Advanced materials enabling HIgh-VOlume road transport applications of lightweight structural COMPosite parts

Reporting

Project information

HIVOCOMP

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Final Report Summary - HIVOCOMP (Advanced materials enabling HIgh-VOlume road transport applications of lightweight structural COMPosite parts)

Executive Summary:

HIVOCOMP is developing two material systems that show unique promise for cost effective, higher-volume production of high performance carbon fibre reinforced parts that meet the requirements of the automotive and other demanding sectors. These materials systems are:

- Unique fast-cycle polyurethane chemistry.Low viscosity, snap cure and a rare combination of high Tg and good toughness. Enables optimised processing, with good resin and composite properties.
- Hybrid self-reinforced composites (SRC) of polypropylene and an optimal carbon fibre fraction. Over 3x the tensile & bending stiffness, while keeping similar levels of the outstanding impact performance of standard SRC-PP. Ready to go into high-volume production.

Achievements:

- Polyurethane based resins with superior processability qualities that are well-aligned with high-volume automotive production requirements were developed, allowing performance for structural parts, with quick processability and application in KTL process. A complete mapping of the resin means that customisation according to part and process is possible, optimising further cycle times and properties.

- Two advanced hybridisation concepts were scaled up for the self-reinforced polypropylene and polyamide composites, under the close collaboration of the research and industrial partners, and were used in the demonstrators’ fabrication.

- Five demonstrators, representing potential high volume applications with different performance and process requirements, were designed and fabricated process. At the same time, optimised virtual designs of selected parts were developed, showcasing the advanced qualities and lightweighting potential the new materials can bring to these parts.

- Modelling and simulation, LCA/LCC, joining and adhesion capabilities were also investigated, helping to provide a more complete solution for the new novel material systems that can be ready for production within a very short timeframe.

The final results were presented at the final project meeting in 16-17 September 2014, hosted by Volkswagen at Gifhorn, Germany.

Project Context and Objectives:

Project context
Current applications of carbon fibre reinforced plastics (CFRP) can be found mostly in sectors where their use is not principally not cost-driven and which have limited production volumes, such as aerospace and sports cars.

To achieve a step-change in the application of high-performance composites in larger-volume applications, new materials systems are needed that combine very short production cycle times with performance that meets automotive requirements.

HIVOCOMP will develop two materials systems that show unique promise for cost effective, higher-volume production of high performance carbon fibre reinforced parts. These are:

1. Advanced polyurethane (PU) thermoset matrix materials offering a combination of improved mechanical performance and reduced cycle times in comparison with conventional matrix systems, enabling CFRP to be used in high volume automotive applications, and

2. Thermoplastic PP- and PA6-based self-reinforced polymer composites incorporating continuous carbon fibre reinforcements offering increased toughness and reduced cycle times in comparison to current thermoplastic and thermoset solutions.

The performance, production cost and recyclability of new CFRP materials systems will be thoroughly tested and benchmarked to ensure they achieve ambitious cost, safety and environmental targets, and the advances validated through the manufacturing of representative demonstrator parts.

The project focuses demonstrating the viability of these materials in passenger cars, but it has identified spin-off applications in other high-volume sectors as well.

Project objectives

WP1 – Development of breakthrough PU matrix chemistry and resulting composite materials
The overall objective of WP1 is to obtain full understanding and control over the envisaged breakthrough PU chemistry, and apply this to achieve composite PU-CF material with the breakthrough properties defined in section Progress beyond State of the Art, paragraph B1.2.2.1. Principal aims of WP1 are therefore:
- Development of the breakthrough PU chemistry by iteratively modifying parameters such as resin composition, incorporation of hardeners, resin rheology and by optimizing the catalysis package.
- Achievement in this way a breakthrough combination of processing characteristics ('snap cure'), mechanical performance and high Tg's
- Assuring these material properties are achieved not only on lab scale but can be replicated in the manufacturing of high-performance PU-CF composites
- Further improvement of processing and mechanical, thermal and electrical properties through the incorporation of nanoparticles in the PU matrix
- Optimisation of processability of the new developed material for State of the Art high-speed production techniques such as light RTM (Quickstep), RocTool and VARI. For injection purposes the material will also be tested on a High Pressure (HP) mixing machine.
- Start the research on the use of the developed material as adhesive for joints, as well as hybrid parts of PU-based composites and metal
- Incorporation of sensing fibres for monitoring material properties in processing and use, assuring further improved understanding of the material behaviour

WP2 - Material development of Hybrid-SRC materials incorporating self-reinforced PP and PA6 hybridised with carbon fibre

The overall objective of WP2 is to obtain full understanding and control over the hybridisation of self-reinforced PA6 and PP with carbon fibres, and apply this to achieve Hybrid-SRC material with the breakthrough properties defined in section Progress beyond State of the Art, paragraph B1.2.2.2. Principal aims of WP2 are therefore:

- Development of Hybrid-SRC composites combining the high stiffness of carbon fibre (CF) composites with lightweight and high toughness of self reinforced polymer composites (SRPC) of PP and PA6
- Development of two variants: high stiffness combined with increased toughness on one hand, and high toughness combined with increased stiffness on the other hand.
- Selection of the optimal strategy (co-mingling/co-weaving/inter-laying) for manufacturing the Hybrid-SRC material
- Assuring optimal final material properties for the chosen hybridisation route after application of hot precompaction and thermoforming methods adapted to the presence of carbon fibres in the Hybrid-SRC
- Evaluation of the industrial scalability of the hybridisation and subsequent manufacturing process to produced large parts at high volumes while maintaining target material properties
- Further improve understanding of the material by monitoring properties and performance during material processing through the incorporation sensing fibres
- Evaluation of the effect of addition of nanofillers to the developed Hybrid-SRC, with the aim of further improving material properties beyond those inherent to the material
- Selection of optimal joining techniques (e.g. adhesion, welding) for the developed Hybrid-SRC, also for possible application composite-metal automotive parts

WP3 - Material modelling at micro/meso-level as input for material development and adaptation of simulation and design tools to new materials

The overall objective of WP3 is to develop reliable micro/meso-level models of how the constituents of the composite materials developed in WP1 and 2 and their processing influence the materials behaviour. The aim is to support the work in these WP's in obtaining full understanding and control over the properties of these materials, and implement this knowledge in appropriate simulation tools. WP3 will therefore:

- Define chemical models that describe the polymerisation reaction of the PU chemistry, including chemorheology, and predict shrinkage, curing behaviour and residual stresses
- Develop process and mechanical models that describe shrinkage, forming and impregnation behaviour of the Hybrid-SRC made with the 3 different hybridisation routes
- Validate micro/meso mechanical models that predict the properties of final composite PU and Hybrid-SRC materials, including stiffness, strength, toughness, damage resistance
- Apply the developed models in simulation tools that can predict impregnation, thermoforming, structural properties and crash characteristics of full parts
- Document the models and simulation tools in a design knowledge base, that can be used by engineers for the application of these materials

We aim to have WP3 strongly interact with the other WP's, using material characteristics analysed in WP1 and 2 for the models, and using modelling results obtained in this WP to define parameters for further improving the material characteristics.

WP4 - Iterative benchmarking of material properties and validation of industrial applications, including LCA

The overall objective of WP4 is to assure that the material developments in WP1 and 2 not only meet the objectives set in the project, but are at all times optimally in line with the requirements for automotive applications. WP4 will therefore:

- Make an feasibility analysis and select the most suitable parts for industrial application of the developed materials in automotive and transport for further work
- Perform a full benchmark at 3 points in the development of the material (M18, M31 and M48), consisting of:
- key material and processing characteristics of the materials developed in WP1 and WP2, against requirements for industrial
- full LCA, cost and recyclability analysis for the developed materials applied in selected reference parts
- Validate of materials developed in the development and simulation of representative parts redesigned to take advantage of breakthrough material properties
- Conclusions on processing characteristics, mechanical performance, LCA, cost and recyclability of the materials and processes

The aim is for WP4 to provide important input for detailed definition and updating of the objectives for the properties of the materials being developed in WP1 and 2.

WP5 - Demonstration and validation of typical transport applications incorporating novel PU and Hybrid-SRC

The overall objective of WP5 is to demonstrate the breakthroughs properties of the materials achieved in terms of processing and mechanical properties, in 5 demonstrator parts representing typical requirements for automotive and transport requirements. WP5 will therefore:

- Prepare the fabrication of demonstrator parts by design of parts, adaptation or creation of moulds and definition of process design and other parameters
- Manufacture the demonstrators in an industrial production scenario, thereby demonstrating the material technologies developed in the project, and validating the processing performance obtained
- Validate final mechanical performance non-destructive and destructive testing on the demonstrators, allowing the final results to be benchmarked against parts made of traditional material

The results of this WP not only provide insight in application of the materials developed in the project, but are an important instrument in communicating the potential of these materials in automotive and transport applications.

WP6 - Management

The main objective of WP6 is to assure the successful execution of the project through effective project management. In this WP, the project will:

- Prepare and implement effective internal communication protocols and tools
- Conduct smooth and effective management and coordination of HIVOCOMP partners, ensuring the achievement of the specific objectives from each of the WPs.
- Assure regular and smooth communication with the EC, regular 6 month steering committee meetings and high-quality reporting to the EC
- Ensure that all project objectives are achieved successfully and on time

WP7 - Dissemination

The main objective of WP7 is to broadly disseminate the project and the breakthroughs achieved in it. In this WP, the project will assure high-impact dissemination to the key industrial and academic actors that can facilitate the uptake of the developed materials, as well as the general public.

Project Results:

WP1 - Development of breakthrough PU matrix chemistry and resulting composite materials

The overall aim of WP1 has been to develop a breakthrough PU matrix chemistry for manufacturing composite Automotive parts via Fast Cycling production (infusion) techniques.

In parallel to this chemistry development four other topics have been investigated:

- Evaluation of SotA production techniques with the novel developed PU resin(s)
- Addition of nano-particles for improving mechanical properties
- Joining of PU-resin based composites
- Incorporation of sensing fibres in PU-resin based composites

Summary

- The project workplan was executed according to the original plan, with three major iterations of resin technology being developed during the course of the project.
- Collaboration with industry partners within the overall project enabled a tuning of the final target material properties.
- Two major new matrix resin formulations were developed: Formulation C and Formulation D.
- Formulation “C” met the agreed targeted set of properties, namely a significantly reduced viscosity, a fast and tunable ‘snap cure’ and a high Tg.
- Formulation C was validated in industrial composite processes and was demonstrated in making good composite parts via Fast-Cycling HP-RTM processing within WP5
- Further research work in the project led to Formulation D with a significant increase in fracture toughness and improved ductility, while still maintaining a good modulus, high strength, high Tg, fast cure and low viscosity.
- Developed PU resins were proven to be processable in industrial state-of-the-art production processes, including both RTM and VARI.

- By selecting the best suitable nano-filler particles and optimizing the processing it has been demonstrated (on lab scale) that addition of Silica R8200 does bring considerable improvements in mechanical properties of the neat resin.
- Extensive work on investigating different adhesives and bonding methods resulted in a good insight on how to bond and which adhesive is the most suitable (1K EP) to use in combination with the PU-composite.
- It has been demonstrated sensing fibres (FBG) can be incorporated successfully generating very valuable data on strains/residual strains during/after cure and post-cure of the PU-composite materials.

Based on input from the different industrial partners the full set of targeted properties has been prioritized and customized in order to meet the needs of the Automotive market. This resulted in two novel developed PU resins, called Formulation “C” and Formulation “D”. Formulation “C” met the agreed targeted set of properties (a significant reduced viscosity, a fast tunable ‘snap cure’ and high Tg) and has been validated and demonstrated in making good composite parts via Fast- Cycling HP-RTM processing within WP5 (demonstrator manufacturing workpackage).
During the third major iteration, Formulation “D” has been developed (to proof-of-concept status) with a significant increase in fracture toughness and improved ductility, combined with a good modulus, high strength, high Tg, fast cure and low viscosity. This system can be seen as an alternative for Formulation “C” where higher toughness and tensile properties are required and where a slightly less high Tg is acceptable.

The figure below gives an overview of how the different formulations are positioned with respect to each other in terms of their mechanical properties.

Figure 2 – Mechanical properties benchmarking of different PU formulations
An overview of the full set of properties of the PU resins from the different iterations is given in the table below.
Table 1 – Properties of different PU formulations developed in the project

In addition the different PU resins have been evaluated by different partners with production techniques such as Vacuum Assisted Resin Infusion (VARI), low pressure RTM (LP-RTM) and high pressure RTM (HP-RTM).
The first two pictures show HP-RTM equipment that is similar to equipment used in industry to manufacture high series of composite automotive parts. With this equipment and the novel developed PU resin it has been demonstrated that panels of 55x55 cm can be manufactured with a demould time of less than 3 minutes.

Figure 3 – HP-RTM setup
One advantage of the novel PU resin is that the resin can be used for VARI as well. The following two pictures show a 1.5m long C-beam that has been infused successfully within 90 seconds and pre-cured in less than 3 minutes. After this the part was post-cured at a temperature of 180°C to achieve a fully cured composite.

Figure 4 – VARI setup
Many composite panels made via RTM processing have been extensively characterized. The comparison made between composite with Formulation “C” and a Ref. epoxy is given in the table below.

Figure 5 – Mechanical properties benchmarking
The overall conclusion is that the composite made with Formulation “C” has similar mechanical properties to the reference epoxy but with a with a much higher Tg (~210°C vs. ~120°C) and easier processing due to the PU’s low, relatively constant viscosity till its snap cure kicks in.

Addition of nanoparticles
Research has been carried out on improving the neat resins properties via addition of nanoparticles. An extensive evaluation of different types of nano-particles resulted in the selection of Silica Aerosil R8200. The best method to introduce the particles was found to be the ISOMIX, meaning the particles were added to the isocyanate-side of the resin formulation. It has been demonstrated (at lab scale) that addition of Silica R8200 can bring considerable improvements in mechanical properties of the neat resin, for example an increase of tensile strain to failure and tensile strength as shown in the graphs below.

Figure 6 – Comparison of PU with and without nanoparticles

In addition composite plates were made via RTM where a percentage between 1-4% of Silica R8200 was added to the PU resin. These composites (see pictures below) have been characterized where for example an increase of tensile properties has proven the concept (modulus +40%, strength +6%, strain to failure +30%).

Joining investigations

Bonding is a common technique for assembling composite parts in the automotive industry. Two different bonding processes have been investigated in order to find the best solution for bonding the PU composite materials to other composites or to metals.

Two-step process:
- Adhesive Betamate 1620 (1K EP) reaches the best shear strength for PU composite- as well for EP composite materials.
- Adhesives Betaforce 2850 (2K PU) and PU resin result in relatively poor bonding in combination with CF-PU laminates independent of CFRP treatment

Single-step process:
- Steel treatment with sandpaper reaches poor bonding compared with the sand blasted and pinned modifications
- Sand blasted specimens resulted in a good bonding with a shear strength of 12 MPa
- Pinned specimens (bottom right picture) have shear strength of about 14 – 18 MPa
- Number of pins has a small effect - Effect of pin height is negligible
- Pins are too stiff, so that they are bent and slide out of the CFRP while testing

Overall, extensive work on investigating different adhesives and bonding methods resulted in a good insight on how to bond and which adhesive is the most suitable (1K EP) to use in combination with the PU-composite.

Sensing fibres incorporation

The last subtask was about the incorporation of sensing fibres (FBG) in PU composite panels. It has been demonstrated sensing fibres (FBG) can be incorporated successfully generating very valuable data on strains/residual strains during/after cure and post-cure of the PU-composite materials.

WP2 - Material development of Hybrid-SRC materials incorporating self-reinforced PP and PA6 hybridised with carbon fibre

Two of the main targets of WP2 were:

1) Development of two variants: VARIANT A - high stiffness combined with increased toughness and VARIANT B - high toughness combined with increased stiffness on the other hand. material

2) Selection of the optimal strategy (co-mingling/co-weaving/inter-laying) for manufacturing the Hybrid-SRC from either variant

Research over the first year at KULEUVEN and UNILEEDS quickly showed that VARIANT A did not show sufficient promise for continuing study. While the aim was to add a small amount of a ductile Self Reinforced Composite (SRC) to a high fraction, and hence high stiffness but brittle, carbon fibre composite, the samples remained brittle until the carbon fibre fraction was below 20%. VARIANT B, where a small fraction of high stiffness carbon fibres were added to an SRC showed much more promise in being able to achieve a balance between stiffness and toughness and so this became the main thread of the study for years 2 to 4.

In terms of hybridizing the high stiffness carbon fibres and the ductile polymeric fibres, three strategies were identified (shown schematically below). In the co-mingling strategy, hybridisation was within each yarn and was achieved using comingled tows of carbon fibre and highly oriented polymer filaments. In the intra-layer (co-weaving) strategy, highly oriented polymer tapes were co-woven with thin carbon fibre/polymer tapes (prepreg). Finally, in the interlayer strategy, layers of SRP sheets were combined with complete prepreg layers.

Intra-yarn hybridisation	intra-layer hybridisation	inter-layer hybridisation
(co-mingling)	(co-weaving)	(interleaving)

The most promising strategy for hybrid carbon fibre/self-reinforced composites is intra-layer hybridisation of self-reinforced polypropylene with carbon fibre. Hybrid self-reinforced composites made using this strategy at KULEUVEN have been found to show a unique combination of stiffness and toughness, in terms of ultimate failure strain and impact resistance. At low strains (<2%) the properties follow roughly a simple rule of mixtures and so are dominated by the high stiffness carbon fibres. The most important aspect is that once the carbon fibres fail (~2% strain), the hybrid SRC is able to survive this event and continue to carry stress (and absorb energy) up to failure strains of ~20%. Extensive research has shown that the two key aspects in controlling this behaviour are the carbon fibre fraction and, most importantly, the level of bonding between the co-woven layers. Fortuitously, normal Hybrid SRC has a moderate interlayer bonding. As the carbon fibres fail, the hybrid SRC is able to delaminate, hence absorbing energy and allowing the layers to remain intact. This is well illustrated in the figure below. Here it is seen that the optimum carbon fibre fraction is around 7%. The stiffness is significantly improved at low strains, but after the carbon fibres fail (accompanied by a load drop) the sample continues to carry stress until a strain of 20%.

If a different balance of stiffness and toughness is required, the result show that for 11% carbon fibres the stiffness is further increased at the expense of the final failure strain which was then measured at 5%. It is considered that adding more carbon fibre prepregs to the hybrid SRC increases the amount of matrix, which also increases the interlayer bonding. When 11% carbon fibre is added, then the bonding is too strong, which limits the ultimate failure strain in tension by limiting the delamination between the layers.

Figure 10 – Stress/strain graph of CRPP with different CF volume fractions

The importance of the bonding was reinforced by using a using maleic anhydride grafted PP as the matrix for the carbon fibre prepregs (sourced by KULEUVEN). Such hybrid composites embrittled at a much lower carbon fibre volume fraction, due to the stronger bonding. Interestingly, the hybrid composites with maleic anhydride also caused a strong reduction in the penetration impact resistance. This resistance returned back to the level of carbon fibre composites. This decrease was much smaller if the matrix in the carbon fibre prepregs was a homopolymer PP. In that case, the penetration impact resistance reduced linearly with the addition of carbon fibres, as the carbon fibres are more easily debonded from the self-reinforced composites. These results emphasised the importance of controlling the bonding on all levels: interlayer bonding, intra-layer bonding and adhesion to the carbon fibre.

The route using hybrid self-reinforced polyamide (investigated at UNILEEDS) was less successful in finding a material combination which balanced high stiffness with a high toughness. The ‘well-known’ stronger level of bonding between nylon and carbon limited any inter-layer bonding, causing the failure to be localised on failure of the carbon fibres resulting in brittle failure of the hybrid SRC. This again reinforced the issue of adhesion as a key controlling factor in tuning the hybrid SRC mechanical properties. Nevertheless, these hybrids still have a ductile response in flexure.

Another key finding is related to the thermoformability of hybrid self-reinforced composites with continuous carbon fibres. Surprisingly, the presence of the high stiffness, continuous fibres (with a limited longitudinal strain of about 2%) did not affect the thermoformability, as the thermoforming process is controlled by the shearing of the layers over each other, which is not hampered by the continuous carbon fibres.

Preliminary thermoforming trails were carried out at UNILEEDS using a simple hemispherical mould. This enabled the optimum temperatures for forming to be identified, in order to manufacture the demonstrator parts.

7% Hybrid SRPP 11% Hybrid SRPP

To manufacture the final demonstrator parts, the small scale sample manufacture had to be significantly scaled up. First the hand weaving used for the research stage of the project had to be transferred to an industrial scale. PROPEX developed technique for co-weaving carbon fibre PP/prepreg tapes with highly oriented PP tapes as shown in the Figure. Here the carbon fibre prepreg tapes are carefully spaced between PP tapes to achieve the required final carbon fibre fraction. Once large sheets of the co-woven cloth had been produced, KULEUVEN developed a batch processing technique to manufacture large hybrid SRPP sheets for the demonstrator production.

The final stage was to take the developed optimum hybrid SRPP material (VARIANT B, intra-layer hybridisation with 7% carbon fibres), made with the scaled up weaving and sample manufacture and produce the chosen demonstrator, which was a SAMSONITE cabin size suitcase.

Using the thermoforming conditions established from the lab scale trials, suitcase shells were successfully produced. These were then assembled by SAMSONITE into demonstrator suitcases (see example on the left) and subjected to all their standard performance tests.

The hybrid SRPP suitcases were found to pass, or exceed, all of the tests used for the current SRPP suitcases. In addition, the hybrid SRC suitcase was 10% lighter than the current all PP suitcase. Further improvements in both performance and weight reduction are expected when the suitcase design is adapted to benefit from the higher stiffness of the shells.

Figure 11 – The Samsonite suitcase demonstrator with the novel hybrid SRC material

The new and novel combined research at KULEUVEN and UNILEEDS has seen the granting of a new joint patent for the production and properties of Hybrid Self Reinforced Polymer Composites 'HYBRID SELF-REINFORCED COMPOSITE MATERIAL' (n° WO/2013/190149)'. A number of joint papers have already been published and more are planned including a review paper to summarise and publish the important new research findings highlighted above.

WP3 - Material modelling at micro/meso-level as input for material development and adaptation of simulation and design tools to new materials

Micro-meso process models for novel PU resin

UNIPG developed specific chemorheological model for the HUNTSMAN PU formulations. These models are based on cure kinetics and viscosity evolution as a function of temperature and curing time. The kinetic model for Formulation C is quite more complex than the kinetic model of formulation B, but good models that fit well the experimental data have been found for both formulations:

The model for the evolution of the viscosity has been also developed by differentiating the two phase of the reaction:

Where ti is the inhibition time.

Finally the evolution of the storage modulus during the evolution of the cure has been also studied by using a specifically designed device in which the resin is confined in a polymeric tube and the system has been studied supposing a two phase system.

Figure 12 - Apparatus used to study the evolution of storage modulus as function of degree of cure
and relative curve

Airborne has contributed in the modeling of the residual stresses developed during the manufacturing, covering the problems coming from the temperature, due to the difference of thermal properties between the two constituents, the environment (mould), and the chemistry of the resin. Due to the particularities of the polyurethane resin, friction between moulds and part are also to be considered, but in a second term.

The validation of the results is performed by comparing the results vs the experimental data provided by EPFL. The simulation are able to follow the experimental trend with accuracy and even detect the initial exothermy peak. As a further results, the distortions of the plates can be observed, detecting the volume change caused by the manufacturing process. In the image below a quarter plate simulation of the plates can be observed, showing almost no difference between Formulation B and Formulation C, being in both cases dominated by the thermal boundary conditions of the circle (mould temperature)

Figure 13 - Quarter of plate with distortions caused by the production process. Formulation B vs Formulation C

EPFL performed RTM experiments with fibre Bragg sensors to monitor the strains evolution during processing carbon fibre composite parts with PU and different benchmark epoxy matrices, this work was extensively reported in WP1. Additionally, EPFL prepared model RTM experiments measuring temperatures at different points so as to provide a good set of comparison points for simulation. The experimental procedure was discussed with ESI and AIRBORNE so as to match the simulation. PUC was used as the matrix, with the biaxial fabric. A first heating run is performed with the dry fabric to measure potential temperature gradients in the empty mould. Then, injection will be performed with the same temperature cycle, followed then by the post-cure at 210 °C. The fabric employed for this experiment was a bidirectional fabric 0/90 provided by SAERTEX (with an areal density of 302 gr/m2). The thermocouples TC1, TC2, TC3 and TC4 were placed between the central plies of the laminate at different distances from the injection point. TC5 was located bellow the fabric, in contact with the mould surface, TC6 between the first and the second plies and TC7 between the second and the third (Figure 1a). Figure 1b shows the evolution of the temperatures at the different points of the CF/PU plates during the VARTM process.

In parallel, several PVT experiments were run on the PUB, PUC, and PUD resin at LTN in Nantes. Initial results on the PUB and PUC showed a bend around 120°C in the shrinkage curve of the resin, which is now attributed to gas escape during heating of the resin. PUD is less prone to CO2 escape and gave a linear CTE as expected. These results can now be implemented in the models, as shrinkage versus degree of cure, and as CTE after cure.

Figure 14 - a) Schematic of the PU-composite plate and position of the thermocouples. b) Evolution of the temperatures during processing

Micro-meso process models for novel hybrids and SRC

A new strength model for hybrid unidirectional composites was developed by KULeuven. This strength model considers a bundle of fibres that can be packed randomly or regularly. Two or more fibre types can be dispersed in various ways in this bundle. The strength model splits each of these fibres in smaller elements and assigns a Weibull strength to each fibre element. The strain is gradually incremented and failure of each element is tracked by comparing its strength to the applied stress. When a fibre element breaks, the surrounding fibre elements are subjected to stress concentrations, which increases their failure probability. Once enough fibre elements have broken, a critical cluster will propagate in an unstable manner and cause final failure.

The model predicts the tensile behaviour of hybrid composites until the carbon fibres fail. Hybridisation with a more ductile fibre will typically delay this failure. This effect is called “the hybrid effect” and can be readily predicted using the developed model. The model provides guidelines for optimally designing hybrid composites. The optimal architecture for a 50/50 ratio of both fibre types is shown in Figure 15. This consists of a layered structure with layers that are just 1 fibre thick. By investigating the fibre breaks and cluster development as a function of strain, the model allows a more fundamental understanding of the failure development of hybrid composites.

Figure 15 - Models developed by KULeuven: (a) optimal dispersion for 50/50 ratio of both fibre types according to a strength model for UD hybrid composites, and (b) Embedded element model of hybrid CF/SRPP composite.

A novel approach to meso-level finite element (FE) modelling of textile composites was developed by KU Leuven. The method is based on so-called “embedded elements” (Abaqus terminology): independent meshes for the reinforcing yarns and the matrix, linked with kinematic constraints. The standard approach is to use continuous meshes in the yarns and the matrix. Complex shapes created by intersection of crimped yarns make a task of matrix meshing with continuous meshes difficult, if not impossible. The problem is aggravated by intersection of the yarn volumes due to not-ideal geometrical models which are used to build FE models. Quality mesh in yarns embedded in the host mesh of the matrix, together with contact surface definitions on the yarn surfaces, solves both problems “with one stone”.

To assess the capability of the EE method, different fibre configurations are considered and compared with the full model, ranging from a single fibre problem (straight and wavy fibres) to unidirectional reinforcement. An approach to deal with volume redundancy, inherent to the EE method, is proposed. The results show that there is an agreement between the full and embedded element technique in prediction of the homogenized elastic properties, stress patterns and stress profiles.

Based on the embedded element method, FE models were created for textile composites, developed in HIVOCOMP, and their mechanical behaviour was investigated in numerical experiments.

Model of joints

The modelling of the adhesive joining of the cross-beam demonstrator was modelled by Fraunhofer ICT-A. First, the adhesive fracture energies of adhesives, used in the automotive industry for structural applications, in combination with CFRP with the polyurethane matrix, developed in HIVOCOMP, were determined by testing. The adhesive fracture energies were used to model the adhesive bonding by cohesive contact. The material models are validated by simulating the tests and comparing the resulting force-displacement curves. The simulation results were in good agreement with the test results.

Afterwards the cross-beam assembly was modelled and the load case of the low-speed crash was simulated. The crash simulation results showed that the damage of the crossbeam in the simulation corresponds with the crash test results. The maximum deflection in the simulation is in the range of the real crash tests. The modelled adhesive was not able to keep the bonding intact during the intrusion of the barrier into the crossbeam.

These models can be used for further improvement of the crash performance. Also further investigations could be done to determine adhesives with better bond capability to PU matrix, such that the crash performance of the crossbeam can be increased.

Macro-models

Impregnation of composite parts

In WP1, project partners have developed several successive new PU resins combining unique processing characteristics such as ‘snap cure’, mechanical performance and high Tg’s. Based on characterization work carried out by University of Perugia in task 3.1 we have been able to integrate new viscosity and cure kinetics models in PAM-RTM, ESI simulation software for Resin Transfer Molding (RTM). PAM-RTM standard models for viscosity and cure kinetics are not fitted to represent the behaviour of the new PU matrix systems as this ‘snap cure’ effect is modelled using an inhibition time during which there is no evolution of degree of cure and viscosity. After this inhibition time, the evolution of those 2 quantities can be very fast depending on temperature.

The implementation of the chemorheological & kinetic models uses UserDLL functionality only available with PAM-RTM parallel solver.

Validation tests cases were defined and the evolution of viscosity and degree of cure has been studied for several temperatures.

Fig 16 - PU Resin Formulation B viscosity and curing evolutions @ 100°C

Those curves show the ‘snap cure’ effect captured by the model developped in PAM-RTM. PAM-RTM evaluation of inhibition time error is kept below 1% at 100°C.

Hybrid-Self Reinforced Composites thermoforming

WP2 main concern is hybridisation of self-reinforced PA6 and PP with carbon fibresin order to achieve Hybrid-SRC materials.
K.U.Leuven ran experimental tests on 2 hybrid-SRC materials developed in Work Package 2:

- HIVOCOMP 0-90-90-0
- HIVOCOMP 0-90-NH-90-0

The experimental results were used to calibrate the composite material model MAT140; a biphasic composite shell element material with thermo-visco-elastic matrix and elastic fibres; already existing in the standard version of PAM-FORM 2G v2013.0.
PAM-FORM 2G for Composites enables realistic and predictive thermoforming analysis of laminated composites. It can be used for dry textiles preforming simulation or pre-pregs (thermoset and thermoplastic) thermoforming simulation.
Table 2 presented below summarizes the mechanical material data used in forming simulations whereas table 3 presents friction coefficients to be used in simulations on next page.

Table 2: Summary of material parameters to be used in PamForm

Material	Hybrid SRPP 0-90-NH-90-0	Hybrid SRPP 0-90-90-0
Density	1500 kg/m3	1500 kg/m3
Poisson’s coefficient	0.25	0.25
E1 = E2	6.7 GPa	7.5 GPa
G	G = f(shear angle) for 3 temperatures	G = f(shear angle) for 3 temperatures
B1 =B2	4.5 MPa	4.5 MPa

Table 3: Summary of friction coefficients to be used in PamForm

Material	Temperature (°C)	Friction coefficient
Hybrid SRPP	165	0.334
	170	0.333
	175	0.333

Simulation of crash resistance of composites

ESI developed an Artificial Neural Network representation of the fibre bundles that comprise a composite ply and eventually of an entire composite ply, based on experimental results obtained on the lab. It was found that a hyperbolic tangent network of at least five “hidden nodes” and standard normalization of input and output was necessary to represent the complex ply degradation and failure during crash. Special care was taken in the implementation of the above mentioned Artificial Neural Network within the associated modified VPS (ESI Group) suite of codes architecture to deal properly with its functioning outside its range of validity in a way that preserves physics based consistency. A procedure was also developed to choose and train the network in a way that avoids “overadjustment”.

A calibration processor was developed within the VPS (ESI Group) suite of codes in order to predict the dissociated failure properties of the abovementioned ply representation and was applied to the P6CP6CP6 laminate, by dissociating the constitutive behaviour of the ply to the volumetric, deviatoric and fibre damage. It then established the optimal damage parameters for the resin deviatoric, resin volumetric and fibre constituents within a typical multiply shell laminate model commonly used for crash event simulation in an industrially representative manner. The results showed very encouraging comparison with the experimental ones, clearly depicting the initial fibre fracture followed by the distinct plateau of polypropylene deformation before eventual laminate failure.

Those VPS developments were applied to the case of a Mercedes bumper which was redesigned using Composites.
Two variants of the bumper were considered and modelled using the interactive calibration module developed in the project using linear and non linear (damage evolution and failure) for Glass NCF ply, Carbon fabric and Carbon UD-NCF.
Those variants were analysed under impact loads by comparing of the deformed / broken shapes. An optimization exercise was then performed to see if it was possible to drastically reduce the stroke displacement by 5 mm. The optimization module of VPS (PAM-OPT) was used with the material options developed in the project regarding the stack-up of the bumper as variables. The result was a hypothetical stack-up of a very different ply combination than the original and with a rather promising bumper response which, although being heavily damaged, did not result in bumper failure.

WP4 - Iterative benchmarking of material properties and validation of industrial applications, including LCA
WP 4 was centered on the applicability of the materials developed in WP1 and 2, and made the link with WP5 where demonstrator parts were manufactured.
The first task concerned the selection of suitable parts for industrial application of the materials in automotive and transport, which were used as virtual or real demonstrator (making the difference between those that were not meant to be manufactured, and those that would be manufactured in WP5). These were selected as structural parts that are currently made of metal, potentially of epoxy based composites, except for the suitcase where the benchmark used the CURV material. A summary of the demonstrators is given in the Figure below.

Figure 17 - Summary of the parts selected in WP4 for evaluation.
For each of these parts, a benchmarking exercise was carried out to evaluate their current cost and environmental impact An in-house Activity Based technical Cost-modelling tool was further developed at EPFL for the Hivocomp cases, and the LCA tool SIMAPRO was used to perform LCA. Standard models for Fuel saving were used to characterize the lightweight for a Euro5 passenger car, and the comparison was performed for all parts after a lifetime of 200'000km.

The potential of the new WP1 and 2 materials was then assessed in terms of mechanical performance, cost and environmental aspects. A database was established to summarize all results of mechanical tests, as well as cost and LCA values for the materials as produced. This database was completed along the project and made available to partners on a regular basis. Main conclusions were that best practice were established in terms of processing routes for all developed materials, that their properties were suitable for structural part processing, as well as their cost and environmental impact, in particular as compared to high Tg based epoxy (for the PU) and to other reference materials for the hybrid materials. Sensitivity analysis confirmed that a main driver for cost and environmental impact is the carbon fibre, and that alternative production or precursors, for example hydro-power and lignin based materials would greatly improve the overall contribution of the reinforcement material. Finally, the parts were redesigned along the project to take into account the material properties as well as alternative materials constructions in order to optimize the part weight and properties. Two examples are given below that are representative of overall results.

Example of case study with PU composites

Figure 18 - Volkswagen B-pillar
The B-pillar demonstrator from a Volkswagen Golf A5 is chosen as a practical example to illustrate our results. The benchmark material for this part is stamped steel, and the weight of the part is 3.2 kg. Alternative scenarios have been defined as follows:

1. Scenario 1: High Tg epoxy/bi-axial carbon fibre fabric (volume fraction =46%)

2. Scenario 2: PU/bi-axial carbon fibre fabric (volume fraction = 46%)
3. Scenario 3: High Tg Epoxy/glass fibres composite (fibre volume fraction = 50%)
4. Scenario 4: a light weight sandwich solution, with a skin in PU(C) composite (CF volume fraction = 46%) and a PU foam for the core (2mm of composite, 4mm of foam), adhesive layer not taken into account here.

Figure 19 - Life cycle cost and environmental impact after 200 000 km, as compared to the steel reference scenario.

The results, shown in the figure above demonstrate that with proper redesign of the part and optimized reduction of weight, both the cost and the environmental impact of the parts can reach a lower value than for the steel counterpart, after 200 000 km of vehicle lifetime. It should be noted that the PU-solutions result in a lower cost and environmental impact than equivalent epoxy materials, as the cure is shorter to reach a high Tg with PU materials. The more important reduction for scenario 3 for CO2 and Resources is related entirely to the replacement of carbon by glass fibres.

Contribution Analysis

Materials used in the project are still under development and a sensitivity analysis demonstrated that the LCA of carbon fibres could be greatly improved by producing them with green alternatives, such as using lignin as precursor or hydropower as energy. The figure below presents the results highlighting the main contributors in the LCA. The use phase and the raw materials are as expected dominant. Manufacture and End-of-life treatment appear as secondary stages in terms of impacts.

Comparatively to the other scenarios, the choice of CFRP material induces an increase of the impact contribution during the raw material phase and a decrease of the impact generated during the use phase. In general, from a metallic technology, where the use phase contribute to more than 80% of the total impact of a car part, the composite technology leads to a balance between use phase and material production.

Figure 20 - Contribution analysis on the Climate Change impact (Kg CO2 eq.) of the B-pillar, after 200 000km

Example of case study with Hybrid materials

Figure n+4 shows the demonstrator of a rear back seat from CRF, selected to illustrate the results for hybrid materials. The original part is in steel and is close to 1kg. The part (and its mould) has been completely redesigned and optimized for the WP2 material: PP filled with 8% of CF. The function of the part is still the same and it is developed in order to be implemented in the next generation of Lancia Ypsilon.

The following scenarios have been investigated:
1. Scenario 1: steel, reference system
2. Scenario 2: WP2 PP 8% of carbon fibres cloth, redesigned
3. Scenario 3: WP2 PA 12% of carbon fibres cloth, redesigned

Figure 21 - LCC and LCA for the rear seat back, after 200 000 km.

In the present case, the cost of the PP8% and PA12% materials were taken as 12 Euro/kg, ie just the price of raw materials (with 15 €/kg for carbon fabric) without any special slitting and hybrid fabric manufacturing costs. Except for the Human Health impact, where the steel scenario is still the best, the composite scenarios present very good results. Besides, here the assumed end-of-life treatment is an incineration with energy recovery, but with the high requirements of recycling in the automotive industry and the properties of the materials, we can imagine further improvements on the LCA of this part, concerning the recycling aspects.

Overall, the redesign exercises led to promising results. In cases where the carbon content is limited, such as the CRF seat back that uses the hybrid materials, weight and cost savings can be reached, if the material cost is adapted to high volume cases. In addition, the aesthetic aspect of the material is beneficial for the part, in both cases of the suitcase and the rear seat back panel, leading to easier dismantling after use. In cases where carbon content is high, in the range of 50% in volume, as proposed for PU-based structural composites, the resin contribution is rather limited on the final part cost and impact. Nonetheless, PU is found to have a rather lower impact overall, in particular if compared to a high Tg epoxy resin that generally has a long cure and post-cure cycle. Finally, the sensitivity analysis shown for the B-pillar as an example, but which can apply to all other parts, showed that key for implementation of carbon into automotive parts is the development of cheaper and more energy efficient carbon fibres, from new precursors or using alternative energy sources.

Finally, in WP4, an analysis was carried out both on the end-of-life technologies nowadays available in Europe and on the components developed in HIVOCOMP by the partners involved. From this study, the following conclusions can be drawn:

(1) the substitution of “traditional” materials (like for example steel) with composite-based materials can be economically and environmentally sustainable as shown in the LCA and LCC analyses when the end of life scenario includes incineration with energy recovery. This contribution is always rather small compared to all other cycles in the life of the part. However, if we have to follow the UE directives on recycling, the substitution will be sustainable only if we propose appropriate post-shredding sorting technologies, which nowadays are not mature enough for composites (especially from an economical point of view, as well as from the aspect linked to the mechanical performances of recycled materials compared to virgin ones); several recycling plants have been started in recent years, but research is needed, together with building up more industrial experience.

(2) these difficulties in the end-of-life management of such materials may seriously compromise the introduction of composites in mass-production vehicles, since they may not guarantee the fulfilment of the targets established by the UE 2000/53 Directive, also from a type-approval point of view.

WP5 - Demonstration and validation of typical transport applications incorporating novel PU and Hybrid-SRC

The HIVOCOMP project applied the novel material systems in 5 demonstrators, four of which are car modules developed by VW, Daimler and CRF and one is a suitcase developed by Samsonite.

The HIVOCOMP demonstrators

B-Pillar reinforcement Demonstrator

Figure 22 - B-Pillar assembly

Design of B-Pillar reinforcement Demonstrator

The aim of the B-Pillar demonstrator was to design a crash requirements related demonstrator part and further produce it in the RTM process with the new PU resin of Huntsman. Therefore the simulation tools from WP3 were used to define the material lay-up and processing route for a fully composite b-pillar.

Regarding the B-Pillar reinforcement requirements, the side impact will be the main criteria to define the ply-book combined with a high toughness. Regarding the PU-Resin and the related advantage of the process conditions and mechanical properties, the design needs a close cooperation to the material development to have a maximum of success.

The approach of the B-Pillar part was to define two different parts, one with glass fibre reinforcement (higher potential of a ductile behaviour for side crash) and another design with carbon fibre reinforcement.

In the figure, the position of the FRP reinforcement (red marked) with the inner- and outer metal B-Pillar parts can be seen.

Fabrication of PU B-Pillar reinforcement Demonstrator

The manufacturing of the B-Pillar parts a preform mould was used to fabricate suitable preforms with the RTM process.

A special 650to press was used for the production of the demonstrator parts of Volkswagen.
After cutting of the layers, the preform process followed. Therefore the layers of glass and carbon fabric were used for the production of the preforms. The fabric stacks were heated up to activate the binder. With the special b-pillar preform tool the fabric stacks were draped afterwards. After the preform process, the finished preforms were layered into the RTM tool. Then subsequently the press was closed and the vacuum process started. After finishing it, the injection process began and after a short curing time, the parts were demoulded and finished.

Figure 24 - Finished carbon reinforcement part

Testing of the B-Pillar reinforcements

The B-Pillar reinforcement part was tested with the inner and outer metal shell (see picture) to get the comparable behavior of the complete B-Pillar. The testing was realized with a modified 3 Point Bending rig and specific test parameters. With a constant load (similar to load cases in the dynamic side crash) a static barrier will bend the B-Pillar which is supported on each end of it.

The results of the 3-Point Bending trials are shown in the following charts. For testing following parts were chosen:

- GFRP B-Pillar reinforcement parts
- CFRP B-Pillar reinforcement parts
- Reference steel parts

Depending on a lot of crack initiators during testing of the assembly it is a challenge to differentiate between the influences of the overlapped effects. The reductions of load in the chart show the failure of material and joining effects in the assembly part. In the FRP parts it is a crack visible after testing. Further the weld seam in the area of the barrier broke during testing.

Figure 25 - Test rig

All in all the first millimetres of intrusion of the barrier during testing are very similar to the reference steel part. That are very good results. Looking to the higher intrusion the steel parts are still better. This could be depended on the interaction of the material, the welding of the reinforced steel compared to adhesive joining of the FRP and the better fracture toughness of the metal part.

Comparing load over intrusion of the carbon and glass fibre reinforcement parts, the glass part shows better and more regular test results against the carbon parts.

This could be reasoned with the lower toughness of the carbon part compared to the glass reinforcement.

Front Structure Demonstrator

Design of Front Structure Demonstrator

The design of the front structure demonstrator consists of two CFRP parts, which are glued together. The inner shell has the geometry similar to a double hat profile. This part is responsible for the stiffness of the crossbeam (low speed crash, RCAR bumper test). The outer shell (closing plate) is responsible for the structural integrity in high-speed crash (Euro-NCAP, 40% overlap). Aluminium adapter parts connect the two series crash boxes with the CFRP crossbeam.

Figure 26 - Front structure demonstrator

Starting from an initial design, the design has been optimized in several iteration steps (by simulation and by experimental tests). The weight saving potential of the cross member is limited: approximately 0.8 to 1.0 kg (compared with the aluminum cross member, without crash boxes and without adapter to crash boxes).

Fabrication of PU Front Structure Demonstrator Components

Before the first PU demonstrator components were manufactured, many prototypes with epoxy resin were prepared. The aim was to test and validate the design and layup-structure of the cross beam as early as possible. For this purpose, several Ureol tools have been milled. Prototypes of closing plate and inner shell were manufactured with different materials (glass, carbon, aramid), fabrics (NCF, woven, UD) and layups. The prototype preparation was done in a VARI process. The epoxy prototypes were also used to prepare and validate the low speed crash test (RCAR Bumper) and the high speed crash test (Euro NCAP, 40% overlap).

For the production of the demonstrator components with PU resin, Daimler provided two moulds: For the production of the inner shell a VAP tool (Keim) and for the production of the closing plate a RTM tool (Alpex).

The PU closing plates were manufactured at Airborne using the VAP process on the lower half of the RTM tool. The quality of the closing plates was very good. There have been some very small areas of dry spots. The PU inner shells were manufactured at Airborne using the VAP process on the aluminium tool from Keim. The produced PU inner shells had some dry spots and voids and larger resin rich areas due to fibre bridging.

In addition to the preparation of the closing plates at Airborne in a VAP process, closing plates were prepared in a high pressure RTM process at Benteler-SGL. The aim was to show the process performance and the possible cycle time reduction with the PU resin in a high pressure RTM process. After a short optimization step a very good quality of the PU parts was achieved. At a tool temperature of 95 °C and with a resin injection rate of 20 g/s, a short injection time of 46 s was possible. The curing time in the tool was 5 min. Due to an increased injection rate (50 g/s) it was possible to completely impregnate the fabrics in a very short injection time of only 18 s (no dry spots, some small shrink holes). The parts were still sticky after 3 Min curing (despite the higher temperature). A further optimization of process and/or of resin would be necessary to prove the intended cycle time (injection + curing) of less than 3 minutes experimentally.

All VAP and RTM parts were trimmed in a fully automated robotic milling cell. Inner shell and closing plate were bonded together. In some cases additional blind rivets were used. The adapter parts were glued and screwed to the crossbeam. The series aluminium crash boxes were connected to the adapter parts.

Crash Testing of Front Structure Demonstrator

The front structure components are tested with two different crash tests: The low speed crash test (sled test) simulates the behaviour of the overall vehicle crash in the RCAR bumper test. The high speed crash test (drop tower) simulates the behaviour of the overall vehicle crash in the Euro NCAP test, 40% overlap. The test parameters of both crash tests have been validated by simulation and by experiments with aluminium series crossbeams. All crash tests were observed with high-speed video recordings. Force-time and force-displacement curves were recorded. The condition of the components after impact was documented by photos.

In the crash tests the following variants were compared:

- Aluminium series crossbeam
- CFRP-crossbeam with PU resin
- CFRP-crossbeam with epoxy resin

The results of the high-speed crash test (Euro-NCAP, 40%) were very good. The structural integrity of the CFRP crossbeams (PU and Epoxy) could be maintained in all tests. Due to the flexible closing plate the crossbeam did not break into two parts. As expected, the inner shell was destroyed whereas the closing plate was bended around impact barrier and motor dummy. The closing plate was only slightly damaged. The crash behaviour of PU and Epoxy demonstrator parts was very similar. A disadvantage in comparison to the series components was that the crash behaviour of aluminium crash box was negatively affected by the adapter parts.

In the 1st low speed test series (RCAR bumper) with epoxy prototypes it turned out that the stiffness of the crossbeam was much too low. Based on these results it was decided that a redesign is required for the inner shell. With the new geometry and layup of the inner shell the results of the 2nd test series have not been far away from our target: 80 - 90% of the kinetic energy was absorbed until the tolerable intrusion of 55 mm. Until the break, the energy absorption was even higher than that of the aluminium cross member. But after the break it is much less. In the 3rd test series different design approaches were tested to increase the energy absorption. Unfortunately, the connection between the crash box and crossbeam was less momentum stiff due to a new adapter design. Because of this, a direct comparison of the PU and Epoxy demonstrator parts with aluminium series cross member is not valid. As in the high-speed tests, the crash behaviour of PU and Epoxy demonstrator parts was very similar. Regarding the crash performance, there were no disadvantages for the components with PU resin. Adhesive bonding was on PU (and on reference Epoxy) without problems.

Inner bonnet Demonstrator

Design of inner bonnet Demonstrator

The design of the Inner bonnet demonstrator requires a load-optimized adaption. Depending on the wind load cases, mainly torsional and bending cases are necessary to design the part structure which is a substitution of the aluminium reference.

The following figure shows the ply book for the inner bonnet part with the ground area (green) and different reinforcement areas (blue, orange, red). For the ground area, carbon layer and fleece layer were used. For the reinforcement areas, also fleece layer and carbon were used.

Figure 29 - Inner bonnet design

Fabrication of the inner bonnet Demonstrator

The processing route for the part with PU-CF was developed with BSCT and Volkswagen. BSCT injected the parts using the vacuum assisted high pressure RTM process, monitoring all available processing parameters. The RTM injection mould was made of aluminium. This RTM mould was adapted at BSCT for high-pressure RTM with the PU-dosing system from FRIMO. After preforming in the RTM-tool, the press was closed subsequently and the vacuum process started. After finishing it, the injection process began and after 4 mins curing time, the innerbonnet parts were demoulded. By the end of the project several innerbonnet demonstrators were finished properly with the below mentioned process parameters. Below one of the produced demonstrator is pictured.

Figure 30 - Finished inner bonnet

Testing of the inner bonnet Demonstrator

The testing method is a static load test with different equivalent static load variants. The normal way for testing the mechanical properties of bonnets, real wind load cases will be measured.

For verifying the parts in this project with different materials, a comparable method is to measure equivalent static load cases. The main focus concentrates on specific stiffness of bending and torsion. To measure these properties, different areas of the bonnet will be loaded. One another measurement refers to a tensile test of the restraining bar which is shown in the picture below.
The testing program shows different methods of static load cases. In this way a comparison of the different materials (aluminium, CFRP with PU and CRFP with EP) will be realised. Before analysing the results it is to consider, that also the joining of the news CFRP parts will have a big influence on the results. The application of the adhesive as well as the manual folding of the bonnets is very important to have a load transfer between inner and outer bonnet.

Figure 31 - Testing process
For testing aluminium bonnets and CFRP bonnets are available. One of them is an epoxy resin bonnet to compare the influences of the different resin systems (PU/Epoxy).

To summarize the results of the different testing methods, promising results in torsional stiffness of the front cross member were reached with the CF-PU inner bonnet. Here the results are better in comparison to aluminium and further a lot better compared to the epoxy part.
However the bending of the back cross member as well as the tensile test of the restraining bar shows less stiffness compared to the aluminium part.
In comparison to the CF-EP part, the stiffness of the new developed CF-PU parts is much better regarding the realised testing methods.

Finally it is to say, that the results of the CF-PU inner bonnet show the potential of the new material, especially in comparison to the CF-EP part. Further optimizations of the bonnet geometry and a focus on the joining of the parts could improve the results additionally.

Rear Seat panel Demonstrator

Design of the rear seat back panel
Traditionally, automotive rear seats are composed by a tubular structure with a metallic panel, joined together by spot welding. The panel is covered by a fabric for aesthetic purposes.
The tubular structure, usually round shaped, connects also the two lower hinges, the upper side lock, the upper handle, the Isofix brackets (not depicted in the following picture) and the headrest connections (not depicted). The biggest half also supports the central safety belt bracket.

Figure 39 - the complete rear seat structure
The aim of the activity was the substitution of the smaller metallic panel with a SRC panel to reduce the component weight thanks to lighter material and the removal of the fabric because the SRC has an aesthetic surface.

Figure 40 - the reference rear seat structure
Among all the Hybrid-SRCs that have been developed and characterized, PP + 8%CF has been chosen because it was the lightest and the cheapest material (a lower cost means a wider range of vehicle where it is possible to apply it).

The panel has been designed according to static tests because only hybrid-SRC material static characteristics were available.
It has been chosen the cargo load floor strength test (overloading) because the experimental test equipment was available and it would have been possible to compare experimental and virtual results.
The test consists of rotating the seat back, applying 50 kg in the centre of the panel and waiting for 12 hours before checking for failures or loss of function (moreover a maximum deformation of the loaded panel pair to 5 mm is admitted).

The structural design has been performed using the ESI SW VPS: starting from a 1.00 mm SRC panel, the thickness has been increased until the displacement was smaller than 5.00 mm. The minimum required thickness was 2.00 mm.
Subsequently the thermoforming process has been simulated using PAM-FORM 2G based on woven textile to evaluate the minimum thickness of the plates to be thermoformed to obtain a 2.00 mm panel.
The bosses clearly visible in the process virtual analysis image have been removed because they were critical points during the thermoforming and their structural contribution was very limited.

The results of the process simulation have been used for the proper design of the dies.

Two more materials have been chosen for the moulding trials: standard CURV® and PA + 12%CF.
As the gap of the mould was fixed, also the CURV® and the PA would have the final thickness pair to 2.00 mm even if CURV® panels were expected to be a little weak and PA panels too stiff.
Panels have been pre-heated in an IR oven, adjusting the parameters to the three different materials requirements.

After some trials looking for the proper processes parameters (IR pre-heating temperature and time, mould temperature, compression pressure and time) some prototypes have been produced per each material.

Figure 43 - the prototypes

To perform the cargo load test the standard back seat has been substituted by the prototype, verifying the aesthetic quality, the assembly and geometrical interfaces.

It has not been possible to assemble the seat cushion and the fabric because of the loss of the proper geometrical fixtures. The cushion has been positioned below the folded seat back to simulate the geometrical normal conditions. Some tests have been performed without cushion to increase the harshness of the test itself.

Figure 45 - the PP + 8%CF prototype assembled on the vehicle (left)
At the end of the tests, no loss of function, residual deformations, initiation of ruptures, cracks, functional demerits, aesthetical damages and any kind of defect that cannot be accepted by the customer have been detected.

All the materials passed the test with flying colours. The PP + 8%CF panel showed a 49% weight reduction compared to the metallic panel, while a new design optimisation loop would allow even further weight reduction.

Suitcase Demonstrator

Samsonite used a Firelite 55 design and mould to produce a demonstrator with the hybrid SRC materials, both PP and PA.
The trials started with 2 different lay-ups for CRPP and different carbon fractions (7 and 11%), while the CRPA sheets contained 3 layers of twill 4/4 pattern with 13% carbon fraction. Also different thicknesses of tapes were used. Based on these press forming trials we learned how to press form CRPP shells with the optimized parameters. The CRPA did not produce satisfactory results.

The optimized parameters from the trials were used to press form the carbon reinforced PP shells and produce the demonstrators.

The demonstrators (fig. 50) were made on our production Firelite press forming mould (fig.51 and fig.52),with adapted processing conditions

Fig 47 - Firelite plug Fig 48: Firelite mould Fig 49: demonstrator
For this project Samsonite has performed drop tests on the shell corners. The standard is 60 cm drop height for the wheels (with crack but remain functional/spinning) and 30 cm drop height for the top corners (no dent). The suitcases are filled with 7-8 kg of weight.
Different layups

All layups met Samsonite QA specs in the drop tests, with some layups performing better than others. Furthermore the results are comparable to the reference Curv® performance.

To conclude, in the framework of HIVOCOMP, the technical feasibility of CRPP composite in luggage application has been proven on cabin size suitcase (=spinner 55cm), which is easier to meet QA SPECs due to lower loading.

The next step is to prove the technical feasibility on a large suitcase (eg. spinner 75cm), which has more demanding QA SPECs.

Based on the drop test results, it can be concluded that the thin carbon tape reinforced PP has better luggage drop performance than the thick carbon tape reinforced PP, due to a different PP matrix which leads to higher adhesion between the lay-ups for thin carbon tape reinforced PP.

The CRPP composite has comparable weight as Curv®, but the stiffness is considerably higher. This opens up the possibility to explore a new design direction with smooth main surface and eliminated ridges. Samsonite designers have brainstormed on a new luggage design.

Potential Impact:

Scientific and technical publications and conference presentations

The HIVOCOMP project has been presented in a number of top level conferences in Europe and globally, including EUCAR Conference and Reception, Aachen Body Engineering Days, SPE Automotive composites conference, EV Symposium, Global Automotive Lightweight Materials, Advanced Materials International Forum, ECCM, ICCM, ICCST, SAMPE, Duracosys, Assocompositi, COMPO, and TexComp among others.

Furthermore HIVOCOMP has published (number??) scientific papers in high level journals, such as Composite Science and Technology, Composites (Part A), Thermochimica Acta, Colloid & Polymer Science, Polymer, European Polymer Journal, as well as published articles in high impact industry magazines such as the SAMPE Journal and Reinforced Plastics.

Exploitable results

The HIVOCOMP partners have produced a number of valuable and exploitable results. To highlight only a few:

1. Patents solicited on the new materials technologies developed in the project.

2. Hybridization of self-reinforced composites.

3. New PU system with high Tg and fast injection and curing time.

4. The complete material mapping of PU resin properties.

5. Knowhow in adhesive joining with PU

6. Better understanding of how matrix properties influence composite properties.

7. Strengthened processing knowledge for difficult-to-preform fabrics and gained knowledge in handling and processing of new PU resins. Processing new materials on standard machines.

8. Composite material models to be implemented in future simulation software packages, including predictive models for strength of fibrous composites, for the hybrid effects and novel finite element approaches to textile composites simulation.

9. Improvements in our manufacturing simulation capabilities for advanced composite materials and creation of new Manufacture-to-Performance value chains.

10. New knowhow on economic and environmental impact results of PU resin composites and hybrid materials.

11. Updated knowhow of how composites (especially PU-CF and SRC material) can be used for reducing the weight of vehicles, with well-selected car parts.

12. New collaborations for co-development between research and industry partners.

Industrial and economic impact

HIVOCOMP expects that the results will be used by automotive OEMs and suppliers to extend the use of composite materials in vehicles and other high volume applications. These are not only VW, Daimler, CRF, Benteler-SGL, Samsonite, Propex Fabrics as direct OEMs and supplier partners in the project, but may be also other European manufacturers.

In the long run, if the project results would lead to 10% of global cars with 5% lower weight and therefore more energy efficient, this could translate to savings of an estimated 7 million tonnes of CO2 emissions.

Additionally HIVOCOMP enhances the competitiveness of the European industry and research entities, as well as strengthens the industrial collaboration with research entities, leading to more efficient processes and innovative products. Successful adoptions of the novel knowhow and technologies in the industrial and commercial level could lead to many millions of euros of turnover generated and hundreds of jobs created or maintained in Europe.

List of Websites:
Website: http://hivocomp.eu/

General email: info@hivocomp.eu

Contacts:
Prof. Ignaas Verpoest
Coordinator
KU Leuven
Ignaas.Verpoest@mtm.kuleuven.be

Harilaos Vasiliadis
Project manager
Bax & Willems Consulting Venturing
h.vasiliadis@baxwillems.eu

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