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Cleanmould

Development of Lightweight, Recyclable Thermoplastic Composite Semi-trailer and Boat Hulls with Enhanced Performance

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Specific Targeted Research Projects

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Table with 3 columns and 5 rows detailing project funding and dissemination levels.

## EXECUTIVE SUMMARY

The Cleanmould program has developed a novel PBT-glass fibre (PBT-GF) thermoplastic composite material (based on CBT® oligomer resins) and modified versions of a vacuum bag consolidation process, VARTM process and VI process to mould components from the material. A pre-preg version of the PBT-GF material and the vacuum bag process have been implemented on a large scale to manufacture two case studies: a flat-bottom boat 5m in length and a flatbed semi-trailer 13.6m in length.

The CBT® resin has been refined to give consistent results in composite applications. Methods have been assessed and proven for adding additional properties such as fire retardancy or self-colouring. A variety of solid and liquid catalysts have been developed that control pot life and 'cure' time to make CBT® resins suitable for different manufacturing processes and for different scales of product. The traditional problems of moisture sensitivity and the requirement for fast heat up rates have been overcome.

Non-crimp woven glass-fibre reinforcement fabrics have been manufactured with compatible sizing and coupling agents, these have been used with liquid forms of the resin and also as a carrier for solid forms of resin-catalyst compounds as intermediate fabrics or pre-pregs. The lamination process has been used to produce a pre-preg on an industrial scale with excellent consistency and repeatability of composite properties – but with limitations of poor drape and poor handling characteristics. An extrusion process has produced a much more promising pre-preg that closer represents a product that could become commercial, possessing excellent drape and handling characteristics as well as thermoforming in the mould and tack between plies, however the technology has not yet been developed to a level where material can be produced on an industrial scale.

Excellent mechanical properties have been achieved from all the manufacturing processes resulting in flexural, shear, and impact characteristics that are equal or better than industry standard polyester-glass fibre vacuum infused laminates. A flexural modulus of 50GPa has been achieved with uni-directional reinforcement and CBT® 160 resin, which is high enough to facilitate the application of the material to stiffness dominated structures such as the trailer case study. The durability and toughness of the material makes it applicable to harsh environments and operator abuse such as in the boat case study.

A methodology has been established for recycling components manufactured from PBT-GF composites at the end of their working lives. This can be achieved through cutting, shredding, compounding with virgin PBT and injection or compression moulding into complex recycled products. As with most recycled products, there is a high level of variability in properties however the mean flexural strength is comparable to that of off the shelf PBT moulding compounds.

A complete redesign of a traditional steel flatbed semi-trailer has been conducted that considers and is designed around the advantages and limitations of the PBT-GF composite material. The brief was to manufacture a semi-trailer with the same functionality as the benchmark, (i.e. the same load area, payload and stiffness) but with added advantages of reduction in weight and aero drag. To achieve this the full space envelope permitted by practicality, legislation and aesthetics has been exploited to increase the depth of the structure and hence its 2<sup>nd</sup> moment of area (I). This has allowed lower cost lower modulus composite materials (compared to steel ~ 30GPa vs ~200GPa) to be applied whilst achieving the same rigidity.

The general shape of the trailer moulds has been kept simple to allow the technicians to physically lay-up the rigid pre-preg into the tool. The high cost of a composite tool with suitably high glass transition temperature has meant that shape was simplified to allow for fabrication of a sheet steel tool.

A monocoque design has been implemented to achieve the design brief and the flat smooth exterior creates low drag surfaces; neat packaging of the trailer hardware has further reduced disruption to the air flow. A computational study has been conducted into the aerodynamic performance of the Cleanmould semi-trailer when fitted with a box superstructure. Aerodynamic bodywork appendages similar to existing bodywork solutions have been added to the computer model and evaluated in terms of overall drag reduction in various cross-wind situations. With the bodywork fitted, the Cleanmould trailer showed up to 12% drag reduction. A CAD model concept was drawn up for an aerodynamically optimised composite trailer with an organic shape to its underside and box superstructure – with no real reduction in load space the drag was reduced by up to 21% which can be expected to relate to over 10% direct fuel saving.

In summary the case studies have successfully been manufactured and show the real benefits to the end user of the application of thermoplastic composites for light-weighting, improving aerodynamics and ruggedizing products. The material itself has been shown to have structural advantages over existing state of the art thermoset composite systems, but has the added advantage that it can be coupled with end of life recyclability and clean VOC free manufacturing processes. The output of this project has extended the state of the art and the technology contained within this project has been developed from TRL level 1 right through to TRL level 6 – i.e. from academic research right through to full demonstration in an industrial context.

## PROJECT EXECUTION

### Original research objectives

The strategic objectives of this program were to provide sustainability in the European transport and other manufacturing sectors through:

- The development of advanced composite materials that are:

Thermoplastic; tough; durable; emit no VOCs; have a high strain to failure; have excellent fatigue, impact, water and chemical resistance; have high fibre volume fraction and thus can reduce component mass; have low density and high specific mechanical properties; are low cost and totally recyclable

- This novel high volume fraction thermoplastic composite material will be used to produce complex components using new manufacturing processes that enhance sustainability through:

Emitting no volatile organic compounds and improving safety through component and design integration; production of high quality structural products that will reduce component weight, consumable, fuel and energy consumption and greenhouse gas and toxic emissions; enabling a cleaner manufacturing environment through the use of inert, dry resins; automating the manufacturing process and reducing the cost and complexity of tooling whilst increasing their flexibility and functionality.

### Expected deliverables

- Design and manufacture a 13.6m flat bed semi-trailer chassis in fibre reinforced PBT, that is 25% lighter and more aerodynamic (in order to achieve a fuel saving up to 7.5% percent or 3198 litres and a CO<sub>2</sub> reduction of 8.5tonnes per year) than an equivalent steel chassis.
- Manufacture an 8m rigid inflatable boat in fibre reinforced PBT that is 10% lighter and has enhanced impact and structural performance over a conventional fibre reinforced polyester/vinylester boat.
- Developed PBT oligomer compounds with low melting point (ie 160<sup>0</sup>C) and viscosity (20cP) that provide excellent heat resistance, impact resistance and manufacturing flexibility.
- Developed techniques to combine PBT oligomer with continuous fibre reinforced fabrics that are easy to handle in the mould, have a controlled fibre (ie 50% by volume) content and high mechanical (ie 30GPa modulus, 700MPa Strength and 30MPa interlaminar shear strength) properties
- Developed new environmentally friendly (i.e. no volatile organic compound emissions) manufacturing process capable of moulding large surface area thick sectioned case study structures in fibre reinforced PBT.
- To increase competitiveness through the automation and modularity of manufacturing processes, and the reduction in fuel use of the order 9% through lightweighting and aerodynamics.
- To undertake a full range of mechanical testing (ie strength, stiffness, creep, fatigue etc) on fibre reinforced PBT materials.
- To undertake in-service testing on the 2 case study structures in order to quantify the technical, economic and environmental benefits.
- To reduce energy and resource use through enhanced product lifespan and recyclability at product end of life and to develop the recycling strategy and methodologies for thermoplastic composite semi-trailers and boats so that they meet the end of life directives (EN2000/53/EC)

### Project's actual outcome

- A novel thermoplastic resin has been developed which allows the manufacture of high volume fraction components through modified versions of the traditional moulding processes of RTM, VI and vacuum bag moulding.
- A novel thermoplastic composite 'pre-preg' has been developed and used to produce very large, complex components.

- Traditional moulding procedures have been modified to accommodate this novel material resulting in enhanced manufacturing procedures, where dry inert raw materials are used, there are no harmful VOC emissions and the use of hazardous chemicals is vastly reduced.
- Improved product sustainability through employment of durable, corrosion resistant materials that increase product life cycle and can be recycled into new products at the end of life.
- Reduction of green house gas and fuel usage in the road transport sector through employment of weight saving high volume fraction composite materials.
- Design & manufacture of a 13.6m fully functional PBT composite, flat bed, tri-axle, semi-trailer.
- Intelligent tooling manufactured that allows for complete freedom in axle-configuration (ie position and number).
- Trailer geometry that provides; improved aerodynamics; structural rigidity (ie 2<sup>nd</sup> moment of area); and a vertically stackable shape allowing multiple trailer chassis to be manufactured in batches and stored/transported in a single trailer foot print before fit-out.
- Manufacture of a lightweight 5m Dory boat hull combining PBT composite and other recyclable thermoplastic composite materials.

#### Other deliverables for the project:

- An R&D strategy for further research and application of PBT composites in this and other industry sectors was planned.
- Development of techniques and knowledge to implement PBT composites in small but high quality and rapidly manufactured components.
- Develop knowledge, skill and experience in designing and manufacturing composite commercial vehicles.
- Train and develop key project management and engineering skills in involved staff.
- Gain publicity for the project partners in their industries and also externally.

### **Broad dissemination and use intentions for the expected outputs**

#### **EU Composite Industry**

- Achievement of the previously impossible goal: economical high volume fraction thermoplastic composite components manufactured from low cost processes.
- Solution to the ever increasing health and safety restrictions on VOC (mainly styrene) restrictions imposed on traditional composite resin systems (i.e. polyester and vinylester)
- A new thermoformable composite material that opens up new assembly practises reducing the reliance on expensive and often environmentally harmful adhesives

#### **EU Trailer Building Industry**

- A novel product that, through weight saving and drag reduction, offers massive in-life savings and an inherent value at the end of life.
- Ability to offer customers increased payload and potential reduced number of trips.
- Increasing economical advantage as fuel prices rise.
- New methods of meeting EU crash safety legislation with reduced mass
- New possibilities for storage and feature integration into the chassis

#### **Public Impact**

- Less pollution of harmful NO<sub>x</sub> and CO<sub>2</sub> from HGV tractor units in urban and rural areas
- 1 trailer can carry more payload so the number of trips is reduced and hence traffic in urban and rural areas is reduced
- Reduced vehicle weight lessens the damage caused to EU road infrastructure, providing improved driving surfaces and less disruption from maintenance.

#### **Other Manufacturing Sectors**

- Automotive, aerospace and construction applications for PBT composite structures

## **COMMUNITY ADDED VALUE AND CONTRIBUTION TO EU POLICIES**

### **European dimension of the problem**

According to the EUROPA website, within the EU 44% of goods go by road. Road traffic contributes to 23% of EU CO<sub>2</sub> emissions (2006) and is expected to rise in 2010. In 2001 road freight travelled 1395 billion tkm and emitted CO<sub>2</sub> at a rate of 0.178 kg/tkm. The composite trailer produced on this project is expected to deliver 10% (~1.5% from weight and 8.5% from aerodynamics) CO<sub>2</sub> and directly proportional fuel savings. If all freight within the EU could realise efficiencies of 10% then a total CO<sub>2</sub> saving of 24,831,000 tonnes could be made.

### **Contribution to developing S&T co-operation at international level. European added value**

This project has brought together the wide range of technical and industrial skills required to economically produce high volume thermoplastic composites. These skills have been implemented to produce the world's first recyclable composite semi-trailer. Four of the partners will continue with further research in the applications and processing of PBT composites, and use this to develop sustainable products in the future. Two of the partners will continue to promote the composite semi-trailer concept and potentially develop further advanced prototype and eventually commercialised products.

### **Contribution to policy design or implementation**

Completion of this project and dissemination of the results will provide legislators and policy makers with evidence that technical solutions exist for more stringent emission regulations, and tougher end of life vehicle directives to be applied to the road transport sector.

## **CONTRIBUTION TO COMMUNITY SOCIAL OBJECTIVES**

### **Improving the quality of life in the Community :**

The manufacturing processes developed herein reduce VOC emissions, use less harmful chemicals, produce less waste and use less net energy compared to traditional process. All these advantages contribute to clean healthier living environments through cleaner air and less land fill contribution.

The composite trailer itself has CO<sub>2</sub> (and other harmful exhaust gasses) emission benefits. Providing cleaner air and less pollution in urban and rural areas. Furthermore the effect of less vehicle weight, and less journeys reduces the road freight impact on EU infrastructure – in turn the public have access to less congested roads with fewer maintenance related disruptions.

### **Provision of appropriate incentives for monitoring and creating jobs in the Community:**

With the current tough economic situation, innovation in the road transport sector and expensive R&D work in the other industrial areas cannot be easily funded and as such this is a poor time to develop a new product line. However it is hoped that either a new SME company (with approximately 10 employees) could be set-up for the production of composite trailers in the next few years or alternatively one of the end user partners could begin production and hire an additional 3 members of full time technical staff.

Importantly this project has helped to maintain jobs during a time of mass redundancy and closures. The manufacturing of the trailer certainly secured permanent jobs at BAE and involved hiring of several contract staff at peak periods.

If the use of this novel PBT composite material is widely adopted the increase in staff required to produce commercial amounts would be significant. A cyclic PBT manufacturing plant in Schwarzheide, Germany would have to increase technical production staff by at least 5 full time employees over the next few years. Application engineers could be employed at Cyclics corp to handle the additional demand.

At EPL a further research program has been initiated that has involved hiring one full time technician, and one graduate engineer.

### **Supporting sustainable development, preserving and/or enhancing the environment :**

The aforementioned environmental impact of the fuel saving trailer is an example of how the current issue of CO<sub>2</sub> emissions is being addressed. However the product is truly sustainable in that it tackles this current issue but also has little environmental impact at the end of its life by providing 100% recyclability.



## Glossary

<b>Dory</b>	- A flat bottom rapid response craft used by emergency services
<b>Twintex®</b>	- A co-mingled composite fabric made from glass-fibres and polypropylene yarn
<b>PBT</b>	- Polybutylene terephthalate – a common engineering polymer
<b>oligomer</b>	- A molecule consisting of a few monomers
<b>monomer</b>	- A small (i.e. low molecular weight) molecule
<b>CBT®</b>	- Commercial name for Cyclic Corporations oligomer of PBT resin system
<b>CBT® 500</b>	- The composite specification of CBT® resin
<b>CBT®160</b>	- A solid compound of CBT® resin and fast acting catalyst
<b>VB</b>	- Vacuum Bag. Used to consolidate components under atmospheric pressure
<b>LTM</b>	- Liquid transfer moulding, liquid resin is combined with reinforcement in a tool
<b>RTM</b>	- Resin transfer moulding, liquid resin is injected into a tool
<b>VARTM</b>	- Vacuum assisted RTM. Liquid is injected into a tool under partial vacuum
<b>VI</b>	- Vacuum infusion, liquid resin is sucked into a tool held under vacuum
<b>DP</b>	- Dew point, a measurement of water content in air
<b>KP</b>	- King pin, a steel pin that connects a semi-trailer to the fifth-wheel of a tractor unit
<b>Monolithic</b>	- Made from the same single material
<b>PBT-GF</b>	- Abbreviation for composite materials containing PBT and glass-fibre reinforcement
<b>FMF</b>	- Fibre mass fraction, the proportion of reinforcement by weight in a composite
<b>FVF</b>	- Fibre volume fraction, the proportion of reinforcement by volume in a composite
<b>CTE</b>	- Coefficient of thermal expansion
<b>Tg</b>	- Glass transition temperature
<b>BM</b>	- Bending moment



## FOREWORD

This document forms the final dissemination report for the Cleanmould project. A complete list of the original project deliverables and milestones can be found below.

### Overview of major Milestones

Milestone	Due Date	Brief Description	Decision Criteria for Assessment
<b>M1</b>	3 months	Case Study Specification Report	Report confirming the perceived technical, economic and environmental benefits
<b>M2</b>	12 months	PBT Oligomer Development	Development of PBT oligomers with low melting point (i.e. 150°C) and low viscosity (20 cP)
<b>M3</b>	18 months	PBT Oligomer Composites	Development of PBT composites with up to 50% Vf with excellent mechanical properties
<b>M4</b>	27 months	Tooling Critical Section Manufacture	Demonstration that critical sections of the 2 case study components can be manufactured
<b>M5</b>	36 months	Validated Case Study Components	2 moulded case study components that have been evaluated under in-service conditions

Deliverables List

Deliverable Number	Deliverable Title	Delivery Date	Nature	Dissemination Level
D1	Case study specification report on semi-trailer	4	R	PP
D2	Case study specification report on boat	4	R	PP
D3	Up to 3 PBT oligomer compounds with reduced moisture sensitivity	10	O	CO
D4	Up to 3 PBT oligomer compounds incorporating pigmentation and fire retardancy	10	O	CO
D5	Determination of optimum form of PBT oligomer	10	O	CO
D6	4 fibre reinforced PBT composite materials	19	O	PU
D7	Optimising fibre sizing and coupling systems	19	O	PU
D8	Process methodology	19	R	PU
D9	Optimised process model and specifications	19	R	PU
D10	Techniques to incorporate inserts	19	R	PU
D11	Mechanical property database	19	O	PU
D12	Case study design reports on semi-trailer	25	R	CO
D13	Case study design reports on boat	25	R	CO
D14	Validate designs of critical sections of semi-trailer and boat	28	P	RE
D15	Report on performance of critical sections	28	P	RE
D16	Prototype case study tooling for semi-trailer	28	P	RE
D17	Prototype case study tooling for boat	28	P	RE
D18	Prototype thermoplastic semi-trailer	31	P	RE
D19	Prototype thermoplastic boat	31	P	RE
D20	Prototype test report on semi-trailer	36	R	RE
D21	Prototype test report on boat	36	R	RE
D22	Recycling methodology report	36	R	PU
D23	Final report	36	R	RE
D24	Quarterly progress reports	36	R	RE
D25	Minutes of quarterly meetings held	36	R	RE
D26	11 Task reports	36	R	RE
D27	Final project report	36	R	RE
D28	Project website	12	R	PU
D29	3 Press releases	36	R	PU
D30	3 Technical articles	36	R	PU

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## INTRODUCTION

This final dissemination report gives an overview of the project remit, the aims, the achievements, and the problems encountered along the way. More detailed reports have been compiled and are referenced herein – however these are confidential to the project partners and commission services. This report gives an overview of the project results that can be disseminated in the public domain.

## 1. WORK PACKAGE 1 – CASE STUDY SPECIFICATION

**Detailed Report :** M1 Report

**Covering:**

D1 - Specification of trailer

D2 – Specification of the boat

### 1.1 WP1 Overview

The selected case study components for the Cleanmould project were:

1. A 5m Dory flat bottom boat manufactured from Twintex® by BAE Systems
2. A 13.6m flatbed semi trailer manufactured from Steel by Basmler



Figure 1: Case Studies

The case studies were deconstructed and thoroughly analysed in order to generate specifications for the prototypes to be manufactured from PBT based thermoplastic composite materials.

## 2. WORK PACKAGE 2 – PBT OLIGOMER DEVELOPMENT

**Detailed Report** : M2 Report

**Covering:**

D3 - Up to 3 oligomer compounds with reduced moisture sensitivity

D4 – Up to 3 PBT oligomer compounds incorporating pigmentation and fire retardancy

D5 - Optimum form of PBT Oligomer

### 2.1 WP2 Overview

Cyclics Corporation have developed a range of resins known as CBT® that, in the presence of a suitable catalyst and a suitable processing environment, polymerise into the common engineering plastic PBT.

The unique attributes of CBT® resins i.e. low viscosity (<40cP) and low melt temperature (<200C) allow high fibre loadings to be achieved in composite laminates. This results in high strength and stiffness properties for the moulded part. The thermoplastic composite material can be used in structural applications where traditionally only thermosets could be used. The thermoplastic composite offers advantages in toughness, recyclability, thermoforming and welding amongst others.

A specification known as CBT® 500 has been refined for use in composite applications. This can be combined with a different range of liquid or solid catalysts to give a wide range of cure times from 2 minutes up to 5 hours. Table 1 below shows a summary of the different processing windows for various catalyst – CBT® compounds.

Catalysts	Cyclics Developmental Name	Form @ room temperature	Commercial Name – One-Part Systems	CBT® Polymerization Time (190°C; 0.3 mol% Sn)	Recommended for use in which process(es)
NONE	XB0	Solid	CBT® 500	--	--
FASCAT 4101 FASCAT 4105 (includes AO)	XB3	Solid	CBT® 160	20-30 min	RTM VB Compression Moulding
FASCAT 4100	XB8	Solid	XL-103	2 hours	VB
FASCAT 4102	XB6	Liquid	--	5 hours	R&D RTM VI

Table 1: Comparison of catalysts

## 2.2 Additives for Fire Retardency and Intrinsic Colouring

Additives have successfully been incorporated into CBT® 500 master batches to add self-colouring (see figure 5) and fire retardency properties. Laminates produced with brominated organic compound additive have been demonstrated to achieve V-0 in the UL-94 horizontal and vertical burn test.

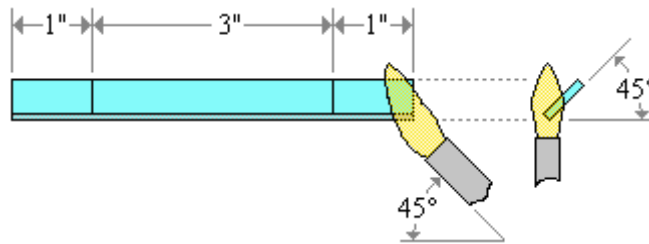


Figure 2: Test Configuration for UL94 Horizontal Burn

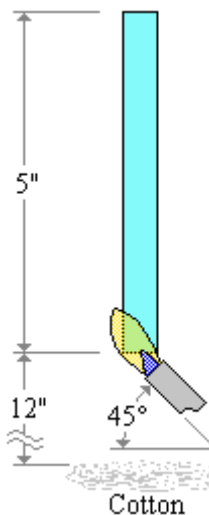


Figure 3: Test Configuration for UL94 Vertical Burn

Rating	Criteria
V-0 (Vertical Burn)	Burning stops within 10 sec after each of two applications of flame. No flaming drips are allowed.
V-1 (Vertical Burn)	Burning stops within 30 sec after each of two applications of flame. No flaming drips are allowed.
V-2 (Vertical Burn)	Burning stops within 30 sec after each of two applications of flame. Flaming drips are allowed.
HB (Horizontal Burn)	Test bar burns at a rate of <3" per minute and stops burning before the 5" mark. HB rated materials are considered "self-extinguishing".
n.r. (no rating)	Materials do not pass HB criteria.

Table 2: Classification of UL-94 results

As table 2 shows the CBT® composite achieved the best possible rating from the UL-94 test for fire retardency by self-extinguishing in less than 10 seconds.

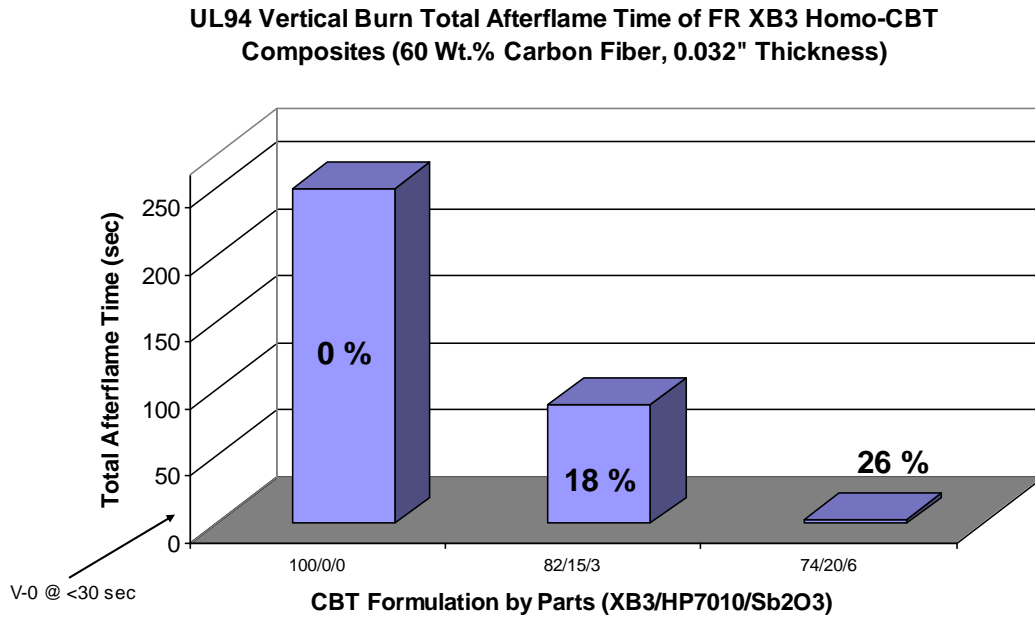


Figure 4: UL-94 Vertical Burn Results for CBT® Resin Based Carbon Fibre Composites

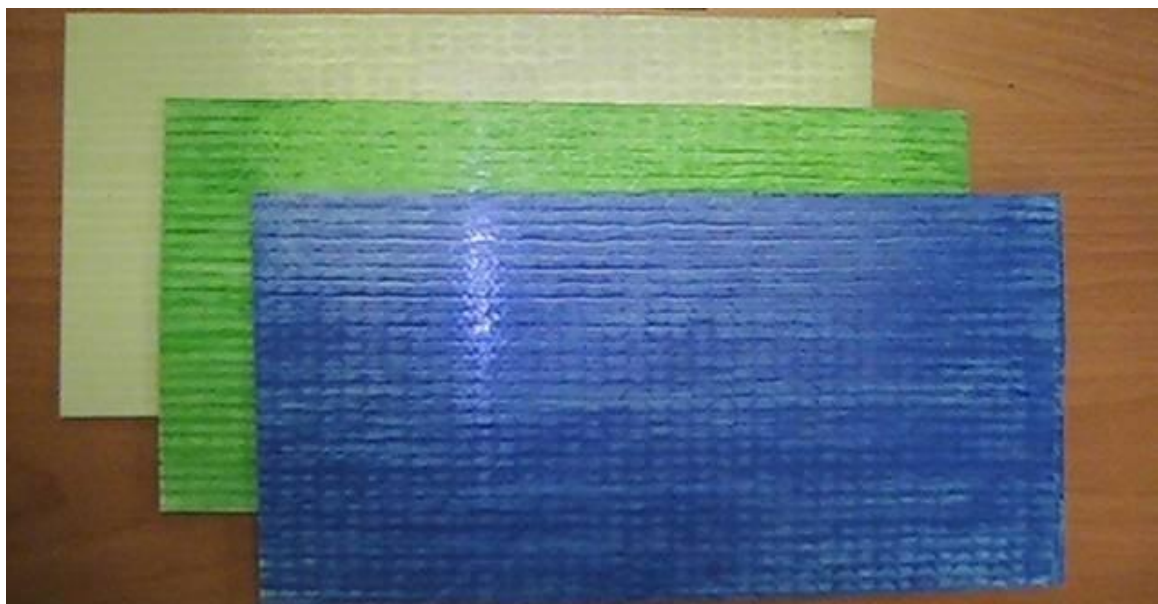


Figure 5: Compression Moulded Pigmented Glass Fibre Plaques:  
(a) CBT® 160 non-pigmented control, (b) green and (c) blue

There is a trade-off with the use of all of the additive compounds. In such a high volume fraction structural composite there is only a very small amount of resin in the laminate so the addition of non-structural additives further reduces the ratio and dramatically reduces the mechanical properties.



### 3. WORK PACKAGE 3 – PBT COMPOSITE DEVELOPMENT

**Detailed Report :** M3 Report

**Covering:**

D6 – 4 fibre reinforced PBT Composite Materials

D7 – Optimised fibre sizing and coupling systems

#### 3.1 WP3 Overview

In order to manufacture early composite laminates using CBT®160 (one-part) resin, Ahlstrom provided dry reinforcement; this was positioned in a tool, sprinkled with the resin in powder form and then heated and consolidated in a press or under a vacuum bag. Figure 6 below shows the powdered resin being sprinkled onto the dry reinforcement using a fertiliser spreader. This approach was very limited; firstly it was difficult to evenly distribute the resin across the reinforcement and as such the accuracy of volume fraction suffered. Only flat plaques could be manufactured, as any inclination of the reinforcement would cause the resin to fall off and collect at the bottom of the tool. Moreover this approach was messy and not ideal from a health and safety perspective. It was using this method of powder sprinkling that Ahlstrom were able to evaluate different sizings and coupling systems. A system traditionally used for epoxy reinforcements (R338) was ultimately found to be the most suitable.



Figure 6: Sprinkling CBT®160 onto dry reinforcement

To improve the heat and consolidate processes it was necessary to combine the two ingredients (dry reinforcement and solid resin-catalyst compound) into an intermediate fabric or 'pre-preg'. A wide range of different technologies have been trialled for the production of a PBT and glass fibre reinforcement pre-preg. However the brittle nature of CBT® resin and its sensitivity to heat stress has meant that only two approaches have been successfully implemented.

### 3.2 Laminated film pre-preg

The first method of producing prepreg is the Meyer GmbH lamination process. Using the equipment sketched in figure 7 and shown in figure 9, the process heats CBT® 160 one-part resin and catalyst in powder form and applies it as a film on one side of a woven reinforcement fabric before being rapidly cooled and consolidated between rollers. The result is a one-sided film prepreg. This material is useable but the thick, stiff and brittle film of resin prevents the prepreg from possessing good drape characteristics. This material was used to manufacture the project case studies but meant that only simple shapes could be used in the trailer and boat design as anything more complicated would be impossible to lay-up. Figure 8 shows the film prepreg being laid into the trailer hull tool – note the clamps and wooden tampers required.

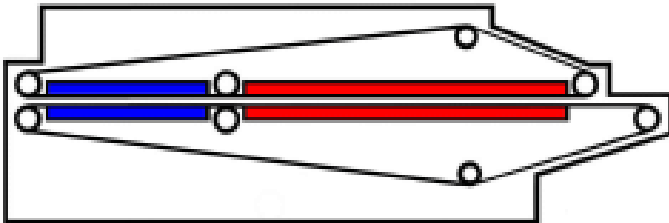


Figure 7: The Meyer laminator KFK-EL 1900



Figure 8: Laying up the Meyer prepreg



Figure 9: Meyer Film prepreg

### 3.3 Extrusion pre-preg

Towards the end of the Cleanmould project Cyclics Corporation ran a trial at Polynov in Canada where a new approach was used to create a more traditional 'pre-preg' – where the fibres were more thoroughly impregnated with the resin in an amorphous state. Polynov used a twin screw extruder to melt granules of CBT®500 neat resin before metering in Reaxis C204 catalyst at the vent section of the screw. The mixed and catalysed compound was forced into a “coat hanger die” that spread a film of molten resin over one side of the reinforcement, the reinforcement was then pulled through two temperature controlled rollers. At the point of nip the resin was forced under pressure, impregnating the fibres and causing excess resin to pool at the nip point. After very rapid cooling the resultant pre-preg was a well impregnated yet very flexible material much more applicable to complex mould geometry. Figure 10 below shows the process and the resulting high drape pre-preg.



Figure 10: Davis-Standard modified extrusion coating process to make pre-preg with excellent drape



## 4. WORK PACKAGE 4 – PBT PROCESS WINDOW DEVELOPMENT

**Detailed Report :** WP4 Report

**Covering:**

D8 – Process Methodology

D9 – Optimised process model and specifications

D10 – Techniques to incorporate inserts

### 4.1 WP4 Overview

EPL, IKV and BAE systems have worked together to develop three manufacturing processes for making structures from CBT® resin based composites. These are 1) *Vacuum Bag Consolidation* using the pre-preg (see sections 3.2 & 3.3 above) and two liquid transfer moulding processes 2) *Vacuum infusion* and 3) *Resin transfer moulding*.

### 4.2 Vacuum Bag Consolidation Method

The vacuum bag consolidation process was used to manufacture the trailer and boat case studies. The schematic for the set-up can be seen below in figure 11.

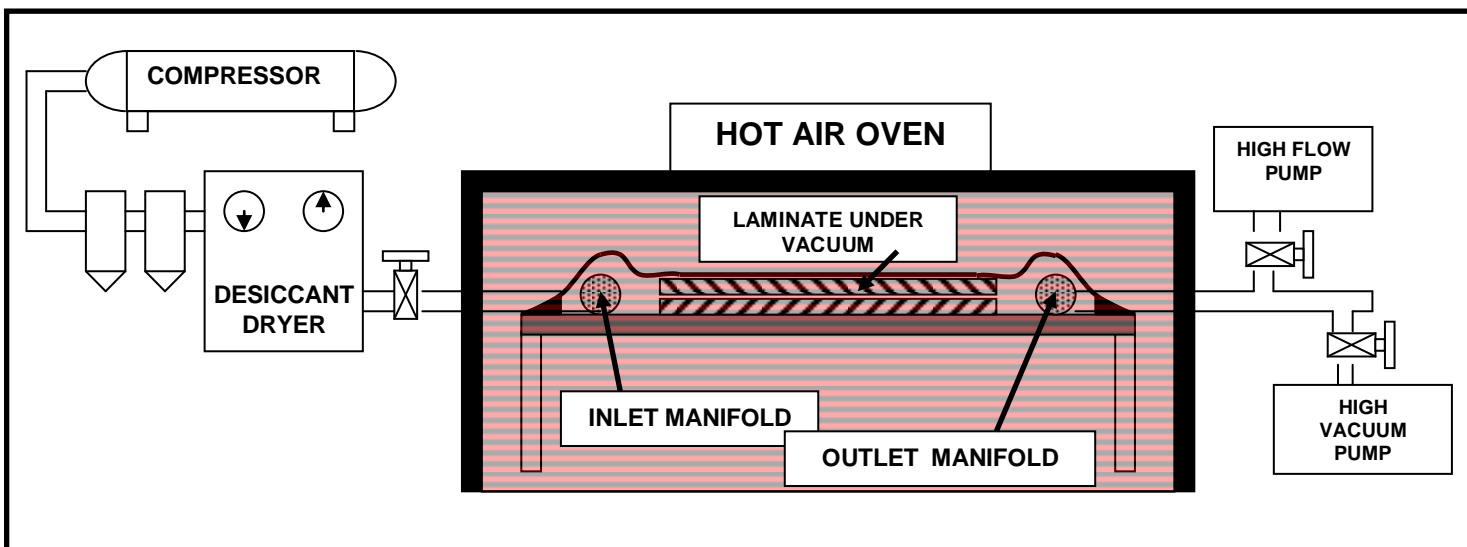


Figure 11 Schematic of VB moulding set-up

### 4.3 Resin transfer moulding method

The resin transfer moulding process (RTM) was developed by IKV, and has been used to manufacture high quality flat plaques for mechanical property analysis as well as a complex 3D monolithic part. Compressed air was used to provide hydrostatic pressure of up to 3 Bar to inject the liquid resin and catalyst mix into a closed tool. Figure 12 shows the equipment used and the parts produced from the RTM method.

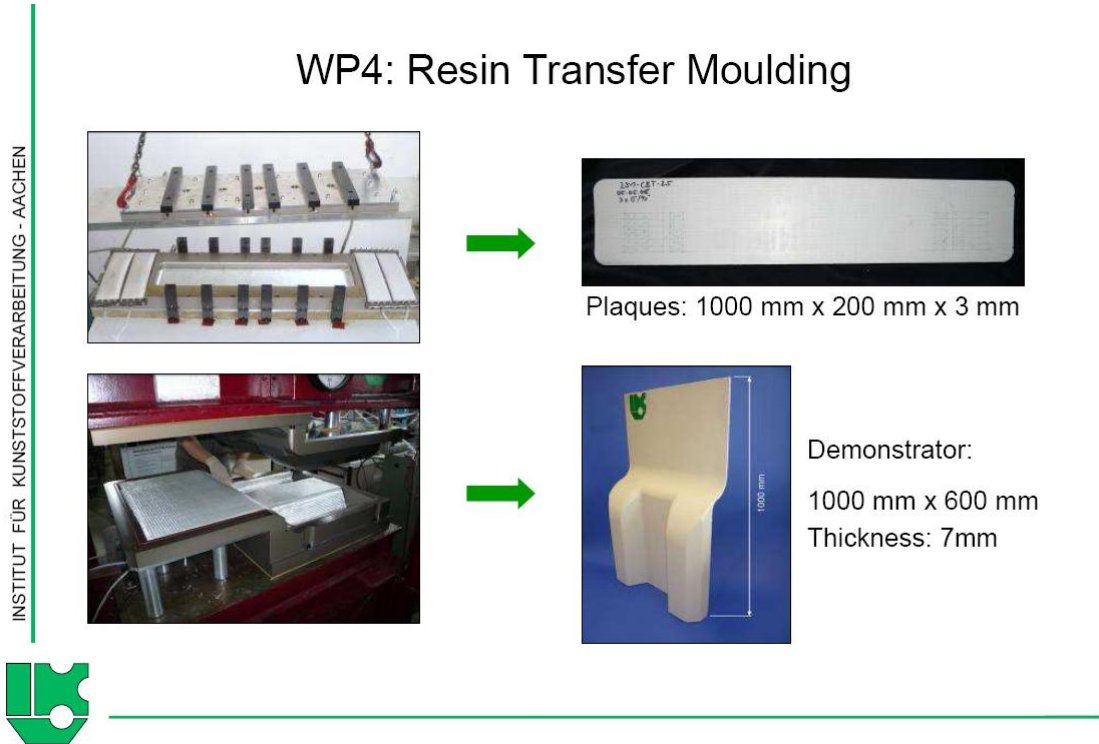


Figure 12: Equipment and components from RTM

#### 4.4 Vacuum Infusion Method

A vacuum infusion process was also established for production of 1m<sup>2</sup> flat plaques. The same liquid form of resin and catalyst was used as in the RTM process however just vacuum pressure is used to suck resin into an open tool with a flexible membrane on top.

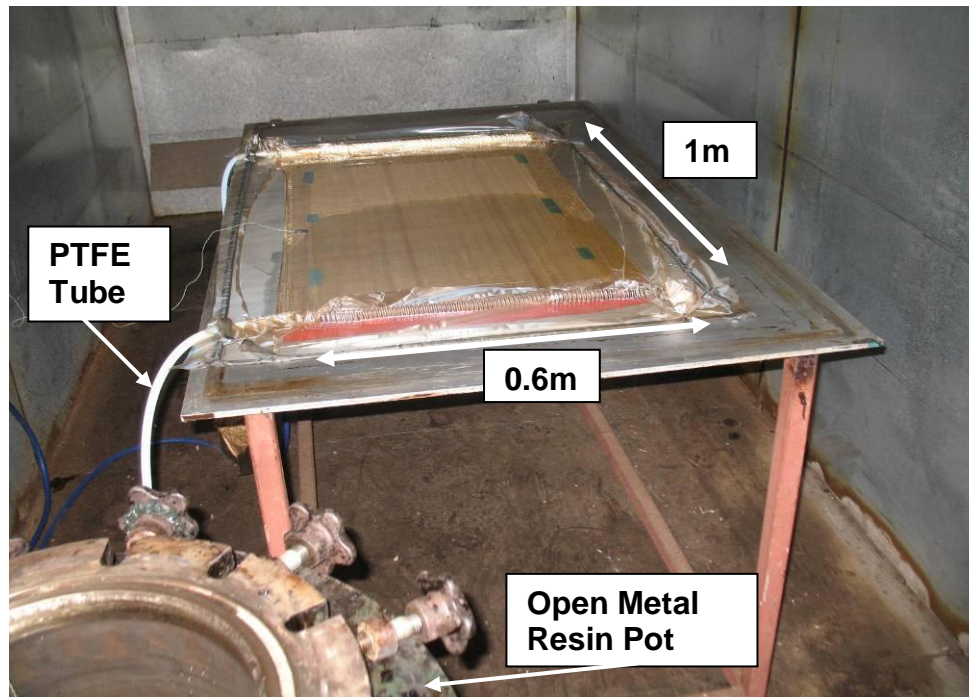


Figure 13: Vacuum infusion process

Figure 13 above shows the equipment set-up used to evaluate the vacuum infusion method. Resin and catalyst was mixed in an open metallic pot then infused along PTFE lines into the glass pack being held under vacuum. All the equipment was housed inside a convection oven to give an isothermal temperature throughout.

## 5. WORK PACKAGE 5 – MECHANICAL PROPERTY ANALYSIS

**Detailed Report :** D11 Report

**Covering:**

D11 – Mechanical Property Database

### 5.1 WP5 Overview

In this work package mechanical properties of laminates manufactured from CBT® resin and glass reinforcement have been measured for four distinct purposes:

1. Arbiter for optimisation of processing parameters for (VI, RTM and VB process described in section 4.2-4.4) in work package 4
2. Evaluation and selection of methodology (VI, RTM and VB) for producing large structures
3. Comparison of pCBT-GF properties to traditional thermoset materials
4. Evaluation of long term pCBT-GF properties

### 5.2 Selection of processing methodology

After developing the three manufacturing process in work package 4 (VB, RTM & VI) vacuum bag consolidation was selected as the most appropriate methodology – this was because the process offered practicality advantages whilst still providing excellent laminate properties. Figure 14 below shows properties of laminates produced from the developed RTM,VI and VB processes. As can be seen all three processes offer excellent and comparable results – however the VB method was the simplest to upscale.

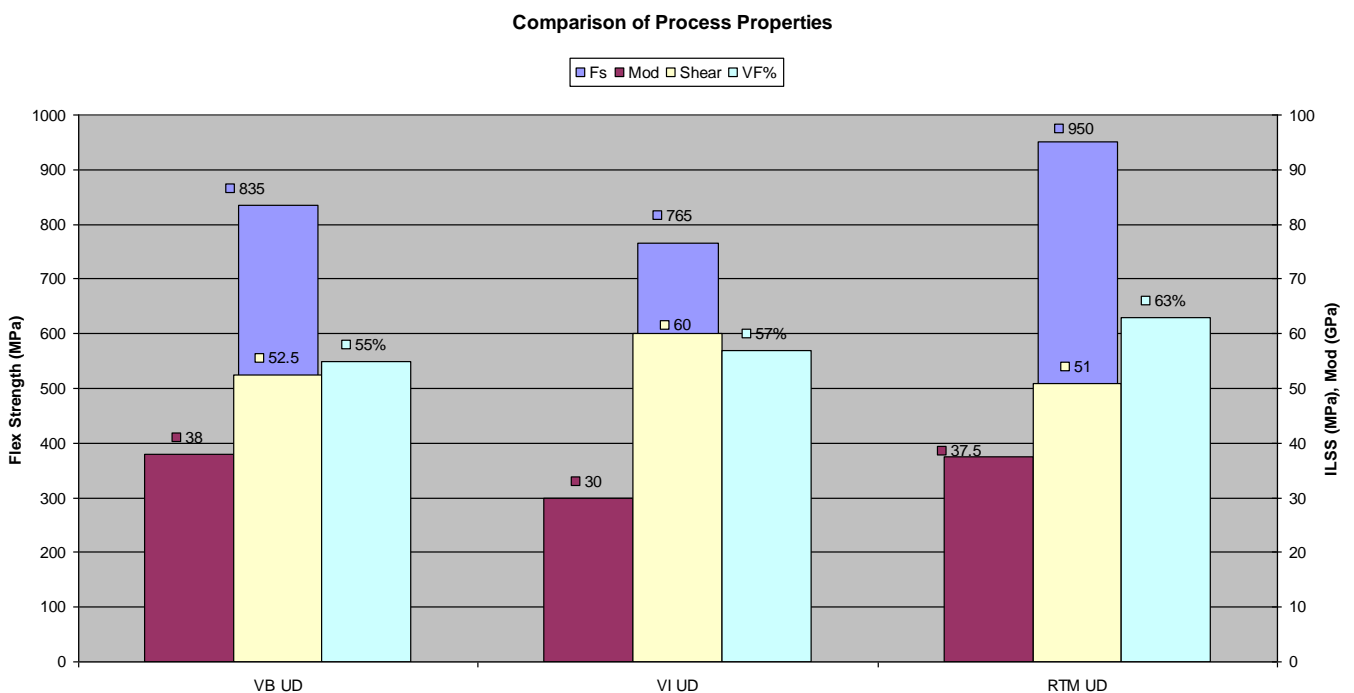


Figure 14: Comparison of uni-directional properties from the three different manufacturing processes



### 5.3 Comparison of PBT-GF to Traditional Thermoset Composite

The polymerised CBT thermoplastic composite was compared to existing products traditionally used for large, structural, industrial or marine composite applications. Three resin systems were compared:

- |                                   |                            |
|-----------------------------------|----------------------------|
| 1. Cyclics CBT®500 & XB6 catalyst | – Cyclic PBT thermoplastic |
| 2. Huntsman XB 3585/HY 951        | – Epoxy thermoset          |
| 3. Büfa Composites OldopalP 80-21 | – Polyester thermoset      |

For this work Ahlstrom's biaxial 600gsm reinforcement was selected and a vacuum assisted resin transfer moulding (VARTM) process was used to conduct liquid transfer moulding of the three different resin systems. This process allowed the variable of volume fraction of the resulting composite to be controlled. By using a 3 mm thickness tool the volume fraction was fixed at 47%.

Three-point bending tests to standard DIN EN ISO 14125 were conducted to measure flexural strength and modulus (see figure 15), whilst DIN 6603 was used to measure impact penetration properties, the set-up can be seen in figure 16 and the results of max force, and energy can be seen in figure 17.

The results from these comparison tests show that CBT® resin can be used to produce parts with comparable properties to thermoset materials. In terms of flexural properties composites made from CBT® outperform polyester both in flexural modulus and flexural strength. Epoxy resin does provide higher ultimate properties but the CBT® resin in its early stage of development returns over 80% of epoxy ultimate properties, this is very encouraging when coupled with the added benefits that the thermoplastic brings (i.e. recyclability).

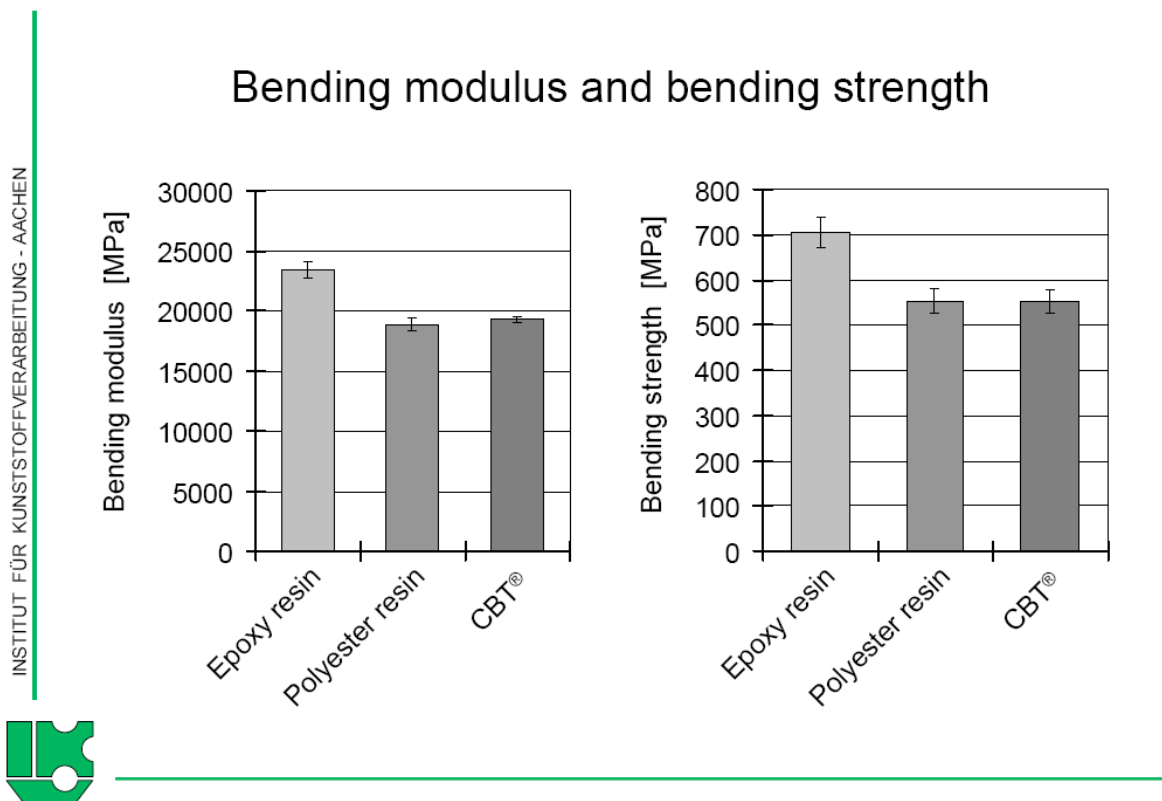


Figure 15: Flexural strength comparison to traditional thermosets

### Impact penetration test

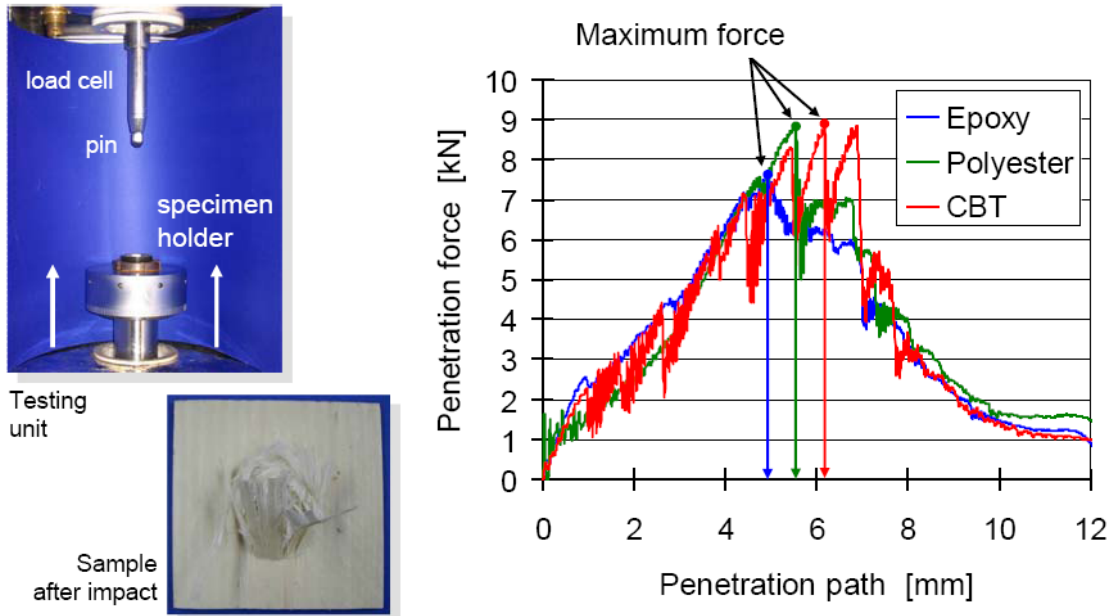


Figure 16: Impact Test - Penetration Force Comparison

### Impact penetration test

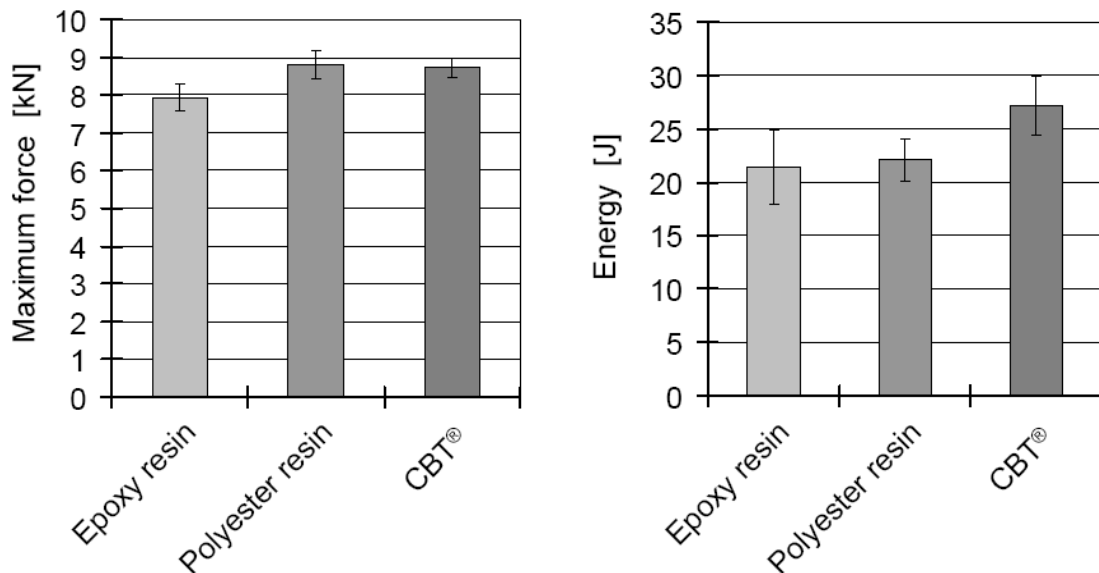


Figure 17: Impact Test - Max Force & Energy Comparison

A durability study has been conducted with several CBT specimens subjected to accelerated ageing through submersion in deionised water at a variety of temperatures (room temperature, 40C, 50C, 60C and 70C); for discrete periods between 0 and 256 days. Several observations were made, and despite a drop-off of properties at temperatures around 60C the stiffness of the composite (ie the flex modulus) remains high, figure 19 shows the sustained flexural modulus versus time. This is an excellent result for stiffness orientated designs such as the semi-trailer case study, and suggests that service life will be several years.

Future work will involve comparing the durability results to traditional thermoset materials, and also relating these results to real time environmental exposure – i.e. 25 days at 40C might equate to 1 year in service. This further analysis will permit designs to ‘life’ any components manufactured from CBT® based composite.

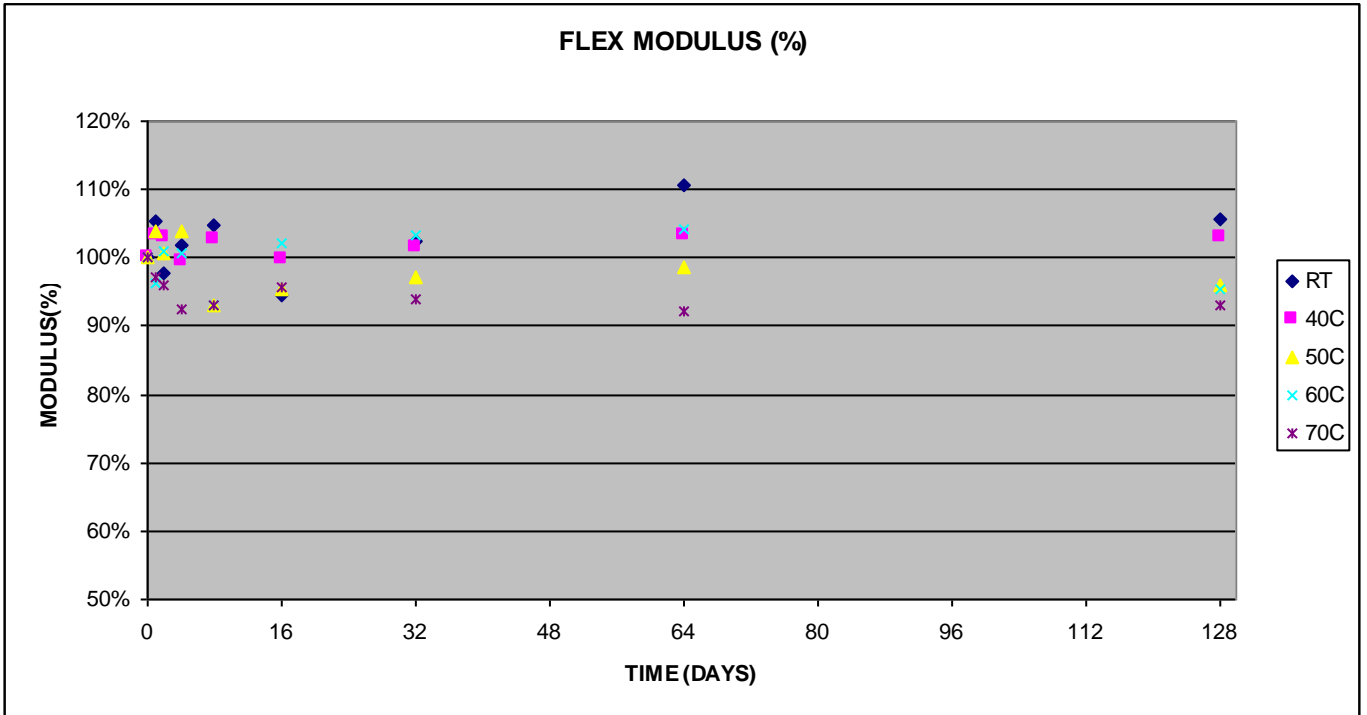


Figure 18: Accelerated aging results: Expressed as a percentage of day 0 flexural modulus

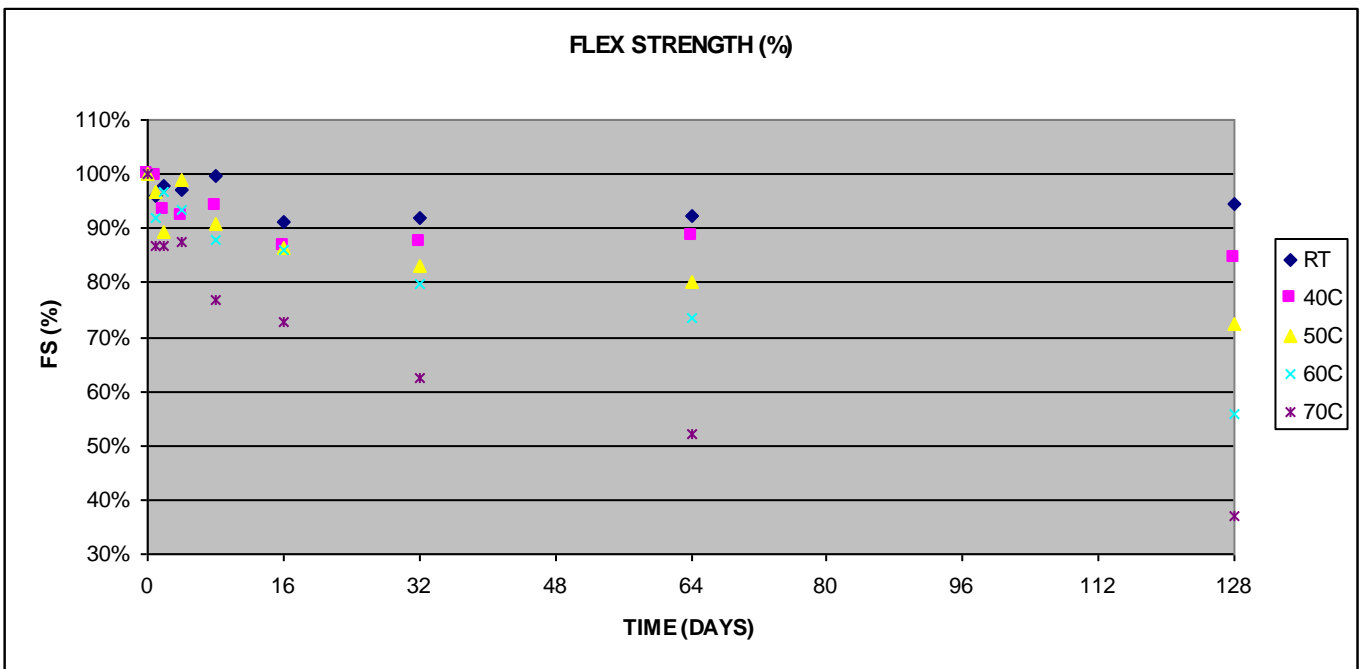


Figure 19: Accelerated Aging: Expressed as a percentage of day 0 flexural strength

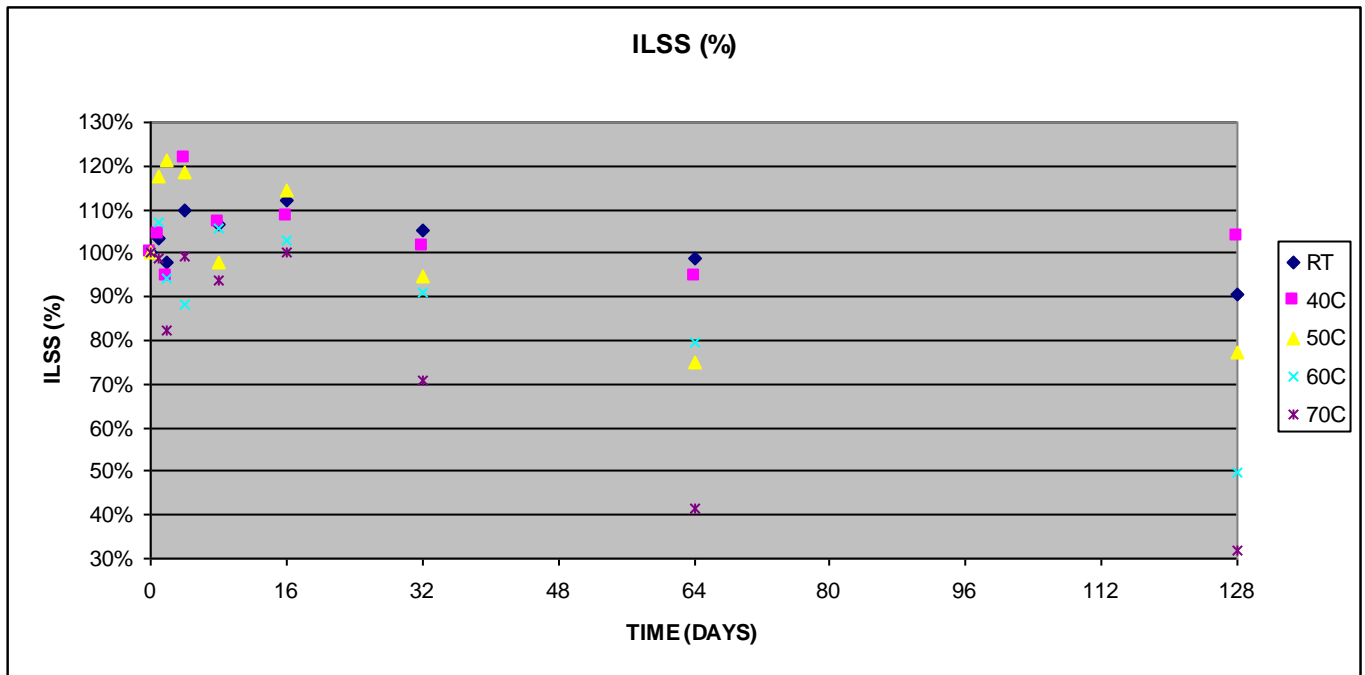


Figure 20: Accelerated Aging: Expressed as a percentage of day 0 inter laminar shear strength

In summary work package 5 has been an initial review of some of the mechanical properties of CBT® based composites. Further work and more comprehensive testing is required to assess both the long term properties of CBT® and also the repeatability of day 0 properties. As work package 4 demonstrated the quality of laminates produced from CBT® resin is heavily dependent on processing, and hence it is predicted that with some refinement to the manufacturing equipment and methodology mechanical properties could be significantly boosted.

## 6. WORK PACKAGE 6 – CASE STUDY DESIGN

**Detailed Report :** WP6 Report

**Covering:**

D12 – Case Study Design Report on Semi-Trailer

D13 – Case Study Design Report on Boat

### 6.1 WP6 Overview

Two case study applications were selected that offered very demanding working scenarios for the developed thermoplastic composite material. The boat case study was traditionally a composite vessel, so little redesign was required to incorporate PBT-GF composite. The majority of the work focused on physically implementing the pre-preg material, which is difficult to work with, into the high toughness and stiffness application.

The trailer case study was a redesign of a steel structure using composite materials, which inherently have a much lower modulus. The design brief was to match the steel trailer's stiffness so that further down the line any superstructure such as a box or curtain could be retro-fitted and experience the same load inputs as it would on a steel trailer. To apply the lower modulus composite material successfully it was necessary to dramatically increase the 2<sup>nd</sup> moment of area of the chassis' cross-section and hence maximise the available space envelope. This resulted in a significantly different and more involved design.

### 6.2 Trailer Structural Design

The starting point was to deconstruct the steel trailer, analyse its construction and calculate its rigidity (see figures 21 & 22). After researching the relevant regulations, hardware sizes and mountings, it was then possible for EPL to pre-define the dimensional boundaries for the composite design, before starting an iterative process to optimise to the design criteria.

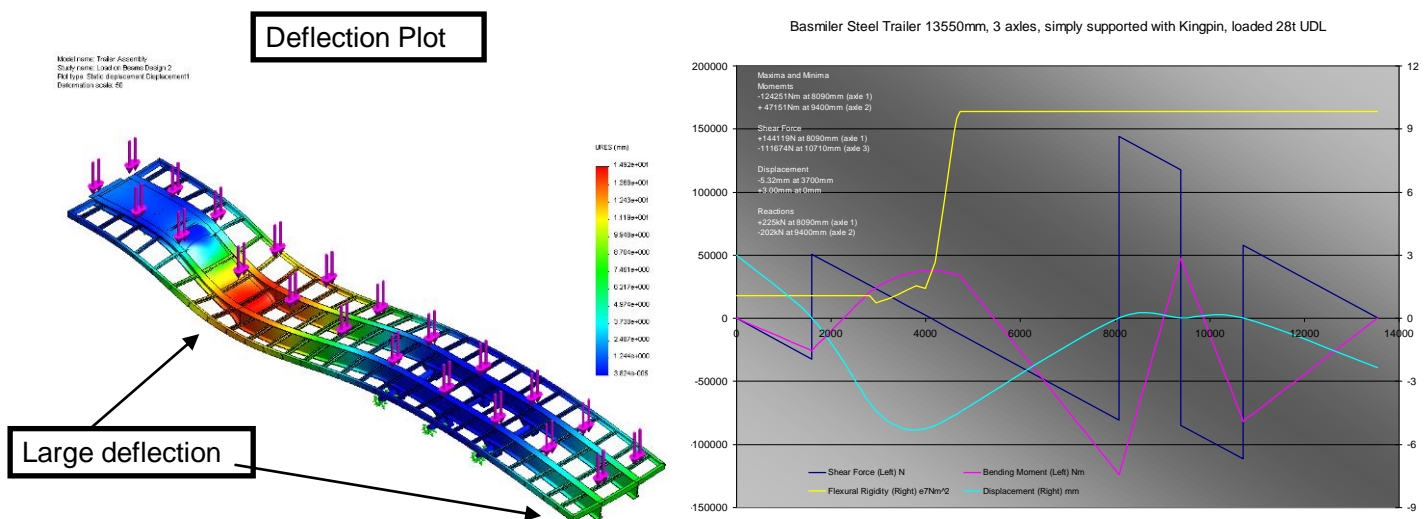


Figure 21: Finite element analysis was carried out on the steel benchmark Figure 22: Beam analysis of the steel benchmark

Along with the ambitious and novel application of composite materials to the design of a HGV semi-trailer matters were further complicated by the limitations of the prototype PBT-GF material. The vacuum bag moulding process was selected to produce the trailer so it was necessary to use the Meyer film pre-preg and design around its poor drape and lack of tack. This necessitated simple flat shapes with little change in curvature. Careful selection of tyres, axles and other hardware allowed EPL to design a constant cross-section design that satisfied the structural requirements as well as maintaining manufacturing simplicity. Figure 23 shows the final design.

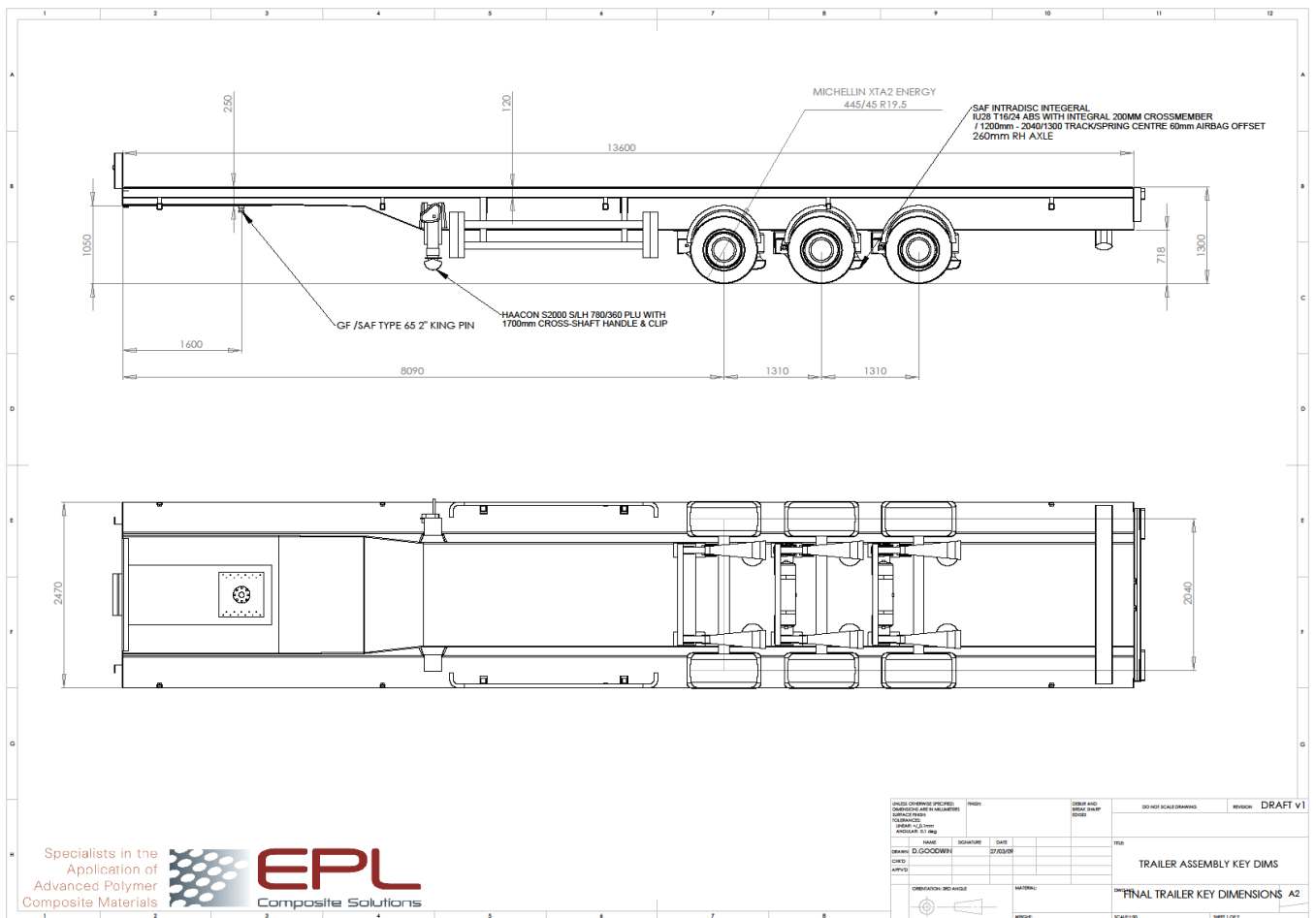
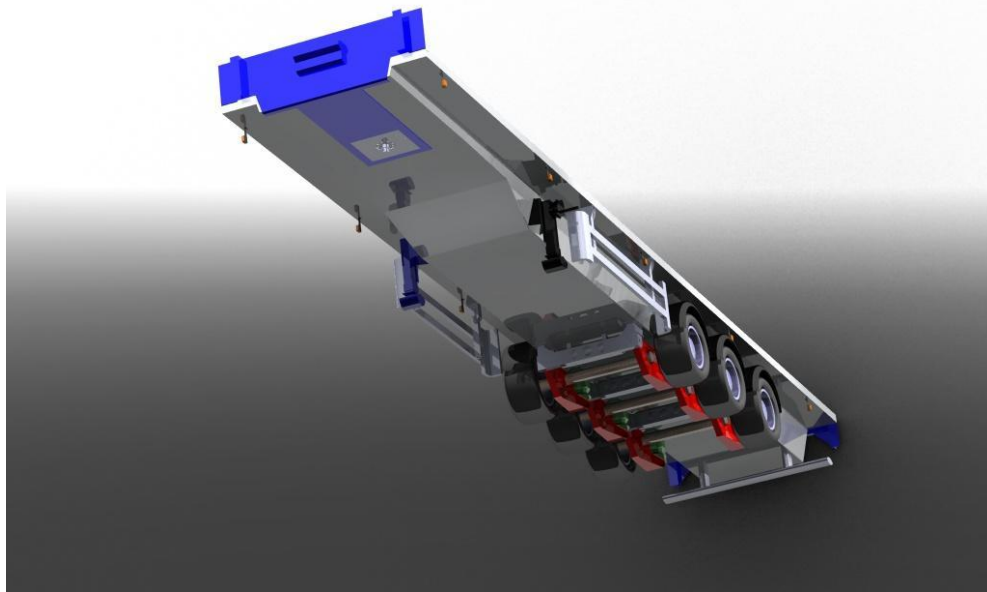


Figure 23: Cleanmould Semi-Trailer Final Design



### 6.3 Aerodynamic Design

Another aspect of WP6 was the computational study into the aerodynamic performance of the Cleanmould trailer design and also the performance of a 'blank-canvas' design for a composite trailer where the limitations of shape induced by the rigidity of the pre-preg material and the use of a fabricated tool, were ignored. Delta Motorsport were subcontracted to carry out the CFD evaluation of the Cleanmould design and then develop the blank-canvas organic design.

To evaluate the design Delta motorsport configured a simulation where the trailer was fitted with a box and was travelling down a motorway at 60mph in three different scenarios: no cross wind, 4-degree and 8 degree cross wind. The Cleanmould trailer design with an array of aerodynamic bodywork appendages (as used on traditional steel trailer) was shown to reduced drag compared to the steel trailer by up to 12.7% at 8 deg cross wind. The organic design showed an even larger reduction in drag even in a no cross wind situation, delivering up to 21% reduction in an 8 degree cross wind.

Table 3 below shows the drag reduction possible from both the Cleanmould trailer with bodywork (see figure 24), and the optimised "organic" design concept (see figure 25).

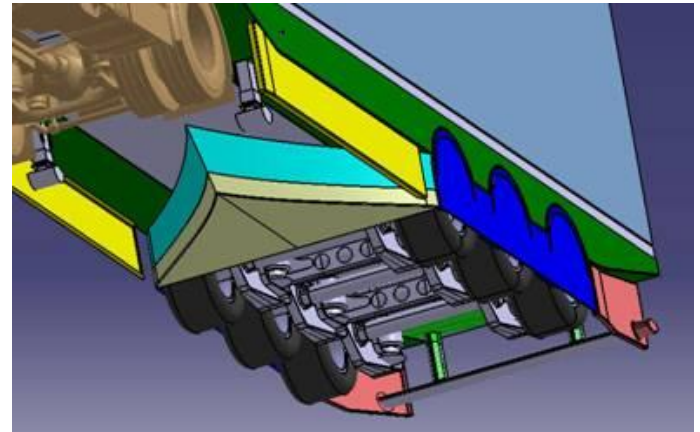
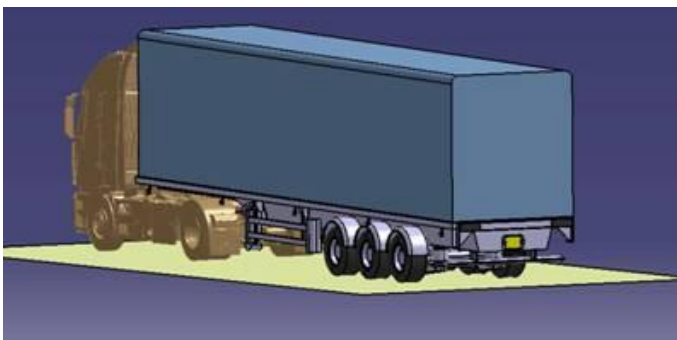


Figure 24: Cleanmould Trailer with Body Work

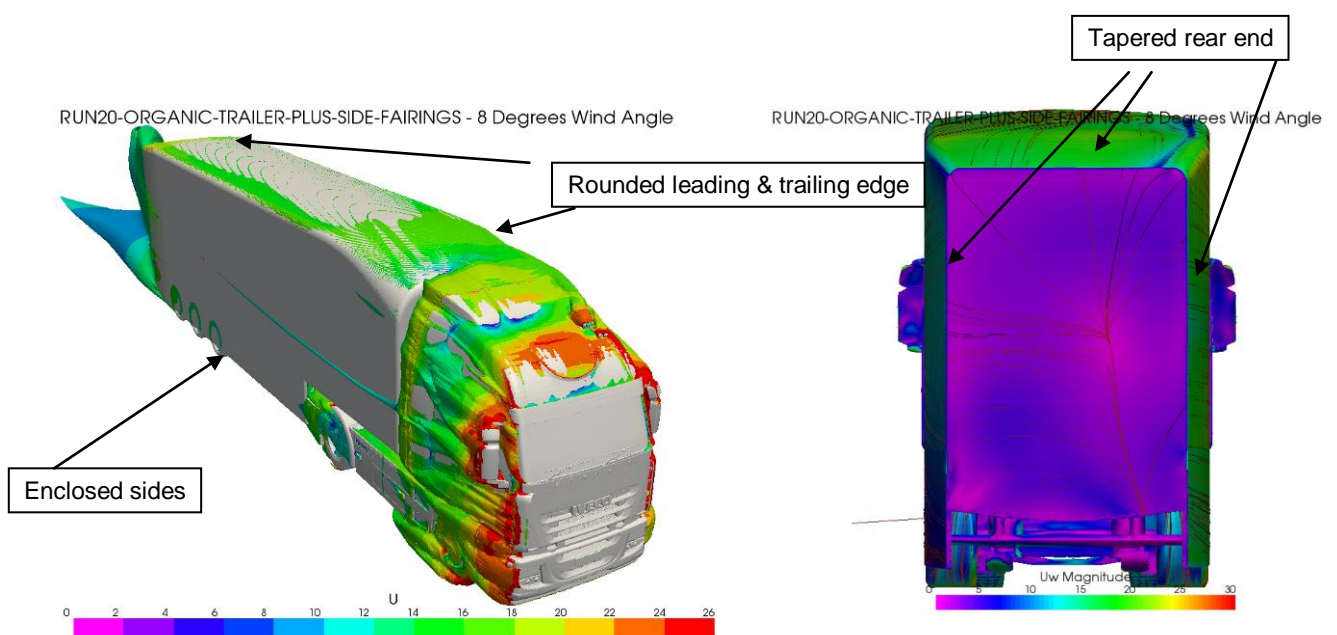


Figure 25: Optimised composite trailer concept

Run	Description	0-deg	4-deg	8-deg
Run 1	Baseline <i>Cleanmould</i> trailer	1799.3	2227.6	2731.6
Run 18	Best "kit of bits" on <i>Cleanmould</i> trailer	1720.9	1961.8	2385.9
	Drag reduction vs Run 1 (%)	<b>4.4%</b>	<b>11.9%</b>	<b>12.7%</b>
Run 20	"Organic" with planar side fairings	1511.7	1766.7	2157.0
	Drag reduction vs Run 1 (%)	<b>16.0%</b>	<b>20.7%</b>	<b>21.0%</b>

Table 3: Summary of CFD results

## 7. WORK PACKAGE 7 – CRITICAL SECTION MANUFACTURE

**Detailed Report :** WP7 Report

**Covering:**

D14 – Validate designs of critical sections of semi-trailer and boat

D15 – Report on performance of critical sections

### 7.1 WP7 Overview

The 'goose-neck' is the area where the hull changes from the deep load-bearing section to the shallow front end that marries up to a tractor unit's fifth wheel.

The goose-neck section possesses several attributes that make it an ideal choice to start the large scale moulding of Cyclics CBT. The goose-neck section (shown in figure 26) is:

1. Large – over 12m<sup>2</sup> surface area
2. Complex – several radii, and double curvature
3. Structural - the goose-neck is the most highly stressed region of the trailer

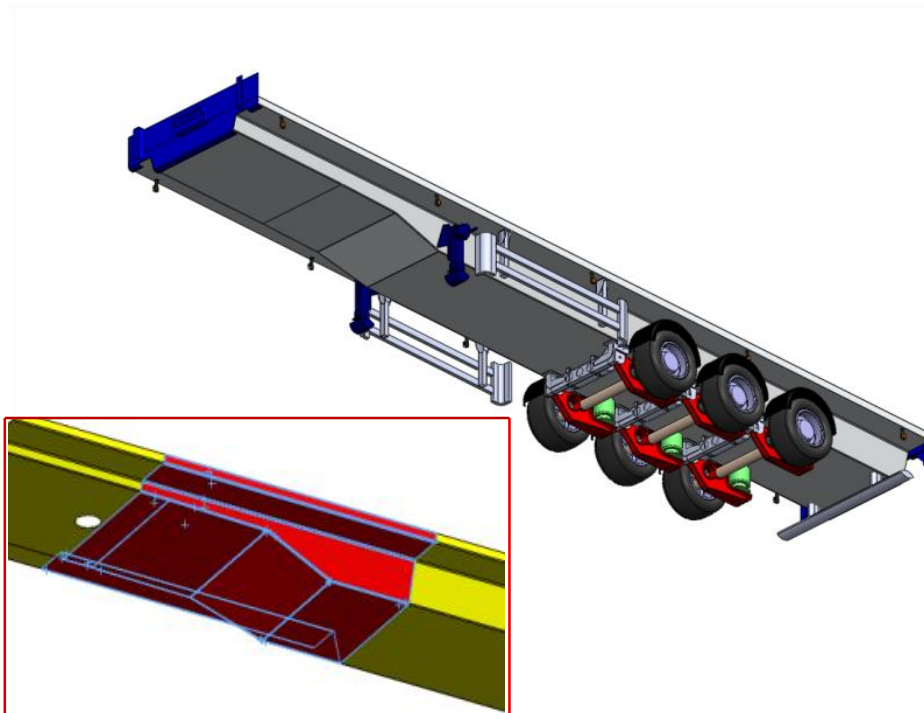


Figure 26 Area selected for the critical section moulding

## 7.2 Lay-up of pre-preg

The pre-preg used was manufactured at Meyer Machines GmbH in July 2009, a combination of tri-axial glass fibre (63051, 1180gsm 60%, FMF) and Unidirectional glass fibre (42024L, 1200gsm, 60% FMF) was used. Both pre-pregs were positioned with the 0° direction running the length of the trailer tool.

The pre-preg has a film of resin on one side and is dry on the side. To promote a consistent part the direction of the resin rich face was alternated in the order:

	4 <sup>TH</sup> PLY: RESIN UP
	3 <sup>RD</sup> PLY: RESIN DOWN
	2 <sup>ND</sup> PLY: RESIN UP
	1 <sup>ST</sup> PLY : RESIN DOWN
	TOOL

The pre-preg roll width is 1.27m and is therefore insufficient to span the entire width of the tool. Each ply consisted of 3 pieces: the bottom, LH side and RH side and a 'pyramid' arrangement was chosen for the overlaps. Ply 1 & 2 were cut to the same width then ply 3&4 were trimmed by 100mm (50mm both sides) to create the pyramid shape shown in figure 27. It was hope that this approach would reduce bridging in the radii.

The lay-up strategy can be seen below.

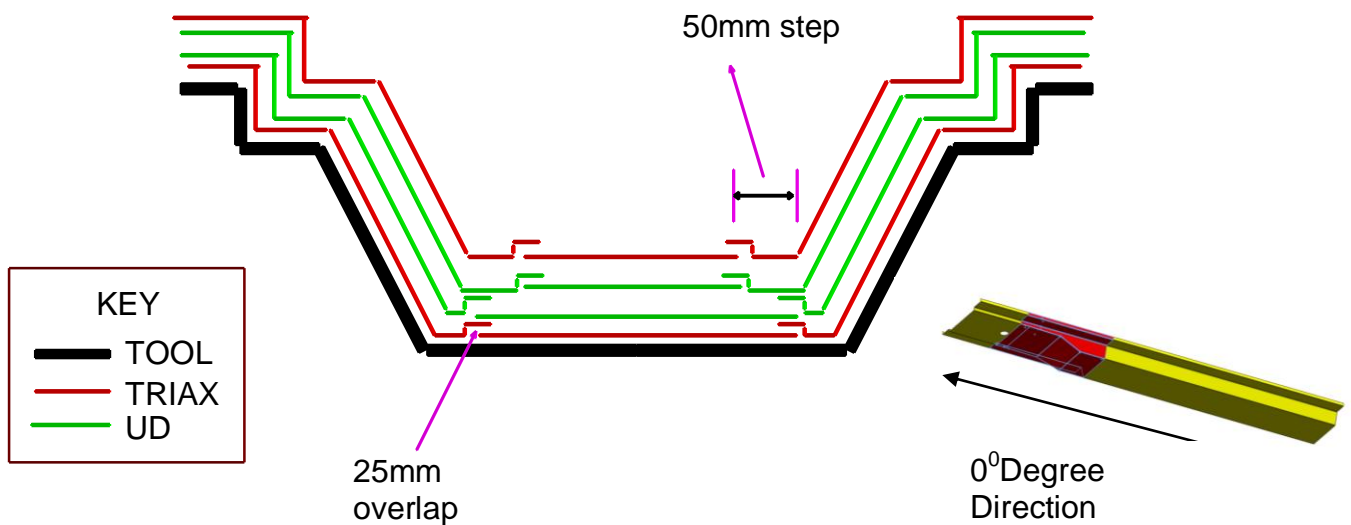


Figure 27 Lay-up Diagram

### 7.3 Processing

The methodology, temperatures and timescales used to mould the critical section were all based on values used in the lab scale work conducted at EPL under WP4. Only the volumetric flow of dry air was increased to correspond with the increased component volume.

The component was laid-up, dried then ramped and cured the whole process took approximately 4hrs without optimisation.

## 7.4 Results

The moulded component shown in figure 29 was of excellent quality and gave the consortium confidence to approve the manufacture of the full scale hull moulding. The distortion from an unbalanced laminate and the high coefficient of thermal expansion (CTE) of the resin was quite significant but on the low tolerance trailer it was at an acceptable level. There were some defects that resulted from the pre-preg material being difficult to position in the tool, such as areas of bridging and creasing of the reinforcement. Generally these issues would exist with any heavy weight fabric without the use of spray adhesive.



Figure 28: Goose-neck critical section moulding



## 8. WORK PACKAGE 8 – CASE STUDY TOOLING

**Detailed Report :** M4 Report

**Covering:**

D16 – Prototype case study tooling for trailer

D17 – Prototype case study tooling for boat

### 8.1 WP8 Overview

A series of test tools have been manufactured from a variety of materials to meet the demanding requirements of high (200C+) glass transition temperature (Tg), dimensional stability and accuracy, low CTE, surface finish, vacuum integrity and low cost. Fabricated steel sheet was selected as the tooling material for the semi-trailer and ACG LTM 217 carbon–epoxy pre-preg was selected as the material for the boat case study.

The prototype semi-trailer tools have been manufactured and implemented to mould the major components of the trailer (i.e. the hull, spine and deck). The 8m RIB boat case study has not been manufactured due to the reasons described in the final activity report. Instead a 5m Dory boat case study was manufactured from an existing steel tool coated with PTFE.

The trailer tools were designed to accommodate the high CTE of steel and PBT. As the tool heated up with the reinforcement inside it would expand rapidly, the reinforcement however only expands slightly but under cooling the part shrinks more than the steel tool – therefore the final component dimension is smaller than the steel tool's original dimension. The tooling was made to be 16mm wider and 80mm longer than the target component dimension. Photographs of the tooling can be seen in figure 30.



Figure 29: Hull, deck, spine and boat tool



## 9. WORK PACKAGE 9 – CASE STUDY MANUFACTURE

**Detailed Report** : WP9 Report

**Covering:**

D18 – Prototype thermoplastic semi-trailer

D19 – Prototype thermoplastic boat

### 9.1 WP9 Overview

The material and process developed on this program have been implemented on a large scale with the manufacture of two case studies, a 5m flat-bottom boat (figure 31) and a 13.6m flatbed semi-trailer (figure 32).

The trailer and the boat have both been manufactured from the Meyer laminated film pre-preg using a combination of Ahlstroms 63051 Traix and 42024L UD reinforcements at 65%FMF with CBT®160 one-part resin and catalyst compound. The manufacturing process used on all the major thermoplastic component mouldings was the vacuum bag consolidation process developed under WP4, where the component is laid-up into the tool then dried in-situ under a flexible membrane vacuum bag (as explained in section 4.2)

The trailer hull moulding represents the largest ever thermoplastic structural component that has ever been made. It is over 13.6m long by over 2.5m wide, with 50m<sup>2</sup> surface area. The wall thickness varies between 8-15mm and the total mass is over 600kg. The boat case study has seen the first ever application of structural thermoplastic composite in a balsa-cored sandwich panel and this is also the first time that PBT-GF composite has been successfully co-moulded with Twintex®.

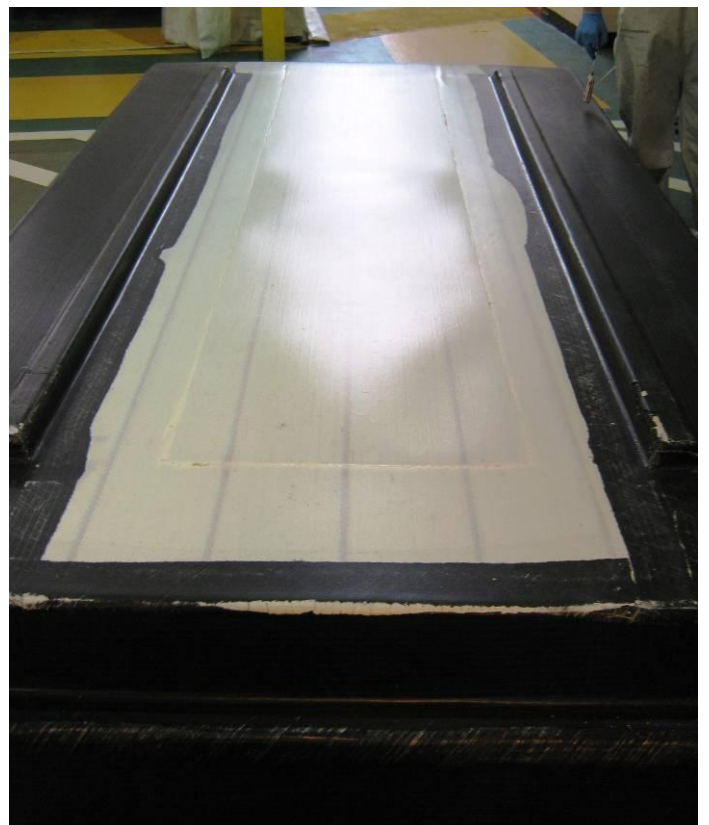


Figure 30: Boat case study



Figure 31: Finished Cleanmould Trailer

## 10. WORK PACKAGE 10 – CASE STUDY TESTING

**Detailed Report :** M5 Report

**Covering:**

D20 – Prototype test report on thermoplastic sem-trailer

D21 – Prototype test report thermoplastic boat

### 10.1 WP10 Overview

The boat case study was not deemed sea worthy due to the issues of bridging around the balsa core in the sandwich panel construction of the floor. Therefore it has not been possible to test the boat case study.

At the time of writing the prototype trailer is awaiting a date for a shake-down test at MIRA proving ground in Nuneaton, UK. Mi Technology have been subcontracted to instrument the trailer with strain gauges and conduct a series of non-destructive static and dynamic tests.

From the work conducted under WP6 – Case study design the areas of high strain have been identified and the proposed strain gauge positions are shown below:

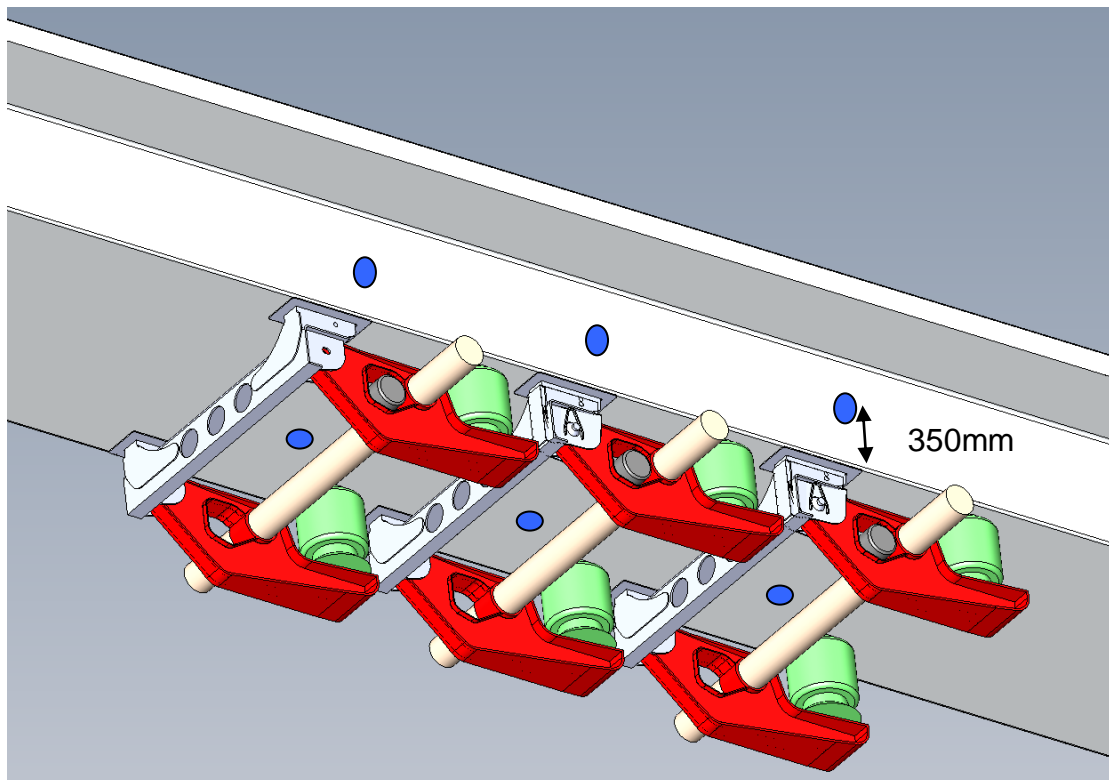


Figure 32: Position of 6 strain gauge rosettes around axles (wheels removed for clarity)

Strain gauges on the drafted sides to measure shear at 350mm up from the bottom composite surface will be used see figure 34. High bending moments (BM) and stresses on the undersides around the axles are also anticipated so 3 more gauges will be positioned here.



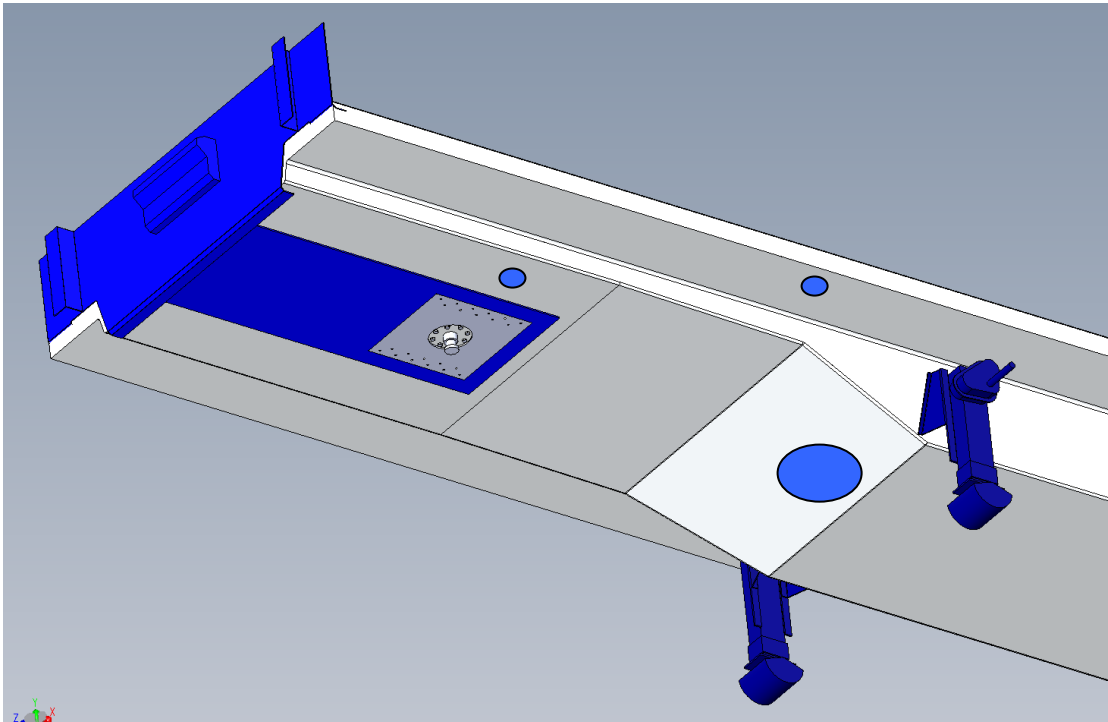


Figure 33: Position of strain gauge rosettes around goose-neck of trailer

High stresses are also expected at the king pin (KP) where the tractor unit transfers the driving, braking, cornering and hitching loads into the chassis. The beam analysis of the composite trailer also suggested an area of high stress on the goose-neck ramp where there is a transition from the relatively flexible front end to the very rigid deep section rear of the trailer. The last area to be analysed is the unsupported shoulder, depending on the positioning of a load on the deck these shoulders could be prone to hogging.



Figure 34 Trailer at Test House Undergoing Initial Static Load Tests

## 11. WORK PACKAGE 11 – DEVELOPMENT OF RECYCLING TECHNIQUES

**Detailed Report :** D22 Report

**Covering:**

D22 – Recycling Methodology report

### 11.1 WP11 Overview

In this work package the recyclability of structures made from the developed thermoplastic material were assessed. Composite laminates were produced under the exact same conditions as the case study components were manufactured – i.e. fibre glass reinforcement with CBT®160 resin processed under the vacuum bag consolidation method. These laminates were then cut into manageable chunks before being shredded and mixed with virgin PBT to create a recycle compound that could be thermoformed into recycled components.

Both injection and compression moulding processes (see figure 35) have been successfully demonstrated using the recycle. However the mechanical properties of the resulting long fibre moulding suffered a great degree of deviation down to the irregularity of fibre length in the shredding process. However the properties are excellent for an added value recycle product and the methodologies developed have been proven with the successful moulding of a complex component.

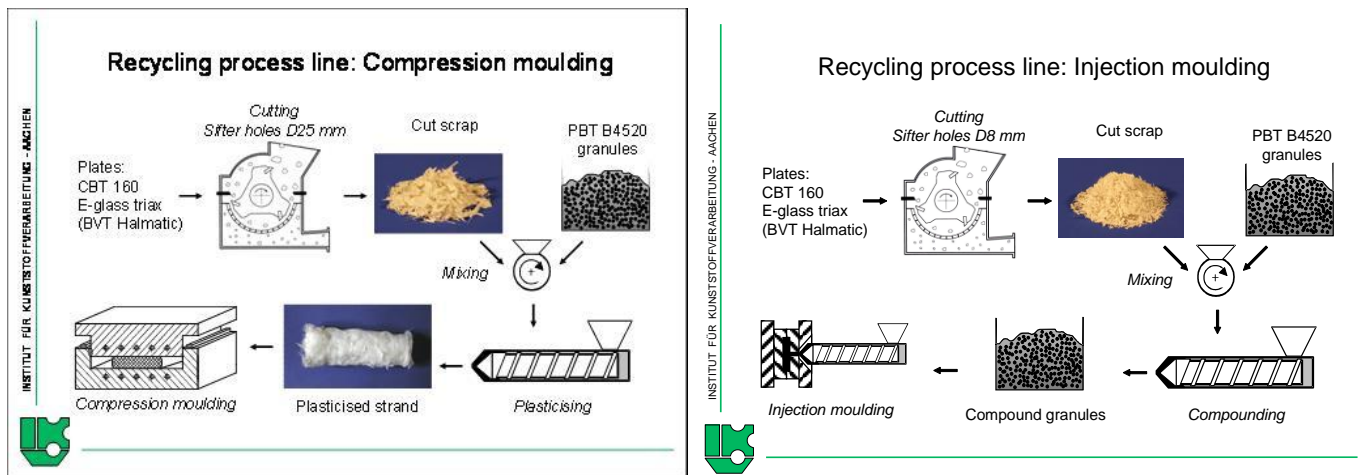


Figure 35: Two methods for moulding recycled pCBT components

Despite the wide deviation in fibre length from the cut scrap comparison of the recycle properties to a standard PBT injection moulding compound (POCAN) shows that the resin is not noticeably degraded by the recycling process, as shown in figure 36.





### Lanxess POCAN vs. Recycling material

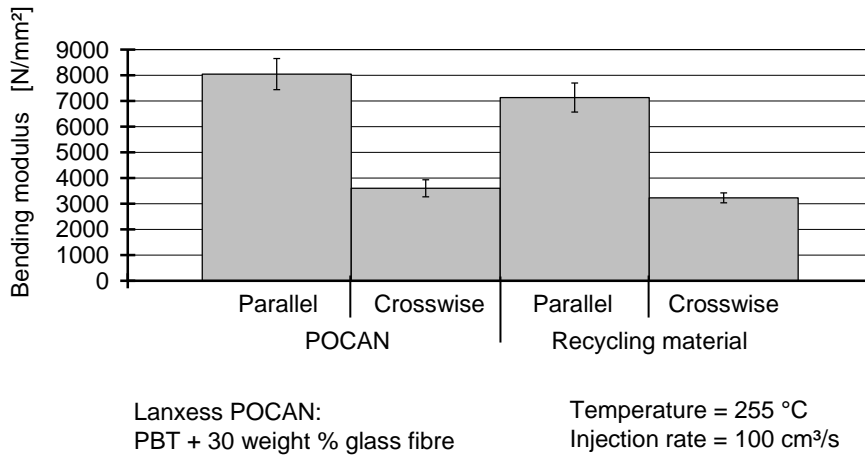


Figure 36: Comparison of Recycled pCBT & POCAN

After the analysis of the two recycling process lines, a complex shaped demonstrating product was moulded to show the potential of the recycling material for the production of high quality products. The component is shown below in figure 37.



### Injection moulding: Demonstrator

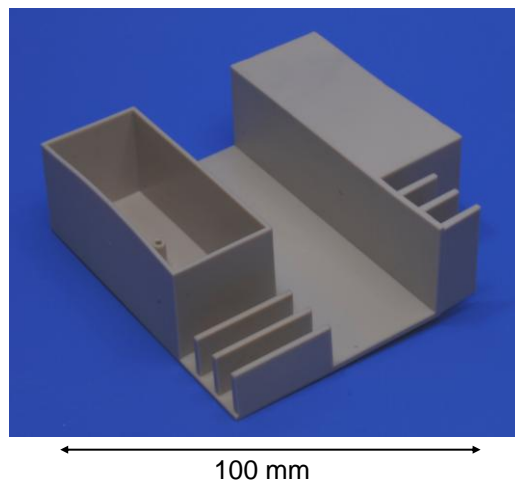


Figure 37: Demonstrator of injection moulding recycled pCBT

## 12. DISCUSSION

The materials and processes used on this project have shown promise in a real manufacturing environment and on a demanding and complex case study application. However before the technologies can be widely adopted some further development is required. The liquid transfer moulding (LTM) processes of RTM and VI show great promise for economically manufacturing complex shapes. However the high cycle times currently prevent the application in a commercial environment. More rapid catalyst systems and better resin dosing and mixing equipment would be required to take LTM moulding of CBT® further.

The pre-preg used to manufacture the cases study components is not a commercially ready solution as the rigidity is simply too high to realise the complex geometries of typical composite applications. The trials conducted by Cyclics to manufacture extrusion pre-preg were not without problems but the result was much closer to a useable product. If vacuum bag consolidation moulding of CBT® composite is to progress further then this extrusion pre-preg needs to be developed.

The initial problems associated with using CBT® resin (sensitivity to moisture, high temperatures and high heat up rates) have all been successfully overcome in a realistic industrial context. No prohibitively expensive equipment or consumables have been used to mould the major case study components. The economics of processing CBT® however are more complicated than just the initial capital expenditure. Thermoplastic composites manufactured from CBT® resin have added value over thermoset counterparts but the raw material is currently expensive, the cycle times for the moulding methods used on this project are long and the energy costs to keep tools heated to 220C are high. All these aspects result in high unit prices. The suitability of CBT® based composites needs to be assessed on a case by case context where the high cost can be offset against the benefits of thermoplastic composites that either enhance an existing product or make development of a component possible for the first time.

The application of composites for a HGV semi-trailer is a novel one. Organisations have developed prototype composite trailers in the past (including EPL & BAE Systems under the ROADLITE DTI project) using various different approaches and with various different objectives. However this project has delivered the first recyclable, maximum payload, tri-axle semi-trailer where none of the original steel trailer's functionality has been compromised but with the added benefits of reduced running costs, reduced pollution and EN2000/53/EC end of life directive compliance have been generated. This is a significant achievement and a leap forward in current state of the art.

At this stage the stumbling blocks for widespread adoption of this material and the associated processes are:

- high raw material cost
- high tooling cost or only simplistic shapes
- long cycle time
- high energy usage in production
- availability of compatible structural adhesives
- availability of in-mould paints or gel coats.

However with further development it is forecast that these issues could be overcome within the next 2-3 years.

## 13. CONCLUSION

The aims of the Cleanmould program were to provide sustainability in the European transport and other manufacturing sectors through:

1. Development of advanced composite materials that are:
  - thermoplastic
  - tough
  - durable
  - emit no VOCs
  - have a high strain to failure
  - have excellent fatigue; impact; water and chemical resistance
  - have high volume fraction and thus can reduce component mass
  - have low density and high specific mechanical properties
  - are low cost and totally recyclable
  
2. Application of the advanced composite material used to produce complex components using new manufacturing processes that enhance sustainability through:
  - emitting no volatile organic compounds
  - improving safety through component and design integration;
  - production of structural products that will reduce component weight,
  - reducing fuel and energy consumption and greenhouse gas and toxic emissions;
  - enabling a cleaner manufacturing environment through the use of inert, dry resin

In these respects the Cleanmould project has been a success. A range of resin – catalyst compounds have been specified and manufactured with an intermediate (or pre-preg) fabric produced to combine the pre-processed resin with glass fibre reinforcement. Three different manufacturing processes have been developed that allow the new composite materials to be turned into high performance components in a clean and VOC free manufacturing environment. The materials and processing technology have been proven on a very large scale with the production of the 13.6m long semi-trailer of which the hull component constitutes the world's largest ever structural thermoplastic composite moulding.

The composite semi-trailer has been shown to be a sustainable solution to the problems facing European road haulage. In the immediacy the weight reduction and aerodynamic benefits of the composite trailer mean direct and significant cost savings to the operator. Furthermore the fuel savings directly correspond with a CO<sub>2</sub> emissions reduction helping the European Union to reach its Kyoto agreement targets.