

CRANFIELD UNIVERSITY

Manmohit Singh Pahwa

Sustainable/Recyclable Composites for Heavy-Duty Vehicle
Floorings

School of Aerospace, Transport and Manufacturing
Manufacturing

M.Sc. By Research
Academic Year: 2019 - 2020

Supervisor: Dr.Sameer Rahatekar
Associate Supervisor: Andrew Mills
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ABSTRACT

Composites are being increasingly used in the automotive industry to fabricate primary and secondary structural components such as tie rods, bumpers and door panels. To comply with the environmental regulations, the automotive sector is adopting sustainable composite materials and manufacturing techniques such as thermoplastic compression moulding. The switch from thermoset to thermoplastic composites to manufacture recyclable components that do not compromise performance is an exemplar.

As a part of this M.Sc by Research project, a critical review of components used in buses and trucks is undertaken to find a suitable component to be replaced with sustainable materials. Components like leaf springs and trailer floorings are studied to understand how significant weight reduction can be achieved using alternative materials. Recyclable and low-cost materials such as polypropylene-based composites are considered for weight reduction and improved sustainability/recyclability.

The replacement of hardwood flooring in heavy-duty vehicles with relatively lighter thermoset sandwich panels is observed in the literature as an attempt to reduce weight. However, a research gap is observed in addressing the recyclability of thermoset panels which form cross-links upon curing. This thesis aims to bridge this gap by providing a lightweight alternative to wooden bus floorings while considering its cost and recyclability. Polypropylene and glass fibre-based thermoplastic sandwich panels are developed and reviewed as an alternative. These panels are manufactured using polypropylene glass fibre skins, polypropylene honeycomb and co-bonded using a thermoplastic-based hotmelt glue.

The manufactured panels are found to be 1.4 kg/m^2 lighter than commercially available birch wood. This decrease in density equates to 51 kg of weight savings when used as a floor in a coach and potential 157 kg weight savings if the panels are used to replace the side panels. Replacing wooden floor panels with thermoplastic alternatives translates to about 1225 litres of lifetime fuel savings and a reduction of 3.4 tonnes in CO₂ emissions for a city bus with more halts.

A three-point bend test is carried out to evaluate the structural performance of the fabricated sandwich panels. The bending test reveals that the manufactured thermoplastic panels show 22 MPa of bending strength. In contrast, the wooden and thermoset counterparts show a bending strength of 34 MPa and 20 MPa, respectively. Low-velocity impact tests are conducted to simulate scenarios like tool drops or hail and debris hitting the floorings. This test at 6 J of impact energy reveals significantly less residual damage when compared to thermoset counterparts.

Keywords: Polypropylene, Glass fibre, honeycomb, sandwich composites, thermoplastic, Bus/Coach floor panels, Trailer & Truck flooring

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LIST OF ABBREVIATIONS

HDV	Heavy-Duty Vehicles
CMV	Commercial Vehicles
PEEK	Poly Ether Ether Ketone
SUV	Sports Utility Vehicle
PP	Poly Propylene
PE	Poly Ethylene
FRP	Fibre Reinforced Plastic
GFRP	Glass Fibre Reinforced Plastic
GVW	Gross Vehicle Weight
BEBs	Battery electric Buses
OD	Outer Diameter
ID	Inner Diameter
BEVs	Battery Electric Vehicles

Introduction and scope of the thesis

Road transport is the most significant way to transport goods in the United Kingdom [4]. The percentage share of HGVs, Vans and Buses towards CO₂ is 16%,15% and 3%, respectively [6]. A significant percentage of emissions makes these vehicles a suitable target for weight reduction since they are used commercially. Introducing sustainability to these vehicles can bring significant changes which can be better for the environment.

Therefore, replacing conventional components such as those made of thermoset plastics with sustainable/recyclable thermoplastic alternatives can significantly impact the environment. Many directives, such as the EU end of life vehicle directive, are being brought in to aid recyclability in vehicles [5].

Implementing such regulations has led to increased use of alternative materials as the manufacturers need to comply with the legislation. Composites, particularly those with recyclable matrices (i.e. thermoplastics), often fit the recyclability/sustainability criterion.

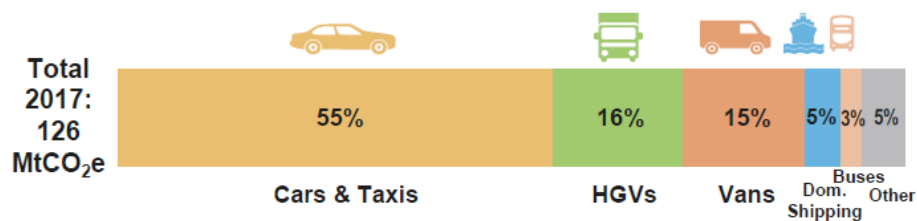


Figure 1: CO₂ emissions by vehicle category [6]

Amongst various classes of trucks, the most fuel needs in the automobile sector are attributed to Class 8 trucks (Trucks with GVW of more than 33000 Tonnes). That fuel is the most significant expense for the owners of these commercial vehicles. As lower delivery costs are the main objective of these businesses, they aim to reduce their single most considerable spending. Besides, 30%-50% of these trucks operate at a maximum allowable limit [9]. Further, since the production rate is not very high, composites' production, which usually has a relatively higher lead time per part, becomes a viable option.



Figure 2: Cross-sectional view of a Bus Chassis and Outer Body

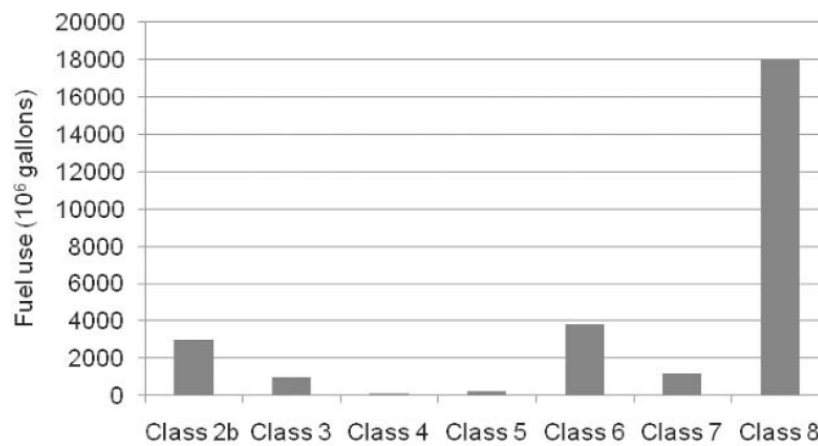


Figure 3: Fuel Use in Trucks by Class [9]

The impact of weight-savings primarily depends on vehicle selection. Among various heavy-duty vehicles [HDVs], city buses certainly make a marketable case, and a saving of around 15-20% is observed in the fuel costs if they are made 20% lighter. It was also established that manufacturers are ready to pay approximately 10£/kg of weight saved [7].

1425.5 litres of fuel and 3.8 tonnes of CO₂ emissions are saved per 100 kg of weight reduction [7]. The fuel savings were averaged across different kinds of city and long-distance buses presented in the literature.

The UK has a bus fleet of **52,200 public** buses [8]. Component change for a large fleet is potentially much more impactful as this enables a significant environmental impact if a viable alternative is presented.

Amongst the various components studied through the literature review, flooring panels present a significant potential for light-weighting (Table 3). Further, being a secondary structural component, they do not require significant structural changes to the vehicle's chassis. Birchwood and Keruing (types of plywood) have been the conventional materials for floorings [1]. There have been attempts to lightweight the floor panels since as early as the 2000s in which glass fibre reinforced wooden floorings were used, and 108 kg of weight was saved [2].

Further, the manufacture of thermoset sandwich made of glass fibre reinforced plastics and balsa wood enables weight-savings of 165 kg [3]. However, the panels are not cost-effective.

While all these panels significantly contribute to weight-savings, thermoset plastics are not recyclable due to cross-linking. Further, the use of balsa wood in some of these constructions does not eradicate the limitations observed in plywood panels, such as moisture absorption and weight/dimensional changes.

If all 52,200 buses are assumed to be using wooden floorings and are to be replaced by an alternative which saves 50 kg of weight, 99180 tonnes of CO₂ emission can be reduced (based on average fuel savings across various types of buses observed in Table 2).

Thus, the primary question is: can a lightweight, cost-effective and recyclable alternative be developed for flooring panels in HDVs? The thesis aims to provide a solution through glass/polypropylene sandwich panels. Sandwich panels that can be remelted (for recycling) are fabricated using polypropylene as a resin for glass fibre reinforced skins. Similarly, thermoplastic-based hotmelt glue is used for the co-bonding of skins to the PP honeycomb core.

The characterisation and mechanical testing of fabricated sandwich panels are undertaken through three-point bending and low-velocity impact tests. These

tests help draw comparisons with conventional wooden flooring panels and thermoset panels presented in the literature.

1 Component identification and manufacturing study

1.1 Weight distribution study

The research aims to sustainably maximise weight-savings in heavy-duty or mass transit vehicles while keeping the manufacturing feasibility in focus. Vehicles with any powertrain will benefit from a reduction of vehicle weight with context to the mileage. The primary focus of the thesis generally remains on the parts which can be replaced with composites.

To study weight-savings and understand the weight distribution among various components, a pie chart was constructed for a Rigid Truck (12T GVW) [7].



Figure 4: MAN 12T GVW [10]

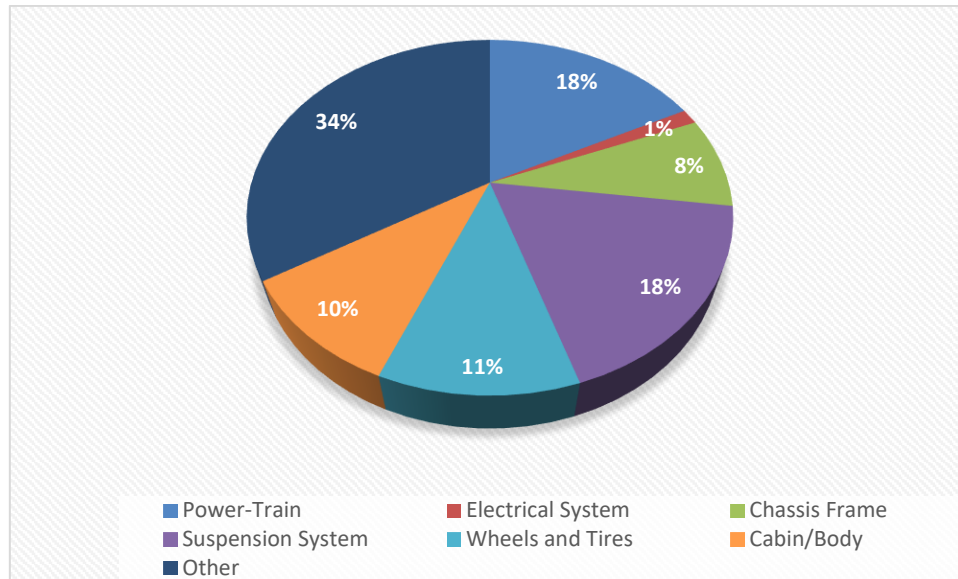


Figure 5: Weight Distribution according to subsystems in a 12-tonne gross vehicle weight truck [7]

The distribution shown in the above chart has similar trends across all kinds of HDVs, where the powertrain is one of the most massive components. The chart reflects the weight distribution for only a conventional diesel version.

Further, a table of parts potentially replaceable with composites on which further study will be conducted is presented below.

No.	Subsystem	Replaceable Parts
1	Engine	- Engine cover - Oil sump
2	Fuel	Fuel tank
3	Transmission	
4	Chassis	- Monocoque - Chassis frame design
5	Suspension	- Four-point link - Tie rods - Front independent suspensions - Leaf springs
6	Wheels	Wheel rims
7	Cab-in-White and closures	- Sidewalls - Roof - Floors

		• Hood • Door and trim systems
8	Miscellaneous	• Bumper beams • Mirror casing
9	Seats	• Driver's seat • Passenger's seat
10	Flooring	• Sandwich floorings
11	Air conditioning	• Air conditioner casing

Table 1: Composite replaceable components based on HDV subsystems

There are many components from commercial vehicles which have a lightweighting potential. The primary targets are the ones that have the possibility of being replaced by composites. However, the viability of these replacements varies from case to case, and industrial processes cannot be expected to change radically. Tooling change should be avoided as it takes a lot of time for companies to manufacture components to break even their production cost.

1.2 Conventional component construction



Figure 6: Conventional Sheet Metal construction of a bus [11]

The reported methods for manufacturing components are:

1. Sheet metal and wood construction, which relies on conventional metal forming processes.
2. Non-sheet metal construction.

There are specific issues with the wooden and steel assembly, including corrosion and opting for this kind of construction, which make the assembly heavy. These issues reduce the mileage of the powertrain. Also, the noise and vibrations caused by the metal are significantly higher than some of the composite materials. Chassis, suspension, drivetrain and the wheels constitute 40 per cent of the vehicle weight.

1.2.1 Cab-in-white and trailer body

Cab-in-white is the cabin in which the driver and a co-driver seat. A study was conducted for the cab-in-white of a heavy domestic truck, where the author

compared the Chinese version with a counterpart abroad and has concluded that the design optimisation alone can save 46 kg of weight of the product [12].

In order to understand the design and manufacturing of the truck, the cabin can be further divided into numerous subcomponents:

1. Hood Liner
2. Cab floor
3. Cab doors
4. Engine tunnel



Figure 7: Cab-in-white for a Mercedes-Benz Actros 2545 [13]

The trailer body has the following significant components that can be replaced :

1. **Wall Panels**
2. **Scruff Liners**
3. **Ceilings**
4. **Inner Floorings**

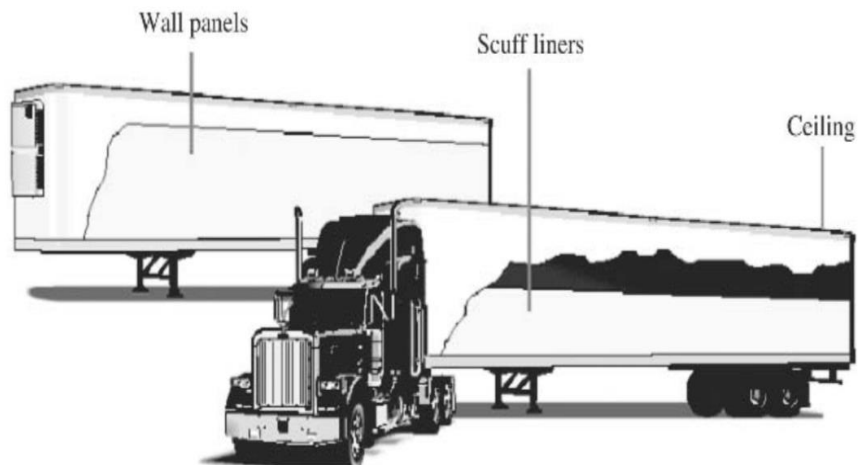


Figure 8: Components of a trailer that can be lightweight [1]

1.2.2 Suspension system (leaf springs)

Low-floor buses are an adequate chassis system for electric buses. However, compact suspensions are vital for a low-floor chassis. Leaf springs are an excellent alternative to the coil spring and damper version of the suspension. Lightweighting in the case of suspension components not only benefits the environment and saves the fuel cost, but it also leads to a direct reduction in unsprung mass. This further leads to an improvement in vehicle dynamics which increases passenger comfort.

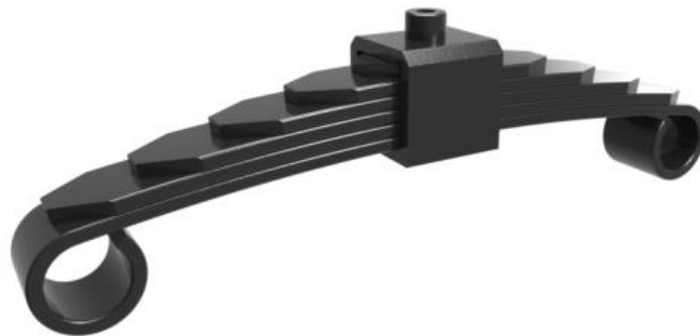


Figure 9: Representative model of a steel leaf spring [14]

Leaf springs generally comprise individual metal plates that reduce in length, as there is a gradual increase in the spring thickness. The coil springs require relatively more space as they require a residual compressive force to avoid solid

height accumulation when the vehicle is jounced, consequently limiting suspension travel.

1.2.3 Suspension system (tie rods)

The suspension contributes a significant amount of weight to a heavy-duty vehicle, as displayed in Table 1, and, therefore, there are specific components that have the latitude for lightweighting to reduce the unsprung mass significantly affecting a vehicle's performance. Steel tie rods, for example, are a convention in heavy-duty vehicles.

A metallic tie rod is made using steel tubes with typically 0.25 inches wall thickness and an outer diameter (OD) of 1.5 or 1.75 inches [15]. This size makes it easier for a standard-sized thread to be tapped into the ends to fit the ball joints. While reducing the weight is essential, if the tensile modulus of the material is less than steel, it will warrant the use of a larger diameter, which may not be possible due to the vehicle's suspension geometry.

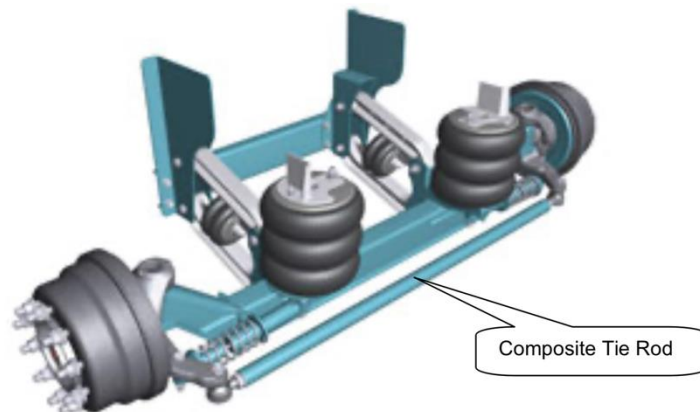


Figure 10: Composite tie rod in “Composite” steerable lift axle application [9]

1.5.4 Bumpers

The bumper market has already seen an influx of composites and thermoplastics, but around 50 per cent of the trucks still use sheet metal. However, since the component is primarily subjected to just wind loads, fibre reinforcement might not be necessary. The critical criterion to look for in a bumper design is the deflection

of 0.5 inches for 50 lb forward force and a deflection of less than 0.5' for a 300 lb downward force.

While thermoplastic polyolefins offer a recyclable solution, options like ABS are not strictly sustainable. Many aftermarket GRP options are available since the part is easily replaceable and, therefore, can be a good option for people who find it affordable [9].



Figure 11: Sheet metal bumpers used in heavy vehicles such as trucks [9]

Door and trim system

A conventional door and trim system in a bus or truck has many components, namely:

1. Trim Module
2. Grab Handle
3. Hardware Module



Figure 12: Major components of a truck door [16]

Some general requirements for the component are a service life of 1.2 miles and 15 years of life. Primarily, there is an excellent potential for improvement, such as lightweighting the door made of steel. A secondary limitation is that a metal door requires various fasteners. A typical freight liner uses 34 fasteners which raises the assembly and labour costs [16]. Dies are required to build such complex components, leading to high tooling cost, which can be a problem for lower production companies.

Further, the compliance in an element with numerous fasteners is high; therefore, rattling and squeaking can occur, which is unappealing to the end-user. Metals have relatively worse NVH characteristics than their plastic or composite counterparts. With the part using numerous items, there is a greater risk of wear and tear, which may lead to surface coating erosions and subsequently expose the component to corrosion.

1.2.5 Bus seat

There are several seats on a bus, which present a huge opportunity for achieving weight loss. The current manufacturing technology mostly uses the parts described in Figure 13 below. As one might notice, these parts contain various components which require assembly and labour cost.

The manufacturing of these components itself is a tedious task, and one can estimate the high lead times involved in cutting various parts of the frame, the

injection moulding of the plastic and the number of bolts required to bring the assembly together [17].

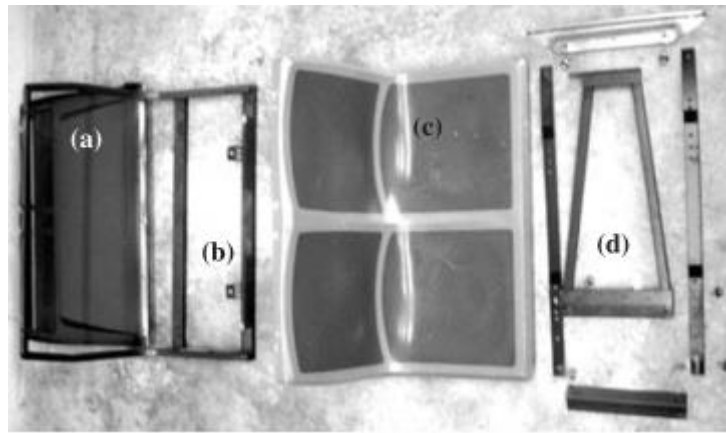


Figure 13: Current seat components: (a) seatback; (b) steel support frame; (c) SMC seat [17]

1.3 Chapter summary:

In summary, the chapter has examined the following areas as a part of the literature review.

Weight distribution in heavy-duty vehicles: The study also explains the weight distribution of a 12 tonne GVW truck and tabulates components according to the subsystems.

Conventional component construction in heavy-duty vehicles: Metals, plastics and wood are acknowledged as the conventionally used materials. Further case studies of parts like bus seats, bumpers and tie rods etc., are used to illustrate conventional metal construction and limitations like corrosion. These case studies help to put in context the impact of lightweighting when using alternative materials such as glass, carbon and natural fibre-based composites which are explained in the next chapter.

2 Composite material-based alternatives for conventional automotive components (Literature analysis and review)

2.1 Body in white

As shown in Figure 14, the cabin body takes around 10% for the given HDV. Thus, saving weight on the entire trailer cabin can substantially increase payload capacity and improve mileage if the payload is constant.

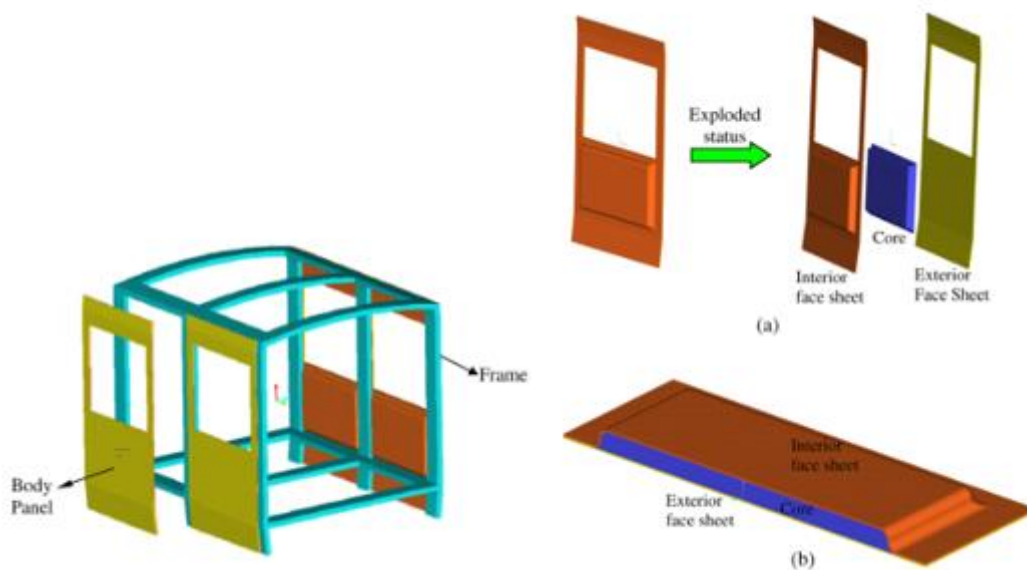


Figure 14: Bus body panels and their configuration [18]

Composite body panels (Glass/PP/polyurethane) weigh 55 per cent less than their metal counterparts made of aluminium face sheets with steel bars [18]. The former weighs around 13.1 kg, and the latter 29.3 kg. This can be translated to 256kg weight-savings if 16 such panels are used. The panels meet the safety requirements specified by the APTA (American Public Transportation Association), which states that the panels should deflect less than 20mm at 2.76 MPa.

2.2 Bus floorings

Plywood panels have been the convention when it comes to trailer decking [1]. While this can be attributed to availability, maintenance and installation, it has numerous drawbacks. Plywood often has a relatively higher density compared to a composite sandwich alternative.

Sandwich structures are often used to replace these panels as they are lightweight and instrumental in resisting bending load. A sandwich structure in composites mainly consists of face layers on each side with a core in the middle. The use of a lightweight core helps in incrementing the moment of inertia as the distance between two layers increases.

Sandwich composites (Glass, PP with balsa wood) can end up saving 30 per cent of the weight, i.e. 165 kg, compared to conventional plywood [1]. The panels also show improved flexural strength and a comparable flexural stiffness to the birch plywood.

The thesis argues that the industry is ready to pay up to twice the cost for 30% of weight-savings and the suggested alternative thermoset panels satisfy the same.

However, the suggested alternative has limitations because the balsa wood core has the same restrictions as plywood in moisture absorption. Also, indications of balsa wood having a relatively unstable supply chain can be a problem if the decking goes to mass production as it risks becoming the bottleneck.

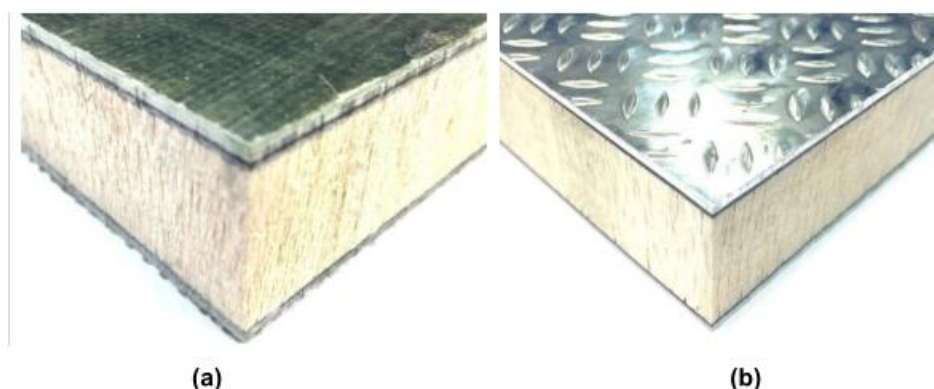


Figure 15: Balsa wood core with grp and aluminium skins, respectively [1]

Although sandwich panels with PP foam cores are economical, they are considered less optimal as they have a relatively higher density than balsa wood cores. This problem can be rectified by introducing honeycombs with a relatively lower density, higher production rate and a more stable supply chain than balsa wood. Honeycombs can also be used in geometries like the curved body panel for buses more easily than balsa wood.

Honeycombs are known for their compressive strength per unit weight and act as an excellent separator for sandwich structures. There are different types of honeycomb structures available, ranging from Aluminium and Nomex to thermoplastic polymers such as PP and PET.

The selection of honeycomb materials is based on the application, loading and binding affinity to the face sheets. Some thermoplastic honeycombs are relatively inexpensive and provide a recyclable, lightweight and stiffer option.

2.3 The suspension (Leaf springs)

Composites have better properties than the individual fibres and resin systems used to make the parts. Glass fibres often make a better alternative due to their high elongation level compared to the relatively brittle carbon fibre [19].

Unidirectional glass fibres often provide the performance adequate to the loads being put onto the suspension. The better directional properties of composites have often been one of the primary reasons they offer lightweighting opportunities. Volvo's XC-90 uses rear transverse GFRP springs for the suspensions; and as the leaf spring suspensions attach to both the wheels, they also act as a body roll reducing agent in these cars.

The process which Volvo used is known as Resin transfer moulding [19], which is appropriate as the process RTM offers rapid processing and customisability.

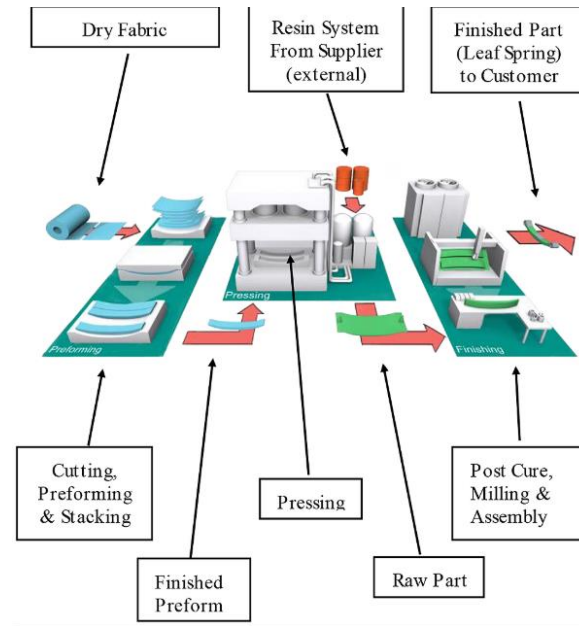


Figure 16: Resin Transfer moulding for production of leaf springs [19]

Volvo manufactured around 100,000 springs a year for its “Scalable Product Architecture” programme through the process. GFRP spring can lead to a weight reduction of approximately 15 per cent. FEA is further used for an in-depth analysis of these springs. Also, prepreg pressing might be optimum if the number of parts is less than 100,000 [19].

When designing the leaf springs, it has always been a critical issue to address the friction between two individual leaves. A mono-spring offers a similar excellent solution. It has been observed that suspension is one of the most vulnerable to moisture and dirt exposure, thus using metals may lead to corrosion, but composites can be the ideal solution. However, the recyclability and the sustainability of thermoset leaf springs need to be addressed.

To quantify the weight-savings obtained from the shift to composites correspond to a significant 60 per cent reduction from the steel counterpart, i.e. from 150kg to 38kg [19].

The fatigue life of a composite spring is five times that of a steel spring and is accompanied by high specific strain energy which is critical for designing these suspensions.

Equation 1: Strain energy of a leaf spring

$$U = \frac{\sigma^2}{\rho E}$$

Where U is the strain energy, σ is the strength, ρ is the density and E is the young's modulus [20].

However, using a thermoset resin complicates these springs' recyclability as recycling glass fibre from thermosets is not economically beneficial. Hence most of the thermoset panels end up in landfills.

A more practical alternative for a Dodge SUV leaf spring in terms of material recyclability standpoint is Polyether ketone (PEEK) and carbon fibre [20]. While this study's purpose is design optimisation, it reports a similar weight-saving of around 50 per cent. 3D printing of the springs is, however, not marketable as the volume required is considerable. Also, carbon fibre is expensive in contrast to glass fibre. Similarly, PEEK can be replaced with alternative thermoplastics.

2.4 Tie rods

CFRP tie rods are 65% lighter than their metal counterparts [15]. These tie rods were built for class 7 (GVW b/w 26 and 33 Tons) and 8 trucks (GVW > 33 Tons). As indicated in Chapter 1, for any lightweighting done in the tie rods, the dimensions of the parts should remain about the same for two reasons:

1. Standard ball joint threads
2. Design of the suspension geometry

Two manufacturing approaches are suggested: first is carbon fibre epoxy prepreg rolled over a sub-assembly of pultruded lines with ball joints at each end.

The second approach is mandrel-based tubes which were threaded on the ends, resulting in high composite materials cost, which is unacceptable.

Delphi Solutions finally made 7000 pieces of these tie rods contract. However, the report indicates that the component is not mass-producible because of the high carbon fibre cost.



Figure 17: The upper tie rod is a metal tie rod, and the lower one is a CFRP tie rod [15]

To tackle the problem, an alternative solution is using recycled carbon fibres as they are available at 70 per cent of the cost and have around 1/4th of the tensile properties of virgin carbon fibre [21]. However, the mechanical analysis is out of the scope of this thesis.

2.5 Composite monocoque



Figure 18: TPI and Proterra composite monocoques [22]

Constructing the frame and body out of composites, i.e. a unified entity, is referred to as a monocoque and offers one of the highest weight-saving potentials. For an 8m bus, the monocoque weighs 30 per cent less than the conventional ones, as can be observed in Figure 18.

A composite monocoque weighs 830 kg, while the bus chassis with a metal frame weighs 1150 kg. The workforce requirement for building a hybrid bus is reportedly reduced by 25 per cent [22]. FEA and design-based optimisation offer insights into manufacturing which are very useful. It explains how the transport sector has been marked as one of the significant contributors to CO₂ by the International Energy Agency. The agency aims to reduce CO₂ emissions by 21 per cent to help limit the global temperature increase to 2 degree Celsius [23]. Also, policies like the Electric Vehicles Initiative (EVI) encourage the production of 250 million BEV units in more than ten countries by 2030. Such regulatory goals render BEVs an inevitable trend.

The construction is a sandwich construction, and the process which is used to manufacture them is VARTM. Both carbon fibre and glass fibre constructions are used according to the optimisation of strength requirements. While the construction uses epoxy as the resin, manufacturing using thermoplastics would have been a better alternative in weight-saving. Nonetheless, it is understandable that penetration is an issue for process change.

Data points obtained when energy consumption and Gross-Vehicle Weight (GVW) are plotted against each other can be co-related through simple expressions [23]. This also indicates that a lower body weight means the battery capacity can be lesser, and thus a lighter battery can be used, which compounds the weight loss.

As an electric powertrain is quite different from a combustion engine, fewer moving parts are required, and in general, this encourages the use of composites. In the end, an improvement of 63.3 per cent is observed over the benchmark in terms of weight loss. Monocoque's shortcomings are the sustainability and costs involved in manufacturing due to the carbon fibre usage. However, it requires in-depth research to confirm the case.

If the resin meets the process requirements, organo sheets or thermoplastic prepregs can be compression-moulded. However, the manufacturing of a complicated part as a monocoque is outside the study's scope.

2.6 Composite roof door

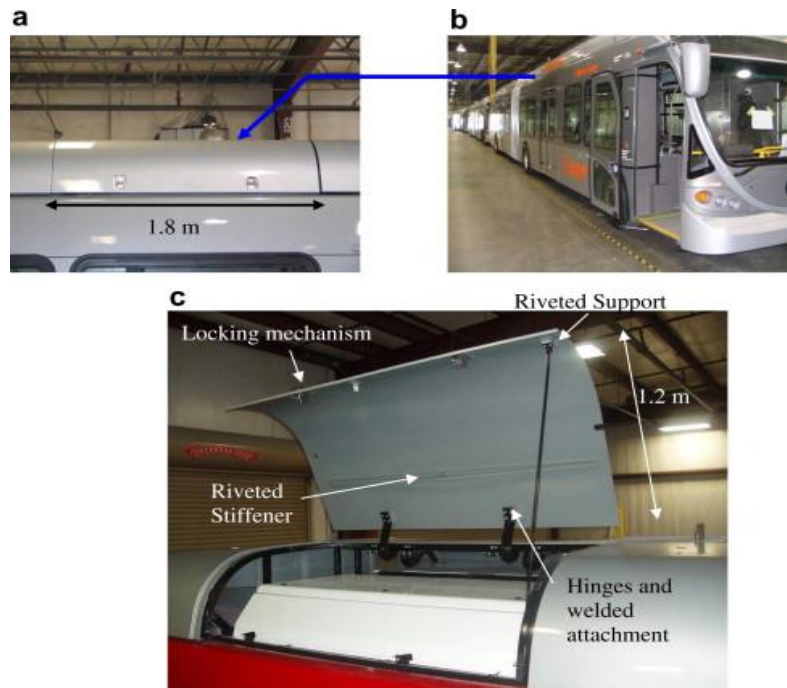


Figure 19: The roof door for the HVAC in a bus [24]

Composites have always been the go-to material for non-structural lightweighting because they can offer better strength and NVH properties than metals. A sustainable case of a roof-door bus design provides an insight into composites' superiority [24]. The paper also supports the co-relation of fuel consumption to vehicle weight by arguing that 75 per cent of fuel consumption is related to vehicle weight. Similarly, Compo bus by Tillotson uses composites and comes out to be 30 per cent lighter and consumes 60 per cent less power.

The process used to manufacture the door is thermoforming. In contrast, the materials used are glass mat thermoplastics (Glass/PP) and thermoplastic polyolefins for an outer covering, making it paint-ready and reinforcing it. The current component is made of aluminium and is 21 kg heavy, and has a sag or depression of 45 mm, which expresses the material's stiffness.

Glass-PP is one of the structurally stiff economical, and sustainable solutions. While PE is significantly more economical than PP, it is difficult to use it in

structural environments due to its low stiffness and strength. Hence this composite is ideal from this study's perspective as it offers a sustainable yet economical alternative to the relatively heavy metal counterpart.

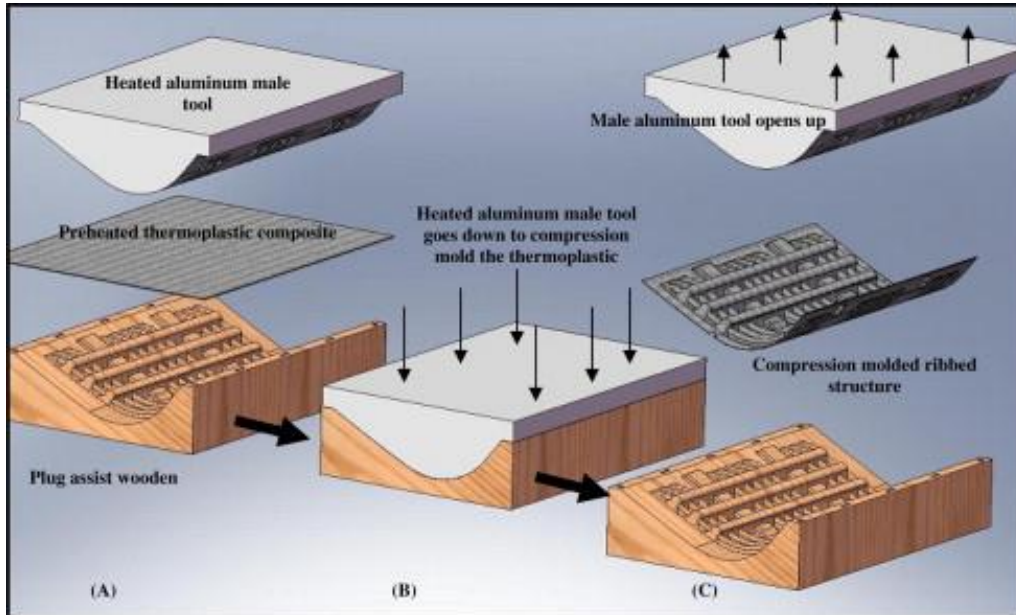


Figure 20: Compression moulding of the thermoplastic inner layer of the manufactured roof door [24]

The study also clearly shows the higher damping ratio, a measure of the damping of oscillations through a material. Aluminium offers a damping ratio of 0.004, and the composite part provides a relatively higher damping ratio of 0.14. Lowering the weight also lowers the centre of gravity, which reduces the risk of a rollover.

After validation, the solution offers weight-savings of 39%, lowers the deflection by 42% and improves NVH parameters by 97 per cent. A lifecycle study can be used to measure the impact of both on the environment, and the potential end-of-life comparisons can be drawn. However, it can be clearly seen that the most considerable effect of the parts is during the service/use period where a lower weight leads to lower use of fuel, and, for that reason, composites are the indisputable winner in this regard.

2.7 Composite door and trim system

Due to the shortcomings of the conventional OEM manufacturer highlighted in Chapter 1, Delphi remanufactured the system with composites, and the following results justified the change as:

1. The assembly was reduced to a 5-part from an earlier 15-part assembly
2. Cost and labour savings of 6.55\$ per piece
3. Tooling cost reduction of 200000\$
4. Mass removal of 2.5 kg from the previous version

The design was a multi-material combination of PP, PE and glass fibre reinforced PP in other components, and the door is recyclable due to the use of thermoplastics. Many other features were introduced, such as anti-rattle fittings, which the customers required.

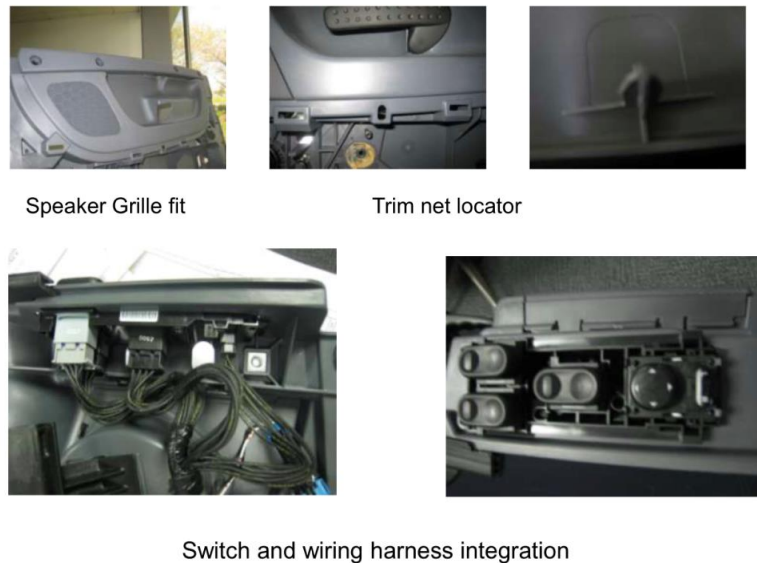


Figure 21: Components of the cab-in-white door [16]

2.8 Chapter summary:

The chapter can be divided primarily into areas of focus, as described below.

Weight-savings (Composite components): Chapter two reviews case studies of composite components to evaluate their manufacturing processes and weight-

savings. The components reviewed are body in white, bus floorings, leaf spring suspensions, tie rods, composite monocoque and composite roof doors.

Composite vs conventional construction: Some of the components mentioned above, like the leaf springs, tie rods and bus floorings, help draw contrasts between the conventional and composite construction of the parts reviewed in chapter 1.

Mechanical performance of composite components: All the components discussed in the chapter show significant weight-savings as the primary benefits; NVH levels are seen to be reduced in components like the door and trim system and roof doors. An increase in mechanical performance is also observed in parts like the leaf springs, where improvements in a strain energy reduction of friction due to corrosion are seen.

Sustainability of composite components: Composite components' use has reduced manufacturing costs and assembly complexity in parts like the door and trim systems. While some of the case studies use thermoplastics such as the roof doors, others fail to address the question of recyclabilities, such as the studies for tie-rods, leaf springs and bus floorings.

3 Sustainability of composites used in bus and truck components (Literature analysis and review)

3.1 Holistic composite trailers (weight savings)

3.1.1 Compositrailer

Compositrailer was one of the first attempts at producing a holistic composite trailer. The overall trailer weight was around 6 tonnes, whereas the conventional steel counterpart weighed 9 tonnes; hence an overall weight-savings of about 3 tonnes was observed. There were failures due to metal subcomponents failing from dynamic loads. However, the venture was shut down later because of the increased cost of production and a lack of interest from the market [1].



Figure 22: Compositrailer (one of the first holistic composite trailers)[1]

3.1.2 Ebsco 3.0

While yet to be brought into production, Netherlands-based Ebusco claims that it can produce a lighter bus service with their bus being 33 per cent lighter than the conventional version weighing at 8530 kg. According to Ebusco, its various benefits include a 500 Km Range, reduced noise and lower weight, as mentioned above. An extended lifetime with a lower total ownership cost is another benefit of this bus [25].

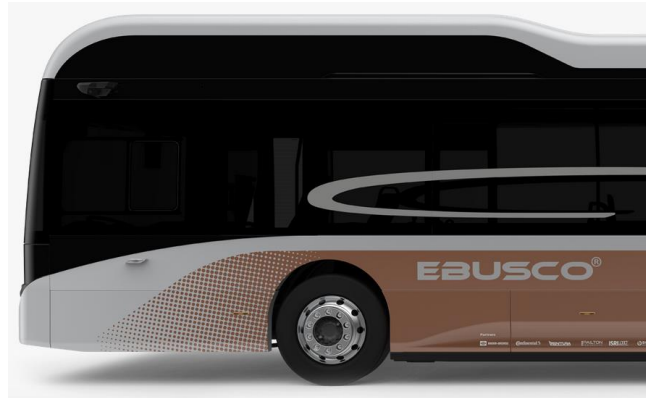


Figure 23: Ebusco 3.0, a composites-based bus [25]

3.1.3 Phoenixx

German manufacturers Kögel and Carbotech designed a trailer using carbon-fibre-reinforced epoxy monocoque tri-axle curtain-side trailer called the Phoenixx. While the manufacturing cost of the trailer was twice the cost of a steel trailer and thirty per cent more than the aluminium counterpart, it manages to save 2300kg over a conventional 6000 kg counterpart, which is significant [1]



Figure 24: Carbon-fibre epoxy-based composite trailers manufactured by Kögel and Carbotech for Walmart [1]

3.2 Fuel and cost-saving analysis

3.2.1 Lifecycle impact of weight-savings on HDVs

The previous chapters have shown that composites help in saving weight in various areas. This chapter quantifies which kinds of HDVs are the most affected by this lightweight based on their respective environmental impact.

Vehicles	Lifetime Performance	Lifetime Diesel savings per 100 kg wt. saving	Lifetime CO savings per 100 kg of weight
	km	litres	Tonnes
City bus, less halts	1 000 000	1485	4
City bus, more halts	1 000 000	2550	6.8
Long-distance, high speed buses	1 200 000	500	1.3
Long Distance, medium speed buses	1 200 000	1167	3.1
Trucks long distance, high speed	1 200 000	889	2.4
Trucks long distance, medium speeds	1 200 000	467	1.2
Light-duty vehicle, average use	375 000	643	1.7
Light duty vehicle, urban commercial use	475 000	1302	3.5
Light truck, average use	300,000	360	1.0
Light Truck, urban commercial	570, 000	1140	3.0

Table 2: Energy expenditure impact per hundred kg weight-savings of various heavy-duty vehicles. [7]

Table 2 is based on empirical calculations factoring in 4 forces, namely rolling resistance, gradient resistance, acceleration resistance and aerodynamic

resistance. The first three are dependent on the vehicle's mass, while the last depends on the shape of the vehicle and velocity [26].

3.2.2 Component lightweighting Impact

One important realisation is that a significant factor contributing to energy expenditure in heavy-duty vehicles is drag. Hence while lightweighting lowers the energy expenditure, it can often be relatively more beneficial for vehicles that make more stops and operate in an urban environment at lower speeds. From Table 2, one can see that city buses with more halts have the most impacts.

This drive-cycle data can be used to draw component-specific comparisons. The first two chapters discussed various components. Excluding a composite monocoque, these components are mutually exclusive in weight reduction. To examine the sustainability aspect of these components, Table 3 presents the possible weight-savings from the literature.

Component	Conventional Materials used	Alternative materials sug.	Potential weight-savings
Cab-in-white	Steel Sheets	Glass fibre/sandwich panels	50 to 70 kg
Trailer Floor	1. Keruing hardwood(26 kg/m²) 2. Birch hardwood 30mm (21kg/m²)	Sandwich Panels (FRP balsa)15 kg/m ²	9 kg/m ² approx. 165kg
Trailer Walls	Glass fibre reinforce the wood (14 kg/m ²)	PP honeycomb sandwich panels (4.8 kg/m ²)	9kg/m ²
Leaf Springs	Steel	Glass fibre epoxy /pp0	112 kg

Tie Rods	Steel	Carbon fibre/epoxy	5kg per Tie rod
Bumpers	Steel, Thermoplastics	Glass fibre/epoxy	50 kg
Door and Trim systems	Sheet metal (Steel) and plastic	GFRP, Thermoplastic	5 kg
Bus Seat	Steel and plastic assembly	Long fibre GFRP	112 kg
Monocoque	Steel and Aluminium	Composites (GFRP, CFRP)	320 kg
Bus Body Panels	Steel and Aluminium	Glass /PP honeycomb	256 kg
Roof Door	Aluminium	GFRP, thermoplastics	8 kg

Table 3: Components discussed in the previous chapters and the weight-savings of each newer alternative.

3.3 Vehicle selection

HDVs with the lowest speeds and more halts typically happen in an urban environment certainly make the more marketable case. The market has rejected complete composite trailers, but modular and subcomponent replacement are certain commercials [1].

Although trucks and buses are built on a similar ladder frame, the regulations might differ; hence the thesis will focus on primarily two kinds of vehicles:

1. City Buses with more halts.
2. Trucks with urban commercial use.

3.4 Component selection

The sandwich panels are chosen as they are relatively simple to manufacture. Also, as a component, they are simple in shape complexity, material choice and manufacturing.

Flooring is a vital component due to lightweighting possibilities, and this lightweighting shows the maximum impact on city buses. The following section draws a comparison between the renewability of thermoset sandwich panels and wooden floorings. This is done to demonstrate the effect of lightweighting flooring panels on a reduction in CO₂ emissions.

3.4.1 Lifecycle impact case study, GFRP balsa sandwich panel vs birch wooden flooring

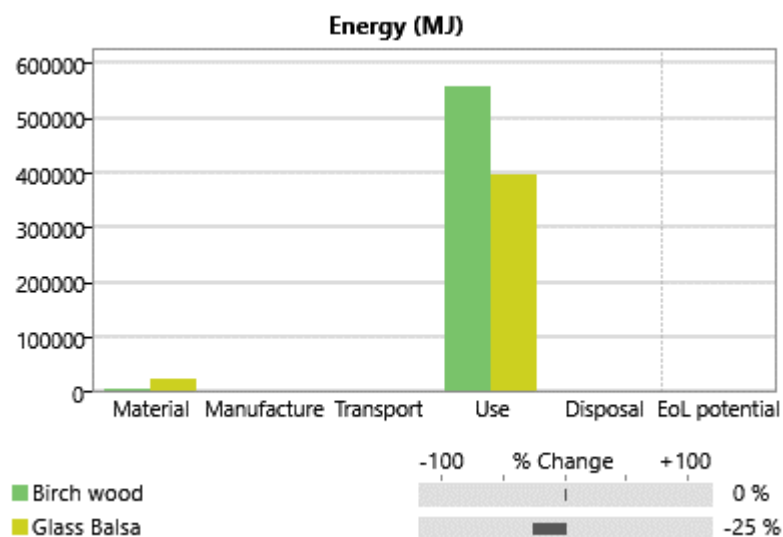


Figure 25: Glass fibre /balsa vs Birchwood energy consumption

The concept of manufacturing sandwich panels seems optimum with the resources available. Also, as seen in the literature, weight-savings make a significant difference of 165 kg for a 13.6 m SDC Trailer with a load-bearing capacity of 40 tonnes [3].

In recent years, core alternatives with steady and reliable supply chains have surfaced. On the contrary, balsa wood has the most limitations of plywood except

being lighter. The literature represents it as a viable option because of its cost-effectiveness and mechanical capability.

Nevertheless, balsa wood reduces the flooring's weight significantly and is a sandwich composite that makes it worthy of investigation. Edupack 2020 was used to calculate the potential lifecycle impact with certain assumptions.

Comparisons were drawn between the following materials:

1. Birch plywood
2. Woven glass fibre /polyester skins with balsa wood as the core

Both samples cover an area of 27m², with EOL potential being considered zero as both thermosets and wood end up in landfills. Since during the lifecycle of an SDC trailer, a truck goes on for 1,200,000 Km, it was assumed that it does work 250 days a year and has a lifetime of 15 years [1].

The properties of the materials and processes are highlighted below :

Material	Weight	Processes
Birch Wood (WISA Truck Plus)	567kg	Cutting, Milling, Adhesive coatings
GFRP/balsa (Components below)	405 kg	Hand Layup
1.Glass fibre (woven)	110 kg	
2.Polyester (orthophthalic)	125 kg	
3.Balsa wood (SB 150 grain)	170 kg	

Table 4: Various components, their weight and processes used for manufacturing used for the analysis [27], [1].

As seen in Figure 25, it is very well represented that the use phase is the most impactful on energy consumption. While wood is a winner for manufacturing and has the least energy-demanding manufacturing processes, it certainly loses out in the use phase, where it has much more impact.

Wood has various undiscussed problems, such as that its moisture content fluctuates between 8-12% at the time of milling to 30%. Trailer can fluctuate in weight by +/- 240kgs [28].

3.4.2 Energy consumption differences for balsa/GFRP and birchwood floorings

Material	Energy consumption (MJ)	Energy consumption (MJ)	Total Energy(MJ)
	Materials and Manuf.	Use Phase	Incl. disposal
Birch Wood	6910	5.58×10^5	5.58×10^5
Glass balsa	26500	3.99×10^5	4.26×10^5

Table 5: Energy consumption data for the materials for floor decking [29]

Thus, while the manufacturing and material expenditure of GFRP and balsa is significantly higher, it contributes to less than 5% of the lifetime energy expenditure. In comparison, the use phase savings are significantly higher, resulting in a net energy savings of 1.32×10^5 MJ.

3.5 Chapter summary :

The chapter can be divided primarily into areas of focus, as described below.

Impact of weight-savings on the environment: The chapter attempted to understand the co-relation of weight-savings to fuel and CO₂ savings, taking into account various types of buses and trucks. It summarises possible weight-savings of components reviewed in chapter 1 and 2 and discusses the maximum potential weight-savings through case studies of composite trailers and buses.

Component selection: The weight-savings in heavy-duty vehicle floorings are observed to be significant through previous literature. However, the suggested alternatives do not address the recyclability of the flooring panels. Hence the

thesis aims at developing completely thermoplastic flooring panels to provide a recyclable solution to the existing alternatives.

Vehicle selection: The strongest co-relation between weight and fuel savings is observed in city buses with more halts and trucks for urban commercial use. Hence replacing floor panels in city buses is deemed appropriate for maximum impact.

Lifecycle impact (Wooden vs composite flooring panels): The chapter also conducts a lifecycle impact study between wooden panels and the suggested GFRP balsa wood floorings used in the literature. It acknowledges that while the conventional wooden flooring panels have lower energy consumption during manufacturing, their overall impact on the environment is considerably higher. This is due to the higher consumption of fuel because of its heavier weight. This further reinforces the importance of lightweighting with regard to the environment.

4 Experimental work on sandwich composite panel fabrication

4.1 Mechanics and design of sandwich panels

Bending loads are the primary loads acting on the floor panels, and because of their placement between two cross members of the frame of the chassis, the load acts normal to them.

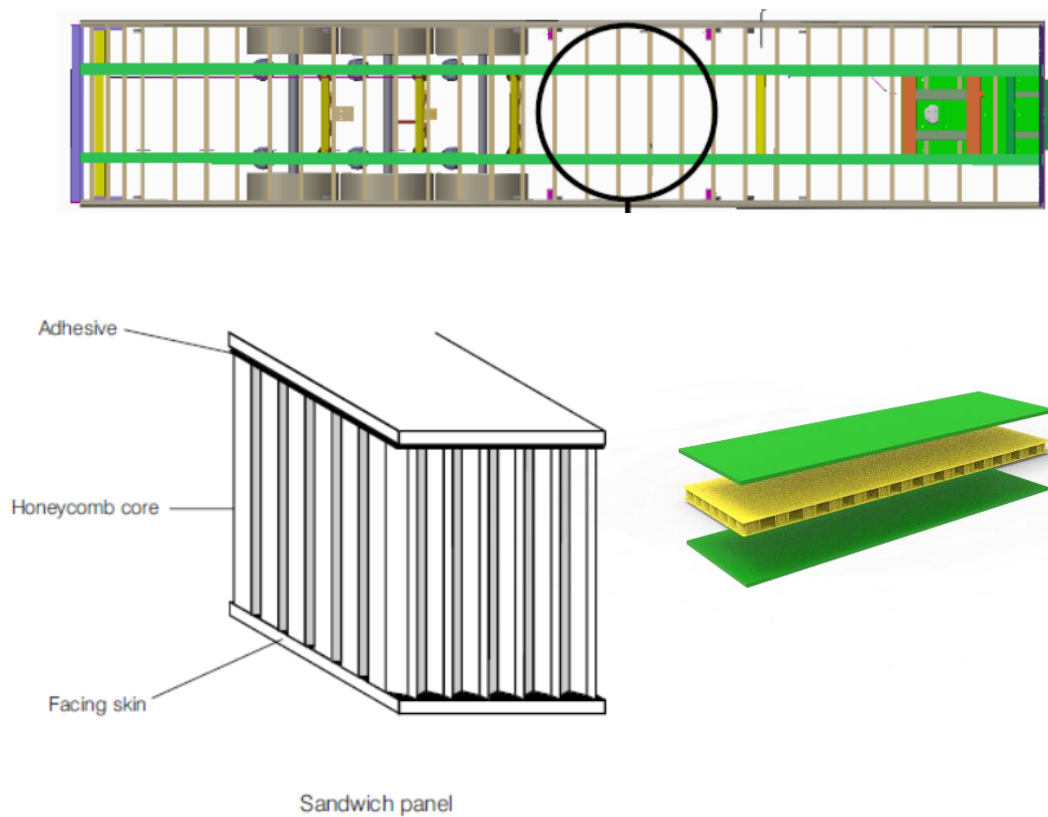


Figure 26: Trailer ladder frame (top); sandwich panel components (bottom-left); exploded view of sandwich panels (bottom-right) [1], [30]

The sandwich panels comprise two sub-components, the **skin** and the **core**. For a sandwich panel, the bending rigidity of the materials is given by:

Equation 2: Bending rigidity of the materials

$$B = EI \quad [31]$$

Where **B= Bending Rigidity**, **E=Young's Modulus**, **I = Inertia about the neutral axis**.

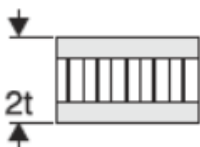
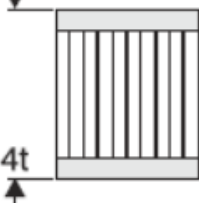
	Solid Material	Core Thickness t	Core Thickness $3t$
			
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Figure 27: Relative Strength to weight sandwich panels [30]

The bending load typically ranges from the highest on the face layers with no load in the face skins' middle or neutral layer. Thus, the introduction of a lightweight core gives a better load distribution profile and increases the moment of inertia by moving the mass away from the axis.

4.1.1 Structural modifications and safety aspects

Since the sandwich panels are a secondary structural component, no modifications are required to the vehicle's frame. The panels rest upon the ladder frame's cross members, as shown in Figure 26(a). To test the structural adequacy, the primary testing criterion used is three/four-point bending. Crash testing is not required as the chassis of the vehicles bear these loads.

Flame retardants need to be added to PP with bamboo and glass fibres as composites show a low LOI value of 18-19% [32]. The limiting oxygen index test is used to evaluate the least oxygen concentration required to enable combustion. PP shows a low limiting oxygen index (LOI) of 18-19 compared to 23-27 for epoxy

[33]. Flame retardants can be used to increase this retardancy, adding 6% of ammonium polyphosphate by weight, for PP-sisal composites, increase LOI from 20% to 31% [34].

4.2 Commercially available flooring solutions

4.2.1 Thermoset panels

The bending load for sandwich panel floorings range to a maximum of 17,200 Pa for out of plane bending (13,000 GVW) [35]. However, commercial products show higher load-bearing capacities; thus, commercial thermoset sandwich solutions are studied to compare and set a benchmark for the manufactured thermoplastic prototypes.

Product Name	Density (kg/m ²)	Thickness(mm)	Bending Strength(Mpa)	Bending Modulus(Gpa)
Top Air Power GRP	8.7	30mm	20	3.7

Table 6: Mechanical properties of commercially available thermoset floor panels[36]



Figure 28: Top AIR Power GRP panel (skins reinforced with polyester) [36]

TOP AIR Power GRP is a commercially available alternative to wooden flooring, made using a thermoset matrix for its skins. While it uses polypropylene

honeycomb, thermoset resin makes the skins challenging to recycle due to the curing process. Prototype production aims to eliminate this problem.

The thickness of the sandwich panels varies from 9mm to 30mm depending on the load, with the higher thickness typically used for trucks and lower thickness is used for buses.

4.2.2 Wooden panels



Figure 29: Metsawood Deck XL [37]

Birchwood and **Keruing** panels are the conventional materials used in manufacturing these floor panels [1]. Such panels are manufactured commercially by Metsawood, which would be used for further comparative study

Product Name	Density (kg/m ²)	Thickness(mm)	Bending Strength(Mpa)	Bending Modulus (Gpa)
Metsawood DeckXL	10.2	15	33.8	10.3

Table 7: Mechanical properties of commercial wooden floor panels[37]

The mechanical properties of the Metsawood panels would be used for the analysis. While wooden panels are inexpensive, they have certain performance drawbacks:

- Dimensional inconsistency
- Mass changes due to moisture ingress
- Easy chipping
- Low flame retardancy.

- Relatively higher weight

4.3 Material selection for sub-components of the sandwich panels

There are four subcomponents to be decided:

- Fibres for the skin
- Honeycomb materials
- Resin for the skin
- Interfacial bonding resin (used between skin and core if co-bonding is used)

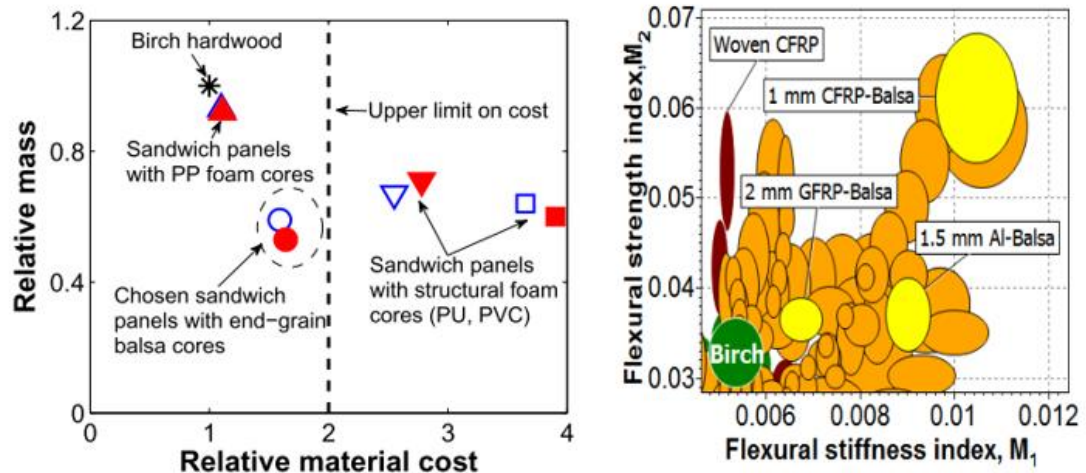


Figure 30: Material selection according to [1]

Balsa wood cores with GFRP skins are suitable for truck floorings amongst various core and skin combinations [1]. Since PP foam cores in Figure 30 have similar cost and mass to birch hardwood, they are not suitable for lightweighting.

PP honeycombs can lower the mass and provide a better lightweighting alternative at a similar cost. This also makes them more suitable than balsa wood due to their lower cost and consistent mechanical properties. Similarly, thermoplastics like PP are less dense than epoxy and provide recyclability for the skin. This is explained in detail in the following sections.

4.3.1 Skin material selection (Fibres)

For fibre selection, there are many options available, ranging from carbon fibre to bamboo fibres. The factors considered are the cost, weight and performance. Since most bending loads act upon the skin layers in a sandwich composite, and fibres have a higher modulus than the resin, they are a load-bearing component. The following are the options considered.

S.no	Fibres	Modulus (GPa)	Density	Volume fraction compression moulding
	Glass Fibres	72-85	2.52	40-60 %
	Bamboo fibres	35-45	1.3	20-40%
	Carbon fibres	225-390	1.93	40-60%

Table 8: Properties of various fibre alternatives [38]

While bamboo is a good option, it is often combustible, making the industry reluctant to consider it. It has a very high rate of flame propagation, 12mm/min, which makes it less suitable without using transportation without adding flame retardants. Natural fibres, like flax, also lack structural properties as they provide a lower volume fraction of the fibres, i.e. 30-45 per cent and absorb moisture.

While carbon fibre structurally has the best mechanical properties, it is undoubtedly much more expensive, and the manufactured skins would defeat the industry provided weight-saving to cost goal of 10£/kg is achieved.

Also, bamboo and flax typically offer lower volume fraction (about 30 %), making it challenging to meet the structural needs in bending test [32]. Therefore, glass fibre is the most appropriate choice.

4.3.2 Core material selection

A broad array of materials was researched, and balsa-core with glass fibre or aluminium treadplates were preferred based on cost-effectiveness and lightweighting capabilities [1]. As seen in Figure 30, PP foam cores are relatively heavier and more expensive than balsa wood; however, this can be changed if PP honeycombs replace them.

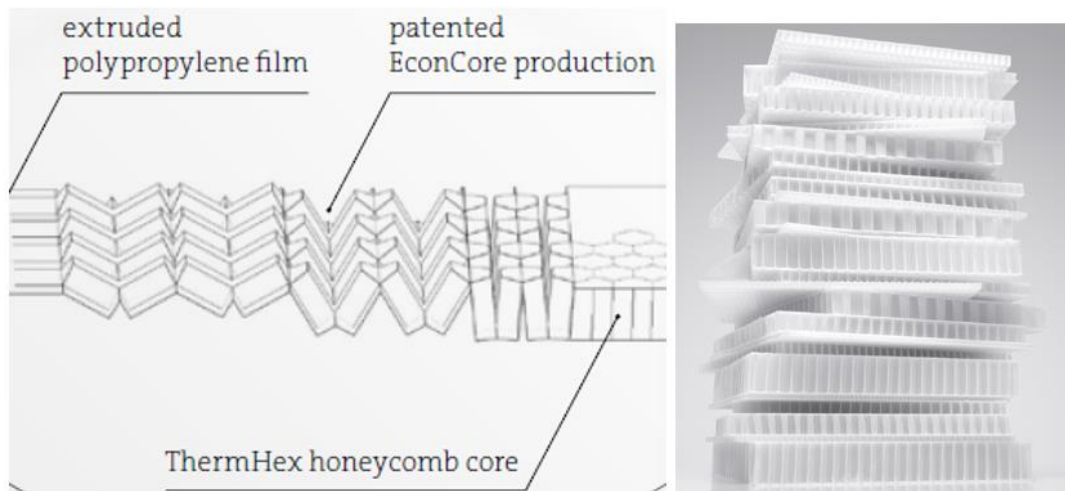


Figure 31: Honeycomb core manufacturing technique Thermhex (left), PP honeycomb cores (right) [39]

PP honeycombs' costs have lowered, and new manufacturing techniques (Thermhex honeycomb cores) enable continuous low-cost production of the honeycombs. According to the literature, PP honeycombs are not a suggested solution based on their cost and mechanical strength [1]. Nevertheless, the characterisation and mechanical testing in Chapter 5 proves that PP honeycombs are considerably lightweight and economical for usage.

4.3.3 Skin resin selection

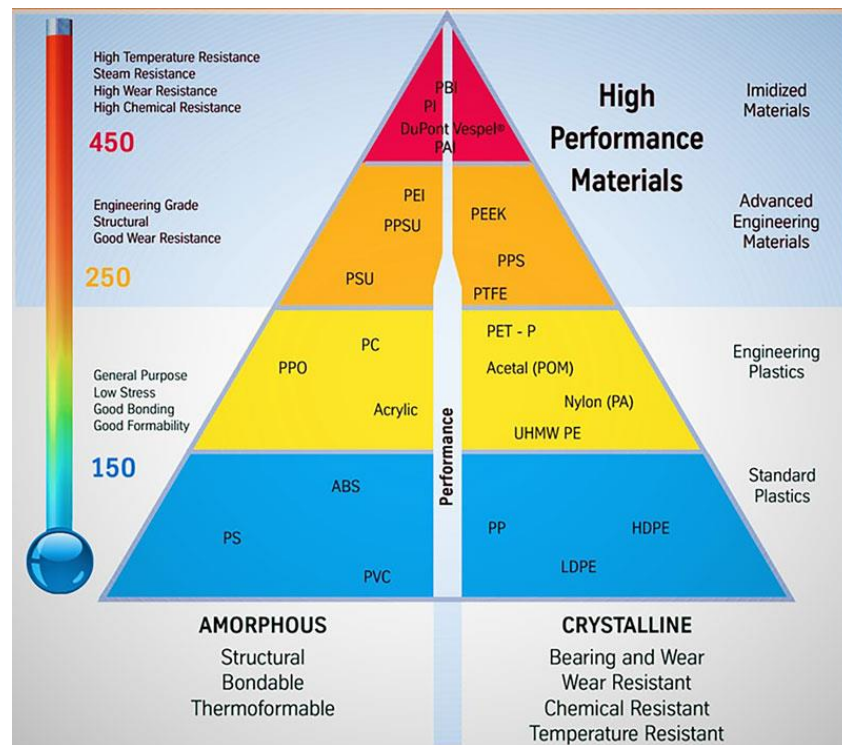


Figure 32: Categorisation of various thermoplastic resins available [40]

As the primary goal is to provide a recyclable solution, an overall similar material for both the core and the resin in the skin is optimum as it makes recycling feasible and easy.

Thus it is ideal to use PP from a recycling point of view; it is economical and relatively structurally sound. While one might select engineering or high-performance plastics, their higher costs, processing temperatures and pressures make it less economical to manufacture, further, material differences with the core decrease in recycling ease.

4.4 Manufacturing of the sandwich panels

Compression moulding was chosen to manufacture the prototypes, primarily the skin layers and PP powder; this was done because of the relatively high flow point of PP and thermoplastics in general, which requires them to be compressed under high pressure and temperature.

However, for the panels being mass-manufactured, it is recommended that one uses organo sheets or thermoplastic prepregs in a continuous manufacturing process. Pre-consolidated prepregs are fed into a constant supply of honeycombs, which is possible due to manufacturers like Thermhex, which can provide a continuous supply chain of honeycombs.

This can be followed with a spray-up of the controlled co-bonding adhesive ensuring optimum layer thickness.

4.4.1 Manufacturing of the skins

Polypropylene in the powdered form was used as the matrix. The DSC data PP has a melting point between 150-160° C [21]. This implies that a low-flow temperature of 170-180° C appropriate to allow better flow for the skins' manufacturing.

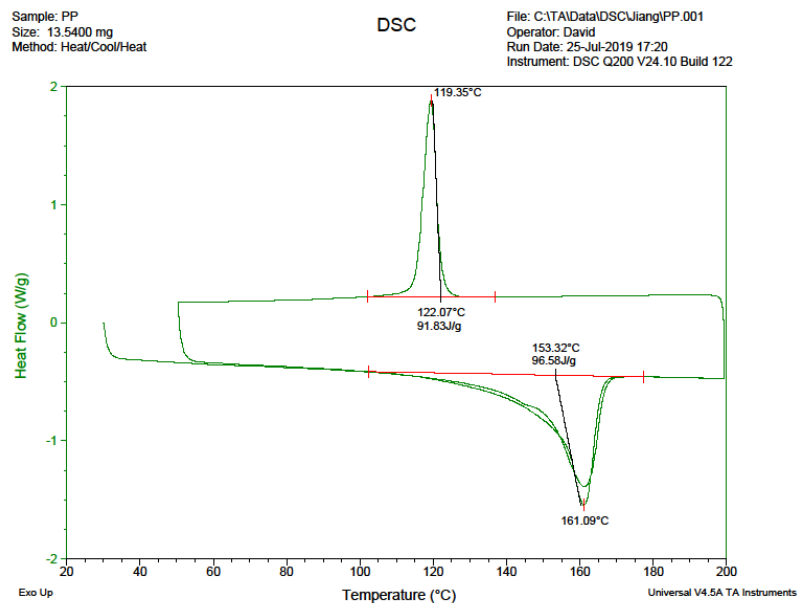


Figure 33: DSC results of PP [21]

14g of PP powder is used to manufacture a 2.2mm thick skin measured to be around 150*100 mm. Skins' compression is executed at 3.2 Mpa, which was slightly lower than that studied in the literature [21]. This is because of the nature of powdered nature of polypropylene as opposed to sheets.

The evaluated pressure and temperature work well as a volume fraction of around 42% are achieved. While a few dry spots are observed, the distribution of the powder upon the layers indeed matters. Meanwhile, an automated spray of the powder can certainly help in both cases.

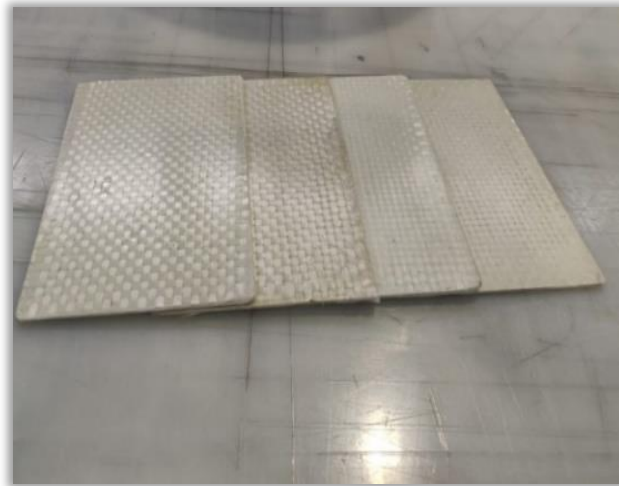


Figure 34: Manufactured Glass fibre PP skins

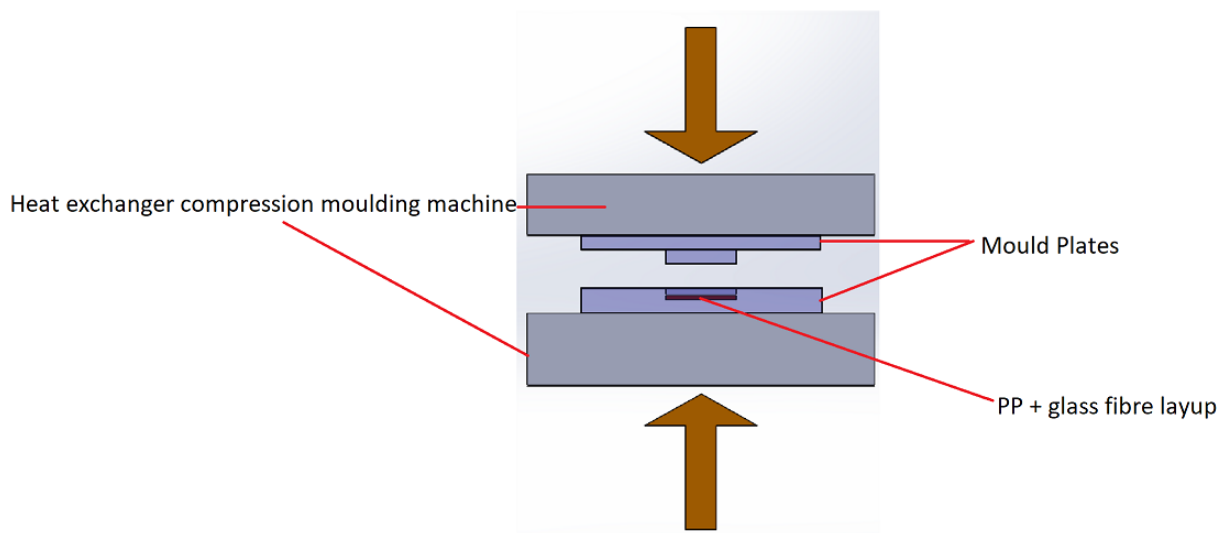


Figure 35: Compression Moulding setup schematic



Figure 36: Compression moulding machine

A layup of [woven,0,90] symmetric was used to reduce cost as unidirectional fibres are relatively economic [29]. Unidirectional orientation provides greater strength in loading (significantly more number of threads in the direction). Woven fabrics are used on the top as exposed unidirectional fibres have a greater tendency to chip away upon impact.

4.4.2 Co-bonding of skins to the honeycomb

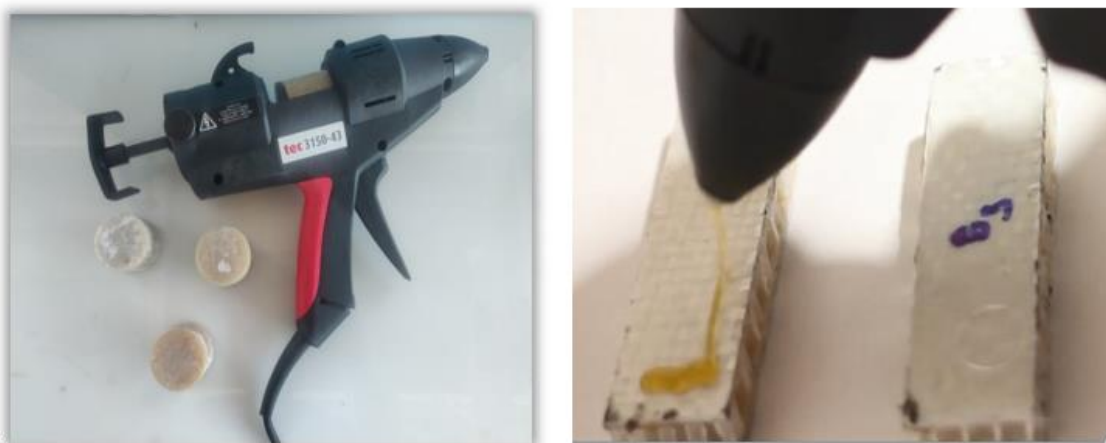


Figure 37: Tecbond 267 glue gun, glueing process demonstration (right) [41]

The next important aspect to be seen in the manufacturing was the skins' co-bonding to the honeycomb. This was a challenge mainly because it aimed to produce a fully recyclable thermoplastic sandwich panel and polypropylene with low surface energy. The latter makes it very difficult to bond, and polypropylene substrates often require plasma surface treatment. It can be seen from studies such as [18] that interfacial bonding was the failure mode.

To avoid these problems, hot melt glue manufactured by Gluegunsdirect, which is made from a completely recyclable combination of polyolefins (Techbond 267) is used. The glue has a softening point of 150-degree Celsius near the melting point of polypropylene; the glue provides an open time of 12 seconds.

Thus, to avoid cold-bonds, substrates are heated to 140-degree Celsius. This allows increased open time for the glue while keeping the temperature lower than polypropylene's melting point. In the end, the pressure of 300N is used to get the glue bonded.

4.4.3 Scanning electron microscope imaging

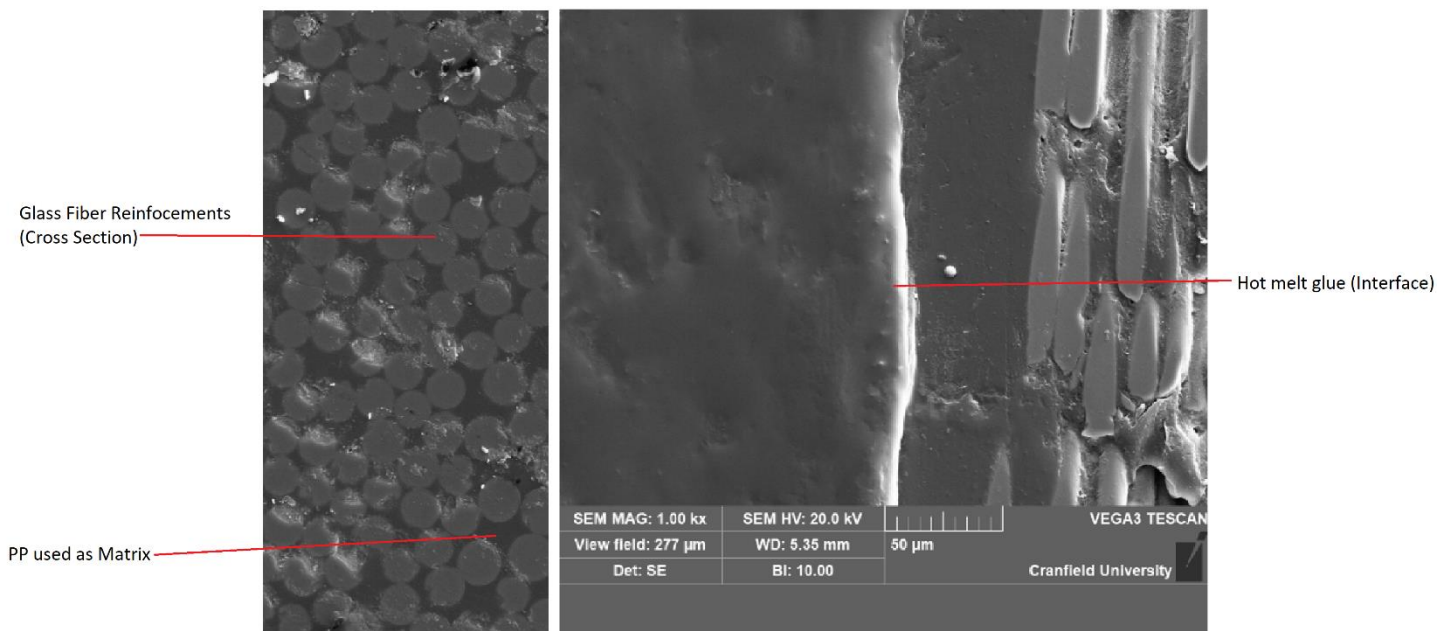


Figure 38(a): SEM Imaging showing PP dispersion at 1.00 kx (left), Figure 37(b) Interfacial bonding 1.00 kx (right)

Upon imaging, it is observed that PP is well dispersed on the right side, where the glass fibres can be seen. A clear demarcation shows that the interface has bonded reasonably well and that the matrix is well distributed in the skin layer.

4.5 Chapter summary

The chapter can be divided primarily into areas of focus, as described below.

Sandwich panel design and construction: It discusses the construction of sandwich panels and explains their capability to reduce weight over metal and wood in bending applications.

Commercial/Conventional flooring panels: This chapter also discusses the thermoset panels used commercially and described in the literature for trailer and bus floorings to save weight over wood. The limitations of both conventionally used wood and reviewed thermoset panels are discussed.

Material selection and fabrication of thermoplastic panels: The material selection and process used to manufacture the glass polypropylene sandwich panels are discussed. The skins' manufacturing using compression moulding and various factors such as layup used in skins and co-bonding through a thermoplastic adhesive are described in detail. The chapter also discusses the practical nature of these bonds after co-bonding. Thus, the chapter provides an understanding of the design and explains the fabrication process for the developed thermoplastic panels.

5 Mechanical testing and the characterisation of sandwich panels (experimental work)

5.1.1 Three-point bend test

5.1.1.1 Significance

The three-point bending test is of prime importance as it helps draw a comparison between the manufactured glass polypropylene sandwich panels and the existing wooden floorings. For the commercial thermoset counterpart (TOP air-power grp), the sandwich panels are tested according to ISO 178, a three-point bend test. Also, thermoset panels studied in the literature for trailer floorings use a three-point bending test to measure structural adequacy [3].

However, due to the specific apparatus's unavailability in ISO 178, the three-point bend test was conducted per the standard ASTM D7250, which is used for bending tests on sandwich panels [42].

The following equations, according to the standard, were used to calculate the bending stress:

Equation 3: Beam Mid Span Deflection

$$\Delta = \frac{P(2S^3 - 3SL^2 + L^3)}{96D} + \frac{P(S-L)}{4U} \quad [42]$$

Equation 4: Core Shear Modulus

$$G = \frac{U(d-2t)}{(d-t)^2 b} \quad [42]$$

Where

Δ = beam mid-span deflection, mm[in.]

P = total applied force, N[lbf]

d = sandwich thickness, mm [in.]

b = sandwich width, mm [in.]

t = facing thickness, mm [in.]

S = support span length, mm [in.]

L = load span length, mm [in.] ($L = 0.0$ for 3-point mid-span loading configuration)

G = core shear modulus, MPa [psi]

D = flexural stiffness, N-mm² [lb-in.²]

U = transverse shear rigidity, N [lb]

5.1.1.2 Related works

Sandwich panels are mechanically built primarily for bending applications since the increase in inertia about the neutral axis due to a thick core leads to an increase in bending rigidity. Thus, three-point bend tests are a primary way to evaluate bending strength.

GFRP and balsa wood sandwich panels have been tested in the literature using a three-point bend test; the 30 mm panels perform exceptionally well as they fail at 45 kN, which is 4 times the wheel load of a 5-tonne pellet [1].

Three-point bending carried out on PP honeycomb-based panels, 32 mm thick, reveals failure at a load of 2080 N [3]. However, the resin used in skin panels and the adhesive has not been specified for these panels.

Similarly, the commercially available thermoset panels, i.e. "TOP AIR POWER GRP", use ISO 178. The standard is based on three-point bending tests to prove these panels' structural adequacy [36].

While the tests help to understand the nature of the bending tests, the data cannot be extrapolated because the configurations and materials vary in the reviewed literature.

5.1.1.3 Test Setup and Methodology

The three-point bend test was conducted on Instron 5500R universal test machine using a 5mm/min speed. LVDT was used to measure the deflection on the specimen.

The bending loading span of 60 mm and a supporting span of 100 mm were used. While this measurement is 5mm less on each side than the prescribed standard due to the mould constraints during the compression, it was ensured that the edge effect does not affect the bending. The machine was equipped with a 5 kN load cell.

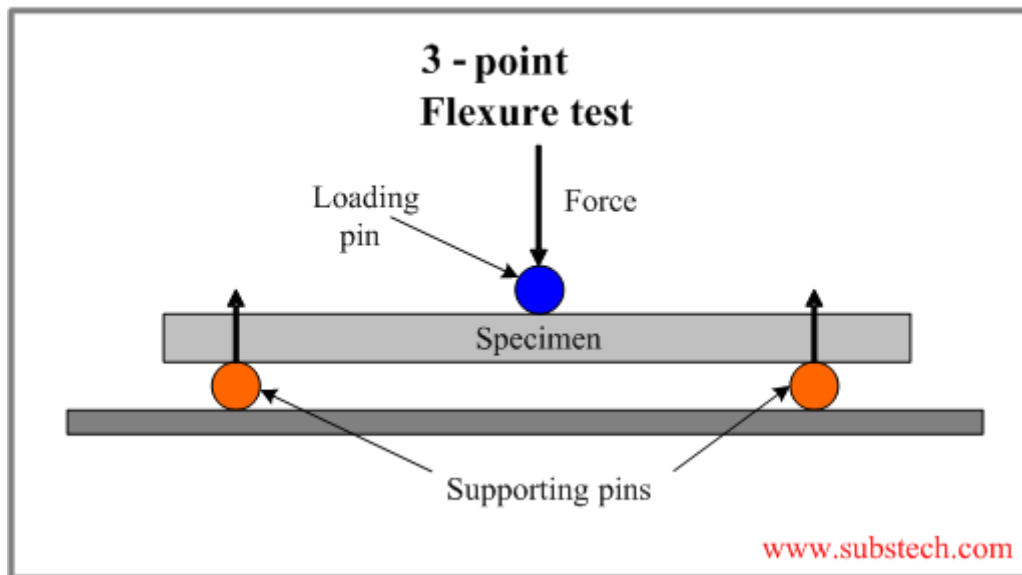


Figure 39: Three-point bending test setup schematic[43]

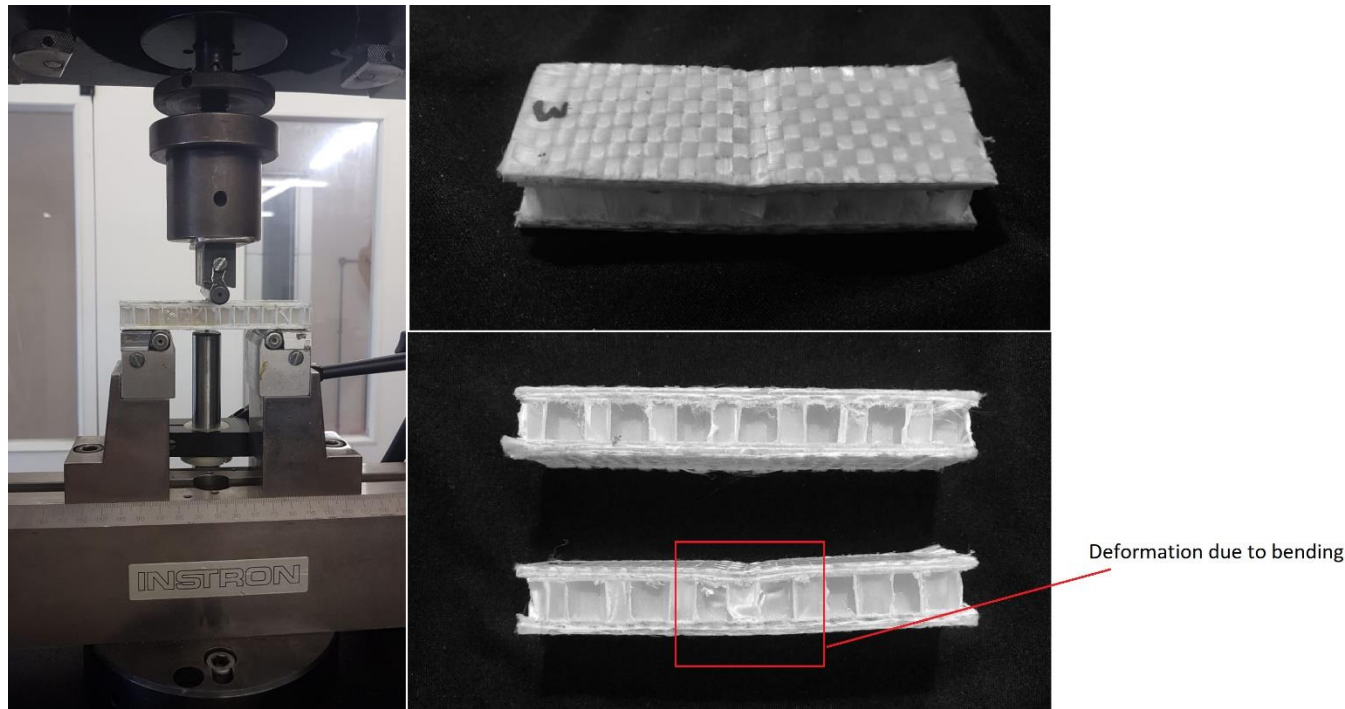


Figure 40: Instron 5500R three-point bending setup (left); failure due to core crushing (right bottom); close-up view (top right)

5.1.1.4 Conclusions

The following conclusions are drawn from the bend test:

1. The three-point bend test yields a bending strength of **22 Mpa** corresponding to a force of **565 N** with a maximum deflection of 2.8mm.
2. The literature has been indicative of interfacial adhesive being the weak link; however, upon visual inspection, it is seen that the co-bonding layer of adhesive upholds its integrity very well.
3. Further optimisations may include adhesive layer thickness optimisation and skin layer optimisation.

5.1.2 Impact testing

5.1.2.1 Significance

Impact testing was done on the prototypes to simulate the effect of impacts on the floors in a bus, such as baggage drops, with hail and debris hitting the road. To simulate the loads on a low floor, a Korean bus test of similar impact tests was performed at 6J of peak load [44].

5.1.2.2 Related works

Apart from the study on thermoset bus panels which does the testing at 6J for the thermoset panels, there have been studies on low-velocity impacts on sandwich panels [44].

Comparison has been drawn between glass thermoset and thermoplastic panels, and the results indicate that while thermoplastic panels are less stiffer than thermoset panels, they offer better load-carrying and deforming characteristics [45]. In the same study, it is observed that lower-density cores complement thermoplastics better, which complements the selection of PP face sheets and honeycomb chosen for fabrication. There has also been a correlation between penetration and skin thickness, and layers of woven fibres. An increase in skin thickness leads to an increased energy threshold for penetration. The panels were tested up to 200 J of energy.

While all these studies demonstrate sandwich panels' behaviour under the low-velocity impact, the configurations and materials of the sandwich panels differ from the panels being tested. Hence the results cannot be extrapolated.

5.1.2.3 Test setup and methodology

Sandwiches of 150* 100 mm were placed under impact testing setup and were tested for the maximum impact used in Korean low-floor buses. This was repeated for three samples, and the sandwich panels confirmed positive results.

The impactor was made to fall from a height that corresponds to 6J of energy. The impactor diameter is 16.15 mm, close to 15.89 mm used in the literature [37]. The data containing contact force time, displacement and energy is measured, and graphs are plotted accordingly (see Figure 45).

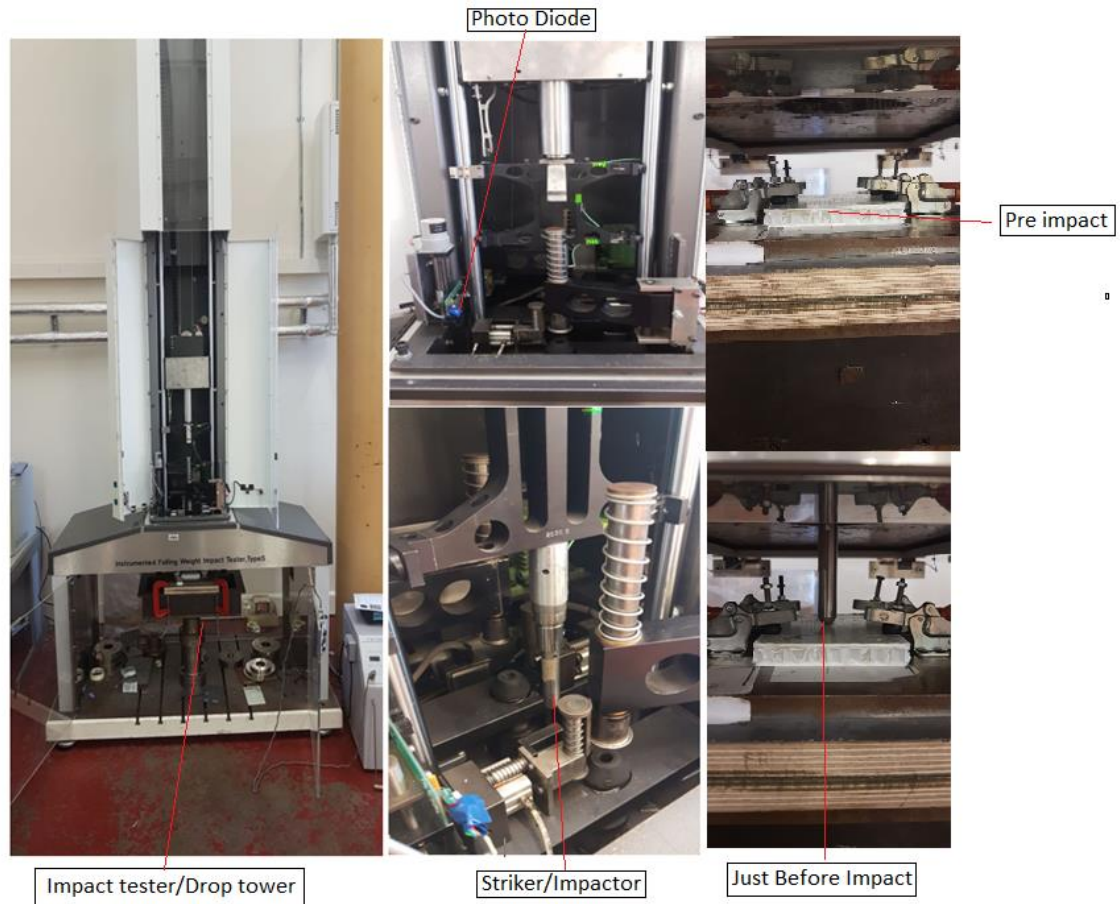


Figure 41: Impact tester components (test setup)

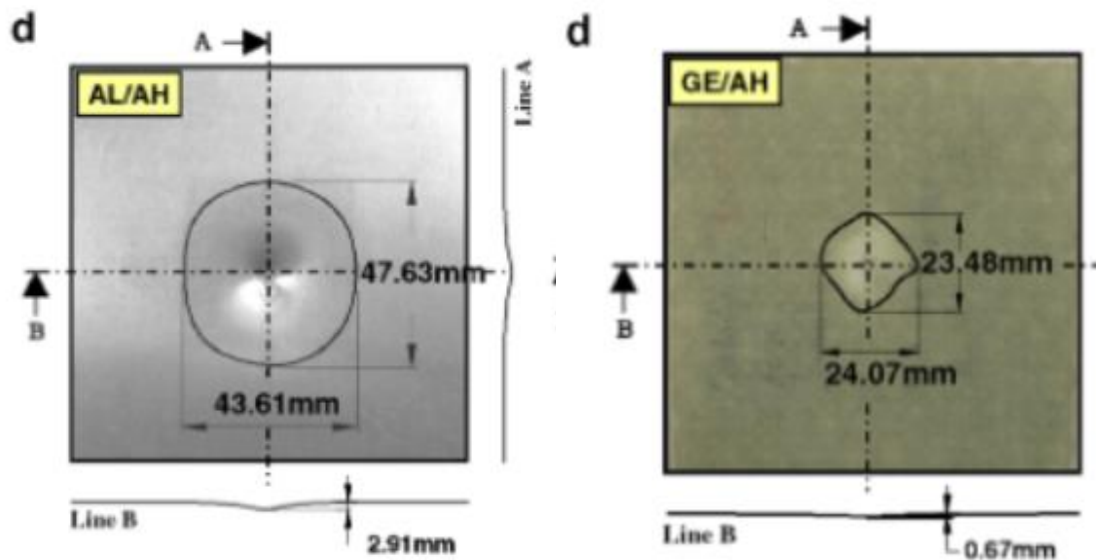


Figure 42: Aluminium honeycomb with aluminium face sheet (left); glass epoxy face sheet with aluminium honeycomb (right); indentation at 6 J impact [44]

5.1.2.4 Conclusions

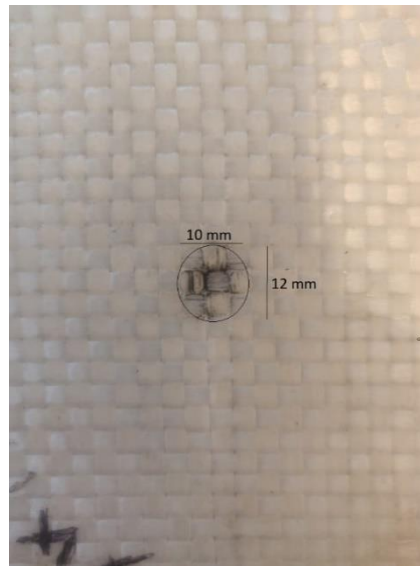


Figure 43: Residual impact at 6 J

PP and glass fibre skins show resistance to the 6J impact, and residual indentation is barely observable to the naked eye. Naked eye measures confirm an area of 10*12 mm samples (Figure 43) for similar energy and impactor size as used in the literature. This is a significant reduction compared to aluminium honeycombs with aluminium and glass face sheets, which have crater sizes shown in Figure 42.

5.2 Chapter summary

The chapter can be divided primarily into areas of focus, as described below.

Three-point bend tests: The preliminary tests conducted upon the panels include three-point bending and low-velocity impacts. As the panels are to be used for bus floorings, the primary load on these panels is flexural. The three-point bend test is conducted to compare the performance of these panels to wood and thermoset panels.

The three-point bend test reveals that the panels have 22 Mpa of bending strength, which is slightly more than thermoset panels which show strength of 20 Mpa. More bending strength validates the structural adequacy of these panels.

Impact testing: Further bus floorings are subjected to certain low-velocity impacts such as baggage drops and debris hitting the floor surface; this is simulated using low-velocity impacts. The panels show stronger impact resistance when compared to the thermoset panels used in the Korean low-floor buses.

Mechanical performance: The panels demonstrate mechanical safety as they provide better bending strength than the commercially available thermoset panels. The thermoset panels are tested to meet bus floorings standards, while the impact tests evaluate them for wear and tear.

6 Results and discussion

6.1 Discussion

6.1.1 Discussion (three-point bend test)

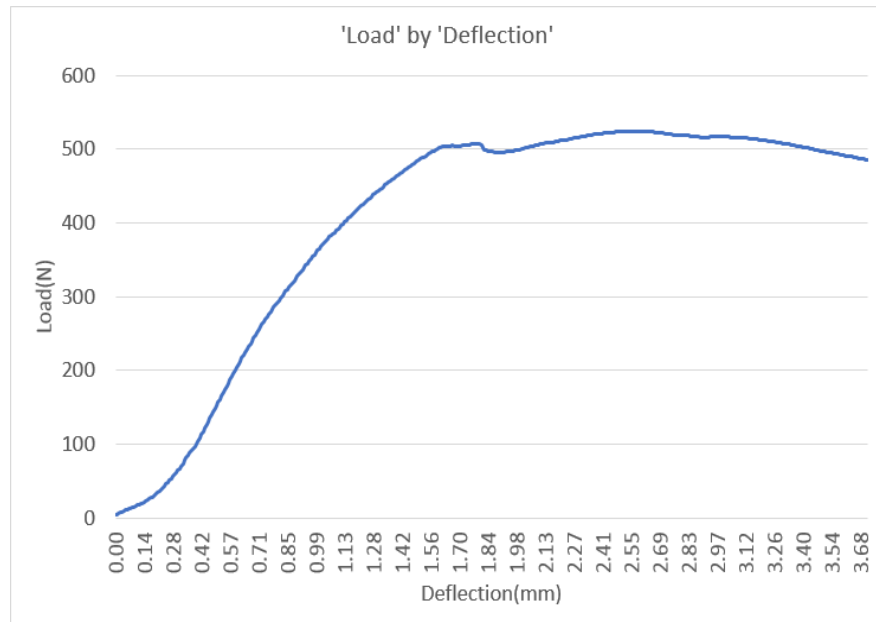


Figure 44: Three-point bend test (load vs deflection curve)

Instron 5500 was used to measure the bending performance, whereas a bending strength of 22 Mpa is achieved when averaged over three specimens (14.8mm thick), mentioned above. This is significantly better than the thermoset commercial counterpart, which displays a bending strength of 20 Mpa for an increased bending rigidity at a thickness of 30 mm.

While wood performs slightly better at 34 Mpa, it is significantly heavier, as shown in Table 7 at 10.2 kg/m² than 8.8 kg/m². The graph in Figure 44 shows elastic deformation up to 565 N for the manufactured polypropylene panels. After that, there is a period of plastic deformation where the failure has occurred. This is demonstrated by an increase in deflection that occurs with no changes in the load.

6.1.2 Discussion (impact test)

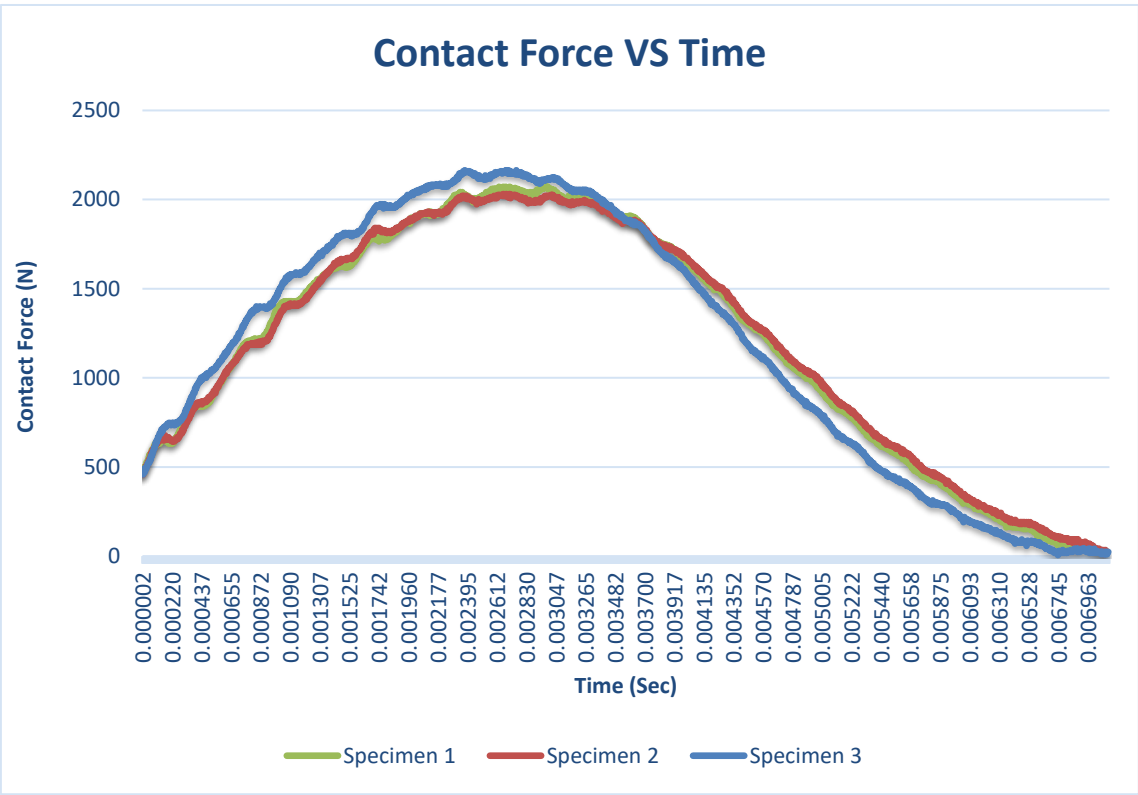


Figure 45: Contact force vs time graph for specimens

Apart from visual inspection, force-time graphs were used to draw analytical inferences, as shown in Figure 45.

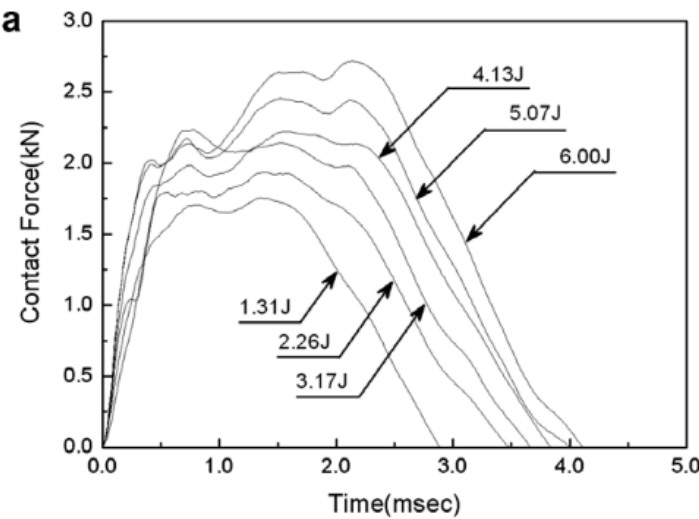


Figure 46: Glass epoxy and aluminium honeycomb impact testing graphs

[44]

The thermoset epoxy counterpart shows elastic response up to the first peak, and then a subsequent drop indicates plastic damage to the skins. This drop is further continued and can be seen through the rise and falls after the first peak. However, the ductility of PP is responsible for lower plastic damage resulting in a smoother curve. The same can be confirmed through visual inspection as residual damage areas are half of that observed in the literature.

6.2 Overall impact of the manufactured panels

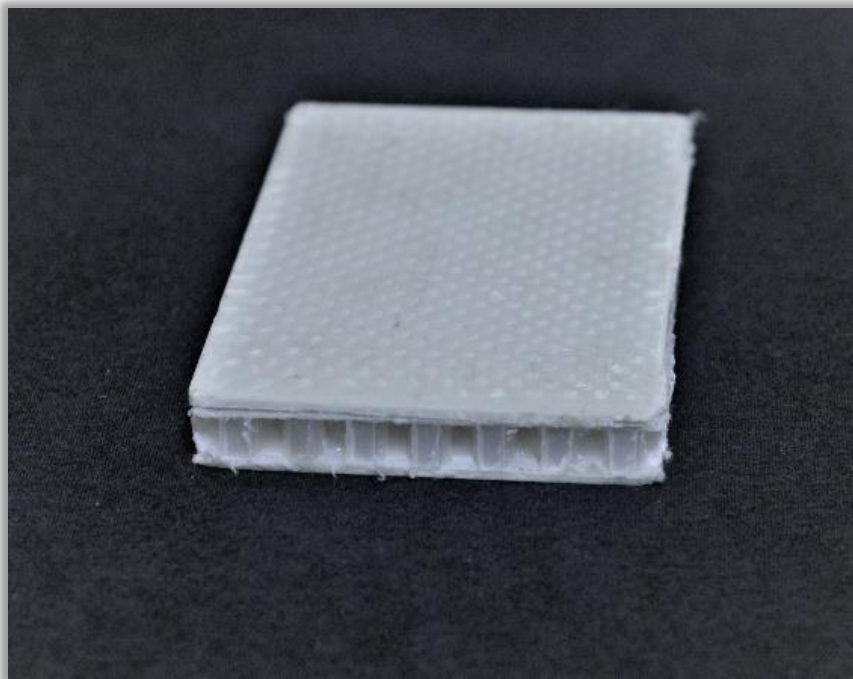


Figure 47: Manufactured Sandwich Panel

- PP's low-surface energy makes it difficult to bond; thus, interfacial failures are observed in previous literature [18]. The manufactured panels overcome this, as demonstrated by three-point bend tests. Significant improvements in taking the impacts are also observed.
- The panels are well in bounds of the estimated 10 pound per kg saved cost bracket for these panels' successful marketability. The low-cost

manufactured honeycombs eliminate the need for an expensive initial manufacturing setup that might be required for thermoforming and pultrusion, making it difficult for smaller companies to break even with the costs.

- Rapid production time is also an advantage that the thermoplastics offer, and the ease of recyclability as the complete panel is made of polypropylene excluding the hotmelt, which is also in proximity of the PP's melting point which potentially makes it easy to recycle. As conveyed in the literature previously, trucks are sent back to manufacturers to recycle. Thus, this can mean saving costs while recycling and meeting the vehicle directives, which enforce recyclability of components.
- The bending strength is on par with the commercially available thermoset counterparts, which proves its structural fit to replace such panels in HDVs.

6.2.1 Limitations

- Steel and wood have been in use for quite a long; the production is cheap, and the supply chain is stable. Whereas honeycomb panels have a relatively lower number of manufacturers and thus have lower availability.
- While the panels' bending strength exceeds that of thermoset counterparts, it is still lower than that of commercial birch wood. This can be changed by increasing the honeycombs' wall thickness and optimising the skins' layups.
- If the skins of the panels are penetrated honeycombs that can be prone to moisture retention, it can lead to the material's degradation.

6.2.2 Weight-saving potential of the manufactured panels

Manufactured composite sandwiches have certain advantages:

- The low material cost of 36 €/m² for a 15 mm panel.
- Approx. 51 kg of weight-savings per bus if used as floor panels. Further use as side panels may extend the weight-savings to around 157 kg

A weight-saving of 51 kg for a 13 m bus having a floor area of 37 m² can be estimated. There is room for further optimisation with the use of thermoplastic preregs and an optimised layup with automatic interfacial resin flow.

Similarly, polypropylene panels can be used for side panels with a weight-saving of 13.1 kg per door which translates to a further potential weight-saving of 157 kg if the bus has 12 such window panes [9].

The skin layup and honeycomb cell size can further be optimised to achieve the maximum potential weight-savings. The panels also show an indicative increased service life with their resistance to impact wear and tear, as demonstrated in Chapter 4.

6.2.3 Environmental impact:

As can be observed in Table 2, city buses with more halts are the most impacted by weight-savings due to low drag at low speeds. The following fuel and CO₂ savings are observed:

If lightweight PP floor panels are used, the lifetime fuel savings in these buses translate to around **1225 litres** of and **3.4 tonnes** of CO₂ savings. Fuel savings for city bus with more halts are used for this calculation (see Table 2).

Further energy and cost reductions are observed when the weight-savings are applied to BEBs. These savings are explained in the following “cost-saving potential” section.

6.2.4 Cost-saving potential

Material cost of 36 €/m² will make the product fall into the marketable price bracket as the finished birch wood counterpart costs 37.5 €/m². While wholly composite made buses provide weight-savings from 33 per cent (3 tonnes) for Ebusco to around 50 per cent for the Phoenixx, market unacceptability has been an issue in the past due to initial tooling costs and manufacturing setups. Thus component level changes have been more acceptable [25].

However, electrification goals by various countries have led to an increase in the number of electric buses. One of the most expensive components in this alternative powertrain vehicle is the battery pack. Previous studies report battery costs to be at around 500\$/ Kwh, which is approximately 385 pounds/ Kwh [23].

A more extensive range, therefore, means a larger battery which in turn means more costs incurred. This is disregarding the fact that further reducing the size of powertrain would eventually have a domino effect, which will lead to reducing the additional weight. The relationship between bus weight and energy consumption is given in Figure 48 below.

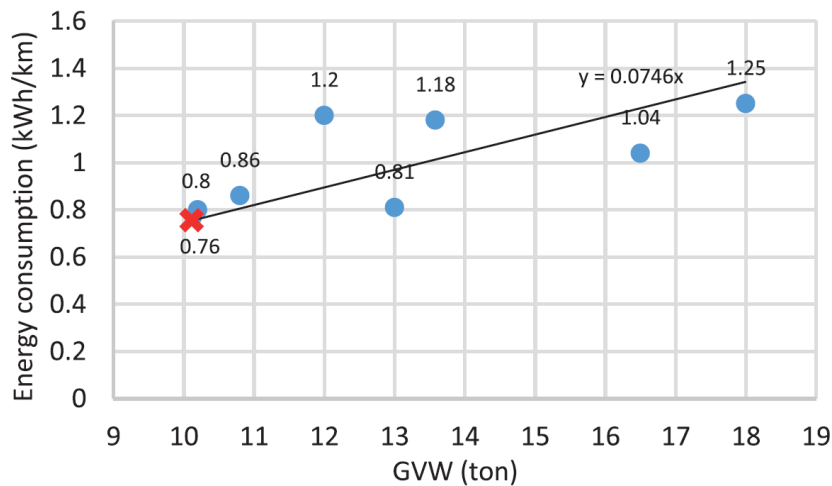


Figure 48: Energy consumed [kWh] vs GVW [23]

The following relationship is observed:

Equation 5: Energy Consumption vs Gross Vehicle Weight

$$\text{Energy consumption(kWh)} = 0.0746 * GVW \text{ (tons)} \quad [23]$$

Thus for a 13-tonnes bus that previously had a range of 500 km, a reduction of 4 kWh is observed upon 100 kg reduction. This further translates to 1540 pounds per 100 kg saved for a 500 km bus. The saving of three tons for the same bus can mean saving 43081 pounds. The general reduction of battery capacity per 100 kg weight can be estimated to be:

Equation 6: Reduction in battery capacity per 100 kg of weight-savings

$$\text{Red. in batt. capacity per 100Kg wt. saved(kWh)} = 0.00746 * R$$

Where R= Range in Kms

Equation 7: Cost saved due to battery capacity reduction per 100 kg of weight Saved

$$\text{Cost saved per 100 Kg weight saved} = 2.87 * R(\text{£})$$

Thus a 3000£ saving can be observed when 200 kg of weight is saved for a bus with a range of 500 km, which is analogous to a bus making a journey from London to Dublin.

6.3 Conclusion

The fabricated sandwich panels bridge the knowledge gap as they are recyclable, lightweight and cost-effective, and thus they can potentially replace wooden and thermoset floorings presented in the literature. The panels show a significant weight-saving of 51kg over wooden bus floorings for a 13 m long coach. This translates to a lifetime of 3.4 tonnes of CO₂ savings in a city bus with more halts and a cost reduction of 765£ in BEVs.

Further, these thermoplastic panels offer better mechanical characteristics than commercially available thermoset counterparts. The manufactured 15 mm panels

show a bending strength of 22 Mpa which is 2 Mpa more than that of 30 mm thick thermoset panels. This improvement can be attributed to fibre layup, increased skin thickness and bonding characteristics of the hot melt glue. Similarly, decreased residual damage for impact tests is observed due to the ductile nature of polypropylene.

While natural fibres require lower energy during manufacture, they have certain limitations like lower volume fraction, moisture absorbance and low flame retardancy. Further, low availability and inconsistency in manufacturing limit their use. Also, lightweighting is of prime importance for reducing CO₂ emissions is much larger in the use phase than in the manufacturing phase. Replacing wooden floor panels with thermoplastic alternatives translates to about 1225 litres of lifetime fuel savings and a reduction of 3.4 tonnes in CO₂ emissions for a city bus with more halts.

The material costs of the panel are lower than that of finished wood products. While the manufacturing costs have not been factored in as they depend on various factors such as the number of panels being manufactured, the weight reduction can justify this increase in cost due to lower fuel usage.

While panels show significant potential as a recyclable lightweight and low-cost solution, the following characteristics could not be achieved:

- A one-step process to manufacture the skins and bond them with the core would have been ideal; however, this could not be achieved due to the high processing temperature of polypropylene coupled with the relatively low compression strength of the honeycomb core.
- High-temperature processing increases initial tooling investment as compared to thermosets, which means that a larger number is required to break even the costs.
- The sandwiches show sufficient bending strength when compared to commercial thermoset panels. While this helps to prove their structural

adequacy, they have 14Mpa less strength than wooden flooring panels of the same thickness. However, it is to be noted that wood weighs significantly more.

6.4 Further research scope

Due to the limited time, many further research avenues are left out of this thesis's scope. However, there is research potential in optimising the weight using thermoplastic prepregs, automated interfacial glue dispersion and optimised skin thickness. Further, NVH and fire retardancy of the panels can be investigated.

While thermoplastic hotmelt glue at the interface is recyclable, it certainly adds a third material to be recycled making; this can be further idealised using ultrasonic welding. In this process, ultrasonic waves generate high friction between the materials, leading to melting and bonding of the thermoplastics. However, the process can be complicated due to the use of honeycombs.

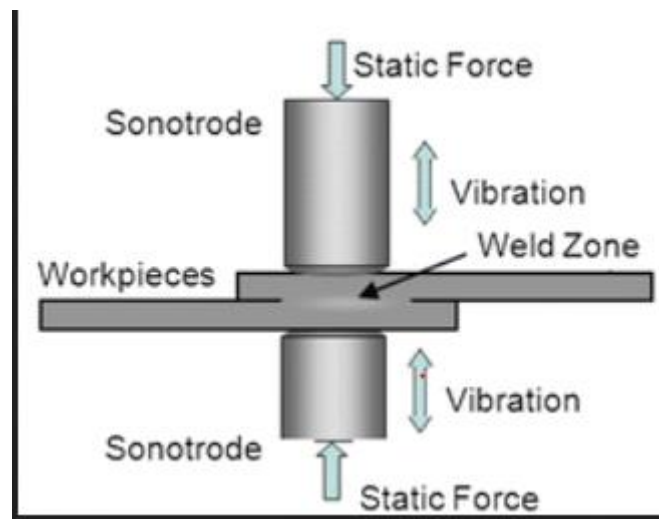


Figure 49: Ultrasonic welding schematic diagram [46]

With flame retardancy, a higher fibre weight fraction can be helpful as fibres resist flame propagation. Further addition of flame retardants is an important avenue that can be explored further in future research.

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