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CARBON AND METAL FIBRE REINFORCED AIRFRAME STRUCTURES – A NEW APPROACH TO COMPOSITE MULTIFUNCTIONALITY

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Abstract

On top of major improvements in propulsion technology and in aerodynamics, step changes of the *airframe structure efficiency* are seen as key contributions in order to achieve the ambitious goals of next generation air transport vehicles. Efforts must concentrate on manufacturing cost reduction as well as on breakthrough-solutions for function integration. State of the art composite solutions for airframe structures offer a poor electrical conductivity compared to metal and the mass to structural performance ratio is very negatively impacted by additional elements needed to fulfil all required electrical functions for system integration (i.e. coping with direct and indirect effect of lightning strike, providing sufficient shielding of electric cables by metal raceways or overbraiding, implementing means for electrical bonding and grounding etc.). Integrating the electrical function into the load carrying function of the composite airframe structures would thus reduce additional masses (and cost) needed for electrical system installation. For this purpose, a new multifunctional composite material is investigated, consisting of carbon fibres and high-strength metal fibres of similar diameter embedded in an epoxy matrix. Investigations focus on electrical properties as well as the mechanical properties and the damage tolerance behaviour of the new composite. The objective is to improve the damage tolerance especially for thin structures, as the metal fibres offer large strain for plastic deformation during impact events.

1. INTRODUCTION

Ever since the very first days of manned air vehicle transportation at the beginning of the last century, engineers had to tackle the difficult challenge of providing a very low-mass but high-load carrying airframe structure, which at the same time had to fulfil many additional functions (affordability, manufacturability, reparability, to name just a few). Natural composite materials like wood and linen were soon replaced by metal, mainly for durability and performance reasons. Since the technology became available and affordable during the middle of the last century, many airframe manufacturers have made wide use of artificial composite structures (e.g. glass fibre reinforced plastics, fibre-metal-laminates, carbon fibre reinforced plastics CFRP), pushed by the need for further structural performance improvements, i.e. providing the structural functions needed with even less mass. Today, CFRP is the primary choice for load carrying airframe structures. However, the lightweight potential of CFRP over modern aluminium alloys is still severely limited due to the fact that additional metal elements and masses are needed to provide important electrical functions for e.g. bonding, grounding, lightning strike protection and electromagnetic shielding. In addition, the failure behaviour of CFRP is brittle, limiting its damage tolerance especially in case of impact and the structure integrity of the airframe in crash load cases. The challenge, therefore, is to modify the CFRP in order to provide the additional electrical functionality for system installation purposes and to overcome today's limiting minimum thickness criteria for damage tolerance. The necessary technology development can be seen as a key enabler for decisive improvements of the cost-value relationship of future airframe materials.

1.1. Airframe Weight and Cost

The challenges of society and politics for the next generation of air transportation vehicles are highly ambitious and extremely demanding. Important targets have been defined on behalf of the European Commission by high level expert groups ("Vision 2020" [1], "Flightpath 2050" [2]). Among these are important goals ensuring safety and security, protection of the environment and energy supply in a highly competitive market:

- In relation to the capabilities of typical new aircraft in the year 2000 drastically reduced emission's in 2050:
  - ○ - 65 % perceived noise
  - ○ - 75 % CO_2
  - ○ - 90 % NO_x
- reduced cost of ownership
  with savings passed on to passengers

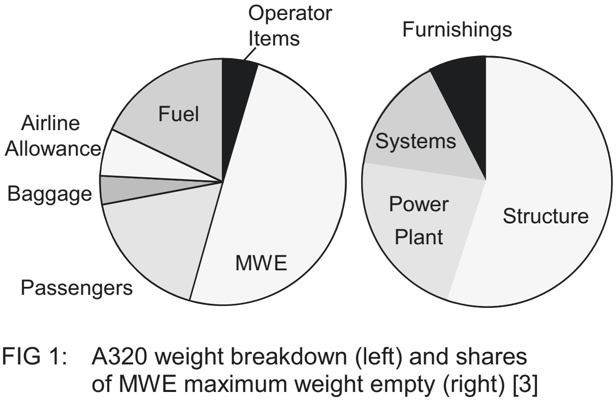


FIG 1: A320 weight breakdown (left) and shares of MWE maximum weight empty (right) [3]

In order to progress from state of the art technology, key improvements are expected from aerodynamics, systems, propulsion and structure. For a typical single aisle aircraft, *structure* is the largest contributor to the maximum take off weight (MTOW) and the maximum weight empty (MWE), followed by power plant and systems, Fig.1. Reducing the mass of the structure has direct impact on fuel burn consumption (and resulting emissions) as well as on maintenance. Fuel burn and maintenance are large contributors to the total operating cost, Fig. 2.

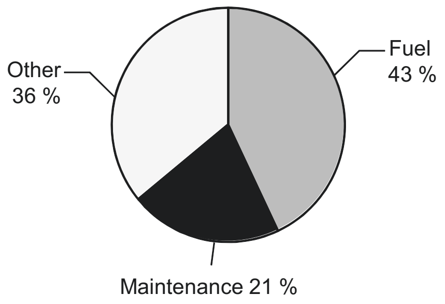


FIG 2: A320 operational cost analysis (IATA 2009, 100 % = US$ 3,852 / FH) [4]

Regarding the relationship of structural airframe mass (including systems) to the transport performance of different civil aircraft over the last decades, it seems at first glance that an asymptotic saturation had soon been reached, with only approximately 25 kg of airframe and system mass needed within modern aircraft for the transportation of one passenger over a distance of 1000 km, Fig. 3. However, it must be stressed that at the same time the functionalities of commercial aircraft have been dramatically increased: where the first transportation aircraft usually only had a radio for the pilot, in-flight entertaining and communication systems for passengers today are considered as state of the art, to give only one example. At the same time, transportation by aircraft has become more and more affordable for the majority of our society.

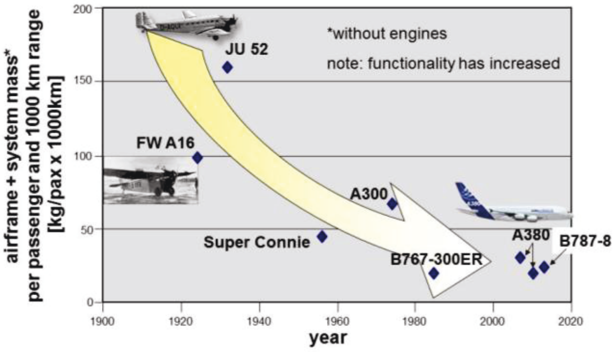


FIG 3: Development of airframe and system mass of commercial aircraft

1.2. Challenges of Modern CFRP Airframe Structures

In order to contribute to further mass reduction of next generation airframes and the subsequent positive snowball effects, R&D efforts must concentrate on affordable design and material improvements. Several advantages of CFRP over aluminium have led to an increasing proportion of this material in latest developments. Among these advantages are:

- high structural performance to mass ratio
- utilization of anisotropy for tailored strength, stiffness and stability design
- excellent fatigue behaviour
- excellent media / corrosion resistance

However, when compared to aluminium alloys such as aluminium magnesium scandium or aluminium lithium and to fibre metal laminates such as Glare®, there are also important disadvantages, limiting today's CFRP lightweight design potential and leading to additional effort and cost in order to ensure compliance with the relevant requirements:

- insufficient electrical conductivity for system installation functions
- poor impact damage tolerance of thin-walled structures
- poor crashworthiness and structure integrity under tension load cases

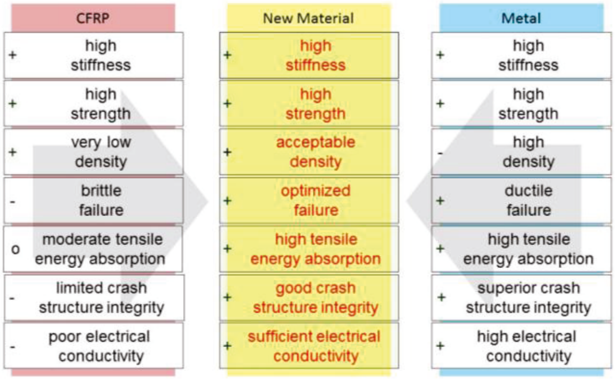
Several attempts have been made to optimize the electrical conductivity of CFRP by modification of the polymer matrix with more or less conductive (nano-) particles. Some examples are discussed in [5]. However, although this method can lead to improvements, it could not be demonstrated so far that a sufficient level of electrical conductivity can be reached which would guarantee an electrical function integration for the modified CFRP similar to that of aluminium or Glare® airframe structures, hence eliminating the need for additional shielding and electrical conduction means as well as their associated weight and cost penalties.

The impact damage tolerance of thin-walled CFRP structures has gradually been improved by the introduction of polymer toughening agents. Thermoplastic polymers and rubber particles were introduced in epoxy matrix systems in different ways for prepregs, enabling substantial improvements of fracture toughness and residual strength properties [6,7]. However, even for CFRP airframe structures fabricated with the latest generation of toughened prepreg systems available on the market today, damage tolerance against probable impact events can be the limiting design driver over other strength and stability requirements, and lead to a minimum wall thickness and subsequent weight penalties far above the comparable values of a competitive metal or Glare® structure [8].

The crashworthy design approach is directly linked to the type of aircraft. Helicopters have very limited crushable airframes. Therefore the key factor for a crashworthy helicopter airframe design is the sizing of the main structural elements to ensure the structural integrity with a survivable cabin volume of 85%. This includes the use of dedicated sub floor crash elements and crash seats to achieve tolerable accelerations on floor level. Investigations on generic structures showed the superiority of composite sandwich designs over monocoque constructions in terms of energy management and composites outperformed aluminium specimens. In house experiences confirm that composite fuselage design allows superior subfloor crash behaviour.

2. CFRP-METAL FIBRE COMPOSITES

Different from research attempts dealing with modified polymer matrix systems, the improvement of important composite properties as well as the integration of electrical functions by means of reinforcing metal fibre incorporation is a promising new approach. The basic idea is to accept a certain increase in CFRP material density, overcompensated by the benefit of eliminating additional electrical system installation items and reduced wall thickness, taking advantage of the ductile failure characteristics, the high tensile energy absorption and the high electrical conductivity of the metal fibres, Fig. 4.



CFRP		New Material		Metal	
+	high stiffness	+	high stiffness	+	high stiffness
+	high strength	+	high strength	+	high strength
+	very low density	+	acceptable density	-	high density
-	brittle failure	+	optimized failure	+	ductile failure
o	moderate tensile energy absorption	+	high tensile energy absorption	+	high tensile energy absorption
-	limited crash structure integrity	+	good crash structure integrity	+	superior crash structure integrity
-	poor electrical conductivity	+	sufficient electrical conductivity	+	high electrical conductivity

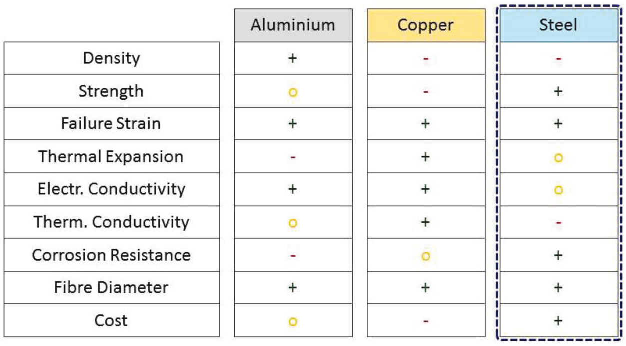
FIG 4: CFRP – metal – fibre - hybrid

Unlike former approaches with fibre-metal-laminates such as Glare®, the semifinished metal material is not integrated as thin sheet or foil material, but as fibre roving material. This is seen as advantageous not only in terms of design freedom (different fibre orientation is possible as well as different ways of commingling etc.) but also in terms of manufacturing efficiency. The idea here is to explore fully automated manufacturing technologies for complex shaped airframe structures with metal and carbon fibre rovings by means of technologies that are already available for CFRP (but not for Glare®), such as automated fibre placement, or weaving processes for non-crimp fabric manufacturing and subsequent infusion processes.

Important selection criteria for adequate metal fibres are:

- cost
- density
- strength
- failure strain
- electrical conductivity
- max. current density
- thermal conductivity
- thermal expansion
- corrosion resistance
- diameter
- surface geometry
- availability

Aluminium, copper and steel fibres are compared in Fig. 5. Steel fibres offer a good compromise between properties and cost. For commercially available stainless steel fibres with a diameter of 10 μm (for comparison: 7 μm for carbon fibres) the electrical resistivity is more than 20 times lower than that of carbon fibres. At the same time, the failure strain is 5 times higher for the steel fibres compared to the carbon fibres.



	Aluminium	Copper	Steel
Density	+	-	-
Strength	o	-	+
Failure Strain	+	+	+
Thermal Expansion	-	+	o
Electr. Conductivity	+	+	o
Therm. Conductivity	o	+	-
Corrosion Resistance	-	o	+
Fibre Diameter	+	+	+
Cost	o	-	+

FIG 5: Comparison of different metal fibre materials

2.1. Preparation of Carbon Fibre – Metal Fibre Hybrid Coupons

In order to investigate the electrical and mechanical potential of carbon - and steel - fibre hybrid material, samples were manufactured by means of the filament winding technology, Fig. 6. Dry roving of steel fibres was mechanically commingled with carbon fibre roving and filament wound on a flat plate. Other specimens were manufactured with separated layers of steel fibre and carbon fibre reinforcement. Laminate layups with different stacking sequences and different fibre volume fractions of steel fibres and carbon fibres were prepared, Tab. 1. In a subsequent step, the filament wound dry textiles were impregnated with a standard epoxy matrix by resin transfer moulding in a closed mould and cured at 180°C for 2 hrs. Specimens were cut from the cured plates and prepared for subsequent testing.

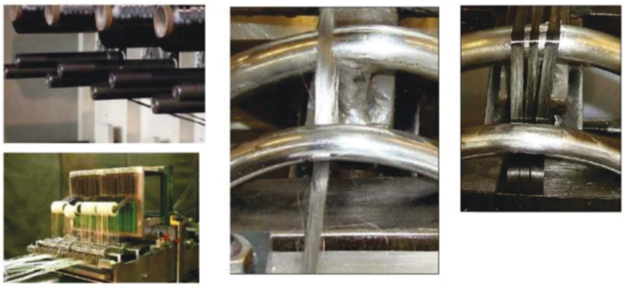


FIG 6: Manufacturing of carbon-fibre – steel-fibre hybrid material by filament winding

TAB 1: Laminate architecture and fibre volume fractions of tested coupons

Laminate	Stacking sequence	Carbon fibre fraction (vol.-%)	Steel fibre fraction (vol.-%)	Resin fraction (vol.-%)
CFRP	$(0^C/90^C/0^C/90^C/0^C/\overline{90^C})_s$ 1)	60	0	40
Hybrid 1	$(0^S/90^S/0^C/90^C/0^C/\overline{90^C})_s$ 1)	38	14	48
Hybrid 2	$(0^S/90^S/0^C/90^C/0^C/90^C/\overline{90^C})_s$ 1)	49	7	44

1) C = carbon fibre reinforced layer, S = steel fibre reinforced layer

2.2. Electrical Conductivity

Electrical conductivity measurements for the laminate in-plane properties have been made with 4-point-measurements on a digital source meter (Keithley 2601A).

Specimens of 2 mm CFRP thickness were sized 80 mm x 25 mm and embedded in an electrically insulating resin.

For all specimens the voltage was measured applying a defined direct electrical current with the electrical contact positioned at both sides of the polished specimen end faces under a defined contact pressure (specimen condition: room temperature, dry).

The specific electrical volume resistivity ρ was calculated by equation (1).

$$(1)\quad \rho[\Omega * m] = \frac{\Delta U * A}{I * L}$$

with

ρ = specific electrical volume resistivity [Ωm]

ΔU = voltage [V]

A = specimen cross section area perpendicular to el. current flow [m^2]

I = applied electrical current [A]

L = length of specimen [m]

The specific volume conductivity σ was determined by equation (2).

$$(2)\quad \sigma[S/m] = \frac{1}{\rho}$$

with

σ = specific volume conductivity [S/m]

ρ = specific electrical volume resistivity [Ωm]

Results from electrical conductivity measurements of multiaxial CFRP (fibre volume content 60 %) and different combinations of carbon fibre, metal fibre and epoxy matrix are shown in Fig. 7.

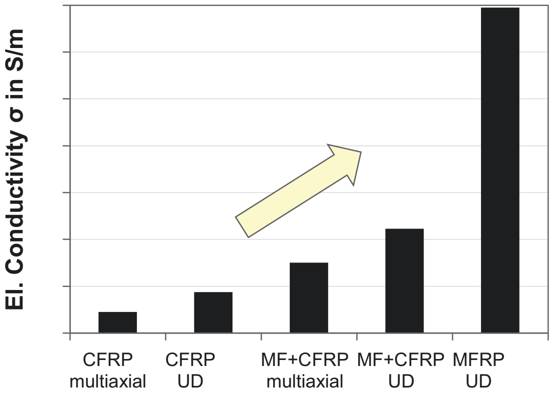


FIG 7: Electrical conductivity of CFRP and carbon-metal-fibre hybrid material, UD = unidirectional, CF = carbon fibre, MF = metal fibre

2.3. Damage Tolerance

Penetration tests were conducted in the style of DIN 66031. Samples were sized 80 mm x 80 mm, circumferentially clamped and impacted. The tup had a diameter of 20 mm. The energy level was set to penetrate the specimen. A typical force displacement plot is shown in Fig. 8.

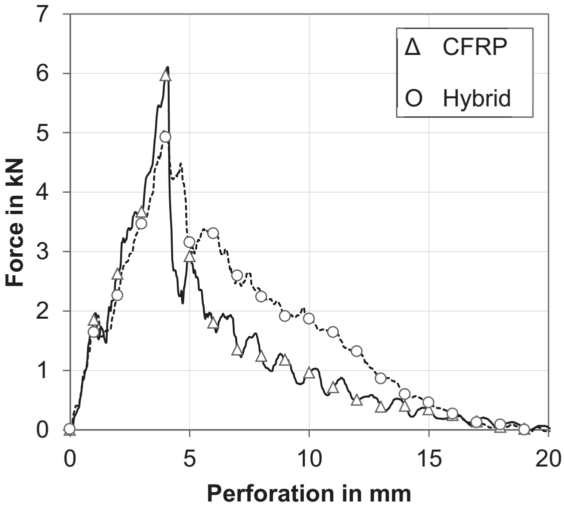


FIG 8: Typical force displacement plot for CFRP and carbon-metal-fibre hybrid material

The area under the force – displacement curve represents the absorbed energy. Compared to the pure CFRP, hybrid material samples with a metal fibre volume content of 7% absorbed approximately 20% more energy.

Bending-tension tests were performed with specimens sized 250 mm x 25 mm. For this purpose, the specimen were clamped at their free edges with a remaining free length of 150 mm and centrically loaded, Fig. 9. Force displacement curves were recorded. A typical result is shown in Fig. 10.

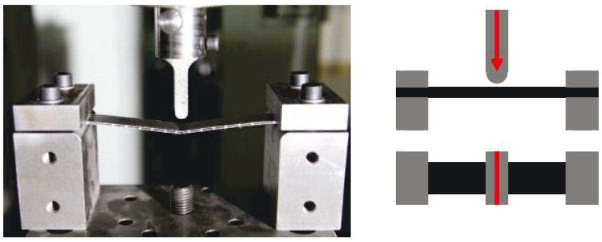


FIG 9: Test set-up for the bending-tension experiments

The hybrid material with a steel fibre content of 7% demonstrates a typical fail safe failure behaviour: After the first failure of the carbon fibres inside the hybrid material the steel fibres remain intact due to their higher failure strain, and the force can be increased again, with its ultimate level even exceeding the values achieved for the pure CFRP.

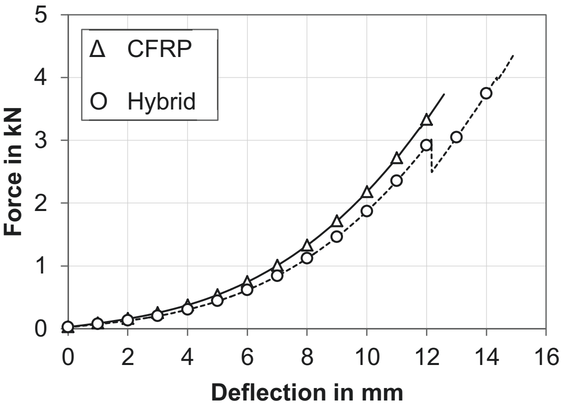


FIG 10: Typical force displacement plot and failure for CFRP and carbon-steel-fibre hybrid material specimen under combined tension-bending load

3. RESULTS

The electrical conductivity of conventional CFRP (fibre volume content 60%) could substantially be improved by the carbon fibre – steel fibre hybrid material. Compared to the pure conventional CFRP the electrical conductivity of a hybrid material consisting of steel fibres (14 vol.-%), carbon fibres (38 vol.-%) and epoxy resin (48 vol.-%) was more than 4 times higher. Assuming theoretical conductivity values of $6.25 \cdot 10^4$ S/m for carbon fibres and $1.25 \cdot 10^6$ S/m for steel fibres, and neglecting the electrical conductivity of the epoxy matrix, the theoretical electric conductivity of this hybrid material can be calculated considering the fibre volume fractions and the corresponding electrical conductivities, leading to a value of $1.98 \cdot 10^5$ S/m. The theoretical value of conventional CFRP with 60 vol.-% carbon fibre content is $3.75 \cdot 10^4$ S/m, again neglecting the conductivity of the epoxy matrix. Following this theoretical approach, the hybrid material should demonstrate an electrical conductivity of more than 5 times the conductivity of pure CFRP. More significant enhancements are feasible with higher steel fibre fractions. However, the measured values were lower than the calculated theoretical values. The steel fibre bundles used for the tests showed some waviness and a twist and, in addition, some deviation from a perfect 0°-alignment, Fig.12. It is therefore possible that during the measurements a portion of the steel fibres that was properly electrically contacted on one side of the test samples did not fully run through the complete sample, reaching the other side, i.e. not 100% of the steel fibres were properly contacted on both interfaces. In addition, the true specific electrical conductivity of steel fibres might be lower than assumed for the calculation. Compared to bulk material properties also sizing effects have to be considered. Further investigations will be necessary to fully understand these effects.

FIG 11: Fracture surfaces of carbon – metal – fibre hybrid specimen with high plastic deformation of steel fibres

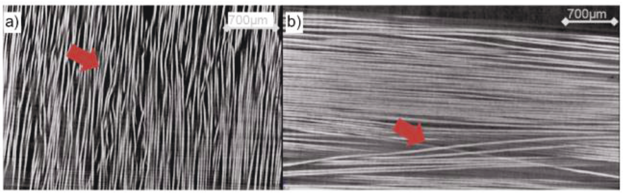


FIG 12: Ondulations (a) and misalignments(b) of steel fibres

The mechanical test results clearly demonstrate the potential of incorporated steel fibres to improve the fracture behaviour of the composite. The high ductility of the steel fibres contributes to enhanced energy absorption during impact and fracture events. A typical fracture surface is shown in Fig. 11. The broken steel fibres demonstrate a high degree of plastic deformation under tensile stress. As shown for combined tension and bending load cases, steel fibres can also increase the ultimate strength capability. However, this potential is limited as long as steel fibres are not free of waviness, ondulations and misalignments, Fig. 12.

4. CONCLUSIONS & OUTLOOK

In order to improve the cost-performance relationship of composites for next generation airframe structures, efforts must concentrate on the improvement of electrical conductivity and damage tolerance. Combinations of fibre reinforced plastics, i.e. fibre metal laminates such as Glare®, provide electrical conductivity and can improve damage tolerance. However, fully automated and efficient manufacturing processes with continuously fibre reinforced plastic and thin metal film material for large airframe structures are very difficult.

In this study, the potential of carbon fibres combined with metal fibres could be demonstrated for improvements of electrical conductivity and damage tolerance. Stainless steel fibres with high strength and high ductility are commercially available in large quantities on the market and offer a good cost-performance relationship.

However, the technology of commingling carbon and steel fibres efficiently to highly sophisticated composite parts for airframe applications is in its infancy, and important tasks remain to be done in future R&D studies:

- Material Development
    - optimization of electrical in-plane and out-of-plane conductivity
    - optimization of steel fibre straightness
    - understanding and optimization of steel fibre-matrix interaction
    - investigation of fatigue properties
- Manufacturing Development
    - development of highly efficient manufacturing technologies for optimized commingling
    - development of optimized weaving technologies
    - development of fibre placement with high deposition rates for complex curved structures
    - straight and precise fibre alignment
- Design Principles
    - optimized lay-up for electrical properties
    - optimized lay-up for damage tolerance
    - development of design principles for electrical contacting
    - …

LITERATURE

[1] European Aeronautics: A Vision for 2020; Meeting Society's Needs and Winning Global Leadership; Report of the Group of Personalities, January 2001

[2] European Commission: Flightpath 2050, Europe's Vision for Aviation, Report of the High Level Group on Aviation Research, 2011

[3] Jackson, P.; Munson, K.; Peacock, L.: Jane`s All the World's Aircraft 2011-2012, Jane's Information Group

[4] US DOT Form 41 Airline Operational Cost Analysis, IATA, March 2011

[5] Noll, A.: Effektive Multifunktionalität von monomodal, bimodal und multimodal mit Kohlenstoff-Nanoröhrchen, Graphit und kurzen Kohlenststofffasern gefülltem Polyphenylensulfid, IVW Schriftenreihe, Band 98, Institut für Verbundwerkstoffe GmbH, 2012

[6] Medina Barron, R. M.: Rubber Toughened and Nanoparticle Reinforced Epoxy Composites, IVW Schriftenreihe, Band 84, Institut für Verbundwerkstoffe GmbH, 2009

[7] Garg, C. A.; Mai, Y.-W.: Failure mechanisms in toughened epoxy resins - A Review, Composites Science and Technology, Volume 31, Issue 3, 1988, Pages 179–223

[8] www.maaximus.eu