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Outcomes of MADMAX the European Network on composites for transport applications

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Résumé :

Au sein de l'union européenne, le transport routier est responsable de près de 20% des émissions de CO₂. Afin de réduire ces émissions de gaz, l'union européenne introduit actuellement de nouvelles normes rigoureuses, réduisant les limites acceptables d'émission de gaz à effet de serre pour les nouveaux véhicules vendus dans les pays membres de l'union européenne. Ainsi, les industries du transport doivent développer des véhicules plus légers tout en maintenant la qualité et la sécurité, si elles veulent respecter ces nouvelles réglementations. Or les matériaux composites offrent la possibilité de mettre au point des structures légères avec une grande capacité d'absorption d'énergie, mais ils restent encore des matériaux relativement nouveaux. Leur comportement mécanique n'est pas complètement compris et maîtrisé, et les procédés de fabrication restent principalement artisanaux, de plus les simulations ainsi que les systèmes de contrôle santé doivent encore être adaptés aux composites.

Les composites apparaissent alors comme une solution prometteuse pour le secteur du transport, et c'est la raison pour laquelle la commission européenne a soutenu le projet MADMAX (Advanced material Textiles for Reinforced Structures for Complex Lightweight Applications) contribuant à l'élaboration d'une plateforme européenne de savoir et de données en matière de composites (fibres/matrice) à hautes performances, de structures textiles et de contrôle santé par capteurs intégrés, afin de favoriser le transfert des avancées scientifiques vers les applications du transport et à destination particulièrement des PME. L'objectif du projet MADMAX était de créer un consortium de laboratoires privés et universitaires soutenus par des industriels clés dans les domaines de l'automobile, de l'aéronautique, du ferroviaire et du naval afin d'étudier les possibilités de diffuser et d'étalonner l'emploi de composites spécifiques. Les principaux résultats du projet seront présentés. Les matières premières, les structures textiles, les méthodes de caractérisations, les méthodes de modélisation pour les simulations procédé et fatigue, les procédés de fabrication, les techniques d'assemblage et le contrôle santé des composites sont autant de thèmes qui ont été couverts par le projet.

Abstract:

Within the European Union, road transport is responsible for about 20% of all CO₂ emissions. To reduce these gas emissions, the European Union is introducing stringent standards defining the acceptable limits for exhaust emission of new vehicles sold in EU member states. Thus, transport industries have to develop lightweight vehicles maintaining quality and safety in order to comply with these stringent gas emission regulations. Composites are offering the possibility to build lightweight structures with an important capacity of energy absorption, but they are still relatively new material. Their mechanical behavior is not fully understood and mastered, and manufacturing processes remain

principally manual work and simulations as well as monitoring systems have to be adapted for composites.

As composites appear to be promising materials for transport sectors, the European Commission supported the MADMAX project (Advanced material Textiles for Reinforced Structures for Complex Lightweight Applications) which contributes to the development of a European “Know-How” platform and database for excellence in high performing fibers and resins, textile reinforcing structures and sensor monitoring composite structures, fostering the transfer of scientific results to civil transport markets and especially to SME’s. The objective of the MADMAX project was to organize a cluster of private and academic laboratories supported by key manufacturers from transport sectors and to investigate the possibility of benchmarking specific composites. The main outcomes of this project will be presented. Raw materials, textile reinforcement structures, characterization methods, modelling methods for manufacturing processes and service life simulations, manufacturing processes, joining techniques, and structural health monitoring of composites were the issues covered by the project.

Keywords: composites, transport, automotive, marine, aeronautic, railway, characterization, manufacturing, modelling, monitoring, joining

1 Introduction

The starting point of Madmax project was to identify the industrial needs and technological limits regarding composites in transport sectors. Currently, composites development in transport industries is impeded by:

- A high price mass-ratio: raw materials of composites (fibers and resins) are expensive.
- A lack of automated manufacturing processes: without automated processes, manufacturing is cost consuming, the production rate is low and the end product quality control is difficult.
- Disparity in material properties: because of the lack of automated processes to manufacture composites, it is not possible to obtain materials with calibrated properties. Moreover, for the railway industry there are additional certifications requirements for fire resistance and for the aeronautic, qualification methods have to be developed for thermoplastics.
- A lack of knowledge in fatigue behavior: there is a lack of fatigue test results which impede to develop reliable ageing behavior models and to have guarantees on lifetime prediction. The main question to be solved is: how to perform accelerating tests representing 40 years of life? System Health Monitoring could certainly be of great help but still has to be developed. Additionally, for the marine industry there are degradations due to the marine environment.
- A lack of knowledge on joining techniques: Reliable joining techniques for composites (homo and hetero-junctions) still have to be developed.

Major obstacles to composites development for each transport sector were revealed. In automotive industry, the main obstacle is the lack of automated manufacturing processes which impede the production of a car in a big series. In railway, fire resistance requirements are a major obstacle. For the marine industry, the main problems are the restricted use of combustible materials (SOLAS regulation) and the aggressive marine environment. Finally, for the aeronautic industry the lack of knowledge on thermoplastics is an obstacle. This study also highlighted the fact that the railway sector is lagging behind the others transport sectors in terms of composites integration. However, a mentality change is required for all sectors and an effort on formation is necessary.

This present article summarizes the work during the project to describe the technological limits and to propose a research roadmap to reach the technologies of the future [1]. The article is divided into 5 parts, each of them dealing with one stage of composites development: from raw materials, to textile

reinforcement structures, to modelling methods, to direct processing methods, and structural health monitoring.

2 Raw material

Composites can be defined as materials made of two or more chemically and physically different phases (e.g. matrix and reinforcement) separated by a distinct interface. Composites can be classified with respect to their matrix, i.e. Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs), and Polymer Matrix Composites (PMCs). The latter is the most used in many technological sectors. The larger diffusion of PMCs with respect of MMCs and CMCs can be generally ascribed to the excellent performance/cost ratio. Particularly, PMCs exhibit a relative low cost of the raw materials (i.e. polymeric matrices), simple manufacturing methods and a good performance/specific gravity ratio.

2.1 Matrices

PMCs properties vary within a relative broad range, given by the number of available polymer matrices, i.e. thermoplastic / thermosetting polymers and corresponding features. When heated, thermoplastics polymer matrices undergo softening/melting and consequently can be mixed with the reinforcing fibres and formed in the final product shape (laminates, bars, etc.). Thermosets undergo irreversible chemical reactions (cross-linking / curing) on part fabrication. The main thermosetting resins used in PMCs are:

- Unsaturated polyester resins: by far the most used
- Epoxy resins: good properties
- Phenolic resins: brittle behaviour

The main thermoplastic resins used in PMCs are:

- Polyolefin: excellent balance between properties and cost
- Polyketone resins: outstanding mechanical properties, the most commercially successful polyketone resin is (PEEK) [2-4]
- Polyarylene sulfide resins: excellent chemical stability and mechanical properties.
- Polyether imide: Polyether imide (PEI) has excellent mechanical properties and good heat resistance.
- Bio-based resins: Market available bio-based polymers encompass a number of macromolecules. Among them, it is noteworthy to cite the poly(lactic acid) (PLA), the poly-L-lactide (PLLA), polyhydroxybutyrate (PHB), Polyhydroxyalkanoates (PHAs), polyamides, polypropylene (PP, from bio-based ethylene obtained converting ethanol), Polyethylene terephthalate (PET), and all thermoplastic materials. Other, partially bio-based resins are thermosetting (e.g. polyurethanes with bio-based dyols), epoxy (bio-based epichlorohydrin from glycerol) [5-8].

Bio-polymers are obtained from renewable sources such as micro-organisms, algae, bacteria, superior plants, etc. Biopolymers can be either synthesized directly or through the synthesis of the monomers followed by polymerisation. Most of the bio-based polymers cited before are employed in the packaging field. The use of bio-based polymer as matrices for composites in demanding applications like the transport sector, is still a niche market at that stage of development.

The factors generally limiting the use of bio-based polymer as matrices for performance composites are:

- The lower overall mechanical performances of bio-based with respect to oil-based matrices

- The important modification of well assessed industrial processes (melt- processing as well as manufacturing of thermosetting composites) that would require bio-based polymers
- The poor durability of bio-based matrices in long-life applications (building/transport)
- The higher cost of bio-based with respect to oil-based polymers (e.g. PP vs bio-based PP)

2.2 Fibres

The two most common synthetic fibres are glass fibres and carbon fibres. Recently, due to the environmental regulations the use of aramid fibres decreases. So instead of focusing on aramid fibres, this part presents natural fibres which are attracting great attention from the construction and automotive sectors.

In terms of life cycle cost, the use of bio-sourced materials, obtained from renewable resources, can be considered as an effective way to achieve carbon neutral economy. In this regard, bio-composites, whose matrix or/and fibres are obtained from biomass, are attracting great interest from many industrial sectors. The market of biocomposites has been growing fast in recent years and the 15% of European composite production in 2012 was bio-composites.

Among natural fibres, flax, hemp and kenaf fibres are regarded as potential composite reinforcements instead of glass fibres by dint of their good specific properties, i.e. their specific modulus and strength. Many scientific and technological efforts have been dedicated to find solutions improving the inherent variability of natural fibres quality and their poor compatibility with polymers. Nevertheless, the poor durability with the hygrothermal ageing and the low thermal stability are still great concerns for natural fibres.

The current adoption of bio-composites in the automotive sector is not driven by a technical demand but by the eco-marketing and governmental regulations. In particular, the existence of governmental incentives may have great influence on the market growth of bio-composites for automotive applications.

2.3 Functional material

Replacing metals by polymer composites has pointed out the issue of conductivity, especially in presence of the large number of electric and electronic devices nowadays used in any kind of transport. An effective barrier to electromagnetic fields must also be guaranteed by lightweight polymer composite. The state of the art relies on modified reinforcing textiles.

Surface modification of the textiles by means of, for example, nickel, leads to a conductive surface also capable to withstand saline environment corrosion. Nickel surface coating provides an effective shielding capability against mid-high frequencies with high attenuation dB (Figure 1). Surface resistance of less than 1 Ohm can be obtained with the surface modification of the reinforcing textile.

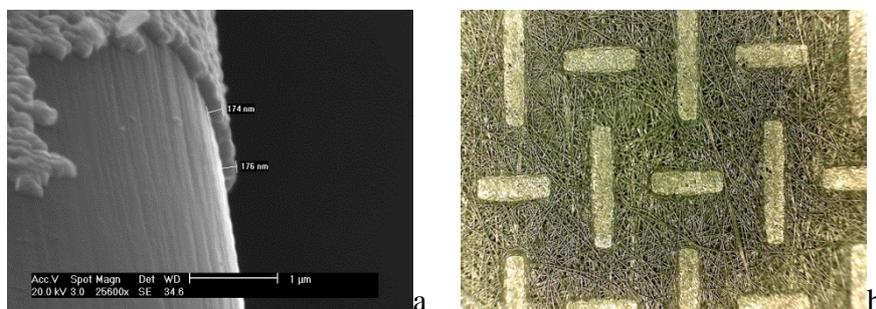


Figure 1: a) Nickel-coated polyester fibre, b) A fabric made of nickel-coated fibres

With the introduction of organic materials, like polymer composites, in transport sectors, mastering the flammability and combustion behaviour of carbon-based materials and reinforces is becoming a technical challenge.

European standards are, for example, defining the fire performances of materials used in rolling stock and aircrafts. The EN 45545-2 – “Fire Protection on Railway Vehicles” defines very high fire safety requirements. Thus, now the use of materials such as polymer composites is challenging with respect to their combustion behaviour, e.g. smoke opacity and toxicity.

Civilian aircraft fire safety is subjected to the USA Federal Aviation Administration Regulation FAR 25.853. The FAR 25.853 aimed at giving passengers an escape time of five minutes. But the possibility to increase the escape time up to 15 minutes is currently being discussed. Such an important increase in the escape time would be further challenging in terms of materials used.

Companies have started to develop and eventually, put on the market, both thermosetting and thermoplastic polymeric composites compliant with reference standards (e.g. phenol prepregs for carriage interiors and structural applications from GURIT®, long carbon fibre reinforced polyethersulfone from BASF®, etc.)

Further development is expected in this field, driven by the evolution of the safety standards in the transport sector [9-11].

The main strategies adopted so far to deliver compliant polymeric composites are:

- To adopt relatively expansive polymer matrices (e.g. highly aromatic macromolecules)
- To use fire retardants additives or as reactive monomers
- To create specific design, in which fire resistant materials shields the underperforming plastics.

2.4 Vision of the future

The future challenges for raw materials concern the following key-aspects:

- To improve the manufacturing processes of PMCs. For example, the development of high speed curing thermosetting resins and low viscous thermoplastic materials would be of great interest.
- To develop fully bio-based PMCs with a good cost/performance ratio capable to guarantee adequate production volume for markets such as the automotive sector.
- To develop functional materials such as self-healing materials. The self-healing capability represents a mid-long term target with a tremendous impact on the potential applications of PMCs. A number of solutions have been investigated so far, mainly by academia and R&D centres. However the Technology Readiness is still too far from the application.

3 Textile reinforcement preforms

In this section, advantages and limits of the different textile structures are reported and then a vision about the future challenges is given. The textile industry is generally divided into four main production sectors related to technology: Weaving, knitting, braiding, and non-woven. Some other technologies can complete the 4 core technologies in order to enable the production of more complex textile structures.

3.1 Advantages and limits of textile preforms

Tailoring the alignment of fibres in a composite material or structure is crucial to maximize properties like strength, stiffness, fracture toughness and damage resilience. Each textile technology introduced before, provide this fibres alignment in preform. The Table 1 summarizes advantages and limits of preform products.

Preform architectures	Advantages	Limits
Woven preform	<ul style="list-style-type: none"> ✓ Good in-plane properties in yarns direction ✓ Good drapability ✓ Highly automated preform fabrication process ✓ Suited for large area coverage 	<ul style="list-style-type: none"> × Moderate degradation of the in-plane properties due to yarn crimp × Low out-of-plane properties and delaminating resistance × Poor fabric stability × High wastage rate × Poor in-plane off-axis and shear properties
Knitted preform	<ul style="list-style-type: none"> ✓ High formability and drapability ✓ Highly automated preform fabrication process ✓ High impact energy absorption ✓ Complex 3D shape and sandwich architecture can be produced using highly automated knitting machine 	<ul style="list-style-type: none"> × Low area covering factor × Poor in-plane modulus and strength properties × Poor fabric stability × Preform assembly step is required for the 2D knit fabric: intensive labour for lay-up process and high wastage rate
Braided preform	<ul style="list-style-type: none"> ✓ Axial yarn set can be added ✓ Continuity of yarn all around the tube geometry ✓ Good balance in off-axis properties ✓ Highly automated preform fabrication process ✓ Well suited for complex curved shapes ✓ Good drapability 	<ul style="list-style-type: none"> × Big size needs a huge machine (Size limitation due to machine availability) × Weak shearing rigidity × Cover factor depends from braid angle and mandrel geometry × No fibre reinforcement into the through thickness × Poor out-of-plane properties × Low interlaminar toughness and post-impact properties
Non-woven preform (by Needlepunching)	<ul style="list-style-type: none"> ✓ Process can produce complex net-shape/near-net-shape preforms ✓ Needle-punched composites with a complex shape can be inexpensive and simple to manufacture ✓ Process can tailor the through-thickness properties for a particular application ✓ Possibility to use recycled material as short-fibres 	<ul style="list-style-type: none"> × Needle-punching degrades the in-plane mechanical properties × Weak mechanical properties compared to aligned preforms × The effects of high speed needle-punching process and multiple needle-punching process on properties are not fully understood × Durability and long-term environmental ageing tests on 3D needle-punched composites have not been fully performed × Predictive models for determining strength performance have not been fully developed

Table 1: Advantages and limits of textile preform architectures

3.2 Vision of the future

Structures with a 3D fibre topology are desired due to their superior multi-axial performance. Efforts have been made to modify 2D textile technologies to produce complex 3D shapes, using generally the so-called 3D-weaving. These technologies are promising solutions but are unable to decouple macroscopic structural topology and microscopic tow/fibre alignments. Most of these 3D solutions are based on the principle of adding out-of-plane reinforcements to 2D planar preforms. Examples of this method are given for z-pinning [12], interlock-weaving [13-15], stitching [16] or tufting [17, 18]. Well-established 3D textile methods such as braiding and knitting have also demonstrate their ability to directly produce near net-shape structures.

Hybridization of textile technologies, like previously presented, can conduct to manufacture near net-shape structures to avoid steps like cut, layup and preforming during composite processing. Hybridization of technologies also allow to add some specificities, like for assemblies with metallic parts, which are the future of textile preforms.

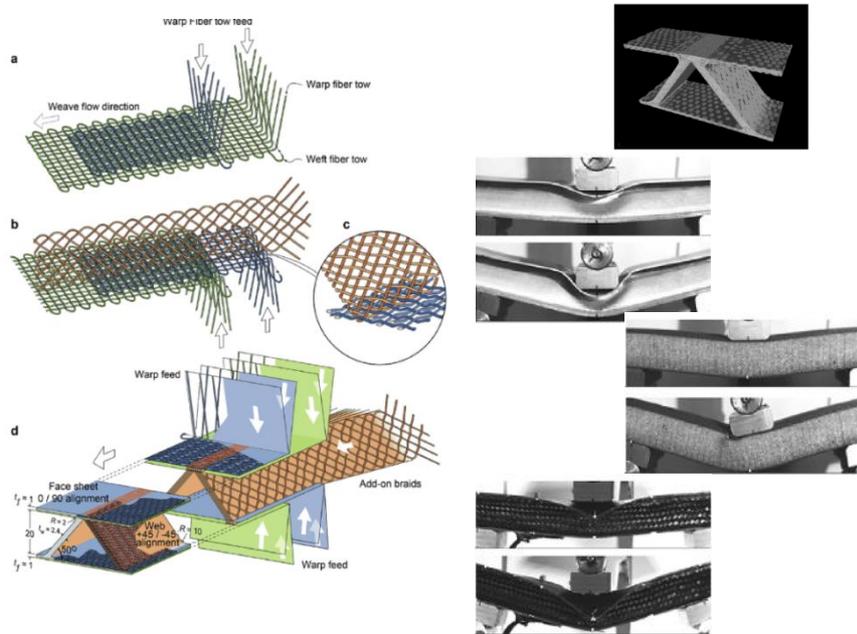


Figure 2: Description of textile process. A beam part and a comparison of metallic and CFRP parts subjected to 3-point bending

The figure 2 [19] shows an example of a beam realized by hybridization of 3D-weaving with braiding of tow carbon fibre. This part, infused with a polymer matrix, has been compared to a metallic version and one obtained by stacking 2D-woven fabrics with the same carbon tows. Quasi-static-3-point bend tests were demonstrated a best mechanical behaviour of the composite manufactured by hybridization textile processes. The figure 3 shows potentialities to produce, in one step, 3D cross-stiffeners net-shape preforms, or joints with a T or H cross-section [20]. In these examples the continuity of fibre is insured by textile technologies (here 3D-weaving) avoiding assembly steps, especially at the crossing of stiffeners. This 3D-textile technology permits to have fibre orientation in 3-direction.

The last example (Figure 4) concerns a seat for truck application, initially realized in metal. The requirements specification displays high mechanical loading zones and specific assembly spaces to join the composite part with metallic part by welding.

To reduce processing costs, the preform is based on comingled yarns (Glass/PP). 3D-weaving technology is used to insure high fibres density at specific regions of the preform, in order to comply with the mechanical specifications. During the weaving process, metallic braids are associated to fibre reinforcement in the specific zones to enable welding. Choosing a thermoplastic process for its reversibility and including assembly specifications at the preform manufacturing step, allow satisfying the requirements for the composite part.

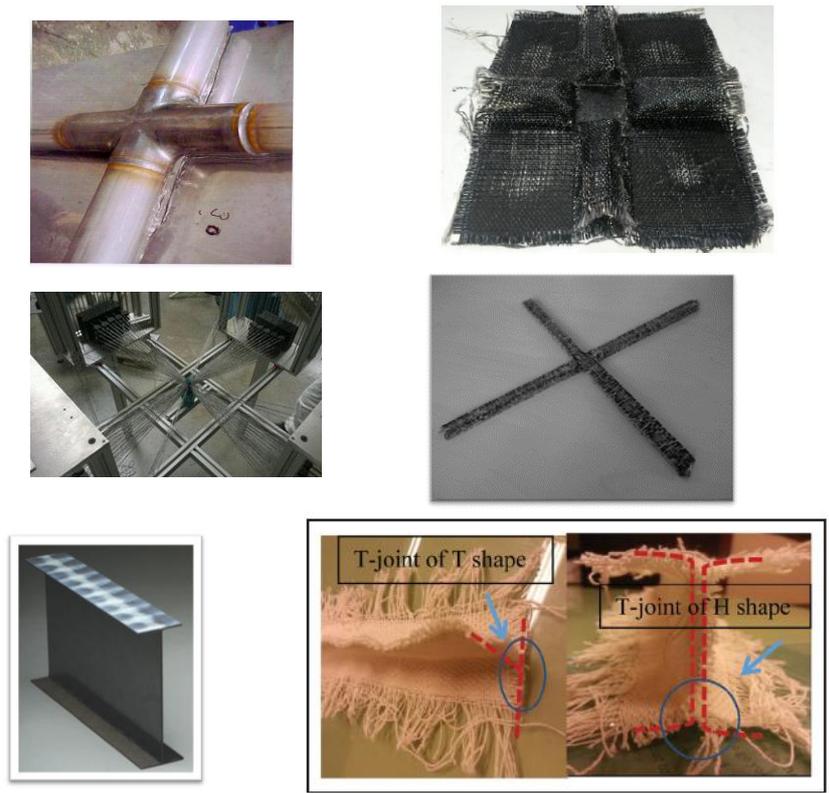


Figure 3: Cross-stiffeners with metal and fibrous parts and a 3D-weaving T-joint

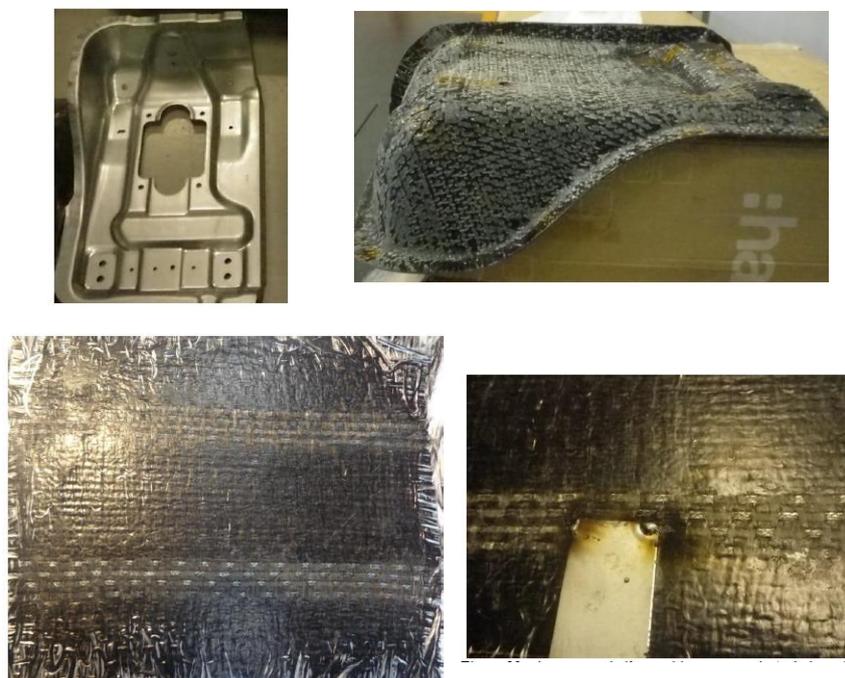


Figure 4: Truck seat with metallic and fibrous part and the insertion of metallic braids for the assembly by welding

4 Virtual prototyping

It is known that new lightweight materials and especially composite materials bring additional challenges to virtual Prototyping. Whereas the methodologies and best practices for performance simulation of structures made of mild steel are well established, this is not the case for composite materials.

In more details:

- Lack of experience in designing structural parts with composite materials except for the high-end car segment, which uses similar techniques as aeronautics, mostly based on tests. These design methodologies require extensive hardware prototyping.
- Composite material is a structure even at the ply level. It is not possible to use black metal approach for testing and characterization due to the size effect. Standard methodologies do not apply.
- Composite materials are not as standardized as metals; each producer of fiber and polymer produces its own raw material and there is a wide spread of manufacturing processes.
- Joining techniques have to be adapted to composites and heterogeneous assemblies between metals and composites.
- Depending on the performance domain, additional challenges such as progressive damage for mechanical fatigue or fragmentation of the composite material for crash have to be accounted for in the simulation, the initiation of the fragmentation occurs at the microscale level and is highly dependent upon the manufacturing process.
- Therefore, continuum mechanics approach is not anymore fully valid beyond first ply failure, and also the initiation of this ply failure is caused by micro porosities
- Influence of microstructure has to be taken into account through appropriate multi-scale methodologies
- As of today, models for nonlinear and damage behavior of composites are heavily dependent from mesh size. This leads to an additional challenge to reach the goal of predictive Virtual Prototyping.
- Last but not least, the influence of manufacturing process over mechanical performance is critical and much more important than for structures made of mild steel, even in the linear elastic domain.

For example, today's methodologies for crash simulation involve at each step of the design, a verification by a hardware test. This is the so called building block approach, from material characterization to joints calibration then to subframe design and to a full scale (Figure 5). At each of this step, a physical prototype test is needed in order to validate and calibrate again the simulation model accordingly. Then simulation can be used to optimize the component or structure.

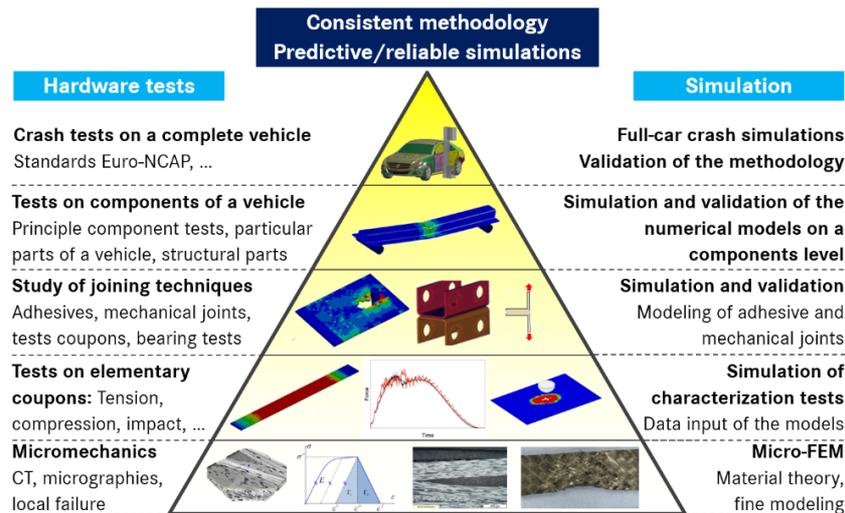


Figure 5: Consistent methodology for crash simulation [21]

Currently, two main aspects should be further developed to be able to virtually prototype composite: the simulation coupling, in order to account for manufacturing effects in mechanical performance of composites and the Virtual Material Characterization to generate material properties solely with the use of numerical simulations.

Under coupled simulation, one aims at covering the mechanical performance simulations accounting for the manufacturing effects (Figure). There is a strong motivation these days to account for the manufacturing effects onto the mechanical performance. These phenomena are known in the composites community from the very beginning, but the use of safety margins appears to be the only way to handle the complexity required by a comprehensive simulation. Taking into account fibre orientation was first possible nearly thirty years ago and remained for long the only manufacturing modified parameters that were incorporated in mechanical simulations. Indeed, the fibre orientation is the main parameter modified by the manufacturing and it is only recently that the industry started to request additional parameters like porosity.

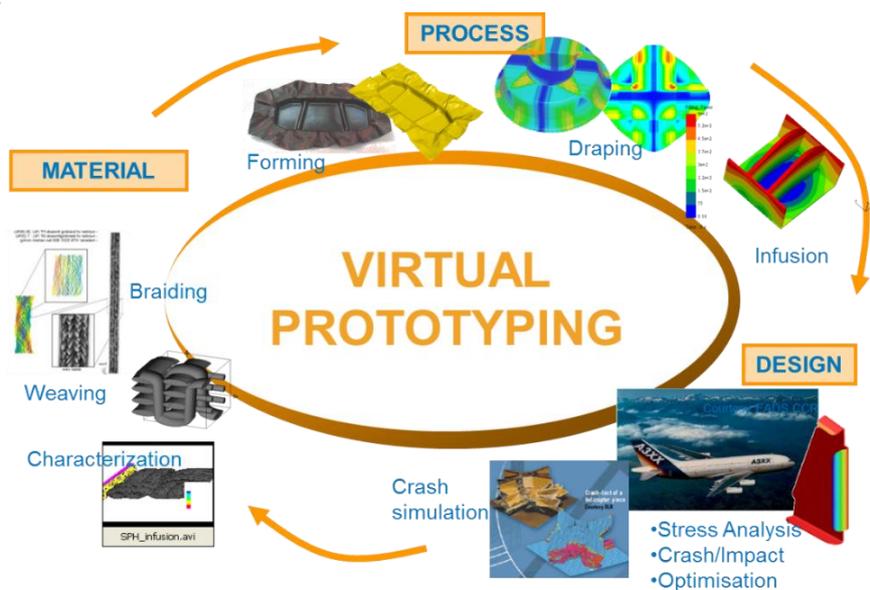


Figure 6: Composite end to end virtual prototyping chain: performance prediction accounting for manufacturing history

Today, most of the commercial softwares are able to account for fibre orientation in their mechanical simulations at least for unidirectional materials. The fibre orientation may be obtained from: a geometric draping analysis, a forming process finite element simulation [22], a robot laying the dry fibres or prepreg tapes or even from measurements coming from a digital image analysis [23]. The mechanical simulation software reads fibres paths descriptions and calculates the strains and stresses based upon these orthotropic orientations. In case of non-unidirectional composites (e.g. woven textiles), special attention has to be paid to the way with which fibre orientation is handled. Sometimes only the first fibre direction is processed and the second direction remains orthogonal. Even though, the shearing occurring during forming process modifies the initial 90° angle. Note also, that the processing of fibre directions is often limited to a rotation of the fibre direction; stiffness modifications resulting from tows sections changes induced by shearing and compression in forming are most of the time ignored.

The status related to failure criteria is much less advanced. There are some academic works showing that such criteria can be developed through Virtual Material Characterization paving the way to fibre orientation dependent failure criteria.

The status in the field of damage modelling is even less advanced. In paper [24], the damage of a Non Crimp Fabric (NCF) composite part was studied. The part exhibits various shearing levels and its mechanical behaviour was simulated by performing physical characterization of the un-sheared and sheared at several angles of the NCF material. This added physical characterization, enables to capture the progressive damage evolution. Again, Virtual Material Characterization seems to be the right technique to industrialize this research work.

As announced, many material parameters are modified by the manufacturing operations: fibre orientation, porosity, thickness, local fibre content, fibre undulations, tows sections modifications, curing degree, crystallization degree, consolidation degree, water content, etc. But again, for the moment, only the fibre orientation is accounted for in the best cases.

A systematic study of manufacturing effects on composites performances is necessary. These studies unfold in two fundamental steps: first the mechanical performance software must be able to handle the additional information coming from the manufacturing simulation; second, the additional manufacturing information must be generated. Existing case studies, demonstrating the importance of manufacturing effects, may serve as a starting point for these works.

In other words, new mechanical behaviour models accounting for a local description of the material and new output of manufacturing simulation are required. Once this will be achieved, it will be possible to move from a part quality process window (where the process parameters are defined in order to satisfy global quality criteria for the formed part, like ‘the porosity must be less than 2%’) to ‘part functions’ process window (where the process parameters will be defined in order to satisfy the part requirements regarding its use). Thanks to such an approach, one will be able to use cheaper manufacturing processes leading to cheaper composite parts.

The Virtual Material Characterization (VMC) became popular during the last years and the recent publications reveal a consolidation phase in this domain. The Virtual Material Characterization is the generation of material properties using the numerical simulation instead of physical tests. The motivation for the development of this technology is to decrease test costs and testing time. Sometimes the VMC appears to be the only possible route toward realistic simulations of structures. This is the case when material properties vary a lot over the studied component, calling for a lot of material properties to be assigned, at the difference of the regular situation where only one set of material data enables accurate simulations. An

example of such a situation where many data sets are needed for a single material is the case where the reinforcement is highly deformed during the manufacturing. This leads to many possible fibre behaviours involving many different local behaviours in terms of stiffness, damage tolerance, permeability, heat conduction. The high number of tests required to really locally characterize the material simply impede from testing and as a consequence, make impossible the use of appropriate material data in simulations. Thus, this forces engineers to rely on safety margins rather than on accurate simulations.

The idea of the VMC is to start from the geometry of a Representative Volume Element (RVE) or Unit Cell (UC) that can be considered as representative of the reinforcement architecture. Then, one assigns material properties to each phase of the composites (fibre, resin, others) and eventually run a test simulation leading to the determination of the desired properties. For instance, running a tensile test in the fibre direction gives the E1 elastic modulus of a composite. Or looking at a CFD simulation at the pressure drop of a resin flow through the unit cell leads to the permeability value in the fibre direction.

There is a recent international benchmark that was organized by the Composite Design and Manufacturing hub at Purdue (USA): the Micromechanics Simulation Challenge. In cooperation with academia, industry and commercial software providers, the Level 1 results are available on the web, showing the current maturity of existing approaches. Level 1 of the challenge covers the prediction of elastic and thermo-elastic properties. Several types of reinforcements are studied: unidirectional, woven textile, short fibres and three-phase composites. The results show that the elastic properties prediction can be sufficiently achieved. The upcoming Level 2 of the challenge, is currently under definition, and aims at covering non-linear phenomena. Level 3 is planned to address damage and failure mechanisms issues.

In the literature, one can find works in the field of thermal and electrical properties [25].

An interesting domain is the prediction of dry reinforcement's permeability. It is now considered that one can rely on the numerical prediction of the permeability, as long as an accurate description of the unit cell is available. The geometry of the unit cell may come from Computer Tomography (CT), from analytical tools like TEXGEN or WISETEX or from simulation including the draping operations [26]. Beyond the determination of the permeability, this technique was used to study the effects of preform variability [27].

Because it allows the generation of material properties for any kind of textile architectures, the Virtual Material Characterization is a key stone in the simulation of 3D textiles. Actually, it is thought that Virtual Material Characterization (VMC) is the only way to provide the support offered by the numerical simulation to metals or other standard composites. It could also be used as a support to the textile architecture creation.

This technique appears also as an appropriate tool for the study of material and process variabilities. And yet these studies are needed to reach a satisfactory robustness in manufacturing processes and in mechanical designs.

5 Toward direct processing

Today, the challenge is to further develop economical, faster and efficient composites processing technologies for the manufacturing of highly integrated parts. The overall cost is highly influenced by the cost of materials, the number of steps in the process and its degree of automation. Automated processes are the most able to take advantage of economies of scale as far as series production is concerned.

Currently, the most advanced applications use prepregs and autoclave manufacturing due to the superior mechanical performance possible from a toughened resin system in a pre-

impregnated composite ply. In addition, the consolidation of prepregs is viewed as a robust process because it does not involve long distance flow of polymer contrary to wet processes since it intrinsically has a good impregnation state. Many aeronautic parts are manufactured with this process [28].

5.1 Examples of current developments

During the past 30 years intensive research and industrial efforts have been spent to develop alternative manufacturing methods to prepreg consolidation in autoclave [29]. For instance, the use of cheaper raw materials (separate fibrous material and polymer) instead of pre-impregnated composite plies has been of prime interest. The second leverage effect one can use to reduce the cost is the reduction of manufacturing steps in production.

Generally speaking, the basic steps in composite manufacturing include:

1. Impregnation of the fibrous reinforcements with the organic matrix,
2. Forming of the part/structure,
3. Curing (for thermoset matrices) or thermal processing (for thermo-plastic matrices),
4. Finishing.

Depending on the process, these steps may occur consecutively or may be overlapping and continuous. One can combine or alternate these steps, depending on the requirements for quality and cost.

Some achievements towards the development of processes with fewer steps and the appropriate materials to do it will be described in the following paragraphs. Two routes have been followed: one consists in developing new material/process pairs and the second focused on the combination/hybridisation of existing technologies.

The need of suitable materials for greater manufacturing productivity and cheaper products leads to intensive research and industrial efforts. The main idea that drove developments was to engineer materials that offer the best trade-off between their processing cost and the robustness of the subsequent steps to manufacture a final composite part.

With this objective in mind several processes have been investigated for producing continuous fibre reinforced unconsolidated prepregs. These materials can be further processed in different ways. These processes include:

- Commingling and co-weaving of thermoplastic fibres with reinforcing fibres. These materials are made by spinning fibres from the thermoplastic polymer and either commingling the polymer fibres with the reinforcing fibres or co-weaving both fibres to produce a fabric. Then that fabric can be used directly as a prepreg (called sometimes semi-preg) where they will be melted and consolidated by applying heat and pressure to force the polymer to flow into the reinforcement and form into part [30].
- Thermoset or thermoplastic film stacking. Films of polymer are alternated with layers of reinforcing fabric [31].
- Extrusion coating of fibre tows and weaving [28].
- Deposition of a polymeric powder or layer on fabrics (Figure. 7) [28].
- Out-of-Autoclave (OoA) thermoset prepregs. OoA prepregs differ from autoclave-processed prepregs in that they are designed to be processed only with a vacuum bag and oven curing [32].



Figure 7: Thermoplastic powdered twill-weave fabric (Chomarat Composites)

Quilted Stratum Process (QSP) or SPRIFORM: An automated lay-up process produces near-net-shape tailored blanks, which are heated and formed into parts in a high-pressure thermoforming press. The part is finished by over-moulding of long fibre thermoplastics to get a net-shape part and create ribs. The Figure 8 displays an example part containing thermoformed blanks which have been over moulded [33].



Figure 8: Over-moulded part (CETIM Nantes)

Continuous-fibre inserts can also be used to enforce and localise high performances in a product. Such inserts can be made with thermoforming of thermoplastic prepreps or obtained by pultrusion. The Figure 9 illustrates over-moulding of long-fibre thermoplastic (in black) around a continuous-fibre pultruded beam (in white).



Figure 9: Front bumper crash beam produced with curved reactive thermoplastic pultrusion (Hyundai, Plastic Omnium, CQFD Composites and Arkema)

Injection-pultrusion is a process under current development [34]. It consists in impregnating continuous rovings or ribbons by injection of a low viscosity thermoplastic resin within the pultrusion die. The impregnated fibrous material is pulled through a die to become an impregnated, formed and crystallised composite with a constant cross-section.

5.2 Vision of the future

New composite manufacturing technologies are needed to provide an alternative to conventional metals and prepreg composites solutions which became the reference in the industry today. The composite processing technologies that need to be developed should yield

the required component shape and properties in a cost-effective, quick, repeatable, robust and environmentally conscious manner.

Several technologies are expected to reach an acceptable Technology Readiness Level (TRL) within few years and become attractive to various industries. Efforts should be placed into the:

- Automated tape placement with in-situ consolidation: this process limits the wastes and optimal performances/weight ratio can be reached since the fibres are placed where necessary [35].
- Hybridisation of processes
 - o Pultrusion + filament winding [36]
 - o Pultrusion + thermoforming + over-moulding [37]
 - o Commingling + micro-braiding + pultrusion [38-39]
 - o Over-moulding of an insert made from
 - Compression of powdered fabrics
 - Compression of Glass Mat Thermoplastics (GMT)
 - Thermoforming of Thermoplastics TP prepregs
 - Pultrusion + Thermoforming

6 Structural Health Monitoring

This part propose an overview of available new techniques capable of following, in situ and in real time, the evolution of the physical properties of the composite material, from its manufacturing to its use in service life.

6.1 State of the art in monitoring techniques

Currently, damage detectors require conventional techniques such as strain gauges, acoustic emission sensors, piezo-accelerometers, fibre optics etc. and external power supplies. The health monitoring system can be either local or global (table 2).

Characterization Techniques	Sensors	Local/Global	Detection mode
Strain and force	Electr. resist. strain gauges Load cells Fibre optic strain gauges Electrical crack wires	L L L L	On-line On-line On-line On-line
Vibration	Piezoaccelerometer Piezoresistive Capacitive Mems	G G G	On-line On-line On-line
Ultrasonic	Acoustic emission sensor Acousto-Ultras. Transd.	G G	On-line Off-line
Impedance	Piezoelectric sensor	L	Off-line
Temperature	Fibre optic	L	On-line

Table 2: Local and global health monitoring methods

To allow a continuous and in service monitoring of structures, one key element concerns the used sensors and actuators which can be either surfaced mounted or directly embedded in the structure. Some of the most promising sensors are described table 3.

Category	Configuration	Physical parameter measurement
Polymer Optical sensor	Embedded	Strain and vibration measurements
Flexible piezoelectric sensors	Surface mounted and Embedded	Vibration measurements (active or passive)
Piezoelectric fibres	Embedded	Vibration and acoustic emission measurements
Vacuum Monitoring sensors	Surface mounted and Embedded	Pressure measurement
Carbon nanotubes	Embedded	Strain measurements
Flexible Piezo-resistive fibrous sensors	Embedded	Strain measurements

Table 3: Surface mounted and embedded actuators and sensors

6.2 Toward wireless SHM and in situ monitoring

The main effort is now focused on the development of Smart textiles, electronics combined with textiles, as this technology will enable the monitoring of the composite part through all its service-life. This necessitates to insert sensors and actuators during the fabrication process of the composite.

To outline such a strategy, we may propose as an example the case of piezoresistive sensors realized from semi-conductive coatings and suited for on line SHM of composite structural parts containing 3D reinforcement [40].

These sensors have been designed to offer following advantages:

- They can be embedded inside the reinforcement during weaving.
- They have all the characteristics of a traditional textile material (flexible, lightweight and are capable of adopting the geometry of the reinforcement and become its integral part).
- Since these sensors are inserted during weaving process, they are subjected to similar strains as the composite itself. Measurement of resistance change with variation in sensor's length is a way of determining in situ strains in the composite material which lead to its final damage.
- The fibrous sensors are not supposed to modify the overall structural and mechanical properties of the composite as they are integrated locally and the bulk of the structure is composed of high performance multifilament tows.
- Insertion of intelligent piezoresistive sensor inside the reinforcement during weaving process is the most convenient and cost effective way of integrating a sensor for SHM of 3D interlock woven reinforcements.

Development and optimization of such piezoresistive sensors has been carried out in order to render them sensitive enough to measure in situ strains inside the composite part. Optimization of sensors is followed by their insertion in the reinforcement during weaving process on a special loom modified and adapted for multilayer warp interlock weaving. The fabrics made of comingled yarns are shown below before the thermos-consolidation process (see Figure 10).



Figure 10: Textile sensors integration during weaving of 2D fabrics and its preparation for consolidation step: a) integrated textile sensors in 2D fabric, b and c) 2D fabric preparation for consolidation step

Finally, thermos-consolidated thermoplastic composites with integrated strain gauges based on PEDOT:PSS are shown below (see Figure 11).

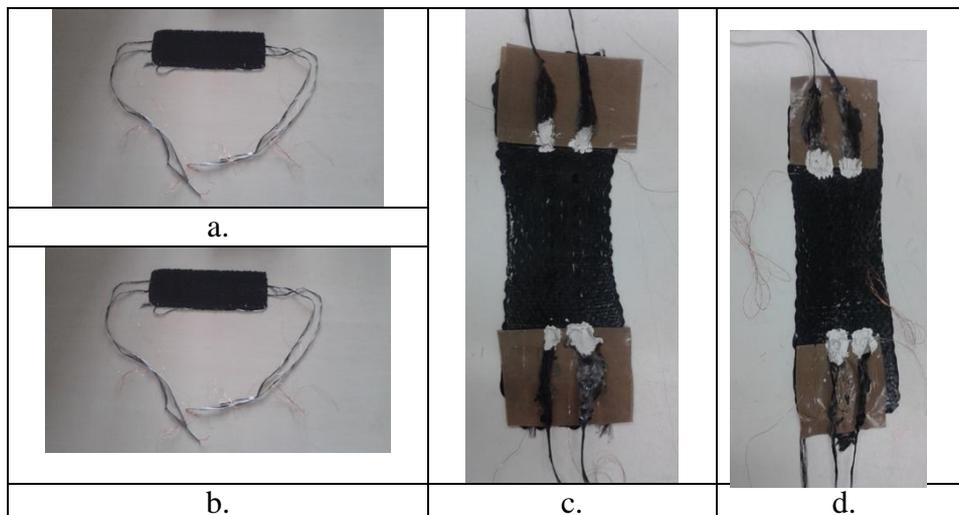


Figure 11: Textile reinforced thermoplastic composites with integrated textile sensors: a) 2D fabric consolidated under pressure of 20-30 bar - case I, b) 2D fabric consolidated under pressure of 20-30 bar - case II, c) 2D fabric consolidated under pressure of 20-30 bar - case III, d) 2D fabric consolidated under pressure of 40-50 bar – case III

6.3 Sensor network with real time data transmission

There is still many key-issues to solve before smart textiles become similar to the human nervous system. Next challenges deal with the development of a complete autonomous hardware/software system integrated to the Smart textile (see Figure 12).

With the development of microelectronic, a potential scenario would be to miniaturize and integrate on a same integrated component circuit the data acquisition, processing, storage and interpretation. Moreover, differently from wired sensor networks, the use of wireless

monitoring calls for the implementation of specific design solutions to cope with data transmission and power supply. An important issue regards wireless communication whereas another recurrent concern is the electrical power supply of the wireless sensor nodes, typically provided by battery replaced periodically. The need for a possible remedy to the issue of power supply in wireless sensor motivates the development of energy saving strategies, as well as the search for technologies to harvest the required power from the surrounding ambient. With the increasing interest for microelectromechanical systems, this part seems to be possible in a next future.

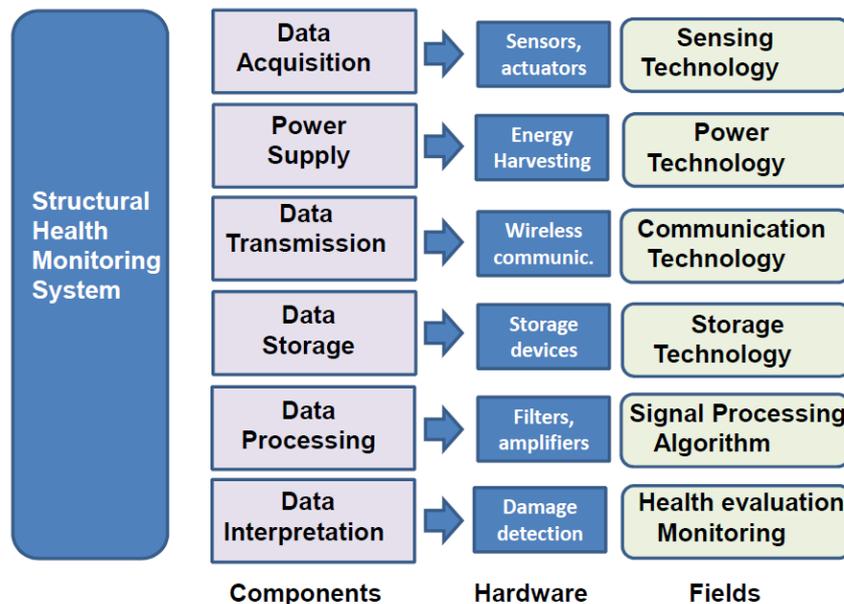


Figure 12: Key-issues for sensor network with real time data transmission

7 Conclusions

With this article, the objective was to establish a vision of 2017 technological breakthrough to facilitate a large scale development of composites materials in aeronautic, automotive, railway and marine transport sectors. A wide area of composites development is covered by the article.

In terms of raw materials, improving the manufacturing processes of PMCs, develop fully bio-based PMCs with a good cost/performance ratio and develop functional materials such as self-healing materials are seen as three main future challenges.

Hybridization of textile technologies, is challenging as it enable to manufacture near net-shape structures to avoid steps like cut, layup and preforming during composite processing.

Predicting the process-induced defects is still an issue and will be even more challenging as new materials and manufacturing technologies are emerging day by day in the modern aeronautic and automotive industries. The need for numerical simulation tools for such materials and processes is critical in the current industrial development to predict the final part quality and minimize the manufacturing cost and development time.

Another challenge is to further develop economical, faster and efficient composites processing technologies for the manufacturing of highly integrated parts. Several technologies are expected to reach an acceptable Technology Readiness Level within few years especially if efforts are placed into the automated tape placement with in-situ consolidation and the hybridisation of processes.

The future of structural health monitoring is the wireless health monitoring using smart textiles. This complex technology, necessitating the insertion of sensors and actuators during the fabrication process of the composite, is currently being developed but there is still many key-issues to solve before smart textiles become similar to the human nervous system. Next challenges deal with the development of a complete autonomous hardware/software system integrated to the Smart textile.

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References

- [1] C. Durand (Editor), D. Coutellier (Project coordinator), “Composites technologies for transport applications: a roadmap”, published in the frame of the Madmax project n° 609253, (2016)
- [2] J. Njuguna, “Lightweight Composite Structures in Transport, Design, Manufacturing, Analysis and Performance”, Woodhead Publishing Series in Composites, Science and Engineering, n° 67, 2016
- [3] O.V. Mukbaniani, M.J.M. Abadie and T. Tatrishvili, “High-performance Polymers for Engineering-based Composites”, AAP Research Notes on Polymer Engineering Science and Technology, 2016
- [4] P. E. Irving and C. Soutis, “Polymer Composites in the Aerospace Industry”, Woodhead Publishing Series in Composites Science and Engineering, n° 50, 2014
- [5] P. Pasbakhsh, A. K. Haghi, and G. E. Zaikov, “Applied research on polymer composites”, AAP Research Notes on Polymer Engineering Science and Technology, 2015
- [6] G. Koronis, A. Silva, and M. Fontul, “Green composites: A review of adequate materials for automotive applications”, Composites: Part B 44, pp.120–127, 2013
- [7] M. M. Reddy, S. Vivekanandhana, M. Misraa, S. K. Bhatia, and A. K. Mohantya, “Biobased plastics and bionanocomposites: Current status and future opportunities”, Progress in Polymer Science 38, pp.1653– 1689, 2013
- [8] M. Murariu, and P. Dubois “PLA composites: From production to properties” Advanced Drug Delivery Reviews, 2016
- [9] A.P. Mouritz, and A.G. Gibson. “Fire Properties of Polymer Composite Materials”. Edited by G.M.L. Gladwell. Springer, 2006
- [10] F. Poutch, G. Fortier, S. Boissel. “Fire and rolling stock prEN 45 545: Does new standard mean new materials?” Crexim. Rail Industry meetings, Lille, France. December 2013
- [11] R. Verleg, and G. Tipping. “Fire Safe Polyester Composites in Mass Transit Applications: The Use of Composites in Mass Transit Applications”, Proceedings of the 2nd Biennial International Composites Africa, pp.229-240. Johannesburg, South Africa. 24 - 25 August 2004
- [12] A.P. Mouritz, “Review of z-pinned composite laminates”, Composites Part A, 38, pp. 2383-2397, 2007
- [13] A.P. Mouritz et al. “A mechanistic interpretation of the comparative in-plane mechanical properties of 3D woven, stitched and pinned composites”, Composites Part A, 41, pp. 709–728, 2010

- [14] C. Dufour et al. “Experimental investigation about stamping behaviour of 3D warp interlock composite preforms”, *Applied Composite Material*, 21, 5, pp.725–738, 2014
- [15] Y.F. Zhang YF et al. “Study on intra/inter-ply shear deformation of three dimensional woven performs for composite materials”, *Materials & Design*, 49, pp.151–159, 2013
- [16] M. Duhovic et al. “Modelling approach for the prediction of stitch influence during woven fabric draping”, *Composites Part A*, 42, pp. 968–978, 2011
- [17] L. Liu et al. “Influence of the tufting yarns on formability of tufted 3-Dimensional composite reinforcement”, *Composites Part A*, 78, pp.403–411, 2015
- [18] G. Dell’Anno et al. “Exploring mechanical property balance in tufted carbon fabric/epoxy composites”, *Composites Part A*, 38, 11, pp.2366–2373, 2007
- [19] S. Kazemahvazi et al. “Confluent 3D-assembly of fibrous structures”, *Composites Science and Technology*, 127, pp. 95-105, 2016
- [20] M. Umair et al. “Development and characterization of three-dimensional woven-shaped preforms and their associated composites”, *Journal of Reinforced Plastics and Composites*, 34, 24, pp.2018-2028, 2015
- [21] O. Cousigné “Contribution to the development of the numerical simulation of CFRP woven materials for crash simulations”, PhD Thesis University of Valenciennes, Nov. 2013
- [22] A.K. Pickett, G. Creech and P.de Luca “Simplified and advanced simulation methods for prediction of fabric draping”, *Revue Européenne des Éléments*, 14:6-7, 677-69, 2005
- [23] A. Dereims, “Inverse characterization method for draping simulation based on automatic measurement of fiber orientation”, *ECCM-17*, Munich (D), 27-30 June 2016
- [24] L. Greve, and A.K. Pickett, “Modelling damage and failure in carbon/epoxy non-crimp fabric composites including effects of fabric pre-shear”, *Composites: Part A* 37, pp. 1983–2001, 2006
- [25] A. Gillet, P. Olivier, A. Al Maghribi, and I. El Sawi, “Prediction of electrical properties of an aeronautic composite”,
- [26] A. Berger, et al. “Crash simulation of wound composite tubes based on multi-level modelling”. In: *International Journal of Crashworthiness* p. 151-164, 2015
- [27] M. B. Goldsmith, B. V. Sankar, and R. T. Haftka, “Effects of architectural variability on thermo-mechanical properties of ceramic matrix composites”, *eccm15 - 15th European conference on composite materials*, Venice, Italy, 24-28 June 2012
- [28] V.H Suong, “Principles of the manufacturing of composite materials”, *DEStech Publications, Inc*, 2009
- [29] S.G. Advani and E.M. Sozer, “Process modeling in composites manufacturing”, *CRC Press*, 2010
- [30] N. Svensson, R. Shishoo and M. Gilchrist, “Manufacturing of thermoplastic composites from commingled yarns-A review”, *Journal of Thermoplastic Composite Materials*, vol. 11, no 1, pp. 22-56, 1998
- [31] S.T. Jespersen, M.D. Wakeman, V. Michaud, D. Cramer, and J.A. Manson, “Film stacking impregnation model for a novel net shape thermoplastic composite preforming process”, *Composites Science and Technology*, 2008, 68(7), pp.1822-1830
- [32] T. Kourkoutsaki, S. Comas-Cardona, C. Binetruy, R.K. Upadhyay, and R. Hinterhoelzl, “The impact of air evacuation on the impregnation time of Out-of-Autoclave prepregs”, *Composites Part A: Applied Science and Manufacturing*, 79, pp. 30-42, 2015
- [33] J.S.U. Schell, L.L. Amory, and D.D. Guillon, “Movement of patches during thermoforming: experiment and simulation”, 19th International Conference on Material Forming – ESAFORM 2016, Nantes, France, 26-29 Apr 2016. Published in: *ESAFORM 2016*
- [34] A. Babeau, S. Comas-Cardona, C. Binetruy, and G. Orange, “Modeling of heat transfer and unsaturated flow in woven fiber reinforcements during direct injection-pultrusion process of thermoplastic composites”, *Composites Part A: Applied Science and Manufacturing*, 77, pp. 310-318, 2015
- [35] Z. Qureshi, T. Swait, R. Scaife, and H.M. El-Dessouky, “In situ consolidation of thermoplastic prepreg tape using automated tape placement technology: Potential and possibilities”, *Composites Part B: Engineering*, 66, pp.255-267, 2014

- [36] B.T. Åstrom and R.B. Pipes, “Thermoplastic filament winding with on-line impregnation”, *Journal of Thermoplastic Composite Materials*, 3(4), pp. 314-324, 1990
- [37] R.J. Dykes, S.J. Mander and D. Bhattacharyya, “Roll forming continuous fibre-reinforced thermoplastic sheets: experimental analysis”, *Composites Part A: Applied Science and Manufacturing*, 31(12), pp. 1395-1407, 2000
- [38] W. Michaeli, and D. Jürss, “Thermoplastic pull-braiding: pultrusion of profiles with braided fibre lay-up and thermoplastic matrix system (PP)”, *Composites Part A: Applied Science and Manufacturing*, 27(1), pp. 3-7, 1996
- [39] L.L. Lebel, and A. Nakai, “Design and manufacturing of an L-shaped thermoplastic composite beam by braid-trusion”, *Composites Part A: Applied Science and Manufacturing*, 43(10), pp. 1717-1729, 2012
- [40] S. Nauman, PhD thesis report “Modélisation géométrique et caractérisation des composites renforcés avec des tissus 3D interlock-mesure in-situ par des capteurs textiles”, ENSAIT Roubaix, 2011