Review of manuscript:

"**Evaluating the Effectiveness of Aluminum Coatings on Patch-Repaired Composites Using Electro-Thermal Analysis**"

Part A: COMMENTS ON GENERAL ASPECTS AND RECOMMENDATION

Using a commercial software for a finite element electro-thermal analysis, Authors have carried out a modelling study on the effects of aluminium-foil coatings for repair patches suitable for parts of aircraft structures based on epoxy - CF composites, which have been damaged by lightning strikes. The main novelty of the work is in the use of different size and shapes of repair patches to determine the effect on the damaged area in different layers. The submitted report has many deficiencies, which would have to be overcome by completely rewriting the text and provide additional information before it can be considered for publication. The main shortcomings can be summarised as follows:

1) The terminology and statements are often vague and misleading. For instance, the word composite is used as if there was there way only one type, corresponding to the specific one that they have used in the analysis. And even when the authors, later in the text, state that the composite is a CF type and eventually mention that the matrix is an epoxy type, the nature of the latter has never been revealed. An example of vagueness is to be found in the statement of objectives, which are also very verbose (Lines 83 – 96).

The research objectives have been simplified, with a special note added: "*The composite materials mentioned in this study are primarily carbon fiber reinforced polymer composites.*" **Please refer to Section 1 (Lines 87 – 94), where the modifications are highlighted in green.**

Regarding the issue of not separately listing the epoxy resin material properties:

In this study, carbon fiber reinforced composites were treated using a homogenization approach, which is standard practice in composite material finite element analysis. The **homogenization method** combines the material characteristics of fibers and matrix (epoxy resin) into equivalent properties for the entire layer, without needing to individually model each fiber and the resin surrounding them. **Comments about homogenization method has been added, please refer to Section 2.2.2 of the original text(Lines 87 – 94), where the modifications are highlighted in green.**

The material properties provided in Table 1-3 are the result of this homogenization process, reflecting the integrated behavior of the entire composite material layer, including electro-thermal properties in both fiber and non-fiber directions. These homogenized properties already incorporate the effects of epoxy resin, particularly evident in the transverse and interlaminar properties, which are primarily dominated by resin characteristics.

Additionally, in the temperature-dependent portion of the model, we referenced data obtained by Ogasawara et al. through thermogravimetric analysis (TGA), which specifically considers the degradation process of epoxy resin at high temperatures, as described in Section 2.2.2. Therefore, although the properties of epoxy resin are not listed separately, their characteristics are fully represented in the analysis through the homogenized model and temperature-dependent material behavior.

2) The usefulness of the data produced is often overstated and the claims are not substantiated by experimental data. There also lack of clarity and precision in the wording, as exemplified in the statement made in Lines 41-42. Although the work is on repair patches for lightening induced damage, there is a mention, let alone elucidation, of the repairing methods used in practice to justify the assigned properties to the materials and the layering strategy of the patches examined.

The analysis used in the work is interesting and the obtained data are potentially useful for the applications mentioned in the report, which could be used in a resubmission of the manuscript. To this end Authors are advised to take into account the comments in Part B of this evaluation report and bear in mind that the readers of Applied Science would not have the specialistic knowledge of FE modelling and/or materials used. It would be useful, therefore, if the following suggestion are explained and/or clarified:

a) The assumptions made for response of each layer to the applied electric field and whether this is affected by the adjacent layers exhibiting different properties.

Please refer to Section 2.2 (Lines 183 – 189), where the modifications are highlighted in green.

b) The role of the aluminium-foil coatings on the patch as a way of spreading out the electrical field from the point of the lightning strike, thereby reducing the current density perceived by the material.

Regarding the role of aluminum foil coatings in composite repair structures, the mechanism can be explained from two key aspects:

①Restoration of conductive pathways:

During patch repair, as mentioned in Section 3.1.2: *"… the misalignment of fibers at the joint face between the patch and the original laminate effectively causes fiber breakage…"* This breakage not only affects structural integrity but, more importantly, interrupts the conductive pathways of carbon fibers. While repair restores structural strength, it cannot fully recover the original conductivity of the composite material. The aluminum coating, as a highly conductive material, bridges these broken areas, reestablishing current conduction paths, thereby preventing current concentration at fracture points and reducing local Joule heating and subsequent thermal damage.

②Overall lightning protection mechanism:

In both repaired and original structures, the primary protective mechanism of aluminum coating is through its excellent conductivity, rapidly dispersing concentrated current from the lightning strike point and reducing the current density perceived by the underlying composite material. When lightning strikes, the aluminum coating guides the current to fasteners, which then transfer it to the aircraft's metal fittings and frame structure, essentially creating a Faraday cage-like protective effect on the aircraft surface. This mechanism significantly reduces the current density and temperature rise experienced by the composite material, thereby mitigating the extent of ablation damage.

Please refer to Section 3.2 (Lines 392 – 395), where the modifications are highlighted in green.

c) Produce quantitative data for the variation of damage through the entire thickness, possibly as plots, to determine the minimum number of layers required for the patches.

Regarding the suggestion to quantify damage variation across the entire thickness range, research indicates that damage propagation in the thickness direction exhibits relatively consistent characteristics. Considering that the thickness of a single composite laminate layer is only 0.191mm, the inter-laminar analysis approach adopted in this study is sufficient to capture key damage features. Through the existing temperature distribution analysis, as shown in Figure 4(e), the number of damaged layers can be clearly identified, which directly guides the minimum layer requirements for patch repair.

Part B. COMMENTS ON SPECIFIC SECTIONS OF THE REPORT

TITLE: - 1) The term “aluminium coating” is vague. It could be replaced with “aluminium -foil coating”. 2) There is no indication of lightning induced damage.

Thank you for your insightful suggestions.

①Regarding the term "aluminum coating" versus "aluminum-foil coating": In actual practice, OEM repair design offices typically issue Technical Dispositions for composite damage repair that can be case by case. The aluminum coating thickness often varies depending on damage size and location, making "aluminum coating" a more appropriate general term that encompasses this variability.

②Concerning the suggestion to indicate lightning-induced damage in the title: The primary focus of this research is on the effectiveness of aluminum coatings in protecting patch-repaired composites, with lightning strike being the specific testing condition. The current title "Evaluating the Effectiveness of Aluminum Coatings on Patch-Repaired Composites Using Electro-Thermal Analysis" effectively communicates this research focus, while maintaining appropriate length and clarity. The lightning strike context is immediately established in the abstract and introduction.

After thorough consideration, the original title has been maintained.

ABSTRACT: - 1) There is no indication of the type of applications addressed by the work. 2) The word “optimized” in Line 9 is an overstatement.

This paper represents a research study that provides theoretical support for patch repairs of composite materials, rather than a specific repair case example. Additionally, the term "optimized" has already been modified to "improved" in the revised version.

1.INTRODUCTION: - 1) Authors provide an extensive account of problems arising from lightning induced damage in aircrafts but say nothing about methods used for repairing the damage. 2) There is no indication of the type of epoxy resin used as matrix for the CF composite under examination. 3) The information provided about the pyrolysis data in the literature (ref 14) is meaningless without identifying the type of resin. Note that there is an enormous difference between the conventional DGEBA and the high-performance types, such as TGDDM likely to be used for parts of aircrafts. 4) There are many vague statements throughout the report, e.g. Lines 42- 44, 85 – 86, 94- 96.

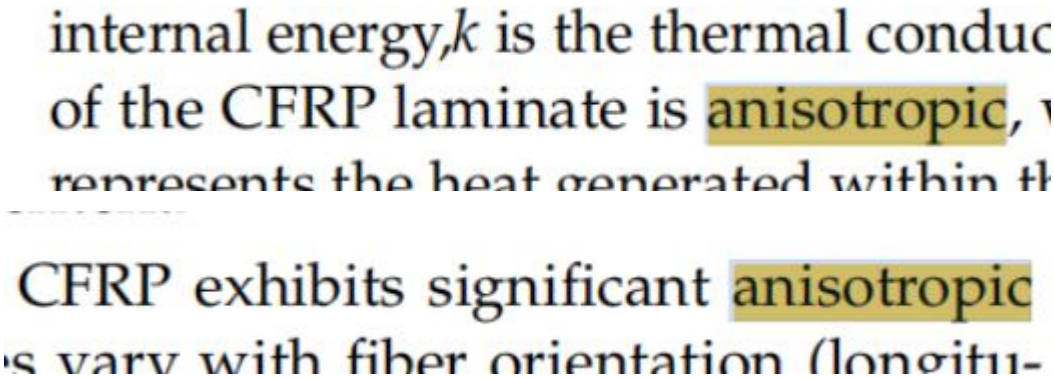
1)**Please refer to Section 3.1.1 of the original text.**

2)The epoxy resin type is already specified in the original text. **Please refer to Section 2.3: "*The specimens were of IM600/133 specification*,"** which indicates the designation of the epoxy resin system used in this study.

3)The reference 14was cited in the Introduction section under "Electro-thermal coupling simulation" and is cited to establish the theoretical foundation and key steps of lightning strike electro-thermal coupling simulation for composite materials. **There was no indication that reference 14 is used as a source for the pyrolysis data adopted in the original text.** The actual material properties and thermal degradation parameters used in our simulations are based on the IM600/133 composite system as specified in Section 2.3, with appropriate temperature-dependent properties detailed in Tables 1-3.

2. ELECTRO-THERMAL……., Section 2.1.3 – There is an invalid generalization that all composites are anisotropic in Line 117 (repeated later in Line 204 in Section 2.2.2).

The statement in the manuscript specifically refers to CFRP (Carbon Fiber Reinforced Polymer) composites, not to all composites in general. The anisotropic nature of CFRP is a fundamental characteristic due to the directional arrangement of carbon fibers within the polymer matrix.



Section 2.2.1 – Regarding the Headings and Data in Tables 1 and 2 (ref 13, 20). 1) it should be stated that these are unidirectional composites, and an indication should be given of the resin type and CF content used. 2) There is inconsistency in denotations used for direction in the two tables. 3) How were these properties measured? Note the quoted accuracy to 2 decimal places for values at high temperatures, < 3000! 4) While the decrease in conductivity at 300 and 360 C in all directions is credible, the constant density up to 360 C is not. The Tg of the resin matrix (TGDDM) is likely to be ~200 C. 5) The statement in Lines 225 – 226 is not credible; Authors should consult the cited paper on TGA data and preferably reproduce in the text as it is valuable for the discussion of the results. 6) The terminology on the on the volatilization of products of the thermal decomposition is inconsistent and sometime wrong, e.g., “sublimation”, which denotes a volatilization of matter from a solid without undergoing decomposition. This is certainly not the case here.

Regarding points 1-4), the material properties data in Tables 1 and 2 are cited from peer-reviewed publications (references 13 and 20). The directional notation inconsistency

between tables has been standardized in the revised version. While these established material properties were validated in their original publications, a brief description of the composite type has been added for clarity.

Regarding point 5), since directly copying from the original text is not appropriate, the results stated in the reference have been paraphrased in Section 2.2.2.

Section 2.2.3 – The Y axis in Figure 2 does not give any indication of the actual values for i, the current.

Regarding the Y-axis in Figure 2, this figure is adapted from the ARP5412 standard manual to illustrate the four typical lightning current waveforms. The purpose is to demonstrate the waveform characteristics rather than specific current values, which vary depending on the lightning strike zone and are detailed elsewhere in the standard.

Section 2.3 – (1) statement in Line 274 is not correct because Epoxy resins are cross-linked macromolecules which do not melt but undergo a large reduction in modulus above Tg, which is likely to be around 200 C for the matrix of the composite examined. However, the choice of 250 C as a reference temperature to denote onset of damage is very good with respect to both decomposition of the resin and the large increase in thermal expansion for mechanical damage. This should be emphasized. 2) The caption for figure 4 should include the term “experimental”. At the same time Authors should clarify the meaning of the images (e).

Please refer to Section 2.2.2 of the original text. The terms 'sublimation' and 'melt' should be substituted with 'decomposition' and 'soften' respectively, to more accurately describe the thermal behavior.

Section 2.4 – (1) The meaning of legends (subfigure a,b,c,d) is not clear. (2) The captions for Figs. 5 and 6 need to be more accurate. Ablation for the type of epoxy resin used in the composite examined starts at temperatures much higher than 250 C. The colours for temperatures above 250 C are not clear. Maybe using much darker colours would be better and use a white background to enhance the visibility of the damaged area. (3) Images for layers at much greater distance from surface should also be shown. It is important to identify the layer at which the temperature falls below 250 C. A plot of temperature gradient at the centre of the damaged zone versus distance from top surface would be a useful parameter to characterize the damage resistance of the material.

The temperature distributions are clearly indicated by the color legends at the bottom of both figures, where eight distinct colors represent eight corresponding temperature intervals. These color-coded temperature ranges provide a comprehensive visualization of the thermal gradient across the examined areas.

As for the visibility concern, the current color scheme was specifically chosen to maintain consistency with our previously published work in this field and to ensure reproducibility of our results. The present contrast levels allow for clear differentiation between temperature zones while maintaining the visual integrity of the thermal mapping.

The selected temperature range (up to 250° C) was based on our experimental observations of initial material property changes and is consistent with established

literature in this area. This temperature range effectively captures the critical thermal transitions relevant to our study's objectives.

3. ANALYSIS ……Section 3.1 – (1) The description and analysis of the repair patches is not at all clear. A sketch is required to show the cross-section of the damaged structure, with a clear identification of the damaged area, with the upper cross-section identified as the repair patch. At the same time, there must be a clear designation of the physical characteristics assigned to the composite structure underneath the patch. (2) The caption of Figure 7 does not accurately describe the nature of the images shown. Section 3.1.2 There are statements that are not substantiated by the data. For instance, in Lines 354 – 360 it is stated that there is not a perfect seamless fit resulting in minute gaps. How was this deduced? In Line 369, what is the meaning of (4.91 ~ 6.55 cm 2). The size of the damaged area must be clarified in terms of temperature. Concordantly a plot of "damaged area" versus distance from surface would be useful as design parameter in relation to patch thickness considerations. Section 3.2 - In Lines 386 – 392 are statements that are redundant for this section or even the entire paper. Section 3.2.1 – (1) Statements in Lines 398 – 401 are not clear. What do the following mean? mitigating breaks, misaligned fibres, junction. (2) Statements in Lines 406 – 409 should have been placed earlier, maybe after Table 3. (3) There is confusion regarding the statement regarding 20 cm coating when earlier the width was given a 30 cm value (Figs 9 and 10). Section 3.2.2 – There is the problem regarding patches smaller than the damaged zone in so far as the zone area and the physical characteristics have not been described. Section 3.2.3 – (1) There is a meaningless statement in lines 444 - 445, while that in Lines 448 – 451 is not substantiated by the data.

Please refer to the original text.

(X) Maybe the total number of images could be reduced and show simply how the geometry of the electrical field at the surface determines the shape of the damaged zone. More important is the area and how it decreases through the thickness. It would also be useful if the comparison between the pristine and repaired structure is presented as side-by -side images. The TGA trace which has been used for the ablation data (loss of weight) should be shown, as these would facilitate the interpretation of the results of the simulation.

4. CONCLUSIONS – (1) The first statement as an objective of the work should appear in the Introduction. (2) Statements in Lines 458 – 462 are vague and not substantiated. For instance, (a) What is "fibre misalignment" within the context of the simulation? (b) What data are there to determine the "optimized" repair structure? (3) Statement in Line 465 is redundant. (4) It is difficult to follow the explanation in point 1 without specifics. Also, the use of the term "dielectric breakdown" may not be appropriate as there has been no evidence. It is unlikely that this would occur, say at 250 C under an electrical spike (i.e., stress of short duration). (5) in relation to point 2, (a) what is the basis for the deduction in Lines 472 – 473, (b) what do the Authors mean by "broader applications"? Give examples! (5) In point 3 there is an association of the data from the work with change in weight with the data from the work without any evidence or rational basis without an elaboration. This is why the TGA curve would be necessary. (6) The statements in Lines 485 – 491 are speculative.

The term 'broader applications' has been revised to 'multiple lightning strike repairs on the same aircraft' to more precisely describe the scenario where aluminum coating would be

applied to multiple repair sites, resulting in cumulative weight increase of the aircraft structure.**Please refer to the original text.**