INNOVATIVE AM DESIGN STRATEGIES FOR INTEGRATING CARBON FIBRE COMPOSITES WITH METALLIC STRUCTURES TO SUPPORT LIGHTWEIGHT MANUFACTURING

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Abstract. Currently, aluminium-based mechanical products are optimized for lightweight characteristics using methods such as topology optimisation or generative designing without compromising on the performance. Additive manufacturing has been playing a vital part in the production of such complex designs. Recent inclusion of high-performance carbon fibre composites (CFC) in the list of additively manufacturable materials is certainly an advantage to achieve lighter and stronger products. The properties of CFC resonate along or even surpasses aluminium in terms of strength-to-weight ratio. Conversely, total replacement of aluminium with whole CFC-based designs is not feasible for applications where heat dissipation is critically required. The solution is to combine individual characteristics of aluminium and CFC in designs which is possible via multi-material approach. However, the process of integrating CFC in design models is not straightforward. There are challenges associated with proper placement of metal and CFC in the design models in order to comply with the additive manufacturing processes while also satisfying the performance characteristics of the products. These constraints and limitations should be taken into account during the development of metal-CFC based multi-material designs. This research study highlights and addresses such challenges by practicing certain design strategies with application on real-world use-cases. This is achievable by coupling Computer Aided Design (CAD) development process with; (1) Finite Element Analysis (FEA) which suggests individual placements of metal and CFC with proper orientations, and (2) keeping in account the manufacturability of metal and CFC, such as their printability and joinability limitations in terms of process parameters, or limitations with topology optimized features. The proper fibres placement and orientation

results in a stiffer, stronger and lighter metal-CFC multi-material design. This design approach aims to extract the full potential of this multi-material combination.

1 INTRODUCTION

In an evolving greener transport world, mechanical products are getting lighter in order to achieve long range operations through alternative energy means and shed reliance on conventional fossil fuels. The dependency on all metallic designs is decreasing and is being replaced by lighter options for higher performance and efficiency gains. Parts are made with lightweight materials like aluminium alloys and polymer-composites. For instance, in aviation sector, just in the last decade, more than 53% of composition by weight were composite materials compared to metals in Airbus commercial aircrafts, a drastic deviation from 90% metallic weight compositions in the decade before last [1]. The metal-polymer multi-material combination is a new prospective in the design world [2, 3].

On the other side, additive manufacturing (AM) is paving the way for smart designs which are just performance focused and offers much weight reduction than traditional manufacturing methods. With AM becoming compatible with the printability of many aluminium alloys and polymer-composites, combining these two materials in AM would further catalyse lightweight designing, especially with the inclusion of carbon fibre reinforced polymers. The properties of these composites nearly match or even surpass the properties of aluminium alloys in terms of strength and lightness. However, producing such lighter designs with this multi-material combination is not straight forward, as in AM, these are printed separately using different processes and have limitations in their joinability. This research proposes that a proper integrated design strategy is required to integrate material, design and manufacturing aspects of Al-CFC combination in the design process. The research is part of ‘MULTHEM’ which is an EU Horizon Europe project.

2 OVERVIEW OF MULTHEM PROJECT

MULTHEM stands for ‘Multi Material Additive Manufacturing for Lightweight and Thermal Management’ [2, 4]. The prospect of multi-material designs is accelerated by the advent of 3D printing technology. Complex organic parts with optimized geometries and multi-materials composition are gaining momentum in order to shed dependency on metal (e.g., aluminium) consequently offering more lightweight solutions for improved performance and efficiency gains. With AM leverage, MULTHEM project [2] (https://www.multhem.eu) explores methods to reduce metallic material dependency in real world applications particularly targeting the transport sector. It takes into account the advantages of additive manufacturing (AM) which offers flexibility in complex design manufacturing, combination of light materials such as aluminium and carbon fibre (CF) composites and topology optimization technique. Combining both the characteristics of aluminium and CFC, this project aims to achieve good mechanical performance, good thermal performance and lightweight solutions for the use-cases involved.

In recent years, most of the development in CF-reinforced polymers for AM has involved the inclusion of particulates of short-Carbon Fibre (sCF), while continuous-Carbon Fibre (cCF) printing remains a relatively novel area of research [5]. The use of cCF brings the highest mechanical reinforcement from the two types of composites. While on the flip side, aluminium alloys possess low density (2.6 to 2.8 g/cm^3) and high thermal conductivities (88 to 251 W/m.K) yet are difficult materials to be developed by AM technologies due to its high energy reflectivity. Laser Powder Bed Fusion (L-PBF) technologies with high-energy source are well established for the processing of aluminium alloys [6, 7]. However, the processing of aluminium alloys by other AM processes like Direct Energy Deposition (DED) [8] also known as Laser Metal Deposition (LMD) needs to be further developed by both processes DED-wire and DED-powder [9]. MULTHEM research targets optimisation of AM materials (aluminium and CFC) individually, their compatibility with AM processes, while also explores their possible combinations and joinability to achieve above goals for better multi-material designs.

2.1 MULTHEM transport sector use-cases

The use-cases in MULTHEM project are related to real world transport applications from electric vehicle (EV) and aviation fields. These include housings and casings of main driving components which are originally made of aluminium material, i.e., an electric motor housing *from an unmanned aerial vehicle (UAV)*, a battery casing *from an electric vehicle (E-Bike),* and a radio-altimeter casing *from a commercial aircraft*. Each of the use-cases come with their own sets of KPIs (Key Performance Index) in the project, listed in Table 1. The most common and significant KPI is the 'mass reduction' which MULTHEM translates as conversion from original metallic designs into lightweight multi-material metal-CFC designs. Reducing mass results in overall performance and efficiency gains in designs. *The scope of current proceeding is confined to EV battery casing use-case only*.

Table 1: MULTHEM use-cases from transport sector and their individual KPIs [2]

Use-case	Improvement KPIs
UAV motor housing	Mass reduction: 30 – 50% Product performance: 20% Lead time reduction: 35%
E-Bike battery casing	Mass reduction: 30 – 50 % Thermal performance: 20% Mechanical properties: 15%
Radio-altimeter casing	Mass reduction: 30 – 50% Thermal performance: below 85ºC Magnetic shielding efficiency: 60 – 25dB

2.2 EV battery casing use-case specifications

The CAD model of the EV battery casing use-case was generated via 3D-scanning method and is shown in Figure 1. At ends, located are plastic end-sockets (in black), and central part of the battery is the main casing made of aluminium 6082 T6. The measured mass of the metallic casing is 0.42 kg *(collectively, total casing mass is 0.631 kg with another internal plastic casing)*. The whole casing is the main focus of design optimisation. The Al casing's overall shell thickness which runs on the casing profile is 1.25 mm. In actual working scenario, the battery is typically mounted on a bike frame inclined 45º from horizontal. However, the battery orientation angle changes if the bike inclination varies e.g., riding on inclined roads, steep hills etc. Therefore, the battery orientation angle is set as a range with values from 0º to 90º. The internal components (e.g., battery cells enclosure, wiring etc.) and end-sockets (comprising power electronics board, switches, wiring etc.) act as mounted-weights on the casing. Heat is generated inside the battery and needs to be dissipated to ambient for cooling purpose [10].

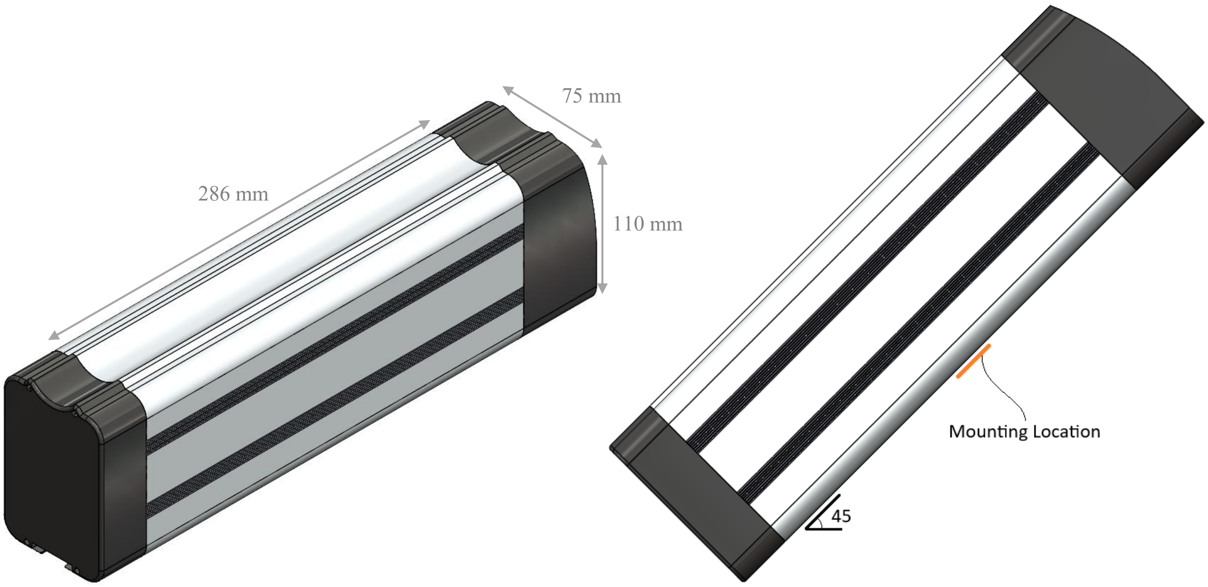

Figure 1: Generated CAD model of MULTHEM EV battery casing use-case with plastic end-sockets (in black) and main aluminium casing (silver) in the middle – (left). Mounting orientation of battery on E-Bike – (right) [10].

3 STRATEGY FOR MULTI-MATERIAL DESIGN OPTIMISATION

3.1 Identification of lightweight design possibilities

In order to achieve a lightweight design of a product, key related possibilities should be identified at first. These are related to material optimisation, advance manufacturing processes and advance design generation techniques, all aligned to contribute towards lightweight design concepts. In MULTHEM project, several possibilities identified for such a design optimisation which uses Al-CFC multi-material combination, are briefed as under [2].

- *Material optimisation:*
  - Selection of lightweight materials fulfilling the use-case operating requirements e.g., different aluminium and carbon fibre composites grades.
  - Optimisation of individual material grades e.g., $AlSi_{10}Mg$, $AlSi_7Mg$, Al 5356, short or continuous fibres in different polymer matrix (PA, PEEK, PEKK etc.).
- *Advance manufacturing:*
  - Selection of manufacturing processes which are suitable for direct, complex and lightweight manufacturing, e.g., Additive Manufacturing (AM) technology – processes such as Material Extrusion (MEX), Direct Energy Deposition (DED), Laser Powder Bed Fusion (L-PBF) etc.
  - Selection of advance joining/welding processes which are suitable for directly bonding different materials (like Al and CFC), e.g., Electron Beam Welding (EBW), Laser Beam Welding (LBW), Robotic – Friction Stir Welding (R-FSW), Over Printing (OP) etc.
- *Advance design generation:*
  - Selection of advanced design development techniques which are suitable for lightweight structures such as topology optimisation, generative design or lattice-based methods, FEA – driven design generation etc.

3.2 Strategy to integrate CFC with metal (e.g., Al-CFC) in lightweight AM designs

The identified possibilities can be tried, exploited and integrated in the design generation process. In additive manufacturing, this is referred to as Design for Additive Manufacturing (DfAM). The integration can be made in terms of, (a) characterisation of different combinations of metal-CFC multi-materials in order to satisfy design requirements such as structural, thermal criterions *(i.e., optimised material properties for the design, e.g., high strength, stiffness, heat dissipation etc.)*. (b) FEA based estimation of metal and CFC placement *(i.e., where to place metal or aluminium and where to place CFC?)* by considering output stresses, distortions etc. (c) FEA based evaluation of best possible paths and orientations of CFC (whether sCF or cCF) and metal (Al) to be in line with the performance expectations of the design under given loads *(e.g., maximising design strength, stiffness etc.)*. (d) Coupling CAD development with material optimisation and manufacturing processes i.e., considering their associated flexibilities and limitations *(e.g., constraints and variables in AM printing processes and metal-CFC joining)* in the CAD model development before feeding into FEA. (e) Optimisation of the CAD model development by coupling it with FEA feedback, (f) exploration of advanced design optimisation techniques such as topology optimisation or generative or lattice-based designing subjected to limitations from AM and joining methods if come any, etc. All above multiple integration points can be explored and exploited in DfAM, hence, resulting in performance optimised lightweight multi-material (metal-CFC or Al-CFC) designs. This devised strategy is briefed in Figure 2.

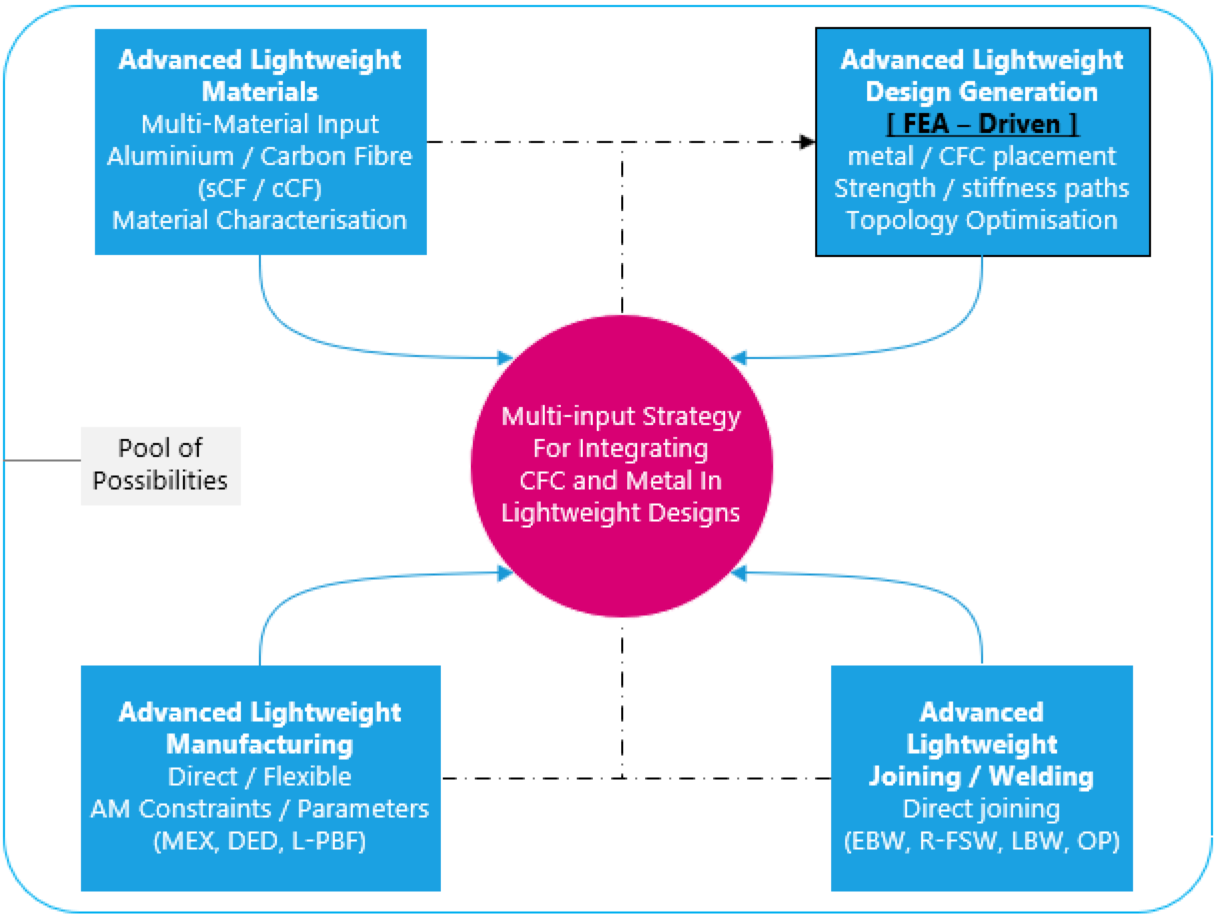

Figure 2: Multi-input strategy for integrating carbon fibre composites (CFC) with metallic (aluminium) structures for lightweight applications.

4 CASE STUDY – EV BATTERY CASING

4.1 Integration of lightweight possibilities into design optimisation of battery casing

As part of material optimisation, $AlSi_{10}Mg$ and Al 5356 from metal, and sCF/cCF – PA6 and PEKK combinations from composite were researched, characterised and optimised for maximum performance gains. It was found from initial trials that $AlSi_{10}Mg$ and sCF/cCF-PA6 multi-material combination was comparatively lighter, cost-effective, compatible with joining methods and suitable for the use-case under the given structural and thermal loads. Direct AM processes; MEX and DED-wire were selected *(as part of the project's requirements)* for the production of composite and Al metal respectively, while, EBW and R-FSW were shortlisted for direct bonding methods [2, 7, 10]. Initial FEA simulations were conducted with Al only to evaluate areas in the design with high/low stresses and distortions, and to estimate which areas required optimisation (see Figure 3). As part of open-design approach on outer metallic casing and with another protective plastic casing retained inside, advance topology and lattice design methods were tested (Figure 4), the outcome and feasibility checks are briefed in Table 2. The organic profiled geometrical features achieved using these methods showed limitations in manufacturing. E.g., cCF-MEX printing is incompatible with organic shapes as it is a 2D – planar printing process and cannot therefore follow paths of random 3D protrusions / pits unless the fibres are cut and reprinted as gaps, consequently decreasing the feature strength drastically.

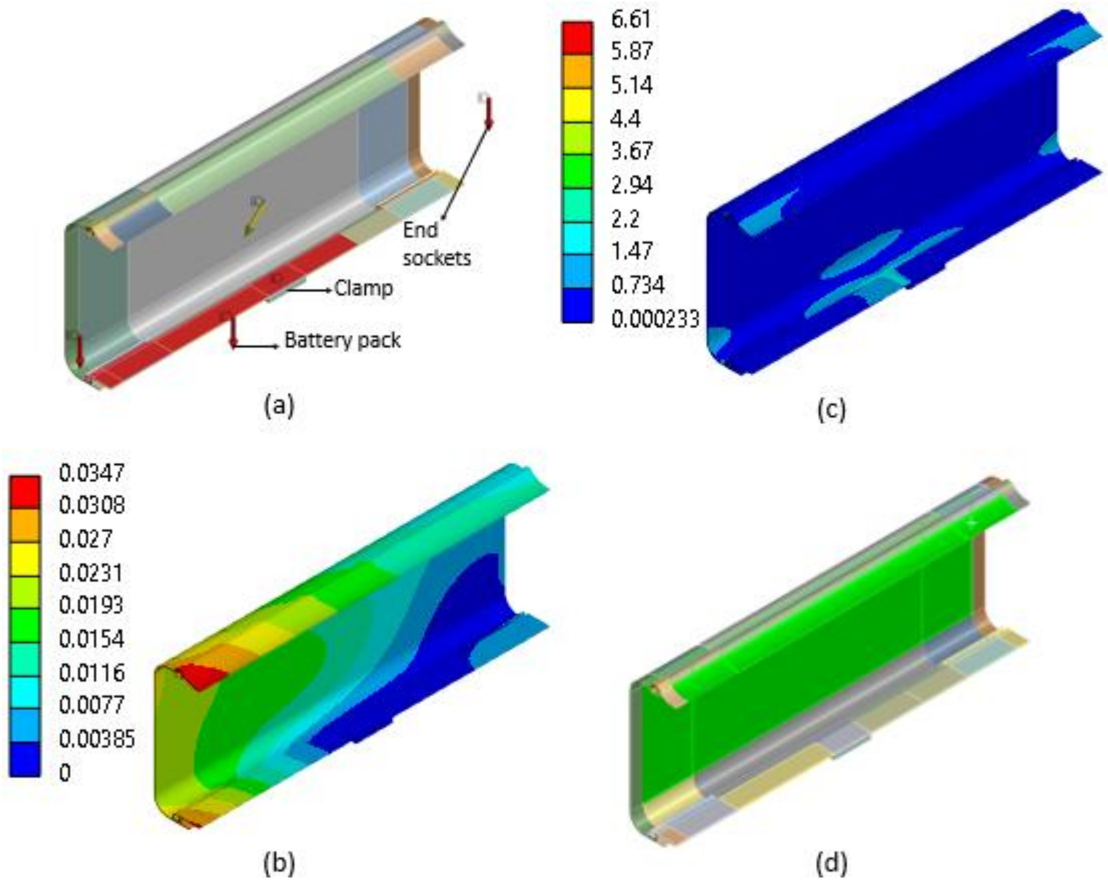

Figure 3: Process flow (a to d) to estimate areas for optimisation in the battery casing design considering initial FEA simulations. (a) FEA setup showing applied loads, (b) distortion contours (mm), (c) equivalent stress distribution (MPa), (d) suggested areas for optimisation (highlighted in green).

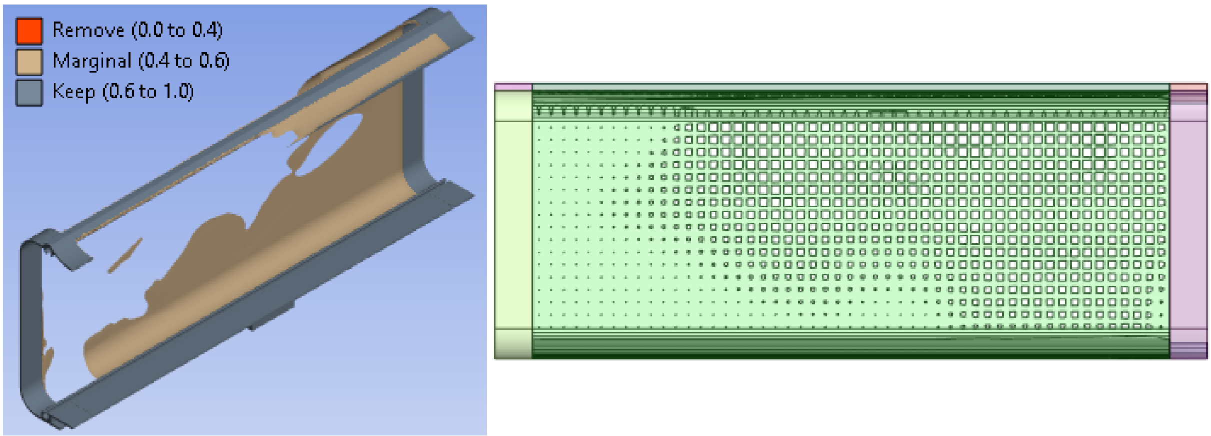

Figure 4: Trials for advance design optimisation methods on the battery casing , topology optimisation – (left), cubic-lattice based design generation – (right).

Table 2: Feasibility checks for advanced design methods explored in the design optimisation process of the EV battery casing use-case [2]

TRIAL METHOD	OUTCOME	FEASIBILITY CHECK [2]
Topology optimisation with 30% mass reduction criteria *(< target KPI of 50%)*	Produced paper-thin geometrical features, thickness ranging from 0.05 to 0.1 mm	- Not satisfying minimum MEX / DED printing process parameters, e.g., for sCF-PA6, min. MEX wall thickness is 0.25 mm, and for Al DED – wire process, it is 2 mm. - EBW incompatible – as it requires forced clamping of joining materials which could cause weaker joints. - R-FSW incompatible – as min. joint thickness is 2 mm, min. overlap distance is 80 mm and no T-joint.
Cubic-lattice based design	Varying wall thickness and depth of cubic cells	- Same as above but with only very small portion compatible with the AM processes. - Could be produced as solid first and then machined.

In closed-design approach, the initial FEA results additionally guided the placement of Al and CFC and its optimised paths/orientations in the original casing design, shown by Figure 5. Areas which required high strength/stiffness were retained with Al metal, while less stressed regions were proposed with cCF-PA6 replacement for closed-design and lightweight purpose. CFC designated areas compatible with the MEX printing process were assigned with the averaged fibre orientation of critical distortion vectors from FEA output, while fibre orientation was adjusted to address MEX printing limitation in non-critical CFC areas (see Figure 5b – 5d). These critical orientations mostly sustain the loads and lie as layers within a matrix of different print layers such as cross, unidirectional etc. Furthermore, other considerations were also taken into account in the multi-material design process, such as strong-orientation of AM material *(e.g., high longitudinal strength parallel to CFC fibres in tension)*, FEA based designability *(e.g., taking advantage of CF traction for strength purpose wherever required in the design and placement of weaker Z-axis or transverse axes in less load prone areas)*, printing processes' parameters and constraints *(e.g., min/max layer thickness/width, min/max horizontal/vertical wall thicknesses – especially in CFC MEX printing where outer layer is coated with sCF-polymer enclosing cCF-polymer layers inside for protection* [2]*)*, and weldability or joinability *(e.g., feasibility checks for R-FSW or EBW welding processes between metal and CFC interface designs). A few of the manufacturing considerations are illustrated in Figure 6.*

All above data was fed into CAD development which was linked to FEA iterations in order to validate the multi-material design and its producibility, and also in order to meet the KPI i.e., 50% mass reduction. Therefore, considering various material, design and manufacturing possibilities and limitations, a lightweight, multi-material or hybrid Al-CFC design of the EV battery casing use-case was achieved (illustrated in Figure 7), reaching up to 95% of the KPI.

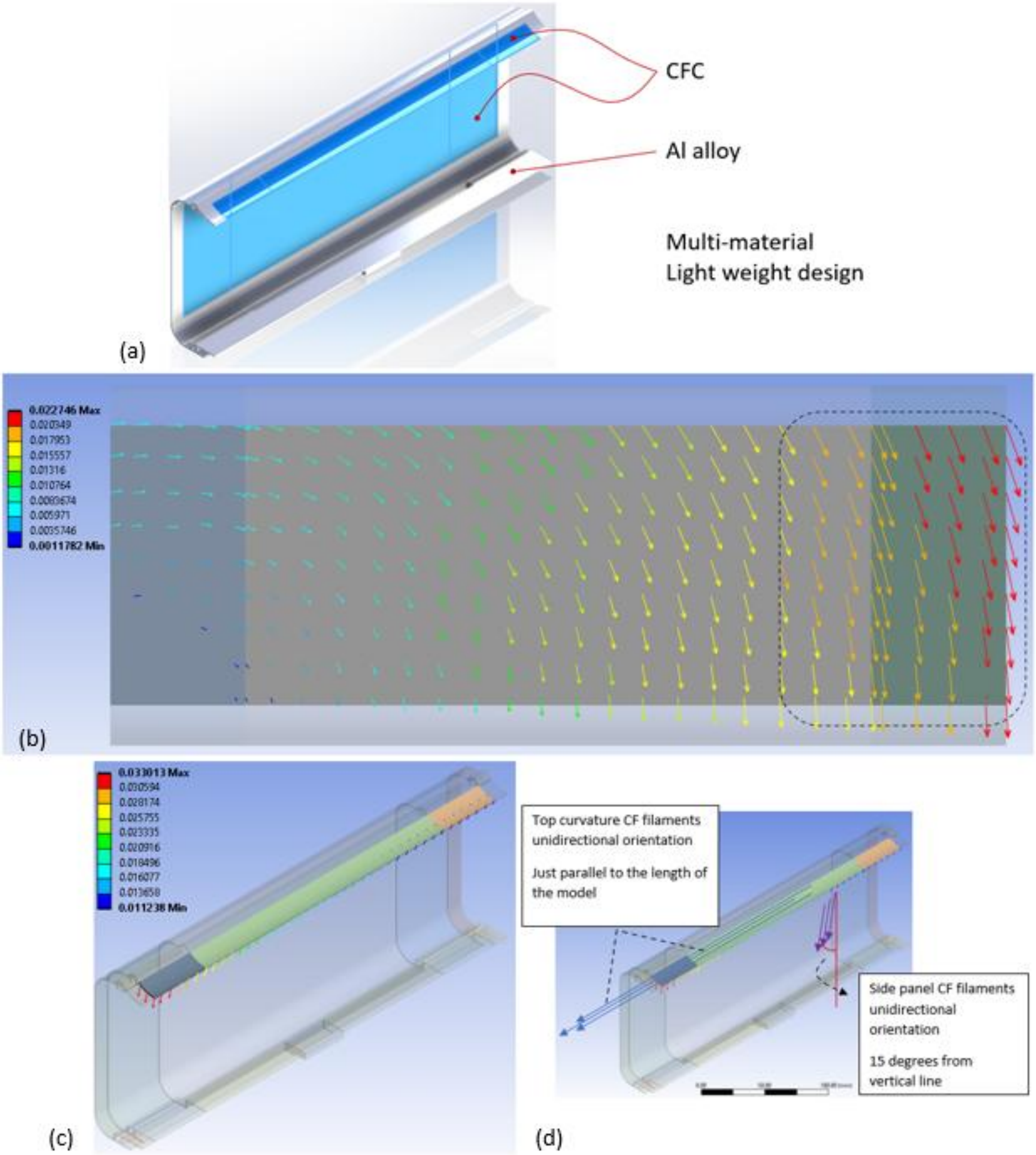

Figure 5: (a) Al-CFC multi-material placement. (b) & (c) FEA distortion output vectors suggesting paths which are used for defining carbon fibre (CF) orientations. (d) optimised orientations of CF in different CFC areas.

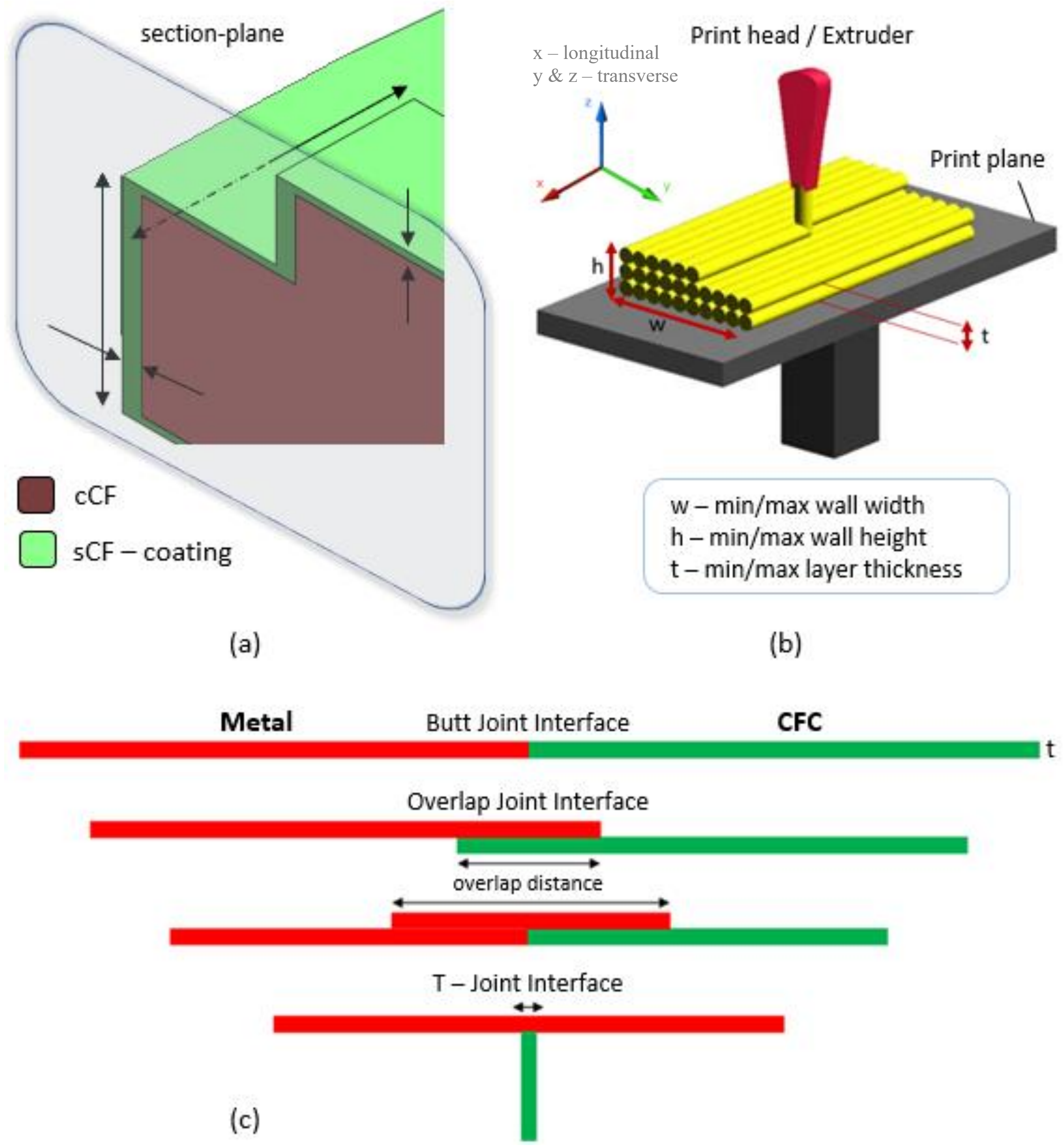

Figure 6: Manufacturing considerations to be taken into account at the CAD development stage. For example, (a) wall dimensions in sCF / cCF composite printing, (b) AM printing planes, longitudinal / transverse axes, process parameters and constraints, (c) different metal-CFC interface types for weldability using advance processes like EBW or R-FSW.

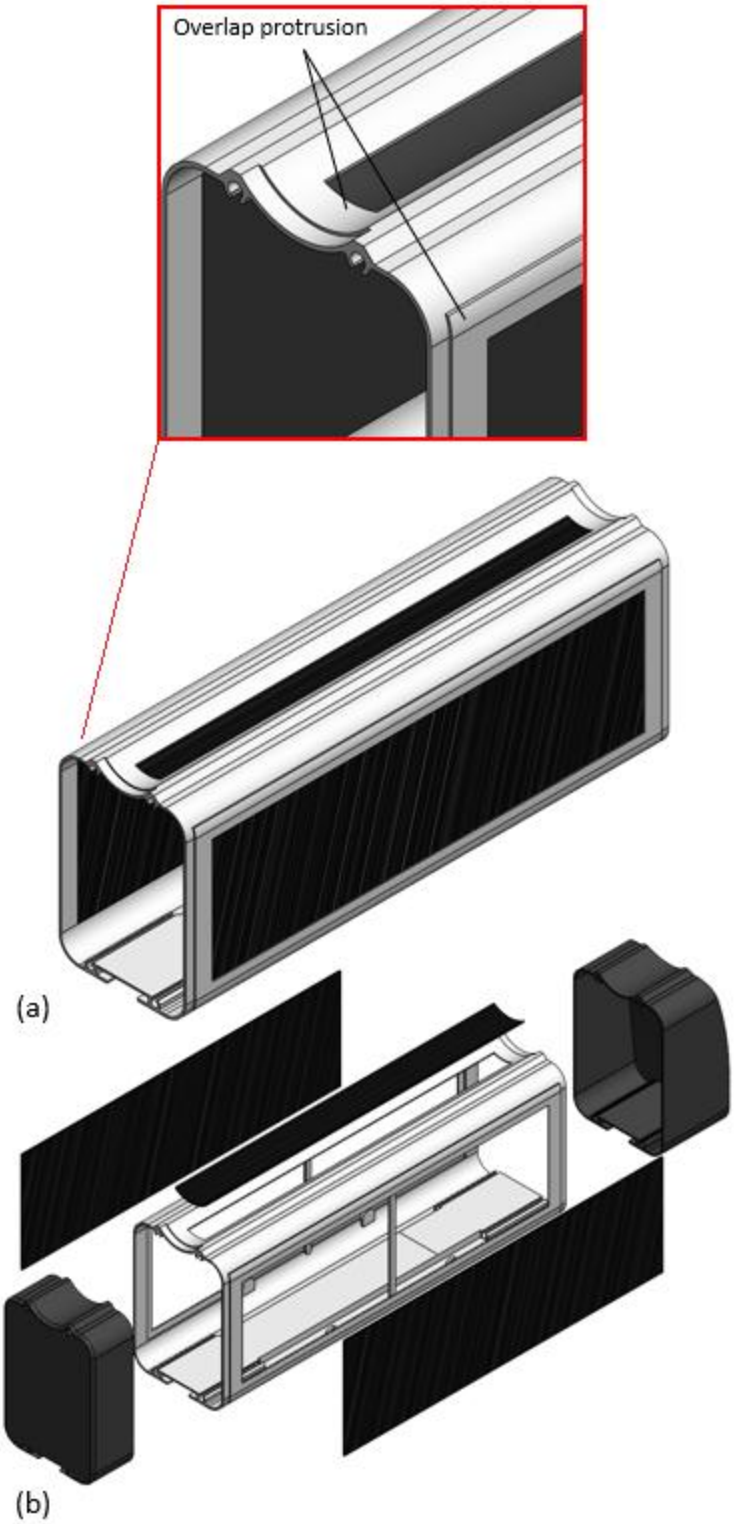

Figure 7: (a) Al – CFC (sCF / cCF – PA6) multi-material design of the EV battery casing use-case. Al & CFC represented as metallic silver and stripe-black, respectively. It also shows overlap protrusion for overlap joining. (b) Exploded view of Al-CFC EV battery – shows CFC top/side panels, main Al body at centre and end-sockets.

12 CONCLUSIONS

- An innovative design strategy to produce additively manufactured multi-material metal-CFC (Al-CFC) designs for lightweight applications is presented in this research. It suggests vast exploration of possibilities and limitations in material optimisation, advanced design methods and advanced manufacturability aspects to be integrated in the design process. Techniques like FEA driven proper placement of metal and CFC in the design, FEA based path optimisation of fibres or design for material strength / stiffness in AM, advanced topology optimisation and lattice-based designing, hybrid metal-CFC bonding with EBW, R-FSW etc. should be explored. The strategy has been demonstrated with an EV battery casing use-case from MULTHEM project (an EU Horizon Europe project: www.multhem.eu), which resulted in converting all metallic aluminium casing into a multi-material Al + sCF/cCF-PA6 hybrid design with a mass reduction of 47.5% *(optimisation of outer Al casing and omission of internal plastic casing in closed-design approach)* [10]. Standalone, the original Al outer casing was optimised up to 22% of its weight with Al-CFC.
- Limitations were experienced in applying open-design approach on the battery casing while exploring advanced topology optimisation and lattice-based design techniques. These resulted in design incompatibility with AM processes requirements (e.g., printing thickness mismatch and therefore the joinability of two different materials using EBW or R-FSW, while also not satisfying the targeted 50% mass reduction KPI. Furthermore, battery safety consideration from external factors such as particulate or fluid infiltration, electromagnetic distortion etc. were also brought in the feasibility check. Therefore, due to these design and manufacturing limitations, the open-design approach was omitted out. *(However, as part of future work, it could be suggested that the open-designs could be developed within the constraints or minimum compatibility requirements of the selected manufacturing processes, provided, robust internal protection is kept in place in the battery casing and higher trade-off for mass reduction is permissible).*
- Prospects of close-design approach were later considered to mitigate above open-design limitations. Parameters and constraints from AM – MEX, DED and EBW, R-FSW processes were integrated within the iterative CAD model development step (see Figure 6) with sub-integration into the multi-material FEA simulations for validation purpose. This approach befitted the design and manufacturability requirements for the use-case nearly achieving the mass reduction KPI with Al-CFC hybrid design.
- The proposed design optimisation strategy emphasises on proper data pooling of all possibilities and limitations in the form of trials and interconnected feedbacks mechanism for various advanced steps / processes involved specifically related to the lightweight multi-material (metal-CFC) additive manufacturing. This way, the research contributes toward adding another dimension in the field of DfAM with hybrid metal-CFRP lightweight designing.

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