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Modeling of Lightning Direct Effects – Interaction of Continuing Current with Aluminum Skins

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Overview

- Background
- Experimental Testing
- COMSOL Modeling
- Results
- Discussion
- Conclusions

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Background

- Lightning
  - Naturally-occurring high-current, high-voltage discharge of electricity in atmosphere
    - Not entirely understood
      - Exact mechanism of electrical charge development/breakdown in the cloud
      - Stepped-leader formation/propagation
      - Ball lightning: a visual perception as a result of magnetophosphenes induced in the visual cortex due to strong electromagnetic transients [1,2]
- Lightning and Aircraft
  - Aircraft is susceptible & vulnerable to lightning
  - Lightning strike to an aircraft in flight may lead to a catastrophic event

[1] Peer et al. **Transcranial stimulability of phosphenes by long lightning electromagnetic pulses**. *Physics Letters A* (2010)
[2] Cooray, G. and V. Cooray, *The open access atmospheric science journal*, vol. 2, pp. 101–105 (2008)

Modern Aircraft - Aluminum & CFRP Skins

- Mechanism of lightning damage to Al & CFRP skins is different

- Lightning attachment & current propagation – Direct Effects
  - Materials physical and electrical properties
  - Composite aircraft
    - $\sigma_{Aluminum}$ ~1000> σ_{CFRP}
    - Additional protection
    - Metallic meshes or interwoven wires

- In-depth understanding of how lightning may affect the integrity of aircraft structure is critical for proper protection design & safety

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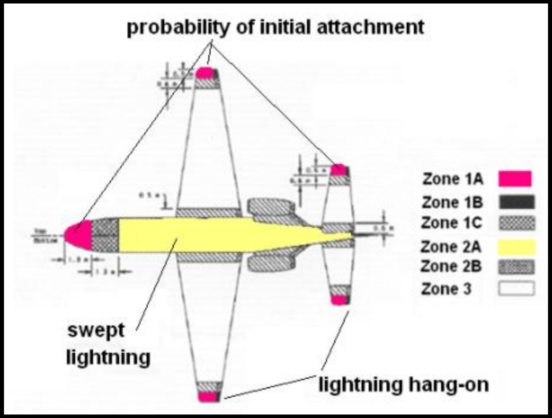
Lightning and Aircraft



- Severity of Damage Caused by Lightning
  - Aircraft geometry dictated
  - Aircraft zones[1]
- Simulated vs. Natural Lightning
  - For analysis, testing, & certification
  - Idealized current waveform components A, B, C, & D[2]
    - A – current pulse: action integral
    - C – continuing current: amount of transferred charge
  - Aircraft zones are defined by certain sequences of I-components
- Choice of Protection/Skin Thickness
  - Physical testing of aircraft skin materials
  - High-current test : laboratory-simulated lightning discharge[3]

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[1-3] SAE Aerospace Recommended Practice 5414, 5412, & 5416

Why Model Lightning?

- No attempts have been made to model physics of the direct effects
  - Develop model capable of predicting the damage
  - Reduce amount of experimental testing
  - Model cases that cannot be easily tested

- Provide a reliable tool for aircraft community able to determine the optimum metal skin thickness or protection for composite skins

- Gain Insight into Occurring Multi-Physical Processes
  - Establish a scientific base in understanding materials behavior under the conditions of simulated lightning
  - Possibly help resolving multitude of conflicting opinions

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Previous Research

- Empirically-derived analytical expression relating constant amount of charge to the melt-through areas
- Dependency of melting effects on current amplitude
  - Rate of charge transfer may be a decisive factor in determining the damage
  - The nature of this dependence is not intuitive
- Due to insufficient experimental work large amount of data is extrapolated

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Our Work

- Long-Term Goal
  - Model damage in composite and aluminum skins
  - Utilize COMSOL Multiphysics simulation environment
- Presently
  - Model continuing current characteristic of Component C in Al skins
    - Long-duration current
    - Rectangular 200-800 A waveform
    - Time 0.25-1 s
    - 200 C (±20%) of charge transfer
  - Typical Damage
    - Melt-through /hot spot formation manifesting into fuel ignition in metal skins
    - Function of material's thickness, electrical conductivity, and surface finish
  - Model Requirements
    - Employ ideal rectangular waveform input parameters
    - Investigate whether a close match with the non-ideal test conditions is possible and damage is predictable

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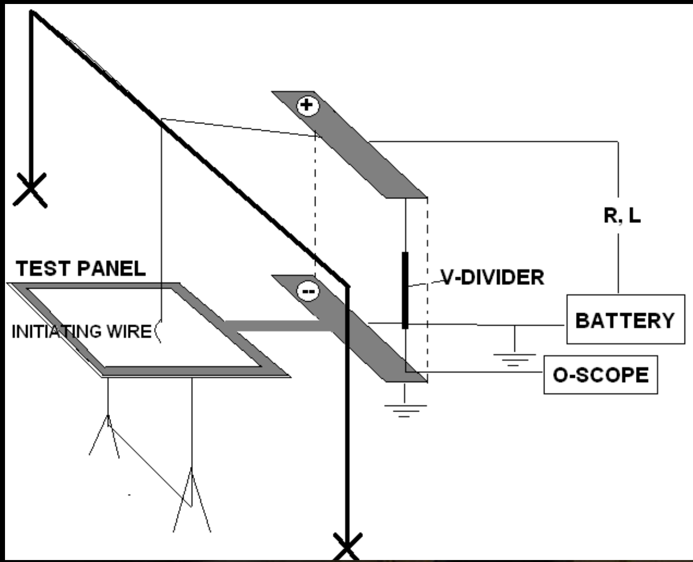
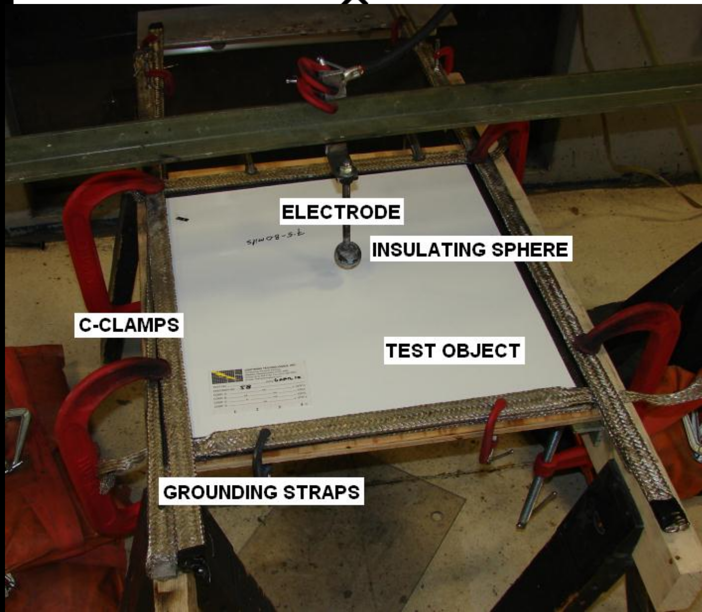
Experiment

- **High-Current Direct Effects Testing**
  - LTI, Pittsfield, MA
  - Continuing current (component C)
- **Six-Case Study**
  - Deliver 200-coulomb charge
  - At 50, 200, & 500-ampere current amplitudes
- **Test articles**
  - 20″-square bare 7075 aluminum sheets
  - 0.028″ and 0.050″ panel thickness
    - Choice of panel thickness - typical aircraft skin thicknesses requirement
- **Measurements**
  - V-t & I-t characteristics
  - Melt-through areas





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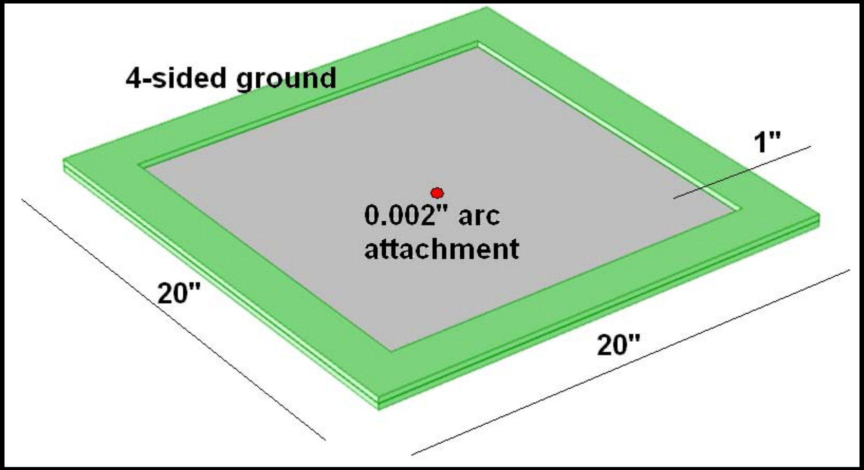
COMSOL Multiphysics

- 3D time-dependent steady-state Joule heating analysis
  - Coupled electrical-thermal interaction
  - Final time temperature distribution
  - System of governing equations

$$-\nabla \cdot \left(\sigma \nabla V - \vec{J}^{e}\right) = Q_j$$

$$\nabla \cdot \left(-k \nabla T\right) = Q + q_s T$$



- Model description
  - Geometry
  - Aluminum 7075 material properties
  - Two frames - ground potential
  - Attachment point -
    high potential – current injection – ideal rectangular I-waveform (V=IR)
  - Resistance of the object under IC's: 2 mΩ (thin) & 1.5 mΩ (thick) panels
  - Aluminum-air heat transfer - heat transfer coefficient 25 W/m^{2}K
  - Temperature-independent Al electrical conductivity
- Extremely coarse free tetrahedral meshing
- Finite element model

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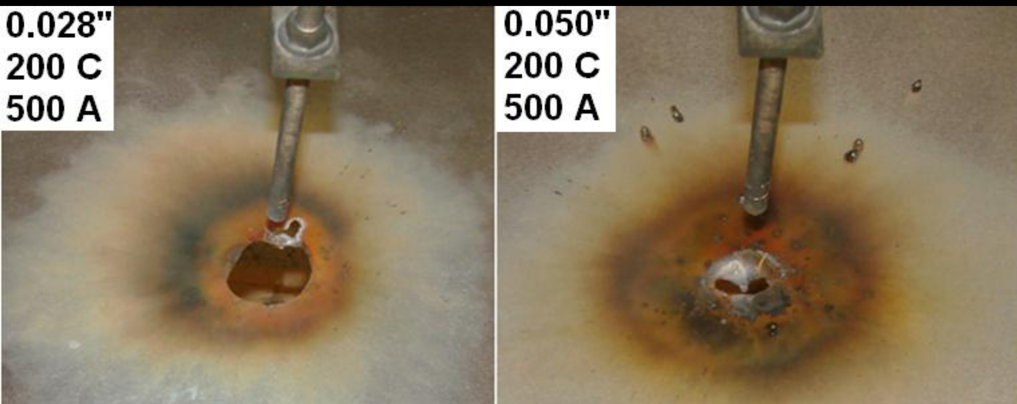
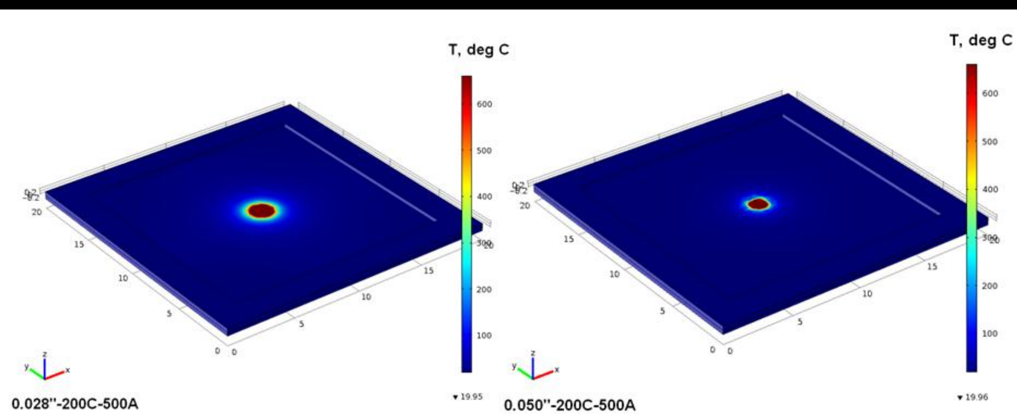
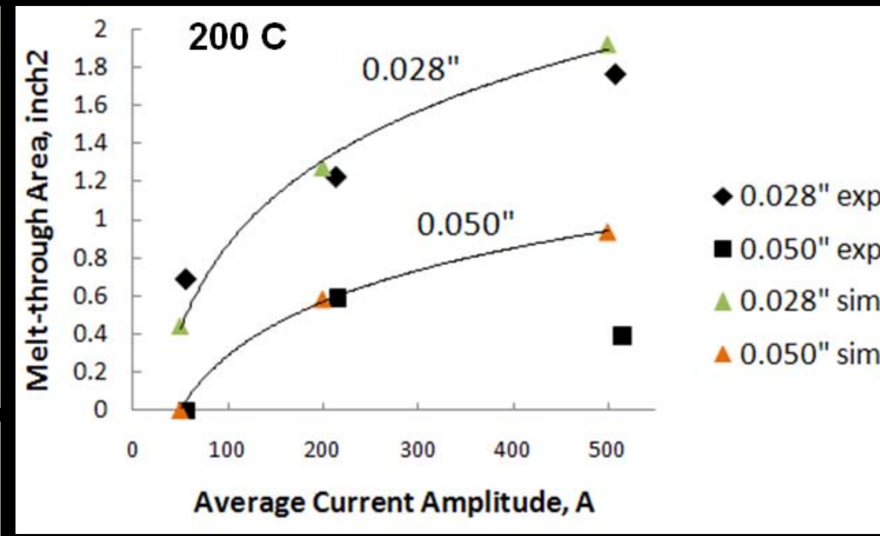
Comparison of Experimental and Simulated Damage Areas





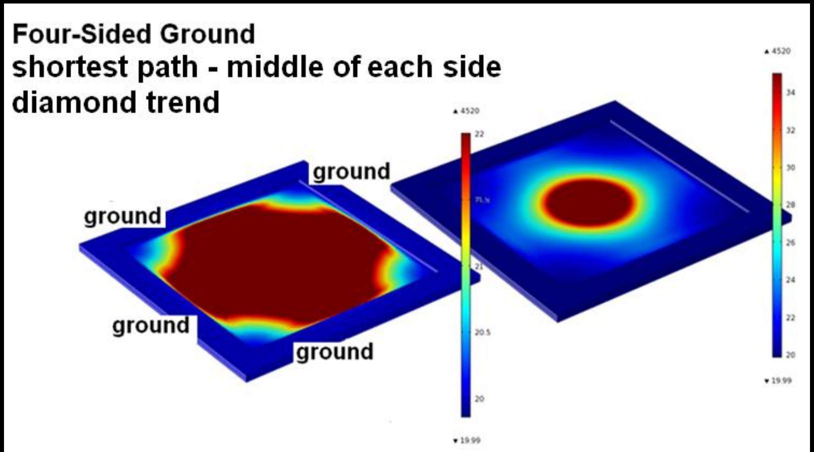
Damage areas & simulated final T-distributions. The red areas are the damage as a result of 200 C at 500 A.

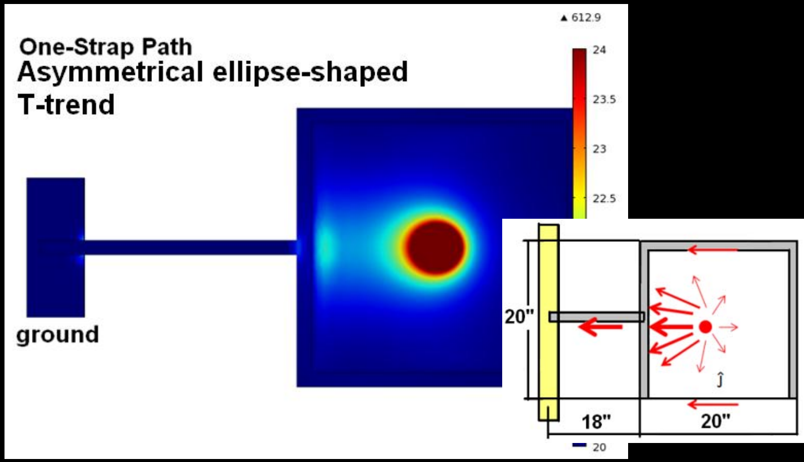


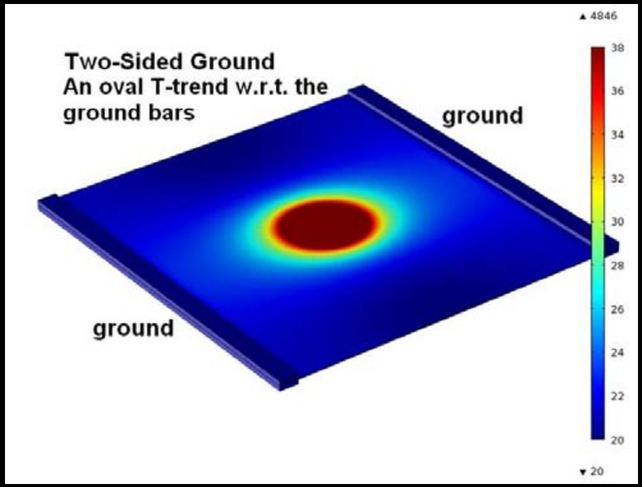
- Logarithmic dependence
- No perfect match obtained
- Imperfectly-shaped damage areas
- Deviation of experimental point
    - Atypical arc evolution
    - Insufficient experimental data
- ρ_{Al}=f(T) was not considered

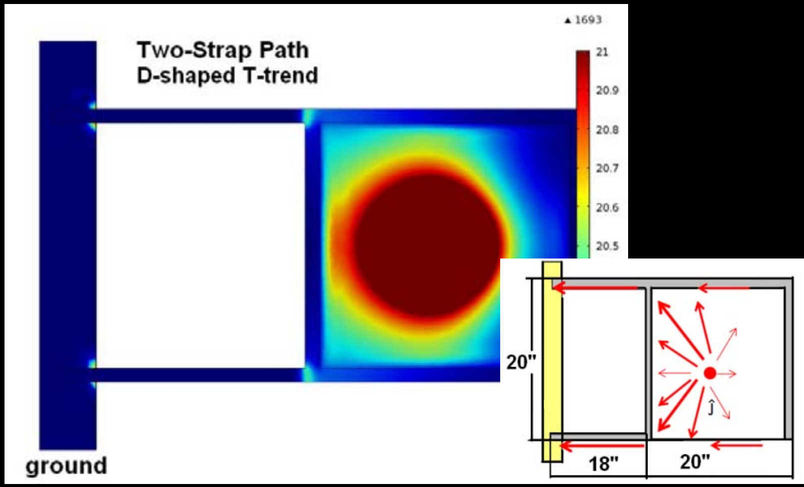
Convenience of the Model

- Helps visualize influence of current return geometry on T-distribution in the specimen









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Concluding Remarks

- Demonstrated a successful effort in modeling of lightning continuing current in bare aircraft-graded Al sheets

- Next Step - Model Upgrade
  - Perform transient analysis vs. time-dependent steady-state
  - Account for proper geometry of the ground return
  - Include T-dependent electrical conductivity of the test object