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ELECTRICAL AND MECHANICAL BEHAVIOUR OF COPPER TUFTED CFRP COMPOSITE JOINTS

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ABSTRACT

Electrical continuity of dissimilar joints controls the current and thermal pathways during lightning strike. Tufting using carbon, glass or Kevlar fibres is a primary to introduce through thickness reinforcement for composite structures and assemblies. Replacing the conventional tuft thread material with metallic conductive wire presents an opportunity for enhancing current dissipation and deal with electrical bottlenecks across dissimilar joints. Simulation of the electro-thermo-mechanical behaviour of joints was carried out to assess the influence of metallic tufting. The finite element solver MSC.Marc was utilised. Mechanical models incorporate continuum damage mechanics (CDM) to capture progressive damage in both composite and aluminium components of the joint. The mechanical models were coupled with electrical and thermal simulations of reference and copper tufted carbon fibre epoxy composite joints to assess both the lightning strike response and mechanical robustness of the assembly as well as the improvements offered by tufting. Validation of the model is based on electrical conduction and temperature measurements alongside delamination tests.

1. INTRODUCTION

Composites are a material of choice in aerospace structures due to their favourable combination of lightweight and high strength, as well as the design flexibility offered by their inherent anisotropy. Naturally, in complex aerostructures composites components are assembled with other parts which may be made from composite or metal, giving rise to demanding joining requirements and at the same time offering additional design solutions. Currently, integration of composite aerostructures with high load bearing capability is carried out mostly by mechanical fasteners. The use of fasteners involves significant challenges related to the openings introduced and the associated stress concentration and local damage [1-2]. New joint designs attempt to address these issues in an efficient manner by integrating aspects of joining within the manufacturing steps of the component and by improving analysis through modelling.

The replacement of metallic parts with composites makes aerostructures susceptible to lighting strike [3]. To overcome this issue, different solutions and materials are used to protect the structure, such as metallic meshes manufactured from aluminium or copper [4-5] or conductive films [6] on the surface of the structure. More advanced techniques are investigated currently to achieve lightning protection for composite structure through providing conductive properties to the structure by applying conductive particles as a network like carbon nanotubes [7] or graphene oxide [8]. More recently the use of metallic tufting has been proposed as a means of improving lightning strike performance of composites [9].

The work presented in this paper aims to address some of the challenges arising from the use of dissimilar materials using FE modelling. Thermal-structural, thermal-electrical and electromagnetic load-case scenarios are investigated for two customised joints of a regional medium turboprop aircraft, operating with different primary functionalities namely mechanical load transfer and electrical current dissipation.

2. METHODOLOGY

2.1 Joints and components

The two joints investigated in this work are a door hinge and diverter strip joint. The door hinge joint connects access door panels of the composite nose part to the rest of the assembly and consists of two components, a metallic part machined from Aluminium 2024 T351, and the carbon/epoxy composite substrate which is made by wet-laying Tenax 450-5 plain weave fabric with Letoxit epoxy resin. The diverter strip joint is responsible for redirecting and dissipating the charge and subsequent thermal loading generated from a potential lightning strike on the tip of the glass/epoxy radome of the aircraft, to the front aluminium bulkhead via a copper mesh covering the carbon/epoxy main body of the nose section.

2.2 Mechanical and damage modelling

Numerical simulation of the mechanical response of the door hinge joint, including plasticity, failure and progressive damage was conducted using Finite Element (FE) non-linear implicit analysis in MSC.Marc. Both aluminium hinge and the composite plate are modelled with continuum damage mechanics (CDM) to simulate the progressive damage. For plasticity and failure initiation of the aluminium hinge, Johnson-Cook material model is used. For the composite plate Tsai-Wu failure criterion is implemented.

The composite plate is an 8 layered laminate with stacking sequence $[(45)_2 /(0)_4 / (45)_2]$ and nominal thickness of 2.16 mm. The properties of a woven layer are reported in Table 1. The door hinge is made from aluminium 2024 T351 with properties given in Table 2. The bolts are modelled as elastic only with modulus of 200 GPa and Poisson's ratio of 0.3. The hinge and bolts are modelled with 8 noded solid elements of ~1 mm in size. The composite plate is modelled with 8 noded solid composite shell elements of ~0.5 mm in size. Contact between all bodies is simulated with 0.7 coulomb friction.

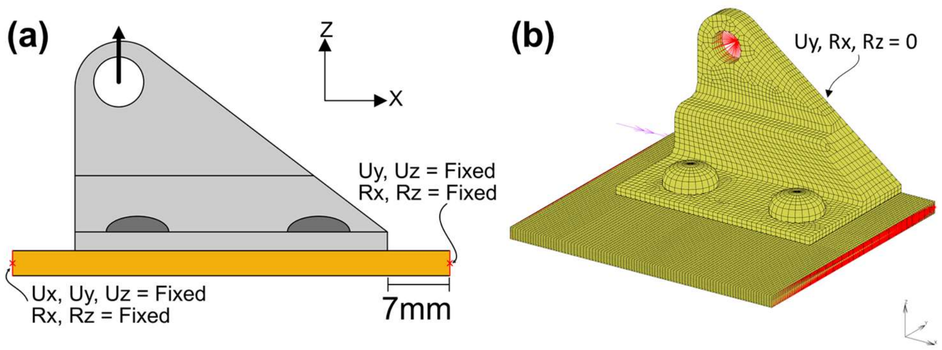

Figure 1 Illustration of door hinge (a) boundary conditions and loading direction in tension and (b) typical deformation profile during loading.

The simulation is setup with two load cases. In the first load case, bolts are pretensioned to 2600 N calculated from a 2.6 Nm applied torque with friction coefficient of 0.2. In the second load case, constant displacement is applied to a reference point positioned inside the hinge hole and rigidly connected with multi point constraint (MPC) to the internal hole surface. The tension load can rotate in the Y axis but is fixed in rotation about the Z and X axis. To model clamping, the edges of the composite plate are rigidly connected to a single reference point with MPC and given the boundary condition (BC) shown in Figure 1a. A half model is created by implementing a symmetry BC on the Y facing surface of the hinge and the plate shown in Figure 1b. Two simulations were conducted, first with only elastic model, i.e., plasticity and damage are turned off in both aluminium hinge and the composite plate - and the second with full progressive damage activated.

Table 1 Composite ply properties - TENAX-PR217+EM317 Woven

Stiffness properties		
E1	46.922	GPa
E2	46.922	GPa
E3	2.724	GPa
G12	2.724	GPa
G23	1.362	GPa
G31	1.362	GPa
v12	0.055	
v23	0.3	
v31	0.02	

Failure Initiation (Tsai-Wu)		
XT	483	MPa
XC	247	MPa
YT	483	MPa
YC	247	MPa
S12	24	MPa

Table 2 Aluminium properties - Aluminium 2024 T351

Stiffness properties		
E1	65.88	GPa
v12	0.33	

Failure Initiation (J-C)	
d1	0.17
d2	0.21
d3	-6.45
d4	0
d5	0

Plasticity (J-C)		
A (Yield Strength)	346.8	MPa
B	487.3	
N	0.495	
C	0	
e0	1	1/s
Tr	-50	°C
Tm	502	°C
m	2.1	

2.3 Heat transfer and electrothermal modelling

The diverter strip joint has been modelled in MSC Marc using 3D 8-noded hexahedral elements. The composite laminate comprises 8 unidirectional layers carbon/epoxy material of 0.25 mm in thickness. The composite overall dimensions are 80 mm × 20 mm × 2 mm. A copper strip with dimensions of are 80 mm × 4 mm × 0.5 mm is located centrally on top of the laminate. The strip is modelled using 4 layers of elements across its thickness. Tufts in the composite laminate are modelled by a homogenised representation of the through thickness electrical and thermal conductivities of the material, based on 99.9% annealed copper wire with a diameter of 0.125 mm. The MSC Marc model of this joint is shown in Figure 2.

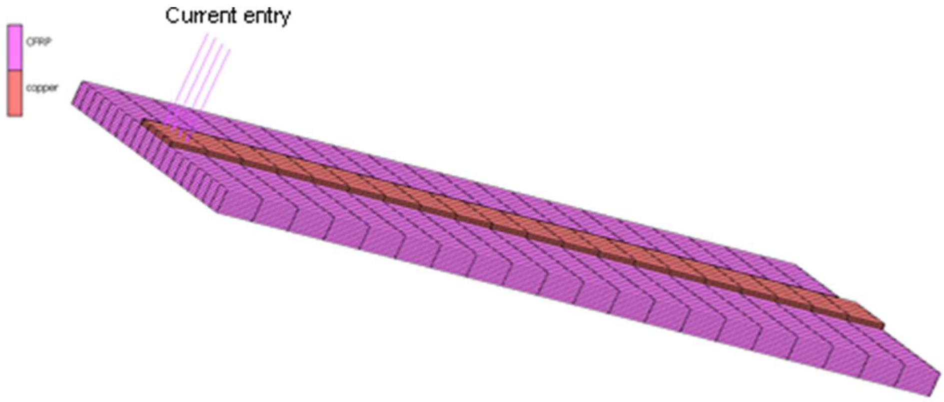

Figure 2 FE model for electrical and heat conduction analysis of the diverter strip joint.

In the electrothermal model, the current is entering from top on one of the strap ends while the opposite side of the part is grounded. The current injected reaches 160 A within 5 s increasing linearly. Natural air convection is applied on all sides. The model incorporates degradation of the resin matrix, following the kinetics:

$$\frac{d\beta}{dt} = Ae^{-\frac{E}{RT}}(1-\beta)^n \qquad (1)$$

The electrothermal model also incorporates thermomechanical effects to represent distortion and stress generation due to thermal gradients. Furthermore, the FE simulation allows representation of delamination through an interface governed by a stress criterion. Once the interface is activated and delamination occurs, the composite laminate and the copper strip form a contact pair in the simulation.

2.4 Electromagnetic modelling

The simulation of electromagnetic effects was performed using magnetodynamic analysis in MSC Marc. The waveform corresponding to a zone 2A lightning strike is used as a boundary condition. The laminate consists of four layers of carbon fibre with 0/90 orientation. A copper strap is attached to the top side of the composite and a copper mesh on its bottom side.

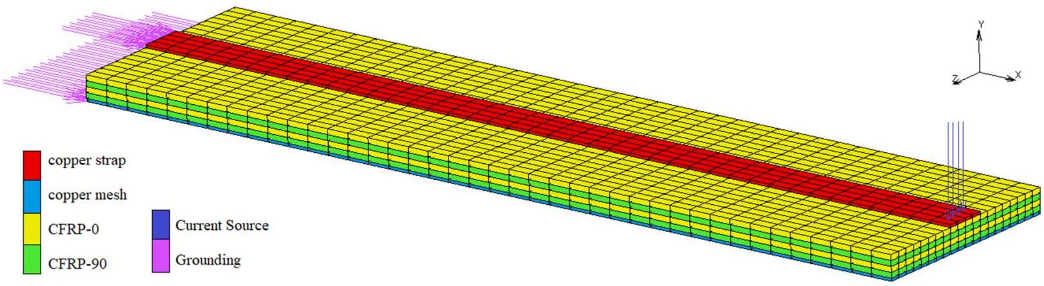

Figure 3 FE model of carbon epoxy composite with a bonded copper strap, indicating location of current injection.

The geometry and the boundary conditions of the model are shown in Figure 3. The applied current source is perpendicular to the face of the elements and the grounding of the components is simulated using fixed electric and magnetic potentials with zero values. The electromagnetic material properties for the metallic and composite parts that are presented in Table 3.

Table 3 Electromagnetic properties used for the electromagnetic modelling.

Materials	Direction	Electric conductivity $[S/m]$
CFRP		
	Longitudinal	$4 \cdot 10^4$
	Transverse	200
	Through-thickness	1
Copper		$58.7 \cdot 10^6$

3. RESULTS

3.1 Mechanical and damage modelling

FE simulation results for the door hinge joint loaded in tension are provided in Figure 4. These results are compared with data obtained in experimental tests. The results show both full damage simulations and elastic only simulations. The stiffness of the door hinge is captured very well with the elastic only model showcasing the non-linearity of the setup represented correctly. The deformation profile is shown in Figure 5a. Continued loading begins to damage the elements around the bolt hole, causing further non-linearity in the results as shown in Figure 5. The first large load drop corresponds to the bolts sliding through the laminate. This event occurs when not all the elements have failed, indicating some contact failure of the simulation. Therefore, any results post this first load drop in the progressive damage model are considered not accurate.

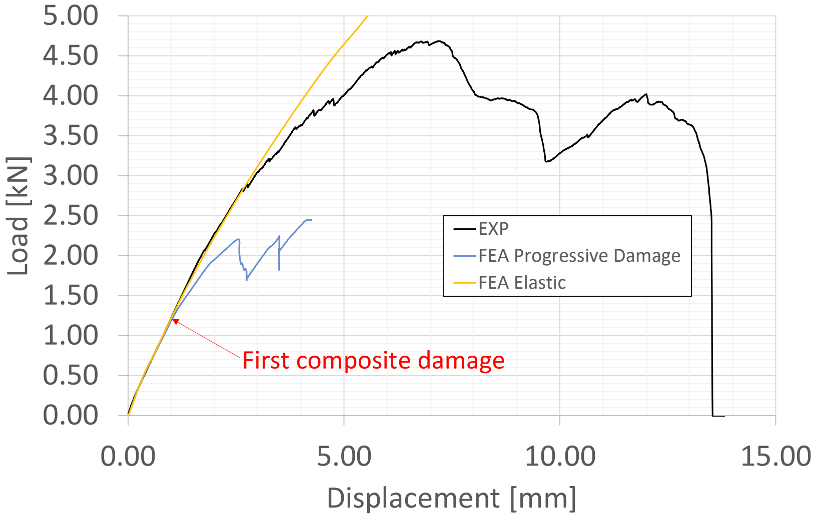

Figure 4 Simulation results of door hinge joint in tension.

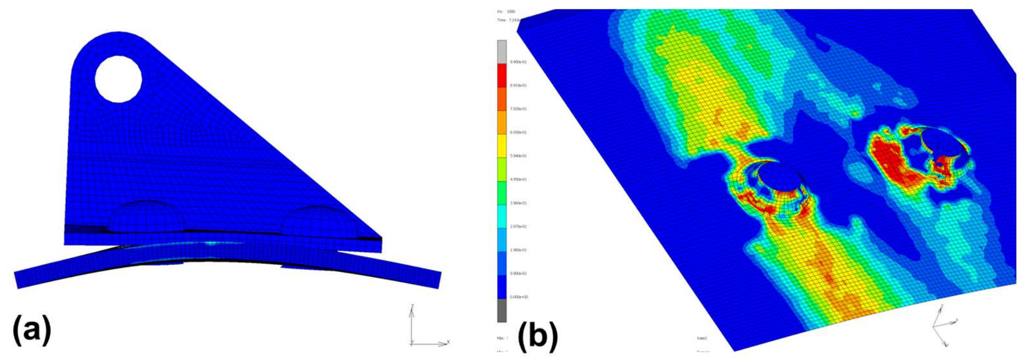

Figure 5 Simulation results showing (a) deformation profile of the joint and (b) damage contour plot showing full pull through failure around the bolt.

3.2 Heat transfer and electrothermal modelling

The four outputs of interest of the FE heat transfer and electrothermal simulation of the diverter strip joint are current density, temperature, part distortion and degree of degradation of the part. The results for these four output criteria are presented in Figure 6. The current density peaks at 80 MA/m^2 as the charge dissipates through the copper strap, at which point the maximum temperature reaches 200°C, on the grounded side of the joint. The maximum structural distortion is observed at the centre of the joint where a displacement of 0.05 mm is reached. The highest level of decomposition is detected on the last third segment of the joint away from point of current injection.

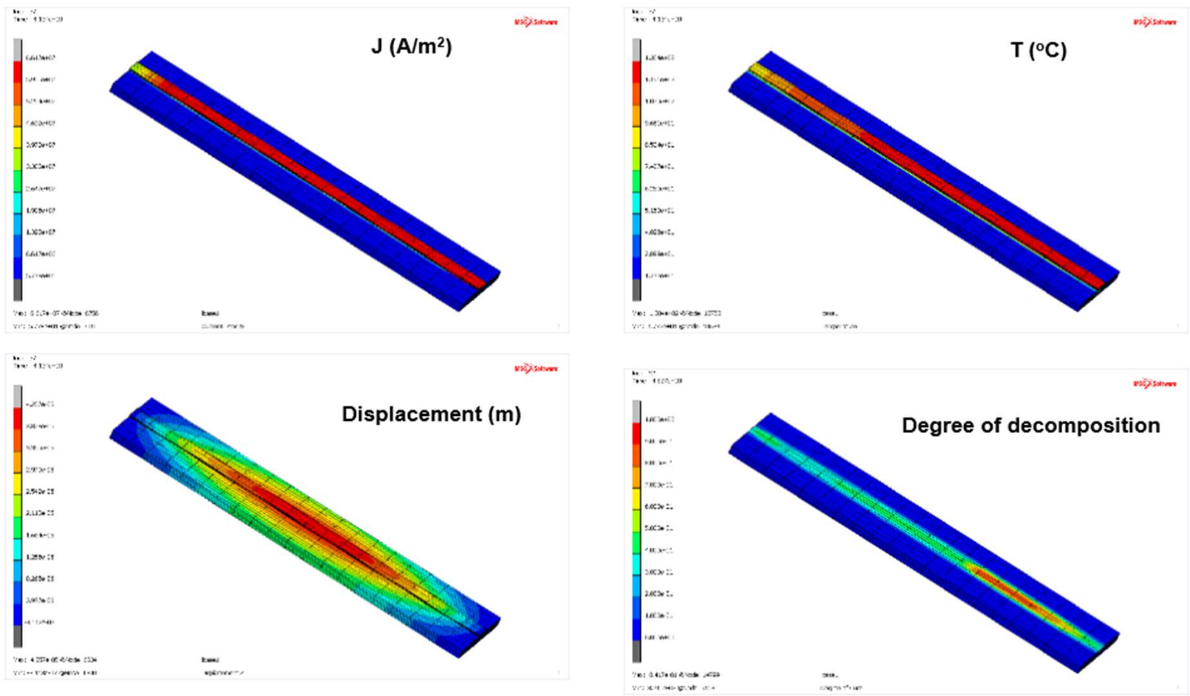

Figure 6 FE model of the electrothermal degradation simulation.

The position of the maximum temperature and associated polymer matrix degradation is governed by the state of delamination. Delamination starts from the side opposite to the current injection and progresses towards the other end of the copper strap. The location of maximum temperature of the composite surface moves with the delamination front as the material losses contact with the copper and the energy areal density dissipated through the composite increases locally. The maximum temperature and degree of degradation estimated are moderated significantly by the addition of tufts in the composite laminate. Insertion of tufts at an areal density of 2% reduces degradation to a half through reduction of maximum temperature by about 30°C.

3.3 Electromagnetic modelling

Figure 7a and 7b present the distribution of the current density and Lorentz force for the carbon fibre composite part at the first and second peaks of the lightning strike waveform. As can be seen in Figures 8a and 8b, the layup influences both distribution of the current density and that of the Lorentz forces for the composite part. This can be linked to the conductive pathways created by the different material orientations. Thus, the design of the composite material should be considered to minimise the lightning strike effects.

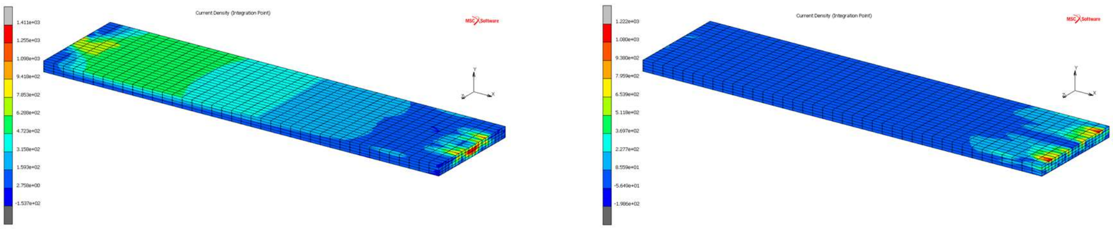

Figure 7 Distribution of the current density for the CFRP part; (a) first and (b) second peaks of the lightning strike waveform.

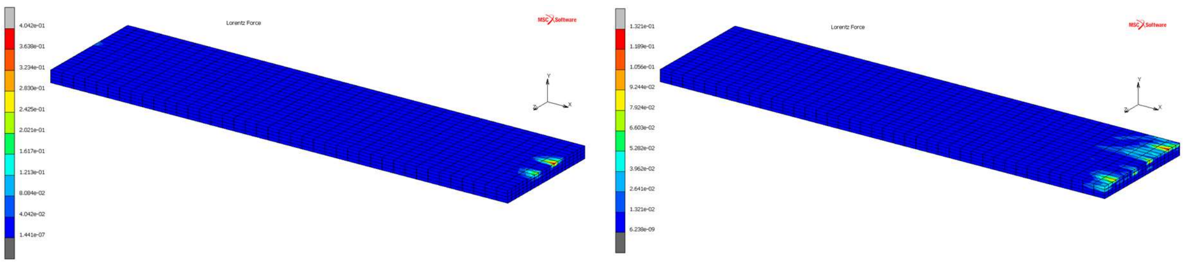

Figure 8 Distribution of the Lorentz force for the CFRP part; (a) first and (b) second peaks of the lightning strike waveform.

4. CONCLUSIONS

This work demonstrated the value of simulating the multiphysics behaviour of complex dissimilar joints. The behaviour of a door hinge and a diverter strip joint were modelled under mechanical and electrical loading. The door hinge model successfully replicated experimental stiffness data. Coupled electrothermal, electromagnetic and electro-thermomechanical models of the diverter strip joint uncovered the effects governing damage due to electrical loading through an interaction delamination effects and material degradation. The simulation showed that tufting of carbon fibre laminates using copper is an effective way for reducing this damage.

The simulation allows fast evaluation of new joint designs, which in the case of tufting can result in significant reduction of damage caused by electrical loading. Further refinement of these models and validation using results of relevant experiments will enhance applicability and allow utilisation within a joint design framework.

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