Boeing Simulates Thermal Expansion in Composites with Expanded Metal Foil for Lightning Protection of Aircraft Structures

Modern aircraft such as the Boeing 787 Dreamliner are comprised of more than fifty percent carbon fiber composite requiring the addition of expanded metal foil for lightning strike protection. Researchers at Boeing are using simulation to verify that protective coatings on the metal foil will not fail due to thermal stress arising from a typical flight cycle.

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The Boeing 787 Dreamliner is innovative in that it is comprised of more than fifty percent carbon fiber reinforced plastic (CFRP) due to the material's light weight and exceptional strength. Figure 1 shows the extensive use of composite materials throughout the aircraft. Although CFRP composites inherently have many advantages, they cannot mitigate the potentially damaging electromagnetic effects from a lightning strike. To solve this problem, electrically conductive expanded metal foil (EMF) can be added to the composite structure layup to rapidly dissipate excessive current and heat for lightning protection of CFRP in aircraft.

Engineers at Boeing Research and Technology (BR&T) are using multiphysics simulation and physical measurements to investigate the effect of the EMF design parameters on thermal stress and displacement

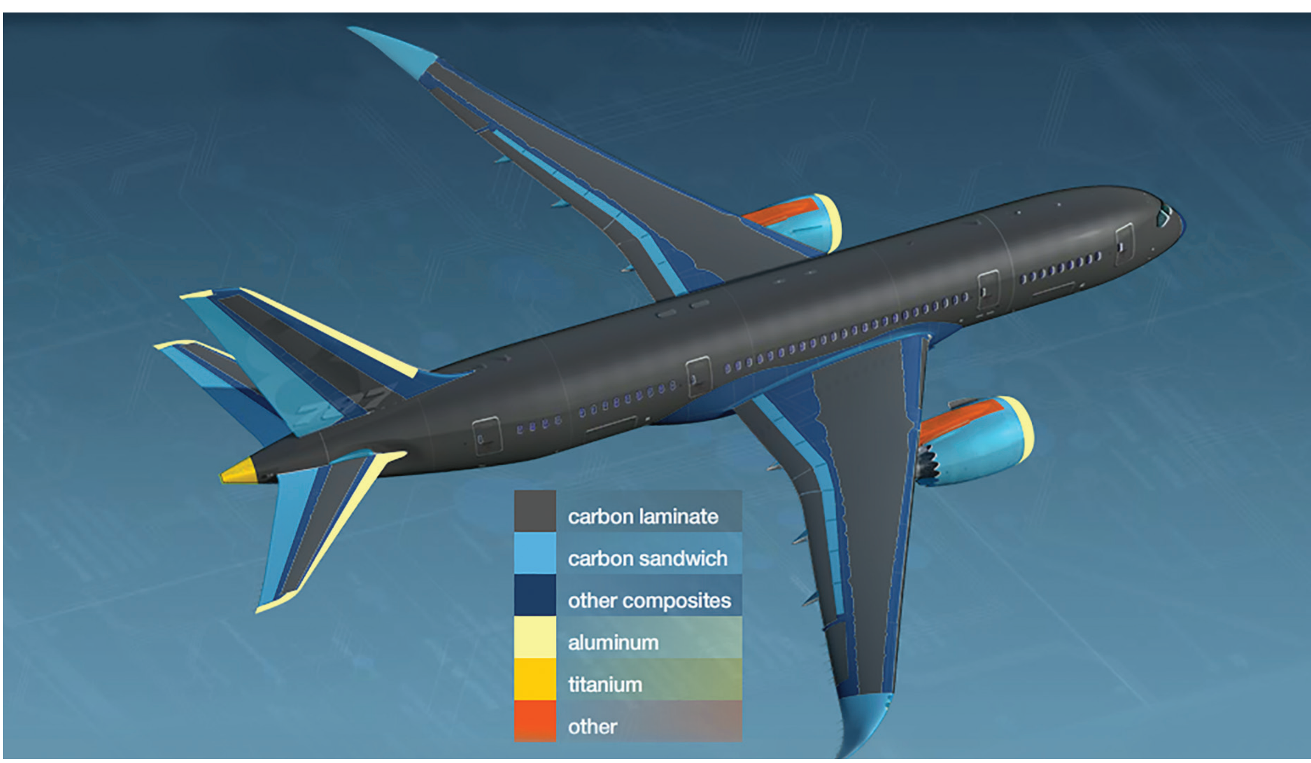


FIGURE 1. Advanced composites used throughout the Boeing 787 account for more than fifty percent of the aircraft body[1].

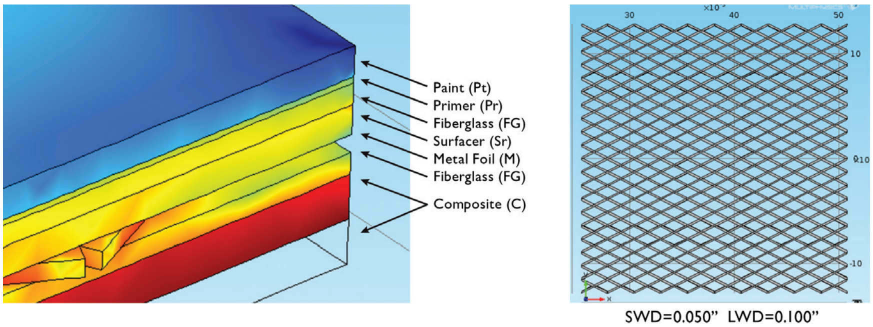


FIGURE 2. At left is the composite structure layup from the COMSOL model and, at right, the geometry of the expanded metal foil. SWD and LWD correspond to short way of the diamond and long way of the diamond. The mesh aspect ratio: SWD/LWD is one of the parameters varied in the simulations.

in each layer of the composite structure layup shown at left in Figure 2. Stress accumulates in the protective coating of the composite structure as a result of thermal cycling due to the typical ground-to-air flight cycle. Over time, the protective coating may crack providing an entrance for moisture and environmental species that can cause corrosion of the EMF, thereby reducing its electrical conductivity and ability to perform its protective function.

Contributing to the research effort at BR&T are project lead Jeffrey Morgan from Sealants and Electromagnetic Materials, Associate Technical Fellow Robert Greegor from Applied Physics leading the simulation, Dr. Patrice Ackerman from Sealants and Electromagnetic Materials leading the testing, and Technical Fellow Quynhgiao Le. Through their research, they aim to improve overall thermal stability in the composite structure and therefore reduce the risks and maintenance costs associated with damage to the protective coating.

SIMULATING THERMAL EXPANSION IN AIRCRAFT COMPOSITES

In the surface protection scheme shown at left in Figure 2, each layer including the paint, primer, corrosion isolation layer, surfacer, EMF, and the underlying composite structure contribute to the buildup of mechanical stress in the protective coatings over time as they are subject to thermal cycling. The geometry in the figure is from the coefficient of thermal expansion (CTE) model developed by Greegor[2,3] and his colleagues using COMSOL Multiphysics® in order to evaluate the thermal stress and displacement in each layer of a one-inch square sample of the composite structure layup.

The structure of the EMF layer is shown at right in Figure 2. In this study, the EMF height, width of the mesh wire, aspect ratio, metallic composition, and surface layup structure were varied to evaluate their impact on thermal performance throughout the entire structure. The metallic composition of the EMF was either aluminum or copper where an aluminum EMF requires additional fiberglass between the EMF and the composite to prevent galvanic corrosion.

The material properties for each layer including the coefficient of thermal expansion, heat capacity, density, thermal conductivity, Young's modulus, and Poisson's ratio were added to the COMSOL model as custom-defined values and are summarized in Figure 3. The coefficient of thermal expansion of the paint layer is defined by a step function that represents the abrupt change in thermal expansion at the glass transition temperature of the material.

In the CTE model, the Thermal Stress multiphysics interface couples solid mechanics with heat transfer to simulate thermal expansion and solve for the displacement throughout the structure. The simulations were confined to heating of the composite structure layup as experienced upon descent in an aircraft where final and initial temperatures were defined in the model to represent the ground and altitude temperatures, respectively.

IMPACT OF EMF ON STRESS AND DISPLACEMENT

The results of the COMSOL simulations were analyzed to quantitatively determine the stress and displacement in each layer upon heating and for

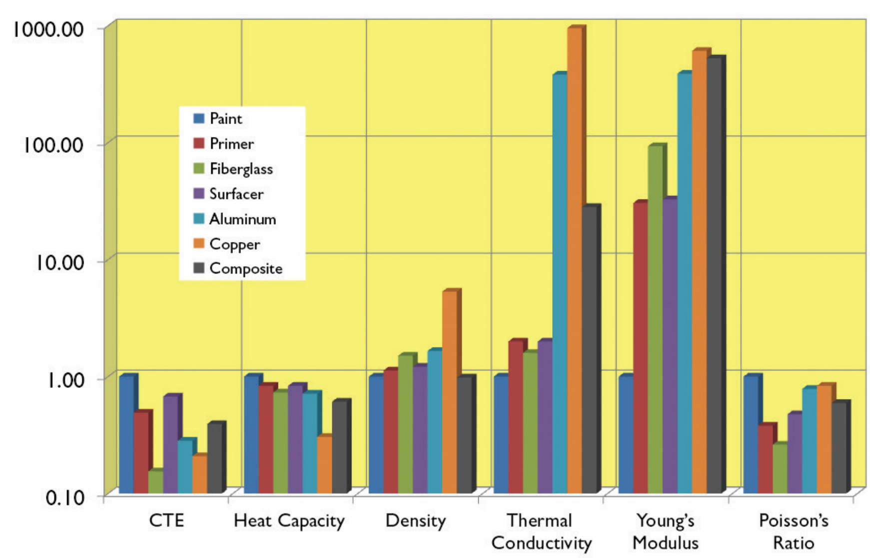


FIGURE 3. Ratio of each material parameter relative to the paint layer. The paint layer shows higher values of CTE, heat capacity, and Poisson's ratio indicating that it will undergo compressive stress and tensile strain upon heating and cooling.

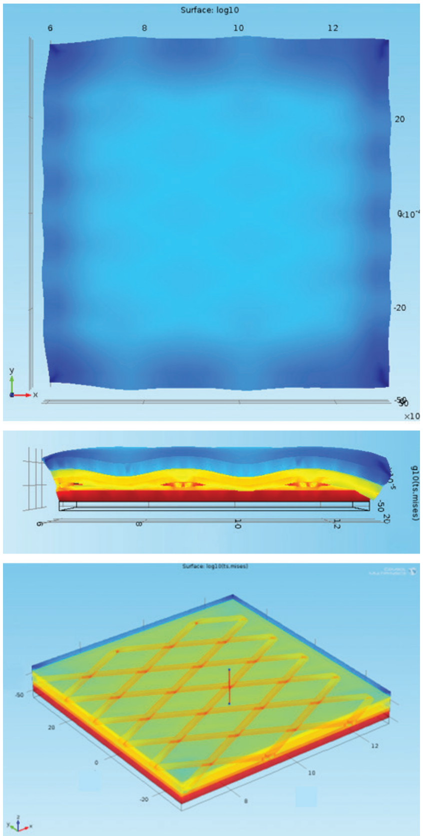


FIGURE 4. Top, middle: top-down and cross-sectional views of the von Mises stress and displacement in a one-inch square sample of a composite structure layup. At bottom, transparency was used to show the high stress in the composite structure and EMF. Stress was evaluated along the vertical line extending through the depth of the sample.

varied properties of the expanded metal foil. An example of the simulation results is shown in Figure 4.

Through the paint layer at the top of Figure 4, it is possible to observe the displacement pattern of the underlying EMF. The magnified cross-sectional view clearly shows the variations in displacement above the mesh and voids in addition to the trend in stress reduction in the uppermost protective layers. Figure 5 shows the relative stress for each layer in surface protective schemes that incorporate either copper or aluminum EMF. The fiberglass corrosion isolation layer required by the aluminum EMF acts as a buffer, causing the stress to be lower in the aluminum than it is in the copper EMF.

Despite the lower stress in the aluminum EMF, simulation results from the variation of the EMF design parameters reveal a consistent trend toward higher displacements in the surface protective scheme with the aluminum EMF when compared to copper. The larger displacements generally caused by the aluminum EMF can be attributed, in part, to the relatively higher CTE of aluminum.

Further analysis of the impact of the EMF design parameters was performed to confirm the effect of varying the height, width, and mesh aspect ratio on displacement in the protective layers. When varying the mesh aspect ratio, it was found that an increased ratio led to a modest decrease in displacement of about 2 percent for both copper and aluminum EMF, where higher ratio values correspond to a more open mesh structure. For any EMF design parameter, there is a trade-off between current carrying capacity, displacement, and weight. In the case of mesh aspect ratio, while choosing an open mesh structure can reduce displacement and weight, the current carrying capacity that is critical to the protective function of the EMF is reduced as well and needs to be taken into account.

> "Increasing the mesh width or decreasing the aspect ratio are better strategies for increasing the current carrying capacity of the EMF for lightning strike protection."

Similarly with regard to the mesh width, varying the width by a factor of three led to a relatively minor increase in displacement of about 3 percent for both copper and aluminum EMF. However, varying the height of the EMF by a factor of four led to an increase in displacement of approximately 60 percent for both aluminum and copper. Figure 6 shows the relative values for displacement through each layer of the surface protection scheme for varied height of copper and aluminum EMF. Due to the lower impact on

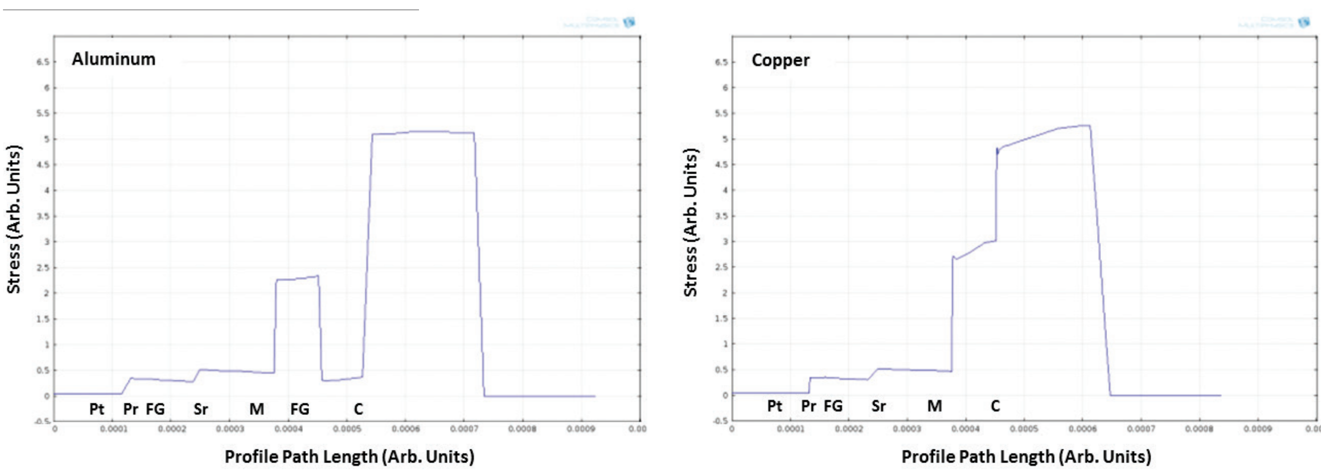


FIGURE 5. Relative stress in arbitrary units was plotted through the depth of the composite structure layups containing either aluminum (left) or copper EMF (right).

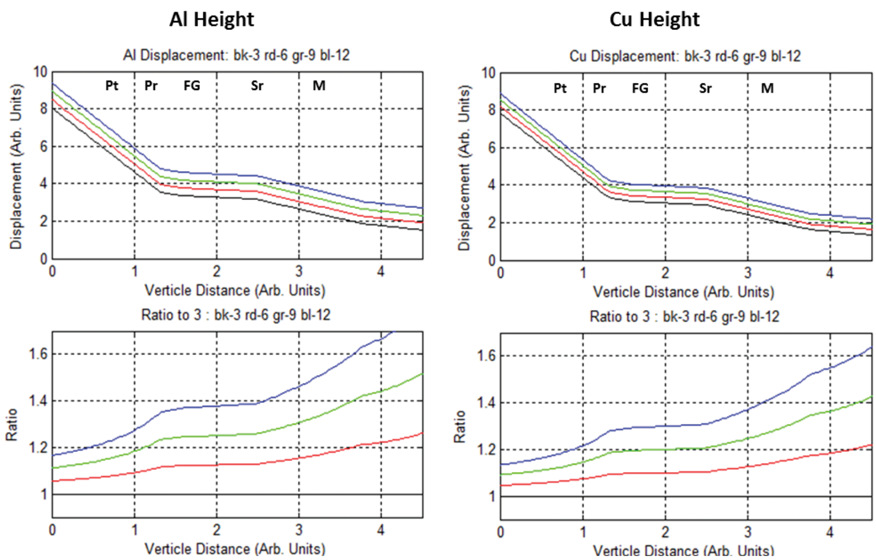


FIGURE 6. Effect of varying the EMF height on displacement in each layer of the surface protection scheme. The graphs at top show displacement in arbitrary units; at bottom, the ratio is the displacement calculated for each height normalized by the displacement for the smallest height.

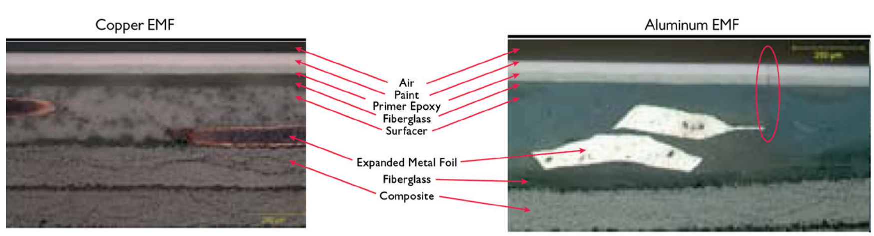
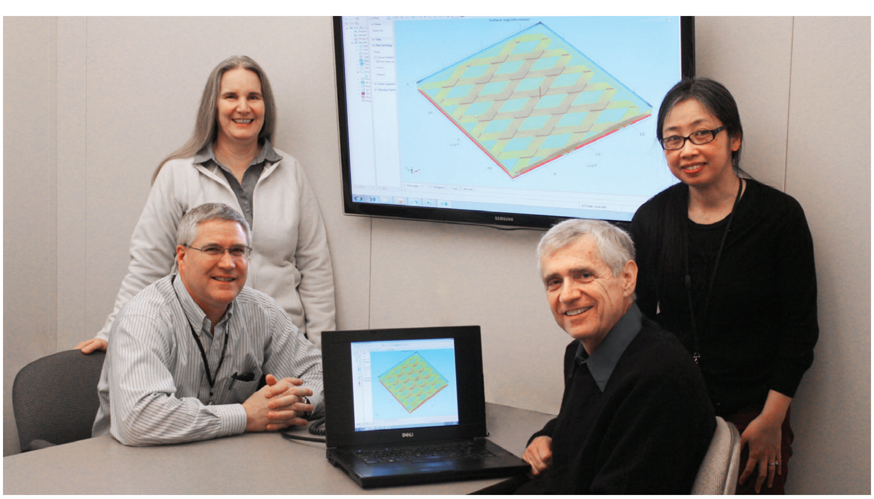


FIGURE 7. Photo micrographs of the composite structure layups after exposure to moisture and thermal cycling. At left, the results for the copper EMF and at right, the aluminum.



Research team at Boeing Research and Technology, from left to right: Patrice Ackerman, Jeffrey Morgan, Robert Greegor, and Quynhgiao Le.

displacement, increasing the mesh width or decreasing the aspect ratio are better strategies for increasing the current carrying capacity of the EMF for lightning strike protection.

RELATING DISPLACEMENT WITH CRACK FORMATION

Greegor and his colleagues at BR&T qualitatively regard any projected increase in displacement as an increased risk for developing cracks in the protective layers since mechanical stress due to thermal cycling accumulates over time.

Experimental evidence supports this logic as shown in Figure 7 in photo micrograph cross-sections of surface protection schemes with aluminum and copper EMF after prolonged exposure to moisture and thermal cycling in an environmental test chamber. The layup with the copper EMF shows no cracks, whereas the aluminum EMF led to cracking in the primer, visible edge and surface cracks, and substantial cracking in mesh overlap regions.

Over the same temperature range, the experimental results correlate well with the results from the simulations that consistently show higher displacements in the protective layers for the aluminum EMF. Both simulation and experiment indicate that the copper EMF is a better choice for lightning strike protection of aircraft composite structures. Multiphysics simulation is therefore a reliable means to evaluate the relative impact of the EMF design parameters on stress and displacement to better understand and reduce the likelihood of crack formation. ■

References

The information presented in this article is based on the following publicly available sources:

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