

# Thermal Simulation and Testing of Expanded Metal Foils Used for Lightning Protection of Composite Aircraft Structures

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## ABSTRACT

Since the 1960's, lightning protection of aircraft has been an important design aspect, a concern for the flying public, aircraft manufacturers and the Federal Aviation Administration (FAA). With the implementation of major aircraft structures fabricated from carbon fiber reinforced plastic (CFRP) materials, lightning protection has become a more complicated issue to solve. One widely used material for lightning strike protection of CFRP structures within the aerospace industry is expanded metal foil (EMF). EMF is currently used in both military and commercial passenger aircraft. An issue that has historically been an area of concern with EMF is micro cracking of paint on the composite structure which can result in corrosion of the metal foil and subsequent loss of conductivity. This paper addresses the issues of stress and displacement in the composite structure layout which contribute to paint cracking caused by aircraft thermal cycling. The analysis of EMF by computer modeling is made using commercially available COMSOL Multiphysics software that is supported by data from limited experimental testing. Variables that are explored include width, height, mesh aspect ratio, weight, composition and surface layout structure. Horizontal displacement profiles parallel to the surface are utilized for performance comparisons.

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## INTRODUCTION

Cracking of coatings and surface layers is evident on a variety of structures including buildings, automobiles and aircraft. In some situations the appearance of the coated or painted surface is degraded and the aesthetic appeal is lessened. However in others, such as composite aircraft structures, paint cracking is both aesthetically undesirable and potentially deleterious from the electromagnetic effects aspect. In the latter case, cracks can propagate into the structure or around fasteners, providing a path for moisture and other environmental species to enter, resulting in corrosion and degradation of the protection measures including expanded metal foils (EMF) required for lightning abatement and safe operation. Consequently, over several decades there have been numerous efforts and investigations<sup>[1, 2, 3]</sup> concerning the degradation of surface layer protection schemes.

Cracking typically develops over extended periods of time due to environmental factors and thermal cycling of the surface layers and substructure. The thermal cycling of aircraft is a direct result of the typical ground to air, then

ground again flight cycle. Subsequently, stresses accumulate in the coatings eventually leading to failure of their protective functionality. There are several contributors to the stress build up including the paint, primer, corrosion isolation layer, surfacer, EMF and the underlying composite substructure.

In this paper we focus primarily on the EMF contribution to the cracking mechanism. A representative surface layer protection scheme is addressed that is composed of the layers mentioned above. The approach taken is to simulate the temperature cycle of the layers using a coefficient of thermal expansion (CTE) model developed with the commercially available COMSOL Multiphysics<sup>[4]</sup> software. The simulation allows determination of the thermal stress and displacements that result. Though the full complexity of crack genesis is not included, some insight can be gained regarding what the sensitive parameters of the EMF may be and the variations that can be employed to mitigate the resulting stress and displacements which lead to cracking. Of particular interest are the EMF width, height, aspect ratio, composition (Aluminum (Al) or Copper (Cu)), and surface layout structure. In the case of Al used for EMF there is a need for fiberglass

between the aluminum and the structure to prevent galvanic corrosion. Though not the major thrust of this paper we also illustrate the potential effect on stress and displacement that results from the glass transition temperature of the paint layer.

In the following, we first describe the COMSOL model that was developed, followed by the simulation and experimental test results, a discussion of the results and a summary of the conclusions drawn from the simulations and testing.

## COMSOL MODEL

The software used to develop our CTE model to simulate the effects of EMFs incorporated in a composite surface protection scheme undergoing thermal excursions was COMSOL Multiphysics<sup>[4]</sup>. This software is a finite element solver that contains a variety of physics and engineering applications with an emphasis on coupled or multiphysics analysis. For our model we used the Thermal Stress Multiphysics Interface that combines solid mechanics with heat transfer. Coupling occurs where the temperature from heat transfer acts as a thermal load for the solid mechanics causing thermal expansion. The interface has the equations and features for stress analysis and general linear solid mechanics, solving for the displacements.

A representative surface protection scheme as shown in Figure 1, was created using the COMSOL model builder. The layup consisted of paint, primer, fiberglass, surfacer, EMF (Cu or Al), and fiberglass on a composite substrate. The height and size of all the layers could be varied using the input parameter list shown in Table 1. In addition to geometrical parameters, the initial and final temperatures could be varied and were chosen to be typical of altitude and ground, respectively. The strain reference temperature was the initial temperature and a representative heat transfer coefficient of 5 W/m<sup>2</sup>K was used.

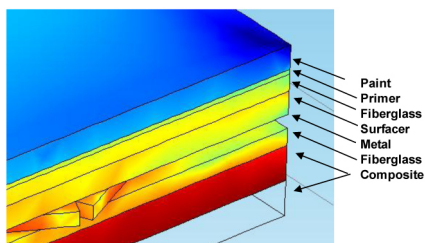


**Figure 1. Representative surface protection scheme modeled using COMSOL Multiphysics. The composite was modeled as two layers indicated by the red and light blue regions.**

**Table 1. Geometrical and thermal parameters used for surface protection model.**

| NAME     | DESCRIPTION               | COMMENT                                                  |
|----------|---------------------------|----------------------------------------------------------|
| SWD      | Short Way Diamond         | Notation Used by DEXMET (Ref. 5) for Expanded Metal Foil |
| LWD      | Long Way Diamond          | Notation Used by DEXMET (Ref. 5) for Expanded Metal Foil |
| H_metal  | Height Metal              | Vertical Thickness of Expanded Metal Foil                |
| W_metal  | Width Metal               | Horizontal Width of Expanded Metal Foil                  |
| L_compo  | Length Composite          | Length on a Side of Coupon Modeled                       |
| H_paint  | Height Paint              | Vertical Thickness of Paint                              |
| H_primer | Height Primer             | Vertical Thickness of Primer                             |
| H_fiber  | Height Fiberglass         | Vertical Thickness of Fiberglass                         |
| H_surfac | Height Surfac             | Vertical Thickness of Surfac                             |
| H_compo  | Height Composite          | Vertical Height of Composite                             |
| T_init   | Initial Temperature       | Temperature at Altitude                                  |
| T_final  | Final Temperature         | Temperature on Ground                                    |
| htc      | Heat Transfer Coefficient | Used Typical Value                                       |

In addition to the height and width, the aspect ratio of the EMF mesh could also be varied. The metallic mesh aspect ratio is given by SWD/LWD where SWD is the short way of the diamond and LWD is the long way of the diamond as described by DEXMET<sup>[5]</sup>, a commercial producer of EMF. Examples of SWD/LWD ratios from 0.25 to 1.0 for a 1 inch square are shown in Figure 2.

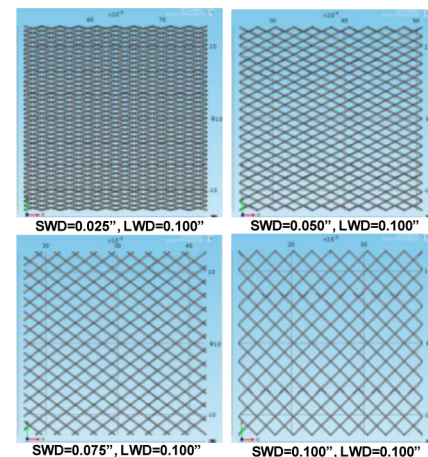


**Figure 2. Examples of SWD/LWD ratios from 0.25 to 1.00 for a 1 inch square EMF.**

The material properties needed for each of the layers were the coefficient of thermal expansion (CTE), heat capacity, density, thermal conductivity, Young's Modulus and Poisson's ratio. Many of these parameters have a dependency on temperature, but for our simple model we used the values<sup>[6]</sup> shown in Table 2 across the temperature range of interest. The one exception was the CTE of the paint layer where a step function was employed at the glass transition temperature,  $t_g$ . For this layer, a step function was employed similar in form to a Fermi-Dirac distribution. In this manner we could slide the  $t_g$  both within and outside the nominal temperature range of interest. Since convergence of the

solution could be sensitive to the abrupt step, we allowed for the step to be rounded if needed. The functional form and plots of the CTE as a function of temperature for  $t_g = 276$  K and 350 K are shown in [Figure 3](#).

**Table 2. Representative input material parameters used for the various layers of the surface protection model.**

| Parameter                   | Paint                                  | Primer   | Fiberglass | Surfacer | Aluminum | Copper  | Composite |
|-----------------------------|----------------------------------------|----------|------------|----------|----------|---------|-----------|
| CTE (1/K)                   | $8.14e-5 T < T_g$<br>$24.4e-5 T > T_g$ | $4.0e-5$ | $12.6e-6$  | $5.5e-5$ | $23e-6$  | $17e-6$ | $3.20e-5$ |
| Heat Capacity (J/kgmK)      | 1260                                   | 1050     | 921.1      | 1050     | 900      | 385     | 770       |
| Density (kgm/m3)            | 1630                                   | 1840     | 2460       | 1980     | 2700     | 8700    | 1600      |
| Thermal Conductivity (W/mK) | 0.419                                  | 0.837    | 0.668      | 0.837    | 160      | 400     | 11.8      |
| Young's Modulus (Pa)        | $1.8e8$                                | $5.5e9$  | $1.68e10$  | $5.9e9$  | $70e9$   | $110e9$ | $9.5e10$  |
| Poisson's Ratio             | 0.42                                   | 0.16     | 0.11       | 0.20     | 0.33     | 0.35    | 0.25      |

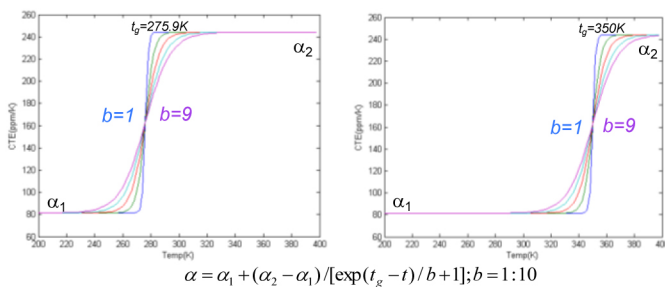


**Figure 3. Representative CTE functional form of paint layer used in the model. Note that a value of  $b=3.0$  was used to decrease the abrupt step in CTE.**

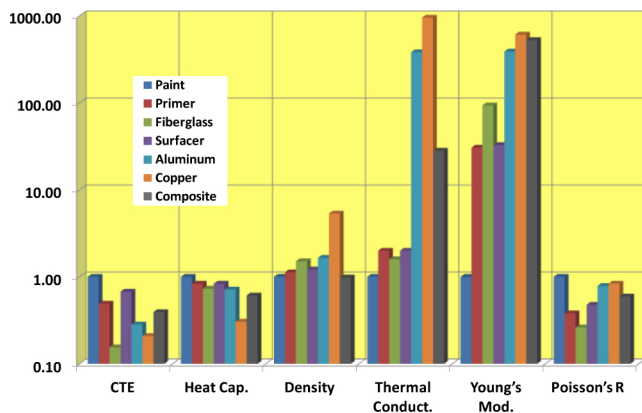


**Figure 4. Ratio of representative material parameters to those of the paint layer.**

As shown in [Figure 4](#), for the representative input parameter values shown in [Table 2](#) it can be seen that the paint has a larger CTE, heat capacity and Poisson's Ratio than the underlying layers. Among other effects, this means that the paint will undergo compressive stress when the layers are heated and tensile strain when cooled. Hot materials under

stress relax through creep, but this effect was not included in our model. For the other material parameters used the density, thermal conductivity and Young's Modulus were larger than the paint layer. In particular, for the EMF Al has a larger CTE than Cu, and a smaller Young's Modulus.

## SIMULATION RESULTS

For the purposes of this paper we confine our simulations to heating over a representative air to ground temperature range which the surface protection scheme is expected to perform. The resulting false color Von-Mises stress and displacement patterns are shown in [Figure 5](#). In this figure the view is from the top paint layer with cross-sectional views from the four sides. Obviously, the displacements have been magnified to highlight the movement that is induced by the temperature cycle. In the central portion of the figure the pattern of the underlying EMF can be seen. We observe variations in the displacement above the metal mesh and voids, that are quite evident in the cross-sectional profiles. Also, we observe high stress (red - high, blue - low) in the mesh itself and the region in the mesh voids where surfacer material was modeled. The profiles show that the stress decreases from the bottom to the top of the surface layers. High stresses are clearly indicated in the EMF as shown in [Figure 6](#), where a semi-transparent stress image was generated.

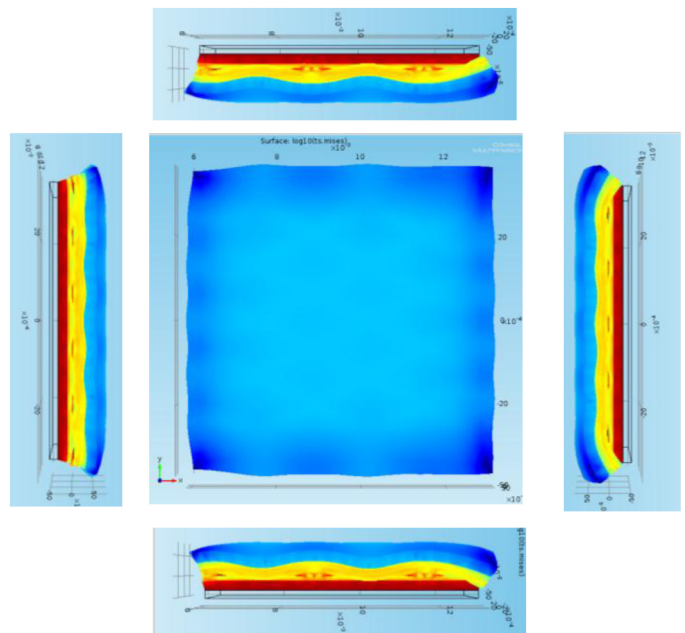


**Figure 5. Von-Mises stress patterns due to thermal air to ground heating cycle. EMF mesh bleed-through is evident in the central portion of the figure and relatively large displacement variations are observed above the metal and voids. Note that the displacements have been magnified for illustrative purposes.**