Analysis of Thermal Strains in Composite Integral Armor

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Agenda

- Background
- Purpose
- Experimental Model
- Finite Element Model
- Theoretical Analysis
- Results and Discussion
- Conclusions

Background

- Need for lightweight alternative to fleet of armored vehicles
- Performance of composite armor
  - Ballistic
    - Single hit vs. multi-hit
    - Gama et al., Mahfuz et al., Monib and Gillespie, DeLuca et al.
  - Structural
    - Mechanical loading (Huang et al., Dávila et al., Mahdi and Gillespie)
    - Thermal loading (not as well characterized)
- Composite armor must operate in diverse environmental conditions

Background

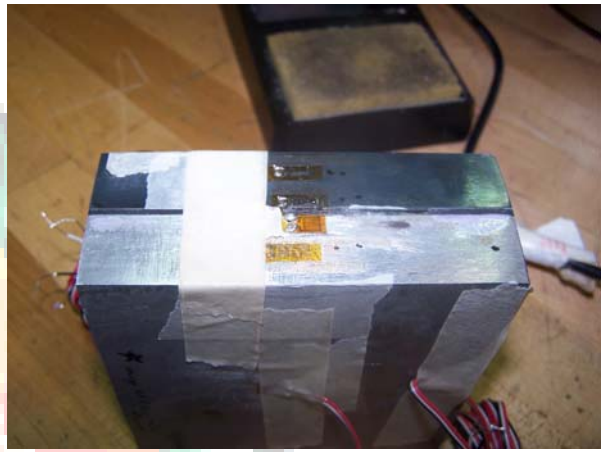
- Thermal loads induce thermal and mechanical strains
  - potential weakening of bonding resin due to varying temperatures
  - weakening of composite armor which may impact survivability and structural integrity

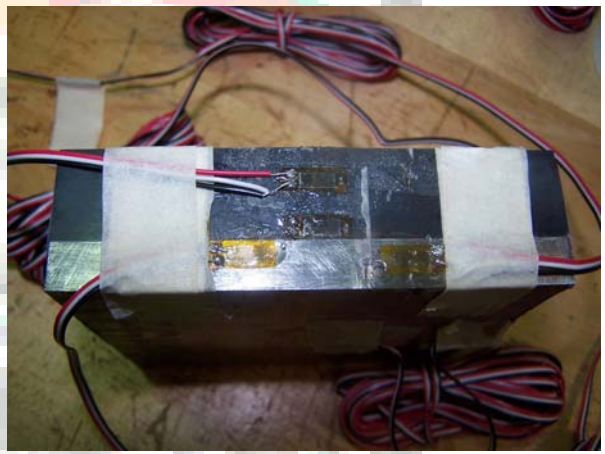
Purpose

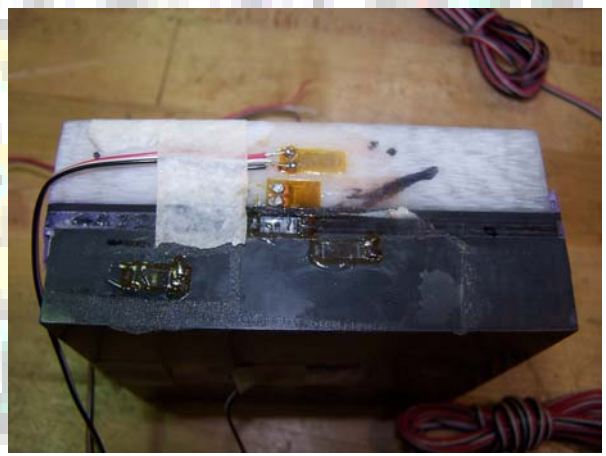
- To investigate the feasibility of modeling thermal and mechanical stresses induced in composite armor due to expected operating thermal loads

Experimental Model

- Analyzed various composite recipes
  - Backplate materials
    - Al 5083, Ti 6-4, and S2 glass blend
    - S2 glass blend had additional IM7 carbon layer
  - Exterior ceramic tile (silicon carbide)
  - Ethylene Propylene Diene Monomer (EPDM) rubber layer used to test decoupling of thermal strains with each backplate material
- Strain gages attached to each layer except for rubber





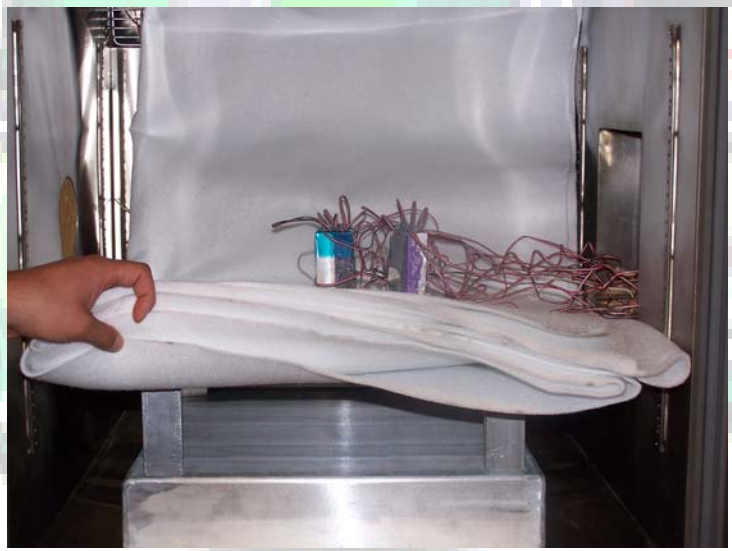


Experimental Model

- Composite specimens tested in environmental chamber at four target temperatures (-51.1ºC, 12.2ºC, 48.9ºC, 82.2ºC)

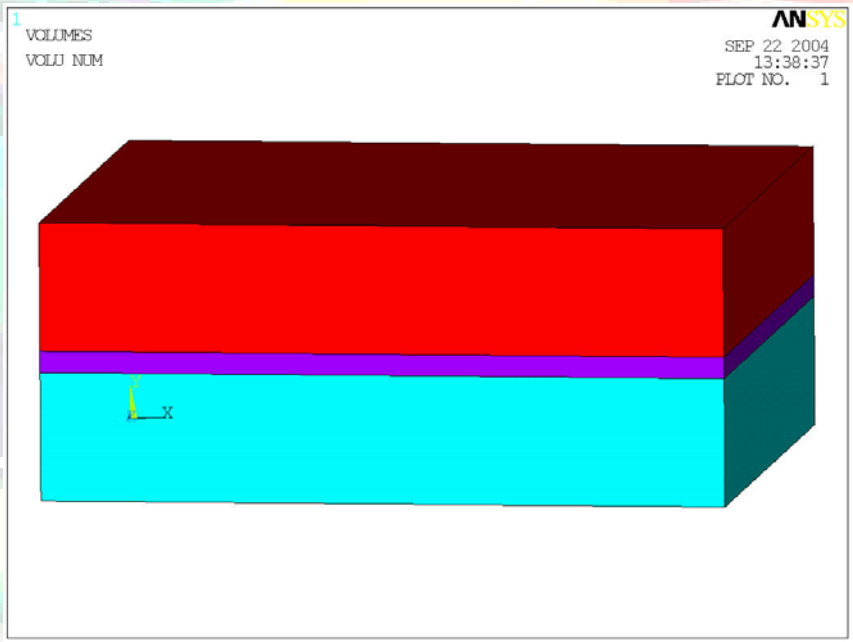
Experimental Model

- Temperatures held for six hours to ensure thermal equilibrium
  - Strain gage readings did not fluctuate
  - Thermal blanket used to prevent thermal shock
  - Strain readings taken every three seconds during entire programming sequence



Finite Element Model

- ANSYS 8.1 used to model composite armor recipes



Finite Element Model

- Boundary conditions on bottom plate
  - One corner node fixed in all degrees of freedom
  - Another corner node on same edge fixed in x- and y- translation
  - Remaining corner nodes fixed in y- translation (prevent overturning)
- Thermal loads from experiment applied to finite element model (-51.1ºC, 12.2ºC, 48.9ºC, 82.2ºC)

Finite Element Model

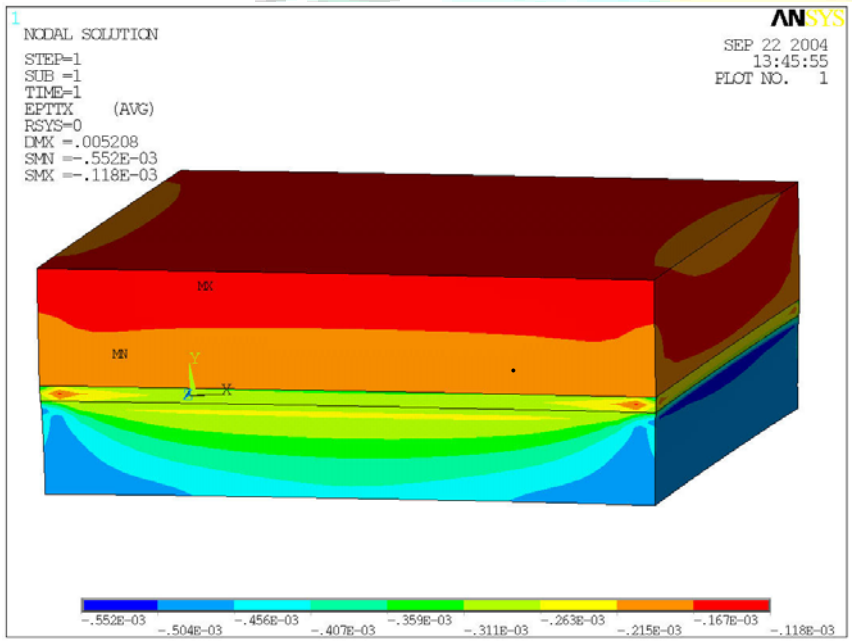
- Material Properties
  - Isotropic properties and linear strain profile assumed for Al and Ti

Sample Name	Young's Modulus (Mpsi)	Poisson's Ratio	Shear Modulus (Mpsi)	Coefficient of Thermal Expansion (x 10^{-6})(1/ºF)
Aluminum	11.1	0.33	4.17	13.1
Titanium	16.5	0.16	6.2	2.2
EPDM Rubber	0.0503	0.49	n/a	320

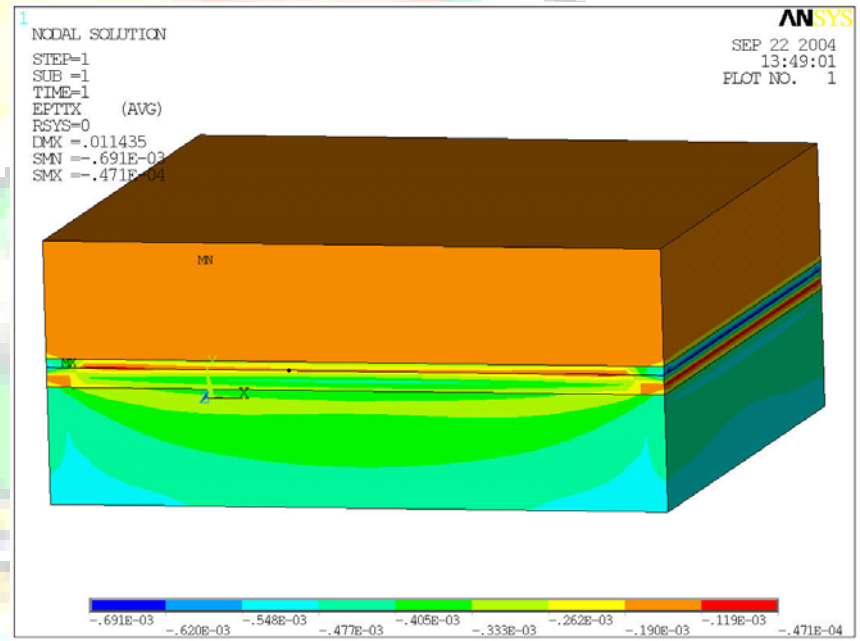
Finite Element Model

- Material Properties (cont)
  - Orthogonal properties for S2 glass and IM7 carbon since each layer has different fiber orientation
  - CMAP used to determine effective properties in each orthogonal direction
- Models generated by ANSYS 8.1 produced strain contour plots; strain contours were symmetric (boundary conditions validated)

Finite Element Model



Strain contour plot of S2 glass specimen at $48.9^{o}C$



Strain contour plot of S2 glass with rubber specimen at $48.9^{o}C$

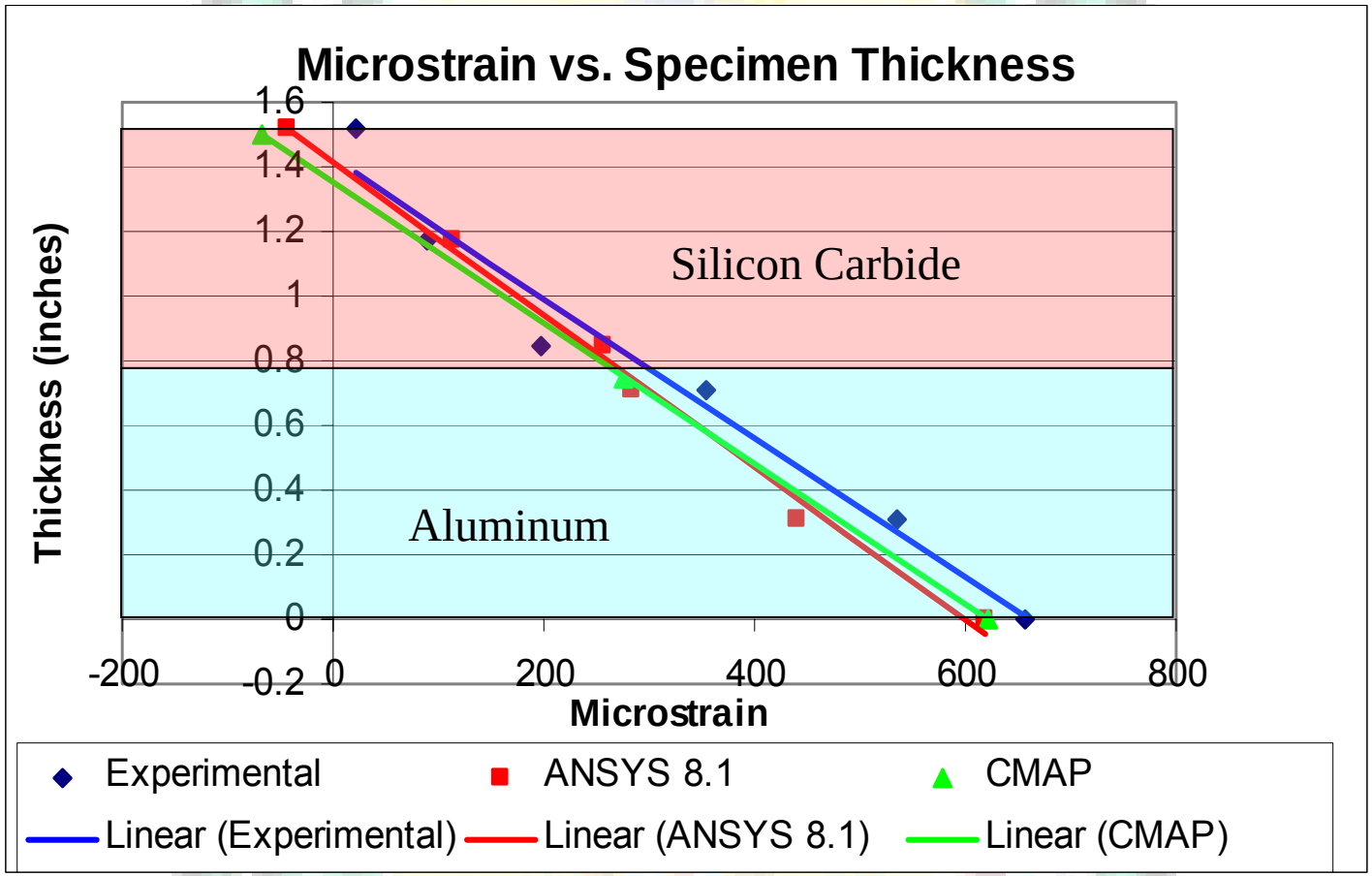
Theoretical Analysis

- Composite Materials Analysis of Plates (CMAP) used to conduct theoretical analysis
  - CMAP uses classical laminate plate theory
    - Assumes infinite plate length and linear strain distribution
    - Strain gages placed in areas without edge effects (nonlinear regions)
  - CMAP also used to determine effective material properties for composite specimens (S2 glass and IM7 carbon materials)

Theoretical Analysis

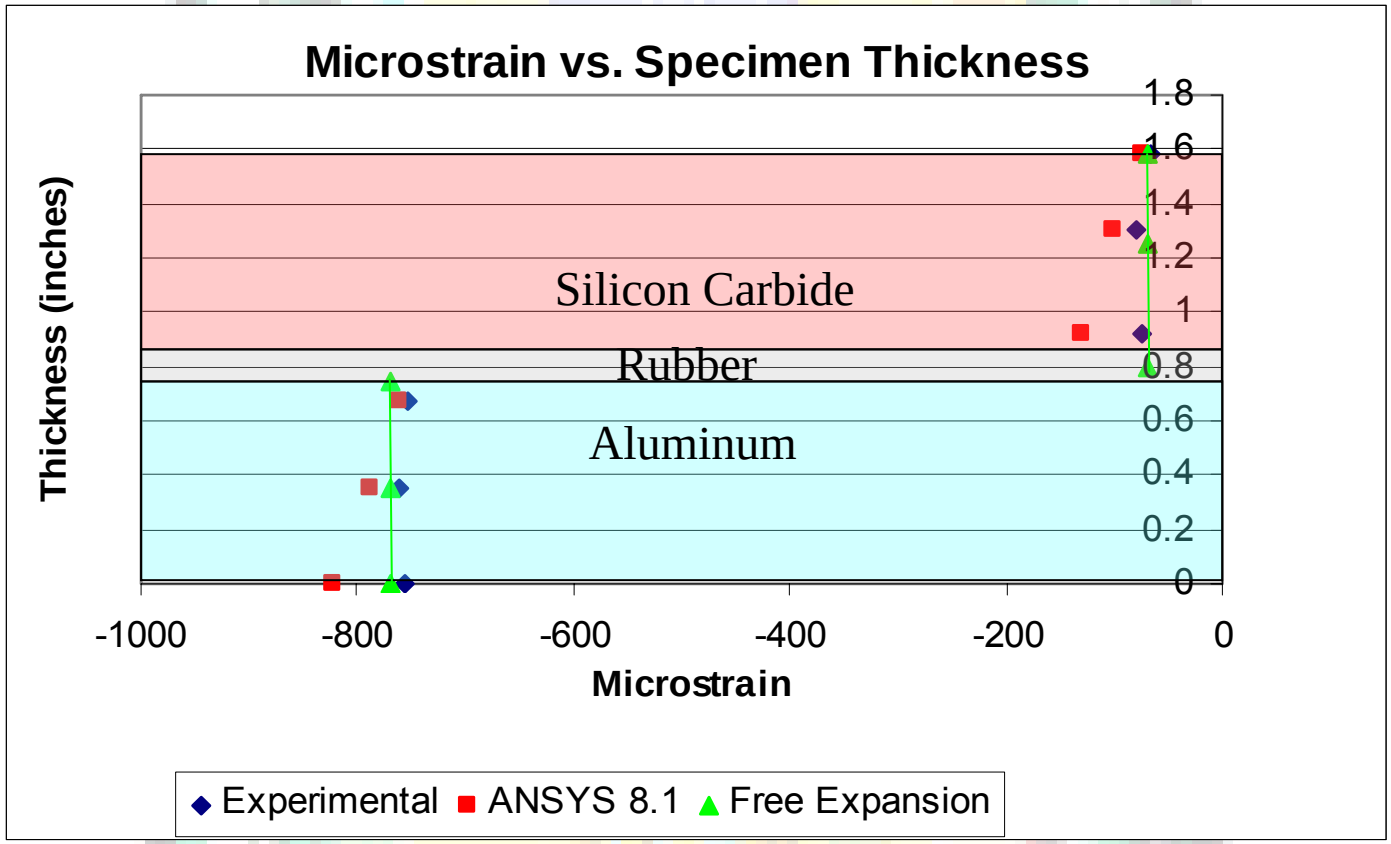
- Linear free expansion
  - CMAP could not accurately model decoupled strains due to compliant rubber layer
  - Bond failure and excessive voids at bonding interface of rubber simulated two non-interacting materials
  - Linear free expansion used for materials with EPDM rubber layer (based on $\alpha\Delta T$)

Results and Discussion



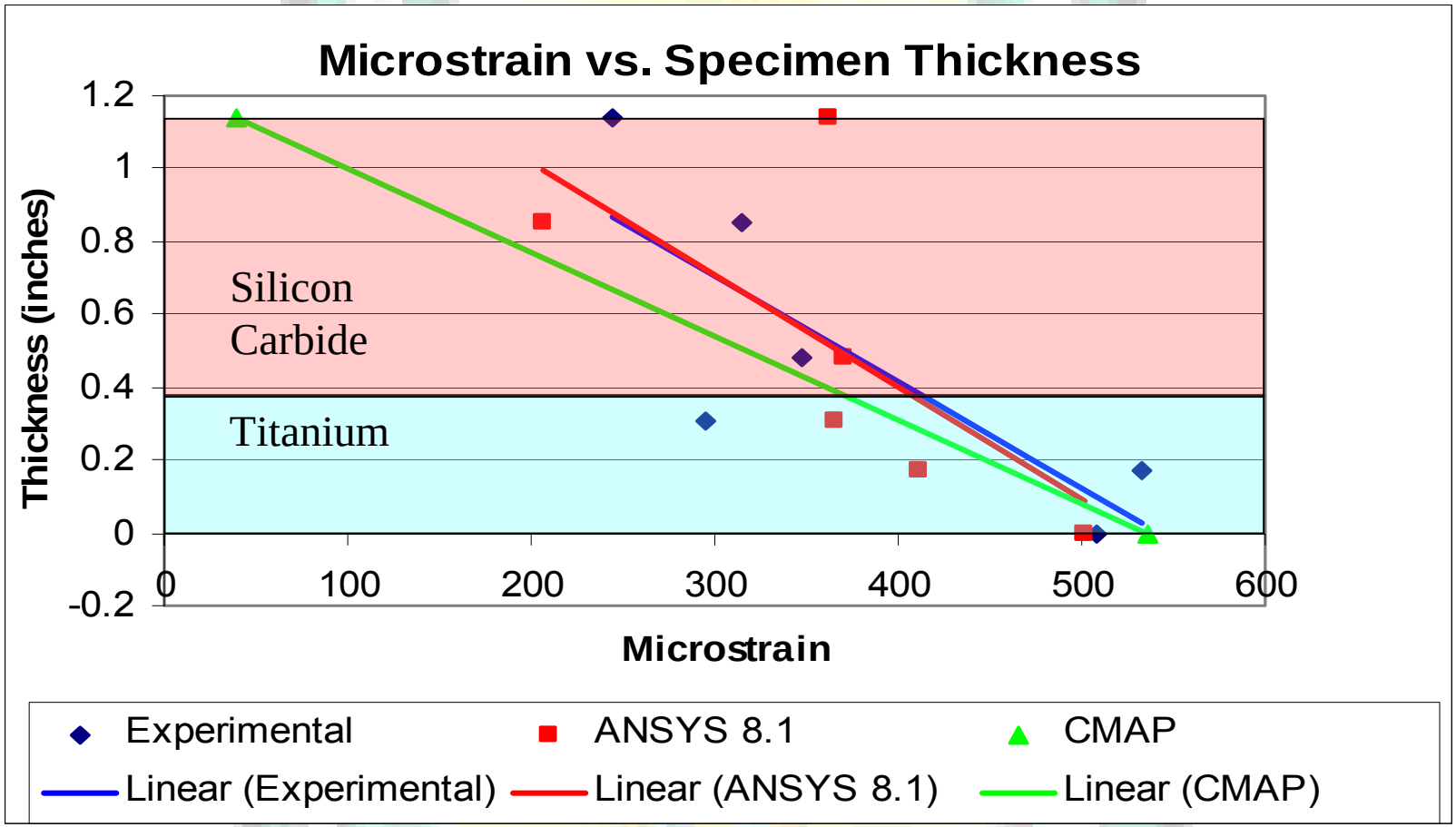
Al5083 without EPDM rubber at 120ºF

Results and Discussion



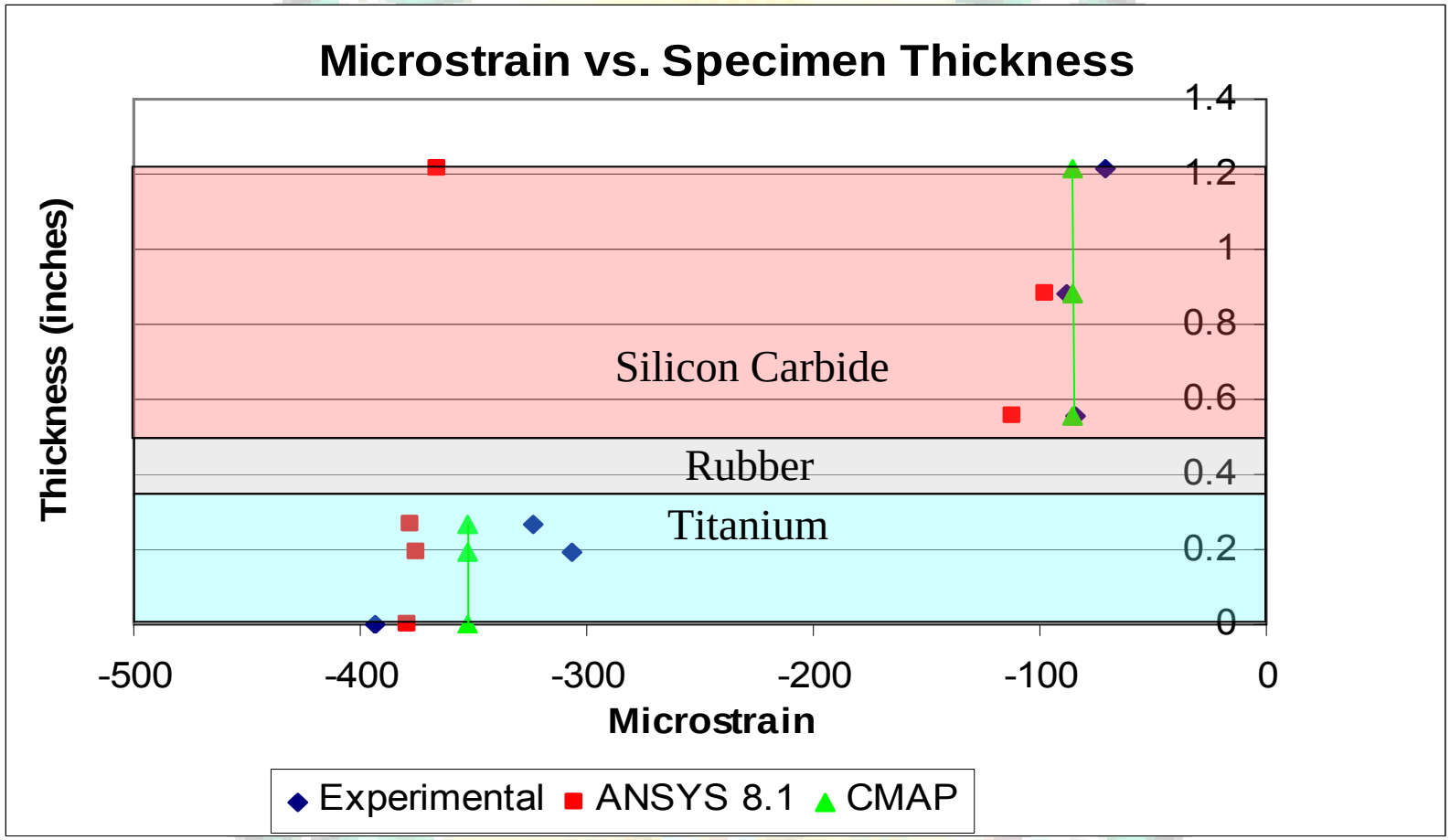
Al5083 with EPDM rubber at 10ºF

Results and Discussion



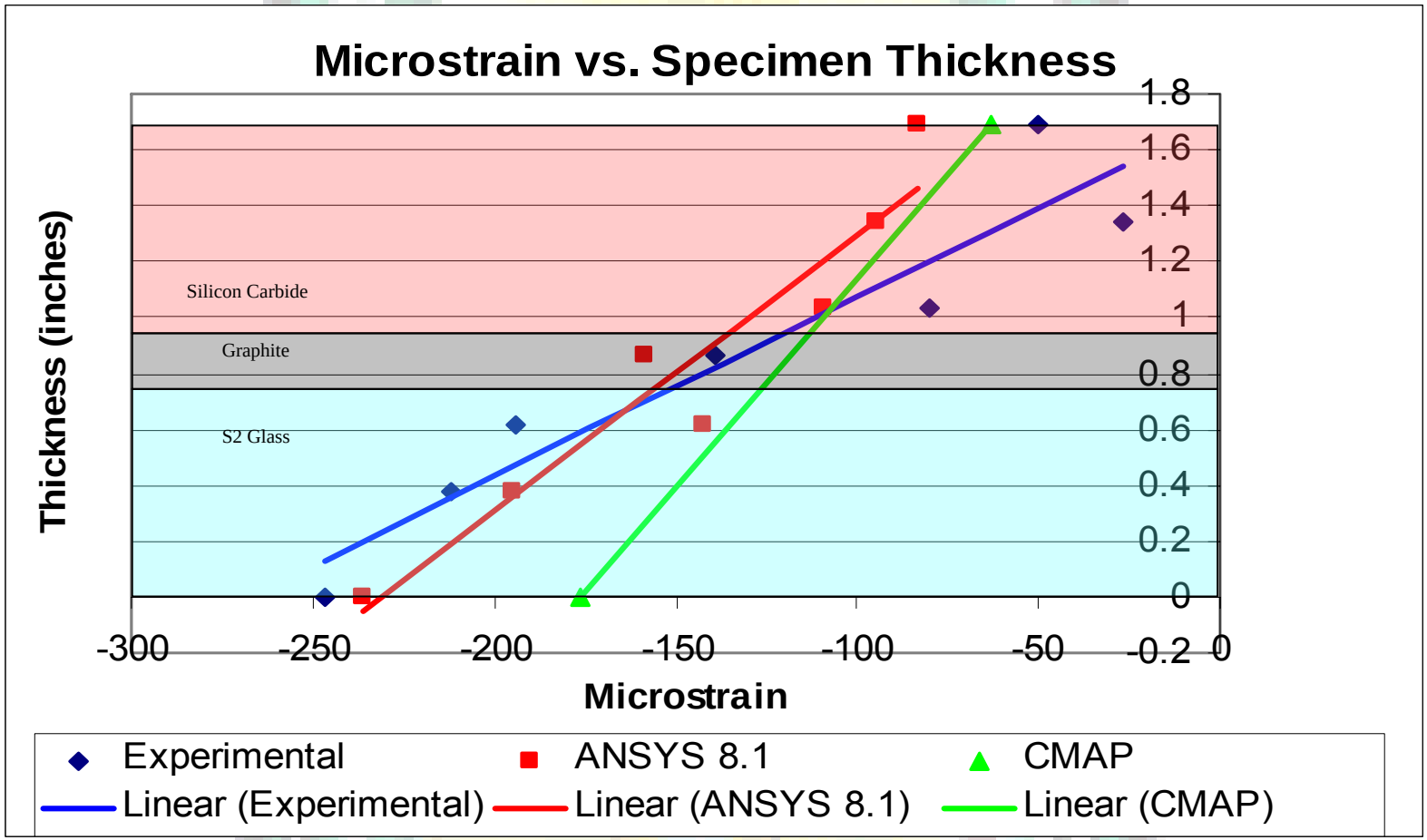
Ti 6-4 without EPDM rubber at 180ºF

Results and Discussion



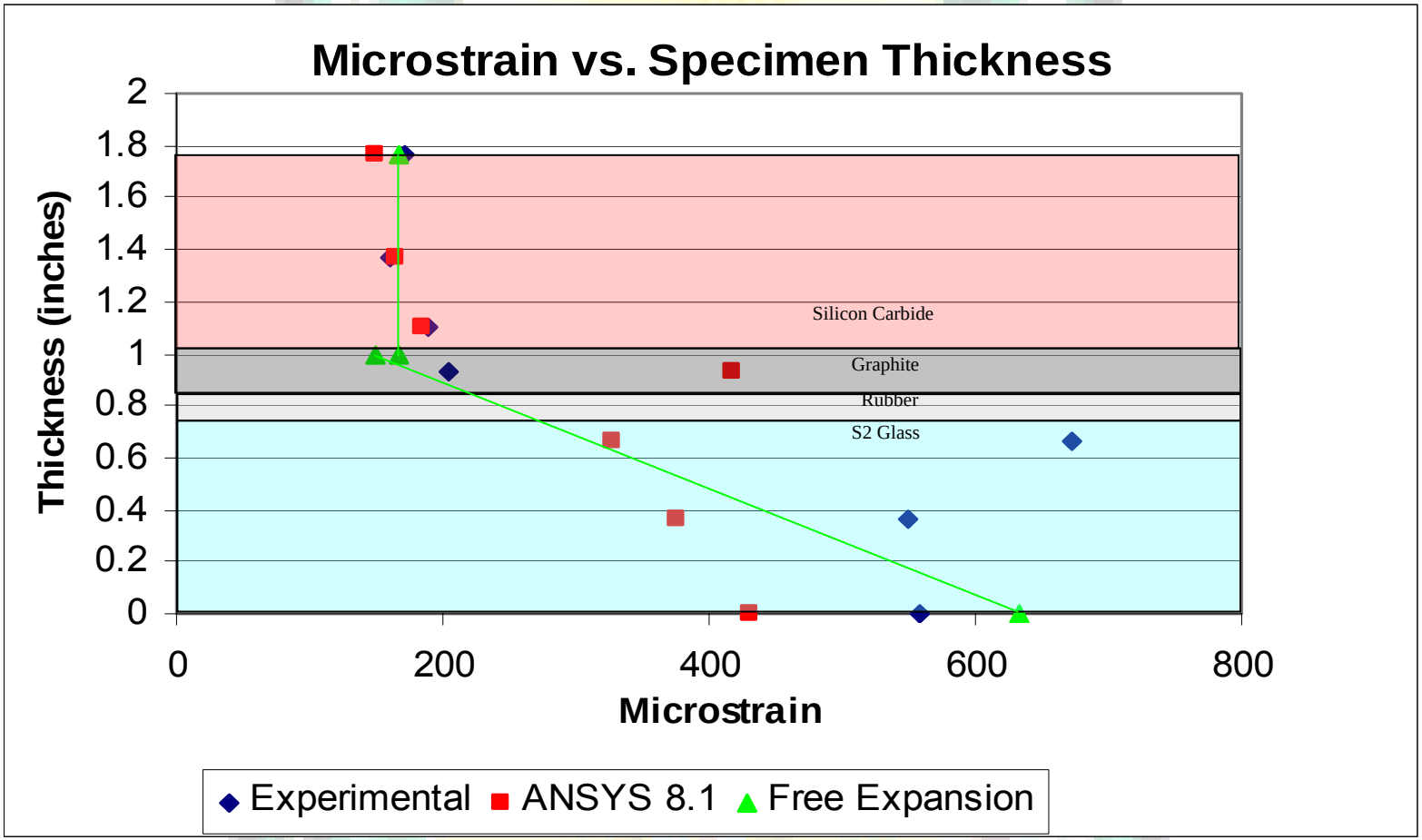
Ti 6-4 with EPDM rubber at 180ºF

Results and Discussion



S2 Glass without EPDM rubber at 10ºF

Results and Discussion



S2 Glass with EPDM rubber at 180ºF

Conclusions

- ANSYS 8.1 finite element model and CMAP model provided fairly accurate thermal and mechanical strains for materials with good characterizations.
- Thermal strain mismatch between materials with significantly different coefficients of thermal expansion caused delamination especially at high temperatures.
- Bonding resin failed to maintain perfect bonding between layers. Low temperature degradation of bonding resin was observed in all experimental recipes with rubber.
- EPDM rubber provided a compliant layer which served to decouple the thermal and mechanical strains between the ballistic protective layer and the structural backplate layer.
- Coupon lay-up procedure should be standardized and manufacture of composite specimens should be within a strict tolerance.

Future Work

- Material properties must be validated at elevated (and lowered) temperatures.
- Non-orthogonal material property tests must be performed on S2 glass, IM7 carbon and EPDM rubber specimens.
- Models can be used to investigate the combination of stresses and strains when a mechanical load is applied to the composite armor, such as in-plane shear loading.
- Cadet capstone design to investigate in-plane shear loading of composite armor.

Questions?