experiment with and without maleic anhydride in the PP film and pointed out that because the non-polar properties of polypropylene have been improved, the composite material of maleic anhydride polypropylene and glass fibre will have better

bonding as well as modulus and fatigue resistance (90).

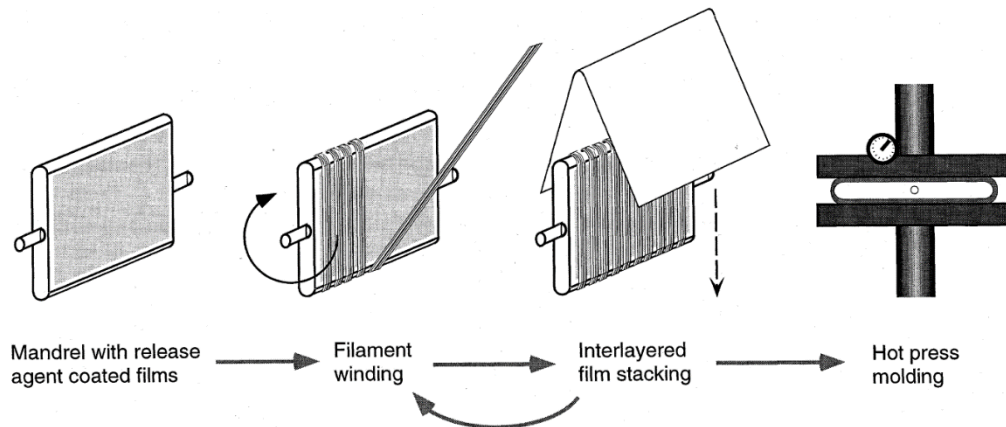


Figure 7. Manufacturing of unidirectional laminates by the film stacking (90)

Filament winding is a similar technique as the film stacking above to manufacture continuous fibre thermoplastics, also winding fibres onto a mandrel (93). However, instead of using a thermoplastic film for stacking, melted thermoplastic is fed onto the fibre before it is winded, similar to manufacturing short-fibre composite pellets. Because the molten plastic would be solidified on the mandrel, this process does not require further compression and usually produces cylindrical products (as fibre could be considered winding on a cylinder). This process could rapidly manufacture thermoplastic composites while the product geometries are primarily limited (91). Also, compared to a composite tube manufactured with woven layers, such a cylinder would have much lower mechanical properties due to the orientation of the fibres. However, it can affect rapid manufacturing and thus could be a suitable technique for manufacturing unidirectional continuous fibre-reinforced thermoplastic prepregs (thin pre-impregnated layer), which are then combined with compression moulding to manufacture automotive components.

Commingled manufacturing was also used for manufacturing continuous fibre-reinforced thermoplastics (92). As the name shows, it is a method that produces a fabric with thermoplastic and reinforcement fibre. The fabric would be cut into the required size, then heated and moulded into desired composite components. It is very similar to the prepreg method in the thermosetting composite material production process in the initial steps, although the

thermosetting resin often needs to undergo curing afterwards, while it often requires hot pressing and moulding to form the final products. This technique could help improve the bonding and impregnation; however, due to the fibres already having a commingled state, the prediction of the melt flow could be complicated (92).

Ye and Friedrich (93) have pointed out in their research that there is 4 primary cost-effective way to prepare thermoplastic composite preforms, as shown in Figure 8, which are all involved in the thermoplastic composite manufacturing methods discussed above. Thus, the preform manufacturing technique in this research will be designed based on these techniques. The component manufacturing technique used in most research above is compression moulding (or simply hot press) which is understandable due to the high viscosity and low melt flow index; processes such as resin transfer moulding or vacuum infusions could quickly develop troubles when introduced thermoplastic matrix. The compression moulding requires the preform to stay at a specific limited region and only press it down through thickness, which vastly reduces the distance thermoplastic needs to travel and thus reduces the difficulty of manufacturing (82–84,86,87). However, due to the limited distance to travel, the mould needs to be appropriately designed to avoid incomplete filling and trapped air bubbles.

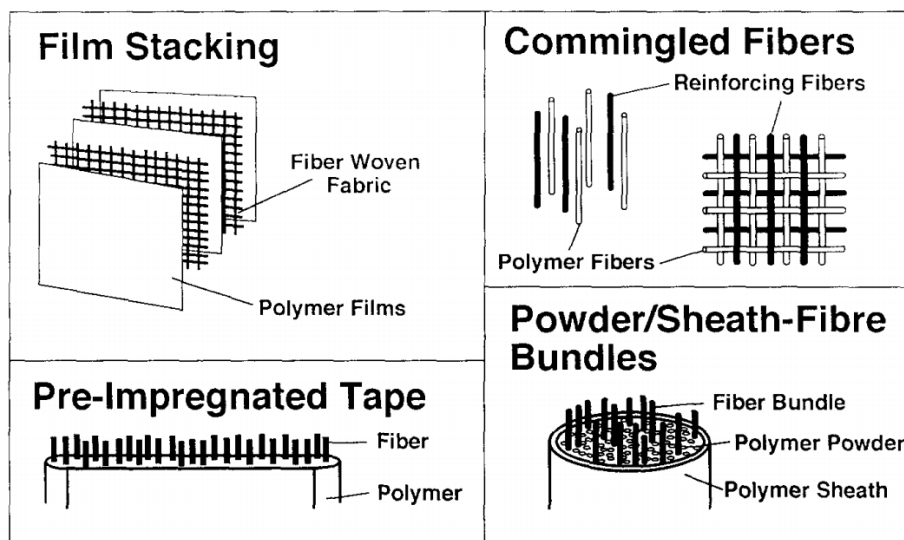


Figure 8. Cost-effective material preforms for thermoplastic composites (93)

2.2.3 Manufacturing Parameters

The manufacturing parameters for a thermoplastic composite component need to satisfy both the fibres and matrix. The main parameters are the processing temperature related to matrix melting and pressure related to the filling of the composites. When using glass or carbon fibres, no matter the random long-fibre distribution or continuous state, manufacturing temperature and pressure, when using PP, would not have too much influence on the results. However, when a natural fibre has been introduced, as mentioned above, a significant mechanical property decrease could be observed in natural fibre beyond 170 °C with the presence of air (51), the maximum temperature needs to be controlled; thus, the choice of the thermoplastic matrix is limited by such temperature. Also, PP could develop thermal-oxidative degradation after 190 °C in the presence of air too (81) while having a melting point around 160 °C -170 °C which could be a suitable combination with natural fibres to avoid property loss, the control of temperature also depends on the mould design as the presence of air or not could influence the temperature when oxidative degradation could initiate, and the time exposed to the air could influence the degradation level. The preform stage would generally have a long period of the presence of air; thus, should limit the temperature to 170 °C when using natural fibres and below 190 °C when using other fibres with PP. When compression using a molten charge or preform, the preforms would only have its surrounding layer exposed in the air at a limited time before forming the component and cooling process; thus, the temperature could stay relatively higher (170 °C -195 °C used in the extruder (82), 200 °C used in extruder (83) and 200 °C used in press for preform (90)).

Pressure is another crucial parameter that needs to be considered to overcome the high viscosity and low melt flow index of thermoplastic materials to fully fill the desired composite component. Inside a closed extruder injection process, the pressure applied was 1200-1500 psi (83) (about 8.3-10.3 MPa) to push the PP fully filled the mould chamber. When using a compression mould with limited matrix travel distance needed, the pressure applied was usually lower than inside an extruder, 25 bar pressure (about 2.5 MPa) was used during a hot press for a PP/glass preform (90). A research study conducted to manufacture

thermoplastic composite from commingled glass and PP yarn by using compression moulding aimed to indicate the ability of different tooling factors (tool design, tool temperature, comingled fabric pre-heat temperature, pressure, and time at certain pressure) to influence the product properties (94). Although too many variables were included in that study thus, not every combination of these variables had been studied, it is enough to show the relationship between applied pressure and the product void content. When rigid mould on both sides is used, a very low pressure (0.2MPa) will result in a very high porosity as high as 47.8%, while sufficient pressure will produce a more or less similar porosity, 1.6% (1MPa), 0.6% (2MPa), 3.4% (4MPa) despite the fact that other parameters (mould temperature, preheating temperature) in these controls are not completely conserved and may lead to a decrease in accuracy (94). However, they also showed that when soft mould (rubber etc.) was used, the pressure would no longer significantly influence the product quality. One of the reasons for this effect could be due to the high viscosity and low melt flow ability of PP; thus, only a more uniformly distributed load could help it to move evenly and fill the cavity better; thus, a relatively soft mould with relatively low pressure could be a strategy to manufacturing thermoplastic composites especially PP which has a low melting point. The pressure of 5 MPa was used to successfully manufacture high-quality jute fibre reinforced PP composite skin during a double-side rigid compression moulding (95). A study of thermoplastic ribs and hinges manufactured under different pressures (0.5/2/4 MPa) shows that when other variables are fixed, the pressure would be inversely proportional to the time that pressure was applied in order to achieve a certain quality product (certain porosity level) (96). Thus, the manufacturing time and the pressure for thermoplastic composites need to be balanced in order to achieve vast manufacturing for automotive industries at the lowest consumption level.

2.2.4 Combination Techniques with Sandwich Core

The combination of thermoplastic composite skin and various core materials is a critical step; unlike thermosetting resins that themselves are often used as various metal/wood adhesives, thermoplastic resins such as PP are mostly not able to bond with metal/wood directly (97). Besides physical connection methods such as rivets, there are two main commonly used bonding methods, adhesives, and fusion to join thermoplastic sandwich composites (97,98). Adhesives, including both thermoplastic and thermoset glues, are always used to improve the bonding between skins and core when some materials are expected to have a low adhesion property, such as the non-polar PP (97). There is no difference from the standard glue principle; most of such bonding is through the intermediate materials with better surface adhesion, forming a layer of connection between the skin layer and the core. Fusion bonding, also named plastic welding, is more direct than adhesives, does not require a third material to help improve the adhesion but is mainly used only for a fully thermoplastic sandwich composite (both skin and core materials are thermoplastic). As the name shows, this technique would slightly melt the surface of both skin and core materials to allow them to diffuse and thus consolidate together after cooling. Such bonding techniques could be achieved in various processes, including a heated vacuum bag, compression moulding or physical (friction) connection tools (97,98).

In Karaduman and Onal's research, fusion bonding using compression moulding at only 1 bar pressure (0.1 MPa) with a temperature of 185 °C was successfully bonded PP composite skins with both PP honeycomb and PET foam core, and no failure related to bonding was founded in their followed mechanical bending testing (95). Another study used a controlled group to join sandwich composites of PP/glass skins and PET foam cores by vacuum bags or compression moulding and with or without additional adhesive film (BEMIS-5250 polyester-based co-polymer). The pressure applied in all their experiments was 1 bar (0.1 MPa), and the temperature applied was 180 °C without adhesive film and over 150 °C with the film. The adhesive film did show the ability to improve the bonding quality that the overall sandwich composite with a

relatively weaker skin (which may be due to uncertainty during skin manufacturing) modulus shows a better sandwich strength compared to those samples having a stronger skin but no presence of adhesive film (99). However, due to the limited number of samples for comparison in their experiment and their slightly lower temperature (over 150 °C vs 180 °C) when applying the adhesive layer, such higher sandwich quality might come from the effect of less damage developed in the PET foam during the joint process at a lower temperature. Although PET foam has a softening temperature of around 80 °C, there were no significant properties lost found in all samples (101), and thus was believed that 1 bar pressure would not damage the PET foam structure after softening temperature at a short time period for composite join.

2.2.5 Summary

In summary, this chapter first surmised some commonly used technologies for the rapid manufacturing of composite materials in the automotive industry and pointed out that most of these technologies lack the applicability of thermoplastic composite materials and are more used for thermosetting resins with better fluidity. Secondly, this chapter introduces some production methods developed for manufacturing thermoplastic preforms which could then be fitted with some of those rapid manufacturing techniques for thermoplastic composites. Considering the requirements needed for the challenge in this research, to have rapid manufacturing of fully recyclable and lighter composites at compatible costs and properties for automotive components, simple preform preparation and direct composite manufacturing should be applied. The compression moulding for preforms such as simply stacking, molten charge or pultruded tape should be a more suitable choice. However, one of the significant parts of the pultrusion process is pulling the fibres, which could not be suitable for recycled carbon fibres due to their discontinuity. Thus, modification of this process would be required for manufacturing the RCF / PP composite tapes. Different from the manufacture of thermoplastic composite, the joint techniques for fully thermoplastic skins/cores with or without the help of adhesive film could be easy under low pressure with either vacuum bagging or compression moulding.

2.3 Testing and Standards

This chapter will introduce some testing that could be used to evaluate the property of the sandwich composite designed and manufactured in this research. Property testing and evaluation is an essential part of this research to help identify whether the raw materials had been shaped into products properly during the manufacturing process, to reflect any defects generated by comparing the theoretical property of the finished product and its actual performance to establish a complete production process to reduce random errors and avoid defects in finished products. Performance evaluation can also be used to analyse the material's applicability in subsequent applications and help product design maximise the use of the material.

2.3.1 Calculations in Sandwich Composites

The simplest case in which composite properties could be directly calculated from the mixing rule using fibre/matrix properties and their volume fraction, respectively, is that all the fibres are perfectly aligned in a single direction, and the load applied to this composite is perfectly parallel or perpendicular to the fibre direction. However, due to the orthotropic properties, these two situations would present an upper and lower property when the fibre volume fraction is not 0 or 100%, which reflects the maximum (parallel) and minimum (perpendicular) properties this composite material could have under an applied load direction. The properties of this composite could range between this upper and lower band when the load applied was between parallel and perpendicular to the fibre direction, and usually, a correction regarding the angle of applied load or different layer of fibre oriented need to be applied to have an accurate prediction of composite properties (100). Due to the random orientation and discontinuity, a recycled carbon fibre mat would have properties hard to predict fully. However, from the results mentioned in the above chapter, 'fibre in a composite'(that composites made from RCF mat at a normalised volume fraction have about 30% mechanical properties compared to virgin carbon fibres products (0,90 oriented) (29)), RCF mats could be estimated to have about 70-80 GPa modulus along the mat direction (assuming that both x / y directions have identical properties, in which the z-direction shows weakness the same as other carbon fabrics). Also, in actual application, due to the random orientation, such modulus of RCF mats is expected to have a specific wider distribution than other fibre materials.

The calculation of sandwich composite properties could not be treated as standard bulk materials due to composite skins' orthotropic properties and a different core property. Structural sandwich composites such as I-beams with homogeneous materials could be evaluated by applying the cross-sectional effects (second moment of area), and thus sandwich composites with a different core material could be similarly transferred into a sort of homogeneous I-beam. The adequate thickness of the I-bar after such conversion could be calculated from the product of the original thickness and the ratio of core modulus to skin

modulus (101). After adding the cross-sectional corrections, sandwich composite properties such as bending strength and modulus could be calculated similarly to bulk materials. Further calculations and equations related to the property evaluation in this research will be conducted in the methodology part.

2.3.2 Three Point Bending Testing

Bending tests are commonly used to evaluate the bending properties of thermoplastic sandwich composites (102–104), including bending modulus, strength, or stiffness. Unlike simple uniaxial tensile or compression tests that are only carried out under a single stress environment, the sample for the bending test is usually subjected to combined loading, such as tension, compression, and shear together. Such combination loading could help estimate whether materials are suitable when needed in a complex loading application such as the lorry floor panels. The test would usually destroy the sample to show the complete change of the sample during bending, from the linear change of the loading vs displacement (elastic deformation) at the beginning to where elastic-plastic damage is initiated, which brings non-linear changes, and then the maximum load will be reached, after which the force is significantly reduced, and eyes could inspect visible macro cracks (102–104). Bending testing requires simple sample geometries such as a tube or flat pane and could be operated using a universal tensile / compression machine by applying a flexible bending fixture (105–107). The sample is usually placed on two high columns with bearings on the bottom support, which can provide point contact and sufficient sample displacement space. During the bending process, the bearing can provide the sample with a certain degree of movement to ensure that the maximum load is always applied to the centre of the sample. The loading (top) fixture typically contains a single bearing which is for three-point bending, and two bearings separated from a certain distance (usually a quarter of the maximum supporting span) which is for four-point bending (102–107). Other unique loading fixtures such as 1/3 load span, one loading head at 1/4 position and one head at 1/3 position or even uniform loading over the whole sample could all be used while a correction is needed to fix the geometry effect via mechanical calculations (106,107) though three-point bending, and four-point bending are the mainly used two testing methods.

The numerical calculation after the bending test has been established by ASTM and other standard systems (105–107). The performance of the test sample can be calculated according to the standard formula, and the data acquired is

stipulated by different standards. At the same time, some custom parameters and the changes brought by them can be corrected, just like the custom top fixtures (105–107). Such equations could also be used to predict the performance of the samples by using raw material properties. However, due to some reasons in actual tests (elastic-plastic deformation, movements under high bending displacement, flexible fixture connection, sample geometries, bearing size), such prediction is only valid for a limited region before significant displacement takes place (elastic-plastic deformation) (103,104). A more accurate prediction of the non-linear sandwich composite behaviour under bending testing could be made by well-controlling these variables and introducing the non-linear change for elastic-plastic behaviour (103,104). Three-point bending test would focus more on a single-point load which would have a minimal region of uniform stress just under the loading fixture head, while four-point bending usually contains a specific region of uniform stress between the two heads. Three-point bending is more likely to produce more significant errors due to manufacturing differences in different regions of the sample, while four-point bending can more accurately measure the bending properties of the material. However, in comparative research of both bending techniques using a large number of identical samples, three-point bending did show more accurate (fewer deviations among all samples) results compared to four-point bending (108). Again, the reason for this could be those real test issues, such as four-point bending consisting of a more complex loading head which would hardly maintain consistency during the test for all samples. The bearing was used aim to provide perfect point supports, but during sample deformation, such point contact would transfer to a surface contact; thus, different bearing diameters would also influence the accuracy with different materials or geometries. Also, the sample movements caused by large deflection would influence the accuracy as the loading span / supporting span changed. Overall, this influence would have more effects on four-point bending testing due to its more complex loading unit (108).

2.3.3 Drop Tower Impact Testing

Impact testing is usually used to understand the impact resistance of materials by comparing the different amounts of energy absorption during the fracture and would be very important for automotive applications such as energy absorption structures or protection layers for goods (109–113). In South Korea, maintaining sufficient impact resistance is vital for bus floor panels after the government published restrictions to limit the bus panel weight, and mostly sandwich composites have become the only candidate for such applications (40). This research studied the impact resistance for several sandwich designs at a similar weight and showed the results that fibre reinforced plastics skins could provide a much stronger impact resistance compared to metal skins when maintaining the same weight (40), and such composites would be a more suitable candidate as bus floors. All impact testing techniques could be described as using a specific energy impact head to collide with the sample, and the impact resistance of the material is evaluated through the residual energy of the head after the impact and the damage level of the sample (109–113). Different impact head geometry, such as round or hammer shape and initial energy and impact speed, will lead to different impact results. Due to the ease of manufacturing the panel structure required for the experiment and adjusting the impact energy/velocity (low-speed/low-energy impact was considered the most dangerous for composite materials to cause delamination), drop tower impact is always used for composite sandwich materials to evaluate the impact properties (109–113). In the drop tower test, an impact holder with a customised head (round, hammer, or even penetrative knives) would be levelled up inside the tower controlled by a computer to a certain height (energy) and dropped freely to hit the sample, which would generally be placed on a hollow supporting platform under the tower.

During a low-velocity impact, it is shown in much research that thermoplastic composites could have more resistance to delamination and would have developed lesser damage compared to thermoset composites (109–111). During one impact test, although the maximum contact load of the thermoplastic composite was only about half of the thermoset composites, the deformability of

thermoplastic took the total energy absorption to the same level as thermoset ones (112); the; the author also pointed out that in some suitable applications such as a wave impact which could highly cause delimitations, thermoplastic could show more impact resistance. The research evaluated the impact behaviour of several sandwich composites with the same skins, but different foam materials and showed that the core shear modulus would primarily affect the maximum impact load and the failure mode under constant impact energy. The maximum load would increase with an increasing core modulus; core shear cracking is the primary failure mode when a weak core was used, while skin bulking showed more with median moulds cores, and delamination became the dominant failure with strong modulus cores (111). However, this research has fixed the sandwich skins; thus, with different foam cores, the ratio of the sandwich skin to core properties is different, and this difference should be the factor in determining the failure mode of sandwich composites. Compression after impact is an additional technique to help evaluate the damage level of composite materials after a low-velocity impact test since damages like delimitation could hardly be visible (112,113). This is accomplished by operating a compression testing on the samples after impact and measuring the residual strength. As mentioned above, natural fibre composites do have a better impact resistance (38,39), and hybrid fabric with natural fibres could also improve impact resistance (114). However, due to the difficulty of recycling, this design will be retained in this study but will not be the primary consideration.

2.3.4 Microscopy Image

Microscopy is a mature technology that can observe objects on a microscopic scale that is invisible to the naked eye. Materials scientists often use it to understand the microstructure of samples for better analysis of sample properties. Microscopy always needs a source to interact with the samples and sensors to receive the required response from such interaction and analysis into desired images, like the simplest version, the optical microscope, which usually uses visible light as a source and naked eyes as a detector for receiving the rebounded light from the sample (115). During this process, additional equipment is always needed, such as the lenses in an optical microscope to help magnify the sample image for the eyes. There are several types of microscopy techniques, by different detecting sources, which could be divided into an optical, electron, scanning probe or even x-ray, which could be further separated by a different response such as scanning electron microscopy (SEM), which uses reflected electrons to generate image and transmitted-electron microscopy (TEM) which using electrons passed through samples to create the image (115). In this research, composites would be studied and analysed using microscopy; thus, details about microscopies would not be further discussed, and specific microscopy techniques that could help understand composite materials more would be included.

Studying the microstructure of composite materials can help verify whether the selection and manufacturing process of the laminate is reasonable and whether the structure of the composite material is the same as in the design at the microscopic level. At the same time, are there any potential weaknesses, such as fibre discontinuity (the specific region with too much resin and the fibres from different slices are not entirely covered) or voids during the manufacturing process. These analyses, as well as whether fibre is bonded into the matrix properly, could all be achieved just through an optical microscope (116). SEM using mainly reflected electrons is suitable for sandwich composite materials; it could show detailed surface information as well as a clear interface between similar materials (117) (such as the Polypropylene matrix and the PET foam or other polymer adhesive included). When using microscopy to analyse a cross-

section of composite materials to reveal the microstructural and defects, digital microscopy could also be used to help the analysis through different assisting tools (118).

2.3.5 Summary

In conclusion, this chapter reviews the conversion of heterogeneous sandwich composites into a homogeneous beam during mechanical calculations and some techniques that are often used and will be used in this research to evaluate the property of composite sandwich materials. Three-point bending could be the most straightforward test to reveal the mechanical properties, such as strength and modulus, of the sandwich composite manufactured in this research. Drop tower impact testing could be utilised when manufacturing simple flat panels as the samples to indicate the impact resistance and to show whether such a design could be sufficient for lorry floor panels to replace the wood panels. SEM or optical microscopy would be used to reveal the fibres embodied inside the matrix, any defects formed during the manufacturing process and the bonding quality between sandwich skins and core.

2.4 Composite Material Recycling

To avoid adverse effects on the government's goal to become more sustainable in the automotive industry, the recycling process of lightweight composite materials is vital to be studied. Understanding the recycling of composite materials can help reduce the environmental impact of widely used thermoset composite materials and the correct use of thermoplastic matrix in future applications to further sustainability. This chapter will review the techniques to recycle existing composite materials products and compare thermoset composites and thermoplastic ones on their difference in the recycling process and the product properties after recycling.

2.4.1 General Recycling Process of Fibre Composites

Since most of the resin of the thermoplastic composite material can be melted by heating, recycling of fibres inside could be much more straightforward compared to thermoset ones, and different raw materials could be added during the heating to reprocess into new products. However, due to the limitation of recycling chamber size, the energy needed to heat and costs, big thermoplastic composite components would still need to undergo the cutting and chopping process the same as thermoset ones for recycling (119–122). Generally, all composite materials need to be cut and chopped by slow speed cutter or crushing mill before the fibre recycling process takes place to obtain the required size to fit into the following process and remove any other materials, such as metal inserts, and this process is when fibres length mostly reduced (to about 5 – 50 mm) and become long discontinuous fibres and would typically take places for all composite recycling (122–126).

The following steps to recycle the fibres would be separated based on thermoplastic and thermoset resins; for thermoset resins recycling process could separate into two general categories, mechanical recycling or fibre reclamation (123,127). Mechanical recycling could be used for most composites with either glass or carbon fibres but is mainly focused on glass fibres due to significant properties lost. In this process, the cut or crushed composite waste that has undergone the initial size reduction process will be further reduced in size by a hammer mill or high-speed mill into particles around 10 mm to 50 mm. These result particles would be a mixture of material containing both fibres and polymers. The finer grade particles could be used as a filler material, and larger particles have a high aspect ratio and do show a fibrous nature, so has the potential to be used as reinforcements (127). Fibre reclamation is a recycling technique that has attracted more research, and it is also more popular with the carbon fibre recycling industry because it can remove impurities as much as possible, retain the most outstanding fibre properties, and able to obtain relatively long recycled carbon fibres (127,128). It can be further divided into pyrolysis, fluidised bed, or chemical assistant process, but in simple terms, it is a method that tries to remove the thermosetting resin in the composite material

by the use of primarily thermal energy or sometimes chemicals to extract the fibre, and different subdivision processes are just the difference in the operations (123). Without the help of any catalysts or solvents, the energy needed to remove most thermoset resins would be significant, and the temperature during such a process would be high enough to damage carbon fibres which would lead to a lower recycled fibre property. Research on the effects of thermal treatment on carbon fibre-phenolic composites (129) has shown that without the help of any chemicals, resins could be entirely removed at a relatively high temperature, starting at around 400 °C. However, at a temperature above this, the recycled carbon fibres would show a reduced diameter due to the initiation of degradation, causing a lower mechanical property. Composites made from recycled carbon fibre, which underwent pure thermal treatment at 400 °C, showed the best mechanical property among all samples, which was concluded in their research. Similar results were also shown in another research that treatment at 450 °C for 1 hour could entirely remove polyester resin in composites without apparent fibre degradation found (130). With the help of chemical treatment, the recycling temperature could be much lower for thermoset composites, with only 90 °C temperature and the application of a mixed solution of peroxide hydrogen and N, N-dimethylformamide (at 1:1 volume ratio and both solutions of 30% concentration) for 30 minutes, more than 90% of the epoxy inside composite could be removed, and the extracted carbon fibre retains 95% of original tensile properties, the same process with a higher temperature at 100 °C could fully remove the resins and improve the retained properties up to 98% (128). Normally, without further treatment, the product would be agglomerated recycled fibre that could be directly pressed into the RCF mat after the thermal process. Compared to mechanically recycled fibres which could mainly be used as a filler material, the thermal process could extract the fibres and retain more properties.

All the processes above for thermoset composites could also be utilised for thermoplastic ones. However, it is not necessary to do so to consume more energy and produce chemical pollution. The thermoplastic composite could

undergo a unique recycling process after the cutting and chopping stage, which could be simply analysed as melting and remoulding (119–122). A glass fibre reinforced polypropylene composite used in a boat was recycled through cutting and chopping, followed by a manufacturing process to produce composite granules. Such composite granules were then used as the raw material for injection moulding. The results showed that this is a suitable way to recycle thermoplastic composite materials and the recycling of different parts (including paint and other contaminants or not) proved that a small number of impurities carried by the scape component would have little effect on the recycled product properties (119). Another research (120) with glass fibre-reinforced, thermoplastic composites utilised the same method for recycling and applied compression moulding for comparison, which went through the same cutting process, but the reduced-sized product was used as raw materials directly in compression moulding. Their results showed that, although the compression moulding products had a higher fibre volume fraction (27.8%) compared to the injection product (19.6%), the tensile strength and modulus were even lower than the injected product, but the notched impact properties on both samples did reach the estimation with compressed sample approximately twice the impact strength. They pointed out the fact that due to inappropriate manufacturing parameters (insufficient temperature and pressing time under that temperature), the compression samples contain many micro-cracks, which could primarily affect the tensile properties; however, due to the impact, testing was operated under a notched sample, as well as higher average fibre length could be reached in compression moulding, the impact properties of the compressed sample could be much higher (120). A novel recycling solution for thermoplastic composite published recently in 2020 (131) had successfully recycled chopped scarp into a molten and mixed dough which was used as a source for manufacturing moulded composite panels. The compression moulding with appropriate parameters and operation did not result in any micro-cracks, which would affect the tensile properties as previous research did (120). It is promising that with appropriate manufacturing parameters, compression moulding could be used directly to recycle thermoplastic composite materials

resulting in products at a relatively higher volume fraction and longer fibre length to maximise the recycled properties. Another possible technique which could be named dissolution to recycle thermoplastic composites could also be achieved by chemicals which can recycle fibres at full length (which only depends on container size, and scrap composites do not need to be cut and chopped into small pieces) (132). A glass fibre reinforced Elium thermoplastic composite was recycled in a glass pan when immersed inside chloroform, the fibres are fully retained, and about 90% of thermoplastic resin was retained by precipitating from the chloroform into methanol (incomplete precipitation and manual operation caused the loss) (132). In their research, the glass fibre extracted by dissolution showed almost no decrease in tensile properties, about 86% stiffness remained after the recycling, and the whole process did not need any thermal energy. This technique's advantage is maximising the properties and keeping the continuity of fibres, which could significantly improve the composite properties made from such recycled fibres. However, they used 5.96 kg chloroform to wash away all the thermoplastic resin in a 0.924 kg composite sample. The dissolved resin could not be entirely precipitated in methanol; thus, a further purification process would occur be required. Also, the time needed to recycle this composite sample entirely was more than 72 hours (132).

2.4.2 On Recycling: Thermoplastic vs Thermoset

For both thermoplastic and thermoset composites, the recycling process to extract fibres or reuse fibres from a scrapped continuous fibre reinforced plastic would always cause significant properties to lose. Although many studies mentioned above have shown that the recycled fibres (single fibres) can retain their mechanical properties to a large extent, when the recycled fibres are used for reinforcement again, the performance will inevitably be significantly reduced, regardless of a thermosetting or thermoplastic matrix. However, the recycling process would need to cut and chop down the scrap composite into small pieces for further treatment, which causes the fibres inside to no longer be continuous. At the same time, the composite material recycling industry will not and cannot only recycle single fibres when processing because the energy efficiency of doing so is significantly low. Therefore, the recycled fibres will mostly be randomly oriented if no special treatment is applied, and such aggregated recycled fibre cannot provide the maximum mechanical property with orientation like virgin carbon fibres. Thus, even a single fibre extracted from the aggregated recycled fibre could have more than 90% of its original mechanical properties, the overall composite would have much lower performance. Studies report that three different composite samples with volume fractions of about 6%;12%;18% made from recycled carbon fibre mats and polypropylene matrices, have flexural moduli of about 1.4;5.5;8.6 GPa respectively (29). The best performance one from these samples only showed about 22.6% effective modulus compared to the original continuous carbon fibre composite of the same design (moduli can reach 13.4; 25.7;38 GPa respectively, according to a typical carbon fibre modulus of 228 GPa and 90% remained after recycling through the composite modulus mixing rule (will be introduced as Equation 1 in 3.3.5.2 Mixing Rule for Composites). The data sheet for commercial recycled carbon fibre non-woven mat (G-TEX M-SM45-200-1200) also shows a modulus of 25 GPa at a 30% volume fraction in a polypropylene matrix, whereas the value for virgin carbon fibre might be 67.1 GPa uses the same estimation technique. Recycled composites based on

recycled carbon fibres could have up to 37% effective mechanical properties compared to continuous virgin composites.

Further treatments on the aggregated recycled fibre could improve the mechanical properties within the products, such as using an air classifier and sieving techniques to obtain oriented chopped recycled fibre from the aggregated recycled fibre (123) or surface cleaning to remove carbon dust during the recycling process (133). Modification on the matrix could work too, such as using maleic anhydride to improve the bonding with the recycled carbon fibre when the PP matrix was used (134).

Currently, thermoset composites are not recognised as an environmentally friendly material by the EU end-of-life vehicle directive as the energy needed to recycle the fibres is significant and also thermoset matrixes could hardly be recycled (17). Mechanically recycled thermoset composites do not need significant energy consumption but could not maximise the retaining properties, and the fibre in recycled products would still be covered by some resin, which would have limited applications. Thermal processing could retain more fibre properties and remove most of the resins at a temperature unlikely to cause carbon fibre degradation. However, this process combined high temperature and a long cycle time (400°C for 2 hours to remove epoxy resin (129) or 450°C for 1 hour to fully remove polyester resin (130)) could consume a significant amount of energy. With the help of chemicals, the temperature and recycling cycle could become more acceptable (100°C and 30mins to fully remove epoxy resins and retain fibre properties up to 98% (128)). However, during this research 30ml chemical solution was used for extracting carbon fibre from 0.2 g composite samples. Although the amount of the solution was believed to be excess for such purpose, a fully immersed recycling process for thermoset composites using this technique could generate a significant amount of waste solution, which would be tricky to deal with in a very environmentally friendly manner.

Although most of the existing thermoset composite material recycling technologies seem to be less energy-efficient and environmentally friendly, it is

essential to extract carbon fibre from the thermoset composite material because thermoset carbon fibre occupies a large part of the existing fibre-reinforced plastics currently. Also, the energy consumption of recycled carbon fibre materials compared to virgin carbon fibre manufacturing is still worthwhile, and landfills or burning of such composite materials would be causing more damage to the environment (135). Compared to thermosetting resin, the thermoplastic resin will become a more advantageous competitor in future when considering the difficulty of recycling as they can be remanufactured at the end of life, which would consume less energy. However, thermoplastic materials also have limitations when using their unique recycling processes.

Chemical dissolution can recycle fibres with very high mechanical properties and does not require thermal assistance simultaneously. The most charming result of this technique is the maintaining of continuous fibre, which is a significant factor that affects the properties of composites made from recycled fibres, as most other techniques which need a thermal treatment all require cutting or chopping the scrap composite into small pieces when fibre inside would be reduced in length significantly at the same time. It is similar to the method of recycling thermoset composites with chemical reagents. However, unlike thermoset recycling, this process is a physical reaction that does not change the matrix and can recycle them simultaneously. However, similar to the thermoset recycling process, this method also requires a lot of chemicals and is time-consuming. Considering the environmental impact of such a high chemical consumption rate and high recovery time, whether this technology can help this research to faster and more environmentally friendly production of fully recyclable lightweight composite materials for automobiles remains unclear. The thermal recycling process would need to cut and chop scarp composite, which would reduce the fibre when continuous virgin fibres were used, however, if the original composite is made from recycled fibres which already contain a specific average length distribution, the effects from cutting and chopping could be little [126] and such recycling process can be used again when the recycled product goes to end of life again. However, the energy consumption by this recycling method is mainly dependent on the matrix material. When a higher

temperature is required for melting, the energy consumption will be more, such as PEEK (Polyether Ether Ketone) than PP. Also, recycling involves mostly melting and solidification cycles that would affect the structure of thermoplastic materials, causing a mechanical property reduction through chain scission. Research on the recycling of PP has revealed the microstructure change during thermal cycles even without thermal assistant degradation, which was mentioned in previous chapters (51–55), the polymer chain would cause scission during the thermal cycle, which would cause average molecular weight reduction, thicker lamellae are more likely to form and a higher crystallinity degree (136–138). In addition, recycling may significantly increase the ageing of the polymer and there may be contaminants during the process, which further affects the performance of the recycled product (137). Research on highly recycled polyethene and PP showed that highly recycled PP would have about a 15% decrease in tensile properties and a 35% decrease in the elongation before fracture, while polyethene would have a higher properties reduction (high-density polyethene tensile properties had a 24% reduction and low-density polyethene tensile properties had 36% reduction) (138). The irreversible ageing characteristics of plastics originate from various influences, including ultraviolet lights, thermal cycles, environmental factors, loading, or chemicals that may affect the performance of thermoplastic composite materials and directly recycling them using melting and remanufacturing could cause product properties from different batches inconsistent (139).

2.4.3 Summary

In summary, this chapter introduces standard recycling technologies for composite materials (except for non-recycling-related topics such as landfill or energy recovery), specifically discusses some unique methods for thermoplastic composites, and compares thermoplastic and thermoset composites from their difference in process as well as the difficulty in recycling. The characteristics of recycled fibres and the processing parameters required by different recycling processes were also compared, among which the thermoplastic matrix showed a more straightforward process with less energy consumption than the thermoset matrix. However, most composite materials in use currently are thermoset ones. Thus, developing techniques to recycle and reuse them is also very important. Thermoplastic composites are more suitable for industries that need to take recycling as an essential factor into consideration. At the same time, thermoplastic composites made of recycled discontinuous fibres have the potential to be directly reprocessed into new products without causing too much damage to the fibres. However, what must be addressed is the degradation of the performance of the plastics due to the ageing during the use of the product and the repeated recycling cycles. In remanufacturing, mixing recycled / virgin matrix at a specific ratio to compensate for the diminished property could be very important in future thermoplastic composite materials recycling applications.

2.5 Overall Research Gaps and Their Significance

The popularity of using carbon fibre composite materials in automotive industries in real life in daily vehicles (excluding special vehicles such as racing cars or heavy-duty construction vehicles) is not very wide, although many studies have shown that the application of carbon fibre composites can significantly reduce the weight of vehicles. Some of the primary reasons could be that most of the commonly used thermosetting resins on the market could not be regarded as recyclable materials, the price of carbon fibre is often costly, and the energy required to produce virgin carbon fibre is significantly high. Based on the works of literature, there is no research on the application of carbon fibre materials in automotive industries that can simultaneously consider meeting the recyclable requirements of the government and the need for lightweight, low-cost, and efficient manufacturing of the automobile industry. Therefore, this study sets the secondary structure of the lorry floor as the target for improvement because most of the panels currently on the market cannot fully meet all the requirements of the above restrictions. One of the aims of this research is to manufacture a fully recyclable composite material substitute that can replace the commonly used plywood laminates on the market and combine all the above requirements.

It takes a lot of energy to manufacture carbon fibre, and because of its superior performance, it is wasteful to landfill composites directly. However, due to the cutting and chopping required for most of the recycling process, the recycled carbon fibre is mainly in the form of a completely random-oriented mat mixed with long discontinuous fibres and short fibres. The mechanical performance of RCF mat inside a composite was not sufficient for applications as primary loading components in vehicles where mostly virgin carbon fibre composites were used. Therefore, research on recycled carbon fibbers reusing in composite materials has remained at the laboratory-level composite material performance comparison, and no potential application was made for automotive applications. However, such recycled RCF mat still has comparable mechanical properties to virgin glass fibres with a much smaller density; thus, secondary structures in automotive components could still be a potential application. In this research,

the lorry floor panel (secondary supporting panels on metal frames), which does not need superior performance, requires improvements in recyclability, maintaining a low cost and being light-weighted could be a suitable application in automotive industries for RCF materials. At the same time, because recycled carbon fibre has not appeared in the market for a very long time, there are few studies on the hybrid use of RCF and other fibre materials. Since most carbon fibres tend to lose more stiffness than their tensile properties after being recycled, adding natural fibres with superior damping properties to combine with RCF to make hybrid composite materials will also be a worthy research direction.

Finally, the current composite preform tapes (thin layer fibre reinforced thermoplastic composite) are all manufactured through the pultrusion process of virgin fibres due to the pulling needed in this process, and there is no research established any customised pultrusion process suitable for RCF tapes. However, with the increasing amount of existing composite materials reaching their end of life in the future and the increasing need to maintain sustainability, the amount of RCF in the market is expected to increase continually. Thus, modifying the pultrusion process for manufacturing RCF composite tapes could be worthwhile in this research. A successful result could improve the manufacturing cycle, which would benefit RCF to fit the rapid manufacturing in automotive industries. Also, there needs to be research about directly remanufacturing from end-of-life RCF composites. It is believed that the significant reason for properties lost in carbon fibres during the recycling is the cutting and chopping stage, when continuous fibres become long discontinuous fibres, while such a process is believed to have limited effects on RCF composites. Research on recycling RCF composites is also one of the aims of this research to figure out how many properties could remain in the composite made directly from molten chopped RCF composites and the potential of multiple direct recycling and remanufacture cycles of RCF composite materials.

3 Methodology

This chapter introduced the design of the fully sustainable sandwich composite, which could improve the lorry panel sustainability but satisfy other required properties at the same time, listed the materials needed for manufacturing such composites and the experiments involved in this study to manufacture the samples and the corresponding testing methods are introduced, as well as the utilisation and calculation of the experimental data to obtain desired material properties.

3.1 Design and Materials

The primary materials included in this research were the RCF mat, polypropylene, and the PET foam core. A random-oriented RCF mat, as shown in the Figure 9 was used, which was sourced from ELG Carbon Fibre Ltd, which was renamed Gen2 carbon now (Cannon Business Park, Darkhouse Ln, Coseley, Bilston WV14 8XR, UK; density 1370 kg/m³). The recyclable fibre was obtained by chopping carbon fibre composites end of their life, followed by a pyrolysis process to remove the thermoset resin and the remaining gathered recycled fibres were compressed into the mat. Two types of polypropylenes were used as the matrix for the RCF mat in this research, one in the form of sheets (1 mm PP sheet; source: SIMONA PP-H natural) with a melting point of 161 °C and recrystallisation temperature of around 122 °C, the elastic modulus of 1.2 GPa and density of 950 kg/m³. And the other polypropylene powder (source: HAI HANG Industry CO., Ltd. China) also with a melting temperature of around 160 °C and recrystallisation temperature of around 121 °C, an elastic modulus of 1.1 GPa and a density of 940 kg/m³. Both polypropylenes had a low melt flow rate of 5g as presented in data sheet. A recycled 10 mm thick PET foam manufactured from recycled plastic bottles (Armacell company) with a shear modulus of 18 MPa and a density of 100 kg/m³ was used as the core for the sandwich structure designed as the truck panels.



Figure 9. Raw materials

Other materials included in this research are, A virgin carbon fibre, ZOLETEK PX35 continuous tow, which has a diameter of 7.1 micrometres, similar to the average diameter of 7.2 micrometres of RCF, was selected as a reference comparison to be tested using the single fibre approach. The datasheet shows

that the PX35 has an average tensile strength of 4137 MPa and an average tensile modulus of 242 GPa. A polyester-based copolymer adhesive film (BEMIS-5256) with a low glue line temperature (148 °C to 181°C) to enhance the bonding between the PP skins and the PET foam core of the sandwich structure, Flax fibre (unidirectional fabrics; density 1290 kg/m³) with average tensile modulus around 50 GPa were utilised as reinforcements for the composite skin in some comparative designs. Woven glass fibre (70GPa modulus) reinforced epoxy (RS-135M) with a fibre volume fraction of 35% manufactured by vacuum infusion was used during the impact property comparison with the RCF composite design in this research.

As proposed in the introduction and literature review, this research aims to develop a fully recyclable sandwich composite at a rapid manufacturing rate for automotive industries (as flooring/side panels for lorries/vans) to satisfy the need for lightweight and regulations. Other essential parameters, including costs, mechanical properties, impact properties, thermo-resistance or environmental resistance, were considered too, but not all of these parameters were tested and verified in this research.

This study achieved the goal of being completely recyclable using the thermoplastic matrix (PP) and the carbon fibres (recycled ones). The main sandwich design in this research was RCF / PP composite skins with recycled PET foam, which allowed a fully recyclable component at a very low density (density would vary with different skin/core thickness ratios and designs, as shown in Table 1). About 3 mm skin samples were used in this research due to the cavity size of the compression mould, and 10 mm foam cores were used as the supplier provided. Unidirectional flax fabric was also used to manufacture a self-sandwich skin manufactured from the stack of outer layer RCF with flax in the middle, which is designed to compare with the pure RCF skins as flax was believed to enhance the damping properties of the sandwich composite and RCF outer layer was believed able to protect the flax from moisture. All the mixed skin design were manufactured and cut in the way to keep the flax fibres all line directed to the length of the samples.

Table 1. The density of different thickness designs (skin fibre volume fraction at 20%)

Single skin/core thickness ratio	3:10	3:20	3:40	5:10	5:20	5:40
Skin thickness (mm)	3	3	3	5	5	5
Overall density (Kg/m ³)	450	316	222	567	411	287
Area density (Kg/m ²)	7.2	8.2	10.2	11.34	12.34	14.34

The goal of rapid manufacturing in this research was aimed to be achieved by using the compression moulding technique. In the initial experimental stage, the stacked PP sheet / RCF was directly heated in the mould cavity inside the compression machine and then compression moulded. However, the heating-cooling cycling of the compression chamber and the mould and the heating of the stacking materials in the mould is very time-consuming. This temperature cycle for the compressor units was unnecessary and is different from the actual industry application, where multiple moulds could be used to separate the heating and cooling cycle from the compression machine and speed up the whole process.

3.2 Sample Manufacturing

3.2.1 Composite Skins Manufacturing

Figure 10 shows the example results of the DSC test for the PP samples, which is similar to the behaviour of PP in most literature and had a melting point of around 160 °C. The samples started to absorb a significant amount of heat above 150 °C, which was maximum at 161 °C; thus, the target of this research was to achieve material temperature at about 161 °C when processing the PP materials. The colling was done slowly after the processing until it reached 110 °C and below when the recrystallisation was believed to be completed, and rapid water cooling would be introduced.

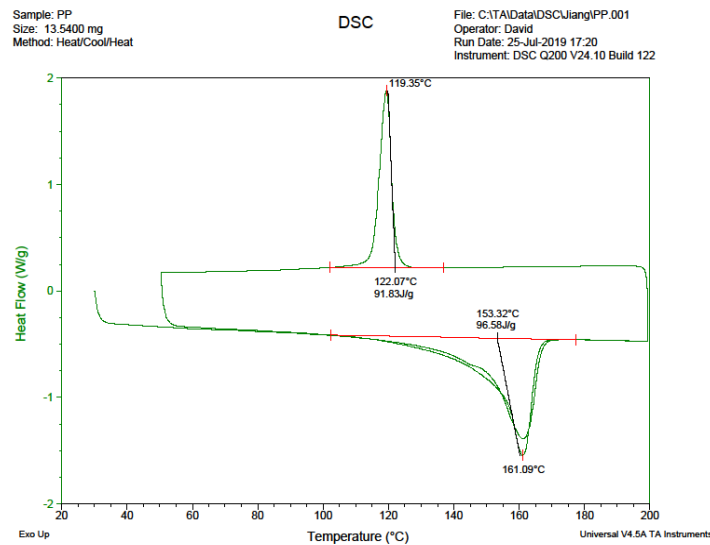


Figure 10. DSC result example for PP sample with melting and recrystallisation peak

The compression moulding process of stacked PP and RCF mat was used to manufacture the composite skins. The procedure for the process was as shown in Figure 11, with materials placed inside the mould, which had a chamber with 150 * 100 * 25 mm dimensions. The mould with stacked PP and fibre layers inside was placed in the compressor, which provided pressure and temperature to melt and push the PP to impregnate the fibre mat. During the initial stage, a PP sheet at 1 mm thickness was used for manufacturing the composite skins. The temperature on the compressor was set at 180-185 °C (it was aimed to

achieve 165 °C on both mould plate surfaces where the thermocouple was attached and believed the mould chamber had a temperature of around 161 °C). The pressure applied was the same as most pieces of literature for PP composite compression at 5 MPa (75 kN for the mould used in this research) throughout the process. The relative position of the top and bottom plate could be read from the control panel of the compressor to indicate the thickness when compared with the position when the mould was fully closed.

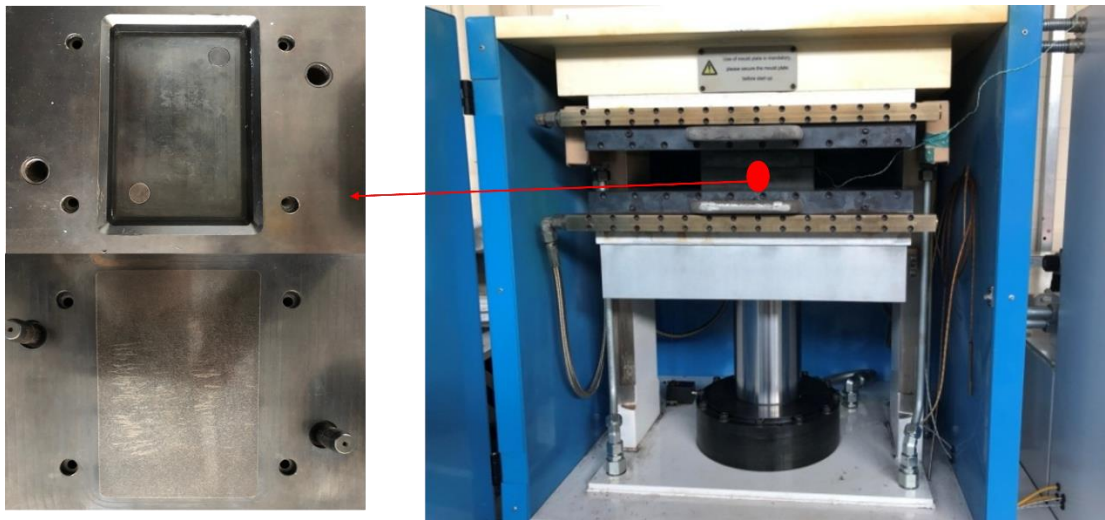


Figure 11. Mould plates and the compression machine

During the process, materials were first stacked, as Figure 12 shows and placed in the mould in the compressor, and the temperature was raised afterwards up to the set values. Once the mould temperature reached the required temperature, the pressure was applied and held for about 15-20 minutes until the composite skin was pressed entirely (when the relative position of the top-bottom compressor plate was stable at desired value). After the required thickness is achieved, air cooling reduces the temperature slowly until the recrystallisation is finished. Water cooling faster was applied afterwards, and the PP composite skin was de-moulded below 50 °C.

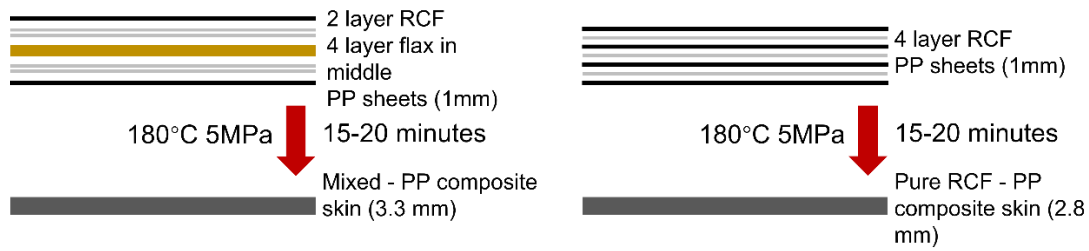


Figure 12. The schematic diagram for the stacking and compression process

Powder PP was used to manufacture the skins in similar procedures as the sheet PP ones, to improve the filling quality and volume fraction and to reduce the manufacturing cycle time and pressure needed for the RCF composite skins. The details about the improvements by using PP powder and tape composite will be discussed in the following chapters in the results and discussion sections. When the PP powder was used, the procedures were the same, but the stacking was formed by more evenly distributed 5 layers of PP powder covering each RCF mat, including the top and bottom surface, instead of 3 layers of 1mm PP sheet inside 4 RCF mats.

3.2.2 Sandwich Composite Manufacturing

The mould was used again when bonding the sandwich composite without the compression machine needed. As the datasheet suggested, a shallow pressure below 0.1 MPa was enough for the adhesive to bond the skins and core together. Thus, the process also worked by using the mould at the required temperature with heavy weights (around 100 kg in total, including the top mould), which could provide sufficient pressure to the adhesive layers inside the mould as shown in Figure 13.

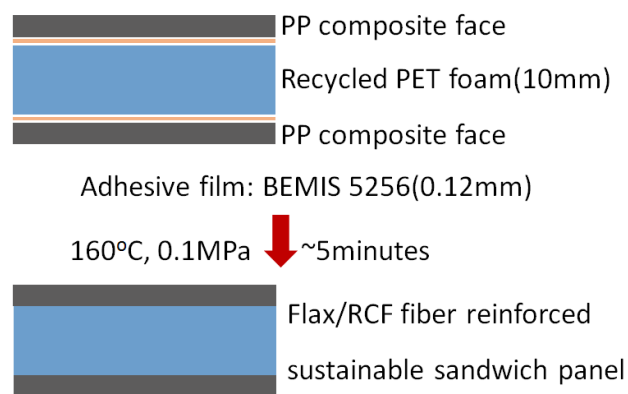


Figure 13. The schematic diagram for composite join

The core materials were cut into a size that was slightly smaller than the mould for fitting and placed inside two manufactured composite skins with BEMIS 5256 adhesive film (4 layers, 0.12mm thick at each side) between them. This stack was put back into the mould with the temperature set at 160 °C (to reach the film melting temperature above 150 °C as the datasheet suggested). Once the required temperature was reached, the top mould was placed on top of the stacked materials, and additional weights were applied to provide pressure to the adhesive layers. This pressure must be maintained for less than 1 minute, and the whole composition could be cooled afterwards. Identical to the manufacturing of the composite skins, slow air cooling was needed to reduce the temperature below the recrystallisation temperature, and water cooling would be introduced beyond this point.

3.3 Testing Techniques and Equations

This chapter will introduce the testing techniques included in this research and the following calculation methods to obtain mechanical properties from the testing results.

3.3.1 Single Fibre Tensile Comparison

Tensile properties (strength and modulus) were tested to compare the single fibres sourced from the RCF mat and those from virgin fibre tows with a similar average diameter. The comparison was aimed to improve the understanding of the RCF mats and to prove assumptions as well as literature results that the recycling process might have limited reduction on fibre properties but the chopping and cutting significantly reduced the fibre length and eliminated the continuity resulting in RCF composite properties only around 30% of virgin carbon fibre (VCF) composites.

With the help of a smooth plastic board and the static electrons to attract carbon fibres, Single fibres from the RCF mat and the chopped virgin fibre tow (PX35) were randomly selected manually. As Figure 14 (a) shows, these randomly selected fibres would be mounted between two paper sample holders and bonded with glues. The sample fibres could be seen with the help of illuminating lights within the window region, which is reserved for the tensile testing at the original length of 10.2mm.

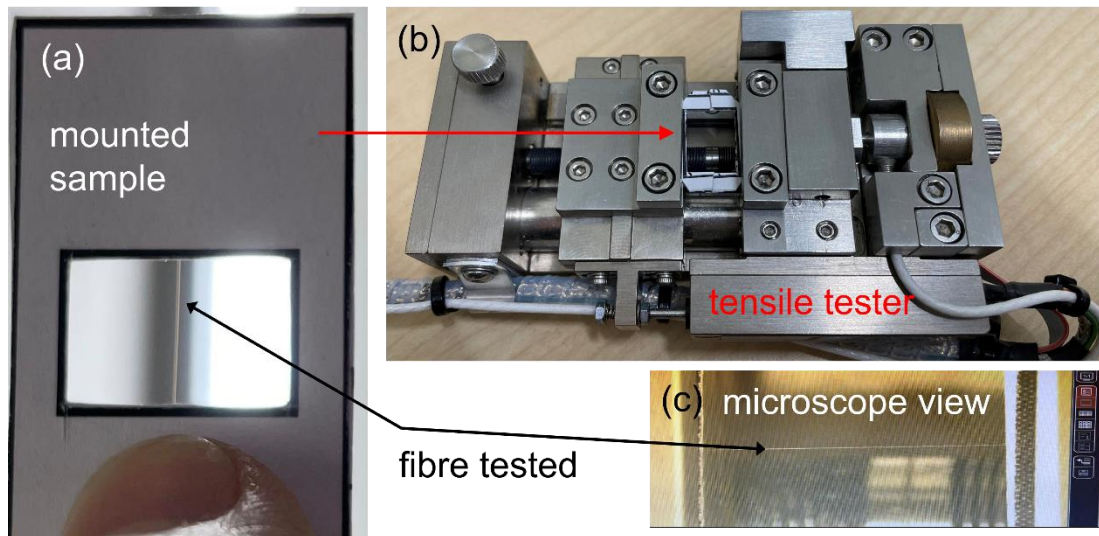


Figure 14. (a) Fibre sample mounted in between two papers with a testing window; (b) Tensile testing equipment; (c) Monitoring of fibre under a microscope.

The prepared samples mounted inside the paper holder would be cut smaller to allow fixing on the tensile tester's clamp, as shown in Figure 14 (b). Screws

would be used to fix the two ends of the fibre to prevent slips, and the two sides of the paper holder parallel to the fibre would be sheared to ensure that only the fibre experiences the stress during the tensile test. Figure 14 (c) shows the screen of an external microscope which was used to zoom up and record the window region to monitor the tensile testing. All the tensile tests were performed with a tester screw rate of 0.1 mm/min to ensure enough data points were recorded, and a 5N load cell was utilised to provide a maximum force resolution. All the tensile tests were performed until the fibre broken with the displayed load dropped significantly. However, due to the very brittle nature of carbon fibre, all the carbon fibre just collapsed and disappeared; thus, no sample fracture image could be captured. With a standard camera or microscope, which had a limited frequency, the moment carbon fibre fractured and flew away could not be captured.

3.3.2 Tensile and Three Point Bending Test of Pure RCF Composites

It is commonly known that nearly all composite materials with a layered structure would show different tensile and bending properties. Thus, to relate the results of single fibre tensile properties and the final sandwich composite application, which focused more on bending properties, this research included both tensile and bending tests on the pure RCF composite skins to comprehensively understand their behaviour in both cases. Also, further comparison between the tensile properties of composite and single fibre could be used to show how many residual properties (effective properties) the RCF mats could have inside the composite to show the level of property reduction from the recycling process (fibre length reduction and fibre discontinuity).

The tensile test was carried out according to the standard for general composite tensile properties evaluation, ISO 527-4:2021. Due to the compression mould size limit in this research (150*100mm), the dumbbell-shaped tensile samples with an overall length of 150mm were selected, as shown in Figure 15. Due to the low hardness of PP, manual controlled saw cutting was not able to make samples into such shape. Thus, CNC machining was used to manufacture the composite tensile samples. The three-point bending test measured the strength and modulus of RCF composites. It can also be compared with the previous single fibre test results to improve the understanding of RCF mats further and prove previous views on the main reasons for the loss of performance of recycled carbon fibre mats. The bending test of the RCF composite is carried out according to the standard of ASTM D7264, and the composite skin produced by compression moulding will be cut to the appropriate size (120mm*13mm*thickness strips). Due to the low hardness of PP, the blade is easily deflected at a fixed slight angle when cutting, so most samples will have an average width in the middle and different widths at both ends. Also, the area weights of the RCF mat were not perfectly constant with that moulding area (150mm*100mm) and varied between 4g to 4.4g; the composite skins would have a thickness varying between 2.8mm - 3.1mm to keep a constant volume fraction at about 20%. All the dimensional differences would be normalised

during the property calculation, as shown in the equations in the chapter “formulas and calculations”.

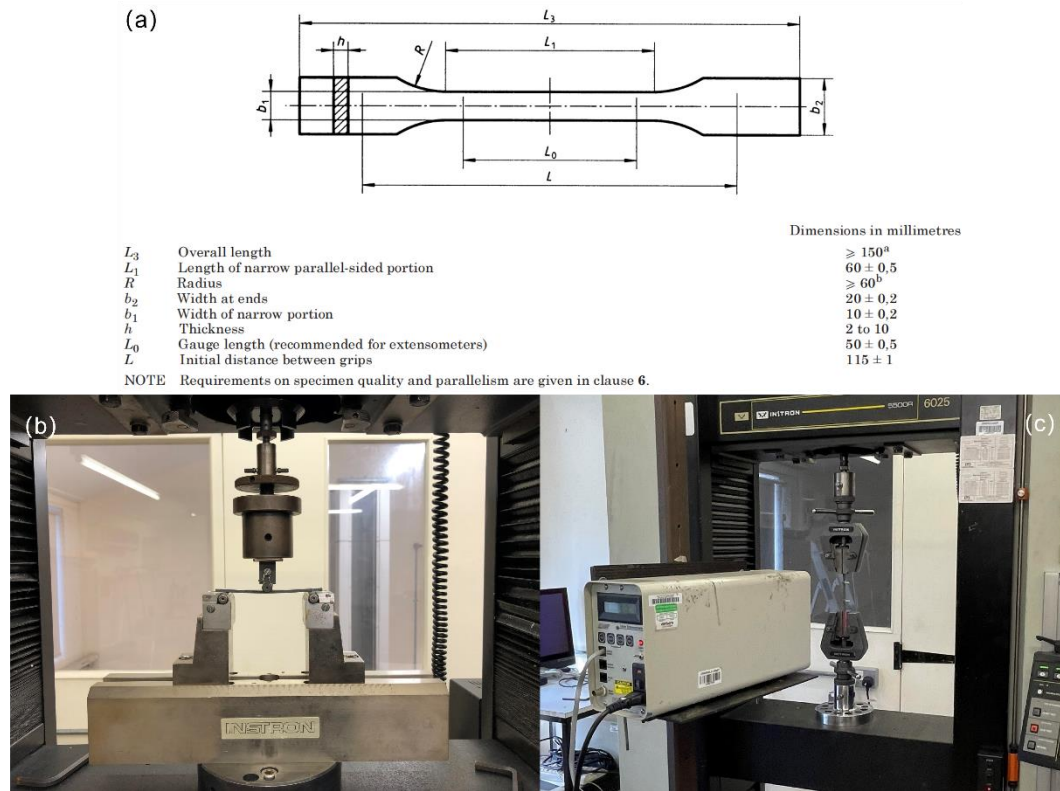


Figure 15. (a) tensile sample dimensions; (b) three-point bending setup; (c) tensile test setup with laser extensometer

Both tensile and bending test was performed using the Instron 5500R tensile/compression machine, and the setup for both tests can be found in Figure 15 (b) and (c). The sample strips prepared for the bending testing would be placed between the supporting roller at a span of 95mm. A load head roller was located right in the middle of the supporting span; press the sample at a rate of 2 mm/min to operate the bending. A 5 kN load cell, one level above the 100N cell, was used as most samples experienced a maximum load over 100N. Each experiment would be stopped once the load had dropped more than half of the maximum load achieved; this is because samples made from high deformability of PP and non-continuous RCF mats were difficult to fracture fully. After the experiment stopped, the load vs displacement data from the tensile

machine would be recorded and used for stress/modulus evaluation and analysis; these processes will be explained more in the chapter “formulas and calculations”. For the tensile test, two sample clamping was used to hold the sample instead of the support and loading rollers. The samples were estimated to have a maximum load of around 2-3 kN; thus, again, the 5 kN load cell was used, and according to the standard for tensile test, a 2mm/min rate was also applied. The bending experiments had a negligible difference between the actual sample deflection and load head displacement and could utilise the load head displacement directly as sample deflection. However, for the tensile test, the eligible elongation was only around the thin tested area due to the different cross sections, and thus a laser extensometer was needed to measure the actual displacement between the two clamps with reflective tape on the sample thin tested area.

3.3.3 Three Point Bending Test of Sandwich Composites

The bending testing of sandwich composites was according to the standards ASTM D7249 and ASTM D7250, with most steps the same as in the previous chapter about composite skin bending. Place the sandwich composite between a support span of 100mm and the bending head in the middle of the sandwich sample, which provides the load. The load cell applied was still 5kN, as most samples experienced a maximum loading of around 1000N, and the loading head rate was still moving at 2 mm/min. Like the previous RCF composite testing, half of the maximum load dropped was considered the point to stop each experiment. The load vs displacement data would be recorded for further property calculation, which will be explained in the chapter “formulas and calculations”.

However, some differences are still applied, including sample dimensions, related property calculations and deflection measurement techniques. The sandwich plates were cut into beams with a width equal to two times their thickness which is the minimum value required in the standards; the length was not modified, maintaining the 150mm. Also, since the sandwich composite samples were much thicker (around 15.6mm to 16.4mm) than those 3mm RCF composite samples, the built-in deflection measurement of the load head was not able to measure the accurate deflection as composite sandwich deformation would also take place during the test, but the actual deflection of the sample was on the bottom skin. Thus, a reflective tape was used on the middle of the sample bottom skin, and a reference point was fixed on the span holder. A laser displacement meter was used to measure the relative position of these reflective tapes during the test, and the displacement was considered the actual deflection of the samples and recorded together with the load data for further calculations.

3.3.4 Drop Tower Impact Test

As mentioned in the introduction, one of the current popular advanced truck panel materials is the sandwich composite with glass fibre-reinforced plastic as skins and polyurethane or polyvinyl chloride foam as a core structure; a drop weight test machine is used to make a comparison of the impact resistance between woven glass fabric reinforced epoxy and the RCF composite skins to show how the RCF composite design could be applicable for truck panels in terms of impact properties. The setup of the drop tower is shown in Figure 16; a platform at the bottom part of the machine was used to clamp and hold the sample panels and prevent any fluctuation after the impact. The test pin was attached to a drop weight connected to the track system on the drop tower tunnel on the top. The big metal rod with a spring on it was used as safety equipment to stop the whole dropping component damage the sample or injuring the operator during reloading when the chamber was opened, and the smaller one below it was used to catch the impactor after the impact to make sure that only one collision taken placed during the experiment for one sample. During one experiment, the impactor would be first lifted to the desired height to gain a desired potential energy and would convert to specific kinetic energy, which controls the amount of desired impact energy. After the collision, the impactor would be rebounded at a certain height and then be captured by the small safety rod to finish that experiment; the rebound height could reveal the residual energy impactor have and the difference between the original high and rebound height would be utilised by the machine software to show the impact energy absorbed by the test sample.

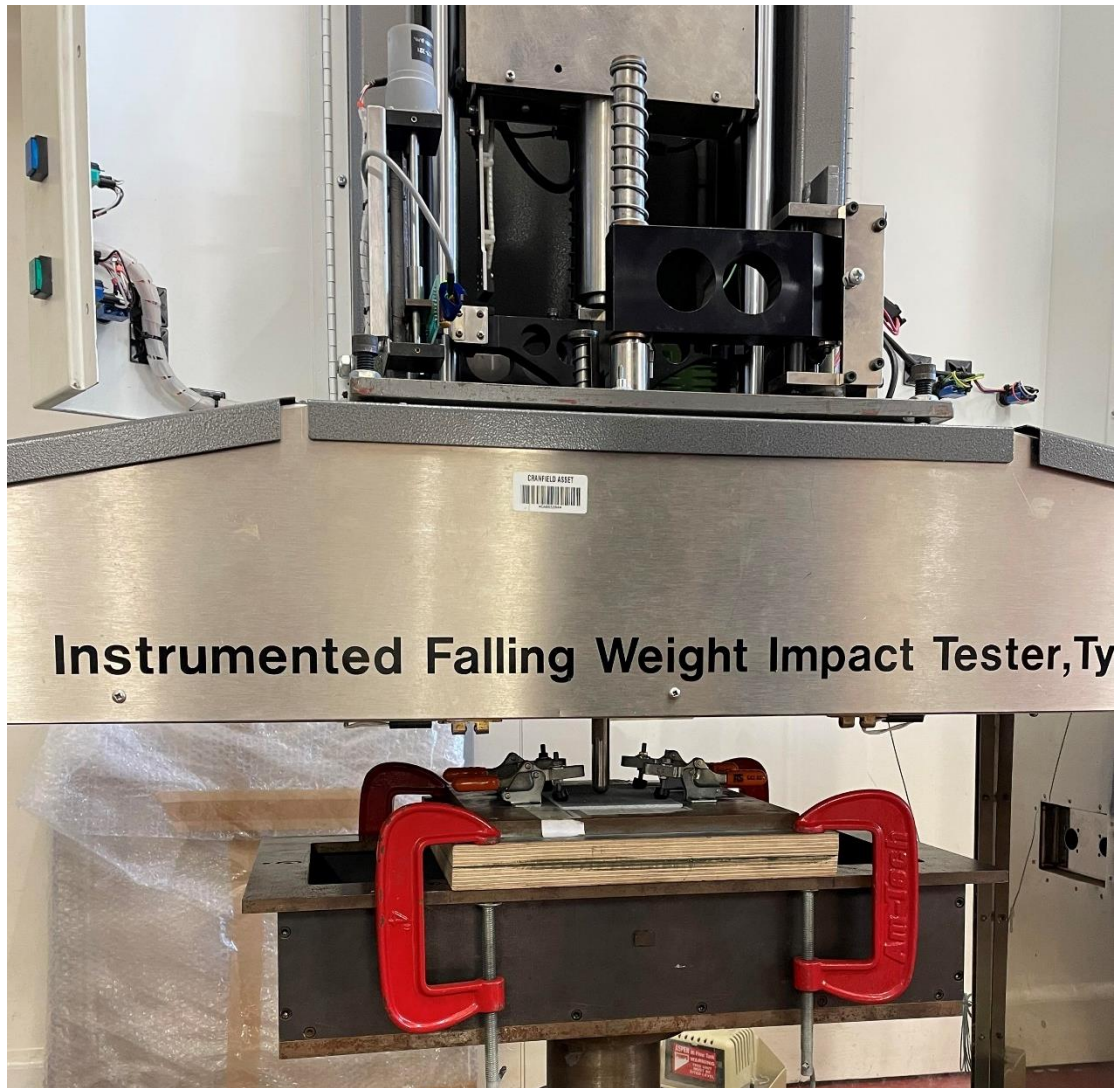


Figure 16. Drop tower impact tester

As most impact damage to the lorry-related panels was slow-speed impact coming from human step pressure, items dropping or heavy items fluctuating on a bumpy road, the low-speed impact was performed in this research and the velocity was always below 3m/s (40). Also, it could be imagined that the impact energy of any collision that could take place to a floor or side panel of commercial lorries/vans would be very limited, thus, small energy would be enough to show the comparison of different panel materials as such application (40). However, as it is shown in this similar work with bus floor panel impact research (40) That minimal energy, such as 1.31J or 2.26J, would not leave any visible damage on the sample, so it was decided to use their largest impact energy, 6J, for the tests in this research to show a clear damage pattern to

make a comparison together with the energy absorption rate. This energy would equal to an object weight of 0.6 kg free falling from one meter high, which is already a relatively rare example of a significant impact in reality for such panel materials in vehicles.

All the samples for impact testing were cut into the dimensions of thickness*150*100mm, the same as the compression moulding. The samples were tried to maintain a constant thickness for comparison, but due to the inconsistency of the RCF mats, all the RCF composites still had a variation from 2.8-3.1mm thickness, while all the glass fibre composites were maintained at 2.9mm thick. Three sandwich composites (the final product design in this research with pure RCF composite skins) with the PET foam core were also tested under the drop tower compared to the RCF composite skins. However, due to the overall thickness of these sandwiches, only the energy absorption could be compared, and the burst damage on the rear side of the impact test could not be shown. The comparison made from the impact test results was only focused on the energy curve changed with time. Corresponding velocity and force were not deeply studied as the energy could show the material energy absorption rate most straightforwardly. Also, the visible damage on both sides of the sample was used together with the energy absorption rate to show the sample characteristic under such an impact.

3.3.5 Formulas and Calculations

In the research, the load vs displacement data is one of the most important results obtained from single fibre tensile tests, RCF composite tensile/bending tests and sandwich composite bending tests. Although all these data would show similar appearance and post-processing techniques for calculating the strength and modulus values, the related equations would be significantly different.

3.3.5.1 Calculating Tensile Properties, Single Fibres & RCF Composites

Calculating the strength and modulus of the single fibre samples from their tensile results was the most straightforward one, which does not need specific equations for explanations as stress could be obtained from the load and the fibre diameter directly while the strain could be obtained from the displacement and the original fibre length within the testing window. The results obtained from the single fibre tensile testing may contain a 'flat' region with only displacement to increase due to the fibre bonded inside the testing window not being perfectly straight, and the sample fibre would be pulled straight before the actual tensile test has taken place. However, as the carbon fibres were perfectly elastic during the test, a nearly straight load vs displacement plot could always be obtained, and thus, the calibration to eliminate that 'flat' region only required a shifting of the data to the left onto the origin point and recalculating the actual original length of fibre for actual strain calculation. The strength of the tensile data could be obtained using the maximum stress of the fibre experienced before breaking with the strain at that particular point, and the modulus would be calculated using the slope of the stress-strain curve (nearly a straight line for a single carbon fibre).

Similar to the single fibre tensile calculations, obtaining the RCF composite tensile properties from the tensile test is also straightforward. The stress could be calculated simply by the thin testing region's force and the original cross-sectional area. The strength of the sample could be obtained from the maximum stress and the elongation at any moment from the calculations of the current position difference of the two reflective tapes and their starting position difference. When plotting all the stress and elongation, the initial straight line (when elastic deformation takes place) could be used to obtain the tensile modulus of the RCF composites.

3.3.5.2 Mixing Rule for Composites

The actual properties of the sandwich composite skins could be complex to estimate due to the random orientation and random length of carbon fibre in the RCF mat; However, the calculation for it was straightforward. In this research, the properties of PP / RCF composite were estimated by mixing rules as shown in Equation 1 with the assuming unidirectional property of RCF was around 30% of virgin carbon fibres (typical carbon fibre modulus value of 228 GPa) at about 70 GPa as they showed around 40% of woven virgin carbon fibre properties in composite (29).

$$E_{composite} = E_f V_f + E_m V_m \quad \text{Equation 1: Composite mixing rule}$$

Where $E_{composite}$ is the overall composite modulus estimated, E_f and E_m are moduli of fibre and matrix, respectively; V_f and V_m are volume fractions of fibre and matrix, respectively.

Thus, the RCF skin modulus was assumed to be around 15 GPa ($20\% \times 70 + 80\% \times 1.2$) when the fibre volume fraction was about 20%. The modulus of mixed composite skin when other unidirectional fibres were involved, such as the flax fibre / RCF self-sandwiched skin, was also predicted in the same way where the self-sandwich effect was assumed not significantly influence the overall properties. Thus, a mixed skin designed to contain about 60% flax fibres and 40% RCF fibres by volume at a total fibre volume fraction of around 30% was assumed to have a modulus around 18.2 GPa ($18\% \times 50 + 12\% \times 70 + 70\% \times 1.2$).

On the other hand, Equation 1 was also used to calculate the effective modulus of the actual RCF mat from the composite modulus obtained via the bending test of RCF composite samples.

3.3.5.3 Calculations Related to Bending Results

Calculating sandwich mechanical properties from bending test results involves a transformation process that converts the low modulus core materials into the same composite skins at a lower modulus, as shown in Figure 17 (101).

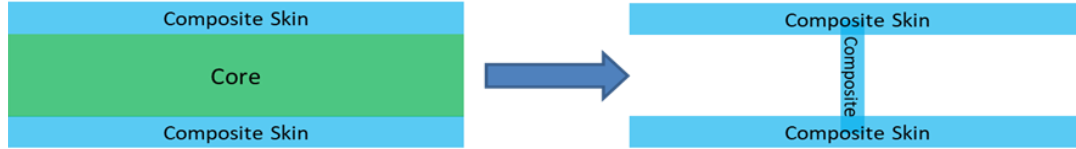


Figure 17. Schematic diagram to illustrate effective core width

Thus, an adequate width would be needed for further calculation and could be obtained through Equation (2).

$$b_{effective} = \frac{E_c}{E_s} b_{sandwich} \quad \text{Equation 2: Effective width for sandwich composites}$$

Where $b_{effective}$ is the effective width of the converted I beam, E_c and E_s are core and skin modulus, respectively, and $b_{sandwich}$ is the overall sandwich width before conversion.

After the conversion, such I beam could be considered to have an overall thickness of t mm, the core thickness of c mm, also known as the distance between the two skins, the overall width b mm, and the effectiveness width b_e mm of the I bar. Thus, the second moment of area I , also known as the area moment of inertia for this converted beam on the x-axis (which is located in the middle of the sample, parallel to both skins. For the case in this research where loading was applied perpendicular to the area formed by width and length, went through the thickness) could be calculated through Equation (3) (140).

$$I_x = \frac{b_e c^3}{12} + \frac{b}{12} (t^3 - c^3) \quad \text{Equation 3: Second moment of area after effective width conversion}$$

However, due to the very low core elastic modulus compared to the skins, the effective width is minimal, which could be neglectable. This is understandable as one of the primary functions of the core materials was to separate and hold

the two composite skins apart, which allowed a higher bending property and stiffness and the main loading experienced in the core was the shear stress. Thus, the first term for calculating the second moment of inertia could be ignored, and for this converted sandwich beam, “ I_x ” could be only related to width, core thickness, and skin thickness.

The result obtained from the bending test was mainly a curve of loading against displacement, which could be used to determine the overall sandwich composite flexural strength and modulus. It is known that for a beam under bending conditions, the flexural strength (σ) could be calculated through Equation (4):

$$\sigma = \frac{My}{I_x} \quad \text{Equation 4: Flexural strength}$$

Where M is the bending moment (N.mm), and y is the distance from the nature axis (mm) (y is equal to half of the thickness). Thus, to calculate sandwich flexural strength, Equation (3) could be input into Equation (4) which would become the following state.

$$\sigma = My \frac{12}{b(t^3 - c^3)}$$

To solve this equation, the relationship between the moment and the supporting span during a three-point bending needs to be included, as shown in the Figure 18, which shows the loading state during a three-point bending test. When a loading F was applied in the middle of the beam, the overall load for the beam was balanced as no velocity was presented (deformation was not counted). Thus, each supporting point would provide $\frac{1}{2} F$ for the conservation. Ignore the presence of the sandwich beam out of the supporting point (Though the length of this part could also affect the shear behaviour under bending to some extent, this effect could be ignored when the length of this part compared to the overall supporting length is insignificant.) and set the left support point as an origin, x as the length at this beam ($x = 0$ on left supporting and $x = S$ on the right supporting). When $x < \frac{1}{2} S$, the overall moment would be equal to $\frac{1}{2} Fx$ towards the upside, when $\frac{1}{2} S < x < S$, the overall moment would be equal to $\frac{1}{2} (FS - Fx)$,

which showed that the beam moment would be maximum at the middle point ($\frac{1}{2}S$) equal to $\frac{1}{4}FS$.

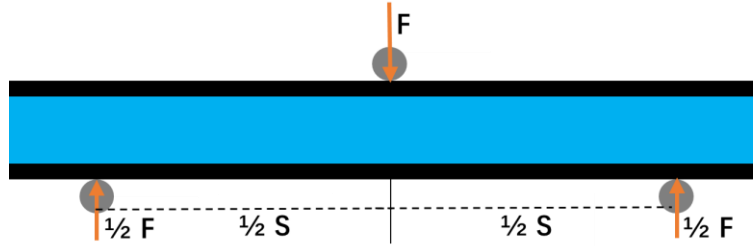


Figure 18. Loading state during the 3-point-bending test

Applied the maximum moment for the above calculations, Equation 5 could be derived to calculate bending strength.

$$\sigma = \frac{FS}{4} * \frac{t}{2} * \frac{12}{b(t^3 - c^3)}$$

$$\sigma = \frac{3FSt}{2b(t^3 - c^3)} \quad \text{Equation 5: Strength for sandwich composite}$$

Where F is the force applied (N), S is the supporting span length (mm), t, b & c are sandwich thickness, width and core thickness respectively

Deflection of three-point bending could be calculated by following Equation as showed in the *Cambridge Structures Databook* (141) when maximum load is acquired from test and the modulus was from materials data sheet.

$$D = \frac{FS^3}{48EI}$$

Thus, when the deflection was obtained from the bending test, overall modulus for the sandwich composite could also be calculated using Equation (6) which is derive from above Equation with the application of Equation (3) together:

$$E = \frac{FS^3}{48DI_x}$$

$$E = \frac{FS^3}{48D} * \frac{12}{b(t^3 - c^3)}$$

$$E = \frac{FS^3}{4Db(t^3 - c^3)} \quad \text{Equation 6: Modulus for sandwich composite}$$

For the case when PP/ RCF composite skins were tested only under the bending, all the calculations could remain the same but just a difference in the second moment of area (I_x) which turned into $bt^3/12$ for the rectangular cross-section with width b and thickness t .

Equations (5) and (6) could be used to calculate the strength and modulus, respectively. Although it seems like these two equations were fully customised for sandwich composite calculations only, they could also be utilised for RCF composite skins to determine the strength and modulus. As both sets of experiments were three-point bending, the coefficient, width, displacement, and load would be used the same way for both sandwich composites and the RCF skins. However, due to the present core materials in sandwich composite, thickness and second moment of inertia related parameters would be different. Thus, when using the Equation (5) for RCF skin strength calculation, core thickness is equal to zero, and one thickness appeared both on the numerator and denominator could be eliminated, which forms the following equation:

$$\sigma = \frac{3FS}{2bt^2} \quad \text{Equation 7: Strength for RCF composite skin}$$

And when using the Equation (6) for the RCF skin modulus calculation with the help of an addition rectangle I_x value $bt^3/12$ could be written in following form:

$$E = \frac{FS^3}{4Dbt^3} \quad \text{Equation 8: Modulus for RCF composite skin}$$

Both results obtained for RCF skin and sandwich samples were in similar styles as load vs displacement plots. Some results would contain a tiny curved “tip” region at the beginning, but other results would be directed straight from the origin point. This was due to the contact between the sample and supporting/loading roller that some samples may have their position slightly

adjusted when the pressure was applied until they had been ‘stuck’ between the rollers.

3.3.5.4 Prediction and Simulation of Sandwich Bending

Sandwich composite behaviour under the three-point bending was predicted by both equation calculations and simulation from FEA analysis. Sandwich composite with identical skins under three-point bending test, the deflection could be calculated through the follow Equation (9) regarding to ASTM standard D7250 (107)

$$D = \frac{FS^3}{48EI} + \frac{FSc}{4Gb(c+t_f)^2} \quad \text{Equation 9 prediction of sandwich bending behaviour.}$$

Where F, S, c, and b had come across on the above equations as loading, supporting span, core thickness and sandwich width, respectively; D is the deflection under load (mm), EI is the flexural stiffness (Nmm²) (rigidity, product of moment of inertia and skin modulus), G is the core shear modulus (MPa or N/mm²), tf is the (single) skin thickness (mm)

The two parts contributing to the sandwich deflection in this equation were independently relaying skin bending rigidity and core shear modulus. During a sandwich bending process, there could be almost no skin shear, and the core elastic modulus is too small to contribute to the core bending; thus, both could be ignored. This equation could be used to calculate the skin rigidity and core shear modulus, respectively, with different sets of loads and displacements; however, due to the fact that sandwich composites would have relatively large plastic deformation zones especially common in thermoplastics. The skin rigidity and core shear modulus results would have relatively significant fluctuations; thus, statistical analysis is required. Equation (9) could also be used to predict the sandwich deflection under an increasing loading with known material properties (skin moduli/geometries and core shear modulus). However, such prediction would be a linear relation and thus become inaccurate when the plastic deformation appeared during the test.

Finite element analysis was also used to simulate the sandwich composite sample beams. The following assumption was made to reduce computation time and improve the numerical efficiency: (1) core materials were perfectly homogeneous and isotropic; thus, shell elements could be applied to the model. (2) Bonding between the composite skins and core materials was strong enough; thus, the failure would not occur due to poor bonding strength. (3) Skins are stiff enough so the distortion of core cells would not disrupt the skin's in-plane deformation. Properties of skins and cores used in the FEA models can be found in Table 2 which was calculated via row material property and composite mixing rules. Both models of the pure RCF and mixed skin samples were subjected to two boundary conditions: Simple support at the ends and force at the centre of the beams. 3-point bending analysis was performed to obtain deformation responses at different load levels and recorded together for load-displacement plots. As a simple linear prediction was performed, thus only the elastic behaviour of the samples could be analysis and compared. The solid 186 (20 nodes) were used to build both sandwich samples and total nodes of 6034 and 6938 were presented in the pure RCF and mixed skin samples respectively. The degree of freedom was allowed in both x, y and z directions.

Table 2: Materials properties used for FEA

Type of Material	E1 (GPa)	E2 (GPa)	G12 (GPa)	G13 (GPa)	G23 (GPa)	μ_{12}	Density (kg/m³)
RCF skin	14.96	1.49	0.52	5.72	0.50	0.4	1034
Hybrid skin	15.24	1.51	0.6	8.07	0.61	0.41	1085
PET foam	0.12	0.12	0.018	0.018	0.018	0.43	100

4 Results: Single Fibre Tensile Tests

This research aimed to design and manufacture a fully sustainable sandwich composite and identify its potential application in automotive industries. Thus, in this chapter, various testing results will be presented, some valuable observations during sample manufacturing and testing will be included, and a comparison of this panel design with commonly used vehicle panel materials either from literature results or a case study will be presented for evaluating the potential application.

As the objectives presented in the introduction chapter, there were five main targets in this research: literature review, single recycled fibre evaluation, RCF composite skin evaluation, fully recyclable sandwich evaluation and potential applications in automotive. Thus, except for the literature review presented in its chapter, the rest four topics with an additional testing comparison part would be presented in the following chapters.

First of all, experiments related to RCF mat were operated to have a better understanding of the behaviour of this material, including the study of single fibre properties to see the influence of the recycling process in this chapter and the study of the composite tensile/bending to see the overall fabric (mat) performance inside a polymer matrix in the next chapter.

4.1 Single Fibre Tensile Results

The results of the single fibre samples are shown in Figure 19. Some examples of the image captured during fibre diameter measurement were shown on the top. The overall diameter distribution of all effective samples (those samples failed during handling and cutting to fit in the tester appropriately) for both the recycled carbon fibre and virgin one (PX35). The data obtained from the tensile test (load vs displacement) was converted into stress vs strain with the help of fibre diameter and original length (after calibration). The maximum stress in each data represents the samples' strength, and the best-fitted line slope in the stress-strain curve represents the modulus. The strength and modulus of all valid samples were counted, and their distribution was shown in figure 19 with the average value and standard deviation. Except for the virgin carbon fibre sample strength distribution, which has only 21 data points due to five invalid results with an abnormal elongation value (from 0.3%-0.7%, which could be a result of damage during handling), all other distributions include 26 valid results as no abnormal elongation was not found in RCF fibre samples, and it would not affect the modulus results for both fibre types.

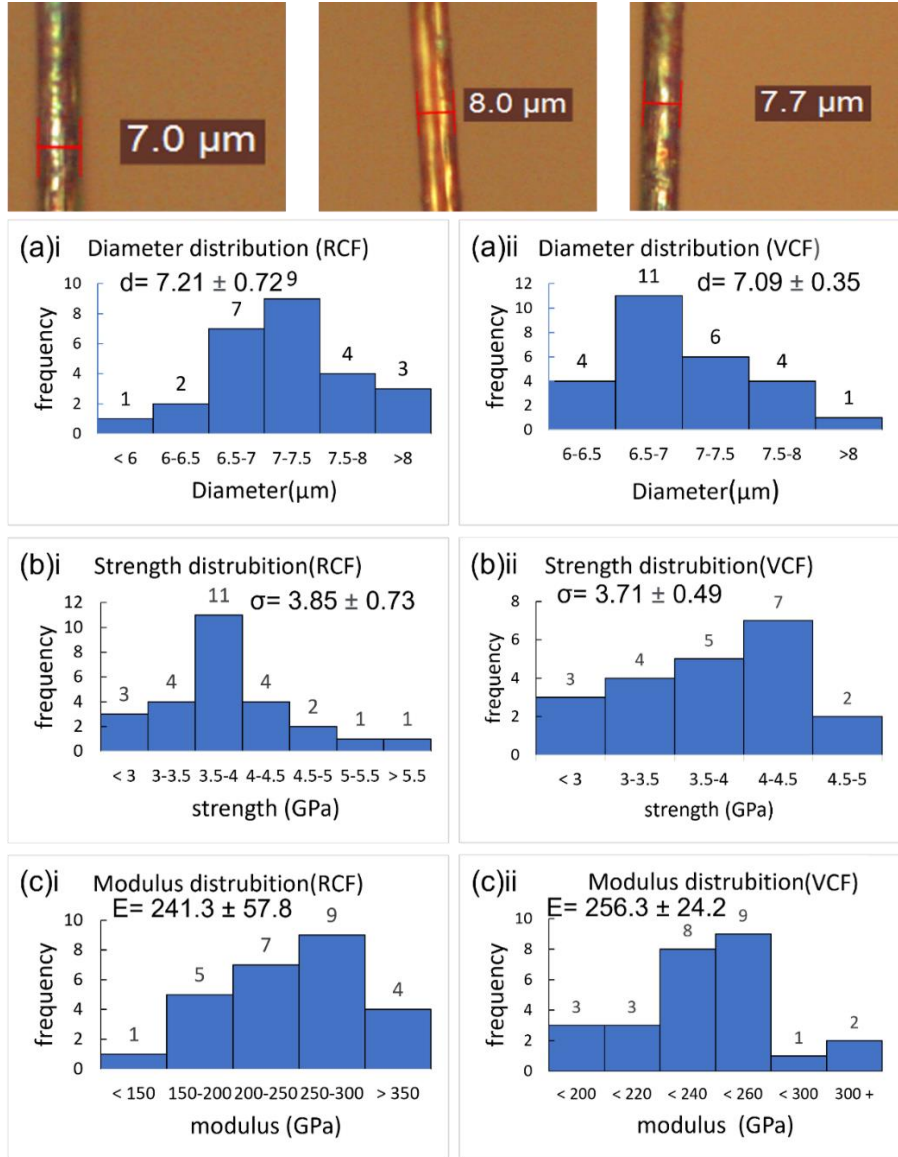


Figure 19. Single fibre samples diameter examples and the distribution with average values and variations (a)i&ii, diameter distribution (b)i&ii, strength distribution (c)i&ii. modulus distribution

4.2 Discussion on Single Fibre Results

The single fibre tensile test results and average values of fibre diameter and mechanical properties are shown in Figure 19. As mentioned before, two types of fibres were included in this comparison, recycled carbon fibre and a comparison group of virgin fibre PX35. The fibre properties of the PX35 were listed in the materials section in “Methodology”, the average fibre diameter of 7.1mm, a strength of 4137 MPa and a modulus of 242 GPa. The resulting distribution of the virgin PX35 fibre was utilised for comparison with RCF single fibres, and the average values were used as a reference for the accuracy of the tensile tester. As shown in figure 19, the strength (3710 ± 490 MPa) and modulus (256.3 ± 24.2) of the virgin fibre did cover the value suggested in the datasheet, which could indicate that the results tested from the tensile tester are accurate and reliable. The variation coefficients, 13.2% for strength and 9.4% for modulus, are also proof of reliable data tested. On the other hand, the distribution of the results indicated that even with commercially available virgin carbon fibres, the consistency between single fibres could still be limited. Even the diameter of the virgin fibre samples showed an average value of the same as the datasheet suggested at 7.1 mm, which is still distributed with a wide range from 6 to 9 micrometres.

The recycled single fibres had a variation coefficient of 19% for strength and 24% for modulus, which is still acceptable to say these data were reliable. However, more samples would be preferred when having such single fibre tensile testing for RCF fibres, such as double or triple the samples tested in this research, to improve the accuracy and reduce the variations. The RCF fibres showed a similar average diameter as the virgin ones, and the average strength and average modulus were also similar. A slight difference in the distribution could be found that the RCF fibres showed a relatively broader range in both strength and modulus, although such a difference was not very obvious due to the limited number of samples tested and only several data presented in that broader range. Also, the standard deviation of all the properties from the RCF fibres was relatively more than those from the virgin fibres, indicating the RCF fibres have a broader range of distribution in properties. Such difference was

expected as the recycled carbon fibre should contain a range of different fibres with different mechanical properties as the fibre was randomly recycled from end-of-life composites which may come from different applications; however, due to the limited amount of RCF samples tested in the research, as well as the random fibre distribution characteristic and a wide variety of sources for the RCF mat. The distribution of these fibre samples picked from the RCF mat may only represent a limited area of the RCF mat, but other locations might contain different fibres having a broader range of properties. The similar single fibre mechanical properties between the RCF fibres and virgin fibres could prove that the recycling process did not have a significant influence on fibre properties, but the chopping and cutting process before the recycling was the main factor that significantly reduced the RCF mat properties. With only the single fibre tensile results, such conclusions were not that solid, but the difference would be more noticeable when including the behaviour of RCF inside the polymer matrix, which would be shown and discussed in the following chapters.

5 RCF/PP Composite Properties

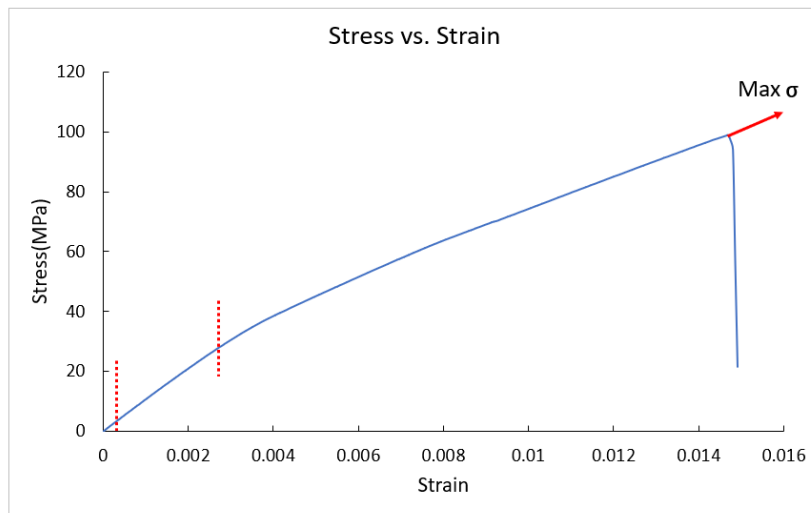
5.1 Effective Modulus Calculation

Before presenting the results of the RCF/PP composites, the simple composite mixing rule needs to be mentioned again to facilitate the understanding of this chapter. It is well known that simple mixing rules were used for evaluating or estimating the composite modulus based on fibre/matrix volume fraction and their modulus. This method would be accurate enough when calculating uniformly distributed continuous fibres but could not predict randomly distributed discontinuous fibres. To make a simple comparison between the single fibre properties and the RCF mat properties inside a matrix, an ideal of effective modulus was utilised in this research based on the simple mixing rules, which assumed that the RCF fibre could fully be aligned and fully continuous and thus should have the same modulus as the simple mixing rule prediction of same fibre and thus, for example, a composite of 20% fibre volume should have an ideal 100% effective modulus of 49.22 GPa calculated from mixing rule 0.2×241.3 (from single fibre tensile results in the last chapter) $+ 0.8 \times 1.2$.

However, the RCF mat would not have a fully aligned and continuous fibre inside. Thus, the assumption was that all the properties differences caused by the alignment and continuity were assumed to come from the original fibre modulus and, thus, where the effective modulus comes from. For example, if one RCF/PP composite modulus was tested as 24.61 GPa, which is 50% of the ideal model, the reason causing this was the alignment and continuity, while single fibre picked out from the RCF mat should still have an average of 241.3 GPa. When using the compelling modulus ideals here, the effective fibre modulus would be calculated as 118.25 GPa $((24.61 - 0.8 \times 1.2) / 0.2)$ and would be considered to have an effective modulus of 49% $(118.25 / 241.3)$. The effective modulus in this research needed to be used to evaluate the behaviour of the RCF mats, and thus it's a comparison of fibre modulus. Such effective fraction could help to clearly show how much property reduction the alignment and discontinuity could have on the behaviour of carbon fibre inside a matrix compared to the modulus tested without the presence of matrix.

5.2 Composite Skin Tensile Results

Due to the difficulty of cutting the RCF composite plate into the desired tensile specimens, only 12 samples were manufactured and tested. Three samples were fractured outside the required thin tested region and thus could not be counted as valid results, and in total, 9 samples with their results were shown in Figure 20. The variation coefficient of elongation, modulus and strength were 16.9%, 3.5% and 12.7%, respectively, which shows sufficient data reliability. Also, one set of example plots of stress against strain and load against displacement from the tensile results; these two plots were identical but with different axis units.



Properties	Mean value with variation
Average Elongation (%)	1.60 ± 0.27
Average Modulus E (GPa)	10.45 ± 0.37
Average Strength σ (MPa)	106.26 ± 13.54

Figure 20. Example plot of PP/RCF composite (20% v.f.) tensile results and the table of overall results

Research had three types of RCF/PP composite samples at a volume fraction of 6%, 12% and 18%, which showed an effective modulus calculated using the way in this research of around 13%, 20% and 22.6%, respectively (29). In our research, samples showed an average tensile modulus around 10.5 GPa, which could use same way $(10.5 - 1.2 (\text{pp}) \cdot 0.8 (\text{pp v.f.})) / 0.2 (\text{RCF v.f.})$ to evaluate the effective RCF mat modulus in composite as about 47.7 GPa which was around

19.8% of single fibre modulus 241.3GPa. Comparing these results and the research work (29), it could be considered that they were in line to show that RCF mat could have an effective modulus around 20% of original single fibre modulus during the composite tensile behaviour. Such value showed significant property reduction compared to the single fibre tensile test results. Thus, a conclusion could be drawn that even the carbon fibres could maintain a very good mechanical property after recycling process in the form of single fibre, the fibre length reduction, discontinuity and random orientation in the mat would have significant property reduction on the tensile behaviour within the composite.

5.3 Three Point Bending Results

It was well known that tensile and bending properties could be different for layer materials, including these RCF/PP composites. Also, bending behaviour would be vital for potential panel applications in automotive. Thus, three-point bending testing of these composite skin samples was also included. As described in the "Methodology" chapter, most RCF composite sample strips for the bending test were 2.8mm to 3.1mm thick and tested with support lengths of 95mm. Although most samples were not uniform in width at both ends, thanks to straight cuts, all samples had an average width just in the middle, ranging from 12.3mm to 13.5mm. The raw data obtained from the bending testing for the RCF composite skin sample strips would be a set of loads against displacements that could be plotted as shown in Figure 21 (a). Similar to the single fibre tensile results, the maximum load would be used in Equation (7) for calculating the strength of each sample. The modulus, on the other hand, is related to the slope of the linear region (between the two red dashed lines), and the difference between the span and displacement of the two sets of points selected in this linear region will be applied in Equation (8) to calculate the modulus of the sample. The calculated strength and modulus of all samples were counted, and the distribution, average values and deviations were shown in Figure 21 in sections (b), (c) and (d). In total, 58 sets of valid results with sample volume fraction controlled with 19% to 21% were obtained, with 30 from sheet PP samples and 28 from powder PP samples; thus, the total and separated distribution were presented to see the effects on the results of these two raw materials forms.

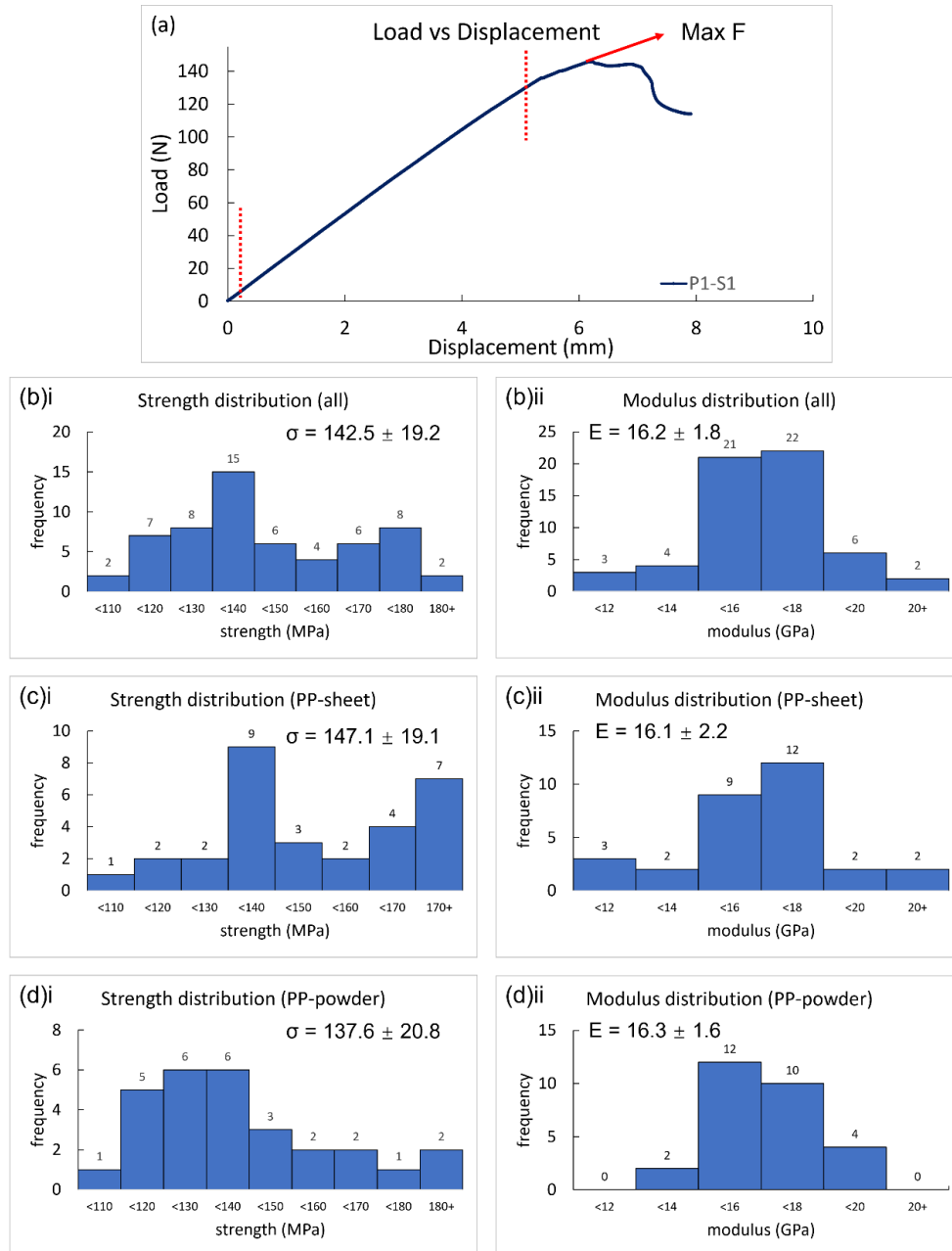


Figure 21. (a) example of RCF composite sample bending result; (b) mechanical properties distribution of RCF composite samples: overall distribution of strength (i) and modulus (ii); (c) mechanical properties distribution of PP-sheet samples strength (i) and modulus (ii); (d) mechanical properties distribution of PP-powder samples strength (i) and modulus (ii)

The RCF composite bending results were mostly in the style as the example shown; this was because the highly ductile polypropylene was used as the composite matrix as well as a limited sample total elongation could be

experienced with those rollers that supported the bending samples; thus, more deflection could be achieved without the matrix being fully fractured, and the load would not drop to zero immediately after the failure occurred as single carbon fibre did. Instead, a continuous dropping loading with more displacement would be presented in the testing of RCF composites, and a much longer time was needed to break the sample entirely apart. Also, just like what is shown in the image after the maximum load was achieved, there was a slight drop in the load but it raised again, which was due to the semicrystalline characteristic of polypropylene. Sometimes, such a second peak was lower than the first one, as this example image shows, but in other cases, this peak could either disappear or high than the first maximum load, and this was why the test needed to be stopped manually once the load dropped more than 30-50% of the maximum load achieved to both saving the testing time and ensure the maximum load has appeared.

The overall modulus of RCF composite from both matrix forms (sheet or powder) could be used together with those single fibre tensile data to provide a better understanding of the RCF mat. The variation coefficient of the overall modulus was 11.1% which means this set of data was reliable. However, this value significantly differs from the single fibre properties (241.3 GPa) tested during the tensile. By comparing the effective modulus and the average single fibre modulus in the RCF mat, it could be concluded that after the reduction in the fibre length and became discontinuity and randomly oriented, the recycled carbon fibre mat only shows a 'remaining' bending modulus of around 31.5%. This comparison could indicate that despite some damage that may occur during the recycling process, the loss of fibre length, continuity and orientation during the cutting and chopping stage before the recycling could be the significant property deduction stage for the fibres. This conclusion was slightly lower than the data sheet information which the RCF mats could show about 37% effective modulus in transverse direction inside a composite.

Also, an interesting result was noticed, showing that the polypropylene and RCF mats were a better combination for bending and compression applications than

tensile applications as the composite tensile property were only about 2/3 of their flexural ones. The reason for this will be concluded from their failure difference shown in Figure 22 in the chapter 5.5 'failure of samples' as only tiny cracks could be founded on the bent samples at their rear side; these composite samples would not fracture into pieces, and the matrix still holds most fibre inside to help transfer and distribute the load. It has been mentioned in this report that the RCF mat contained chopped fibres at a limited length; the matrix is a significant element in connecting all the random fibres when taking the load. Thus, the bent samples having most matrix still connected survived from a relatively more minor total elongation under the sample deflection state could help the whole sample to take more load. On the other hand, the tensile samples that experienced a direct elongation could have matrix easily fractured, thus not able to take any load even if the fibre inside was not broken.

In conclusion, this section generally presented and discussed the flexural and tensile testing of RCF/PP composites, as well as a comparison of some literature results to better understand the RCF mats in both their single fibre state and the overall performance in matrix. With the results and discussion presented in last chapter about the single fibre tensile testing, one of the main conclusions could be drawn that the recycling process to extract fibre from the composite materials did not cause too much fibre property loss, which is consistent with literature results, at least these recycled fibres were at the same properties magnitude compared with the virgin fibres. The RCF mat compared with continuous unidirectional carbon fibres inside a matrix, does lose a lot of mechanical properties that it only has 31.5% residual flexural modulus and about 20% tensile modulus under the same matrix and volume fraction. The leading cause of such significant performance loss is identified as the result of the cutting and chopping stage before the actual recycling, which significantly reduced the fibre length and caused discontinuity and random orientation.

5.4 Controls of the RCF/PP Composite Manufacturing Process

Before the actual manufacturing process using the compression moulding of composite samples, a small tablet test was conducted to help understand the RCF and PP under compression and the processing temperature. A cylindrical hole with a diameter of 20 mm was drilled in the middle of a cylindrical steel column, and two round steel bars with a diameter of 20 mm were inserted into this hole from two sides to act as the two moulding plates for the compression. The area was calculated, and some weights were placed on the top of one steel bar to provide the pressure needed for the compression process. This small test rig was aimed to mainly verify the best-fitted temperature and pressure for manufacturing the RCF-PP composites. Although the reference temperature in the DSC results suggested the melting temperature (peak) at around 161°C, these results were obtained within a fully closed chamber in good thermal insulation conditions. The actual temperature needed for the compression moulding with gaped at mould edges that allowed trapped air bubbles and excess matrix to flow out might be different. The pressure needed for the RCF-PP composite manufacturing was selected from the literature at 5 MPa, but it turns out that this value could again be different based on different polypropylene forms and different RCF mat thicknesses.

In this small tester, some interesting results have been discovered. First of all, due to the design of this instrument, to avoid the steel bars at both ends being stuck and unable to be taken out, there was no set of gaps. The steel bar wall and the inner wall of the steel column are tightly fit, so the tablet composites produced contain large air bubbles that cannot be expelled. This implies why the actual composite manufacturing mould needs to have a larger gap on the sides to allow the elimination of trapped air. Through experiments on this test rig, it was also found that when powdered PP is used as the matrix, the pressure required to press the composite is much less than that of sheet PP (only around 1MPa was needed). The temperature was also studied through the small test rig, and it was found that about 161°C in the materials would be sufficient for the compression process. However, to achieve such a temperature, the mould (steel test rig components) temperature would be more

than 165°C due to the thermal energy lost to the surrounding environment. Also, due to the small test rig having a nearly closed chamber, air bubbles would remain inside the samples as well, but no air from the surrounding environment could contact the sample during the compression process. An extremely limited amount of oxygen was presented within the chamber, and thus, it was founded that there was no noticeable polypropylene degradation (clean samples with no yellowish found by the naked eye) even with a temperature up to 250°C inside the small test rig. It has been found through small test rigs that during compression with only load from the vertical direction, a very small number of fibres will be displaced along the in-plane direction, which could be negligible because the fibres inside the RCF mat were entangled together. Thus, in this research, the fibre's initial and final composite weight were utilised with the density of both fibres and polypropylene to calculate the fibre volume fraction and overall density. Also, due to this method used in this research for controlling the RCF composite volume fraction, a range of RCF mat weight causes the final RCF composite samples to have a range of thickness with the same volume fraction.

After testing on a small test rig, the actual fabrication of RCF composites started as in the methodology section, the manufacturing initiated with sheet PP and the RCF layer (around 0.7mm at normal state and around 0.4mm after press). Most samples were controlled at a 20% volume fraction but had a range of thickness from 2.8mm to 3.2mm due to the different area weights of the RCF mats selected. With the help of the edge gaps between the male and female mould, excess polypropylene and air bubbles could be eliminated. They can be told through the observation of the side excess PP walls on the sample plate manufactured that big bubbles on the sides indicate a poor quality inside the composite as there was not enough displacement of PP to the sides, and air bubbles can still be trapped inside the matrix (due to the high viscosity of PP, a large amount of air bubble would tend to move together with PP flow). In contrast, tiny air bubbles in the side walls indicate a good filling inside the composite. An excess amount (about 20-30%) of PP was needed during the manufacturing to ensure it was enough to squeeze out the air presented inside

the RCF mat. Also, the side walls formed by the excess PP could be used to tell any significant degradation that could be noticed through naked eye observation as the yellowish colour would be presented with degradation of polypropylene and the excess side wall region having a best air exchanging condition where the degradation would be most likely to initiate. It was noticed that different from the small rig test, which had a nearly closed chamber and did not show any PP degradation at 250°C, the PP inside the compression moulding process would start to show degradation at around 180°C, and the further temperature seems to speed up the degradation process, a longer processing time after 180°C could also increase the degradation level. Thus, in this research, when placed the samples inside the mould and started to heat, the manufacturing needed to be carefully controlled to just above 161°C before the compression load was applied, and the processing time was preferred to be fast, both reducing the degradation risk and improve the manufacturing cycles for industrial rapidity need. This degradation temperature was in line with the literature that PP would start to degrade only above 280°C but could have thermal assistant oxidation around 180°C.

As a comparison, a fine powder PP (around 30 micrometres) was used as the matrix material for manufacturing the RCF composites in similar stacking and compared to the sheet PP products. The mechanical properties, strength and modulus distribution of both samples can be found in the results section in figure 21. The variation coefficients of all results lay between 9.8% and 15.1%, indicating that all results were reliable. However, with the difference in average strength and modulus between the two types of RCF composite samples, no solid evidence could be found to say any possible difference between the powder samples and sheet samples in modulus, but the overall strength of the powder samples was a bit smaller. The smaller strength could be a result that some tiny air bubbles may remain in some samples as the quality of the composite was determined using the side walls, but powder samples tend to have a lot of tiny air bubbles on the side wall due to the powder characteristic and not related to the filling quality. Some powder may not fully melt and resolidify together as when entirely breaking the powder PP samples apart; a

tiny white mist could be found, which was considered some powder particles. This could be further indicated from the bending results that both the strength and modulus for the sheet PP sample had a similar variation coefficient of around 13-14% in modulus, but the powder samples had a noticeable difference (around 5%) in the strength compared to the sheet ones. As defects would tend to have more effect on the tested strength compared to modulus, it was considered that such variation difference was formed by the minor defects, including air bubbles or non-sintered particles.

Such an issue would not be faced by the sheet PP samples, but the manufacturing process related could be more complicated as the low flowability of melted PP. In this study, due to the difficulty of filling, the sheet-like PP needs a pressure of about 5MPa to achieve a better-finished product, while the powder usually only needs a pressure of about 1MPa. When the pressure is applied after the mould reaches a suitable temperature, the sheet PP samples often require 20-30 minutes to reach the desired thickness, while the powder sample usually can be pressed within 5 minutes. When considering the processing time, it must be mentioned that the time loss is significant when the compression machine is used to heat up and cool down in this experiment. It usually needs about 40-60 minutes to heat the whole component to the required process temperature, and another 30-50 minutes would be needed when cooling is applied. This time consumption is very high, but, understandably, the conditions of this experiment are based on laboratory benchmarks, and the moulds and instruments are not designed for mass production. When such production is carried out in the actual industry, alternate heating and cooling of multiple moulds can be used, and the cavity of the compression machine can be maintained at the required processing temperature to reduce energy loss and speed up production efficiency.

In this research, some chopped virgin fibre tended to be used to compare with the RCF composites similar to those single fibre tensile comparisons. However, due to the issues encountered during the manufacturing, imperfect composites were produced, and their results could not be utilised to make a property

comparison with those RCF composites. The chopped virgin fibre tows were in the form of randomly oriented bundles but were not entangled together. Thus, when the chopped fibre was spread inside the module, it tended to form a state like a paper formed from the fibre suspension and mainly packed up along the in-plane direction. No fibre could be aligned along the vertical direction and thus would produce a fibre layer thickness that could not be reduced by compression. This is different as that entangled fibre in RCF mats produced some level of support in the vertical direction, allowing more PP to flow (under compression) through the mats and provide a better filling. As well, there was only vertical compression with such a manufacturing technique. Some other techniques which provide a flow or pressure along the fibre direction, such as vacuum infusion, could be more suitable with the chopped fibres, but with the low flowability PP and compression moulding, the composite material produced would be similar to some pieces of paper inserted between polypropylene layers, which do not have a well mixing and forming a structure similar to a sandwich, with pure PP layers and pure fibres layers being physically bonded together. Thus, such results would not present well-mixed and filled sandwich composites and thus did not include in any comparison. Of course, these composite material samples can prove from the side that RCF mats and PP and compression moulding are a more suitable combination. However, RCF in other production techniques such as vacuum injection moulding, this support force/fibres in the vertical direction will become a disadvantage hindering the flow/filling.

In general, this section discusses the impact of various parameters and materials on the production process, from the initial small test rig to the compression moulding used in formal production, including the temperature, pressure and process time required. At the same time, this chapter also discusses some possible effects of various parameters on sample quality and performance. Finally, this chapter could make some conclusions that the powder PP samples had a smaller flexural strength, but no significant modulus difference compared to the sheet PP samples but required a much lower processing pressure and time. A more detailed comparison between the overall

life cycle benefits and drawbacks of using powder or sheet PP will be discussed in the Life cycle analysis section.

5.5 Failure of Samples

Figure 22 shows some examples of RCF composite skins samples (a) after the three-point-bending test and (b) after the tensile test. The top face failure areas where contacting with the load head during the bending test and were circled in blue with the magnified image on the right hand side next to the blue circle mark. The failure areas on the bottom face of the bending tested samples were circled in red and the magnified image on the right hand side next to the red mark as well. The bottom was where maximum tensile strength occurred during the bending test while the top experienced the maximum compression strength, thus it could be founded that the red area showed more polypropylene elongation (turning white) and cracks while the blue area showed some buckling. Overall, the displacements in bending samples were smaller than tensile samples. A clearer polypropylene elongation region and a more apparent crack could be found in the tensile samples, as shown in Figure 22 (b).

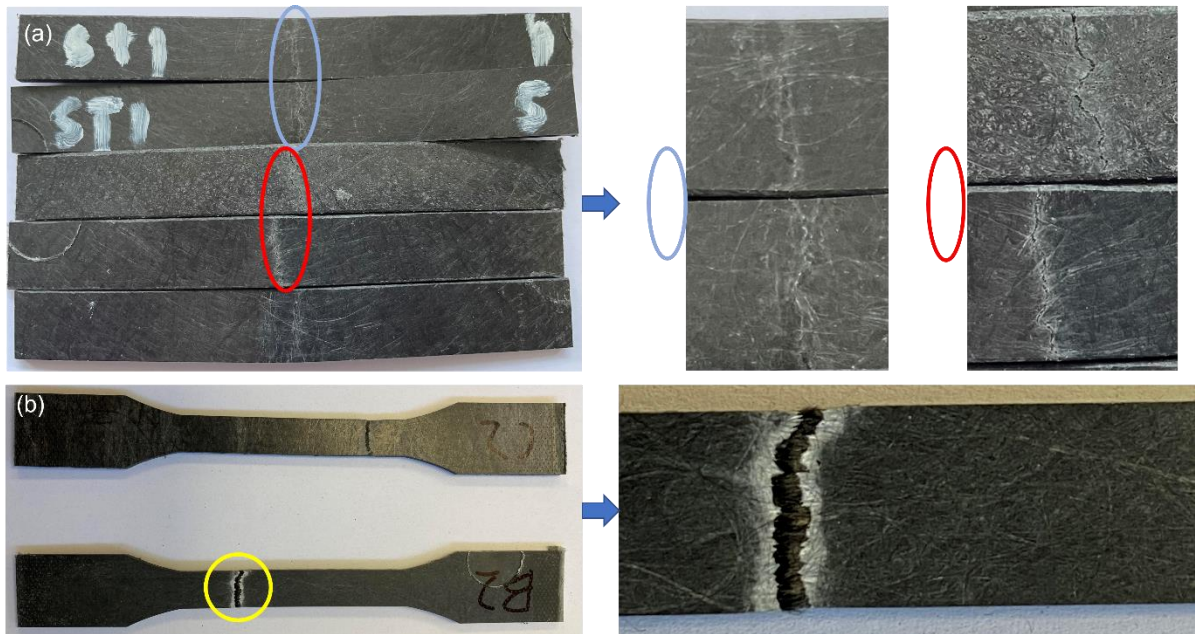


Figure 222. (a) RCF composite samples after the three-point bending test, (b) RCF composite samples after tensile test

Except the randomness of the RCF mats and thus a not perfectly uniformed compression, such failure difference was considered to be one of the major reasons to cause the difference of the bending and tensile properties of the

RCF/PP composite skins. As less displacement inside the bending samples, polypropylene could still hold the sample together and transfer the load onto the fibres that allowed such composite to have a better bending performance.

6 Sandwich Composite Properties

6.1 Sandwich Bending Results

The results of the two types of the sustainable sandwich composite were treated the same way as those RCF composites. Figure 23 shows a set of load vs displacement data examples of (a) pure RCF skins samples and (b) mixed skins samples with an example of the FEA simulated results. The difference and layup for the two sandwich composite (skins) were explained in chapter 3.2.1, 'Composite skin manufacturing' in Figure 12. The pure RCF composite skins were at a volume fraction of 20% same as those samples tested in RCF composite results. The mixed skin was at a volume fraction of 30%, with 12% of them from the RCF mat and 18% of them from flax fabric. The example plot contains the actual experimental result in blue (till the maximum load was reached), the analytical prediction made from the calculation through Equation (9) in red, the FEA analysis in yellow and a black dotted recalibration line to eliminate the initial curved 'tip' from sample alignment when the testing started.

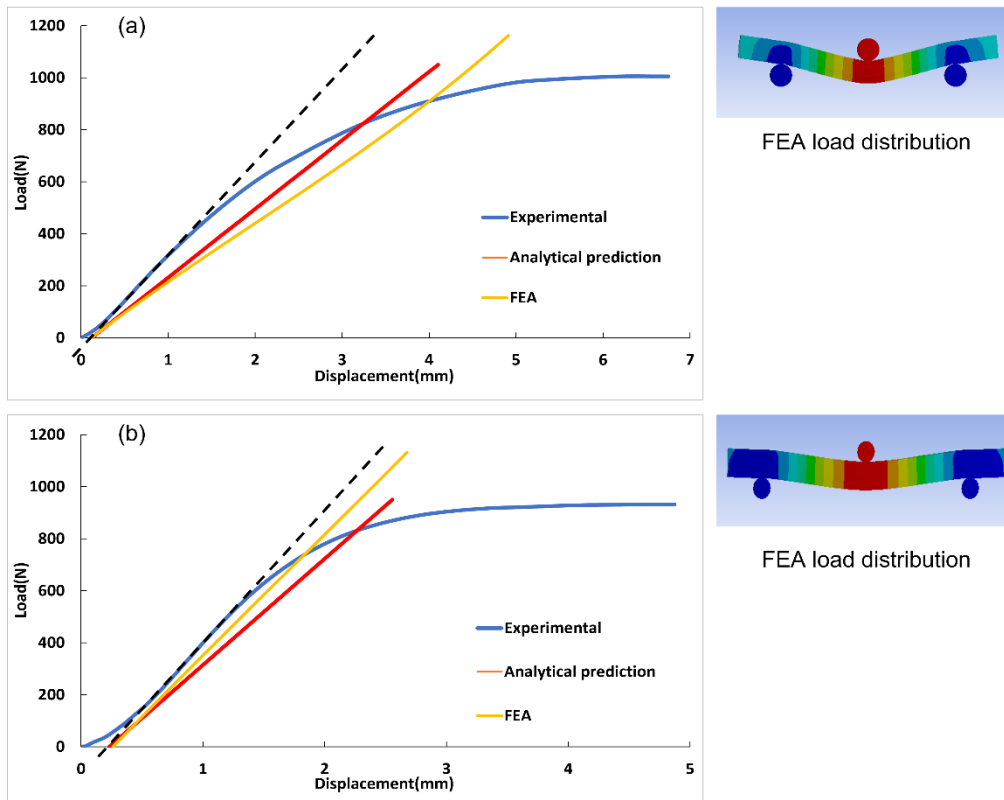


Figure 233. Sandwich beam bending result example: (a) pure RCF skin samples, (b) mixed skin samples

There were only 5 valid results from the mixed skin sandwich composites (16.2-16.2mm thick) and 6 valid results from the pure RCF ones (15.3-15.6mm thick). Thus, no distribution diagram was utilised for the sandwich beam bending results, but a list of average values in Table 3, including the calculated strength from Equation (5) and modulus from Equation (6), total material cost and density. The material cost was estimated from particular materials costs per unit weight and the weight constitution of the sample composite. The density was estimated from initial fibre weight, final product weight and raw material densities, which were kept constant during the manufacturing (some PP would be pressed out as excess to allow better filling in the product; thus, the matrix weight would not keep constant during the process).

Table 3: Sandwich composite properties

Sample Property	Flexural strength (MPa)	Sandwich bending modulus (GPa)	Material cost (£/kg)	Density (kg/m³)	Density (kg/m²)
RCF skin sandwich	76.7 ± 8.8	2.21 ± 0.31	7.1	562	6.8
mixed skin sandwich	41.9 ± 6.8	1.15 ± 0.21	6.7	551	8.0

There were only 5 to 6 samples tested for the two types of sandwich composite samples, the pure RCF skins sample and the mixed skins sample. Thus, no distribution diagram was created for the composite samples, and the properties were directly presented in Table 3 with their average values and standard deviations. In figure 23, an example of both sample types was shown with their actual experimental plot of load against displacement, (modulus) correction line, FEA results and the analytical prediction made from material properties with Equation 9 were also presented together. The blacked dotted line was the correction line used to modify the small ‘tip’ that appeared in the initial experimental results due to the sample rearranging itself under the load to be fully ‘clamped.’ The correction would affect the actual displacement; thus, both predictions were moved to the same intersection point between the correction

line and x-axis. The actual displacement is a factor included in the calculation of sandwich modulus in Equation (6), and same as previous treatments, 2 separated points would be selected within the black dotted line for calculating the sample modulus. The sandwich strength, calculated using Equation (5), was only related to the maximum load achieved and thus would not be affected by this correction. All the samples were kept tested until the load was dropped more than 50% of the maximum load, the same as other bending experiments but due to the limitation in the image size. However, it was not meaningful to show a continuous line kept flat till 20-30 mm deflection until failure; thus, only the initial part of the diagram, as shown in the example results graph.

By comparing different lines in the load and displacement plot, it could be concluded that the prediction made from the calculation using raw material data in Equation (9) and the prediction from the FEA were similar. As the FEA was simulated based on a static loading condition with the foam material assumed as elastic elements, thus it was not able to predict the actual deformation when the whole sandwich beam stepped into the plastic zone, which was those nearly flat regions. Similarly, the equation for predicting the sandwich behaviour was related to the effective modulus that turned the sandwich composite into an effective I beam, which, again, elastic properties were input inside the equations and thus unable to predict the further deformation behaviour. Both predictions show an underestimation compared to the modified line, representing the sandwich composite's modulus. However, the underestimation for the pure RCF samples was more than for the mixed samples, which can tell from the broader gap in RCF samples even with a broader displacement range shown on the x-axis. This was believed to be a result of underestimating the RCF mat effective modulus as the prediction was made before the result analysis, which assumed only at 70GPa but was calculated to be around 76GPa from the RCF composite bending results in the previous chapters. The pure RCF skin contains 20% RCF mats in volume while the mixed skin contains only 8%; thus, the underestimation was more in the pure RCF sandwich samples. Despite the lower effective modulus of RCF mats used for prediction, both simulations did show a relatively accurate prediction of the sandwich behaviour before the

plastic deformation shows where the actual results plot starts to show a decreasing slope.

Table 3 shows the calculated properties of both sandwich composite samples. The material costs and densities were estimated using the average value or the middle point of ranged values; thus, no variation was included. The strength and modulus were calculated from the test data by equations 5 and 6. Similar overall density was presented in both samples, but a much lower area density was shown in the pure RCF sandwich samples. This was due to the thickness difference that the RCF skins were at 2.8mm, but the mixed skins were at 3.2mm. The effect of the skin and core thickness ratio on the overall density and area density can be founded in Table 1. As this research was aimed to replace currently used panel materials in vehicles for more sustainability, thus the area density was included in the property, which could be more straightforward to compare the materials for such applications. The material cost, on the other hand, would not show inconsistency difference as RCF was more expensive while the flax fibres were at a low cost and thus, the area costs were not explicitly listed. Both strength and modulus results, again, did show variation coefficients of 11.5%, 14%, 16.2% and 18.3% for both samples, respectively. These values are still within the reliability range but relatively high due to the limited sample size. Also, neither sample has a consistent thickness due to maintaining a controlled volume fraction, but this may lead to some properties differences as all tests were under the same conditions, including the flexural span, but these parameters do not have the same index level (according to the formula 5, 6) can therefore produce unpredictable differences. The average modulus and strength of the mixed skin sample were much smaller than the pure RCF composites; it could be a result of the unidirectional flax fabric was not suitable for combination with PP under the compression, just like what happened to the chopped fibre tows discussed in the last chapter and would be explained more with the help of the SEM images in the next chapter.

6.2 SEM Results of The Sandwich Composites

Figure 24 shows example images from the SEM of the sandwich composite samples, including the main interest areas, the bonding interface, and the fibre filling. Background scattering electrons were used in these captured images as they could show a better contrast of different substances to check the filling and bonding quality. The magnification and scale could be found in all images. The interface between the RCF composite skin and the foam was shown in Figure 24 (a)i with hollow foam bubbles and an adhesive layer with a thickness of around 200 micrometres. The further magnified image in the same region as shown in (a)ii shows the skeleton of the foam structure underneath the adhesive layer, and some adhesive enters the composite skin zone and is mixed with the PP matrix. All the images were captured using a tested sample; thus, cracks could be founded propagated along the flax composite zone as shown in (b)i. Some flax agglomerate knots could be found in the image, and a magnified image of them is shown in (b)ii, with a reference of the RCF composite zone at the same magnification shown in (b)iii.

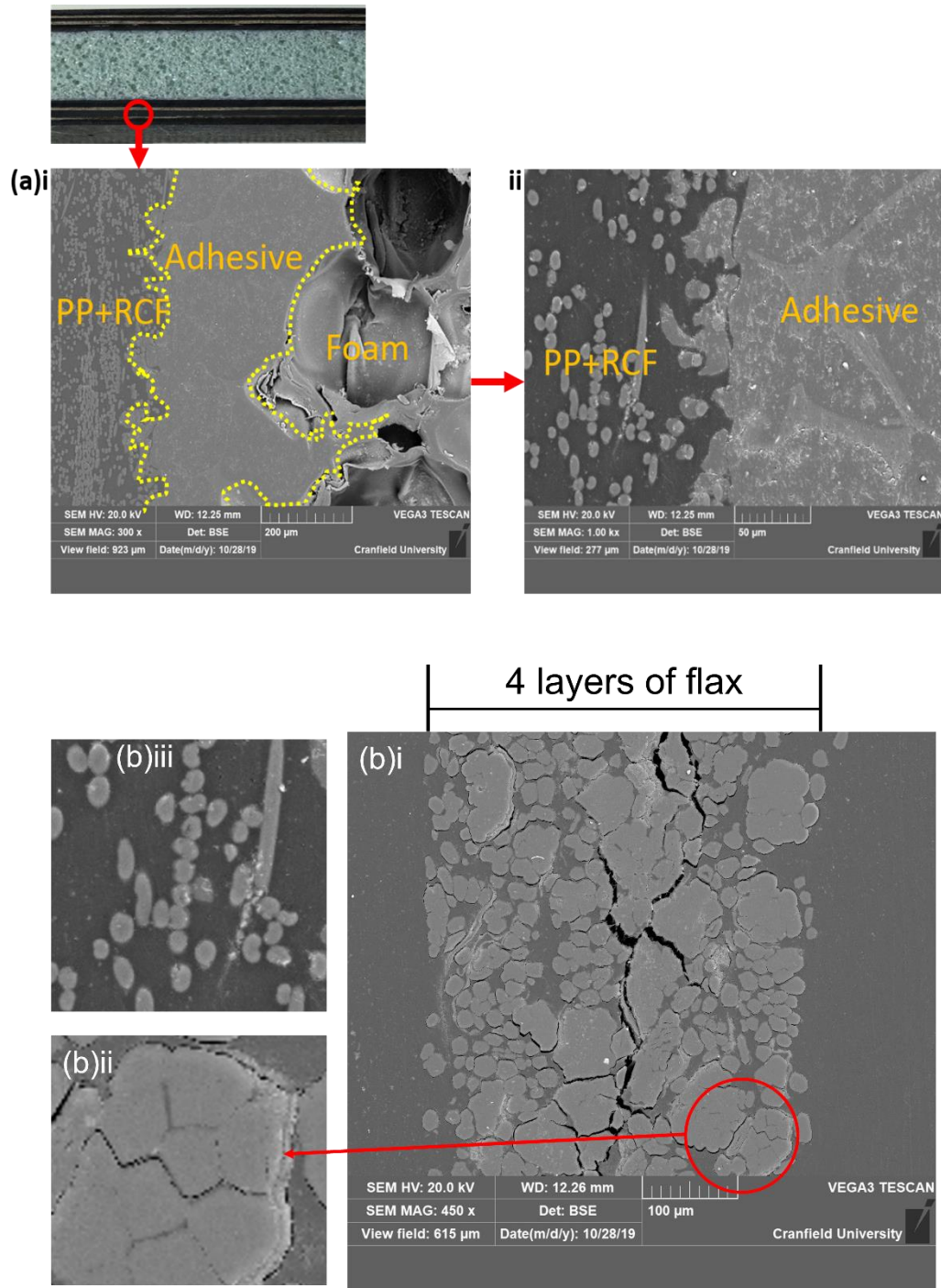


Figure 244. (a)i SEM image of the sandwich bonding interface; (a)ii magnified interface region; (b)i SEM image of the flax composite region in the mixed skins; (b)ii magnified flax fibre agglomerate; (b)iii comparison of RCF carbon fibre gathering at the same magnification

Figure 24 (a) shows the SEM image example of the bonding area between the sandwich skins and the PET foam core. The hollow foam bubbles were shown on the right-hand side of image (a)i, while some RCF composite was shown on the left side. The light grey dots and lines were the carbon fibres, and the dark grey region was the PP matrix that covers the carbon fibres. This image was captured from the cross-section of the sandwich beam, and it could be told from the stack of materials that from left to right of this image was the through-thickness direction of the samples. It can be said the fibre was all pressed to oriented in-plane due to the pressure of compression moulding during manufacturing, which can be proved from the image too that no fibre was lined in the through-thickness direction. By the magnified image (a)ii, it can be told that some of the foam bubbles were filled by the adhesive as the foam skeleton could be found underneath the adhesive region, which was good for better bonding strength. In general, no apparent defects could be found inside this image and the bonding region and RCF composites region of other images, which was not shown. Thus, the filling of the RCF composite and the bonding could be considered good quality.

On the other hand, the SEM image of the flax composite region from the mixed skin composite sample could tell some different stories. First, the image was captured after the sample was tested, and an obvious crack propagated through the flax composite could be found. This, together with the information from the Figure 23 and Table 3 of the tested samples, it could be concluded that the mixed skin samples were different from the pure RCF samples, do not have a core failure but damage occurred in the skins. The reason for this could be a result of poor flax filling, as it could be told from the image that the flax composite was not a well-mixed product; the middle region where flax fibres presented could have a flax volume fraction of more than 70%, but a thick pure matrix region was on the sides. These poor-mixed composites could have a lower mechanical property than expected as stress could not be well distributed in such composites. Thus, the stress concentration area would be similar to defects which cause a reduction in mechanical performance. One of the reasons that caused such poor mixing was the characteristic of the flax fabrics

as natural fibres were not grow into infinite length, and most long natural fibre (fabric) was formed by twisting fibres together at the ends to splice. Another reason was the manufacturing process similar to chopped short fibre, which could not provide a good quality composite under compression moulding with PP; the flax fabric was unidirectional and did not have support in the through-thickness direction. Thus, with the compression pressure and the low flowability PP, the flax fabrics would be quickly pressed together closely, and the matrix would be more likely to be pressed out from the side but not through the fabrics. Also, flax fibre could experience slight degradation with the presence of oxygen at high processing temperature as a light caramelisation smell had appeared after the mixed skin compression during the experiments. So, for processing flax fabrics with PP matrix, a fully closed mould that holds the fabric and molten PP injected with the pressure might be a better manufacturing technique.

In general, the mixed skin composites did not show the expected properties in this research because of the incompatibility between the materials, manufacturing techniques and manufacturing parameters (moulds), while the RCF mat did show good compatibility with PP under compression moulding. Also, the adhesive BEMIS-5256 was suitable for bonding PP, and PET foam surfaces as for both types of sustainable composite samples, the failure under bending was unrelated to the bonding.

6.3 Failure of The Sandwich Samples

Figure 25 (a) shows one example of sandwich composite (with pure RCF skins), which showed core failure under the bending (the region with red marks). However, such core failure was only shown in the pure RCF samples, while the mixed skin samples experienced some level of skin buckling, as shown in the blue circle region of Figure 25 (b), and no other visible damage could be founded.

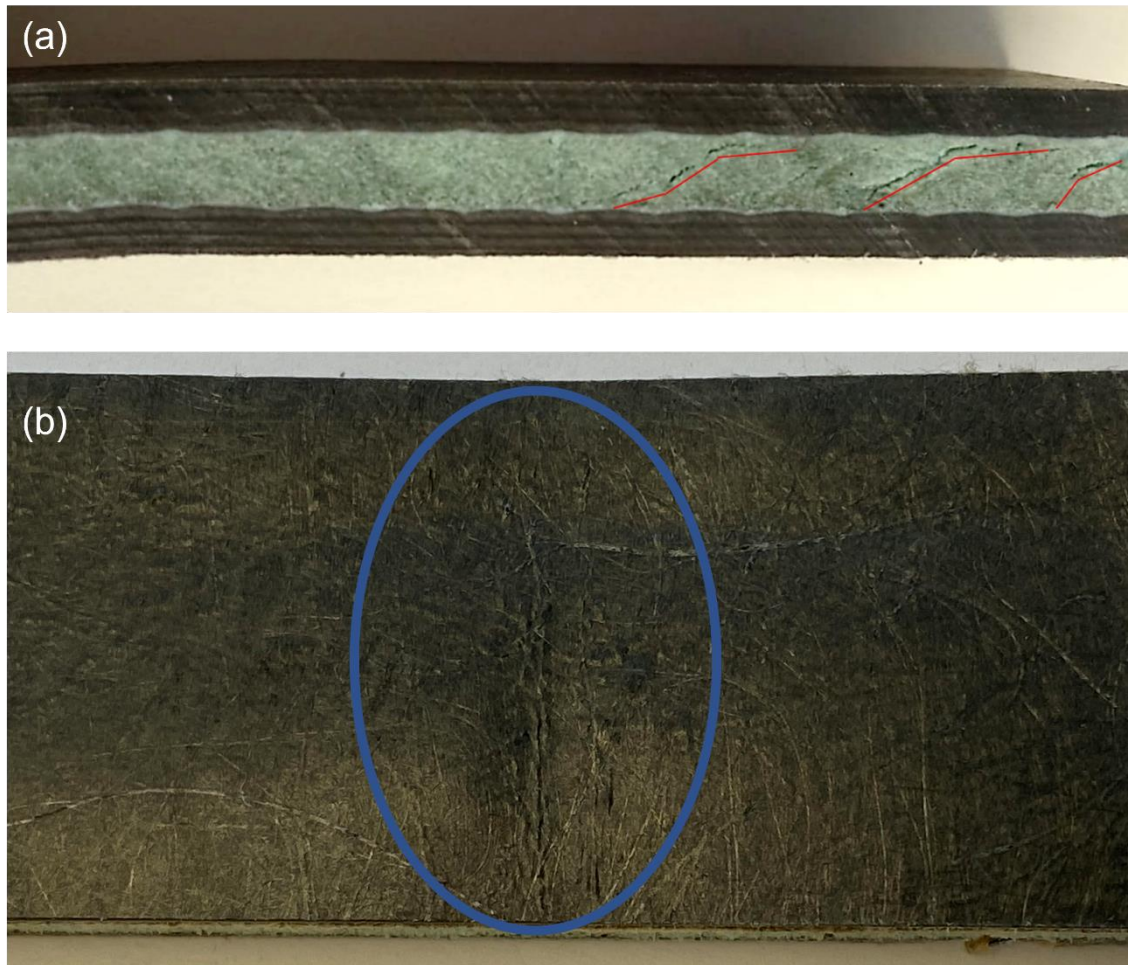


Figure 255. (a) pure RCF skins sandwich foam core failure at three-point bending test, (b) mixed skins sandwich skin buckling failure

Compared to the maximum deflection of around 6-10mm when the RCF composites skin would be broken apart, the sandwich composite had a much higher deflection of around 20-30mm at the same support span. Such high deflection without broken apart could be a result from the sandwich core, which

was well bonded with the skins and supported them from being broken apart. Also, as mentioned previously, all the sandwich samples were not fully broken apart during the test, which stopped a significant load reduction when failure occurred, such sandwich composite still able to take some load after failure and samples were maintained in a complete beam structure after the test. An interesting scene happened when the test was completed that although the elastic deformation region (the initial straight lines) in the result plot was very small, all the samples almost returned to their original shape slowly (some hours) after the tests like a rubber material. However, it can still be seen in Figure 25 (b) inside the blue circle that the hybrid skin sample still experienced some permanent buckling which cannot be recovered after the test. Different failure modes could also be found in this Figure from the two types of sandwich samples. A skin failure in the mixed sandwich composite occurred due to the crack formed and propagated inside the flax region in the top composite skin which contacted the load head. This will be explained more in the next chapter with the help of SEM images. On the other hand, the pure RCF sandwich samples failed due to the core failure, while the RCF composites skins could still stand more load. This could also be found in Figure 25 (a) that some small cracks were shown in the foam after the testing.

6.4 Impact Comparisons Between GFRP, RCF/PP Skins and The Sandwich Composite

As mentioned in the methodology, two different materials were tested through the drop tower impact machine, which can be further divided into 4 different types, glass fibre reinforced epoxy, RCF/PP composite skin (powder PP), RCF/PP composite skin (sheet PP) and a sandwich composite of RCF/PP skins and PET foam core while these skins in sandwich samples were also made from powder PP. In total, 3 samples were tested in each type, and the resulting impact energy results are presented in Figure 26. However, due to the thickness of the sandwich sample approaching the limit of the 4 stable clamps, as shown in Figure 16 in chapter 3.3.4 “drop tower impact test”, thus the sandwich samples were not fully fastened, and one sample experienced the force from the base during the impact and experienced fluctuating data thus only two valid results were shown for the sandwich samples. When the impactor was at the starting position, the energy shown was 0, which means all the energy were stored in the form of potential energy at that moment, and the maximum energy shown in all images around 6J was the moment of impact. Afterwards, due to the rebounding and gaining height, the kinetic energy would be converted to potential energy again. However, because the tested material absorbed some energy, the impactor could not return to its original position. Thus, the energy difference between the starting and ending positions would equal the amount of energy the material absorbed. In this case, starting with 0J in the plot, the final energy would equal the energy absorbed. With the maximum impact energy, the energy absorption rate of a particular sample

could be calculated, which is also shown next to the legend of each curve.

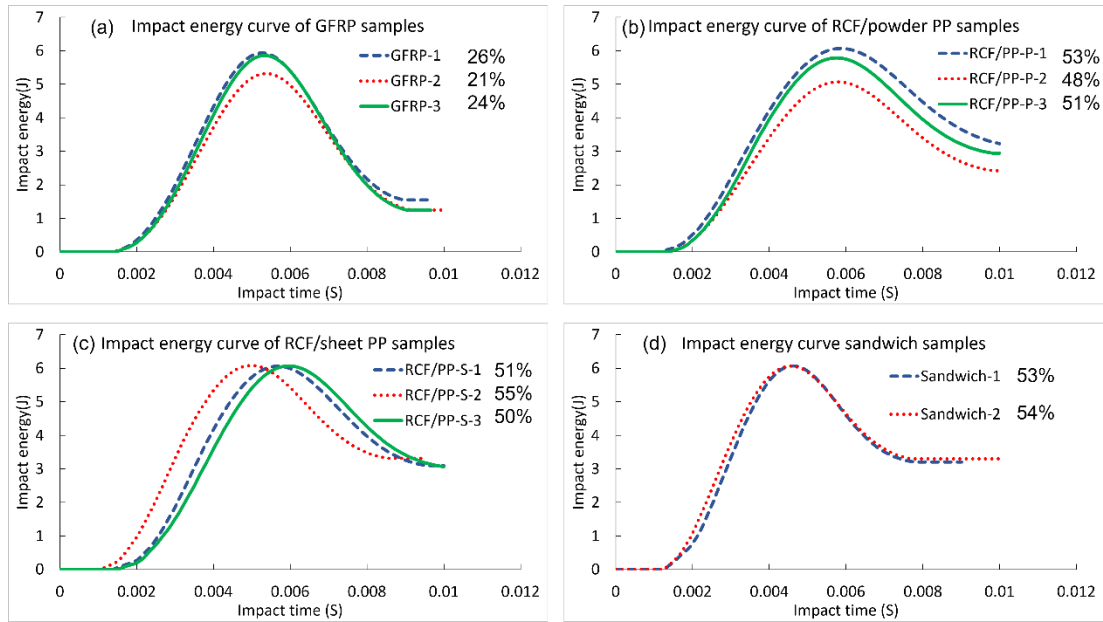


Figure 26. Results of impact energy against time from drop tower tester

As shown in Figure 26, the final energy shown for each sample is equal to the energy absorbed by the sample during the test. Therefore, it can be seen that the RCF/PP composite samples can absorb more impact energy than GFRP, which can bring benefits of reducing cargo vibration in the application of lorry/van panels. The percentage next to the legend shows the proportion of the final absorbed energy of the sample to the total impact energy, which also reflects the difference between RCF/PP composites and GFRP in terms of absorbed energy. However, on the other hand, neither the shape of the energy curve itself nor the energy absorption percentage can tell the difference between the samples made of powdered PP and those made of sheet PP. Meanwhile, although sandwich composites with foam cores were expected to absorb more impact energy, actual data did not show any significant difference between them and pure RCF/PP skins. The only noticeable difference between the sandwich and the skin is that the impact time of the two sandwich samples will be slightly less than any other skin samples; this difference may be due to the difference in the machine reaction time caused by the difference in sample thickness, or the adding of the foam material changed the overall elasticity. However, no further information was found that might have caused this effect.

The following Figures 27,28 and 29 also shows the corresponding impact damage. Since the impact was hitting the upper surface of the sample, the impact energy was also spread to the inside of the sample, and the thickness of all the samples except for the sandwich structure was about 3 mm. So, the sample exhibited a minor dimple on the top surface but a more significant busted blemish on the rear side. Also, the sandwich samples only show similar top surface damage as the RCF/PP composite skins, while due to a thicker core and bottom composite skin layer, no damage could be found at the rear side at all and thus, the image of sandwich samples was not presented.

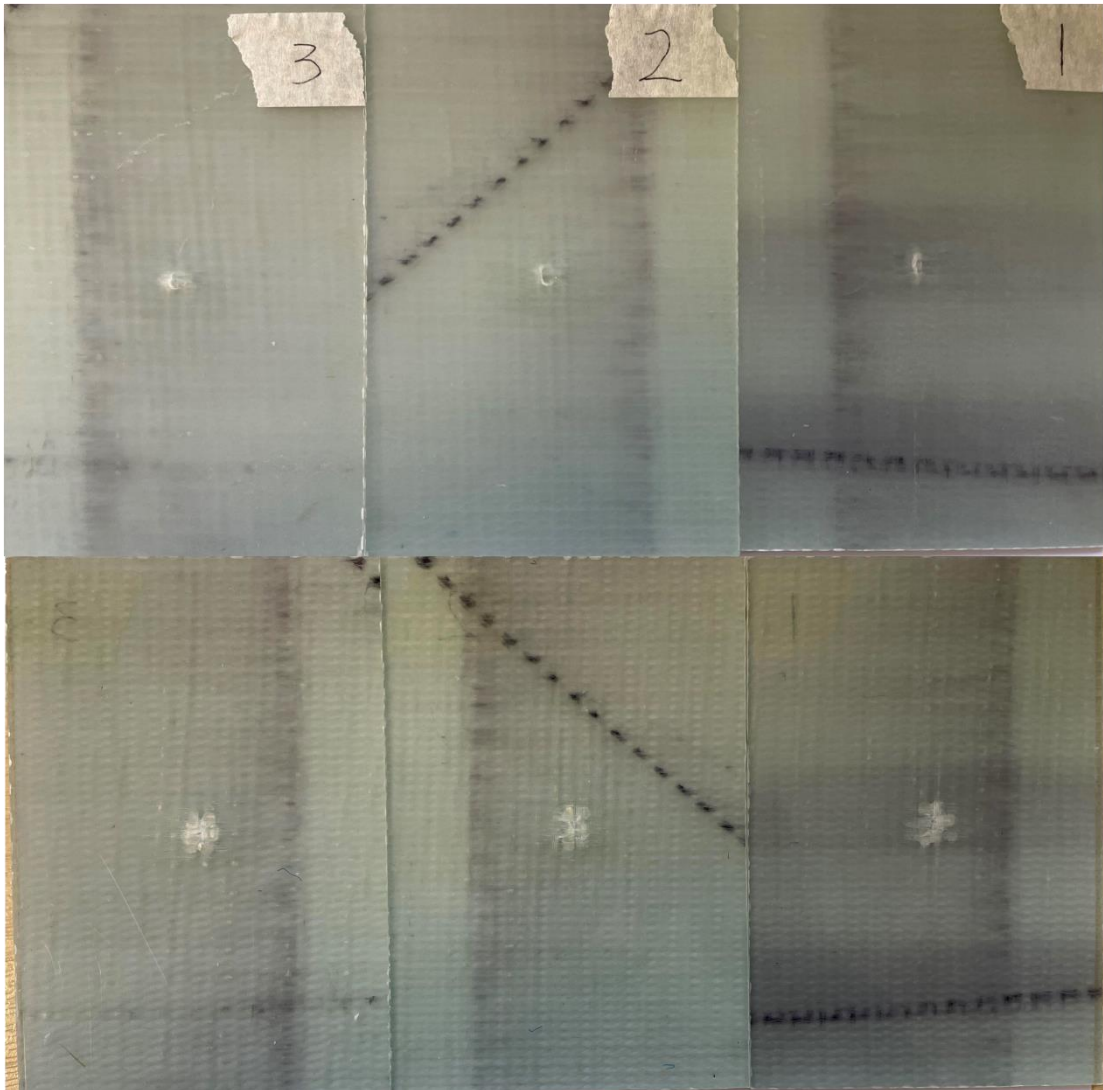


Figure 27. Top and rear side image of GFRP samples after impact



Figure 28. Top and rear side image of RCF & powder PP samples after impact

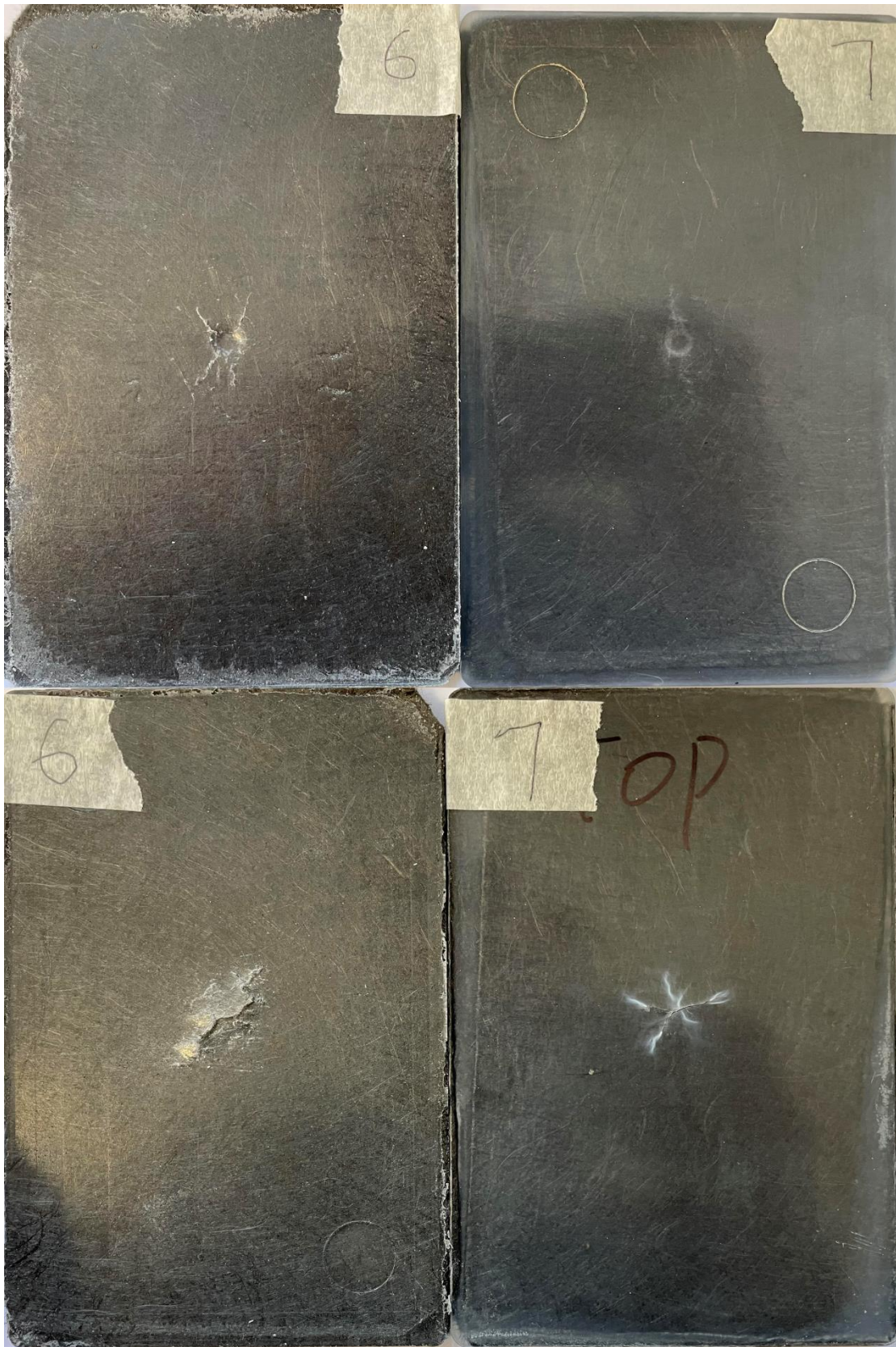


Figure 29 Top and rear side image of RCF & powder PP sample 6 compared to RCF & sheet PP sample 7 after impact

By comparing the damage caused by the impact test, as shown in Figures 27 and 28, it could be seen that under the impact of 6J energy, all samples except the excessively thick sandwich structure exhibited minor upper surface damage and a more significant back burst damage which formed from the spade of the impact shockwave. Although the figure was not particularly obvious, the actual GFRP samples are slightly different from the RCF/PP samples. Their upper surface still maintains a relatively smooth and level morphology. Without the help of the changed colour, it was almost impossible to find that the samples had been damaged. This common phenomenon is found in most epoxy composites when impacted. However, the hardness, strength and modulus of PP were slightly smaller than that of epoxy, and a small dent left after being impacted on the upper surface could be founded in all RCF/PP samples. Due to this characteristic of epoxy, the same back burst damage will appear slightly smaller than that of RCF/PP on the GFRP sample, but when the GFRP sample was observed obliquely from the side by light reflection, it could be found that the GFRP sample had a damaged area at almost the same size as most of the RCF/PP sample. Due to the inhomogeneity of the RCF mats, a few samples also showed huge continuous cracks; like the upper skin of sample 5, shown in Figure 28, it can be seen that there is a strip that occupies almost half of the total sample length of large cracks. In contrast, the damage to the GFRP samples under impact was very consistent. The sandwich sample is too thick, there is no more information to show other than the upper surface dents consistent with other RCF/PP samples. However, there is no significant difference between the samples produced with sheet PP and the powder PP, as shown by the comparison in Figure 29. The damage in all the sheet PP samples was more consistent and similar to Sample 7. The most significant difference between the two different PP raw material samples after impact testing can be seen from the comparison in Figure 29. The sheet PP samples appeared more compact, and only a few prominent white cracks appeared, while the powder sample appeared looser so that many white spots could be found in the damaged area. An interesting phenomenon was noticed in the difference between powder and sheet PP samples during the impact test and the sample

cutting and bending test. The samples produced from powder PP will be looser than the sheet raw materials. This looseness is reflected in the connection between the matrix materials. The matrix in the samples manufactured from sheet PP was entirely connected, while the powder samples often contain a small amount of PP that is not entirely connected to the entire matrix but is wrapped inside some fibres, so a few scattered PP particles were found after cutting and breaking the samples.

Generally saying, regarding impact behaviour, the RCF/PP composite skins designed in this research could compete with the typical side panel skin of glass fibre and epoxy in terms of the damaged area under same impact level but a much better energy absorption rate.

7 Recyclable Sandwich Composite for Van Side Panels: A Case Study

A schematic diagram of a refrigerated van (Mercedes Sprinter Luton) is shown in Figure 30 (a) as for a case study to evaluate the feasibility of using the sustainable sandwich composite design in this research as a side panel for vans. This panel is a secondary structure in refrigerated vans as most of it would be supported by the metal framework on the side as well as some middle supporting bars. Thus, these panels were required only to provide adequate strength and thermal insulation at a relatively low density. Common panel materials for such panels are mainly sandwich composites of GFRP skin and non-renewable/non-recyclable PVC or PU foam core; some sandwiches also include metal, plywood or block plastics. These materials currently used as the van panel were not fully recyclable; therefore, the composite sandwich design in this research should be beneficial for expanding the overall vehicle sustainability. The lorry box size was 4.1 x 1.9 x 2.25m, and a total payload of 1000kg was assumed in this study, and the deflection was predicted from Equation (9) in the methodology. Wind loads were estimated to be perpendicular to the side panels and uniformly distributed, as shown in Figure 30 (b) because the wind could provide the maximum bending moment to the panels at such an angle. The pressure caused by the dynamic wind flow during the driving was not considered as it would be directed outwards, and the estimated overall drag force would be smaller than directly perpendicular wind pressure at a smooth surface. It can be observed from Figure 23 that the experimental deflection result of the sandwich composites before the plastic deformation occurred was 1.5% of the maximum length. This part could be described as the linear elastic deformation region within which the deflection prediction made from Equation (9) with material properties could be in line with the actual results. Thus, it can be safely deduced that plastic deformation would not occur before a deflection of 1% of the maximum length. Two scenarios were considered in this case study, as shown in Figure 30 (b): (i) Only two side edges support the panel. (ii) The panel is supported by two side edges and one middle bar. Such scenarios also assumed that the edges and middle bar had

significantly higher mechanical properties than the panels, which could then be assumed to be solid/rigid support for these panels. The prediction of the lorry side panel behaviour under the perpendicular wind load can be graphically visualised in Figure 30 (c). Such a lorry panel with only two side supports could be used in applications exposed to the UK wind weather having an average wind speed of 23 m/s. Besides, this panel can survive a vehicle turning speeds below 15m/s when the lorry is fully loaded, and all the pressure from the items is perfectly focused on the middle point of the panel. The analysis illustrates that the two-point support (blue line) can also endure the average UK storm speed (36 m/s), shortly beyond which it fails. Moreover, the three-point support (red) offers much less deflection for all wind speeds, even tolerating the wind speed of a typhoon (43 m/s). Also, in actual application, not only the two ends of the panel but also the two sides on top and bottom of the panel would be supported as well. Thus, the ability of such a lorry panel to stand a wind load could be even more.

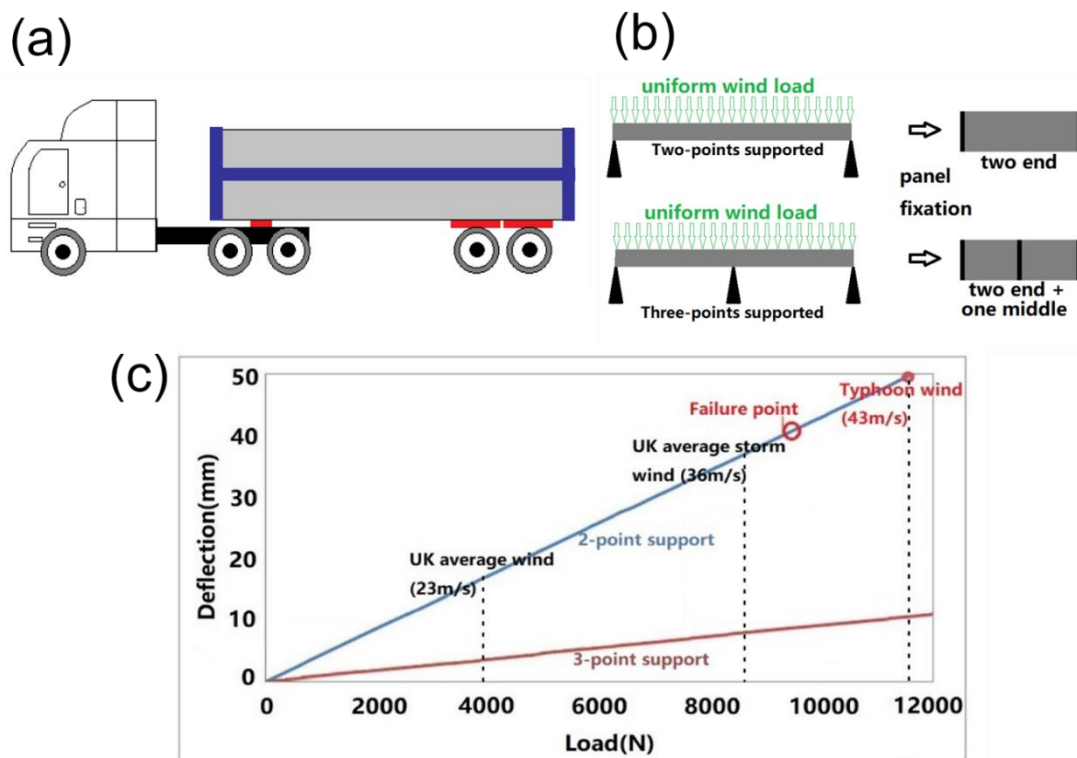


Figure 30. (a) Schematic of a truck with grey side panels and blue supportive frames; (b) Wind load and supporting system illustration (c) Flexural behaviour prediction of truck panel with sustainable design

CES EduPack software was utilised to compare the sustainable panel design (pure RCF sandwich one) in this research with some commonly used panel materials in the market in terms of specific flexural properties and density, as shown in Figure 31.

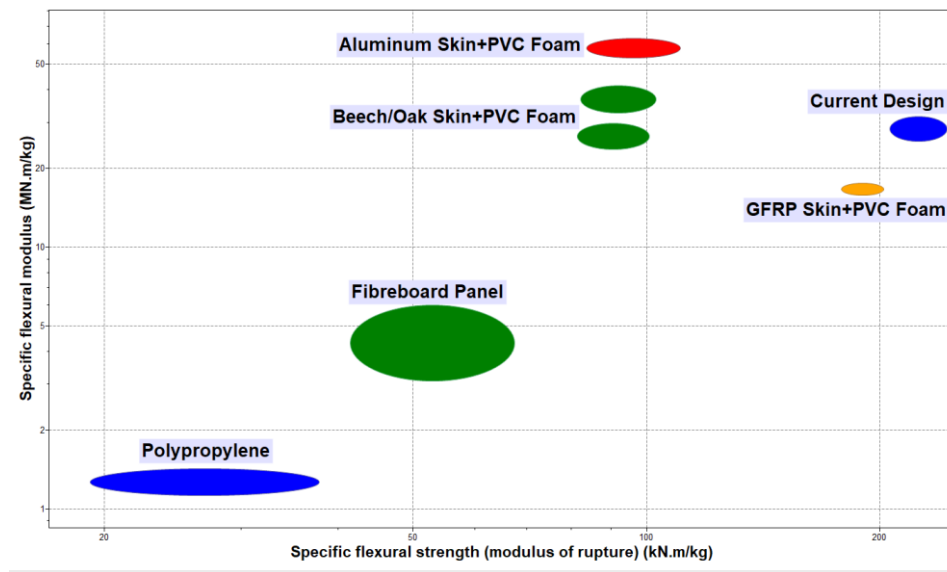


Figure 31. Specific flexural modulus vs Specific flexural strength to compare currently used truck panel materials with current sustainable design (Source: CES EduPack software)

The variables for all the sandwich panels were controlled at uniform load testing with simple end support; 4 m span length; 5 mm/ 50 mm/ 5 mm sandwich design similar to the previous lorry panel case study; 35% volume fraction GFRP skins and 20% volume fraction RCF/PP skins were used for comparison to match the impact test samples. Considering the specific flexural performance of the current sandwich design (pure RCF skins) as per the plot in Figure 31, it is evident that the design proposed in this research displays better mechanical properties than most of the candidates in the market. The mixed skin design with flax fibres faced two significant problems in this research, as mentioned in the discussion section for sandwich properties in chapter 5.3. The first issue

was the reduction in mechanical properties during the high-temperature treatment. Upon comparing the flexural rigidity of the experimental and theoretical predictions, flax fibre had lost about 20% to 30% of its mechanical property (modulus) after a temperature treatment of 180 °C for 20 minutes which was in line with most research about the temperature effect on flax fibre properties (51–53). The second issue was a weak affinity of natural fibres with the PP matrix and compression moulding process, thus its inability to attain 100% performance without surface treatments. It could be noticed in the SEM results in chapter 4.5 that the flax fibre would tend to be pressed together before the PP could enter such a location and comprehensively cover all fibres. These two problems need to be resolved before the recycled sandwich composite design with flax in this research can be used for lorry panels while the pure RCF/PP skins sandwich composite showed itself as a good candidate for such applications.

8 Conclusion and Future Research

In conclusion, this study addressed an aim to manufacture a fully recyclable sandwich composite that utilising the recycled carbon fibre mat and polypropylene and also intended to resolve the need for lightweight and recyclable materials in the automotive and transportation industries and proposed an application that could be improved by the sandwich design in this research which still relies heavily on non-recyclable materials: the secondary panel for trucks/lorries.

The first objective of designing such a fully recyclable sandwich composite has been completed with the help of the literature review.

The second objective to better understand the recycled carbon fibre was completed through the single fibre tensile test, which results were presented in chapter 4, the randomly selected single recycled carbon fibre from the RCF mat had comparable mechanical properties as those randomly selected virgin PX-35 fibres, but relatively wider property range due to more type of sources presented. A further conclusion could be made, which was in line with most research on carbon fibre recycling, that the commercial recycling process did not significantly affect the mechanical properties of the fibre, although a specific performance loss ratio cannot be given due to the unknown source of the recycled carbon fibres. Recycled fibres are at least maintained at the same order of magnitude as the virgin carbon fibres, with moduli around 240GPa.

The third objective was more complicated and included more content, so this research partially completed this objective by studying the different kinds of RCF/PP composite skins, which results were presented in chapter 5. Compared with the previous single fibre mechanical results, the RCF/PP composite skins show an effective modulus at up to 31.5% at three points of bending and 19.8% at tensile, and the major conclusion was that instead of the worrying recycling process which mostly studied, the chopping and cutting process of end-of-life composite to fitting the recycling process might causing the fibre to have more

significant property loss. Also, it is suggested for more bending loading application when applying polypropylene as the matrix for the RCF mats due to a better performance resulting from the limited deformation in bending than tensile, which allowed more load to be continuously transferred after the failure occurred. Impact testing revealed that the RCF/PP composite design in this study had similar impact resistance to GFRP materials commonly found in similar van panels; with the same impact energy used, most RCF/PP exhibited a similar damage size as GFRP. However, the specific residual properties after impact were unknown due to the lack of a dedicated instrument for post-impact compression testing. At the same time, the RCF/PP samples showed slightly poor consistency in the impact test, but on the contrary, their energy absorption rate was significantly higher than that of GFRP, so it can greatly reduce the impact of vehicle bumps in the application of lorry/van panels to protect some of the more fragile goods better.

The fourth objective, to integrate the flax fibre inside the RCF/PP composite skins and to manufacture the fully recyclable sandwich design with the recycled PET foam core, followed by mechanical testing and characterising, was completed and presented in chapter 6. In conclusion, both types of the sandwich composite had been successfully manufactured and tested; the BEMIS-5256 was successfully bonding the PP and PET surface together and provided sufficient adhesion that caused the core to crash first during the bending test. The pure RCF/PP skins achieved similar properties as predicted and were sufficient for further application as van-side panels. The impact properties did not differ much from pure RCF/PP composite skins due to the limited impact energy and the sample thickness, but they are still sufficient to be considered a better candidate for GFRP composites as a flooring panel. The SEM images revealed a good filling in RCF/PP composites and a good adhesive zone, on the other hand, the SEM also revealed a flaw of the flax fibres in the mixed skin design, which were agglomerated by the pressure of the hot press before the PP was sufficiently wetted, resulting in imperfect packing and thus a lower mechanical property.

The final objective was completed through the case study and current panel materials comparison in the chapter 7. By the performance from previous testing, the estimation in the truck side panel case, and the comparison with other common materials. It can be seen that the sandwich of pure RCF/PP composite skin (with sheet PP) and recycled PET core proposed in this study has good mechanical properties to be a candidate for the desired application. The design has specific mechanical properties similar to the best products on the market today, with better energy absorption and the possibility of full recovery due to using adhesive with a lower melting point than the core and skin melting temperatures. Therefore, the separation of the skin and the core and the melting and remanufacturing of the skin can be both achieved at a low temperature (both below 200 degrees Celsius). On the other hand, the design of incorporating flax and the use of powder production has certain disadvantages. Adding flax will not only make the entire cortex material more complicated but also increase the difficulty of recycling (unlike pure PP/RCF, which can be directly melted and softened and then reproduced directly, flax also needs to worry about decomposition over time, so it is often impossible to recycle and reuse directly), while the overall mechanical properties are reduced due to the production process. Powder PP can improve production efficiency and significantly reducing the time required for heating and material flowing after melting. However, powder PP requires more energy and brings a certain degree of performance instability. It can be seen that the consistency of powder samples is slightly worse than that of sheet PP in all experiments. Therefore, which raw material is better may require further comprehensive comparison and evaluation in the future.

Thus, the future work that needs to be done is also clear from the conclusions. First, the uncompleted design and improving the pultrusion process in objective three was necessary for research in future as its benefit could be significant in improving the reusing the carbon fibres. Second, compression after impact test was also necessary to show the difference between the GFRPs and RCF/PP composites more comprehensively. Third, a better design and manufacturing process to bring the flax fibre into such a recyclable design was necessary as

the current compression process was unsuitable for manufacturing flax fibre composites with a PP matrix. And finally, a more comprehensive life cycle study on how such change in material weight could affect fuel consumption and the energy needed to transition to such a new design would be necessary for future analysis.

REFERENCES

1. Cui H, Hall D, Lutsey N. Update on the global transition to electric vehicles through 2019. International Council on Clean Transportation [Internet]. 2020;(July). Available from: <https://theicct.org/publications/update-global-ev-transition-2019>
2. Del Pero F, Delogu M, Pierini M. The effect of lightweighting in automotive LCA perspective: Estimation of mass-induced fuel consumption reduction for gasoline turbocharged vehicles. J Clean Prod [Internet]. 2017;154:566–77. Available from: <http://dx.doi.org/10.1016/j.jclepro.2017.04.013>
3. Kim HC, Wallington TJ. Life Cycle Assessment of Vehicle Lightweighting: A Physics-Based Model to Estimate Use-Phase Fuel Consumption of Electrified Vehicles. Environ Sci Technol. 2016;50(20):11226–33.
4. Bein T, Mayer D, Hagebeuker L, Bachinger A, Bassan D, Pluymers B, et al. Enhanced Lightweight Design - First Results of the FP7 Project ENLIGHT. Transportation Research Procedia [Internet]. 2016;14:1031–40. Available from: <http://dx.doi.org/10.1016/j.trpro.2016.05.173>
5. Hara D, Özgen GO. Investigation of Weight Reduction of Automotive Body Structures with the Use of Sandwich Materials. Transportation Research Procedia [Internet]. 2016;14:1013–20. Available from: <http://dx.doi.org/10.1016/j.trpro.2016.05.081>
6. Delogu M, Del Pero F, Pierini M. Lightweight design solutions in the automotive field: Environmental modelling based on fuel reduction value applied to diesel turbocharged vehicles. Sustainability (Switzerland). 2016;8(11).
7. Mayyas AT, Qattawi A, Mayyas AR, Omar MA. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy

- [Internet]. 2012;39(1):412–25. Available from: <http://dx.doi.org/10.1016/j.energy.2011.12.033>
8. Burd JTJ, Moore EA, Ezzat H, Kirchain R, Roth R. Improvements in electric vehicle battery technology influence vehicle lightweighting and material substitution decisions. *Appl Energy* [Internet]. 2021;283(November 2020):116269. Available from: <https://doi.org/10.1016/j.apenergy.2020.116269>
 9. Belingard G, Chiandussi G. Vehicle Crashworthiness Design - General Principles and Potentialities of Composite Material Structures. CISM International Centre for Mechanical Sciences. 2011;526.
 10. Joost WJ. Reducing vehicle weight and improving U.S. energy efficiency using integrated computational materials engineering. *Jom*. 2012;64(9):1032–8.
 11. Czypionka S, Kienhöfer F. Weight reduction of a carbon fibre composite wheel. *Science and Engineering of Composite Materials*. 2019;26(1):338–46.
 12. Taub AI, Luo AA. Advanced lightweight materials and manufacturing processes for automotive applications. *MRS Bull*. 2015;40(12):1045–53.
 13. Krause W, Henning F, Tröster S, Geiger O, Eyerer P. LFT-D - A process technology for large scale production of fiber reinforced thermoplastic components. *Journal of Thermoplastic Composite Materials*. 2003;16(4):289–302.
 14. Gardie E, Paramasivam V, Dubale H, Tefera Chekol E, Selvaraj SK. Numerical analysis of reinforced carbon fiber composite material for lightweight automotive wheel application. *Mater Today Proc* [Internet]. 2021. Available from: <https://doi.org/10.1016/j.matpr.2020.12.1047>
 15. Park CK, Kan CD (Steve), Hollowell WT, Hill SI, George Washington University A, LLC WTHC, et al. Investigation of Opportunities for

Lightweight Vehicles Using Advanced Plastics and Composites. National Highway Traffic Safety Administration. 2012;(December):416p.

16. Demertzi M, Silvestre JD, Durão V. Life cycle assessment of the production of composite sandwich panels for structural floor's rehabilitation. Eng Struct [Internet]. 2020;221(July):111060. Available from: <https://doi.org/10.1016/j.engstruct.2020.111060>
17. Kelly JC, Sullivan JL, Burnham A, Elgowainy A. Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions. Environ Sci Technol. 2015;49(20):12535–42.
18. Das S. Life cycle assessment of carbon fiber-reinforced polymer composites. International Journal of Life Cycle Assessment. 2011;16(3):268–82.
19. Duflou JR, De Moor J, Verpoest I, Dewulf W. Environmental impact analysis of composite use in car manufacturing. CIRP Ann Manuf Technol. 2009;58(1):9–12.
20. Akhil A. B, Shaik Usman Shaa G, Dr. K. Senthil Kumar. Experimental and Numerical Analysis of Polymer Matrix Composite Material for using in Automobile Bumper. International Journal of Engineering Research and. 2016;V5(06):501–6.
21. Center for Automotive Research. Technology Roadmaps: Intelligent Mobility Technology, Materials and Manufacturing Processes, and Light Duty Vehicle Propulsion. The ASHA Leader. 2017;22(6):20–2.
22. Statista. Automotive material mixes of a typical vehicle in 2025 [Internet]. 2021. Available from: <https://www.statista.com/statistics/270252/material-use-in-car-production/> Accessed on 10 May 2021
23. Lyu MY, Choi TG. Research trends in polymer materials for use in lightweight vehicles. International Journal of Precision Engineering and Manufacturing. 2015;16(1):213–20.

24. Shan Y, Ou J, Wang D, Zeng Z, Zhang S, Guan D, et al. Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. *Nat Clim Chang* [Internet]. 2021;11(3):200–6. Available from: <http://dx.doi.org/10.1038/s41558-020-00977-5>
25. Wang Q, Wang S. Preventing carbon emission retaliatory rebound post-COVID-19 requires expanding free trade and improving energy efficiency. *Science of the Total Environment* [Internet]. 2020;746:141158. Available from: <https://doi.org/10.1016/j.scitotenv.2020.141158>
26. Tian X, An C, Chen Z, Tian Z. Assessing the impact of COVID-19 pandemic on urban transportation and air quality in Canada. *Science of the Total Environment* [Internet]. 2021;765:144270. Available from: <https://doi.org/10.1016/j.scitotenv.2020.144270>
27. Echegaray F. What POST-COVID-19 lifestyles may look like? Identifying scenarios and their implications for sustainability. *Sustain Prod Consum.* 2021;27:567–74.
28. St-Pierre L, Deshpande VS, Fleck NA. The low velocity impact response of sandwich beams with a corrugated core or a Y-frame core. *Int J Mech Sci* [Internet]. 2015;91:71–80. Available from: <http://dx.doi.org/10.1016/j.ijmecsci.2014.02.014>
29. Fernández A, Santangelo-Muro M, Fernández-Blázquez JP, Lopes CS, Molina-Aldareguia JM. Processing and properties of long recycled-carbon-fibre reinforced polypropylene. *Compos B Eng.* 2021;211(October 2020).
30. Teli RM, Lakshminarayana H V, Kaup V. Analysis and Design Optimization of Composite Floor Panel of Mass Transit. *International Journal of Engineering Research & Technology* [Internet]. 2014;3(7):874–82. Available from: <https://pdfs.semanticscholar.org/e767/21ec71f79d481bc2b6dcf9d4dbddb a6756e1.pdf>

31. Hagnell MK, Kumaraswamy S, Nyman T, Åkermo M. From aviation to automotive - a study on material selection and its implication on cost and weight efficient structural composite and sandwich designs. *Heliyon*. 2020;6(3).
32. Alphonse M, Bupesh Raja VK, Gopala Krishna V, Kiran RSU, Subbaiah BV, Chandra LVR. Mechanical behavior of sandwich structures with varying core material - A review. *Mater Today Proc*. 2021;44(2020):3751–9.
33. FINNISH FOREST INDUSTRIES FEDERATION. HANDBOOK OF FINNISH PLYWOOD [Internet]. 2002. Available from: <https://koskisen.fi/wp-content/uploads/materials/Handbook-of-Finnish-Plywood.pdf> Accessed on 26 May 2021
34. Richard O. Blade TM Panel Specification Comparison Chart [Internet]. Available from: <https://donbur.co.uk/news/panel-specification-comparison-chart> Accessed on 22 May 2021
35. Wambua P, Ivens J, Verpoest I. Natural fibres: Can they replace glass in fibre reinforced plastics? *Compos Sci Technol*. 2003;63(9):1259–64.
36. Mohanty AK, Misra M, Drzal LT. Sustainable Bio-Composites from Renewable Resources in Green Materials world. *J Polym Environ*. 2002;10(April):19–26.
37. Singh JK, Rout AK, Kumari K. A review on *Borassus flabellifer* lignocellulose fiber reinforced polymer composites. *Carbohydr Polym*. 2021;262(March).
38. Muneer Ahmed M, Dhakal HN, Zhang ZY, Barouni A, Zahari R. Enhancement of impact toughness and damage behaviour of natural fibre reinforced composites and their hybrids through novel improvement techniques: A critical review. *Compos Struct*. 2021;259(August 2020).

39. Pingulkar H, Mache A, Munde Y, Siva I. A comprehensive review on drop weight impact characteristics of bast natural fiber reinforced polymer composites. *Mater Today Proc.* 2021;44(2020):3872–80.
40. Shin KB, Lee JY, Cho SH. An experimental study of low-velocity impact responses of sandwich panels for Korean low floor bus. *Compos Struct.* 2008;84(3):228–40.
41. Awais H, Nawab Y, Amjad A, Anjang A, Md Akil H, Zainol Abidin MS. Environmental benign natural fibre reinforced thermoplastic composites: A review. *Composites Part C: Open Access.* 2021;4(August 2020).
42. Haag K, Padovani J, Fita S, Trouvé JP, Pineau C, Hawkins S, et al. Influence of flax fibre variety and year-to-year variability on composite properties. *Ind Crops Prod [Internet].* 2017;98(2017):1–9. Available from: <http://dx.doi.org/10.1016/j.indcrop.2016.12.028>
43. Charlet K, Baley C, Morvan C, Jernot JP, Gomina M, Bréard J. Characteristics of Hermès flax fibres as a function of their location in the stem and properties of the derived unidirectional composites. *Compos Part A Appl Sci Manuf.* 2007;38(8):1912–21.
44. Baley C, Morvan C, Grohens Y. Influence of the absorbed water on the tensile strength of flax fibers. *Macromol Symp.* 2005;222:195–202.
45. Tajvidi M, Najafi SK, Moteei N. Long-term water uptake behavior of natural fiber/polypropylene composites. *J Appl Polym Sci.* 2006;99(5):2199–203.
46. Overcash M, Twomey J, Asmatulu E, Vozzola E, Griffing E. Thermoset composite recycling – Driving forces, development, and evolution of new opportunities. *J Compos Mater.* 2018;52(8):1033–43.
47. Karuppannan Gopalraj S, Kärki T. A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: fibre recovery, properties and life-cycle analysis. *SN Appl Sci [Internet].* 2020;2(3):1–21. Available from: <https://doi.org/10.1007/s42452-020-2195-4>

48. He D, Soo VK, Kim HC, Doolan M. Life Cycle Primary Energy Demand and Greenhouse Gas Emission benefits of vehicle lightweighting with recycled carbon fibre. In: *Procedia CIRP*. 2021. p. 43–8.
49. Steenkamer DA, Sullivan JL. On the recyclability of a cyclic thermoplastic composite material. *Compos B Eng*. 1998;29(6):745–52.
50. Zhilyaev I, Brauner C, Queloz S, Jordi H, Lüscher R, Conti S, et al. Controlled curing of thermoset composite components using infrared radiation and mathematical modelling. *Compos Struct*. 2021;259(November 2020):1–12.
51. Gassan J, Bledzki AK. Thermal degradation of flax and jute fibers. *J Appl Polym Sci*. 2001;82(6):1417–22.
52. Bourmaud A, Le Duigou A, Gourier C, Baley C. Influence of processing temperature on mechanical performance of unidirectional polyamide 11-flax fibre composites. *Ind Crops Prod* [Internet]. 2016;84:151–65. Available from: <http://dx.doi.org/10.1016/j.indcrop.2016.02.007>
53. Li Q, Li Y, Ma H, Cai S, Huang X. Effect of processing temperature on the static and dynamic mechanical properties and failure mechanisms of flax fiber reinforced composites. *Composites Communications* [Internet]. 2020;20(February):100343. Available from: <https://doi.org/10.1016/j.coco.2020.04.009>
54. Van de Velde K, Baetens E. Thermal and Mechanical Properties of Flax Fibres as Potential Composite Reinforcement. *Macromol Mater Eng*. 2001;286(6):342–9.
55. Mizera C, Herak D, Hrabe P, Kabutey A. Effect of temperature and moisture content on tensile behaviour of false banana fibre (*Ensete ventricosum*). *Int Agrophys*. 2017;31(3):377–82.
56. Oksman K, Skrifvars M, Selin JF. Natural fibres as reinforcement in polylactic acid (PLA) composites. *Compos Sci Technol*. 2003;63(9):1317–24.

57. Stavrov D, Bersee HEN. Resistance welding of thermoplastic composites-an overview. *Compos Part A Appl Sci Manuf*. 2005;36(1):39–54.
58. Mei J, Ao Y, Jiang W, Liu J, Zhou Z, Huang W. Investigation on the shear behaviors of carbon fiber composite sandwich panels with the X-core. *Marine Structures*. 2021;77(November 2020).
59. Wong YC, Mahyuddin N, Aminuddin AMR. Development of thermal insulation sandwich panels containing end-of-life vehicle (ELV) headlamp and seat waste. *Waste Management*. 2020;118:402–15.
60. Qu J, Ju D, Gao S, Chen J. Research on the dynamic mechanical properties of polymethacrylimide foam sandwich structure. *Compos Struct* [Internet]. 2018;204(July):22–30. Available from: <https://doi.org/10.1016/j.compstruct.2018.07.078>
61. Vita A, Castorani V, Germani M, Marconi M. Comparative life cycle assessment of low-pressure RTM, compression RTM and high-pressure RTM manufacturing processes to produce CFRP car hoods. *Procedia CIRP* [Internet]. 2019;80(March):352–7. Available from: <https://doi.org/10.1016/j.procir.2019.01.109>
62. Miller B. Resin transfer molding. *Plastics world*. 1990;48(6):60–4.
63. Leclerc JS, Ruiz E. Porosity reduction using optimized flow velocity in Resin Transfer Molding. *Compos Part A Appl Sci Manuf* [Internet]. 2008;39(12):1859–68. Available from: <http://dx.doi.org/10.1016/j.compositesa.2008.09.008>
64. Rondina F, Taddia S, Mazzocchetti L, Donati L, Minak G, Rosenberg P, et al. Development of full carbon wheels for sport cars with high-volume technology. *Compos Struct* [Internet]. 2018;192(February):368–78. Available from: <https://doi.org/10.1016/j.compstruct.2018.02.083>
65. Walbran WA, Verleye B, Bickerton S, Kelly PA. Prediction and experimental verification of normal stress distributions on mould tools during Liquid Composite Moulding. *Compos Part A Appl Sci Manuf*

- [Internet]. 2012;43(1):138–49. Available from: <http://dx.doi.org/10.1016/j.compositesa.2011.09.028>
66. Shojaei A. Numerical simulation of three-dimensional flow and analysis of filling process in compression resin transfer moulding. *Compos Part A Appl Sci Manuf*. 2006;37(9):1434–50.
 67. Jeon JH, Yoon CK, Park SH, Lee W Il, Kim SM. Assessment of Long Fiber Spray-up Molding of Chopped Glass Fiber Reinforced Polydicyclopentadiene Composites. *Fibers and Polymers*. 2020;21(5):1134–41.
 68. Halley PJ. Rheology of thermosets: the use of chemorheology to characterise and model thermoset flow behaviour. *Thermosets*. 2012;92–117.
 69. Kazemi ME, Shanmugam L, Lu D, Wang X, Wang B, Yang J. Mechanical properties and failure modes of hybrid fiber reinforced polymer composites with a novel liquid thermoplastic resin, Elium®. *Compos Part A Appl Sci Manuf*. 2019;125(May).
 70. Dong C. An equivalent medium method for the vacuum assisted resin transfer molding process simulation. *J Compos Mater*. 2006;40(13):1193–213.
 71. Hindersmann A. Confusion about infusion: An overview of infusion processes. *Compos Part A Appl Sci Manuf* [Internet]. 2019;126(August):105583. Available from: <https://doi.org/10.1016/j.compositesa.2019.105583>
 72. Akif Yalcinkaya M, Sozer EM. Effect of part thickness variation on the mold filling time in vacuum infusion process. *Journal of Reinforced Plastics and Composites*. 2014;33(23):2136–50.
 73. Yenilmez B, Senan M, Murat Sozer E. Variation of part thickness and compaction pressure in vacuum infusion process. *Compos Sci Technol*

- [Internet]. 2009;69(11–12):1710–9. Available from: <http://dx.doi.org/10.1016/j.compscitech.2008.05.009>
74. Ning H, Pillay S, Thattai parthasarathy KB, Vaidya UK. Design and manufacturing of long fiber thermoplastic composite helmet insert. Compos Struct [Internet]. 2017;168:792–7. Available from: <http://dx.doi.org/10.1016/j.compstruct.2017.02.077>
 75. Park CH, Lee WI. Compression molding in polymer matrix composites [Internet]. Manufacturing Techniques for Polymer Matrix Composites (PMCs). Woodhead Publishing Limited; 2012. 47–94 p. Available from: <http://dx.doi.org/10.1533/9780857096258.1.47>
 76. Kurcz M, Baser B, Dittmar H, Sengbusch J, Pfister H. Replacing steel with glass-mat thermoplastic composites in automotive spare-wheel well applications. SAE Technical Papers. 2005;2005(724).
 77. Zhang G, Xiao Y, Yan J, Xie N, Liu R, Zhang Y. Ultraviolet light-degradation behavior and antibacterial activity of polypropylene/ZnO nanoparticles fibers. Polymers (Basel). 2019;11(11):16–8.
 78. Haque MMU, Goda K, Ito H, Ogoe S, Okamoto M, Ema T, et al. Melt-viscosity and mechanical behaviour of polypropylene (PP)/wood flour composites: Effect of pulverization of wood flour with and without water. Advanced Industrial and Engineering Polymer Research [Internet]. 2019;2(1):42–50. Available from: <https://doi.org/10.1016/j.aiepr.2018.11.001>
 79. Shangguan Y, Song Y, Peng M, Li B, Zheng Q. Formation of β -crystal from nonisothermal crystallization of compression-molded isotactic polypropylene melt. Eur Polym J. 2005;41(8):1766–71.
 80. Da Costa HM, Ramos VD, Rocha MCG. Rheological properties of polypropylene during multiple extrusion. Polym Test. 2005;24(1):86–93.

81. Esmizadeh E, Tzoganakis C, Mekonnen TH. Degradation behavior of polypropylene during reprocessing and its biocomposites: Thermal and oxidative degradation kinetics. *Polymers (Basel)*. 2020;12(8).
82. Bledzki AK, Letman M, Viksne A, Rence L. A comparison of compounding processes and wood type for wood fibre - PP composites. *Compos Part A Appl Sci Manuf*. 2005;36(6):789–97.
83. Yang HS, Wolcott MP, Kim HS, Kim S, Kim HJ. Properties of lignocellulosic material filled polypropylene bio-composites made with different manufacturing processes. *Polym Test*. 2006;25(5):668–76.
84. Bartus SD, Vaidya UK, Ulven CA. Design and development of a long fiber thermoplastic bus seat. *Journal of Thermoplastic Composite Materials*. 2006;19(2):131–54.
85. Caltagirone PE, Ginder RS, Ozcan S, Li K, Gay AM, Stonecash J, et al. Substitution of virgin carbon fiber with low-cost recycled fiber in automotive grade injection molding polyamide 66 for equivalent composite mechanical performance with improved sustainability. *Compos B Eng [Internet]*. 2021;221(September 2020):109007. Available from: <https://doi.org/10.1016/j.compositesb.2021.109007>
86. Balaji Thattai parthasarathy K, Pillay S, Ning H, Vaidya UK. Process simulation, design and manufacturing of a long fiber thermoplastic composite for mass transit application. *Compos Part A Appl Sci Manuf*. 2008;39(9):1512–21.
87. Hartness T, Husman G, Koenig J, Dyksterhouse J. The characterization of low cost fiber reinforced thermoplastic composites produced by the DRIFT™ process. *Compos Part A Appl Sci Manuf*. 2001;32(8):1155–60.
88. Ku SM, Reddy GS, Surappa S. Characterization and Fabrication of Pultruded Structural Products of Composites. 2016;6(8):2284–9.

89. Fairuz AM, Sapuan SM, Zainudin ES, Jaafar CNA. Polymer composite manufacturing using a pultrusion process: A review. *Am J Appl Sci*. 2014;11(10):1798–810.
90. Gamstedt EK, Berglund LA, Peijs T. Fatigue mechanisms in unidirectional glass-fibre-reinforced polypropylene. *Compos Sci Technol*. 1999;59(5):759–68.
91. Henninger F, Hoffmann J, Friedrich K. Thermoplastic filament winding with online-impregnation. Part B. Experimental study of processing parameters. *Compos Part A Appl Sci Manuf*. 2002;33(12):1684–95.
92. Van West BP, Pipes RB, Advani SG. The consolidation of commingled thermoplastic fabrics. *Polym Compos*. 1991;12(6):417–27.
93. Engineering M. Film Stacking Fiber Woven Commingled Fibers i ~ Reinforcing Fibers Powder / Sheath-Fibre Bundles Pre-Impregnated Tape olymer Sheath. 2006;48(1995):317–24.
94. Wakeman MD, Cain TA, Rudd CD, Brooks R, Long AC. Compression moulding of glass and polypropylene composites for optimised macro- and micro-mechanical properties II. Glass-mat-reinforced thermoplastics. *Compos Sci Technol*. 1999;59(5):709–26.
95. Karaduman Y, Onal L. Flexural behavior of commingled jute/polypropylene nonwoven fabric reinforced sandwich composites. *Compos B Eng [Internet]*. 2016;93:12–25. Available from: <http://dx.doi.org/10.1016/j.compositesb.2016.02.055>
96. Hou M, Yee L, Mai YW. Manufacturing process and mechanical properties of thermoplastic composite components. *J Mater Process Technol*. 1997;63(1–3):334–8.
97. Grünewald J, Parlevliet P, Altstädt V. Manufacturing of thermoplastic composite sandwich structures: A review of literature. *Journal of Thermoplastic Composite Materials*. 2017;30(4):437–64.

98. Yousefpour A, Hojjati M, Immarigeon JP. Fusion bonding/welding of thermoplastic composites. *Journal of Thermoplastic Composite Materials*. 2004;17(4):303–41.
99. Wang J, Mao Q. Methodology Based on the PVT Behavior of Polymer for Injection Molding. *Advances in Polymer Technology*. 2012;32(2013):474–85.
100. J.W.Martin. *Materials for Engineering* [Internet]. 3rd ed. Woodhead Publishing Limited; 2006. 200–210 p. Available from: <https://doi.org/10.1533/9781845691608.2.185>
101. Tabatabaiefar HR, Mansoury B, Khadivi Zand MJ, Potter D. Mechanical properties of sandwich panels constructed from polystyrene/cement mixed cores and thin cement sheet facings. *Journal of Sandwich Structures and Materials*. 2017;19(4):456–81.
102. Harizi W, Anjoul J, Acosta Santamaría VA, Aboura Z, Briand V. Mechanical behavior of carbon-reinforced thermoplastic sandwich composites with several core types during three-point bending tests. *Compos Struct* [Internet]. 2021;262(October 2020):113590. Available from: <https://doi.org/10.1016/j.compstruct.2021.113590>
103. Lu T, Chen X, Wang H, Zhang L, Zhou Y. A novel experiment-based approach on nonlinear bending analysis of thermoplastic composite laminates. *Compos B Eng* [Internet]. 2021;209(November 2020):108611. Available from: <https://doi.org/10.1016/j.compositesb.2021.108611>
104. Liu H, Liu J, Ding Y, Zhou J, Kong X, Harper LT, et al. Modelling damage in fibre-reinforced thermoplastic composite laminates subjected to three-point bend loading. *Compos Struct* [Internet]. 2020;236(January):111889. Available from: <https://doi.org/10.1016/j.compstruct.2020.111889>
105. States U. Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear. *Annual Book of ASTM Standards*. 2019;08(2008):1–16.

106. States U. Standard Test Method for Facing Properties of Sandwich Constructions by Long. Annual Book of ASTM Standards. 2011;i(C):1–9.
107. States U. Standard Practice for Determining Sandwich Beam Flexural and Shear Stiffness. Annual Book of ASTM Standards. 2010;i:1–8.
108. Mujika F. On the difference between flexural moduli obtained by three-point and four-point bending tests. Polym Test. 2006;25(2):214–20.
109. Vieille B, Casado VM, Bouvet C. About the impact behavior of woven-ply carbon fiber-reinforced thermoplastic- and thermosetting-composites: A comparative study. Compos Struct [Internet]. 2013;101:9–21. Available from: <http://dx.doi.org/10.1016/j.compstruct.2013.01.025>
110. Arikan V, Sayman O. Comparative study on repeated impact response of E-glass fiber reinforced polypropylene & epoxy matrix composites. Compos B Eng [Internet]. 2015;83:1–6. Available from: <http://dx.doi.org/10.1016/j.compositesb.2015.08.051>
111. Akil Hazizan M, Cantwell WJ. The low velocity impact response of foam-based sandwich structures. Composites Part B:Engineering. 2002;33(3):193–204.
112. Williams GJ, Bond IP, Trask RS. Compression after impact assessment of self-healing CFRP. Compos Part A Appl Sci Manuf [Internet]. 2009;40(9):1399–406. Available from: <http://dx.doi.org/10.1016/j.compositesa.2008.05.021>
113. Feraboli P, Kedward KT. Enhanced evaluation of the low-velocity impact response of composite plates. AIAA Journal. 2004;42(10):2143–52.
114. Albahash ZF, Ansari MNM. Investigation on energy absorption of natural and hybrid fiber under axial static crushing. Compos Sci Technol [Internet]. 2017;151:52–61. Available from: <https://doi.org/10.1016/j.compscitech.2017.07.028>

115. Murphy DB, Davidson MW. FUNDAMENTALS OF LIGHT MICROSCOPY. 2nd ed. Fundamentals of Light Microscopy and Electronic Imaging: Second Edition. 2012. 5–28 p.
116. Hayes BS, Gammon LM. Void Analysis of Composite Materials. Optical Microscopy of Fiber-Reinforced Composites. ASM International; 2010. 137–155 p.
117. Wu Q, Li M, Gu Y, Wang S, Zhang Z. Imaging the interphase of carbon fiber composites using transmission electron microscopy: Preparations by focused ion beam, ion beam etching, and ultramicrotomy. Chinese Journal of Aeronautics [Internet]. 2015;28(5):1529–38. Available from: <http://dx.doi.org/10.1016/j.cja.2015.05.005>
118. Paciornik S, dAlmeida J. Digital microscopy and image analysis applied to composite materials characterization. Revista Materia. 2010;15(2):183–91.
119. Otheguy ME, Gibson AG, Findon E, Cripps RM, Ochoa Mendoza A, Aguinaco Castro MT. Recycling of end-of-life thermoplastic composite boats. Plastics, Rubber and Composites. 2009;38(9–10):406–11.
120. Henshaw JM, Owens AD, Houston DQ, Smith IT, Cook T. Recycling of a Cyclic Thermoplastic Composite Material by Injection and Compression Molding. Journal of Thermoplastic Composite Materials. 1994;7(1):14–29.
121. Finch, Sue; Thomason, Neil; Cumming G. Recycling Carbon-Fiber-Reinforced Thermoplastic Composites. Journal of Thermoplastic Composite Materials. 1996;9:239–45.
122. Vincent GA, de Bruijn TA, Wijskamp S, Abdul Rasheed MI, van Drongelen M, Akkerman R. Shredding and sieving thermoplastic composite scrap: Method development and analyses of the fibre length distributions. Compos B Eng [Internet]. 2019;176(June):107197. Available from: <https://doi.org/10.1016/j.compositesb.2019.107197>

123. Pakdel E, Kashi S, Varley R, Wang X. Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes. *Resour Conserv Recycl* [Internet]. 2021;166(November 2020):105340. Available from: <https://doi.org/10.1016/j.resconrec.2020.105340>
124. Liu Y, Liu J, Jiang Z, Tang T. Chemical recycling of carbon fibre reinforced epoxy resin composites in subcritical water: Synergistic effect of phenol and KOH on the decomposition efficiency. *Polym Degrad Stab* [Internet]. 2012;97(3):214–20. Available from: <http://dx.doi.org/10.1016/j.polymdegradstab.2011.12.028>
125. Palmer J, Ghita OR, Savage L, Evans KE. Successful closed-loop recycling of thermoset composites. *Compos Part A Appl Sci Manuf* [Internet]. 2009;40(4):490–8. Available from: <http://dx.doi.org/10.1016/j.compositesa.2009.02.002>
126. Iwaya T, Tokuno S, Sasaki M, Goto M, Shibata K. Recycling of fiber reinforced plastics using depolymerization by solvothermal reaction with catalyst. *J Mater Sci*. 2008;43(7):2452–6.
127. Pickering SJ. Recycling technologies for thermoset composite materials-current status. *Compos Part A Appl Sci Manuf*. 2006;37(8):1206–15.
128. Xu P, Li J, Ding J. Chemical recycling of carbon fibre/epoxy composites in a mixed solution of peroxide hydrogen and N,N-dimethylformamide. *Compos Sci Technol* [Internet]. 2013;82:54–9. Available from: <http://dx.doi.org/10.1016/j.compscitech.2013.04.002>
129. Park JM, Kwon DJ, Wang ZJ, Gu GY, Devries KL. Effect of thermal treatment temperatures on the reinforcing and interfacial properties of recycled carbon fiber-phenolic composites. *Compos Part A Appl Sci Manuf* [Internet]. 2013;47(1):156–64. Available from: <http://dx.doi.org/10.1016/j.compositesa.2012.12.002>

130. Abdou TR, Botelho Junior AB, Espinosa DCR, Tenório JAS. Recycling of polymeric composites from industrial waste by pyrolysis: Deep evaluation for carbon fibers reuse. *Waste Management*. 2021;120:1–9.
131. Vincent GA, de Bruijn TA, Wijskamp S, van Drongelen M, Akkerman R. Process- and material-induced heterogeneities in recycled thermoplastic composites. *Journal of Thermoplastic Composite Materials*. 2020;1–22.
132. Cousins DS, Suzuki Y, Murray RE, Samaniuk JR, Stebner AP. Recycling glass fiber thermoplastic composites from wind turbine blades. *J Clean Prod* [Internet]. 2019;209:1252–63. Available from: <https://doi.org/10.1016/j.jclepro.2018.10.286>
133. Shi J, Bao L, Kobayashi R, Kato J, Kemmochi K. Reusing recycled fibers in high-value fiber-reinforced polymer composites: Improving bending strength by surface cleaning. *Compos Sci Technol* [Internet]. 2012;72(11):1298–303. Available from: <http://dx.doi.org/10.1016/j.compscitech.2012.05.003>
134. Wong KH, Syed Mohammed D, Pickering SJ, Brooks R. Effect of coupling agents on reinforcing potential of recycled carbon fibre for polypropylene composite. *Compos Sci Technol* [Internet]. 2012;72(7):835–44. Available from: <http://dx.doi.org/10.1016/j.compscitech.2012.02.013>
135. Giorgini L, Benelli T, Brancolini G, Mazzocchetti L. Recycling of carbon fiber reinforced composite waste to close their life cycle in a cradle-to-cradle approach. *Curr Opin Green Sustain Chem* [Internet]. 2020;26:100368. Available from: <https://doi.org/10.1016/j.cogsc.2020.100368>
136. Aurrekoetxea J, Sarrionandia MA, Urrutibeascoa I, Maspoch ML. Effects of recycling on the microstructure and the mechanical properties of isotactic polypropylene. *J Mater Sci*. 2001;36(11):2607–13.

137. Meran C, Ozturk O, Yuksel M. Examination of the possibility of recycling and utilizing recycled polyethylene and polypropylene. Mater Des. 2008;29(3):701–5.
138. Jansson A, Möller K, Gevert T. Degradation of post-consumer polypropylene materials exposed to simulated recycling - Mechanical properties. Polym Degrad Stab. 2003;82(1):37–46.
139. Broekel J, Scharr G. The specialities of fibre-reinforced plastics in terms of product lifecycle management. J Mater Process Technol. 2005;162–163(SPEC. ISS.):725–9.
140. ToolBox E. Area Moment of Inertia - Typical Cross Sections I [Internet]. 2008. Available from: https://www.engineeringtoolbox.com/area-moment-inertia-d_1328.html Accessed on 26 Sep 2021
141. Cambridge University Engineering Department. Structures Data Book. 2018. Available from: <http://teaching.eng.cam.ac.uk/sites/teaching.eng.cam.ac.uk/files/Documents/Databooks/Structures%202018.pdf> Accessed on 28 Sep 2021

