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Daniel Coutellier

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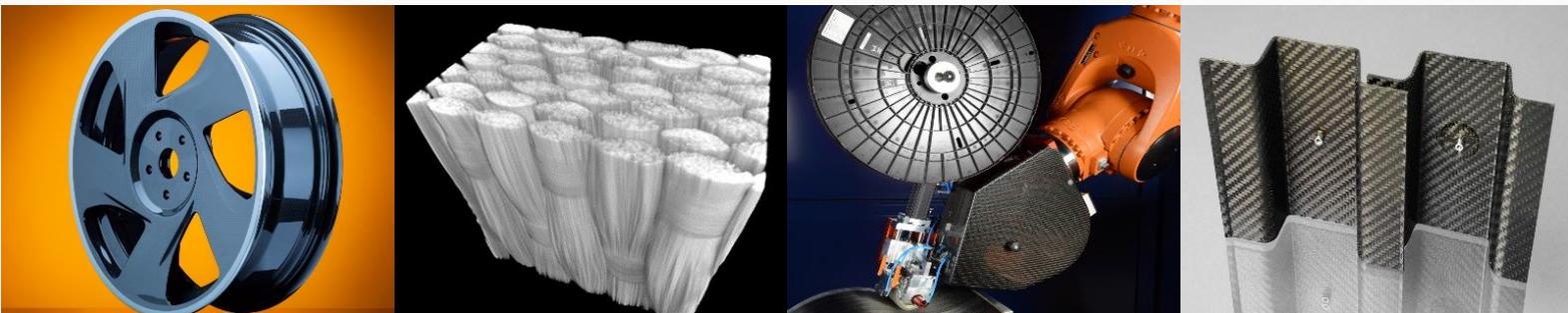
MADMAX

Advanced material textiles for reinforced structures for complex lightweight applications



Advanced material textiles for reinforced structures for complex lightweight applications

Composites technologies for transport applications: A roadmap



Madmax project n° 609253

7th framework Programme for NMP Theme

“Advanced material textiles for reinforced structures for complex lightweight applications”

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SUPSI



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Introduction

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Within the European Union, road transport is responsible for about 20% of all CO₂ emissions. In order to reduce these gas emissions, European emission standards define the acceptable limits for exhaust emission of new vehicles sold in EU member states. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. For example, the EU regulation N° 443/2009 sets an average CO₂ emissions target for new passenger cars of 130 grams per kilometer. A target of 95 grams per kilometer will apply from 2021. To comply with these stringent gas emission regulations, transport industries have to develop lightweight vehicles maintaining quality and safety. Composites are materials which are able to respond to the transport industry's changing need. Indeed composites are offering the possibility to build lightweight structures with interesting mechanical properties and an important capacity of energy absorption. But composites are still relatively new materials: their mechanical behavior is not fully understood and mastered, 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 is financially supporting some projects aiming at developing composites technologies under the 7th Framework Programme for NMP theme "Nanosciences, nanotechnologies, materials and new production technologies". Among them, the MADMAX project (Advanced material Textiles for Reinforced Structures for Complex Lightweight Applications) 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 is 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 starting point of Madmax project was first to identify the industrial needs and technological limits regarding composites in transport sectors. For that, interviews of key employees in transport industries (automotive, aeronautic, railway and marine) were conducted.

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. In the marine industry, there is also the problem of mastering infusion process for large parts, and in the aeronautic, processes for thermoplastics are desired.
- Disparity in material properties
Because of the lack of automated processes to manufacture composites, it is not possible to obtain materials with calibrated properties, there is always a variability in end products properties. Thus, the current debate about composites certifications. 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. Thus there is also a lack of knowledge on joint fatigue behavior.

Major obstacles to composites development for each transport sector were revealed with this study. 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.

The present book takes into consideration the domain of expertise of Madmax partners to precisely describe the technological limits and industrial needs previously identified and to propose a research roadmap to reach the technologies of the future. Madmax partners are actually covering a quite large range of areas regarding composites, thus all technical stages of composites development can be discussed in the book. Moreover Madmax partners have diverse origins; they are coming from academic institutions (ARMINES Mines Douai, ECN Ecole Centrale Nantes, ENSAIT Ecole Supérieure des Arts et Industries Textiles in Roubaix, ENSIAME Ecole Nationale Supérieure en Informatique Automatique Mécanique Energétique Electronique in Valenciennes, ITM Institut für Textilmaschinen und Textile at the Technological University Dresden, SUPSI Scuola Universitaria Professionale della Svizzera Italiana), private institutions (Fraunhofer Institute for Production Technology IPT in Aachen, NTT Next Technology Tecnotessile Societa Nazionale di Ricerca r.l, IRT Railenium Technological Research Institute), associations (IVGT Industrieverband Veredlung – Garne - Gewebe – Technische Textilien e.V., Texclubtec, Up-TEX association) and private companies (ESI group S.A, Soliani EMC SRL).

Madmax partners and authors are writing this book to give their vision of the future regarding composite technologies in order to set off new research projects with partners from outside the consortium. So the book points out the boundaries of knowledge and can be seen as a call for projects. The book is divided into 7 chapters, each of them dealing with one stage of composites development: from raw materials, to textile reinforcement structures, to characterization methods, to modelling methods, to direct processing methods, to joining techniques and structural health monitoring.

The first chapter reviews the principal raw materials, fibres and resins, used to manufacture composites and details their material properties. Promising fibres and resins for future composite structures are also highlighted.

The second chapter recalls the main textile reinforcement structures and details their advantages and limits. Technological innovations are seen in the hybridization of reinforcement techniques to improve 3D preforms.

The third chapter analyses the currently used characterisation methods and proposes some non-conventional methods.

Chapter four is dealing with modelling methods for manufacturing processes and service life simulations. New modelling challenges are concerning new materials and new manufacturing processes that are emerging day by day in transport industry.

Manufacturing processes are reviewed in the chapter five and focuses on ways to reach one-step direct processing.

The chapter six reviews advantages and limits of joining techniques currently used for composites and highlights the most promising technologies.

The chapter seven focuses on structural health monitoring for composites parts. The future of process monitoring and damage detection will certainly pass through the development of wireless structural health monitoring. Finally, the conclusion reviews the keys innovative technologies for each stage of composite development and invites engineers and researchers to join the consortium and set up joint research projects.

1 Raw Materials

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Introduction

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 (Figure 1.1). 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.

This chapter describes the state of the art of raw materials used in composites, such as reinforcing fibres and polymer matrix materials in terms of technology and market trend. Some perspectives on the scientific research and industrial developments are also discussed.

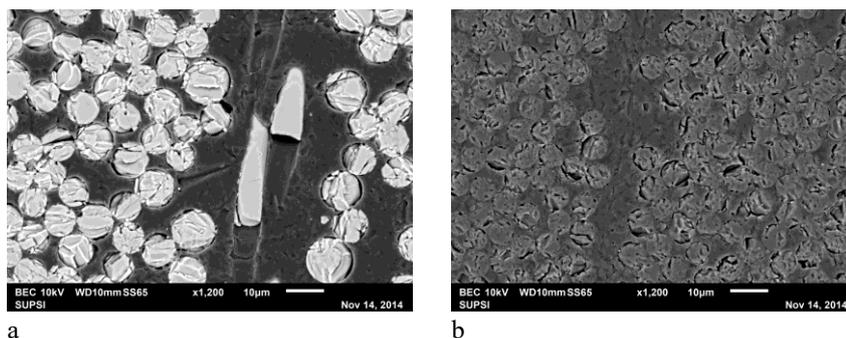


Figure 1.1: Section of an epoxy resin composite reinforced with a) glass fibres and b) carbon fibres

1.1 Reinforcing fibres

Above all, this chapter summarizes the current industrial use and technological developments of the two most common synthetic fibres, namely glass fibres and carbon fibres. Recently, due to the environmental regulations such as REACH (Registration, Evaluation, Authorization and restriction of Chemicals), the use of aramid fibres decreases, even though they are still widely adopted for some special applications such as armours and helmets. So instead of focusing on aramid fibres, this chapter ends by presenting natural fibres which are attracting great attention from the construction and automotive sectors.

1.1.1 Glass fibres

The most distinguished advantage of glass fibres is their low price. Thus, their market share in composite material industry is about 95%. In spite of their excellent strength, their modulus is relatively low and their density is also great compared with carbon fibres. Therefore, the lightweight performance of glass fibres is moderate.

Properties	E-glass	S-glass	Carbon
Modulus (GPa)	72-78	88-91	230-600
Strength (MPa)	2600-3800	4380-4590	3500-6000
Elongation (%)	4.5-4.9	5.4-5.8	1.5-2.0
Diameter (μm)	6-21	6-21	5-15
Density (g/cm^3)	2.54-2.55	2.48-2.49	1.79
Price (USD/kg)	1.1	1.5	30

Table 1.1: Comparison between glass fibres and carbon fibres

The most popular applications of glass fibres are transports and constructions (i.e. 69% market share) followed by electronics and sports goods [1]. In particular, the market growth is highly dependent on the economy of each country and there is no common trend in the world market. The use of glass fibres are rapidly increasing in developing countries such as Eastern Europe, Turkey and Brazil, Russia, India, China, South Africa (BRICS) where new infrastructures are being constructed and where the labour cost is relatively low. The production of glass fibre composites are

stagnating in Western Europe such as France and Spain whereas it is growing in the UK (construction) and in Germany (automotive).

In 2014, the total production of glass fibre composites is estimated to be 2.2 million tons. The most popular materials are discontinuous fibre reinforced plastics for which the production reached about 1.16 million tons in 2014, thanks to low manufacturing cost and the ease of use of conventional polymer processing equipment such as injection moulding machine and extruders, which can be used without any technical difficulty.

In Table 1.2, the production of glass fibre composites in tons, for Europe is given in function of the manufacturing process. We can see that the production of high performance composites by automated processing techniques such as Resin Transfer Moulding (RTM) and Glass Mat Thermoplastic (GMT) / Long Fibre Thermoplastic (LFT) are steadily increasing. Main applications are for automotive parts where lightweight is required. Conversely, the production by labour intensive processes such as open mild processes is decreasing and the manufacturing of pipes and sheets is stagnating in Europe. Their production is assumed to move to developing countries where new infrastructures and building are constructed.

	2014	2013	2012	2011	2010
SMC	190	184	188	198	198
BMC	74	71	70	69	69
SMC/BMC	264	255	258	267	267
Hand lay-up	138	142	145	160	160
Spray-up	94	90	90	98	92
Open mould	232	232	235	258	252
RTM	132	126	120	120	113
Sheets	84	84	78	77	72
Pultrusion	48	47	47	51	47
Continuous processing	132	131	125	128	119
Filament winding	79	78	80	86	82
Centrifugal casting	66	66	67	69	66
Pipes and tanks	145	144	147	155	148
GMT/LFT	121	114	108	105	100
Others	17	18	17	16	16
Sum	1043	1020	1010	1049	1015

Table 1.2: Glass fibre reinforced composite production in Europe (metric tons, Composites Market Report 2014 [1])

To further expand the market for glass fibre composites, some technical challenges should be addressed:

- Use of thermoplastic matrices:
Thermoplastic matrices have many advantages over thermoset ones such as the ease of storage, the high impact resistance and the recyclability. In the automotive sector, some Sheet Moulding Compound (SMC) / Bulk Moulding Compound (BMC) parts are being replaced by GMT/LFT. For the latter ones, the market is steadily increasing at a rate of 6% per year, due to the recycling issue and the impact strength. Currently, glass fibre reinforced thermoplastics occupy only 10% of structural composite materials reinforced by glass fibres. Therefore, there is a great potential in this subject.
- New process development and automation:
Glass fibres are relatively cheap compared with other lightweight materials such as carbon fibres and aluminium alloys. Nevertheless, the processing cost of high fibre content composites used as textile reinforcements is not low enough. This is mainly due to long process cycle times and expensive semi-products such as prepregs. Moreover, most of processing methods are labour intensive. To demonstrate its economic viability, new cost effective manufacturing technologies by automation should be developed.

1.1.2 Carbon fibres

In spite of their high performances and low density, carbon fibres have been limited to high-end products in aerospace, biomedical and military applications, due to their high price. As the environmental regulation gets stricter, the principal method to reduce gas emissions in transport industries such as civil aeronautics and automotive is to produce even lighter vehicles. Thus carbon fibre reinforced composites are considered as attractive alternatives to replace the conventional metal parts.

The market for carbon fibres has been rapidly increasing, except in 2009 when the financial crisis took place. The world production of carbon fibres in 2008 was of 31 500 tons. This figure increased by 47.6% reaching 46 500 tons in 2013, leading to an average annual growth of 8.1% (Composites Market Report 2014 [1]). Behind this remarkable growth is the wide adoption of carbon fibre composites in the transport sectors. For example, the share of carbon fibre reinforced polymers in the structural weight of a Boeing 787 Dreamliner reached 50% and this share increased to 53% in the case of an Airbus A350. Carbon fibre composites have also been adopted in electrical vehicles such as Tesla Roadster and BMW i3. Moreover, many car makers are in close relationship with carbon fibre producers to cut down the carbon fibre price and ensure a consistent supply, such as BMW-SGL and Ford-Dow Akas.

	Manufacturer	2013	2014	2015	2016
Small tow	Toray	20.80	26.80	26.80	27.80
	Mainland Chinese manufacturers	13.16	14.66	16.49	22.01
	Toho Tenax	11.50	11.50	11.50	11.50
	Mitsubishi Rayon	7.40	10.80	10.80	12.80
	Formosa Plastics	8.75	8.75	8.75	8.75
	Hexcel	7.30	7.30	9.80	11.20
	Dow-Aksa	3.50	3.50	3.50	3.50
	Cytec	2.50	2.50	2.50	5.00
	Holding company composite	1.50	1.50	3.20	3.20
	Kemrock	2.50	2.50	2.50	5.00
	Hyosung	2.00	2.00	6.50	6.50
	Taekwang industrial	1.50	1.50	1.50	1.50
	RT-Chemcomposites	0.20	0.20	0.20	0.20
	Total capacity	80.46	91.36	101.89	114.31
	Theoretical capacity	56.32	63.95	71.32	80.00
Large tow	Toray	15.30	17.30	20.30	20.30
	SGL	9.00	12.00	15.00	15.00
	Mitsubishi Rayon	2.70	2.70	2.70	2.70
	Total capacity	27.00	32.00	38.00	38.00
	Theoretical capacity	24.30	28.80	34.20	34.20

Table 1.3: Carbon fibre production capacity and theoretical production capacity in 10³ metric tons [2,3]

In Table 1.3, the carbon fibre production per manufacturer is presented. Small tows, containing less than 24 000 filaments, are usually employed for high-end products such as satellites and leisure/sports goods. Large tows, containing more than 24 000 filaments, are relatively cheap and used for automotive and wind energy applications.

For carbon fibre reinforced composites, continuous processes such as filament winding, pultrusion, and prepreg lay-up are the most common processing techniques (see Table 1.4).

Processing technique	Market	%
Pultrusion / Filament winding	38.10	40
Prepreg lay-up	34.34	37
Resin infusion	11.76	13
Compression moulding / Resin transfer moulding	6.12	7
Others	3.76	4

Table 1.4: Carbon fibre reinforced composite market per processing technique (100 million USD, Composites Market Report 2014 [1])

The USA and the Western Europe are leading the carbon fibre reinforced composites market followed by Japan. In the USA, the main market is dedicated to aeronautic and defence industries, whereas in Western Europe, three main sectors are sharing the market: the automotive industry, the wind energy and the aeronautic and defence industry. Japan leads the carbon fibre production in the world and occupies the third place in the world market of carbon composites. Finally, the growth of Chinese share is particularly remarkable because the wind energy industry and aeronautics are boosting up the market.

So far, the market expansion of carbon composites has been led by the civil aircraft industries whereas the market for military applications is limited. It is expected that the future market growth will be led by the automotive industry where the need for lightweight solutions becomes critical because of the environmental regulation on the gas emission and fuel consumption.

For more extensive use of carbon fibre composites, the actual designing philosophy has to be rethought and new techniques should emerged like low cost carbon composites fabrication techniques. Anyhow, the most crucial issue regarding carbon fibres is their high price. Currently, carbon fibres are already adopted in some mass production cars, in particular electrical vehicles like the BMW i3. Their share in BMW group is still small and the carbon fibre price, and thus the car price, is still too high for a wide adoption in mass production brands. It is estimated that the carbon fibre price should pass under 10 USD/kg, more precisely it price should be around 5 USD/kg, to be able to replace conventional metals by carbon composites in mass production car manufacturing. During the last decade, many carbon fibre

manufacturers made significant investment to reduce the production cost by economy of size. Today, the price of carbon fibres for automotive applications has been decreased to 12-14 USD/kg. To further decrease the carbon fibre production cost, some potential solutions could be:

- To develop a supply chain for low cost and high performance carbon (i.e. 1 700 MPa of strength and 1.70 GP of modulus), especially for automotive applications
- To create strategic alliances between carbon fibre manufacturers and car makers
- To develop new low cost precursors like the lignin based precursors for carbon fibres developed by Zoltek and ORNL [4,5].

1.1.3 Natural fibres

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 bio-composites has been growing fast in recent years and the 15% of European composite production in 2012 was bio-composites.

Bio-composites can be classified into two big categories: Wood Plastic Composites (WPC) and Natural Fibre Composites (NFC). In 2012, WPC occupied 74% of bio-composites market whereas the share of NFC was 26%. With the USA and Canada, the North America is the main market of WPC and the principal applications are for construction industry, with decking, siding and fencing. Conversely, NFC are dominant in European market, especially for automotive applications. For example, 90 000 tons among 92 000 tons of the total European production of NFC were consumed in the automotive sector in 2012.

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. According to Nova institute [6,7], the market of natural fibre composites in 2020 is estimated to reach 350 000 tons with strong government incentives, whereas it would be only 120 000 tons without government incentives (see Table 1.5). Conversely, the influence from governmental incentives on the market of bio-composites for construction applica-

tions is rather weak. In general, many construction applications from bio-composites are manufactured by extrusion process which does not represent a major technical barrier. Thus, the market growth does not depend on the technological progress but on the increase of demand.

	Production in 2012	Bio-composites	Forecast in 2020, Without incentives / With strong incentives
	190	Construction, extrusion	400 / 450
WPC	60	Automotive, press moulding & extrusion / thermoforming	80 / 300
	15	Granulates, injection moulding	100 / >200
NFC	90	Automotive, press moulding	120 / 350
	2	Granulates, injection moulding	10 / >20

Table 1.5: Bio-composites market in 2012 and a forecast in 2020 in 10³ metric tons (Nova institute 2013 and 2014) [6,7]

1.2 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.

In the following sections, a selection of polymeric materials used in PMCs is briefly introduced.

1.2.1 Thermosetting

1.2.1.1 Unsaturated polyester resins

Unsaturated polyester resins are by far, the thermosetting resins the most used, thanks to their applications in many mass-production products. The success of these resins is related to their processing conditions: these resins can be cured at room

temperature and can be used in a broad range of manufacturing techniques, such as open-mould spray up, compression moulding, RTM and casting. Polyester resins have lower mechanical properties and larger curing volumetric shrinkage compared to phenolic and epoxy resins, but they are easy to handle and are relatively cheap [8- 10].

1.2.1.2 Epoxy resins

Epoxy resins have high mechanical strength, excellent dielectric properties, and good chemical corrosion resistance. They show high performances at relatively elevated temperatures up to 121°C. Epoxies are easy to cure and have low shrinkage. The matrix adhesion on the reinforcing fibres is generally very good. Epoxy resins have also an excellent dimensional stability and durability [8-10].

1.2.1.3 Phenolic resins

Phenolic resins are high cross-linked aromatic structures that exhibit hardness, rigidity, strength, heat resistance, chemical resistance and good electrical properties. The solidification process of phenolic resins should be carried out under high pressure and these resins undergo relatively large volume shrinkage. Phenolic resins have good compression performances, good chemical and ablation resistance. A drawback of phenolic resins is their brittle behaviour.

Because of their good fire performances, phenolic resins find applications in the aeronautic field, such as aircraft interior. Other important applications sectors are, so far, offshore oil and gas platforms, mass transit and electronic applications [8, 10].

1.2.2 Thermoplastic

1.2.2.1 Polyolefin

Polyolefin composites (e.g. polypropylene and polyethylene) tend to be used in cost sensitive applications. To improve the mechanical performance of the polymeric matrices (i.e. relatively low performance commodities), composites have been reinforced with fillers/fibres.

Because of their excellent balance between properties and cost, fibre (e.g. glass fibre) reinforced polyolefin composites have become widely applied in many different applications, including automotive, construction, and consumer products [8-10].

1.2.2.2 Polyketone resins

They exhibit outstanding mechanical properties, toughness, radiation-resistance and good flame resistance. Polyketone resins can stand both thermal and harsh environments maintaining their mechanical properties.

The most commercially successful polyketone resin is the Polyether ether ketone (PEEK) [8-10].

1.2.2.3 Polyarylene sulfide resins

Polyarylene sulfide resins (e.g. PolyPhenylene Sulfide – PPS) have excellent chemical stability and mechanical properties. The macromolecules have also very low flammability (i.e. UL94 = V0). Polyarylene sulfide resins are often reinforced with short fibres rather than continuous fibres [8-10].

1.2.2.4 Polyether imide

Polyether imide (PEI) has excellent mechanical properties and good heat resistance. PEI overcomes the PEEK performances in terms of service temperature. Indeed, PEI has high glass transition temperature, high using temperature and low moulding temperature [8-10].

1.2.2.5 Bio-based resins

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.

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) [11-14].

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)

1.3 Mention of Functional Materials

1.3.1 EMC shielding

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 1.2). Surface resistance of less than 1 Ohm can be obtained with the surface modification of the reinforcing textile.

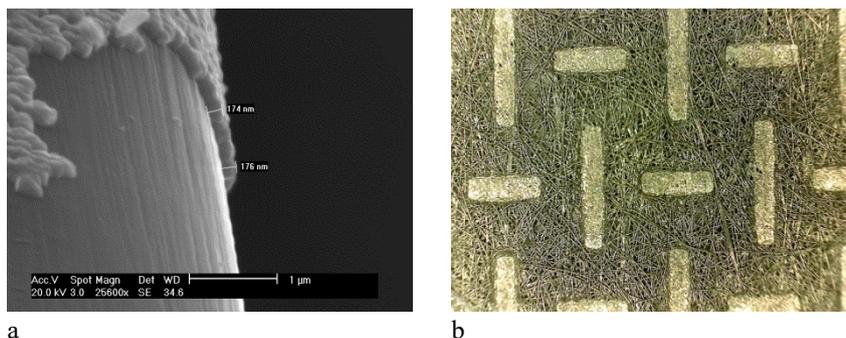


Figure 1.2: a) Nickel-coated polyester fibre, b) A fabric made of nickel-coated fibres

1.3.2 Materials for Fire Safety

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 [15-17].

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.

1.4 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.

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2 Textile reinforcement preforms

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Introduction

In a composite part made from textile preform and resin, the textile preform leads to the mechanical properties of the composite part. The performance of the fibre reinforced composite material depends upon: the fibre and matrix material characteristics, the interface properties and the architecture of the fibre reinforcement. The last one refers to fibre continuity and linearity, fibre orientation and arrangement, structural integrity, fibre volume fraction and fibres proportion relative to their orientation. As a result of these factors, the fibre composite material is considered heterogeneous and anisotropic. Furthermore, the fibre reinforcement architecture is a dominating factor which has to be appropriately selected and designed in order to respond efficiently to the application conditions (load type, load orientation, temperature, etc... [1]). There is a range of well-established methods to produce arrangements of reinforcement, [2] .e.g. textile technologies using high performance fibres such as carbon, or glass fibres (which represent 90% of the market). These methods as well as the textile preforms obtained were described in a large number of publications, so-called classification. In the first part of the chapter, the main current textile technologies associated to the classifications are described. For each process, and consequently each textile preforms manufactured, advantages and limits will be outlined. In a second part, called vision of the future, association and hybridization of these processes to produce net-shaped 3D preforms close to the final composite materials will be presented. Some examples from the literature will illustrate this section. The objective of this chapter is to provide key information to enable the reader to determine which textile preforms can meet his need and which manufacturing technologies would allow him to obtain the required preforms.

2.1 State of the art

In this section, a review of different textile structures is presented. In a first part, the current textile technologies are listed to understand their basic principles and the resulting properties of products. Then, in a second part, advantages and limits of each technology are succinctly reported.

2.1.1 Main current textile technologies

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. These technologies are extensively described in the textile literature [3-10].

2.1.1.1 Weaving

The most well-known textile technology is the weaving process. The Principle is the interlacing of 2 orthogonal in-plane yarn sets (weft and warp) according to a weave pattern [11]. Woven fabrics are made of looms in a variety of weights, weaves and widths. Wovens are bidirectional, providing good strength in the directions of yarn or roving axial orientation ($0^\circ/90^\circ$), and they facilitate fast composite fabrication. However, the tensile strength of woven fabrics is compromised to some degree because fibres are crimped as they pass over and under one another during the weaving process. Under tensile loading, these fibres tend to straighten, causing stress within the matrix system [12]. Several different types of weaving are used for bidirectional fabrics. In a plain weave, each fill yarn (i.e., yarn oriented at right angles to the fabric length) alternately crosses over and under each warp yarn (the lengthwise yarn). Other weaves, such as harness, satin and basket weave, allow the yarn or roving to cross over and under multiple warp fibres (e.g., over two, under two). These weaves tend to be more drapable than plain weaves. Woven roving is relatively thick and used for heavy reinforcement, especially in hand layup operations and tooling applications. Due to its relatively coarse weave, woven roving wets out quickly and is relatively inexpensive. Hybrid fabrics can be constructed with varying fibre types, strand compositions and fabric types. For example, high-strength strands of S-glass or small-diameter filaments may be used in the warp direction, while less-costly strands compose the fill.

2.1.1.2 Knitting

Two basic types of knitting processes are warp knitting and weft knitting. In warp knitting process multiple yarns are fed into the longitudinal direction of the machine and each yarn forms a line of knit loops in the fabric direction. While, in the weft knitting process, single yarn is fed into the transversal direction of the machine and forms a row of knit loops [13]. The loop form gives the structure high conformability to cover complex shape surface without wrinkles or need to cut and overlap sections. Furthermore, the knitting process enables to produce net shape or

near net shape preforms. In experimental study investigating the in-plane properties of weft knit preforms, similar performance between weft knitted composite and random mat composite have been observed. Moreover the in-planes performance of weft knit preform is much lower than that of conventional 2D woven composite [14, 15]. However, knitted composite exhibits higher fracture toughness than conventional 2D woven, unidirectional or random mat composite [8]. Similarly, knitted composite showed higher damage tolerance and impact energy absorption [16].

2.1.1.3 Braiding

Braided structures are created by interlacing yarns in inclockwise and anticlockwise directions in order to form a bias structure along the longitudinal axis [17]. According to the interlacing patterns, braided structures can be divided into diamond, regular, and Hercules braids, and, based on the appearance and cross-section, braids can be classified as flat, tubular, or fancy braid [18]. Braided fibrous materials are finding increasing applications in aerospace, automotive, and general engineering. Indeed, their unique seamless interlaced structures prevent unraveling, as well as mitigating damage, in comparison to twisted or filament wound structures [19, 20]. Braided structures have extensive applications, ranging from ropes, cordage, hoses, reinforcement coverings, composite tubes, and rotor hubs, to parts in automobile and aerospace industries. Compared with laminated composites, braided composites have excellent integrity due to the seamless interlaced structure [21].

2.1.1.4 Nonwovens

Nonwoven, or mat is defined as “a manufactured sheet, web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, whether or not additionally needled. The fibres may be of natural or man-made origin [21]. Nonwovens are primarily manufactured by a four-step process. In the first step, the polymers or fibres are prepared for the second step, where fibres are arranged together to form a 2D web of desired basis weight. The second step is known as the web formation process. This web does not possess much resistance to mechanical deformation and the fibres in the web need to be interlocked or fused or bonded together. The third step refers to the web-bonding process. The fourth and final step refers to web finishing whereby the enhancement of functional properties is achieved. Webs are mainly formed through dry-lay, wet-lay or polymer-lay processes. Nowadays electrostatic-lay like electrospinning is also widely used to produce fibrous webs. The fibres in nonwovens are held together whether by mechanical interlocking or by the fusing of thermoplastic fibres or by bonding with agents such as rubber, starch, glue, casein, latex, a cellulose derivative or a synthetic resin. Nonwoven materials are extensively used in a wide range of applications from liquid absorption, air purification and thermal insulation to personal protection [22]. Composite nonwovens, such as multi-layered or multi-component structures using a mixture of different

raw materials or integration of different process technologies, are designed and developed on the basis of targeted applications. In automobile non-woven materials are used for side, front and back liner, floor mat, sheet cover, wheelhouse cover, oil filter, engine air filter, and sound absorbing panel [23].

2.1.2 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 [24]. Each textile technology introduced before, provide this fibres alignment in preform. The Table 2.1 summarizes advantages and limits of preform products previously introduced.

Associated to these preforms potentialities, advantages and limits can be illustrated by the comparison of mechanical properties of various composites based on these preforms. The specific tensile properties of Plant Fibre Reinforced Plastics (PFRPs) and Glass Fibre Reinforced Plastics (GFRPs), which are dominating the composite market, were compared by Shah [25]. It revealed that non-woven preforms with thermoset or thermoplastic matrix presents weaker properties compared to aligned preforms (denoted unidirectional or multiaxial) at this composite scale. The conventional textile technologies have significantly evolved over the last century especially by using technical fibres as glass or carbon fibres. However, some limitations are associated to the employment of conventional textile processes in manufacturing technical fibre reinforcement preforms:

- Relatively high degradation of technical fibre/yarn on the conventional textile machineries are occurring. The conventional machineries are not adapted for poor flexible material like glass fibre or conductive material such as carbon fibre.
- Conventional machineries allows only the production of planar (2D) or thin cylindrical preforms. Consequently the final composite product has poor out-of-plane properties unless a reinforcing process with fibre reinforcement in the through-thickness direction of the preform is employed to complete the fabrication.

Preform architectures	<i>Advantages</i>	<i>Limits</i>
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 2.1: Advantages and limits of textile preform architectures

2.2 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 [26], interlock-weaving [27-29], stitching [30] or tufting [31, 32]. 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.

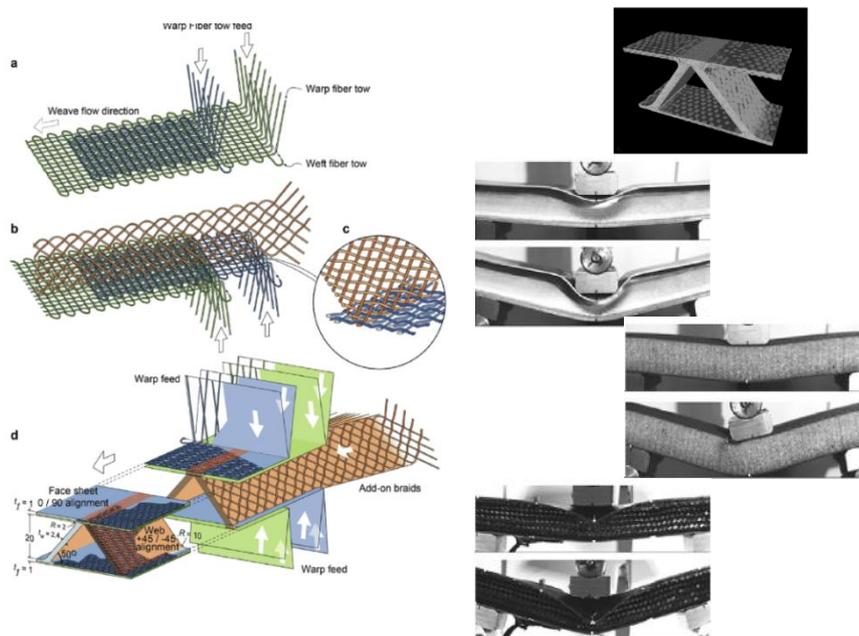


Figure 2.2: Description of textile process. A beam part and a comparison of metallic and CFRP parts subjected to 3-point bending

The figure 2.1 [33] 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 2.2 shows potentialities to produce, in one step, 3D cross-stiffeners net-shape preforms, or joints with a T or H cross-section [34]. 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.

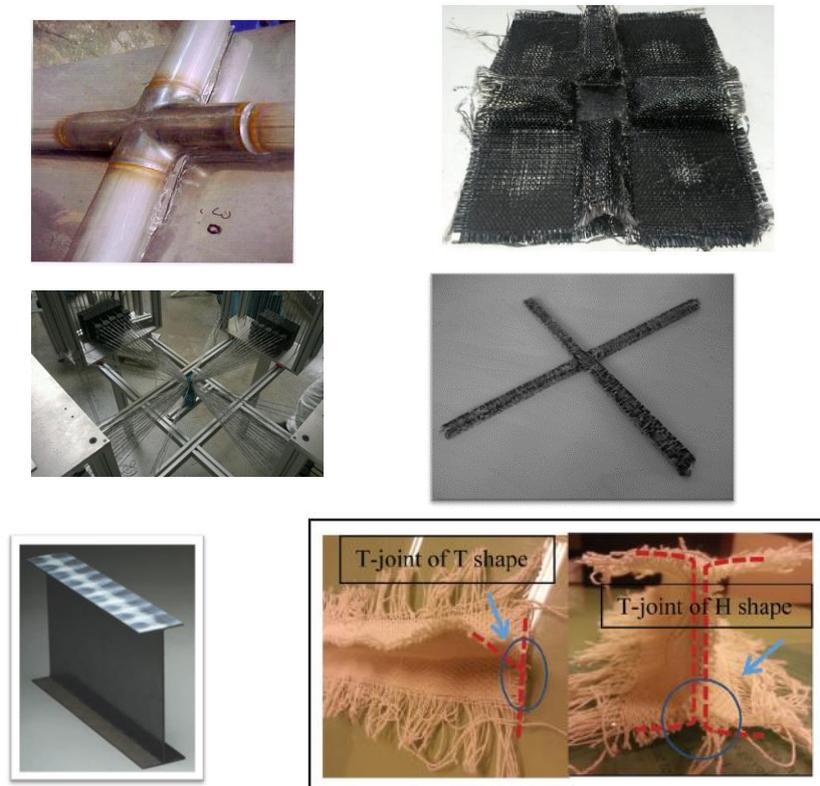


Figure 2.2: Cross-stiffeners with metal and fibrous parts and a 3D-weaving T-joint

The last example (Figure 2.3) 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.

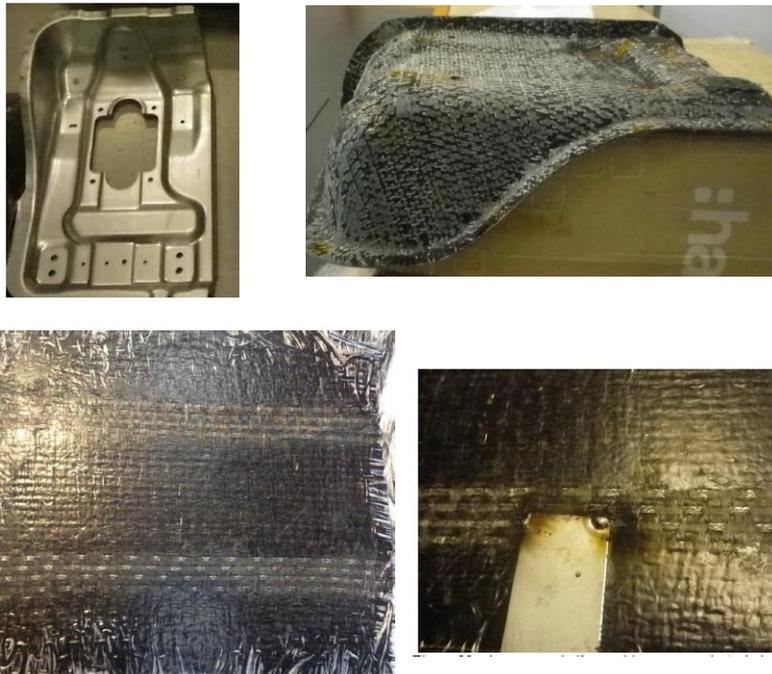


Figure 2.3: Truck seat with metallic and fibrous part and the insertion of metallic braids for the assembly by welding

2.3 Conclusion

The manufacturing process of composite parts remains the most important step, representing 60% of the added value of a composite part. The combination of liquid polymers with textile fibre architectures is thus, besides the textile preforming processes, the most time-consuming and cost generating process [35]. Furthermore composite parts must satisfy complex, various and coupled requirements concerning mechanical, thermal, and environmental conditions. Carbon fibre reinforced lightweight structures are actually the most important substitution material for these structural applications with low mass, high stiffness and strength. The ability to use

the specific anisotropy of the reinforcing fibres offers additional potential for custom-tailored load applications. Taking into account these specifications at the pre-form manufacturing step can contribute to cost reduction, from 30-50 €/kg to 15 €/kg for CFRP. Textile technologies offer a lot of potentialities to meet these objectives.

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3 Characterization methods

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Introduction

Testing is an area of vital importance for composites. It plays an important role in the design and the development of new materials and structural parts, as it provides fundamental information for both initial and final assessment of any application.

Today, several norms (ASTM, EN, ISO...) are available to determine composite materials intrinsic properties. All these norms regulate the realization of tests on relatively simple samples. However, with these samples, it is not possible to generalise the material characterization at a structural scale and under complex loading.

Thus, this chapter introduces some examples of non-conventional test methods that have been designed from scratch, applied and approved by Madmax project partners and their affiliates, during their activities. When possible, advantages of these non-conventional test methods are compared against limitations shown by standardised characterization methods. It also suggests research axes to improve the testing methods proposed.

3.1 Examples of non-standard testing methods

3.1.1 Drapability assessment of fabrics preforms

3.1.1.1 Limitations of current standard methods

Drapability is a property that allows a fabric to be bent in more than one direction with double curvature. Until recently, studies about drapability were focused on fashion effects. The formability of a fabric was then considered as its ability to fit the human body. Thus, the drapability was more or less a property of the fabric determining its aesthetic appearance both in static and dynamic conditions [1-3].

When dealing with textile reinforced preforms for composites, drapability has a technical meaning and refers to the ability of a fabric to conform to the surface of a mould, and not to a human body anymore. Basically, there is only one drapability test codified by a standard norm, but other instruments able to measure properties

linked to the drapability are available. The drapability test BS 5058 73 (2012), similar to the AFNOR G 07-109 assesses the capability of the fabric to modify its shape under the sole effect of its weight, from flat to undulated, against an edge with a low curvature laying on a horizontal plane (Figure 3.1).

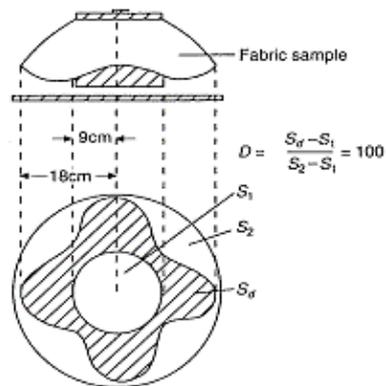


Figure 3.1: Representation of the BS 5058 drapability test

This standard is fully satisfactory as long as textiles for apparel and upholstery are concerned. It is also recommended for non-woven fabrics. Indeed, it gives an objective and quantitative measurement of D the natural draping effect [4]. The coefficient D is defined as the ratio of the draped ring projection area to the non-draped ring area multiplied by 100. The instrument measuring this coefficient D has been developed by Cusick in 1961 (Figure 3.2).

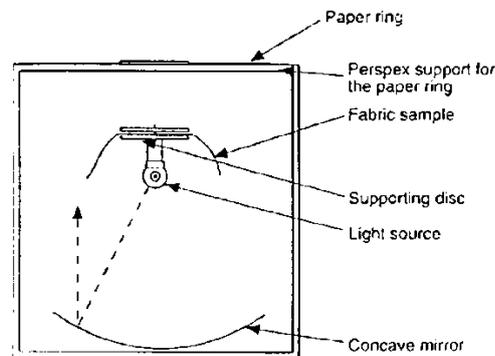


Figure 3.2: Cusick's Drapability Meter

The value of the surface S_d is calculated cutting and weighting the shadow of the sample on the paper ring. This can be easily calculated once the specific weight of

the paper is known. Recently, a system using image analysis techniques was developed to automatically measure the drapability. A schematic representation of the whole system is given Figure 3.3.

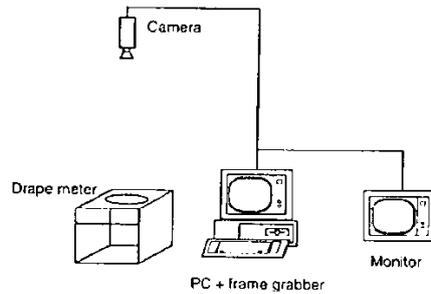


Figure 3.3: Schematic representation of a drapability measurement set-up using image analysis techniques

Another type of test is the “jutting strip method” or “cantilever method”, developed by Pierce (1930) and included in the FAST system.

FAST stands for Fabric Assurance by Simple Testing and is an objective method for the determination of various mechanical characteristics of a fabric. The FAST method can also be an alternative drapability test for the woven fabrics. This system determines various mechanical characteristics of a fabric and permits a quick comparison with expected values. In this way, it can also serve as a quality control instrument. The bending properties of a fabric may be easily correlated to its drapability. Indeed, the capability of a fabric to bend by the only action of its weight can be assimilated to the drapability.

Different versions of FAST are existing: FAST-1 is an instrument determining the compression properties of a fabric, FAST-2 determines the bending properties of a fabric, and FAST-3 is an extensometer.

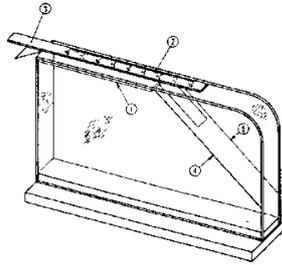


Figure 3.4: Schematic representation of the instrument FAST-2 determining the bending stiffness

The principle of the FAST-2 stiffness test is shown Figure 3.4. A rectangular strip of fabric is allowed to bend under its own weight to a fixed angle when projected as a cantilever. The fabric sample in the instrument represents a cantilever beam that is uniformly loaded by its own weight and bends downward until it reaches 41.5° , with respect to the norm BS 3356. Then the classical theory is applied, considering the strip like a cantilever inflected under the action of the force $P = pl$, where p is the weight per unit of length. According to the classical theory the maximum drop is:

$$f = \frac{P l^3}{8 EI} \quad (3.1)$$

Where EI is the bending stiffness.

For woven fabrics, FAST-2 provides objective measure of the bending properties. Moreover, thanks to a relationship between stiffness and drapability properties, it is possible, for example, to verify if a twill fabric has a higher drapability than a plain or a satin woven fabric. With this method the bending stiffness is measured taking into account the length of the juttred strip when the fabric touches the inclined plane, under the action of its weight.

In general it is known that knitted fabrics have a very good drapability, better than the warp/weft ones: this is due to the possibility of the thread to reach a higher extension if the structure is deformed to obtain a not plain shape.

3.1.1.2 Proposition of a new non-conventional drapability test

For the study of composites, a different kind of test, that could be applied to technical textiles was developed within the Textiform Craft project BRST-CT98-5175.

In thermoset and thermoplastic composites, a fabric has a good drapability if it can conform to a particular shape without making wrinkles, because a wrinkle could

generate an abnormal distribution of material in the part, leading to a useless thickening of the structure at a particular point.

A non-standard test was developed taking into account the particular production process of thermoplastic composite structures for which knitted textile preforms needed to be evaluated. The thermoforming process, in particular, requires accurate knowledge of the fabric behaviour, since the fabric is forced to adapt to a mould which will contain lower curvature radiuses in different planes. In this case, it is necessary to assess the capability of the fabric to let yarns slip under shear tensions while adapting to the shape. Also, it is important to evaluate the resulting area density of the fabric through local measurements in the areas undergoing large deformations. Finally, the effect of pressure has to be addressed, since the force applied to the mould can cause considerable stresses. As a consequence of the limited adaptability of the fabric to fit the desired shape, wrinkles may be formed. These wrinkles, under the mould pressure, can damage the fibres up to breakage. In order to avoid these wrinkles, the fabric might need to be pre-tensioned, thus diminishing the risk of having highly dense areas at critical zones.

Different thermoforming processes are available: we can use pre-consolidated fabric to be heated before their insertion into the mould, or use a fabric obtained from yarn that contains thermoplastic fibres, or use fabric to couple with thermoplastic films. But regardless of the thermoforming process selected, it is certain that the capability of the fabric to adapt to the mould shape is extremely critical for the success of the process.

Taking that into account, a test regarding formability and residual density after forming was proposed and implemented. The system to be used, consists of:

- a conical male mould
- a unit permitting the fabric to adhere completely to the mould
- a repeatable fabric tensioning system

It is therefore possible to observe at which level the structure can have conformability problems like the formation of wrinkles after the moulding process, and eventually measure the dimensions of these wrinkles.

So here, the drapability does not refer to the ability for fabric to conform to a surface solely under its own weight anymore, but is the property for fabric to conform to a particular surface under the action of a pressure, thus simulating the process of moulding. This way, the concept of drapability loses all the aesthetic connotations and acquires an operative description. Indeed, it's the process of construction of the composite object, starting with a knitted thermoplastic preform, that determines the property.

Let's described the testing system more in details. The conic moulds used are actually truncated cones. Various cones with different heights but the same top diameter, top radius and angle have been machined. Each cone is associated to a hollow cylinder, the internal diameter of the cylinder corresponds to the base diameter of the cone, plus a clearance to allow the fabric to pass through. This clearance

should depend on the fabric thickness, but in practice the difference in step (6mm) in the height of the cones makes this parameter not critical.



Figure 3.5: Set of cones and related cylinders (from the shortest A to the highest H)

The cone is placed on a platform where a tensioning system consisting in a set of four equal weights, is mounted.



Figure 3.6: Apparatus with the four tensioning weights

The test procedure starts by trying to conform the textile structure to the shortest cone “A” and its corresponding small cylinder, thus simulating the action of a mould. If no wrinkles are formed, the sample is passed to the subsequent higher cone. The last cone fitted by the fabric specimen without wrinkles, establishes the drapability-formability level of the fabric.

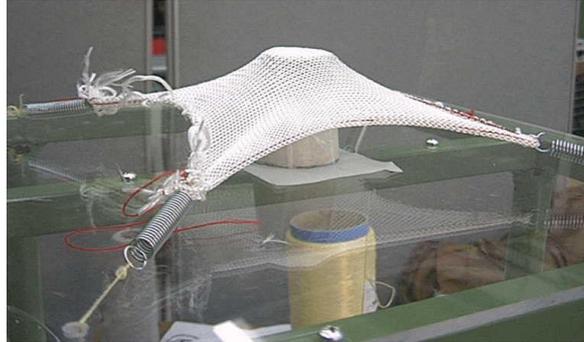


Figure 3.7: Fabric pre-tensioned by weights on one cone

Once the “final” cone has been reached, the shape of the structure is immobilised by pouring a thermoset resin with a fast hardener onto it. To this purpose, cones and cylinders are previously treated with detaching agent. In this way it is possible to have a stable specimen of the deformed textile structure and to compare its drapability against different fabrics.



Figure 3.8: Fabric sample “frozen” with resin

Table 3.1 summarizes the outcome of the test by tracking the sequence of cones used. In the case presented, level “G” was reached without wrinkles.

TEXTIFORM (Craft No. BRST-CT98-5175)**Drapability test**

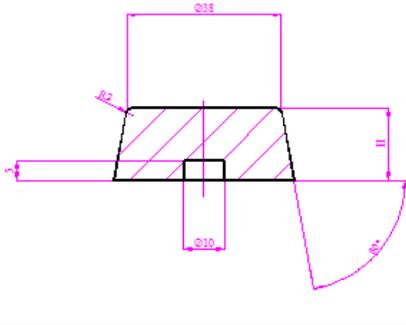
Test N.	2	Date	15/03/00	Prot. N. (sample received)	R.M.40999
Producer	BUCK	Material	CF TORAY FT300 PPS TORAY 300 72-190		
Reinforcement type		NONE			
					
Cone	H (mm)		Level of cone reached		
A	6		YES		
B	12		YES		
C	18		YES		
D	24		YES		
E	30		YES		
F	36		YES		
G	42		YES		
H	48		No		

Table 3.1: Drapability test report**3.1.1.3 Advantages and limits of the non-conventional drapability test**

The test has been applied to ten different types of knitted fabrics, all featuring in general higher drapability than woven or stitched fabrics. This test was particularly useful, not only to compare different commercial fabrics, but also to help designing and developing new fabrics for different applications.

The shaped specimen obtained by this method allows to assess other properties of interest such as the shape of the wave of the wrinkles in the area surrounding the cone. Additionally, the force applied to the cylinder and required for the fabric specimen to correctly fit the cone shape, can be measured and compared to the work needed during the moulding process.

By cutting the specimen, it is also possible to measure the variation of thickness within the fabric as well as the ratio between the area density of the deformed part and the one of a non-deformed specimen similarly impregnated. It could also be interesting to find the dimensions of an acceptable wrinkle, that is to say a wrinkle

in the fabric that does not cause serious problem in the mechanic behaviour of the structure. This could be determined only after different trials with (knitted) fabrics transformed in the desired object with the polymerization of the thermoplastic component. The method described is basically an empirical test which provides both global qualitative and local quantitative results. Depending on the final part to be moulded, the male mould shape may change.

3.1.2 Bi-axial tensile testing of flat materials

3.1.2.1 Limitations of current standard methods

The traditional dynamometer tests performed on materials are typically unidirectional. However, for anisotropic materials, and for different applications, tensile testing of flat materials in biaxial state i.e. along two orthogonal axes, becomes necessary. Recently a biaxial dynamometer able to investigate stresses and deformations of materials such as textile structures and preforms for composites, laminates, polymer films, nonwovens, paper, cardboard, rubber, etc. was developed by Sächsisches TextilForschungsInstitut (STFI) and l'Institut Français du Textile et de l'Habillement (IFTH), Next Technology Tecnotessile [5-8]. The capability to monitor and store significant quantities of data during the test, allows reliable performance with a high degree of repeatability. A multiaxial standard test which is often used is the bursting test, in which a circular test specimen is brought to breaking by applying a uniform pressure on the surface while maintaining the edge blocked. The test has some disadvantages, such as the difficulty in determining the relationship between the principal stresses, the uneven distribution of stress and strain, and the difficult analysis of the results.

3.1.2.2 Description of the biaxial tensile test

The biaxial dynamometer provides a reliable method for material characterization and laboratory results analysis. The apparatus is formed by a base structure composed of actuators for the camps and of a diverse set of sensors placed strategically to monitor the specimen behaviour under mechanical stress, and until failure.

3.1.2.3 Description of the equipment

The base structure is constituted of modular elements made of steel profiles mounted in a pre-stressed condition, supported by four columns, so that the horizontal plane is at convenient working height. In this plane, the four actuators are positioned in two opposed orthogonal directions, suitably sized to achieve the quantitative characteristic of the test device detailed below.

The testing system allow to apply a wide range of stresses and strains on samples. Thus, it has been necessary to implement a versatile clamping systems, in order to suit each range of application. The tensile actuators are driven under displacement control. In absence of standardized procedures for the application in question, the provisions of consolidated standards for uni-axial tensile tests are taken as a reference, for tests in one or two directions. The machine is provided with a control

system on four axes which allows to move the clamping jaws of the gripping of the sample with variable displacement speeds and with programmable cycles. The system allows to detect anisotropy and deformation limits and the load strength of the materials. The forces applied to the specimen in the two directions are detected thanks to eight load cells mounted in couples at each clamp to detect any non-symmetrical loads originating from inaccurate positioning or defects in the specimen. Because of high variabilities in materials behaviour, two deformations measuring methods have been implemented in order to optimize the system performance with the range of deformations to detect. During the test, a control system using a Proportional – Integral – Derivative PID procedure ensures an accurate positioning of the specimen at the centre.

3.1.2.4 Proposition of procedures

The first method is based on an artificial vision system. The specimen is prepared by generating some reference marks on the upper face of the specimen. By means of an image post-processing software, the marks coordinates are recorded during the test, thus the field of deformations on the surface of the fabric can be calculated at any given time. The resolution of this method is in the order of 1 mm, which allow to provide rich information, but in some cases it can be insufficient to determine strain values.

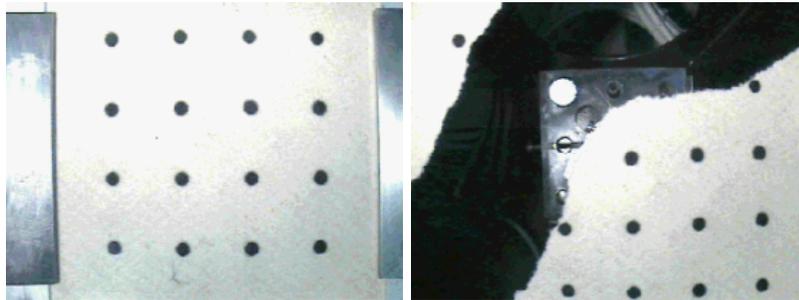


Figure 3.9: Sample prepared for optical deformation detection

The second method detects the overall deformation along each axis with the help of a device accurately measuring the displacement of clamps in the vicinity of the bi-axially deformed area, based on strain gauges.

The deformation of a thin metal foil is detected by strain gauges. To optimize the measurement, the thin metal foil is rigidly connected at its end to the terminals and is loaded in bending with a constant torque while strain gauges are arranged on the opposite sides. The deformation detected is then converted into the displacement of terminals. The extensometer, specifically designed for the application and validated up to a measuring range of 10 mm, uses a deformable stainless steel foil.

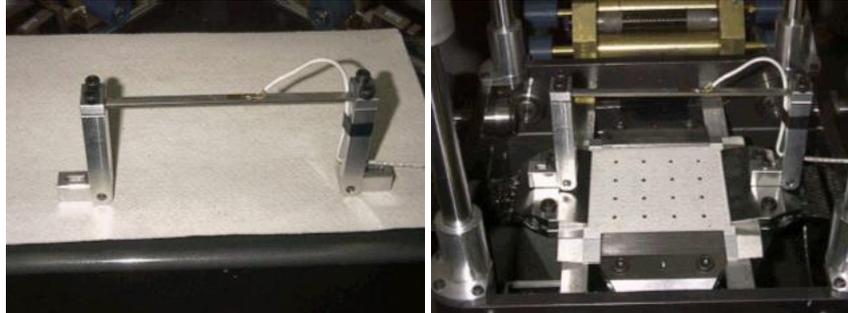


Figure 3.10: Extensometer for global sample strain measurement

3.1.2.5 Results and advantages of the biaxial tensile test

The method and prototype developed give us a glimpse of the potential applications of the test device. The system architecture, with its hardware and software components presents a lot of advantages. The system is stable, the user can control the parameters regulating the process, the monitoring of different characteristics is easy and the system has an important storing capacity of data and images. All these characteristics enable reliable performance with high degree of repeatability. Potential applications concern: the analysis of stresses and deformations in two directions, and the mechanical characterization of textile structures, films, paper, membranes, composites.

The technical specifications are detailed below:

- Number of axes (each with independent control) 4
- Number of load cells per axis 2
- Maximum load per axis 12 000 N \pm 1 %
- Strain rate minimum-maximum 10-500 mm/min
- Maximum displacement per axis 50 mm
- Measuring frequency (max) 1 Hz
- Clamp width 200 mm
- Minimum distance between clamps 150 mm
- Deformation control via camera: frame rate (max) 1 Hz
- Resolution 0.3 mm
- Sample size (max) 200x200 mm

The method still can be improved, for example, by reducing the transversal rigidity imposed by the clamps.

3.1.3 Crash tests

3.1.3.1 Limitations of current standard methods

Crash tests can be extremely expensive [9-11] as they require full scale prototypes, accelerometers and several high speed cameras. Hence crash tests are widely employed for testing inexpensive prototypes like helmets. But, when it comes to vehicles parts, tests for the selection and design of new composites are made on representative small scale specimens to reduce the testing costs.

3.1.3.2 Description of the non-conventional crash test method

Between 2014 and 2016, two Italian projects were aiming at improving the safety of pedestrians and cyclists being hurt by trams and improving the resistance of suitcases. In the framework of these projects, a method has been devised to test the impact resistance of several composite samples.

An instrumentation should be able to quickly deliver a maximum of information without any risk for the equipment. The sample is placed horizontally. The impact energy is produced by accurately placing an impacting object of suitable mass, hardness and shape. The air friction becomes a constant for equal object size and falling height.

The method was applied to determine the best material combinations in function of the application. For the suitcases problematic, the material should not break and undergo the minimum permanent deformation or damage. For the pedestrian accident, the purpose was to maximise the adsorbed energy whatever the importance of damage for the material, in order to minimise the biological consequences for the human body impacted.

For an accident in public transport, a bowling ball with an adequate weight was selected to represent a human head impacted at 7 m/s with an energy of 190 Joules. The sample was placed on the floor, to reproduce the vehicle inertia and inner rigidity. The Head Injury Criterion (HIC) had been adopted as a widely acknowledged method to assess the risk of biological damage. It relates the effects of head acceleration with its duration: larger accelerations may be tolerated for shorter times:

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \right\}_{max} \quad (3.2)$$

Where t_1 and t_2 are the initial and final times in seconds of the interval during which HIC attains a maximum value. a the acceleration is measured in g the standard gravity acceleration. The maximum time duration of HIC, $t_2 - t_1$, is limited to a specific value between 3 and 36 ms, usually 15 ms.

This method requires the use of accelerometers. But for a preliminary assessment, the first bounce flying time of the ball, determined by the help of a high-speed camera (500 frame/s) can serve as an initial selection criterion. Indeed, this value is directly related to the maximum bounce height reached and allows to calculate the

amount of energy absorbed by the sample under test. The ball is considered as rigid, and its penetration within the specimen was determined. For that purpose, a high-speed camera is focused on the upper area of the ball when the ball reaches the sample, and an adequate spot lighting and a measuring tape were carefully prepared. Readings were taken in static conditions to calibrate the system based on the minimal distance between the sample and the floor.



Figure 3.11: Impacting ball being filmed

3.1.3.3 Results and advantages of the new crash test method

For both applications the test provided full satisfaction. In particular in the case of human protection, tests allowed a rapid comparison of forty materials and their combinations, with completely different behaviour and costs. It was possible to obtain combinations of composites showing no bounce at all, among a selection of materials exhibiting three or more bounces. In these cases, the high speed camera was employed to evaluate the deceleration time with a uniform acceleration assumed and to measure the penetration depth. These measurements allow to improve the selection of the most promising materials, thus allowing to design and assemble original combinations of commercial products. Concerning the HIC results of the different materials tested, the HIC values were progressively decreasing, with a ratio of ten between the first and the last material tested.

3.1.4 Material characterization under dynamic conditions: the Split Hopkinson bar test

3.1.4.1 Limitations of current standard methods

In most of the case, material stress-strain curves are obtained at relatively low strain rate. However, materials mechanical behaviours are different at low or higher strain rates, like in the case of an impact (e.g. car crash or bullet). Proper design requires data collected under diverse conditions, including high strain rate and shock waves.

3.1.4.2 Description of the non-conventional split Hopkinson bar test

The split Hopkinson bar test is the most commonly used method for determining material properties at high rates of strain. The split Hopkinson Pressure Bar allows testing materials within the frequency range of 100-10 000 Hz. The main elements of a Split Hopkinson Bar consists of three long aligned pressure bars:

1. The striker bar (red)
2. The incident bar (blue)
3. The transmission bar (blue)

The specimen is mounted between the incident and the transmission bars (2 and 3). The impact of the striker bar generates the stress pulse. The generated tensile wave propagates throughout the device. The wave is partially reflected at the incident bar/specimen interface and partially transmitted through the specimen to the transmission bar. By comparing dynamic strain response along the incident and the transmission bar (minimum frequency response of all the components in the data acquisition system should be at least 100 kHz), material constants like Young's modulus or mechanical stress under dynamic conditions are determined.



Figure 3.12: Scheme of an Hopkinson bar

3.1.4.3 Results and advantages of the non-conventional split Hopkinson bar test

Historically thought for monolithic materials, nowadays a number of Hopkinson bar set-ups have been developed or are under development for testing composites materials. The purpose of these works is to get reliable data on high strain rate behaviour of composites materials such as lightweight polymeric composites [12-15], to be used in the transport sector.

3.2 Vision of the future

For composites materials, it is essential to develop more and more efficient test protocols in order to be able to determine the composite structural behaviour with an accurate integration of material component's real behaviour.

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4 Modelling and simulation

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Introduction

In this chapter, scientific approaches for the modelling and simulation of composites are reviewed, with the perspective of reaching an ultimate goal: composites virtual prototyping.

Virtual prototyping has reached industrial maturity over 20 years for metals, through advanced models in finite element code and methodology and knowledge buildup by the industrial end-users. This is not the case for composites where trial and error approach based on hardware testing is the norm, even in industries like aeronautics, which have gradually introduced the usage of composites for 20 years.

The domains to be covered in virtual prototyping for performance evaluation range from pre-design and statics to vibration, crash, impact, durability and life time assessment and reparability.

Mastering the composites value chain is one of the main priorities in transport but also in other industries (building and energy) in order to develop lightweight innovative structures with appropriate mechanical properties and improved quality. It must be produced with optimal trade-offs for cost, safety and comfort. An important issue is also to reduce the energy for production, material waste, to enhance product life cycle, re-use and recycling; but without sacrificing the notion of performance at affordable cost. The need for composites structures is increasing; however there are still major limits acting against their development, which are the following: high cost, long and labor intensive production, quality issues, lack of versatile and flexible processes, tailored properties difficult to achieve with current technologies, low qualified work forces, but also the lack of modelling tools to virtually prototype products, to evaluate, upfront the manufacturability and performances properties, manufacturing process and cost.

The chapter is divided into three main parts: the first one deals with manufacturing processes modelling, the second one with mechanical performance analysis and the last one is about coupling manufacturing and performance analysis for virtual prototyping. In addition, we outline some particular features of commercial and academic softwares for numerical simulation and discuss their merits and limits with respect to the current industrial needs.

4.1 Modelling manufacturing processes

4.1.1 Prepreg based manufacturing processes

Here we will discuss the state of the art for the numerical simulations of three representative prepreg based manufacturing technologies, namely autoclave moulding, Automated Tape Layup (ATL), a.k.a. Automated Fibre Placement (AFP), and thermoforming.

4.1.1.1 Autoclave moulding

According to Steve Tsai, thermoset prepreg curing had been art rather than science until 1970s [1]. Since the early 1980s, thermoset prepreg composites manufacturing have been analysed by numerical simulation [2,3]. Today, the degree of cure and heat transfer inside thermoset prepreg can be relatively accurately modelled. The prediction of process-induced defects such as air voids, resin rich or poor zones, fibre misalignment and residual stress is still a big challenge even though many research papers have been published on this topic [4]. In particular, the modelling of residual stress leading to warpage, spring-in or spring-back is a big issue. Some commercial computer codes have been developed to predict the residual stress formation and resulting deformation of composite parts [5]. The main problem lays in the identification of material behaviour during the curing, however. Many different constitutive models have been employed such as elastic, thermo-elastic and thermo-visco-elastic models in the literature [6]. It has been well known that the thermo-visco-elastic model represents better the prepreg behaviour during the curing than the other models, in particular for thick composite part manufacturing. Nevertheless, the experimental characterization of thermo-visco-elastic behaviour is very difficult because composite prepreg consists of elastic fibres and thermo-visco-elastic thermoset resin which undergoes the phase transition. Therefore, the main research efforts should be made for accurate material behaviour characterization during the prepreg curing.

4.1.1.2 Automated tape lay-up / automated fibre placement

Instead of manual prepreg lay-up, automated lay-up using a robot is attracting great attention as a cost-effective manufacturing technology. Depending on the width of prepreg, this process is called either Automated Tape Lay-up (ATL) for wider prepreg or Automated Fibre Placement (AFP) for narrower prepreg. In some

cases, AFP can also represent automated dry fibre placement to obtain a preform which is subsequently followed by resin impregnation for Resin Transfer Moulding (RTM) process or resin infusion process. Both the thermoset and thermoplastic prepregs can be employed. Today, ATL of thermoset prepreg such as carbon/epoxy prepreg is widely used to manufacture modern aircraft fuselages. The most common heating methods are hot nitrogen gas jet impingement and laser heating. The former one is a low cost method for a low temperature range and usually used for thermoset prepreg processes. The latter one is more expensive in terms of energy consumption and investment. Thus, it is applied to thermoplastic prepreg processes where the melting point of thermoplastic matrix is relatively high.

The most important objective is to obtain a good adhesion between adjacent prepreg layers. In particular, the key parameter is the temperature at the nip point which is the first contact point between the substrate prepreg and the incoming prepreg. Therefore, most of research efforts have been made on heat transfer analysis. Nevertheless, a significant discrepancy still exists between numerical simulation results and experimental results.

There are two main issues to address in the numerical simulation of heat transfer. Firstly, the heat transfer during this process involves different physics which are highly coupled with one another, such as heat conduction inside prepreg, radiation from heat source and natural or forced convection by the air flow around the prepreg [7]. Hence, it is a kind of conjugated heat transfer where the boundary condition for heat conduction is decided by the surrounding air flow and the boundary condition for the air flow is decided by the temperature of prepreg surface. In most of modelling work, the boundary condition for heat conduction in prepreg, viz., convective heat transfer coefficient, is assigned arbitrarily as a constant value. However, the real distribution of heat transfer coefficient is highly non-uniform depending on the position, because heat convection can be described by Nusselt number of Rayleigh number which is decided by local Reynolds number.

Secondly, the material properties such as thermal conductivity and specific heat capacity, exhibit a strong variation depending on the temperature [8]. In particular, thermoplastic polymers show an endothermic reaction around their melting point where the thermal properties are significantly changed. Hence, the numerical modelling results, where constant material properties are considered, should bring about unreliable results.

Once the temperature distribution is known, the adhesion between adjacent layers can be modelled. The most common modelling approach is to regard the interfacial adhesion as a combination of intimate contact where the roughness at the prepreg surface disappears and of autohesion, a.k.a. healing or reputation where polymer molecules get across the polymer interface, as suggested by Lee and Springer [9]. Even if this model is based on a very simple assumption on the material configuration and phenomenon, it can represent well the influence from the process parameters such as temperature and pressure, and from the material properties, in particular the matrix viscosity, upon the adhesion strength. In general, it has been known that the time for intimate contact is much greater than the time for autohesion

for aromatic polymer matrix composites such as APC2 (whose matrix is PEEK) at elevated temperature [10]. Some variations of Lee and Springer model have been summarized in a reference [11].

4.1.1.3 Thermoforming

Thermoforming, also called hot stamping, sheet forming, or cold compression moulding is a highly automated process where pre-heated prepreg, usually thermoplastic prepreg (even though thermoset prepreg is also adopted in some cases), is compressed in a cold mould to be shaped in a complex form followed by a cooling phase.

The main issue in the thermoforming process modelling is the predictions of material deformation such as the changes of fibre orientation and of fibre volume fraction which have a great influence on the manufacturability as well as on the mechanical properties of final parts. Because composite prepreg is a combination of textile reinforcement and of polymer matrix, its drapability is decided not only by the textile architecture but also by the matrix viscosity. As a matter of fact, the behaviour of each constituent, i.e. textile reinforcement and polymer matrix, has been well characterized and can be modelled independently.

For example, textile reinforcement is modelled at different scales. At the microscopic scale, each fibre filament is modelled as beam or bar elements and their deformation is modelled considering the friction among them [12]. At the mesoscopic scale, fibre yarns are modelled by three-dimensional volumetric elements while they are considered as a homogeneous material with anisotropic properties [13]. At the macroscopic scale, fibre textile is modelled by solid-shell elements, while it is regarded as a homogeneous material with anisotropic properties in the same manner [14]. In both cases, all the deformation modes are characterized by experimental methods, biaxial tension test for tensile behaviour, shear frame or picture frame test for intra-laminar shear behaviour, clamping test for bending behaviour and compression test for out-of-plane compression behaviour. The common constitutive models are a hyper-elastic model and a hypo-elastic model [15]. In both cases, the textile deformation behaviour is independent of temperature and of strain rate, even though it exhibits a strong non-linearity.

Conversely, polymer matrix is a viscous material whose behaviour is dependent on temperature and strain rate. Today, polymer rheology is well characterized and the research on its numerical modelling is very abundant in the literature.

Consequently, composite prepreg consisting of fibre textile and polymer matrix is a thermo-visco-elastic material. Hence, its behaviour is highly non-linear. Moreover, its behaviour depends on strain rate and on temperature as well. In early work, some researchers proposed a homogenization approach based on a viscous model, a non-linear elastic model or a visco-elastic model, while considering the properties of each constituent [16]. In spite of its simplicity and convenience, those models fail to represent the entire spectrum of material behaviour. By experimental meas-

urements of prepreg, however, it is very difficult to characterize the material behaviour over a wide range of temperature and of strain rate, because the number of tests is too large. Nevertheless, recent papers on the experimental characterization of prepreg at high temperature show satisfactory results [17].

Other important issue to address in the numerical modelling is to predict process-induced defects such as voids, resin poor/rich zones and wrinkle formation (Figure 4.1). The mechanism of void generation in the thermoforming has well been identified as consolidation – deconsolidation – reconsolidation [18]. More work is still required to obtain quantitatively accurate simulation results.

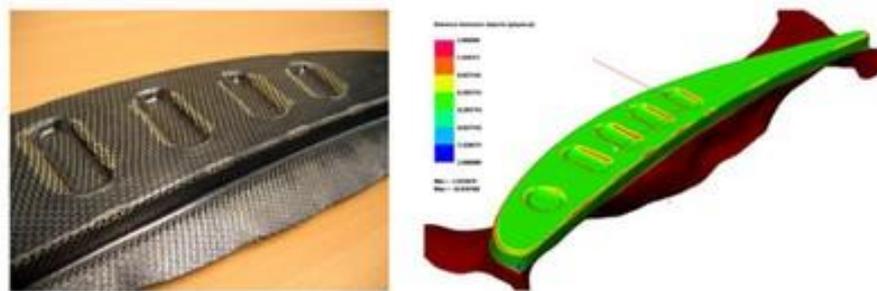


Figure 4.1: Example of thermoforming simulation (Copyright ESI group)

4.1.2 Liquid composite moulding processes

In this section are discussed liquid composite moulding processes where dry reinforcement preplaced inside the mould, called preform, is impregnated by liquid resin which is subsequently cured under heat. There are many different classifications of these processes. In this chapter, we classify them into two big categories, namely, rigid tooling processes and flexible tooling processes.

4.1.2.1 Rigid tooling processes

Two processes are in this category: Resin Transfer Moulding (RTM) and Compression Resin Transfer Moulding (CRTM), where the fibre preform is impregnated by liquid resin between metallic male and female mould platens. The gap height between the mould platens is fixed during the RTM process whereas it is decreased during the CRTM process.

Since several decades, there have been many research efforts to model the resin flow, heat transfer and resin curing during the RTM process. Currently, the most conventional numerical scheme is the finite element method employing control volume where Volume Of Fluid (VOF) method is used to track the mobile flow front location. Indeed, textile reinforcements have a highly heterogeneous microstructure which consists of fibre yarns containing a number of fibre filaments. Hence, there are different types of pores inside the textile reinforcements, namely macropore between the yarns and micropore between the fibre filaments inside the yarn. It would

be a proper numerical approach to analyse the resin flow at the microscopic scale or fibre filament scale by Stokes equation considering the surface tension at the resin-air interface or at the mesoscopic scale of fibre yarn scale by Stokes-Brinkman equation considering the capillary pressure inside the fibre yarn [19]. This approach leads to a prohibitive computation burden in the case of large part manufacturing simulation, however, and the numerical simulation at the macroscopic scale is widely used for industrial developments.

In general, the resin flow in fibre preform is described by Darcy's law regarding the fibre preform as a homogeneous porous medium whose ease of resin flow is represented by a single parameter called permeability. Today, there are some commercial simulation packages for the RTM process simulation [20, 21]. They can predict the resin flow pattern quite well in a qualitative manner (Figure 4.2). The main issue in the RTM simulation is the uncertainty of permeability data. Indeed, there is a strong scattering in the experimental data even for the same fibre reinforcement [22, 23]. Currently, there is no standard method to measure the permeability of fibre reinforcement. Moreover, most industrial parts have complex geometry where the fibre preform is highly deformed, i.e. sheared or bent, inside the mould, whereas the preform permeability is generally measured inside a flat mould where the preform is not submitted to any deformation. As a matter of fact, the deformation of textile structures can be simulated by a finite element package which is available for the modelling of fabric draping during the performing or thermoforming process [24].

Another important issue is the modelling of air void formation and transport. As the RTM process is widely employed to fabricate structural parts in the aeronautic sector, the void defects leading to significant degradation of the mechanical performance is a great concern. There have been some empirical models to predict the air void formation which was implemented in a commercial code [25]. This model is not enough satisfactory especially in the case of large industrial part manufacturing simulation. One of the key phenomena to consider in the numerical modelling is the air void migration along the resin flow [26]. Indeed, the residual air voids are usually reduced by a bleeding process where the air bubbles are swept away from the mould along the resin flow even after the mould is completely filled by the resin. The conventional resin flow approach adopts the single-phase flow analysis where only the liquid resin flow is considered whereas the presence of air flow is ignored. In the future work, the multi-phase flow where the incompressible air flow as well as the compressible resin flow, are considered, should be investigated to address this issue [27].

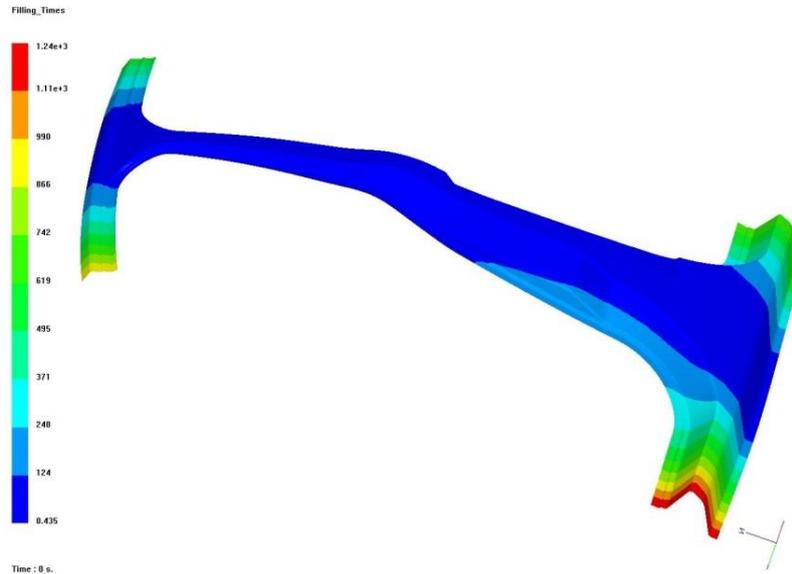


Figure 4.2: Example of mold filling process simulation (Copyright ESI group)

In recent years, new materials and processes are introduced in the aeronautic and automotive industries. For example, functional particle charged resins are widely used in the aeronautic and railway applications, to improve impact resistance, flame retardancy and electrical or thermal conductivity. Hence, there is a strong need for simulation tools to predict the filtering of particles by the fibre reinforcement during the RTM process. In the automotive sector, High Pressure-Resin Transfer Moulding (HP-RTM) and CRTM processes are attracting great attention to decrease the process cycle time. In those processes, the fibre preform is submitted to large deformation induced by the high pressure resin flow. This topic should be intensively addressed in the numerical modelling considering the fluid-structure interaction.

4.1.2.2 Flexible tooling processes

In this category of processes are Vacuum Infusion (VI), Vacuum Assisted Resin Infusion (VARI), Vacuum Assisted Resin Transfer Moulding (VARTM), Seaman Composite Resin Infusion Moulding Process (SCRIMP), Vacuum Assisted Process (VAP) and Resin Film Infusion (RFI) where a flexible tooling such as vacuum bag is used replacing the metallic mould platen in one side while the metallic mould is still used in the other side. In general, the resin flow is driven by the differential pressure between the atmospheric pressure and the vacuum which is applied to the preform stack inside the mould. Thus, the fibre preform undergoes the deformation which varies along the change of resin pressure. The main issue in these processes

lays in the difficulty to accurately predict the fibre volume fraction and the dimensions, in particular the thickness, of final parts. According to the pressure distribution, the fibre volume fraction and part thickness are highly non-uniform. Furthermore, this uncertainty leads to inaccurate prediction of mould filling time. Today, some commercial codes provide the simulation modules for vacuum infusion process modelling which lead to a significant error in the quantitative fill time prediction even if the qualitative flow pattern prediction is accurate enough [20, 21].

In fact, this topic has been studied in many research papers considering the interaction of resin flow and fibre deformation. Nevertheless, there are still two principal issues to address to further improve the numerical modelling.

Firstly, the deformation behaviour of fibre reinforcement should be carefully characterized. Because the main deformation mode in those processes is the compaction or decompaction of fibre reinforcement in the thickness direction, the constitutive relation between the out-of-plane normal stress and strain is obtained by the compression test of dry fibre reinforcement in a universal test machine. It has been known that the behaviour of fibre reinforcement is different for compaction and for decompaction [28]. Moreover, the behaviour of wet fabric and dry fabric is also different because of lubrication effect between fibre filaments during the deformation [29]. Indeed, fibre reinforcement is initially compacted before the resin impregnation. The fibre preform is subsequently swelled, i.e. decompaction, once it is impregnated by the resin. Therefore, the deformation behaviour of fibre reinforcement should be carefully selected according to the specific process stage in the numerical modelling of vacuum infusion processes. Nevertheless, it is very difficult to experimentally characterize the decompaction behaviour of wet fibre reinforcement. Hence, it is crucial to carefully characterize the deformation behaviour of fibre reinforcement according to the wet or dry state and to the compaction or decompaction mode.

Secondly, the only deformation mode of fibre reinforcement considered in most research work is the through thickness strain. Then, the force balance among the external atmospheric pressure, the fibre deformation stress and the resin pressure is dealt with respect to the normal stress equilibrium in the thickness direction. It has been shown in some references that the interlaminar shear stress gradient may make significant influence on the prediction of the resin flow and the final shape of composite parts, in particular at the corners or angles of complex parts [30, 31]. This approach needs a great number of three-dimensional elements which lead to a very huge computational cost, whereas most of research work addressing this issue have employed two dimensional mesh in numerical simulation. Nevertheless, there have been significant progresses in the numerical simulation of dry textile reinforcements and of the resin flow in fibre reinforcements, at different scales, i.e. from microscopic to macroscopic. Therefore, the future research efforts may be focused on the numerical modelling approaches to combine two expertises, viz., the resin flow in the fibrous medium and the deformation of the textile reinforcements.

4.1.3 Discontinuous fibre reinforced composites moulding processes

The following describes the current features and needs in industrial development of simulation tools for the compression moulding and the injection moulding. In particular, we discuss the state of the art and perspectives in the modelling of the fibre orientation, fibre volume fraction and fibre length in final parts.

4.1.3.1 Compression moulding

The most common materials for the compression moulding are Sheet Moulding Compound (SMC) and Bulk Moulding Compound (BMC) where discontinuous fibres are mixed with thermoset polymer. The material flow has been modelled by generalized Hele-Shaw (GHS) model or Barone-Caulk model by considering the mould cavity as a thin flow channel where lubrication approximation is valid [32]. As the shear rate during the material flow is relatively low, the fibre length is well preserved through the moulding cycle. Conversely, the distribution of the fibre orientation and the fibre volume fraction in a final part is greatly affected the material flow pattern.

The fibres rotate along the material flow during the moulding process and the fibre orientation state which was initially at a random state can exhibit an anisotropic state in a final part. This phenomenon is called flow-induced fibre orientation. In general, the fibre orientation state is represented by orientation tensor while the interaction between fibres is considered by Folgar-Tucker model [33, 34]. Because the usual fibre length is much larger than the mould cavity height, the fibre orientation state is generally represented in the two-dimensional state. There is another important phenomenon in the compression moulding, namely, fibre separation or segregation. Due to the interaction between fibres, some fibres cannot migrate along the main flow but stay at the initial position. Consequently, this interaction induces a fibre content gradient between the upstream and the downstream. These two phenomena have been investigated independently. In the modelling of fibre orientation, fibre separation has been ignored assuming that the fibre content is uniform. The dependency of fibre separation on the fibre orientation and the flow direction has also been ignored in the conventional modelling approaches. As the fibre content increase more and more for the structural parts in the automotive sector, the interaction between fibres becomes more and more important and the coupling between the fibre rotation and the fibre migration may become stronger [32, 35].

A new trend in the SMC development is the use of carbon fibre SMC either in chopped fibre tows or in continuous fibre strands. Carbon fibre tows are more flexible than glass fibres and the conventional orientation model where the fibres are regarded as rigid bodies may not work for carbon fibre SMC. Moreover, unidirectional continuous fibre strands are less susceptible to flow-induced fibre orientation and leads to preferential flow which in turn influences the chopped fibre orientation

state. So far, few research papers are studying carbon fibre SMC despite of increasing interest in the automotive sector. This topic will be one of the main issues to address in the numerical modelling of compression moulding.

4.1.3.2 Injection moulding

In general, the fibre length in the injection moulding is much smaller than the mould cavity height. Thus, the fibre orientation exhibits a three-dimensional state, characterized by different orientation states at the skin and core layers. In some commercial packages, three dimensional mould filling simulation modules are available to consider the fountain flow effect and the temperature gradient in the thickness direction [36-38]. Today, the three dimensional orientation state of short fibres in the injection moulding is successfully modelled. Some commercial packages provide also a computational module to obtain the mechanical properties from the fibre orientation state in a final moulded part [36].

Recently, Long Fibre Reinforced Thermoplastics (LFT or LFRT) are attracting great attention from the automotive industry by dint of their good mechanical performance. In general, the fibre length of moulded LFT is greater than 1 mm, which is comparable to the mould gap height. Hence, the wall effect on the fibre orientation is not negligible and the conventional three-dimensional fibre orientation model has a limitation to accurately represent the fibre orientation at the skin layer. Another critical phenomenon in the injection moulding of LFT is the fibre separation. Due to the long fibre length, some fibres are trapped at the solidified skin layer and cannot migrate along the main stream of material flow. Hence, there is a significant difference of fibre content between the upstream and the downstream [39]. Therefore, new fibre orientation and separation models considering the interaction between the fibres and the mould walls are needed for the numerical modelling of LFT injection moulding.

Contrary to the compression moulding of SMC, the fibre length as well as the fibre volume fraction and the fibre orientation may be non-uniform in a final part. This is due to high shear rate of the material flow during the plastification inside the barrel and the fibre breakage induced by the filling inside the mould cavity. Indeed, the original fibre length of LFT pellets is significantly decreased in the final moulded product. There are still many issues in terms of numerical method and physics model, because the numerical modelling should take into account not only the mould filling inside the mould cavity but also the plastification inside the barrel.

By virtue of significant research efforts, the resin flow, the heat conduction and the resin curing are successfully simulated by commercial codes. Nevertheless, there are still some issues in predicting the process-induced defects such as air voids, residual stress, fibre deformation, chopped fibre orientation and separation, and fibre breakage which may have a great influence on the mechanical and physical properties of final parts. 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.

4.2 Mechanical performance analysis

4.2.1 Stiffness and strength simulation

The stress analysis is well established for laminated composites with the so-called Classical Laminate Theory (CLT), where the first paper by Stavsky and Reissner goes back to 1961. The deficiencies related to the assumptions of the CLT were studied and alternatives proposed over the years to better model the real 3D stress fields inside a laminate [40]. Concerning computational cost, a significant breakthrough has been made using the Proper Generalized Decomposition (PGD) method. Depending on the material structure, it allows for a full 3D simulation at the cost of 2D simulation [41]. The simulation of textiles is dominated by the reutilization of approaches initially introduced for laminates. A bidirectional woven textile is commonly modelled by a superposition of two unidirectional plies, representing the warp and the weft direction, respectively. This deficit in specialized modelling techniques becomes even more dramatic when it comes to 3D textiles with advanced mesoscopic material structures.

Due to the large discrepancy in the length scale between local micro- and mesoscopic material structure and the actual composite part, the direct modelling of fibres and tows is not feasible in a composite part simulation. Software tools like WISETEX [42] and TEXGEN propose to generate geometrical models of the local material structure in order to perform numerical characterization simulations and to determine effective material properties.

Regarding strength, three World Wide Failure Exercises were organized by Hinton, Soden and Kaddour and the results were extensively documented [43, 44, 45]. Here also, the focus has been on unidirectional composites and a lot of works remain to be done for textiles. A specific mesoscopic approach has been investigated [46], but until now there has been no commercial tool that would democratize this kind of simulation (Figure 4.3).

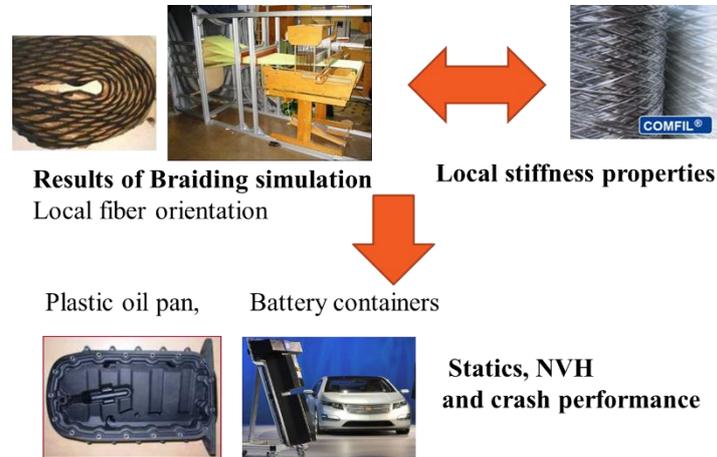


Figure 4.3: Integrated approach using local material structure (courtesy MAPICC 3D FP7 project)

Simulation tools to support the development and use of new textiles are highly needed. One needs to have in mind that material models for the steels and aluminium that were developed in the past (like high Strength Steel for instance) were nearly developed in parallel with the actual alloys.

4.2.2 Progressive damage and failure simulation

The progressive damage failure analysis has made significant progress in the past, mainly by using Continuum Damage Mechanics that gave sound thermodynamic foundations to the modelling of composite damage. In France, the initial works by Ladevèze [47] were quite successful and this model appears today as a standard for a proper damage simulation (Figure 4.4).

When simulating composite damage, or any material exhibiting strain softening, one can observe a strong mesh dependency. Back in 1983, Bazant proposed some techniques [48] that have recently regained some interest [49] and which are now implemented in commercial codes. These approaches are often used in conjunction with delay-effect techniques [50].

Example :UD Ladeveze global ply model

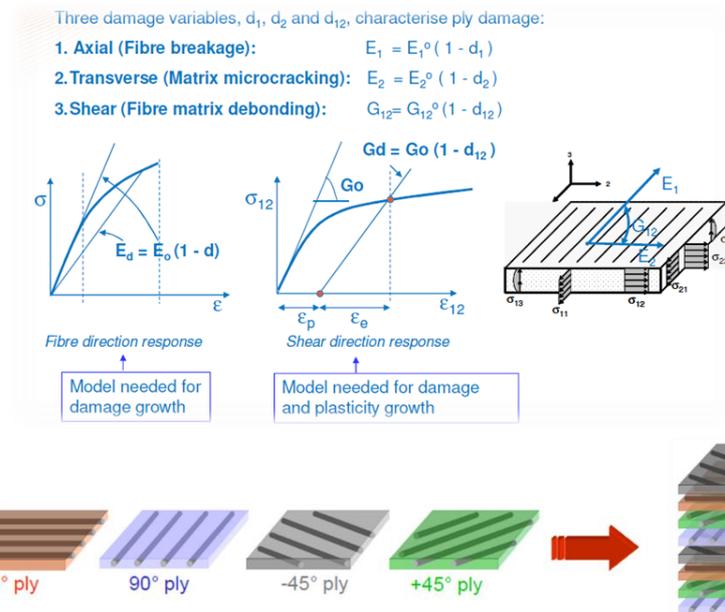


Figure 4.4: Ladeveze progressive intraply damage model and numerical assembly of a multilayered stack-up

In spite of these advances, the composite crushing simulation is still involving material calibration related to the part and loads under consideration. And, to be useful, the calibration must be used in the frame of a building block approach [51]. This is not surprising, when one has in mind the role of the debris in such an event: it is difficult to predict in a deterministic way the creation of all the debris, not talking about the friction force effects resulting from these debris.

A special discussion has to be conducted on delamination modelling. Delamination is very common, for example in the case of an automobiles side crash and for aeronautic brackets. Today, simulation techniques based on failure mechanics approaches are well established in commercial software. Some softwares [52] even propose to distinguish between the initiation and the propagation of the delamination cracks. The delamination (in mode I or mode II) is initiated when the traction reaches a critical value. The subsequent crack opening is defined by G_{IC} and G_{IIC} respectively the strain energy release rate in normal and shear direction [53] (Figure 4.5).

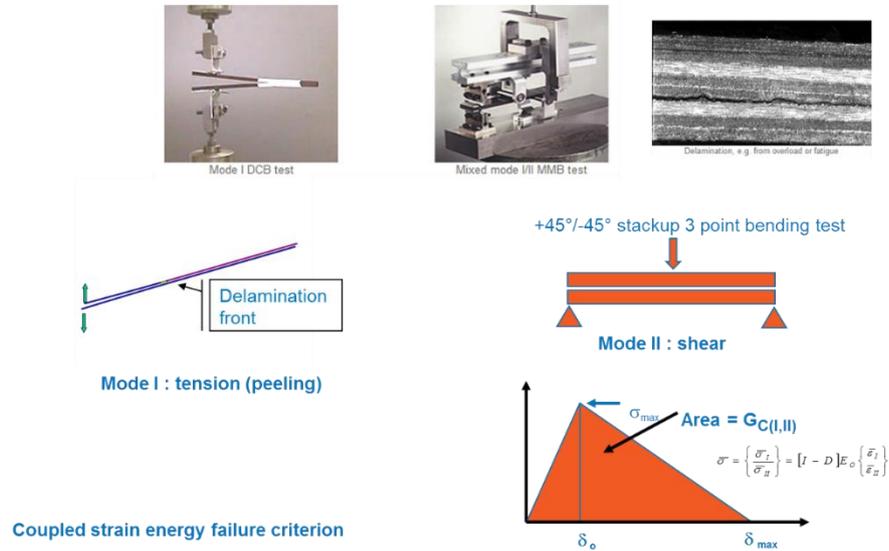


Figure 4.5: Illustration of calibration tests for delamination models in mode I (tension) and mode II (shear)

The coupling between intra-ply and inter-ply was studied in the recent years [54]. Although some specific phenomena and dependencies were demonstrated, it seems that this thematic will remain an academic topic of research for some time.

4.2.3 Fatigue and ageing simulation

Today, the ageing simulation is limited to the investigation of 1D models. In this frame, the effects of the existing state of stress, of the curing degree, and of the temperature are under investigation [55]. Soon, studies about the interactions between moisture and damage tolerance will certainly be conducted. A possible strong motivation will be related to the increasing use of thermoplastic composites in the automotive industry for which the moisture is critical. With this in mind an evolution of the analysis from 1D model to a fully coupled 3D simulation is eligible.

The status of fatigue for composites is somewhat surprising. Generally, composites are much less sensitive to fatigue than metals. But composites and metals have different fatigue behaviour: in composites fatigue damage starts to grow at the beginning of the service life, whereas for metals sudden fatigue failure occurs after a certain amount of cycles. And because of the differences on the noise and vibration behaviour, it is critical to track the growth of fatigue damages.

Two large modelling classes are proposed: the first class is based on simple extensions of methods developed for metallic materials, and the second class of methods introducing a fatigue kinetics that is plugged in a continuum damage model [56,

57]. However, a clear statement about the usability of the different methods cannot be given yet.

4.3 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 4.6). 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.

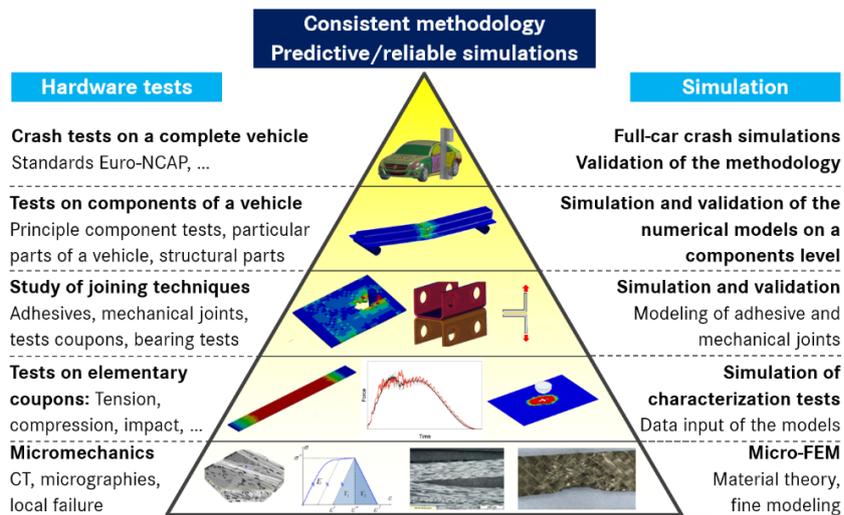


Figure 4.6: Consistent methodology for crash simulation [58]

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.

4.3.1 Coupled simulation

Under the title 'Coupled Simulation', one aims at covering the mechanical performance simulations accounting for the manufacturing effects (Figure 4.7). 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.

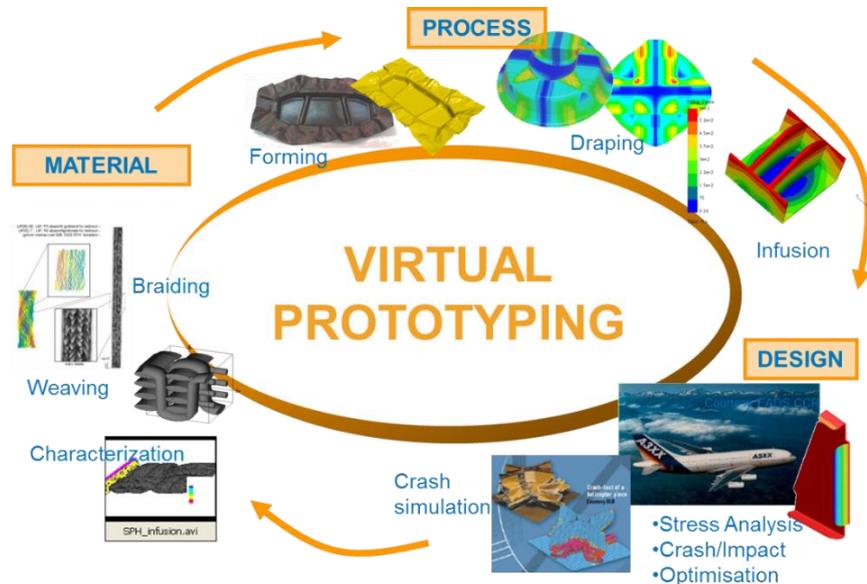


Figure 4.7: Composite end-to-end virtual prototyping chain: performance prediction accounting for manufacturing history

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 [59], a robot laying the dry fibres or prepreg tapes [60] or even from measurements coming from a digital image analysis [61]. 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 (see next section of this chapter) paving the way to fibre orientation dependent failure criteria.

The status in the field of damage modelling is even less advanced. In paper [62], 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.

4.3.2 Virtual material characterization

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 E_1 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 [63].

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 TEXTGEN [64] or WISETEX [43] or from simulation including the draping operations [65]. Beyond the determination of the permeability, this technique was used to study the effects of preform variability [66].

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.

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5 Towards direct processing

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Introduction

Advanced polymer composites have proven weight/performance superiority over metals in many structural applications. However, high material and manufacturing costs have limited applications to military, aerospace, sport & leisure, advanced automotive vehicles and new generation of commercial passenger aircrafts. Polymer composites are more expensive than metals, but, if processed efficiently, they can become competitive parts at a similar cost, even at a lower cost in the near future. Currently the costs associated with the production of structural composites have still not been lowered to the level where the overall cost of composite parts is lower than that of metallic parts.

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.

5.1 State of the art

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 (Figure 5.1). 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[1].



Figure 5.1: Example of blade manufactured using carbon/epoxy prepregs consolidated in autoclave

5.1.1 Direct on-step processing versus multi-step processing

During the past 30 years intensive research and industrial efforts have been spent to develop alternative manufacturing methods to prepreg consolidation in autoclave [2]. 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 thermoplastic 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.

For instance, the starting material for many composites is a prepreg i.e., a fibre tape or fabric pre-impregnated with resin and partially cured. Prepregs are then consolidated and finally cured in autoclave. By contrast, in pultrusion the steps of impregnation, forming and curing (or thermal processing) are overlapping and taking place in one continuous process. As a consequence, the development of the consolidation in autoclave technology can be addressed as successive weakly coupled steps, in contrast to the pultrusion process where the strong coupling between all mechanisms introduces additional difficulties.

In principle, for the highest quality, experience gained in the aeronautical industry has shown that the whole process should be broken down into small steps and each step done at a different time. However, to lower manufacturing cost, many steps have to be combined so that the process can be done at one time (one-shot process or direct processing) or within a lesser number of steps. As a consequence,

one-shot or direct processes are more challenging to develop due to the simultaneity of inter-dependent phenomena. It is clear that for direct processing technologies it is essential to develop a scientific basis for understanding how inter-dependent process variables will affect the final properties and performances of composite parts. Modelling and simulation tools for processes can speed up the development cycle for new manufacturing processes and innovative designs in that context.

5.1.2 Examples of current developments

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

5.1.2.1 Materials

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 [3].
- Thermoset or thermoplastic film stacking. Films of polymer are alternated with layers of reinforcing fabric [4].
- Extrusion coating of fibre tows and weaving [1].
- Deposition of a polymeric powder or layer on fabrics (Figure. 5.2) [1].
- 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 [5].



Figure 5.2: Thermoplastic powdered twill-weave fabric (Chomarat Composites)

5.1.2.2 Processes

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 5.3 displays an example part containing thermoformed blanks which have been over moulded [6].



Figure 5.3: 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 5.4 illustrates over-moulding of long-fibre thermoplastic (in black) around a continuous-fibre pultruded beam (in white).



Figure 5.4: 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 [7]. 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 (Figure 5.5).

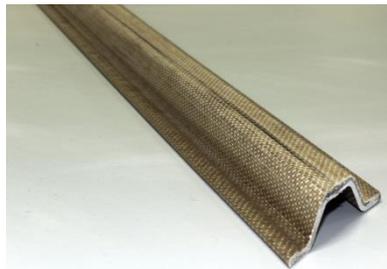


Figure 5.5: Omega-shaped profile produced with low viscosity thermoplastic injection/pultrusion (Solvay, Centrale Nantes, CETIM, AMGP)

5.2 Vision of the future

5.2.1 Technologies 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 [8].
- Hybridisation of processes
 - Pultrusion + filament winding [9]
 - Pultrusion + thermoforming + over-moulding [10]
 - Commingling + micro-braiding + pultrusion [11-12]
 - Over-moulding of an insert made from
 - Compression of powdered fabrics
 - Compression of Glass Mat Thermoplastics (GMT)
 - Thermoforming of Thermoplastics TP prepregs
 - Pultrusion + Thermoforming

5.2.2 Challenges and guidelines for research projects

Several challenges arose when direct processing is of concern. Since around half of the cost of composite products is due to material costs, product cost reduction requires using as cheap as possible available materials. Also, an acceptable composite quality will require good process cost and robustness. The expected challenges can be split into three categories:

- Process
 - Increasing productivity (overlapping of manufacturing steps)
 - On-line control to increase robustness
 - Real-time supervision/control
 - Machine learning
 - Multi-material assembly
- Materials
 - New generation of cost-effective semi products
 - Process speed-up and consequences on raw materials
 - Sustainability and wastes
- Design/Performance
 - Part optimization, think composites, not black metal
 - Integrate manufacturing design within mechanical design
 - Reversed engineering to decrease development time and trial/error procedures

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6 Joining techniques

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Introduction

Driven by the steadily increasing demand for energy efficient processes, the industry has to develop new materials. In the past couple of years the material producing industry developed high performing materials for all kind of applications. Manufacturers are facing the challenge to assemble these materials with methods adjusted to their properties.

In certain industry sectors such as civil aircraft, weight saving is crucial for energy efficiency. Most applications in these sectors are based on multi-material as well as multiple part solutions. In order to develop their full weight-saving potential, high performance light-weight materials need to be joined effectively.

Composite materials have anisotropic properties due to the matrix and fibre material arrangement. While assuring the same mechanical properties, composite technologies can significantly lower the weight of a structure. To achieve this goal, composite materials inherent properties such as fibre-fair design have to be considered for the joining process.

Multiple proven assembly techniques are available such as material locking, adhesive bonding and mechanical fastening solutions. The scope of this joining technologies review is to present these techniques, to evaluate their potential concerning the joining of composite materials as well as to set up a road map.

6.1 General bond requirements and assessment criteria

Some applications require specific features concerning the environmental conditions of the assembly (corrosion resistant, heat resistant, etc.). Moreover, the choice of joint has a significant impact on the assembling process regarding the degree of automation and production rates. Joints need to fulfil different tasks such as to ensure a strong connection of at least two or more parts, the bonding of dissimilar

materials, structural efficiency as well as optimally disassembly. Further requirements are the load transportation, the fulfilment of strain requirements, the possibility of inspection and most importantly the prevention of adding additional weight, space or costs. Multiple joining related assessment criteria are used to ensure the comparability of the presented techniques (Figure 6.1).



Figure 6.1: Characterization of joint properties by mechanical testing

6.2 Material Locking

Material locking joint is one of the most important and suitable joining technologies for composites and presents several different advantages. They are classified into welding, which is a thermal joining of the matrix materials from the parts without adding unlike material and adhesive bonding. The joint area is thereby heated up over melting temperature of thermoplastic matrix and pressure is applied for a defined period of time. The matrix materials diffuse into each other during welding and bond strength develops. For heating various techniques exist: friction, ultrasonic, conduction, induction, laser, spinning and resistive implants. On contrary, adhesive bonding is joining by applying an additional material in the joining area [1].

Generally adhesive bonding of thermoplastic composites is challenging due to material properties. The strength of an adhesive bonded joint is mainly defined by its geometry (area), flow of force (optimum is shear force only) and further criteria such as void content. The maximum force is limited by the material in the joint. Hereinafter, different welding techniques and adhesive bonding are presented [2].

6.2.1 Friction welding

In linear vibration welding, two parts are brought into contact under pressure. One part is fixed and the other vibrates parallel to the joint surface to generate heat and melt the polymers. Finally parts are held under pressure until the molten polymer consolidates. Spin or rotation welding is a modification of friction welding. It enables joining a circular part by spinning and pressing it simultaneously on the joining area.

Potentials and Barriers

It is possible to weld multiple parts simultaneously and thereby realize high production rates with friction welding. The process is easy to control and insensitive to surface preparation. It can be applied to all sorts of thermoplastics and can be automated. It is best suited for small-to-medium sized parts and enables high-volume production. However, it is not suited for non-planar joints and causes fibre distortion/ displacement in the joint area thus lowering mechanical properties. The machinery is costly when multiple frequencies, pressures, amplitudes and easiness of control are required [3].

6.2.2 Ultrasonic welding

The ultrasonic welding process uses high frequencies in combination with pressure to induce molecular motion, thus creating intermolecular friction which leads to heat formation. Energy directors have to be pre-moulded on the components to concentrate the frictional energy (Figure 6.2).



Figure 6.2: Ultrasonic welding of fibre reinforced thermoplastics

Potentials and Barriers

Ultrasonic welding is basically suitable for high-volume production and continuous welding of large parts. It is a clean process with a low amount of welding bead and better suited for joining semi-crystalline and amorphous polymers than crystal-

line polymers. It is one of the most common welding processes in the plastic industry. A major drawback is the necessity of energy directors, with polymer structures, on the joint area.

These structures significantly influence the joint strength. Therefore, extensive knowledge on energy director design is crucial for high weld properties. In addition, fibre content in composite parts influences the welding. However, once successfully developed, automation is possible and the process can be scaled up. For higher speeds and bigger joint areas, the equipment needs to be adjusted, as higher power is necessary. The ultrasonic welding technology is suitable for high-volume production [4].

6.2.3 Induction welding

The components to be joined are submitted to an alternating electromagnetic field. Under presence of electrically conducting loops on the joint, heat is induced and melts the polymer. When cooled down, both parts are bonded together.

Potentials and Barriers

Induction welding is a clean process as it enables a focused heat introduction in the joint region. Additionally it is fast with sufficient bonding properties and has the potential to weld a broad range of geometries and materials. The choice of induction elements directly affects the production rate.

However, electrically conducting elements in the joint are necessary, such as carbon or metallic fibres. These elements can lower mechanical properties of the joint because they can act as stress concentrators. Furthermore, uniform heat distribution is hard to achieve [5].

6.2.4 Hot Tool welding

In hot-tool welding, the components are pressed against a hot plate for melting polymeric material and subsequently parts are pressed against each other.

Potentials and Barriers

The main process parameter is the welding thickness and penetration. The strength and ductility of the joint depends on the welding penetration. Fibre reinforced components with short welding penetration exhibit higher strength and ductility at the joint than high welding penetration, because the fibres remain mainly in the load direction. Welding process time strongly depends on the part geometry. The main advantage of hot tool welding is the possibility of welding complex geometries within one step.

It is a relatively simple to use technology and enables good results for low melting polymers. On contrary, the molten polymer tends to stick to the hot plate. Therefore, tools require special surface treatment and implies cleaning operations. For high temperature welding, the technology is limited as the surface treatment lifetime depends mainly on temperature. Besides, the part size is restricted as the entire joint is realized in one step [6].

6.3 Adhesive Bonding

Adhesive bonding is a widely used industrial joining process in which an adhesive is used to join at least two components. Multiple adhesive types exist and can be divided into three categories: two-components mix adhesives, two-component no mix adhesives and one component adhesives.

Two-component mix adhesives require pre-mixing before application. When both components are brought together, there is a limited pot life (crosslinking process). In general, epoxies and polyurethanes fall into this class.

Two-component no-mix adhesives do not require pre-mixing before application. The adhesive is applied to one surface and requires an activator which starts the reaction. The activator is applied on the opposite surface. Acrylic and anaerobic adhesives fall into this group.

One component adhesives do not require pre-mixing. In case of one component epoxy adhesives, the mixture is ready to use and needs to be kept cool in order to avoid the reaction start. One component polyurethane adhesives start bonding in contact with atmospheric moisture.

Further adhesive types are cyanoacrylates, hot-melt adhesives and solvent- or water-based adhesives.

Potentials and Barriers

The usage of adhesive bonding has a multitude of advantages. Stress is distributed uniformly over the joint area and thus avoids stress peaks in comparison to mechanical fasteners. Furthermore, this technology enables weight gaining, sealed joint areas and most importantly smooth surface designs. Nevertheless, bonding two components with adhesives has also drawbacks. Before applying the adhesive agent, extensive surface cleaning under strict atmospheric control has to be conducted. Moreover, once both components are joined, it is difficult to inspect and check the quality of the joint. There is no reliable non-destructive quality control method which limit the usage of adhesive bonding techniques. Nonetheless, adhesives require in general cooled storage and feature limited shelf lives once mixed or in contact with the atmosphere which causes non-negligible costs [7].

6.4 Material locking and adhesive bonding trade off

The presented material locking techniques have different properties and are assessed Table 6.1 to ensure comparability.

	Fibre-fair design	Pre- and post-processing Effort	Multi-material usability/ compatibility	Lightweight potential	Structural/ dimensional flexibility
Welding	Friction welding	●	○	○	●
	Ultrasonic welding	○	●	○	●
	Induction welding	○	●	○	●
	Hot tool welding	○	●	○	●
Bonding	Adhesive bonding	○	●	○	●

Match: ● very good ○ poor

Table 6.1: Material locking and adhesive bonding trade off

- Fibre-fair design is essential for composite materials. The mechanical characteristics of parts depend on flawless fibre pathway.
- The pre- and post-processing efforts determine whether a joint area needs to be prepared before the process or whether it requires post treatment. It significantly influences the process cycle times.
- Multi-material usability/ compatibility determine whether the technology is fit for joining different materials.
- The lightweight potential shows the technology's capability to ensure the assembly of multiple parts, without significant weight addition.
- The structural/ dimensional flexibility gives information on the flexibility of the process, for example it indicates if the required tools allow easy access.

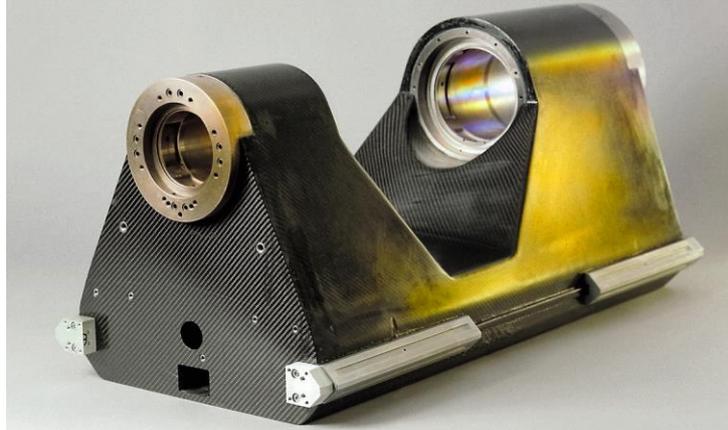


Figure 6.4: Example for multiple bonding technologies (Fraunhofer IPT)

6.5 Mechanical Fastening

The mechanical fastening of workpieces can be realized by multiple ways. In general, the workpiece is either drilled, deformed or put under thermal stress in order to create the bonding. Following technologies are widely used in industrial processes.

6.5.1 Bolts and rivets

For bolts and rivets, an overlap between the joined parts is generally required. Initially a hole needs to be drilled through all parts to insert the bolt or rivet fastener. Moreover, the bolt or rivet is inserted and fixated. Generally a two sided access is necessary for the joining, although blind rivets require only one sided access. Bolts have the particularity to be demountable.

Potentials and Barriers

The mechanical joining of two components using bolts is a repeatable process that allows the assembly and disassembly for repairs and maintenance without damaging the parent materials. Furthermore, little or no surface preparation is required, which is important for applying additional joints in difficult environment within a repair. On contrary, a stress concentration and fibre discontinuity is created around the joints by drilling through the composite and thereby cutting the fibres [8].

Therefore, bolts and rivets are non-fibre fair joining technologies. Regarding application of composite as a lightweight material, bolts and rivets joints are an additional weight to the structure. Therefore, it reduces the weight-saving potential of such composite structures. Besides, metallic joints are exposed to the potential risk of galvanic corrosion. Especially aluminium and steel tend to corrode when exposed to carbon fibres and an additional coating is required. Rivet fasteners feature the same potentials and barriers as bolt fasteners. However, the usage of rivets generally

does not offer the opportunity to disassemble the joined materials without damage [2].

6.5.2 Joining by forming

Joining by forming describes a method to join components by local deformation without additional components. The parts, or at least one part, is plastically formed and creates a form fit.

Potentials and Barriers

Generally, parts joined by forming do not raise the weight of the structure. This technology is therefore interesting for lightweight industry. Furthermore, joining of multi-material systems is easily possible. However, joining of two thermoplastic composites is complex, as a polymer matrix needs to be heated up for plastically forming. In addition, fibre reinforcements are affected as they are either destroyed or displaced in joint area. Besides, a two sided access to the joint is necessary [9].

6.5.3 Loop connection

Loop connections were developed specifically for composites due to fibre fair design. Fibres loop the bolt, which directly transfers the forces to fibres. To reduce internal stresses, the difference of inner to outer diameter should be minimized.

Potentials and Barriers

Loop connections are highly fibre fair and enable the transfer of high forces, even though practical applications are difficult to develop due to the complex design and production process. Furthermore, the technology is limited to tensile loads. To implement loop connections, the whole part needs to be optimized for the specific design. For example, during layup, the loop connection already needs to be considered.

It is only for parts with simple geometry or one dimensional load direction that the application of loop connections is worthwhile. The technology is already used in aerospace with high mechanical requirements and low cost-sensitivity. Bearing-less composite rotors of helicopter have loop connections to minimize parts number, weight and complexity of the assembly unit. Furthermore, thanks to its high pull forces, the technology is used in construction industry, for example in roof structures or bridges [10].

6.5.4 Press fit

The force fit is enabled due to a perpendicular acting force. A movement of the joining parts is avoided as long as the counterforce is not exceeded. For tensile loads on the part the pull force is critical, whereas for torque shafts the torque force needs to be considered. In addition, the force fit is always implemented in combination with the form fit which is the load carrying part.

Potentials and Barriers

For tubular parts, the force fit is a potential joining technology as it can be already integrated in a prior winding process. Combined with an adjusted geometry, the force is transferred by the form fit. High loads can be transferred and it is suitable in particular for the transfer of torque. On contrary, many thermoplastic matrices have a tendency to creep and only limited forces can be thereby transferred.

The press fit can be well adapted for tubular parts. The connection part is thereby used as part of the cone in the winding process. For production of big volumes, an automated winding process, in which the joint is already included is possible. The technology is in use for production of torque shafts. Further applications need to be examined carefully regarding applied forces and used material [11].

6.5.5 In-/ Onserts

In-/ Onserts are used for the assembly of composite or metal structures (Figure 6.5). Such inserts have the purpose of mating fasteners, attachment points or load transfer points. The geometry of such inserts varies broadly. It is possible to implement them during the layup of basic structure, or in a following step.

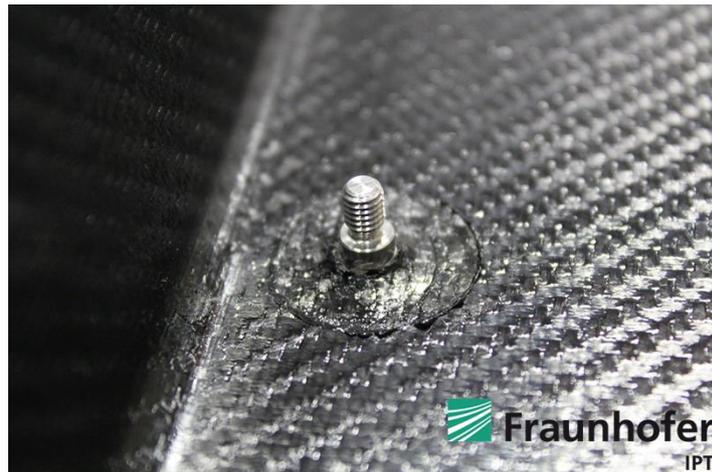


Figure 6.5: Integrated insert in organo sheet by thermoforming

Potentials and Barriers

Insert technology enables a local and fibre fair joining. Connection strength can be significantly higher than for bolted joints. Such a technology further enables multi-material joining. Moreover, joints can be demounted, even though insert remains in composite.

In addition, the processing of the joint is feasible in parallel to primary processing steps, in particular during the stamp forming. On contrary, designing such joints is long and complex and prior simulation would be difficult to instigate. The implementation of inserts in composite part is complicated as a deep knowledge of joint

design and processing parameters are required. However, once successfully developed, the process can be automated including low cycle times. Snap joints are another option to design the part with integrated joining functions. The main advantages of such solutions are the easy access for quality inspection, the absence of added weight by joining the structure and the repeatable possibility to assemble and disassemble the components [12].

6.6 Mechanical fastening trade off

The presented material locking techniques have different properties and are assessed in Table 6.2 to ensure comparability.

	Fibre-fair Design	Pre- and post-processing effort	Multi-material usability/ compatibility	Lightweight potential	Structural/ dimensional flexibility
Bolts/ Rivets	●	●	●	●	●
Forming	●	●	●	●	●
Loop connection	●	●	●	●	●
Press fit	●	●	●	●	●
In-/ Onserts	●	●	●	●	●

Match: ● very good ○ poor

Table 6.2: Mechanical fastening trade off

- Fibre-fair design is essential for composite materials. The mechanical characteristics of part depend on flawless fibre pathway.
- The pre- and post-processing efforts determine whether a joint area needs to be prepared before the process or whether it requires post treatment. It significantly influences the process cycle times.
- Multi-material usability/ compatibility determines whether the technology is fit for joining different materials.
- The lightweight potential shows the technology's capacity to ensure the assembly of multiple parts, without significant weight addition.
- The structural/ dimensional flexibility gives information on the flexibility of the process, for example, it indicates if the required tools allow easy access.

6.7 Future Perspectives

Despite the advancement of the current joining technologies, assembling fibre reinforced plastics still stays a challenging task. However, the ongoing development of the society to a greener future, demands innovative solutions that fulfil higher standards. The future joining technology cannot generate additional weight to a structure. Weight reduction is more than ever in the focus of attention.

Another main characteristic is the ability of the technology to ensure short process times. Especially adhesive bonding techniques depend on thereon. The additional weight using adhesive bonding is negligible, but it requires extensive preparation of the joint surface. Furthermore, inline inspection and disassembly possibilities are also major steps towards safe, reproducible and automatable joining technologies.

Today's innovative materials allow multi-material solutions that are better fitting the chosen application. Each material has characteristic properties that have to be considered when choosing a joining technique. Especially composite materials set new challenges in this matter. The future joining techniques need to be multi-material functional in order to allow complex and lightweight structures.

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7 Structural Health Monitoring

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Introduction

Because of the increasing interest for composite materials in the field of the transport, researches are focusing more and more on techniques capable of following the evolution and the integrity of composite materials from their manufacturing to their putting into service.

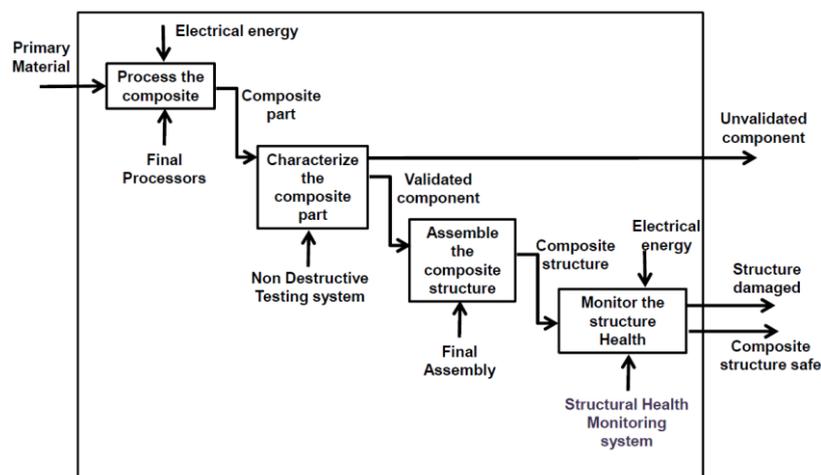


Figure 7.1: Process and use of the composite material

At present, the monitoring of the composite structure is made in two stages (see Figure 7.1). A first stage consists in applying the usual techniques of non-destructive testing to characterize the composite parts once fabricated, for example using the process of Resin Transfer Moulding (RTM). This non-destructive tests are realized in order to validate if the composite parts may be assembled or not on the final structure. Here, the objective is to prevent every defect inherent to the manufacturing step and ensure the reliability and the reproducibility of the composite parts.

Once this stage passed, the focus is on the composite structure's integrity monitoring, throughout all its life cycle. In this case, traditional monitoring techniques can be applied but there is currently a large attention on the development of the so-called Structural Health Monitoring techniques (SHM) which use either embedded or surface mounted transducers to monitor the structure integrity. Clearly questions that arise from now, are to know if it is possible to characterize the composite material during its process, and at the same time and to insure a high safety during its use.

Among the possible solutions, the use of Smart textiles, consisting of electronics combined with textiles, seems to have a very promising realm in science and technology nowadays because of commercial viability and public interests [1-7]. Smart textiles play as well a significant role in the European textile sector and help the textile industry in its transformation into a competitive knowledge driven industry. These kinds of textiles combine knowledge from many disciplines with the specific requirements of textile. Many materials and systems are available as well as devices for sensing and actuation, but they are not compatible with a textile or with the textile production processes. They could be transformed into a textile compatible structure or even in a full textile structure [7].

For textile reinforced composites, one possible solution is to use intelligent textile materials and structures, which provide real possibility for on line and in situ monitoring of structural integrity. Such intelligent materials are made by coating or treating textile yarns, filaments, or fabrics with nanoparticles or conductive and semi conductive polymers, giving them specified performance [8].

Characterization of new textile sensors, preforms and textile-reinforced thermoplastic composites include determination of their electrical, electromechanical, mechanical, thermal and interface phenomena properties, as well as the morphological characteristics of the surface and cross section of textile sensors and textile reinforced thermoplastic composites. In addition, the conductivity of textile sensors depending on temperature and humidity conditions must be investigated as well.

The main goal of this chapter is therefore, to 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. In section 7.1, some definitions will be briefly recalled concerning, on one hand composite types and their failure mechanisms and on the other hand the health monitoring. Section 7.2 will be dedicated to the state of art of health monitoring in composites, whereas section 7.3 is focused on the future, i.e. the wireless health monitoring using smart textiles.

7.1 Definitions

7.1.1 Composite types

Three main types of composites, related to the process used during their production, are given below:

- Thermoset composites realized by the infusion of a resin within the reinforcement structure;
- Thermoplastic composites obtained after the thermo-consolidation (in heated moulds under pressure) of the preform made of comingled or other type of complex yarns composed of thermo-fusible tows or materials and reinforcement tows;
- Stamping technologies could also be used in order to give the desired shape to the composites based on plane fabrics obtained by knitting or weaving.

7.1.2 Failures mechanisms in composites

Several fundamental definitions concerning the failure mechanisms in composites may be found in this section.

a) Damage

Damage can be defined as changes introduced into a system that adversely affects its current or future performance. In this definition implies that the concept of damage is meaningless without a comparison between two different states of the system, one of which representing the initial and often undamaged state. In structural and mechanical systems, the definition of damage will be limited to changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the current or future performance of these systems [8, 9].

b) Defect/ flaw

In terms of length-scales, all damage begins at the material level. Although not necessarily a universally accepted terminology, such damage is referred to as a defect or flaw and is present to some degree in all materials. Under appropriate loading scenarios, the defects or flaws grow and coalesce at various rates to cause component and then system-level damage [8].

c) Failure

As the damage grows, it will reach a point where it affects the system operation to a point that is no longer acceptable to the user. This point is referred to as failure. In terms of time-scales, damage can accumulate incrementally over long periods of time, and is thus associated to fatigue or corrosion damage. On relatively shorter time-scales, damage can also result from scheduled discrete events such as aircraft

landings and from unscheduled discrete events such as enemy fire on a military vehicle or natural phenomena hazards such as earthquakes [8].

7.1.3 Health monitoring definitions

Health monitoring is a concept that requires a comprehensive and quantitative description of performance covering a large spectrum of limit states that may govern throughout the life cycle of a composite material. There are four principle limit states defined as:

- Utility and functionality
- Serviceability and durability
- Safety and stability at failure
- Safety at conditional limit states

Each limit state incorporates a number of limit events, that should be considered in design and evaluation. The proper subjective as well as objective and quantitative indices for limit events determine the attainment of a limit state. Most limit events are governed by defects in design, materials or fabrication, or by various loading events associated with some probabilistic model.

The critical remaining issue related to the definition of performance is the formulation of objective, quantitative criteria for each limit event, and then find appropriate tests, measurements and simulation methods for assurance that the desired performance limits will not be exceeded in the limit events expected during the life cycle of the composite part. The concept of health monitoring promises to provide the data and information for various types of composites to serve for formulating objective performance indices. The importance of unambiguous and quantitative indices for ensuring performance is quite evident; performance limit states and the corresponding limit events serve as critical foundations for performance based design and evaluation [10].

7.1.3.1 Health

Engineers use various indices for defining health depending on purpose. Although it is pragmatic to use deterministic indices that are mainly related to “structural safety” most engineers recognize the need for a broader definition that relates to the definition of performance discussed earlier. After all, the main purpose for evaluation of health is the prognosis of future performance.

It is thus desirable to define the health of a composite part as its system reliability to possess adequate capacity against any probable demands that may be imposed on it in conjunction with the limit states defined previously. It is important to emphasize that system reliability should cover the entire spectrum of limit states and limit events and not just “structural safety” [10].

7.1.3.2 Health monitoring

Health monitoring is the tracking of any aspect of a structure’s health by reliably measured data and analytical simulations in conjunction with heuristic experience so that the current and expected future performance of the composite part, for at

least the most critical limit events, can be described in a pro-active manner. The single most important distinction of health monitoring from a typical in-depth composite part evaluation and testing practice, is the minimum standards that are required for analytical modelling for reliable computer simulations, and how the measurements, loads and tests are designed and implemented in conjunction with the analytical simulations [10].

7.1.3.3 Structural identification

Structural identification is defined as the development of an analytical model of a composite structure that is quantified, tested and validated by correlating simulations model with corresponding measurements from the structure. Structural identification is both the starting point and the core of health monitoring. Applications of the structural identification principle provide the most reliable manner of characterizing a structure for analysis and decision making as it goes through its life cycle. The structural identification principle is what should guide engineers in determining the minimum number of measurements needed to accurately and completely characterize a structure in order to reliably evaluate its health at the serviceability and safety limit states [10].

Structural identification provides the most objective and reliable manner of documenting the global mechanical properties of a structural system and assessing its physical condition, load-rating, vulnerability, maintenance and retrofit needs etc. The “characterization” is also used by the engineers to describe the concept. It offers an understanding of all the critical mechanisms of flexibility, energy dissipation and inertia; the three-dimensional response kinematics; the resistance mechanisms; the critical structure regions; the mechanisms of resistance at the critical regions, the localized force, deformation and accumulated damage states at the critical regions. This information is essential to reliably assess and identify the available capacities of stiffness, strength stability, deformability, hardening and energy dissipation in the structure.

The following steps are essential for the structural identification of a structure:

1. Collecting information, conceptualizing and a-priori modelling to accurately represent the existing knowledge about the structure.
2. Defining a design of experiments based on analytical and preliminary experimental studies.
3. Conduction of full scale modal and controlled load tests to identify, verify and evaluate global and local behaviour. These tests are conducted in conjunction with in-depth visual inspections of the composite structure, local Non Destructive Examination (NDE) techniques, and in many cases material testing to identify and assess the extent of any existing deterioration and damage.
4. Processing and conditioning the resulting experimental data to mitigate any errors and assure experimental data quality.

5. Progressive calibration of analytical models by adjusting mechanical properties and boundary and continuity conditions to reflect the physical parameters measured from the full scale states.
6. Utilization of the calibrated model as a basis for management decisions.

7.1.3.4 Structural Health Monitoring

The process of implementing a damage detection and characterization strategy for engineering structures is referred to as Structural Health Monitoring (SHM). Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The SHM process involves the observation of a system over time, using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features, to determine the current state of system health. For long term SHM, the output of this process is periodically updating the information regarding the ability of the structure to perform, its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure [8].

The classical methods for periodical maintenance use many NDE techniques which require extensive human involvement and expensive procedure. Moreover, this kind of periodical inspection cannot give any information concerning accidents and failures occurring between two successive overhauls. In order to overcome such shortcomings, it is now possible to use 'sensitive' material. A material or a structure is said to be 'sensitive' when it includes sensors providing real time information about the material itself, or its environment. Continuous health monitoring of materials would result in improved durability and safety of structures.

The basic idea is to build a system similar to the human nervous system, with a network of sensors placed in critical areas where structural integrity must be maintained. Mathematical algorithms based on a "neural network" can then be trained to recognize patterns of electrical signals that represent damage, such as fibre strains or breakage and matrix cracks. In broadest terms, therefore, SHM comprises a distributed network of sensors that are deployed as integral parts of a structure and capable of collecting and sending information to an interrogator or electronic monitoring device [11].

Damage identification is carried out in conjunction with five closely related disciplines that include [8]:

- Structural Health Monitoring (SHM)
- Condition Monitoring (CM)
- Non-Destructive Evaluation (NDE)
- Statistical Process Control (SPC)
- Damage Prognosis (DP)

Typically, SHM is associated with online–global damage identification in structural systems such as aircrafts and buildings.

CM is analogous to SHM, but addresses damage identification in rotating and reciprocating machinery, such as those used in manufacturing and power generation.

NDE is usually carried out off-line in a local manner after the localisation of the damage. There are exceptions to this rule, as NDE is also used as a monitoring tool for in situ structures such as pressure vessels and rails. NDE is therefore primarily used for damage characterization and as a severity check when there is a priori knowledge of the damage location.

SPC is process-based rather than structure-based and uses a variety of sensors to monitor changes in a process. Indeed, process changes can be due to structural damage.

Once the damage detected, DP is used to predict the remaining useful life of a system.

7.2 State of the art on traditional monitoring techniques

7.2.1 Local/global approaches, detection mode: on line or off line

Currently, damage detectors require conventional techniques such as strain gauges, acoustic emission sensors, piezo-accelerometers, fibre optics etc. and external power supplies. Two main strategies are possible to monitor the health of composite structures. The first one is the detection of the damaging event continuously, i.e. the detection of the Acoustic Emission (AE) energy that is generally released when the material is bent or cracked due to an external load (pressure, impact, temperature, etc...). This strategy needs permanent on-line monitoring [12-14]. The second strategy consists in detecting the damage itself by periodically checking the structural health. Damage detection is then made by comparing the initial state to the actual one. In this situation, the health monitoring system can be either local or global. For the local inspection, the sensor must be in the damaged region, registering permanent strains due to the damage [15-16] or mechanical impedance variation of the structure. For the global inspection, stimulations are produced in view to induce a structural response, analysed by the sensors. These stimulations can excite the full structure for modal [17] or static analysis [18], or only a small region for the acousto-ultrasonic technique [19-20]. Table 7.1 summarizes all these local and global health monitoring methods.

Characterization Techniques	Sensors	Lo-cal/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 7.1: Local and global health monitoring methods

7.2.2 Inventory of various actuators and sensors

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. Advantages of embedded and in surface SHM sensors is that they will be able to allow the monitoring during the process of the composite as well as during its service life (see Figure 7.2).

Some of the most promising sensors are described in Table 7.2 and detailed below.

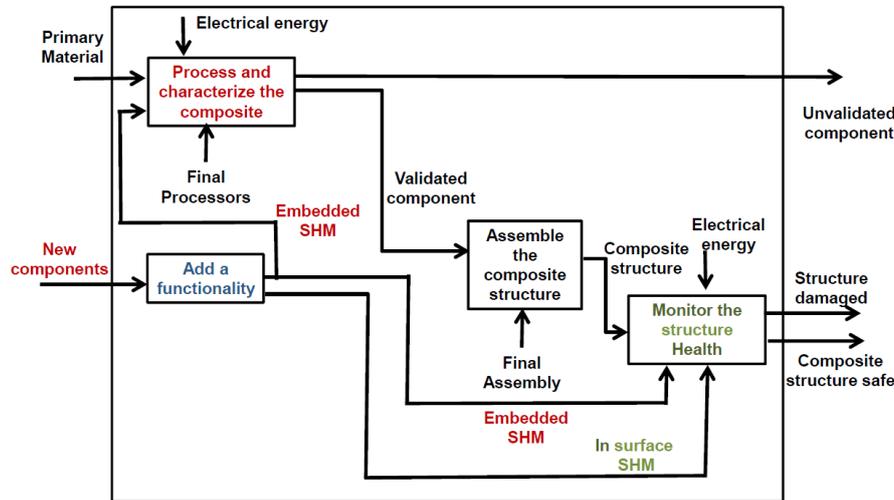


Figure 7.2: Process and use of functionalised composite structure

Optical fibre sensors have attracted a considerable amount of attention in the Structural Health Monitoring (SHM) field, since they are small, lightweight, immune to electromagnetic interference, environmentally stable, and have very little signal loss over extremely long distances. In general, they can be categorized into three classes: interferometric sensors, distributed sensors, and grating-based sensors. Each category has a large variety targeting diverse types of measurements and applications. Previous studies have successfully demonstrated that fibre-optic-based systems are highly sensitive to wide-ranging damage modes in advanced composite materials represented by Carbon Fibre Reinforced Plastic (CFRP) [21-22].

Piezoelectric materials such as lead Zirconate Titanate (PZT), Polyvinylidene Fluoride (PVDF) and aluminium nitride (AlN) can be surface mounted or embedded in structures for sensing and actuation, as they naturally possess the required electromechanical coupling. For example, the paper [23] described the fabrication and initial validation testing of the Stanford-Multi-Actuator-Receiver-Transduction (SMART) Layer-concept. This concept involves the use of printed circuit technology to produce a thin flexible, dielectric film with an array of networked piezoceramic actuators/sensors, which is embedded within a conventional composite laminate. It was shown that the layer does not significantly degrade the mechanical behaviour of the composite, and that by measuring the phase delay between the transmitted and received stress wave during the cure process, the state of cure can be monitored. Subsequent research [24] showed that such layers can be integrated into composite structures fabricated by RTM and filament winding processes, and that the concept can be applied to either active or passive sensing to monitor the health of the structure throughout its lifetime.

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Category	Configuration	Physical parameter measurement
Polymer Optical sensor	Embedded [21-22]	Strain and vibration measurements
Flexible piezoelectric sensors	Surface mounted [23] and Embedded [24]	Vibration measurements (active or passive)
Piezoelectric fibres	Embedded [25-26]	Vibration and acoustic emission measurements
Vacuum Monitoring sensors	Surface mounted [27] and Embedded [28]	Pressure measurement
Carbon nanotubes	Embedded [29]	Strain measurements
Flexible Piezo-resistive fibrous sensors	Embedded [30]	Strain measurements

Table 7.2: Surface mounted and embedded actuators and sensors

Although not as common as piezoelectric wafers or thin films, piezoelectric fibres have also been investigated as possible active components of fibre-reinforced composites. In this purpose, [25] developed tests on fibre sensors laminated into a glass fibre reinforced plate and showed a high sensitivity to impact events whereas [26] discussed the potential of these Active Fibre Composites for SHM in comparison with conventional piezoelectric elements.

Comparative Vacuum Monitoring (CVM) sensor offers also an effective method for in-situ, real time monitoring of crack initiation and/or propagation. Its principle is based on the fact that a small volume maintained at a low vacuum is extremely sensitive to any ingress of air and is thus sensitive to any leakage. Therefore, a crack in the material beneath the sensor allows leakage resulting in detection. This technique can be either surface mounted [27] or embedded [28] between components or within material compounds such as composite fibre in order to detect damage. In the case of embedded CVM sensor devices [28], these sensors are connected with an optical fibre network through transducing mechanisms. The distributed CVM

devices detect damage, and the fibre-optic network gathers the damage signals and transmits the information to a measuring instrument.

SHM also takes advantage of the recent advances in nanotechnology and sensing in order to monitor the behaviour of a structure, assess its performance and identify damage at an early stage. Nanotubes have also been investigated in detail for use as sensing mechanisms, both for smart textile applications and for structural health monitoring of composites. For example, the carbon nanotube thread was integrated into three-dimensional braiding materials and used as a sensor to monitor strain and also to detect damage in the three-dimensional braided composite material [29]. Significant challenges still exist in their development, for example the efficient growth of macroscopic-length carbon nanotubes, controlled growth of nanotubes on desired substrates, durability of nanotube based sensors and actuators, effective dispersion in polymer matrices and their orientation.

7.3 Towards wireless Structural Health Monitoring and in situ monitoring

7.3.1 In situ sensor only

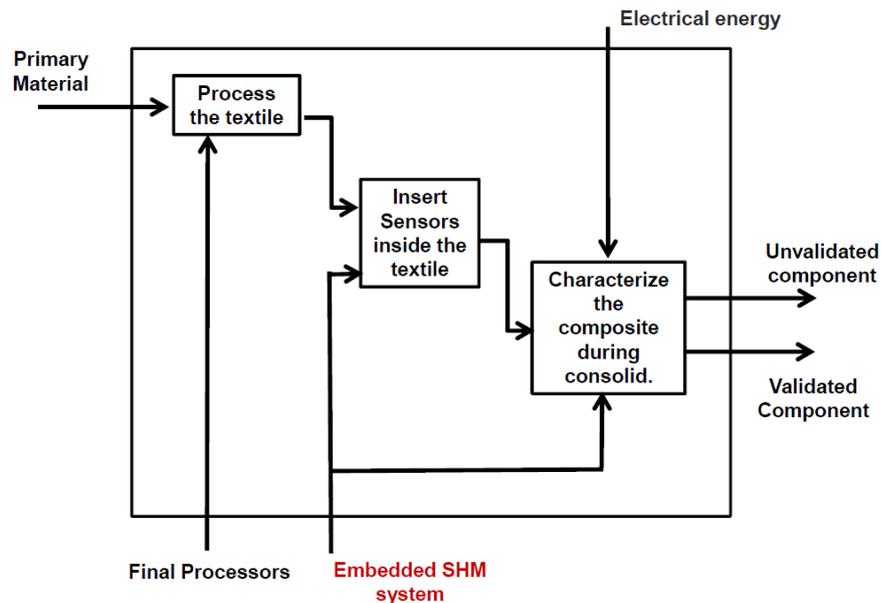


Figure 7.3: Insert sensors inside textile during the composite fabrication

As mentioned in the introduction, 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 (see Figure 7.3).

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 [31].

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. Sensitivity is important as the targeted application usually undergoes very low strains and even such low strains and/or vibrations during the life time of composite parts are critical. Piezoresistive sensors are often used in areas where structural integrity cannot be compromised (aircraft wings, bodies etc).

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. In a woven fabric, warp direction is the same as that of weaving, while weft direction is perpendicular to the warp direction. In this research work fibrous sensors are inserted in the weft direction. The reinforcement is then impregnated with epoxy resin using infusion process to form a stiff composite material.

Several different semi-conductive coating formulations for intelligent textile structures exist. The one chosen here was developed by Cochrane et al. [31]. The fundamental principle of functioning of such intelligent coatings is based on forming (and deforming) of electrical conductive paths (percolation networks) in a coated layer, made of conductive nano-charges. This phenomenon is responsible for electrical resistance variation in the coated layer with change in its length. Thus textile substrates coated with such a piezoresistive layer can be used as a strain gauges in composite materials.

Once the sensors are optimized, they are ready to be inserted in the reinforcement during weaving process. For insertion in conductive fibre based reinforcements like

that woven using carbon multifilament tows, the sensor was coated with Latex Abformmasse supplied by VossChemie® so as to insulate the sensor from surrounding carbon tows (see Figure 7.4).

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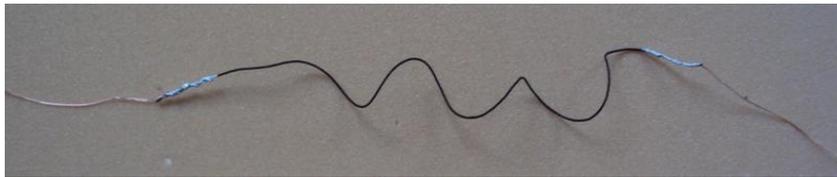


Figure 7.4: Carbon black coated sensor with polyethylene double-ply substrate

Another possible approach in fibrous strain gauge sensors design and production aims at the utilization of semi conductive polymer material such as PEDOT:PSS [32]. The coating thickness and uniform distribution of coating layers are very important factors and have diverse effects on the properties of the textile sensors developed as well as on end-user applications. The textile strain gauges have been integrated to the fabric during the weaving process in order to monitor in situ failures during the life time of composite parts (see Figure 7.5).



Figure 7.5: Textile sensors integration during weaving of 2D fabrics, ARM computer controlled hand weaving loom

The fabrics made of comingled yarns are shown below before the thermos-consolidation process (see Figure 7.6).

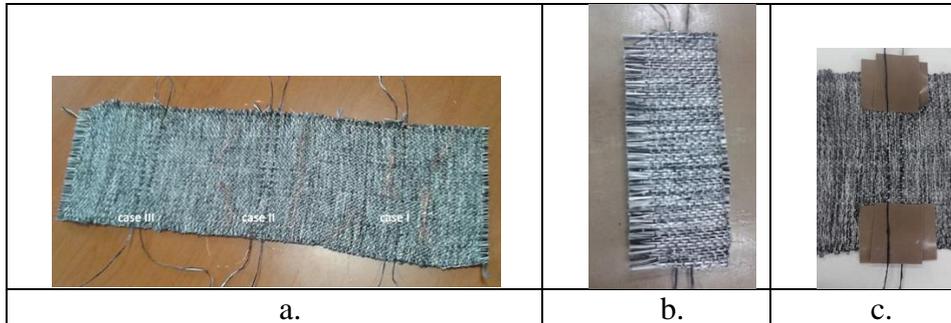


Figure 7.6: Textile sensors integration during weaving of 2D fabrics and its preparation for consolidation step: a) integrated textile sensors in 2D fabric, b and c) 2D fabric preparation for consolidation step

Finally, thermos-consolidated thermoplastic composites with integrated strain gauges based on PEDOT:PSS are shown below (see Figure 7.7).

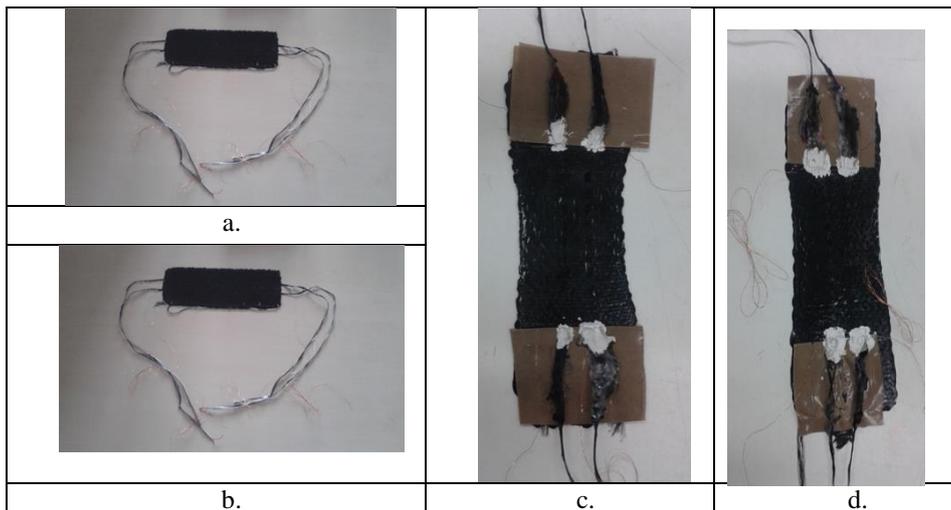


Figure 7.7: Textile reinforced thermoplastic composites with integrated textile sensors: a) 2D fabric consolidated under pressure of 20-30 bar - case I, b) 2D fabric consolidated under pressure of 20-30 bar - case II, c) 2D fabric consolidated under pressure of 20-30 bar - case III, d) 2D fabric consolidated under pressure of 40-50 bar – case III

7.3.2 Sensor network with in situ data acquisition

Strain gauges are a class of sensors which are used in many types of applications. Electrical-type strain gauges convert a displacement into an electrical signal. Their output is usually a change of resistance.

In a resistive strain gauge, the stretching causes a change in geometry so as to increase the resistance of the gauge. Since the gauge material is not incompressible, the resistivity also changes with the change in geometry. The gauge factor for a resistive strain gauge is given as:

$$K = \frac{\left(\frac{dR}{R}\right)}{\left(\frac{dL}{L}\right)} = 1 + 2\nu + \frac{\left(\frac{d\rho}{\rho}\right)}{\left(\frac{dL}{L}\right)} \quad (7.1)$$

Where:

R = Resistance of the gauge (Ohm)

L = Length of the gauge (m)

ν = Poisson's ratio

ρ = Resistivity of the gauge material (Ohm.m)

Gauge factor depends on the material properties and conduction mechanism in the gauge material. For semi-conductive materials much higher gauge factor values are achievable. In the following paragraph, an approach for the development of flexible textile strain gauges is described.

Strain gauge amplifiers can be used to amplify output from a Wheatstone bridge. The data can be then fed to data acquisition module and can be displayed on computer using software interface. This data is now ready to be used and manipulated in any suitable format. Figure 7.8 shows schematic diagram of the data amplification and acquisition set-up used.

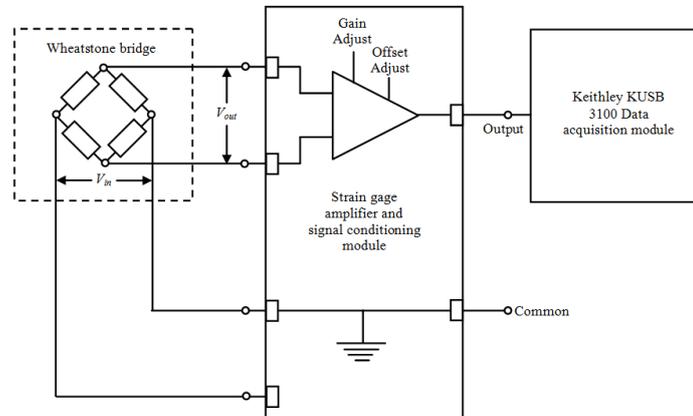


Figure 7.8: Schematic of instrumentation amplifier connected to Wheatstone bridge

The tensile measurements of three layered developed textile reinforced thermoplastic composites were performed according to the test standards DIN EN ISO 527-1 and DIN EN ISO 527-4 on the Instron testing machine (Figure 7.9). The tensile experiments were performed with a speed of 2 mm/min, and 115 mm difference between clamps.



Figure 7.9: Instron composites tensile testing machine

GF/PA sensors show higher elongation at rupture of 7.20% and lower “k” factor (1.3412) than other textile sensors, but number of copper wire turns have to be taken into account. Force at rupture is 260.73 N.

The results of electromechanical tests are shown in the Figure 7.10.

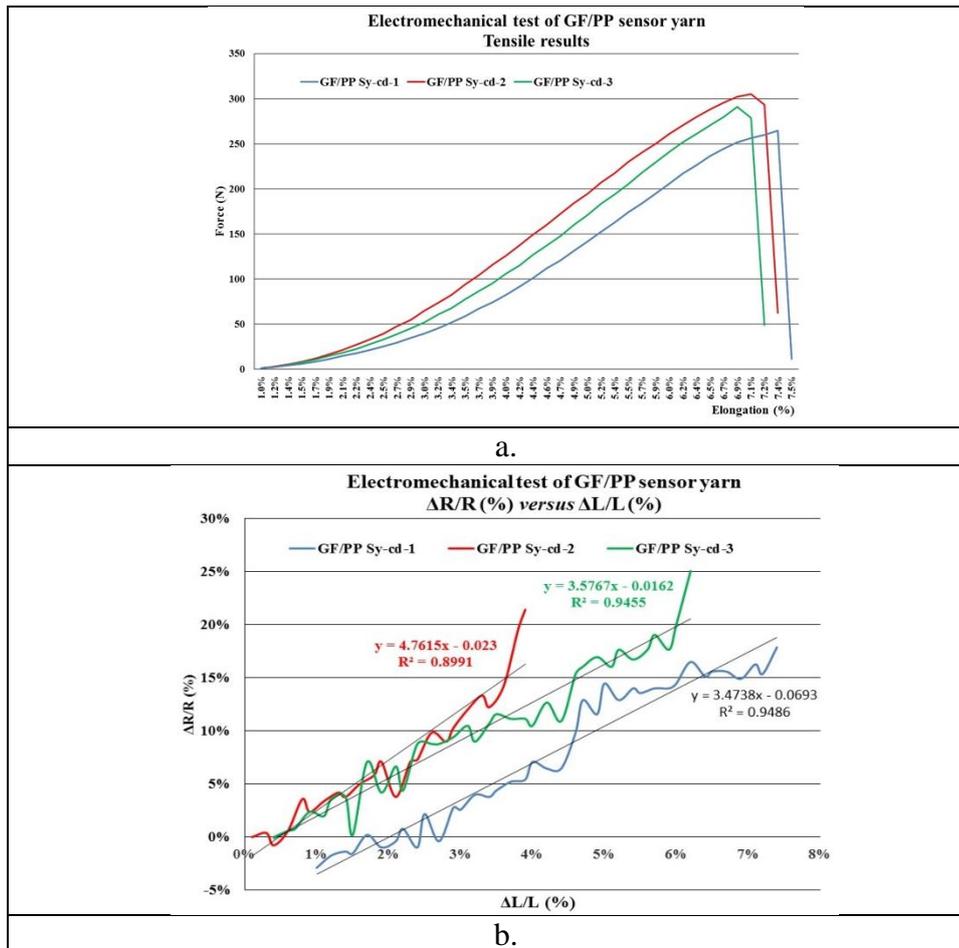


Figure 7.10: Electromechanical tests of GF/PP sensors with conductive drops after copper wires insertion: a) tensile results, b) graph with a $\frac{\Delta R}{R0}$

as y axes and $\frac{\Delta L}{L0}$ as x axes

Work is now in progress to miniature packaged electronics proposed in Figure 7.8, in order to place the data system acquisition in situ with the sensor networks.

This part would allow downloading periodically the data recorded on microprocessors integrated to the textiles on a laptop.

7.3.3 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 7.11).

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.

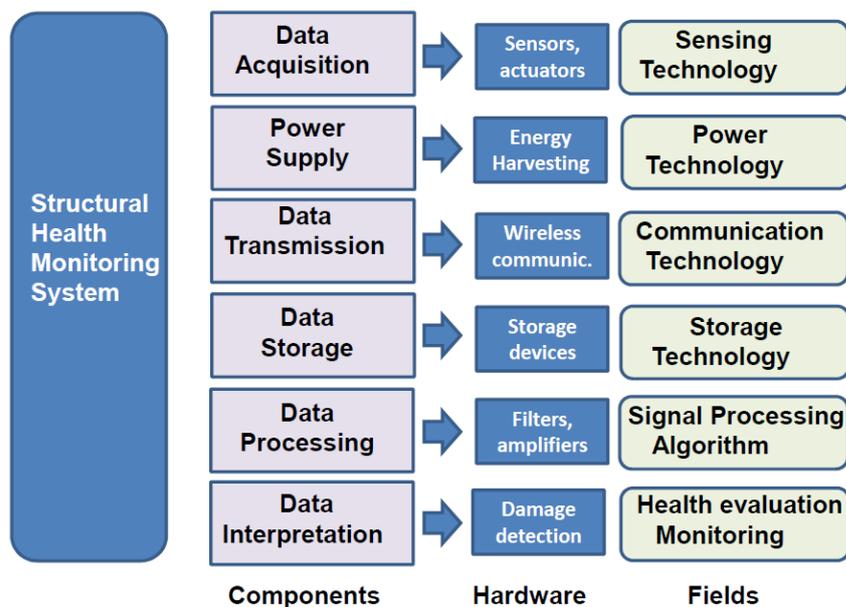


Figure 7.11: Key-issues for sensor network with real time data transmission

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Conclusion

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For Madmax partners, the objective of this book is to share their vision of the future concerning composites technologies in order to set off new research projects. A wide area of composites development is covered by the book within the 7 chapters.

The chapter 1 reviews raw materials used in composites, such as reinforcing fibres and polymer matrix materials in terms of technology and market trend and discuss some perspectives on the scientific research and industrial developments. 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.

The chapter 2 aims at providing key information to enable the reader to determine which textile preforms can meet his need and which manufacturing technologies would allow him to obtain the required preforms. Different association and hybridization of the main manufacturing processes to produce net-shaped 3D preforms close to the final composite materials are also discussed. 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. It also allows adding some specificities, like for assemblies with metallic parts, which are the future of textile preforms.

The chapter 3 deals with characterization methods and introduces some examples of non-conventional test methods for drapability tests, bi-axial tensile test, crash test and Split Hopkinson bar tests. Potential and barriers of these non-conventional test methods are discussed in regards to the limitations shown by standardised characterization methods. Some research axes to improve the testing methods proposed are also suggested.

Scientific approaches for the modelling and simulation of composites manufacturing processes and composites mechanical performances are reviewed in the chapter 4. Particular features of commercial and academic softwares for numerical simulation are outlined and their merits and limits with respect to the current industrial needs are discussed. 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.

The chapter 5 presents the ways toward one direct composite preforms processing. 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 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.

Multiple proven assembly techniques such as material locking, adhesive bonding and mechanical fastening solutions are described in the chapter 6. The potential of these techniques concerning the joining of composite materials is evaluated. Despite the advancement of the joining technologies, assembling fibre reinforced plastics still stays a challenging task. Indeed, in that domains the requirements are high: the future joining technology should not generate additional weight, should be able to ensure short process times and allow inline inspection and disassembly possibilities and need to be multi-material functional in order to allow complex and lightweight structures.

The chapter 7 proposes 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. 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.

With this book, we wanted to establish a vision of 2016 technological breakthrough to facilitate a large scale development of composites materials in aeronautic, automotive, railway and marine transport sectors. A lot of scientific and technological problems are still impeding a wide use of composites in structural parts. Thus, it subsist a lot of challenges to take up regarding composites development, and Madmax partners are proposing their help in that task. Future projects with Madmax partners and other partners to be determined should lead to new collaborations at a European scale.



<http://www.madmaxcluster.org>