A FRAMEWORK FOR EFFICIENT DESIGN OF MULTIFUNCTIONAL-CFRP FOR FUTURE AIRCRAFT

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Abstract: *The development of multifunctional carbon fibre reinforced polymer (MF CFRP) with the combined mechanical, electrical, and thermal functionality offers a route to increased light-weighting for aircraft systems. This paper presents a framework for efficient, early-stage identification of viable solutions for MF CFRP applications with a focus on the detail surrounding the capture of appropriate electrical, mechanical, and thermal requirements of the MF CFRP and defines the limitations and thresholds for the MF CFRP design space. By understanding the key drivers behind the boundaries and the limitations of this design space, future research efforts can be directed at identifying solutions to enable the realisation of MF CFRP which has required functional properties.*

Keywords: aircraft electrical power system; multifunctional materials; carbon fibre reinforced polymer; design space

1 Introduction

Metallic structures on aircraft are multifunctional, providing structural functionality alongside electrical functionality: forming the electrical current return path for the onboard electrical power system (EPS), electromagnetic interference (EMI) shielding, and lightning strike protection. However, most structures on state-of-the-art aircraft are made from carbon fibre reinforced polymer (CFRP) due to their superior lighter weight and mechanical strength properties compared to traditional metallic materials. Due to the poor electrical conductivity of CFRP (e.g. in-fibre direction of UD [0^o] CFRP is 30 – 40 kS/m compared to aluminium (35 MS/m) [1], its unadapted structure is not considered to have electrical and structural multifunctionality for electrical power applications. The development of multifunctional CFRP (MF CFRP) with appropriate electrical, structural, and thermal properties offers a route to light-weighting aircraft systems, opening new design spaces and opportunities for the electrification of aircraft. A significant challenge for the development of MF CFRP is the complexity of the design space, and interdependencies between mechanical, electrical and thermal (MET) functionality requirements. There is a need for the development of an efficient design methodology to identify viable design spaces and approaches for materials that meet multifunctional requirements and can be manufactured at scale.

This paper presents a framework (Figure 1) for efficient, early-stage identification of viable candidate approaches for a MF CFRP structural component which also functions as electrically conducting pathways for a more electric aircraft (MEA). The framework is sub-divided into four phases, which step through from the capture of baseline system requirements to the build and test of a hardware prototype. This paper focuses on Phase-1 and Phase-2.

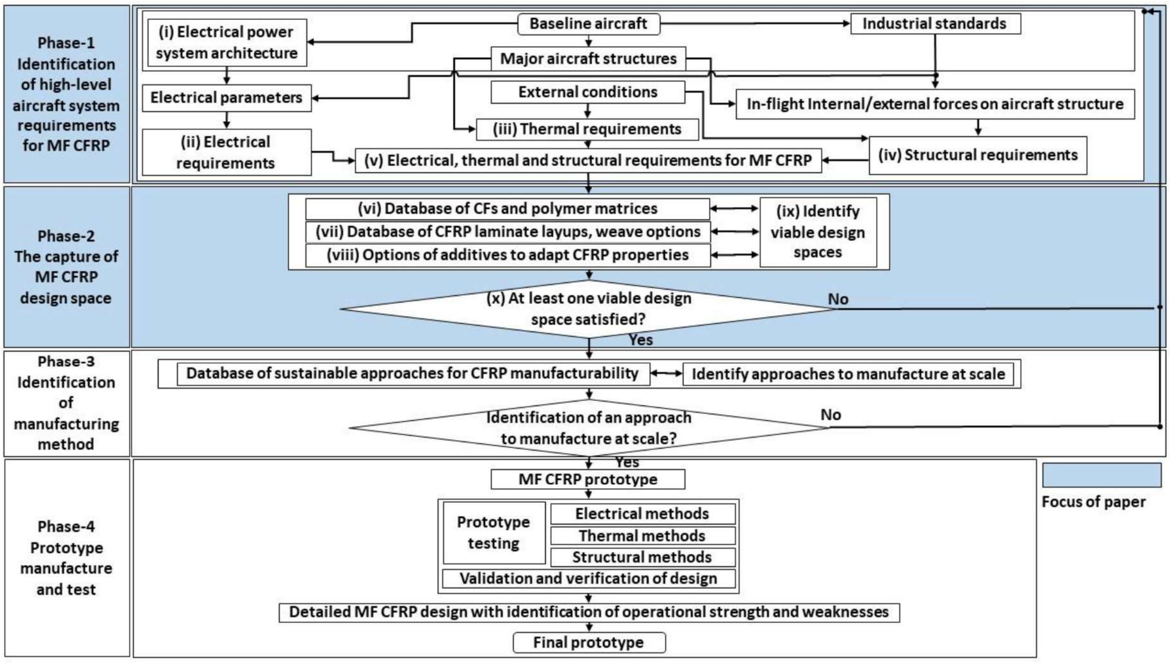

Figure 1. Framework for early-stage identification of viable MF CFRP solutions

2 Identification of high-level aircraft system requirements for MF CFRP

2.1 Aims and objectives of Phase-1

Phase-1 of the framework takes in the baseline electrical and structural requirements associated with a particular aircraft to identify the high-level requirements of the MF CFRP. The processes within Phase-1 from i to v (Figure 1) include consideration of interdependencies between different functionalities and consideration of industrial standards.

2.2 Overview of the state of the art aircraft EPS architecture

An EPS architecture has a significant influence on the electrical and thermal properties required by MF CFRP, and as such is captured in part i (in Phase-1) of the framework in Figure 1. The more-electric aircraft (MEA) concept has been implemented on the current state of the art aircraft, e.g. the Boeing 787. On an MEA, systems which were typically powered by mechanical, hydraulic or pneumatic power are now driven by electrical power. As such, the electrical power rating of an EPS for an MEA is ~1.5 MW. The electrical power is a mixture of alternating current (AC) and direct current (DC), at a range of voltages from 28 V_{dc} up to +/-270 V_{dc} and 230 V_{ph} rms. The majority of electrical power is supplied by gas turbine engine driven generators. Power electronic converters step the power between AC and DC and provide control functionality [2].

2.3 The capture of electrical, thermal and mechanical requirements for MF CFRP

The MF CFRP must have appropriate mechanical, electrical and thermal (MET) properties which are captured in ii - iv in Phase-1 of the framework in Figure 1. These are combined in v of Phase-1 and passed to Phase-2, for the capture of viable design spaces for the MF-CFRP.

2.3.1 Electrical requirements

The electrical requirements of the MF CFRP depend on the function that the MF CFRP is expected to perform. The main considerations are the electrical current, voltage and frequency levels. The focus of the framework is the design of MF CFRP for low frequency (<MHz) electrical current conduction, as part of an EPS. The electrical conductivity of the conducting pathway through the CFRP must be high enough such that, the voltage drop across the conducting path must meet the appropriate industrial standards, and the heat dissipated, due to resistive losses in the conducting pathway (Joule heating), does not cause the glass transition temperature (T_g) of the resin matrix to be reached. Considering a 500mm length of cable within the EPS at $28V_{dc}$ and conducting 10A with a 4% acceptable voltage drop, the required conductivity is ~3 MS/m. For comparison, the conductivity in the in-fibre direction of UD [0°] CF is 30 – 40 kS/m [1].

2.3.2 Thermal requirements

Alongside assuring that T_g of the CFRP is not reached by Joule heating during electrical conduction, the thermal conductivity of the material must also be considered. This determines the material effectiveness for dissipation of heat that has been induced externally or internally. Hence, thermal conductive properties are crucial to maximise understanding of how heat from Joule heating may dissipate through CFRP. Finally, ideally, the coefficients of thermal expansion (CTE) of the different CFRP components are matched as closely as possible. However, differences in CTE between polymer matrices and CF result in thermal stress between the CF and matrix as the CFRP heats up. This leads to the formation of interlamination cracks, and consequently mechanical strength loss and failure of CFRP [3].

2.3.3 Mechanical requirements

The nature of the strength required for the material of aircraft structural elements varies with stress type. For instance, aircraft wings and stabilisers encounter bending stress under which both tensile and compressive stress act on the material due to gravity and the in-flight air pressure difference between the upper and lower surfaces of the wings [4]. The aircraft fuselage section faces compressive stress owing to external and cabin (inner) pressure differences. Therefore, the key mechanical properties which a CFRP component must possess are high tensile, compression, flexural, and shear strengths.

3 The capture of MF CFRP design space

3.1 A High-level overview of Phase-2 of the framework

During Phase-2 of the framework, from databases of CFRP design elements, system design trades are carried out to identify an appropriate design space for the MF CFRP, to meet the requirements identified in Phase-1. It is possible that a viable design space will not be identified, hence iteration of the requirements from Phase-1 is needed (indicated by the arrow growing from part x of Phase-2 back to Phase-1 in Figure 1. The purpose of developing a design space is to delimit the options of the best available elements (fibre, matrix, layups, additives to adapt properties) to utilise them for MF CFRP, in order to identify approaches to comply with the design requirements of properties passed down from Phase-1.

3.2 Database of methods to adapt the MET design space

Parts vi – viii of Phase-2 are databases of methods and materials which can then be combined with the MET requirements from Phase-1 to identify viable design spaces for MF CFRP. The three distinct databases are CFs and polymer matrices (part v), different CFRP layup and weave options (part vii) and finally, options for adapting the CFRP properties using additives (part viii). Each of these three areas is discussed below.

3.3 Comparison of different carbon fibres and polymer matrices

Figure 2 and 3 compare the fibre dependent properties of commercially available carbon fibres (CF): Polyacrylonitrile (PAN) and pitch CF. Aluminium alloys are included for comparison, as CFRP is favoured over the use of aluminium for structures on state-of-the-art-aircraft. Data for the figures were collected from available online product databases of manufacturers [5-9]. Figure 2-3 indicate that the selection of one CF over another results in trade between electrical, thermal, and mechanical functionalities of the carbon fibre. Compared to PAN CF, pitch-based CFs have one order higher electrical conductivity (up to ~2 MS/m), 1-6 times better thermal conductivity, and ~1.5 times higher tensile modulus properties (up to 900Gpa). Pitch-based CF has lower strength (3-4 GPa) than PAN-based CF (3-7 GPa). However, Pitch and PAN fibres have considerably higher tensile strength than aluminium alloys [10].

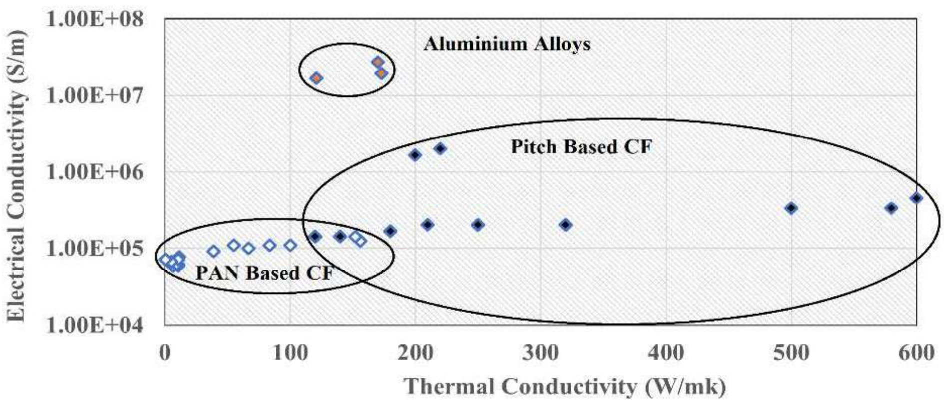

Figure 2. Electrical conductivity vs thermal conductivity of commercially available carbon fibres

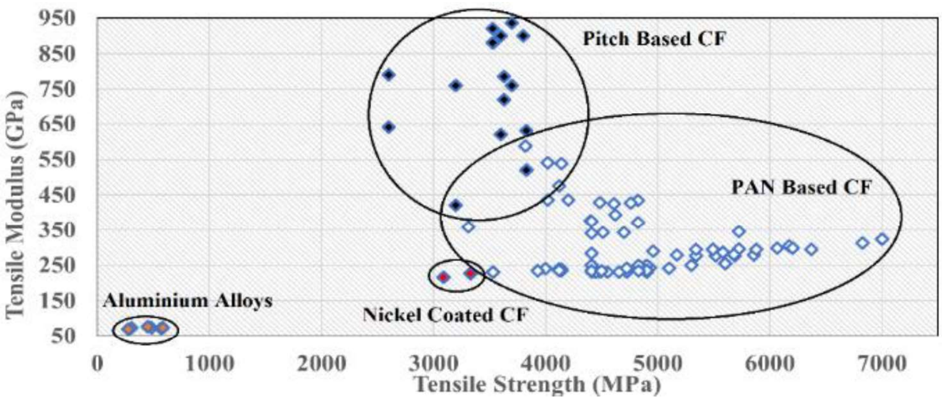

Figure 3. Tensile modulus vs tensile strength of commercially available carbon fibres

A comparison was carried out of matrix-dominant, compressive, flexural and interlaminar shear strength (ILSS) and T_g properties of commercially available CFRP, which have been manufactured using ten different types of thermoplastic and thermosetting based matrix resins. Figure 4 and 5 represent the comparison of compressive, and flexural strength and ILSS. The choices of resins in Figures 4 and 5 are defined in Table 1.

Inspecting the data showed that epoxy, PEEK and BMI based CFRP have superior mechanical and thermal properties with excellent flexural (1.5 – 2.2 GP) and compressive (1 -1.5 GPa) strength. In terms of T_g (which ranged between 90 to 454°C for all matrices compared) and ILSS, epoxy and PEEK resins show inferior characteristics to BMI-CFRP which has T_g in the range of 320°C and ILSS of 100 MPa. For Epoxy, T_g is around 180°C, while PEEK possesses lower T_g (140°C) and lower ILSS (75 MPa). As T_g and ILSS are important matrix attributes for CFRP to perform well in a high-temperature environment, therefore, BMI can be considered as a suitable resin to be used in MF CFRP with good strength appropriate electrical functionality for an MEA EPS.

Table 1: Matrices used in commercially available prepregs are mentioned in Figure 4 and 5.

Prepreg Serial Number 1-50	Matrix Type
1 → 11	epoxy
12	Polyphenylene Sulfide (PPS) (Thermoplastic Resin)
13 → 20	Polyether ether ketone (PEEK) (Thermoplastic Resin)
21	Polyaryle ether ketone (PAEK)(R)
22 → 32	Cyanate ester
33 → 44	Bismaleimide (BMI)
45 → 47	Phenolic
48	Polyimide (PI)
49	Polyethylene terephthalate (PET) (Thermoplastic Resin)
50	Polycarbonate (PC) (Thermoplastic Resin)

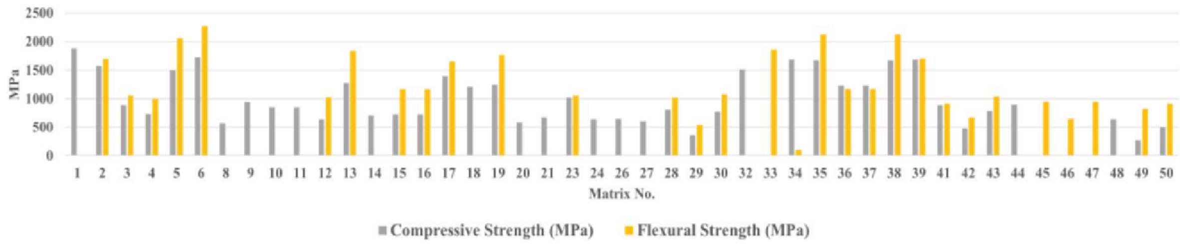

Figure 4. Flexural and compressive strength of available CFRP Prepregs with different matrices

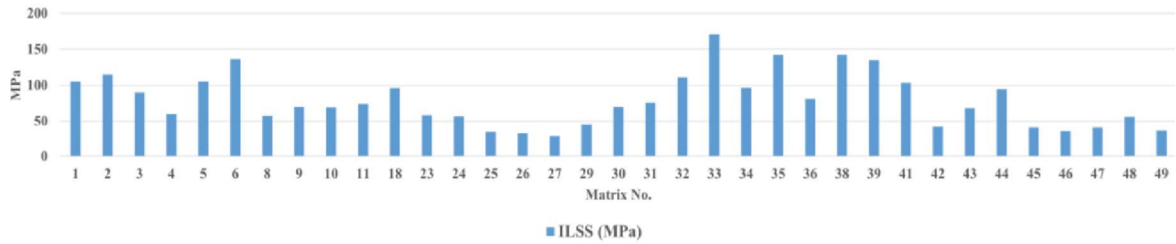

Figure 5. ILSS of commercially available CFRP prepregs with different matrices

3.4 CFRP laminate layups and weave options

The MET properties of a CFRP structure are all sensitive to the layup of the fibres within the structure, which is the focus of the second database in part vii of Phase-2. Table 2 summarizes the mechanical implications of different orientations of carbon fibre plies within a layup mentioned in the literature [11].

Table 2: Selected design considerations for fibre orientation

Design Consideration	Description	Reason
Symmetric orientation	Material symmetric laminate concerning mid-plane.	To eliminate the stretching, shearing, and twisting coupling.
Balance	An equal number of plies of opposing angles	To reduce shear stiffness coupling.
Contiguity	Limited adjacent plies with the same fibre orientation	To prevent crack propagation and ply edge effect
Max. 45° orientation difference between adjacent plies	-	To prevent crack propagation and delamination by reducing ILSS

These design consideration for CF plies layups are based on developing a mechanically robust CFRP. From an electrical perspective, the anisotropic electrical and thermal conductive properties of CFRP are sensitive to layup. For example, along the x-axis, the electrical conductivity of 0 and 90° oriented plies is 22 KS/m and 56.1 S/m respectively [12]. Identification of appropriate design trades between MET properties is required to find a balance between appropriate structural strength and appropriate electrically and thermally conductive CFRP.

3.5 Additives to adapt CFRP properties

The third database of properties in part viii of Phase-2 focuses on methods to adapt the MET properties of CFRP using additives. Different methods have been proposed in the literature to improve the CFRP conductivity in the matrix dominant directions. These methods either modify the fibre surface (e.g., growth of carbon nanotubes (CNT) on fibre to increase conductivity from 0.003 S/m to 0.38 S/m by [13]), modify the matrix by adding conductive additives in it (e.g., enhanced conductivity by adding CNT to a matrix, 10^{-5} (no CNT) to 66.2 S/m (with CNT) [14]) or use the additional layers of conductive elements within CF plies (e.g. silver-plated interleaves increased in-fibre and through-thickness electrical conductivity from 25 kS/m (without interleave) to 50 kS/m (with interleave) and from 12.225 S/m (without interleave) to 500 S/m (with interleave), respectively) [15]).

These methods improve the CFRP conductivity properties but based on the processing technique of incorporating additives in it, these methods can have a detrimental effect on the mechanical properties of CFRP due to decreased interfacial bonding between fibre and matrix because of additive [14]. For example, matrix modification with CNT increases the viscosity of the matrix, causing poor wettability of fibres with resin, hence, leading to poor CFRP compression strength (e.g. from 112 MPa (without CNT) to 65 MPa (with CNT) [13]. Similarly, a decrease in flexural strength (e.g. from 584.5 MPa (without bucky paper) to 378.25 MPa (with bucky paper)) has been reported by the addition of bucky paper between CF plies associated with a decrease in fibre volume fraction due to the additional layers [16].

4 Identification of viable design spaces for MF CFRP

In parts ix and x of Phase-2, the databases inform the determination of the viable design spaces for the MF CFRP and the trades between MET properties. In part ix of Phase-2, the process for mapping out the initial design space and then carrying out appropriate system design trades is needed. From the MET requirements identified from Phase-1, approaches to achieving these requirements can be identified from the databases (parts vi – viii). However, the interdependencies between the different MET requirements and the approaches to reaching these must be considered.

A methodology is needed to assess the options for MF CFRP design to meet the design requirements. One methodology may be to determine methods for each of the MET requirements, which will enable requirements to be met, and from that to assess whether a viable design space is available. For example, if the structural requirements are such that a material with high compressive (matrix dependent) strength is required, then pitch carbon fibres may be an option. Layups with pitch fibres that meet the mechanical properties can then be down-selected. Independently to this, approaches to achieve appropriate electrical and thermal conductivity are identified. If no viable design space is identified for each of the MET requirements individually at this stage, part x in Part-2, then the design requirements must be reassessed, as no collective viable design space can exist.

As part of the feedback loop between Phase-2 and Phase-1, the limitations of the design spaces identified in Phase-2, part ix, are fed back to Phase -1, and inform the redesign (e.g. reconsider an aspect of the EPS design to adapt the electrical requirements) and capture of MF CFRP.

If methods can be identified to meet the MET requirements individually, then an assessment must take place to ascertain if there is a common design space where all requirements are met. If not, then appropriate system trades must take place in areas where design flexibility is identified. For example, it may be possible to use pitch rather than PAN fibres and still meet mechanical requirements. Or it may be possible to change the pathway taken by the electrical current through the CFRP by adapting the method of electrical bonding to the component, which may open up available design space. However, if no viable solution space can be found, then the underlying systems in Phase-1 must be adapted, and the MET requirements adjusted.

5 Conclusion

The efficient design and down-selection of MF-CFRP which meets MET requirements is challenging due to the need for adapting CFRP significantly, attaining appropriate combined MET properties, and the interdependencies between these properties. This paper has presented the early stages of a framework to enable the design of MF-CFRP and provide a logical approach to navigating MF CFRP design and the interdependencies with the wider systems (electrical power, structural and thermal) design. The next steps for this work are to develop in more depth the interdependencies between the electrical, thermal and structural requirements, and identify the key system design thresholds such that, for example, part of an electrical power system on an aircraft is designed such that its cabling can be formed by a structural, CFRP panel.

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