LARGE SCALE MANUFACTURING OF LIGHTWEIGHT 3D MULTIFUNCTIONAL COMPOSITES

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Abstract

The project 3D-LightTrans aims to create a highly flexible manufacturing chain for the low cost production of integral large scale 3D textile reinforced polymer composite parts. In a novel approach, multi-material semi-finished fabrics made of hybrid yarn are formed to deep draped fixed multilayered and multifunctional 3D-textile pre-forms. These are then efficiently processed into the final composite part by thermoforming. This paper presents the results achieved by the project consortium during the last three years. Special focus is placed on the material processing challenges, from hybrid yarn sizing through the fabric weaving, draping and fixation, to the final consolidation process. Modeling, simulation and testing of material properties and behavior, as well as of the production processes, are extensively used.

1. Introduction

Polymer composites combine the lightweight and low cost of polymers with the superior properties of the reinforcing material, while woven fabric reinforcement leads to higher performance, controllability of properties and flexibility for customization. On the other hand, 3D textile composites have been developed because they exhibit, thanks to the use of z-binder for the through-thickness reinforcement, better delamination properties, impact and fatigue resistance than conventional composites. Commercial applications of textile reinforced polymer composites (TRPCs) are however restricted to few cost intensive, small series niche markets. The reason is threefold: (1) too wide a range of possible constituents and difficulty in processing them, (2) too slow, inflexible and expensive production processes, including draping and lay-up, and (3) lack of flexibility in the realization of complex 3D pre-forms.

The project 3D-LightTrans was launched in the spring of 2011 to solve this problem, by implementing a manufacturing chain for low-cost textile reinforced polymer composites (TRPC) based on a new concept. Hereby, a number of promising research level approaches are further developed to a stage of industrial maturity within an integrated low-cost mass manufacturing chain [1]. The 3D-LightTrans consortium consists of 18 organizations from 8 different countries. The industrial participants are two automotive end-users (Centre

Richerche Fiat (CRF) and Bentley), a manufacturer of textile based protection products (Federal Mogul Systems Protection), three coating, fixation and textile equipment manufacturers (Coatema, Van de Wiele and Dornier), one robotic and automation specialist (Promaut), and one yarn, textile and composite producer (PD Glasseiden Oschatz). The academic and research partners (AIT, Ghent University, Grado Zero Espace, ITM at the Technical University of Dresden, Leitat, Onera, SVUM and PRISME at the University of Orleans), as well as the SME Xedera and the industrial association NWTexNet, contribute with their expertise in materials processing, modeling and characterization, production technology and industrial manufacturing.

The project targets are four: a) a *substantial increase of achievable complexity and flexibility in the realization of 3D fabrics*, b) a *new procedure for highly efficient production of TRPC parts*, c) the *establishment of the complete manufacturing chain*, comprising multifunctional product design and modelling simulation, automation, quality control, and application specific finishing processes and d) *demonstrating the technology* by manufacturing of chosen mass products from the automotive sector, with an average overall cost reduction of 45%.

2. The 3D-LightTrans approach

3D-LightTrans concept is based on the use of hybrid yarn integrating thermoplastic material and structural fibers. The hybrid yarn is then woven to create 3D fabrics, which can be then directly consolidated in a fast and efficient thermoforming process. The procedure is supported and enhanced by special 3D weaving, draping and fixation processes. The result is not only a huge increase in product quality and reproducibility, but also a radical time and cost reduction. The main process steps are described below [2,3]:

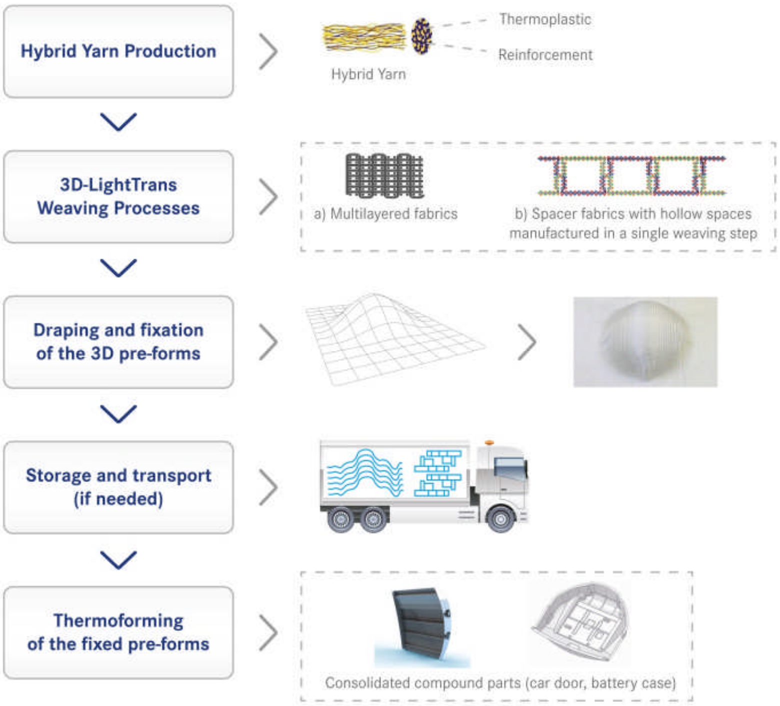


Figure 1. The 3D-LightTrans process chain for 3D textile reinforce polymer composites.

- *Hybrid yarn manufacturing*. Hybrid yarn, composed of reinforcement material (glass) and thermoplastic matrix, is produced using a flexible and reliable manufacturing process. The hybrid yarn can be realised with customised properties and different compositions.

- *Weaving*. The hybrid yarn is woven to create multifunctional textile preforms, such as double shell or spacer fabrics, and 3D multilayer fabrics. A preliminary local, in-line pre-fixation takes place at this stage, in order to ease the later draping process.

- *Draping and fixation*. The draping of the locally pre-fixed textile into the desired final 3D-form is performed in a fully automated way. A novel fixation process can be used to simplify the storage and transportation of the 3D fixed form prior to the final consolidation, in the case that thermoforming takes place at a different place or in a later time (draping and fixation performed in an intermediate, dummy tool).

- *Thermoforming*. The final composite part is consolidated by a fast and efficient thermoforming process. Neither infiltration nor injection of the matrix material are required, as the thermoplastic matrix is already incorporated in the yarn. The process is very stable and extremely efficient, since a long lasting curing time –as customary with thermoset matrix- is not required anymore, and the pre-form geometry can be fixed in advance onto an intermediate dummy tool, reducing the occupation time of the forming tool.

Modelling and simulation are extensively used- both for the processes, and for the material properties and behavior at the micro, meso and macro level. The results are contrasted with those obtained from experimental data with yarns, test fabrics and thermoformed plates. The 3D-LightTrans technology will be demonstrated by manufacturing two automotive components designed by CRF and Bentley (a tailgate and spare wheel well, resp.).

3. Development of the 3D-LightTrans technology

3.1 Validated modeling and simulation toolbox

A comprehensive simulation toolbox with four major modules has been implemented. Two of the modules are concerned with the modeling and simulation of material and structures. One of them covers the meso-scale modelling of the dry fabric architecture (starting from the micro-scale properties of the glass fibre and thermoplastic fibre, air-mingled into the hybrid, commingled yarn), while another module module is devoted to the micro-, meso- and macro-scale modelling of the final composite part. The micro-scale modeling computes the mechanical behavior of the consolidated yarns from the constituent behavior, taking into account the fiber distribution and volume fraction. The micro-scale homogenization of the consolidated hybrid yarns has been modeled by Onera using ZeBuLoN. The meso-scale modeling considers the average mechanical behavior of the material, taking into account the fabric architecture and the yarn shapes, and has been implemented by UOrl and Onera using Abaqus. Finally, UGent has developed (using also Abaqus) the macro-scale modelling of impact behaviour of thermoformed plate, where the composite material itself is modeled as a homogeneous anisotropic material with properties obtained from calculations at the lower scales or from experiments [4].

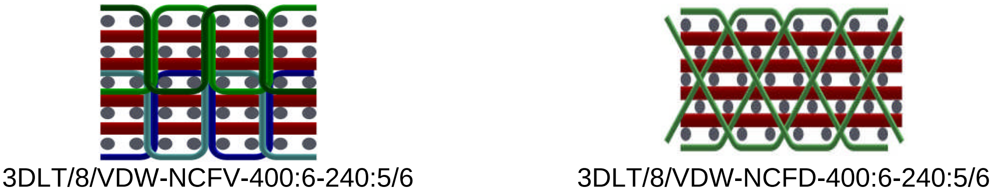
In order to create a knowledge-based manufacturing approach, different process steps, as well as the complete manufacturing chain, are modeled and simulated. The simulation of the draping of the dry fabric architecture and fixation of certain areas of the dry fabric has been accomplished by TU-Dresden using a finite element analysis (FEM) model [3], and validated with experimental tests done at PRISME [5]. CRF has performed the simulation of the thermoforming process using PAM-Form. Finally, the complete process chain has been modeled by GZE using the software ARENA.

Extensive experimental tests and measurements have been performed mainly by PRISME, TU-Dresden, Onera, UGent, SVUM and Leitat, not only to provide input parameters to feed the models, but also to validate the results of simulation. This includes the uniaxial, biaxial and shear testing of fabrics; friction, compaction, bending and forming tests on fabrics; ultrasonic inspection of the impact of moisture absorption on the thermoformed plates; impact test and micro-CT scans. The modeling and simulation tools have been successfully validated with at least one selected 3D woven composite, namely 410tex diameter commingled glass-polypropylene (PP) yarns, and a weave architecture with 4 warp-5 weft yarns with 45° Z-yarns (see Fig. 2). Still, they have been developed in a way general enough to allow to change the fibres, polymer matrix or fibre weaving architecture, and some of them have actually also been tested and provided satisfactory results with Glass- Polyethylene terephthalate (PET) yarn, the composition selected for the final demonstrators [3].

3.2 Manufacturing of dry multilayer and 3D shaped fabrics

Commingled yarn provide better impregnation of the thermoplastic material in between the glass fibers. However, the glass fiber can be damaged during weaving at a later phase, and also during the production of the hybrid yarn, with the yarn damage leading to a strength reduction of the commingled yarn [6]. Consequently, TU-D set the research priority not only in attaining a homogeneous distribution of the individual components along the thread cross section, but also in guaranteeing a gentle processing of the reinforcement threads. Finally, TU-D and PD-GO succeeded to modify and optimize the air mingling process for the *manufacturing of hybrid yarn*, not only with PP (the material used in the first experimental phase), but also with PET (the matrix material chosen, due to it higher temperature stability, for the manufacturing of the demonstrators). This was achieved by tuning process parameters like the fiber yarn count, yarn feeding speed, air pressure and adjustment of the flyer [2,3]. As a result, a very high reproducibility of the composition of the hybrid yarn could be achieved with increased productivity rates (approximately. 500 m/min). At the same time, the abrasion and hairiness could be reduced without compromising the final mechanical properties severely. The modified air mingling machine for hybrid yarn production has been delivered by PD-GO, and hybrid glass-PP and glass-PET yarn have been successfully produced and delivered for weaving, characterization and further work within the project.

Two distinct *weaving* approaches have been followed within the project: multilayer fabrics for the processing to deep draped pre-forms, and 3D-shaped spacer fabrics. Concerning the multilayer fabrics, Z-reinforcement is known to improve the delamination behavior and the out-of-plane properties, especially in 3D stress and impact loading [5]. Therefore, TU-Dresden has designed, realized and evaluated several *multilayer fabric* patterns in different weft densities with additional z-reinforcement in different orientations.



3DLT/8/VDW-NCFV-400:6-240:5/6 3DLT/8/VDW-NCFD-400:6-240:5/6

Figure 2. Different weave architectures of 3D multilayer fabrics [3]

In fabric A, the position of weft yarns in the different layers is the same, the z-yarns are vertically oriented and interlock just 3 layers of weft yarns. In fabric B, the position of weft yarns is shifted between the layers, the z-yarns are diagonally oriented and interlock the 5 layers of weft yarns. As mentioned, the yarn can be damaged during the production of the 3D-fabric, the main cause of damage during weaving being abrasion of the fibres with each other and with the loom machinery [6]. PRISME measured a reduction of up to 28% breaking strength and 17% Young modulus in yarns extracted from the woven fabric [7] (yarn damage increasing with increasing weft density), and further experimental analysis shows the additional influence in the mechanical properties of the reinforcing fabric of the yarn arrangement in the fabric and of the properties of the hybrid yarn [2], beyond weft density. Considering all this, a new Dornier loom has been modified and optimized for the 3D-LightTrans technology. After successful installation at TUD, fabric of GF/PET 840 tex (final yarn architecture) has been produced with it for manufacturing the finals demonstrators [2].

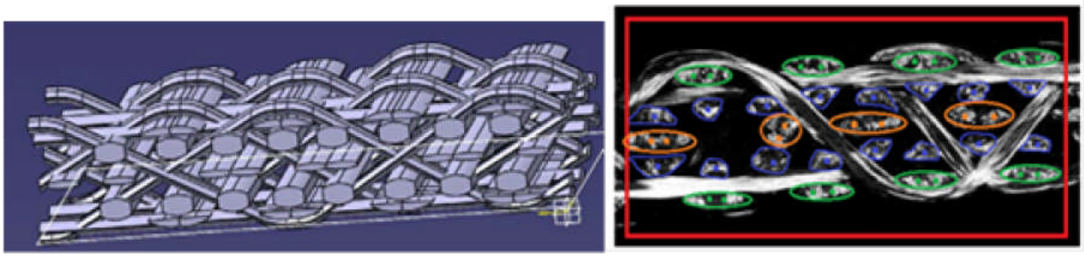


Figure 3. Unit cell of the 3D-fabric (UORL) and analyses of a micro-CT scan showing the real internal structure and highlighting the yarns and contact positions (UGent) [5]

On the other hand, a technology for 3D-shaped fabrics has been implemented. Conventional spacer fabrics (pile weaves), connected by additional pile yarns show poor mechanical properties (elasticity and deformability under applied load). In the approach followed in the 3D-LightTrans project, in contrast, the 3D-woven spacer fabrics are constructed of woven outer layers connected by woven cross-link fabrics. Such constructions exhibit better mechanical properties, such as tensile, compressive, flexural strength and impact resistance [8]. The spacer fabric technology has been implemented by TU-D on a double rapier weaving machine in cooperation with Van De Wiele, and the pattern for different structures of *3D shaped structures* (spacer fabrics) has been created.

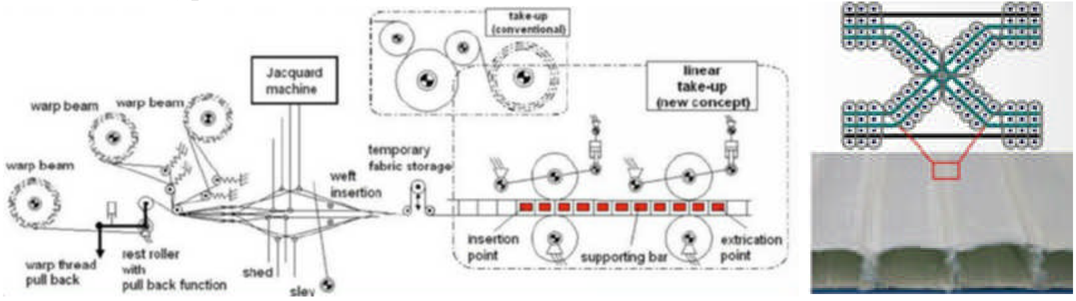


Figure 4. Modified double-rapier weaving machine and multilayer woven spacer structure (right)[2]

Local *pre-fixation* can be used to create a local increase of mechanical stiffness in well-defined areas previous to the draping [9]. A crucial issue here is the determination of suitable zones for the local structure fixation. In the 3D-LightTrans project, this is achieved by simulating the draping behavior of the textile structures, with provides information on the fibre orientation after forming [3]. Further, a novel pre-fixation method has been evaluated by Coatema. This method consists in applying heat on special fabric samples (manufactured by TU-D), which integrate selected distinctive yarns with modified properties for local pre-fixation. Different fabric configurations and heating methods were tested by Coatema, and evaluation was performed by means of optical analyses, tensile test and bending tests. The following picture shows the increase in bending stiffness introduced by pre-fixation.

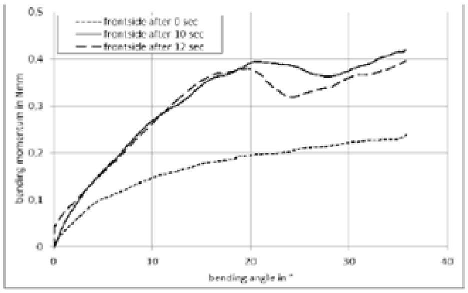


Figure 5. Increase in the bending stiffness of 3D-LightTrans fabrics introduced by pre-fixation

3.3 Manufacturing of the final textile reinforced composite part

As a result of the pre-fixation, the path planning for the automated, robotized *draping* operation is made simpler, because the draping takes place more homogeneously thanks to the presence of defined pre-fixated areas, the flow of forces is better balanced, and the number of wrinkles is reduced. In the next step, draping simulation is used by TU-D to provide a first estimation of the effectiveness of different draping strategies. The simulations performed by TU-D analyze the forming of the fabric into the 3D geometry. The implementation of the automated, robotized draping procedure is addressed by Leitat and Promaut. A first demonstration system with self-developed draping tools and force control integrated in a robotic system, is already available.

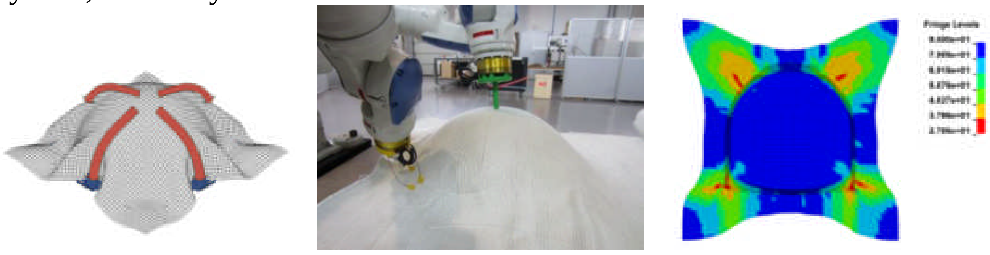


Figure 6. Simulated robot draping strategy and preliminary robot draping test with robotic grippers

One of the key advantages of the 3D-LightTrans technology is the possibility to fixate the fabric. Hereby an intermediate step is added, where the flat multilayer fabric is processed to a fixed 3D pre-form, with already fixed geometry, but not yet consolidated material. To enable this, different *fixation* methods have been being explored by Coatema, including thermal activation and the use of additional binders. The increase in stiffness created by the fixation process should be sufficient to avoid additional draping or shearing affecting the complete pre-form as a consequence of handling, storage and/or transport. The fixed pre-forms can thus, if required by logistic or supply chain requirements, be placed into the thermoforming tool at a later stage without needing to repeat the draping procedure.

During *thermoforming*, complex processes take place in the fabric. After the thermoplastic fibre filaments inside the yarns start melting (with significant changes in the rheology of the polymer and in the viscosity), the thermoplastic polymer begins to flow, constrained by the glass fibre architecture. At the same time, the pressure exerted by the thermoforming press leads to a strong compaction of the fabric (more than 50%). In order to achieve the desired results, it was crucial to understand the influence of the different factors and to correlate the process parameters (temperature, pressure…) with the final composite properties. This was achieved through modeling and simulation, as well as through systematic thermoforming tests performed by FM-SP. Hereby, the process parameters were varied and the thermoformed plates properties verified by means of CT-scans, micrographs, measurements of thickness and mechanical properties, and visual inspection of the surface. Certain waviness in the in-plane warp and weft yarns, a non-linear behavior and the importance of plastic deformation in compaction have been observed. The study of the impact behavior of the final consolidated 3D-LightTrans plates performed by UGent, TU-D and Leitat, shows a good correlation between the experimental results, using a well-instrumented drop weight test, and the results of simulation, with modelling based on a Continuum Damage Mechanics (CDM) approach [4]. With improved knowledge on the process, development of and first experiments with thermo-press tools for deep draped parts by LKR and FM-SP are currently on-going.

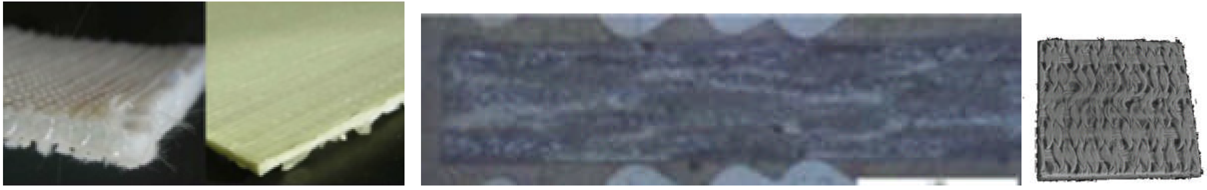


Figure 7. Compaction of the multilayer fabric [2]; micrograph of glass/PP composites after thermoforming, showing black zone (=pores) and waviness of the yarns [4] (right).

4. Demonstrators

The 3D-LightTrans manufacturing chain will be demonstrated for two specific end products from the automotive sector. The *spare wheel well* selected by Bentley is a large, complex, deep drawn part that forms part of the rear chassis structure of the vehicle and performs a wide range of roles, including the storage of the batteries and spare wheel. The exterior is smooth and passes close to the exhaust, the interior is complex and interfaces with a large number of components, which will require structural metallic inserts. This component will utilise the multi-layer material form and will be separated into 2 parts.

The CRF demonstrator is a *top-hinged tailgate* (hatch), a door at the back of a vehicle that is hinged at the top and opens upward. This component is made from two parts, the outside panel and the inner structural part. The objective is to reduce the weight with reference to the current steel part and to guarantee the same functionality. The material choices and manufacturing processes were chosen to reflect the requirement for a Class-A painted surface and to accommodate very high localized loads introduced through the hinges and latches.

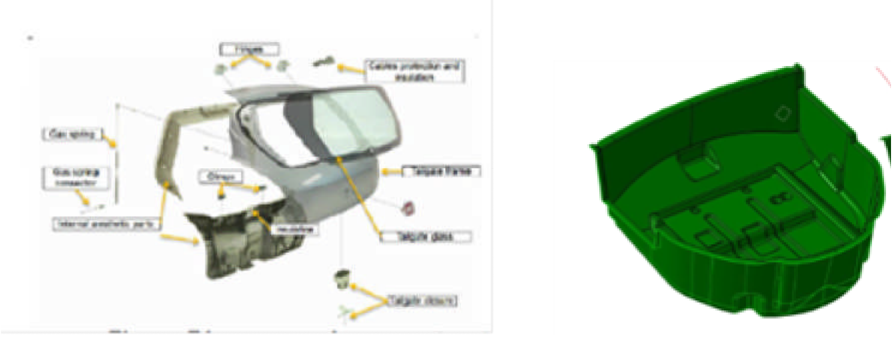


Figure 8. 3D-LightTrans demonstrators: CRF tailgate and Bentley's spare wheel well.

During the design phase, consideration has been made for the constraints of the textile geometry and architecture, and of the preforming and pressing processes, while retaining the full functionality of the parts at minimum cost and weight. The representative meso-scale geometries and their FE representation, material behavior of the constituents, have been created. The load cases have been defined and the testing regime (using the Automotive OEM partners internal standards) established. On the other hand, the adaption of the machinery for the large scale production of the fibre feedstock and the textile machinery for the production of the preforms has begun and there are no known issues preventing the delivery of the material. Further, in order to ensure and facilitate the real future industrial deployment of the 3D-LightTrans technology, the partners Promaut, GZE, AIT, Xedera and CRF are also exploring the scale-up for mass production and aspects of product life cycle, as well as relevant supply chain concepts and business models.

5. Conclusions

The project 3D-LightTrans was launched in the spring of 2011 to develop a novel approach for the large scale manufacturing of low cost textile reinforced polymer composite parts. In the three years elapsed since then, the consortium has successfully implemented the manufacturing of hybrid yarn, multilayer and spacer fabric weaving, and pre-fixation and fixation technologies. Further work is on track to finalize the implementation of the automated draping procedure, the consolidation thermoforming process, and the finishing processes required to produce the automotive demonstration parts. This paper has shown how use of modeling and simulation in the 3D-LightTrans project leads to a deeper understanding of the material behavior, enabling the prediction of the material behavior and properties and the optimization of the different processing steps.

Acknowledgement

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