



**AFRL-RQ-WP-TM-2013-0264**

**SPATIALLY TARGETED ACTIVATION OF A SHAPE  
MEMORY POLYMER-BASED RECONFIGURABLE SKIN  
SYSTEM**

**Greg Reich, James Joo, and Nate DeLeon**

**Design and Analysis Branch  
Aerospace Vehicles Division**

**Richard Beblo and John Puttmann  
University of Dayton Research Institute**

**DECEMBER 2013  
Interim Report**

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# REPORT DOCUMENTATION PAGE

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<b>14. ABSTRACT</b> The objective of the project is to investigate the thermomechanical behavior of engineered shape memory polymer (SMP) materials for use as composite reconfigurable skin systems in morphing aircraft applications. An anisotropic, reconfigurable skin based on selective heating of a cellular SMP material will be designed and investigated to understand its material characteristics.					
<b>15. SUBJECT TERMS</b>					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT:</b> SAR	<b>18. NUMBER OF PAGES</b> 40	<b>19a. NAME OF RESPONSIBLE PERSON (Monitor)</b> James J. Joo
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			



# **Spatially Targeted Activation of a Shape Memory Polymer Based Reconfigurable Skin System**

**Dr. Greg Reich  
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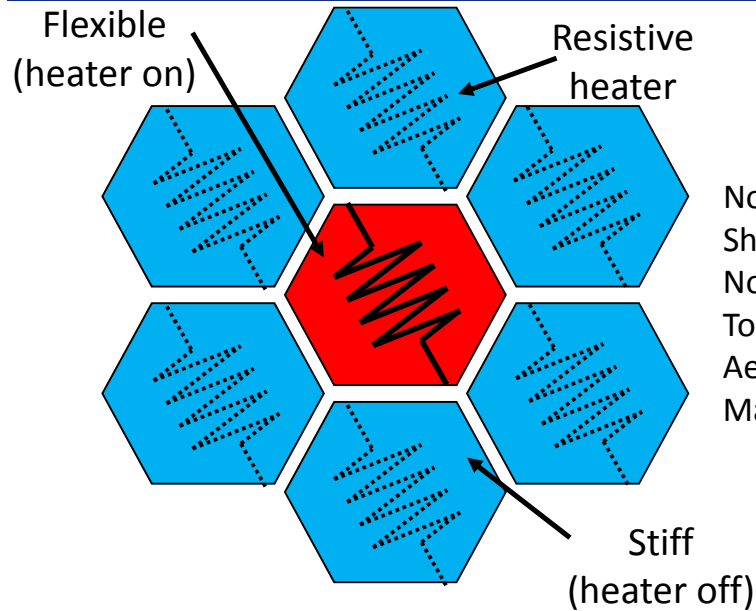
# Outline



- **Project Outline**
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- **System Modeling**
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- **Heating Pattern Optimization**
- **Future Work**
- **Conclusions**

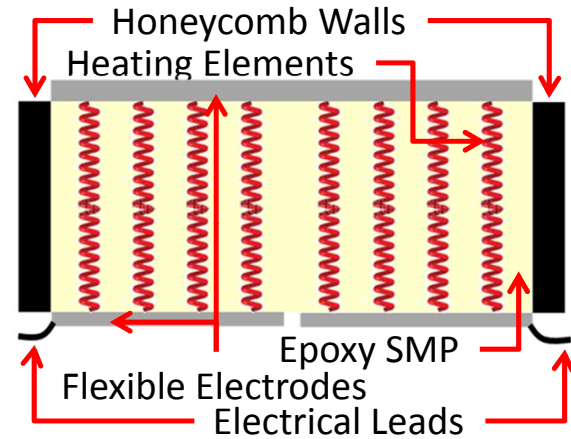


# Project Outline



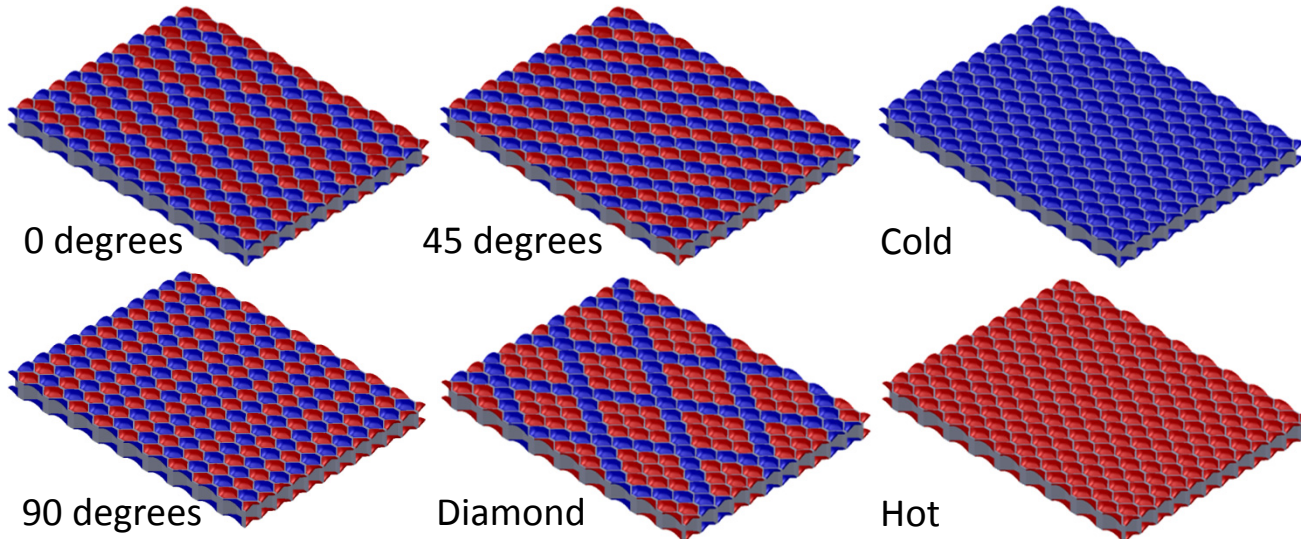
### Skin Objectives (via MAS)

- Nominal Panel Size 15" x 20"
- Shear from 30° to 75°
- No Wrinkling of Skin
- Total Skin Weight <0.95 lb/sqft
- Aerodynamic Load 400lb/sqft
- Max Out-of-Plane Deflection 0.1"



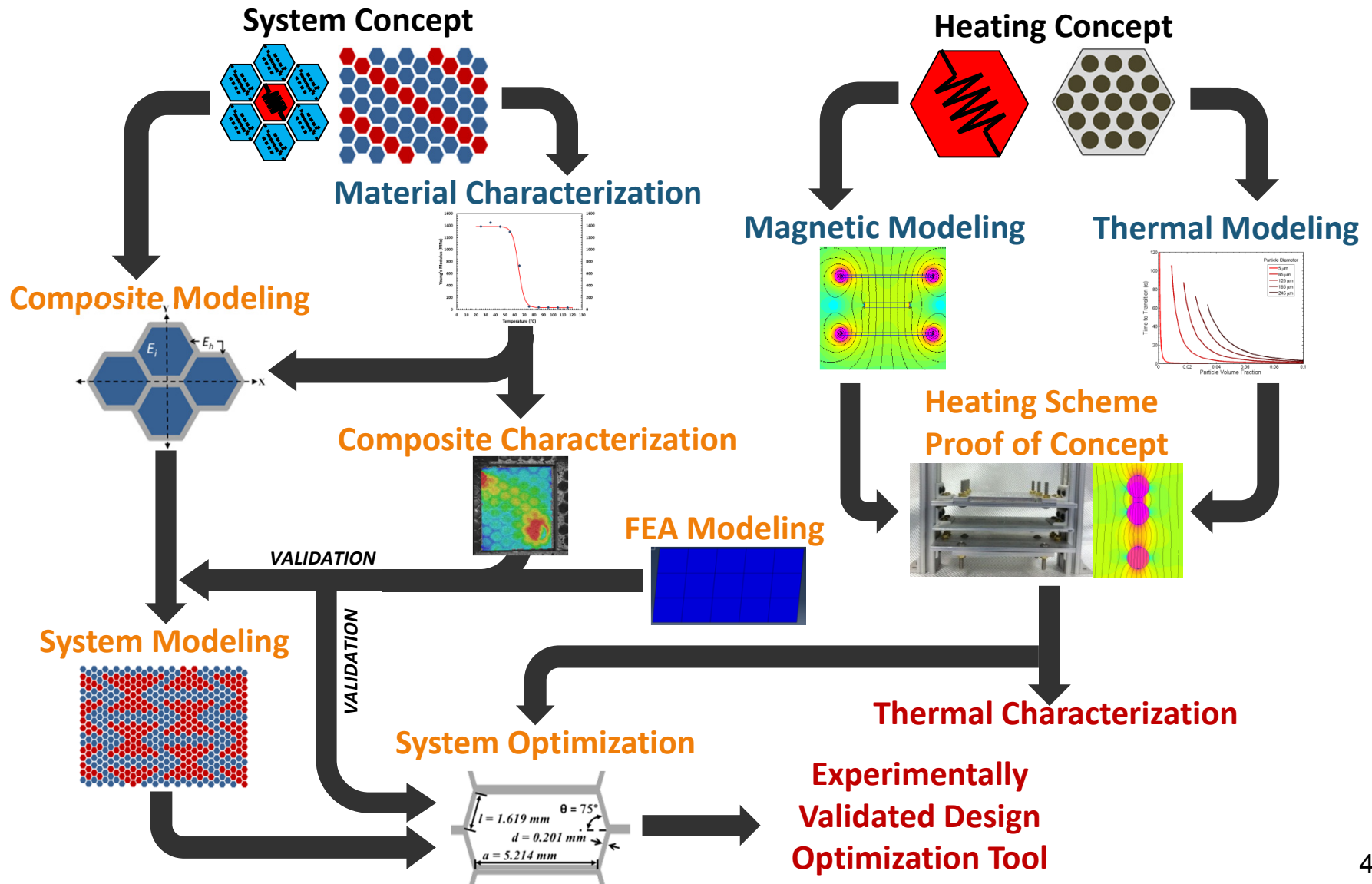
### Heating Patterns

- 0 degrees
- +45 degrees
- 45 degrees
- 90 degrees
- Diamond
- Large Honeycomb
- Auxetic
- Isotropic
- 0 Poisson
- Top/Bottom
- Left/Right



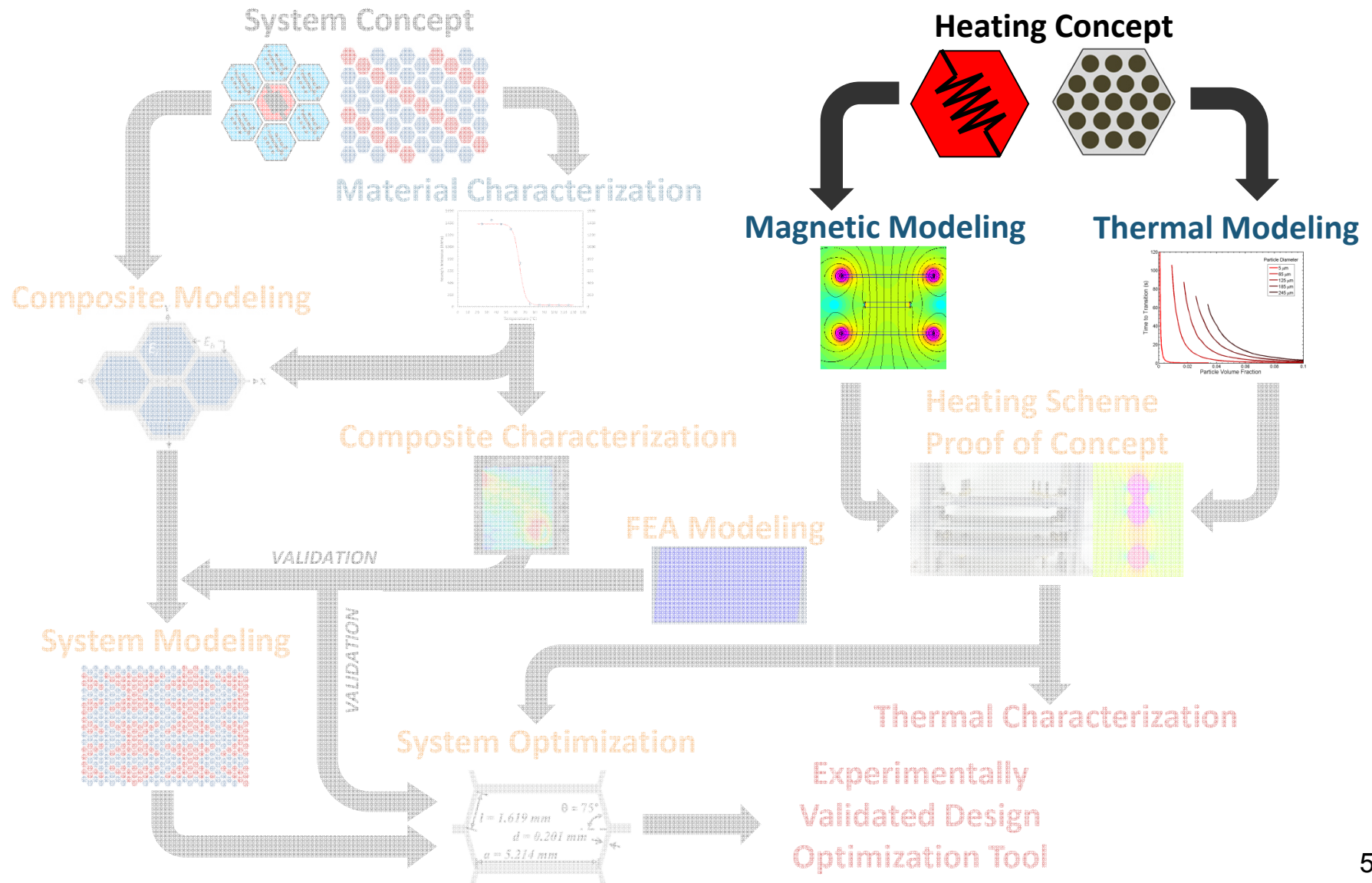


# Project Roadmap





# Project Roadmap

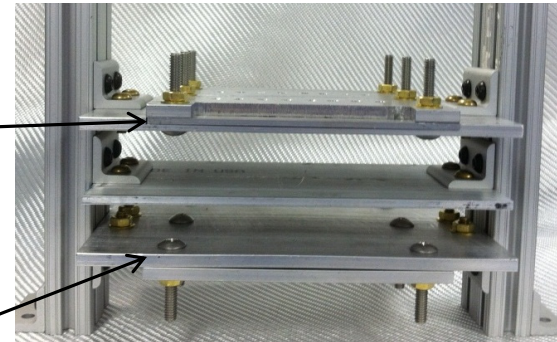
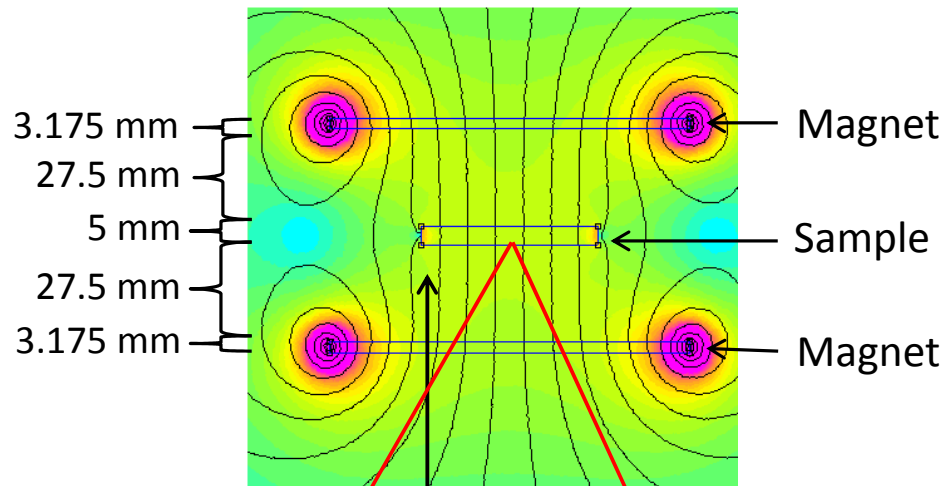




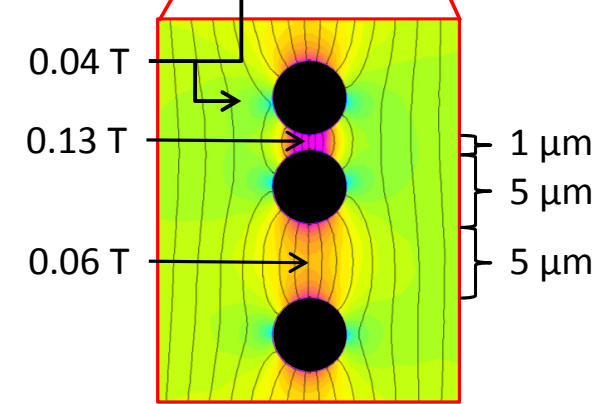
# Magnetic and Thermal Modeling



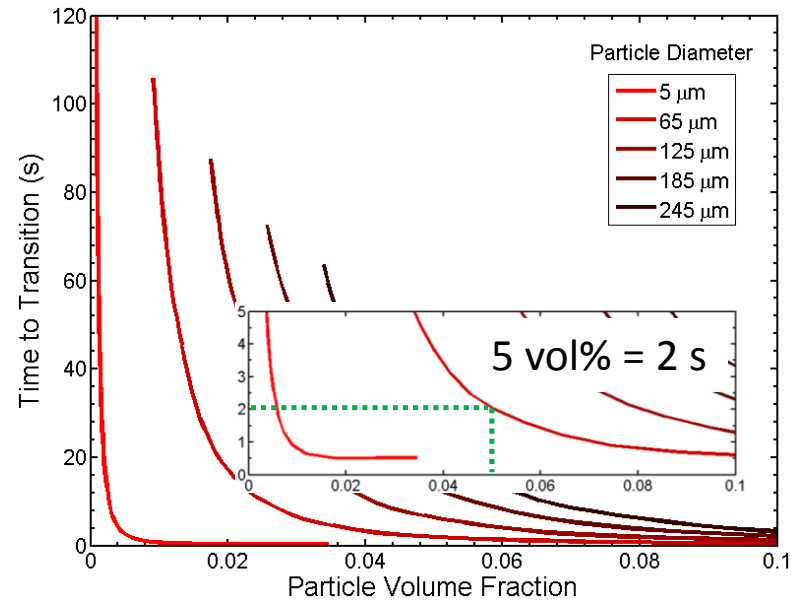
Magnetic Field Lines Between Two Magnets



Nickel: 3-7  $\mu\text{m}$  diameter  
Epoxy SMP  
Neodymium (NdFeB) N42SH magnets

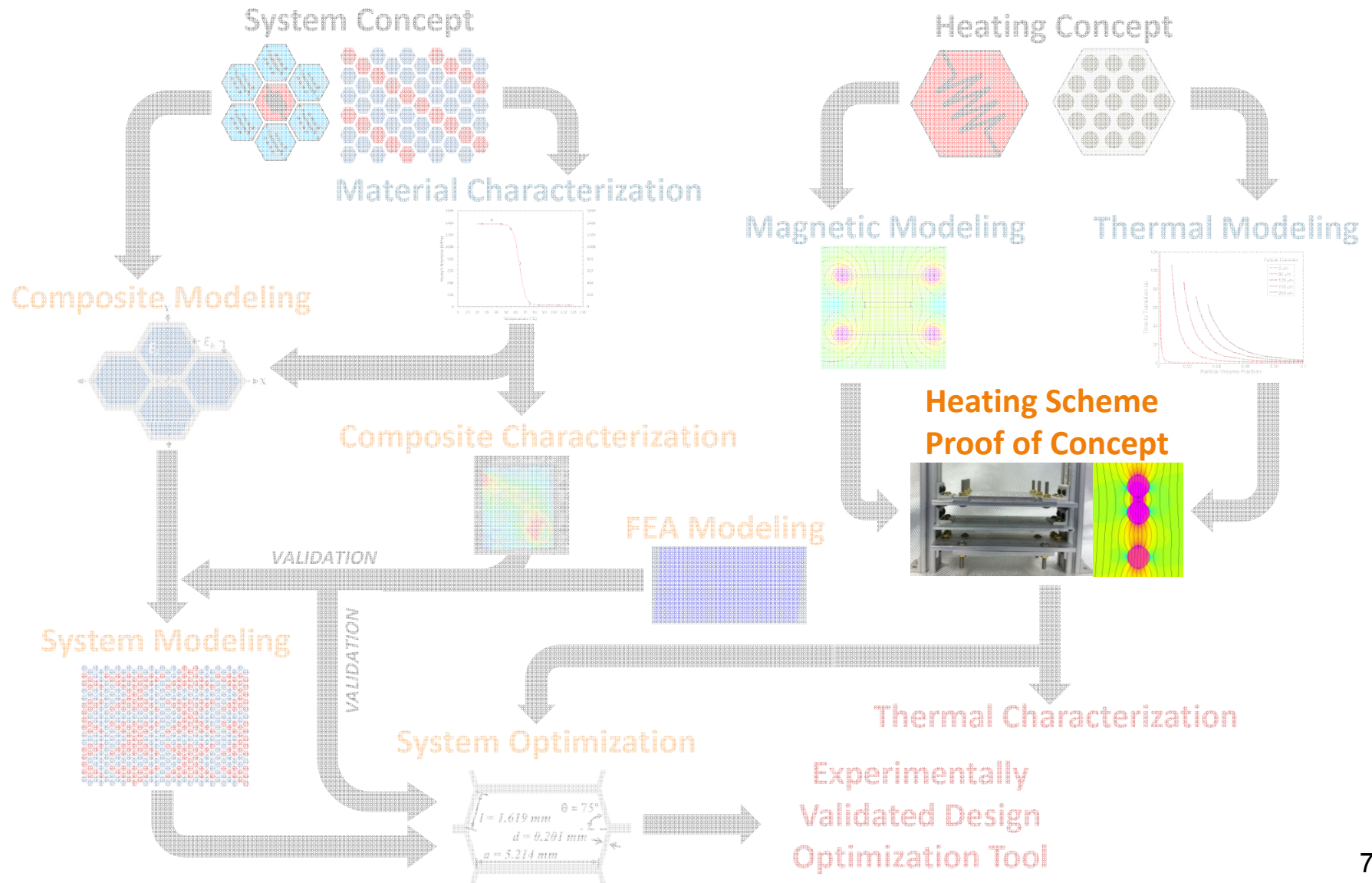


Magnetic Field Lines b/t Ni Particles





# Project Roadmap





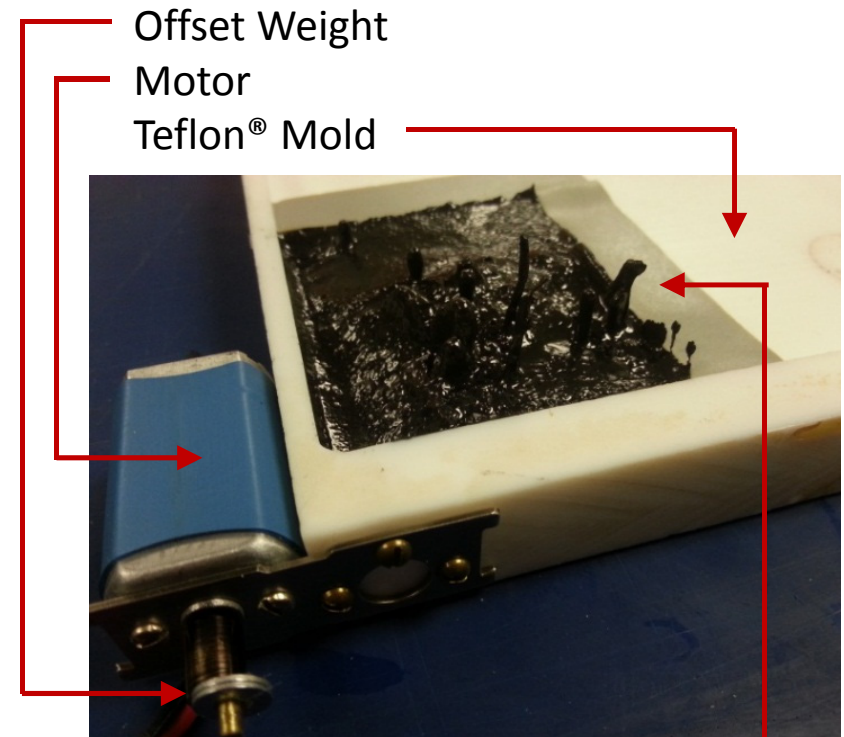
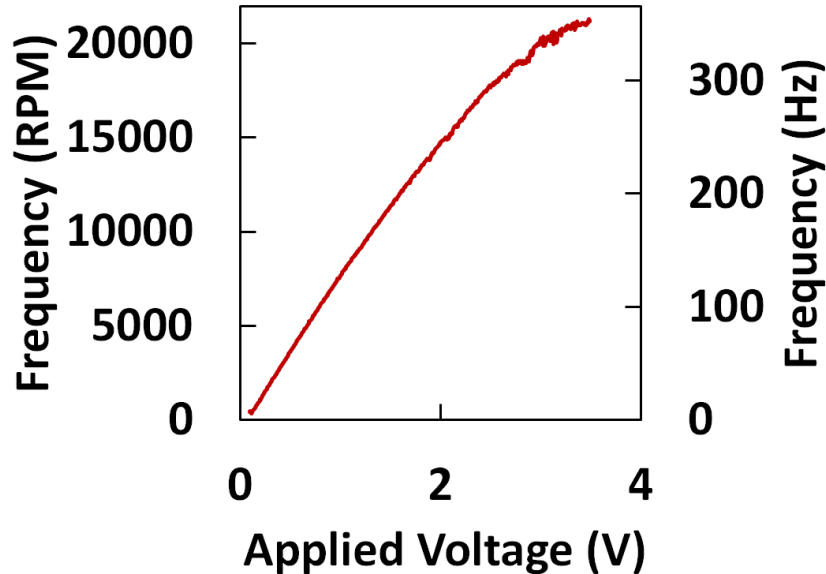
# Heating Scheme Proof of Concept



Velocity of a particle subject to a pulsating fluid

$$u = \frac{3\rho}{\rho + 2\rho_s} v_\infty$$

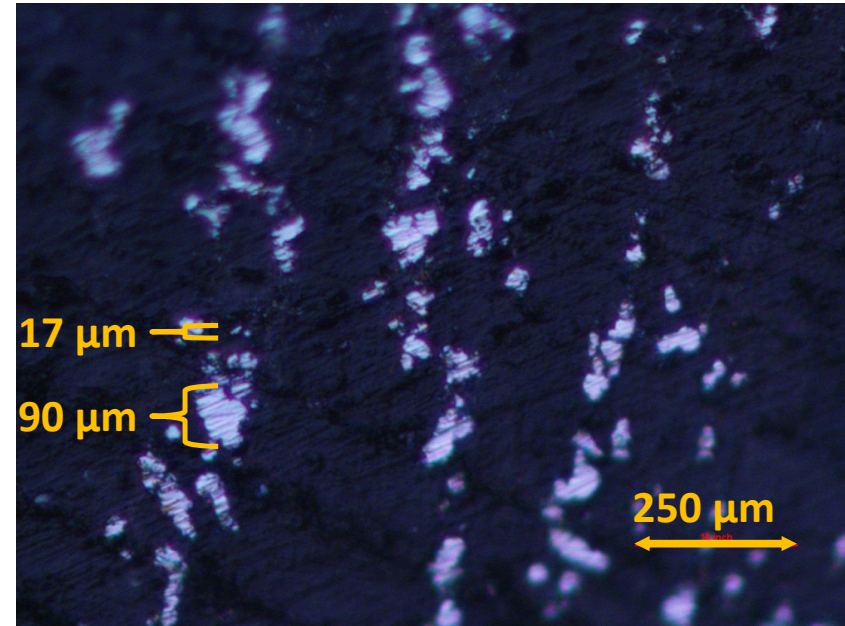
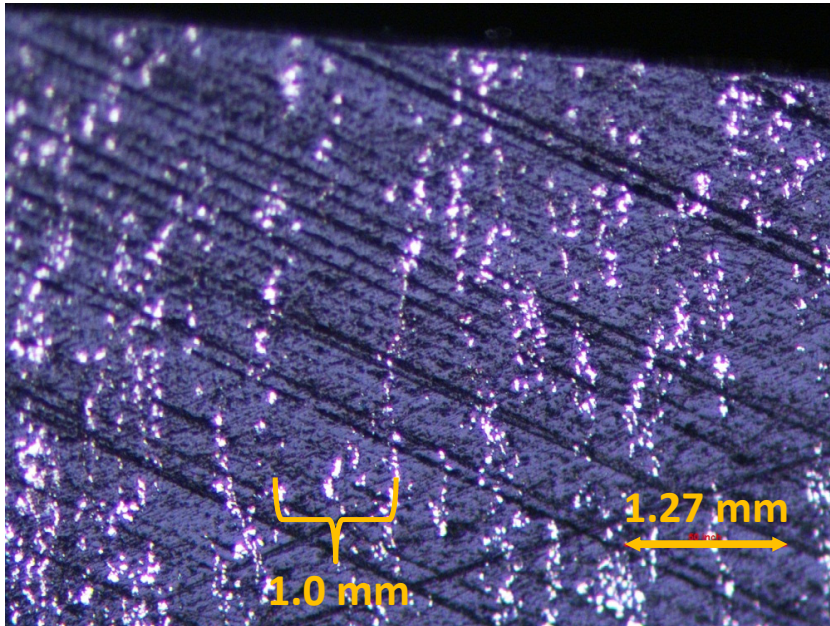
$u$  particle velocity  
 $\rho$  fluid density  
 $\rho_s$  particle density  
 $v_\infty$  imposed pulsating field



Peaks: magnetic field too strong  
magnetic field unbalanced



# Heating Scheme Proof of Concept

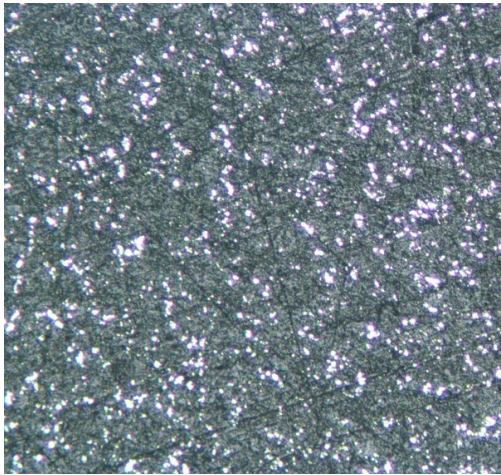


5 vol% 3-7  $\mu\text{m}$  Nickel particles  
Neodymium magnets 40mm separation  
350 Hz vibration  
212°F for 3 hours  
Mold: 10 x 10 x 0.75 cm

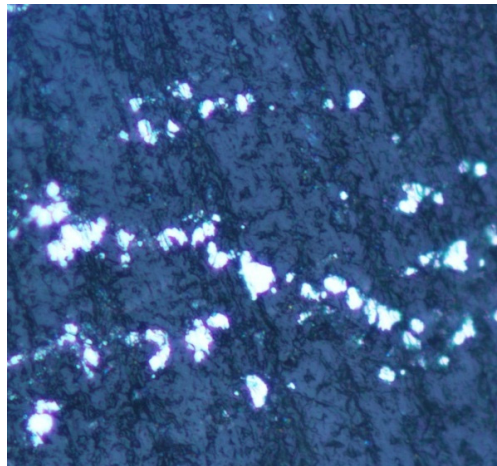
$\phi_c = 0.41$  (50  $\mu\text{m}$  diameter,  $\delta_c$  10 nm)  
 $\phi_{\text{exp}} = 0.10$   
10 vol%, 10V, random orientation: 60s



# Heating Scheme Proof of Concept



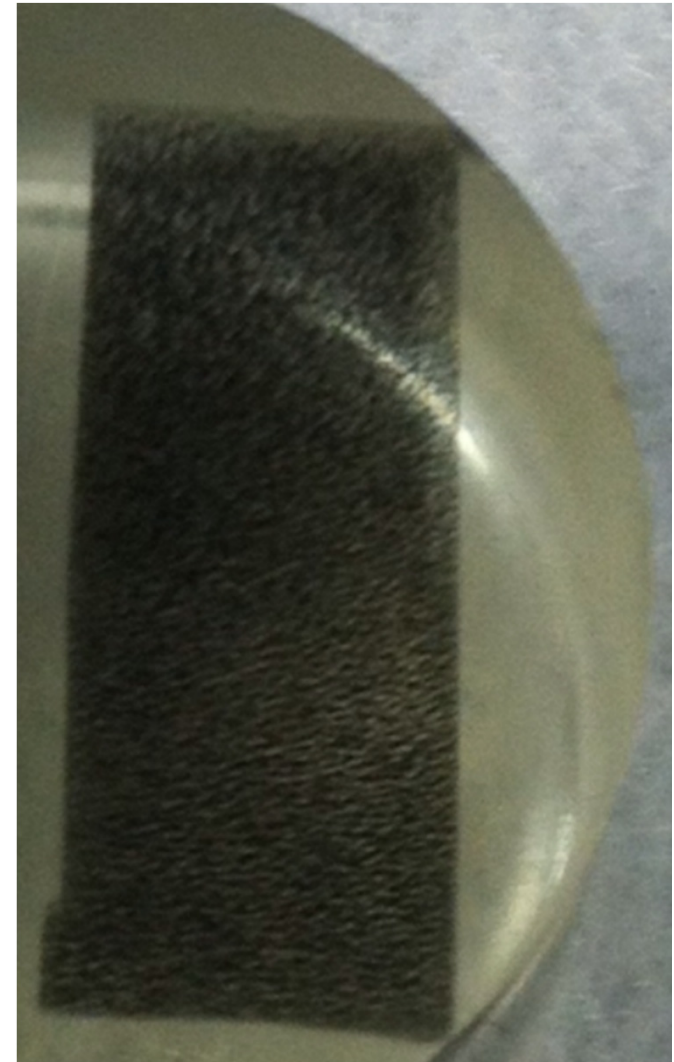
End View of Nickel



Side View Nickel

Tested several Copper, Steel,  
and NiChrome mesh electrodes  
100x100 Cu most promising

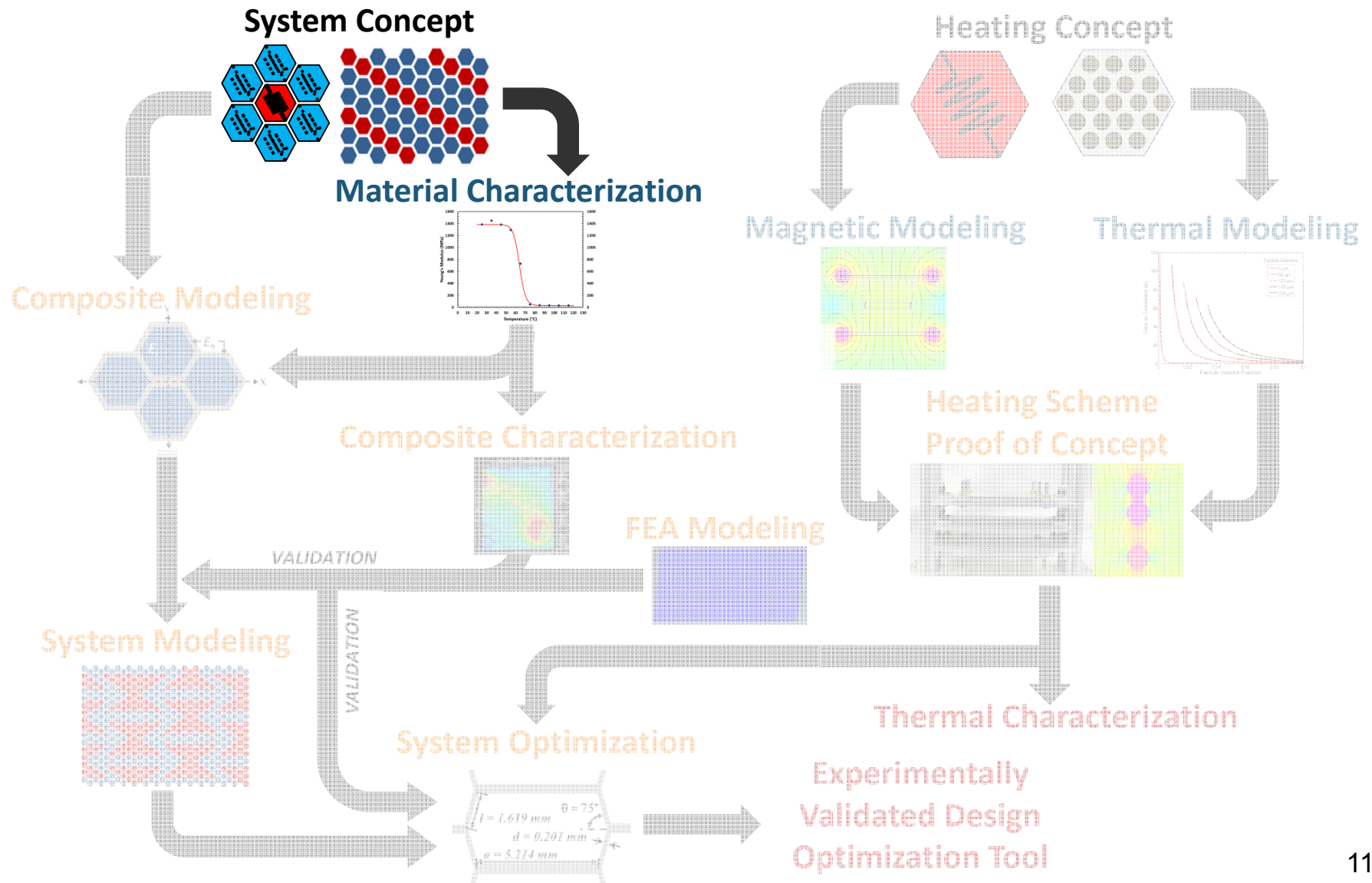
Current activation: 10V, ~60s



End View of Particle Chains



# Project Roadmap



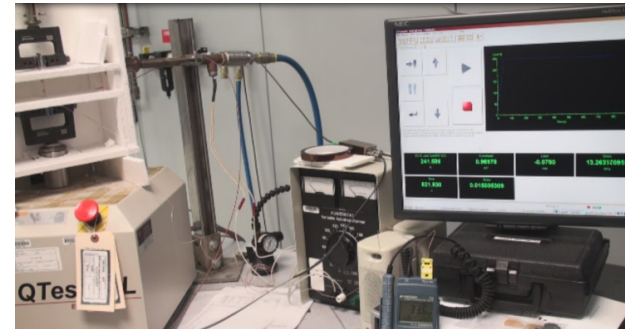


# Epoxy SMP Characterization



## Epoxy SMP Formulation

0.02 mol (7.28g) EPON 826  
0.01 mol (2.3g) Jeffamine D230  
100°C for 1.5hr, 130°C for 1hr

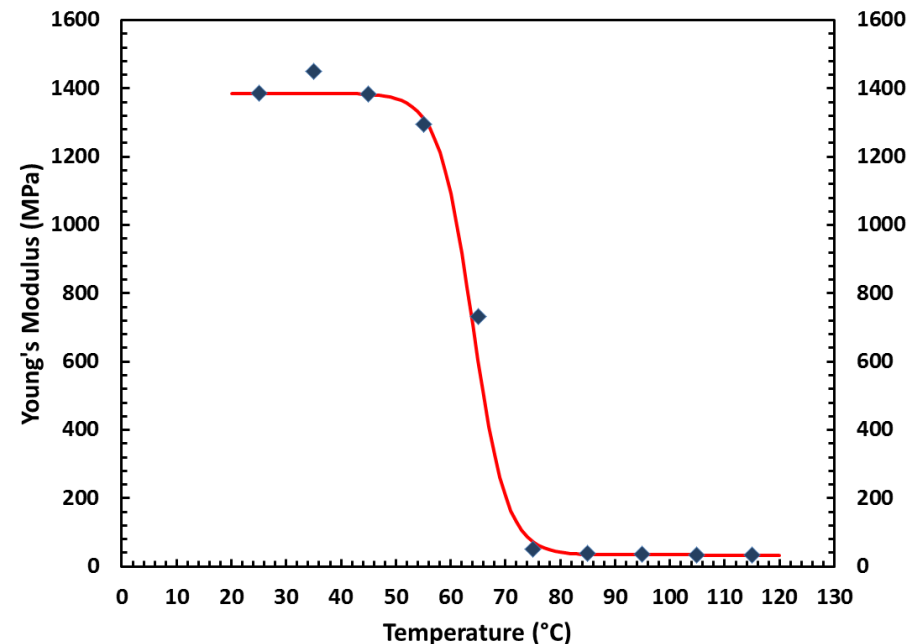


Epoxy SMP Characterization

## Experimental Results

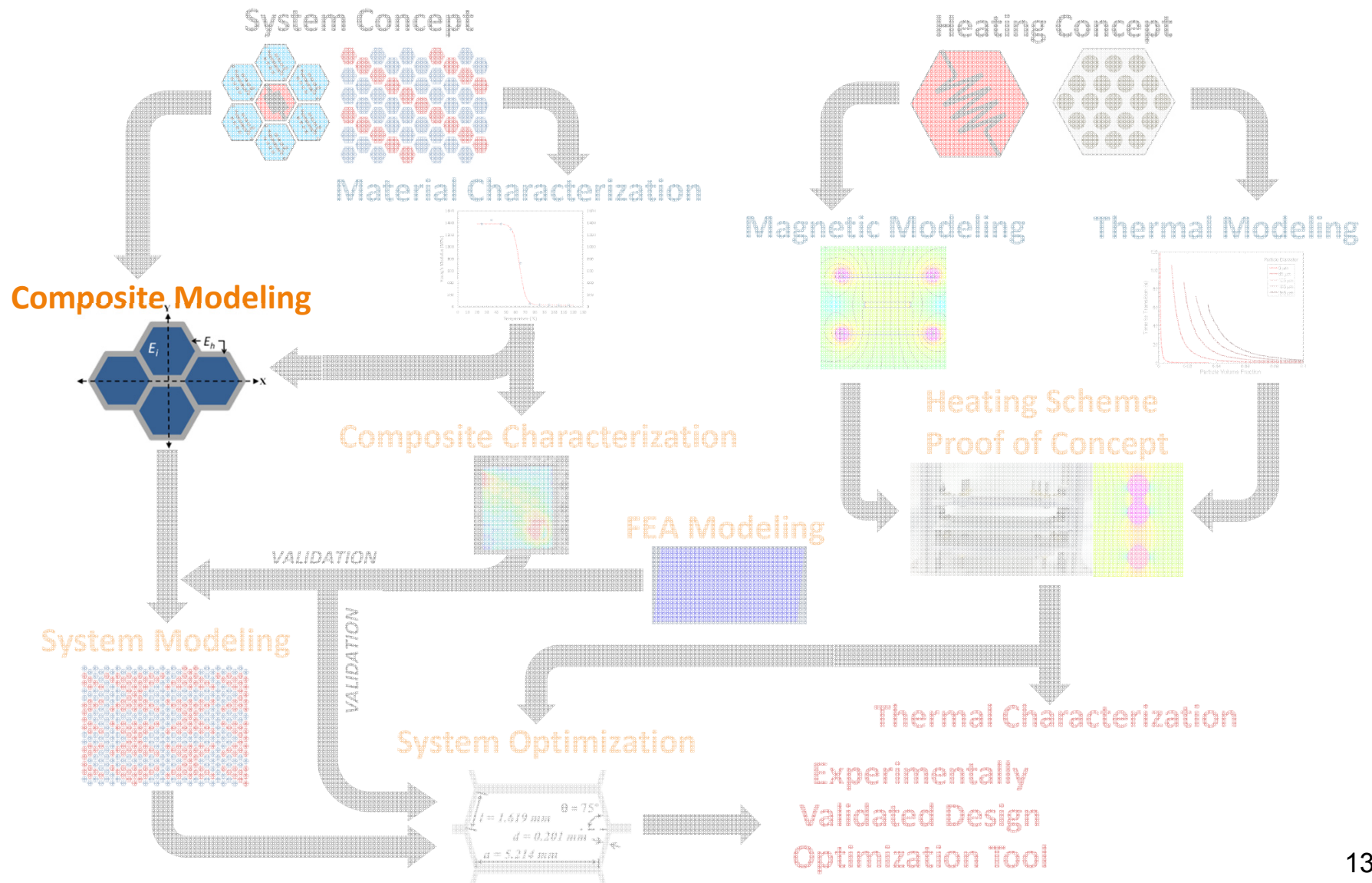
$T_g$	65 °C
E (ambient)	1300 MPa
E (115 °C)	19 MPa

Values consistent over several batches, 0-8 week sample age



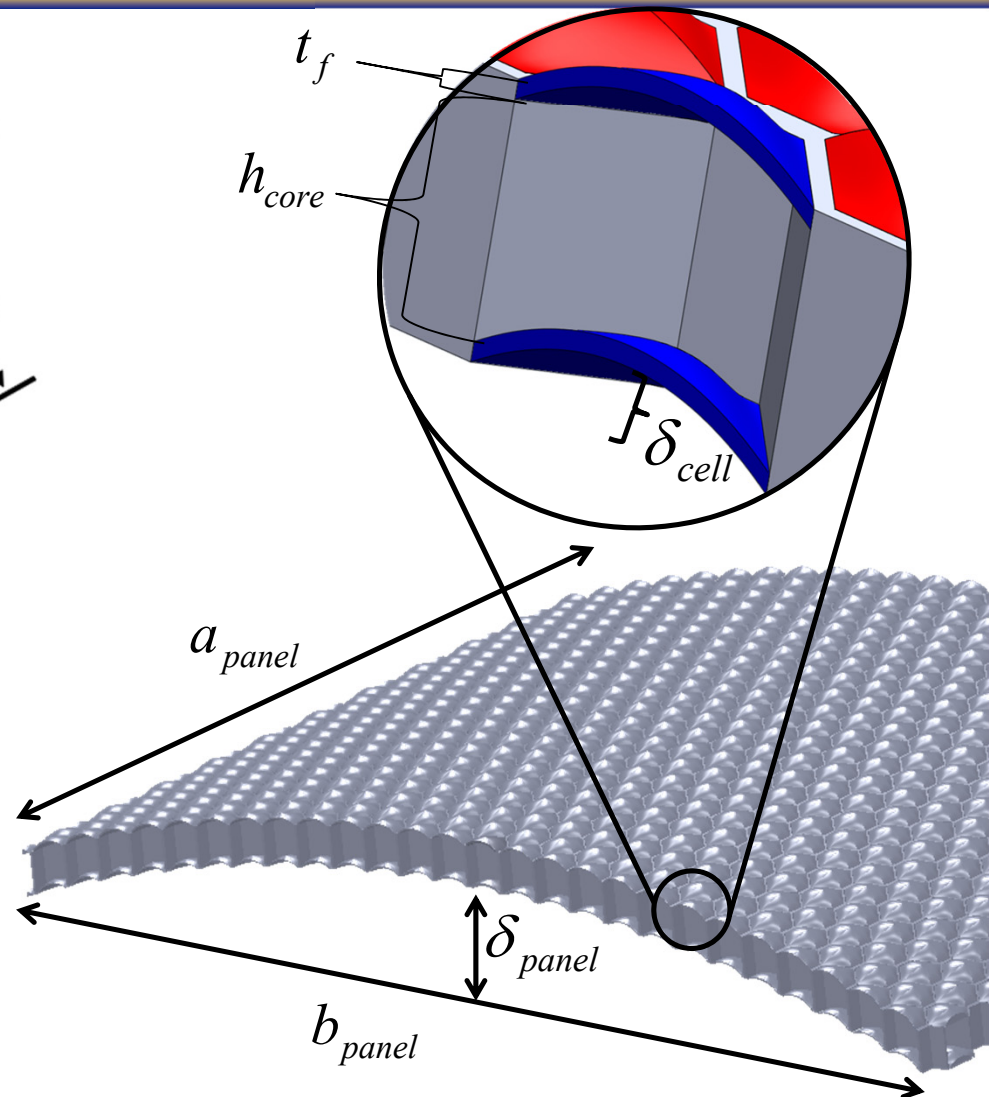
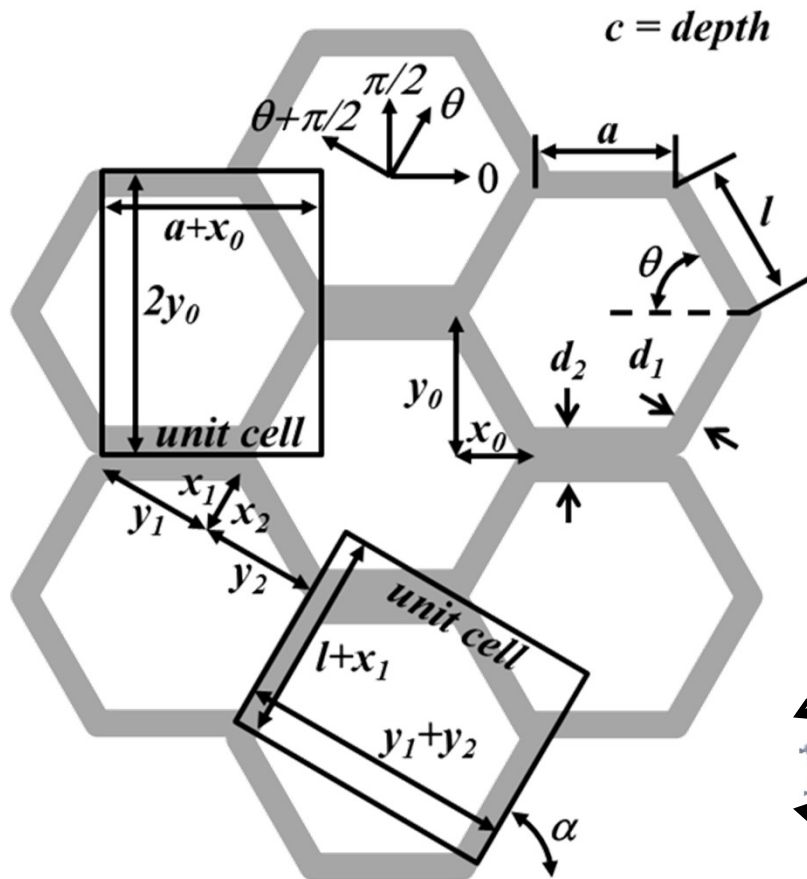


# Project Roadmap



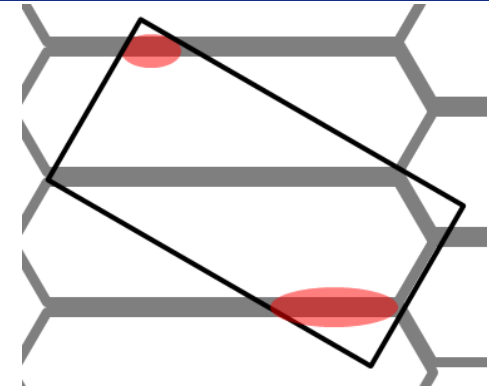
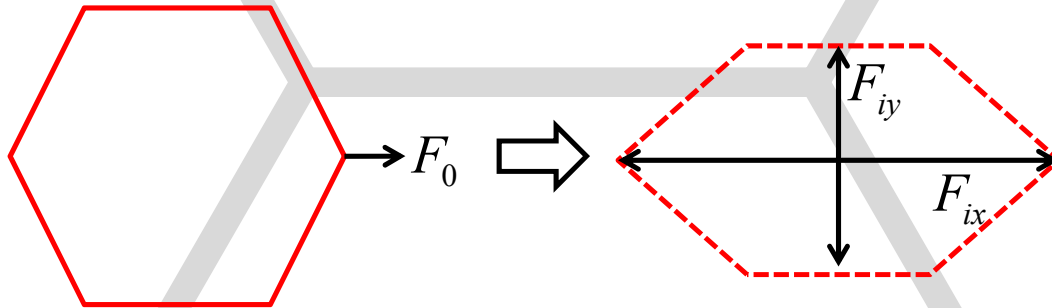


# Composite Analytic Model

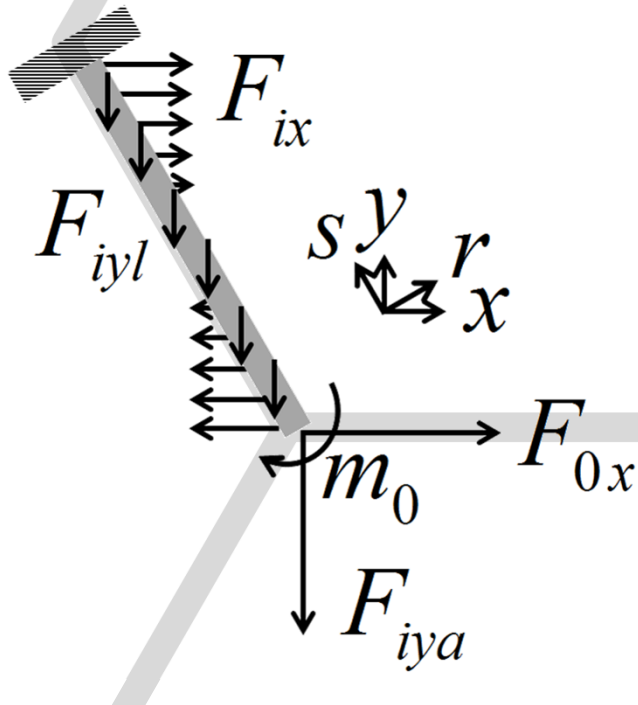




# Composite Analytic Model



Non-compliant Geometry



$$\delta_j = \sum_m \left\{ \left[ \int_0^{L_m} \frac{N_m^2}{2E_m A_m} \partial z + \int_0^{L_m} \frac{M_{x,m}^2}{2E_m I_{x,m}} \partial z \right] \frac{\partial}{\partial F_j} \right\}$$

$$\delta_0 = \delta_a + 2\delta_{lr} + 2\delta_{ls}$$

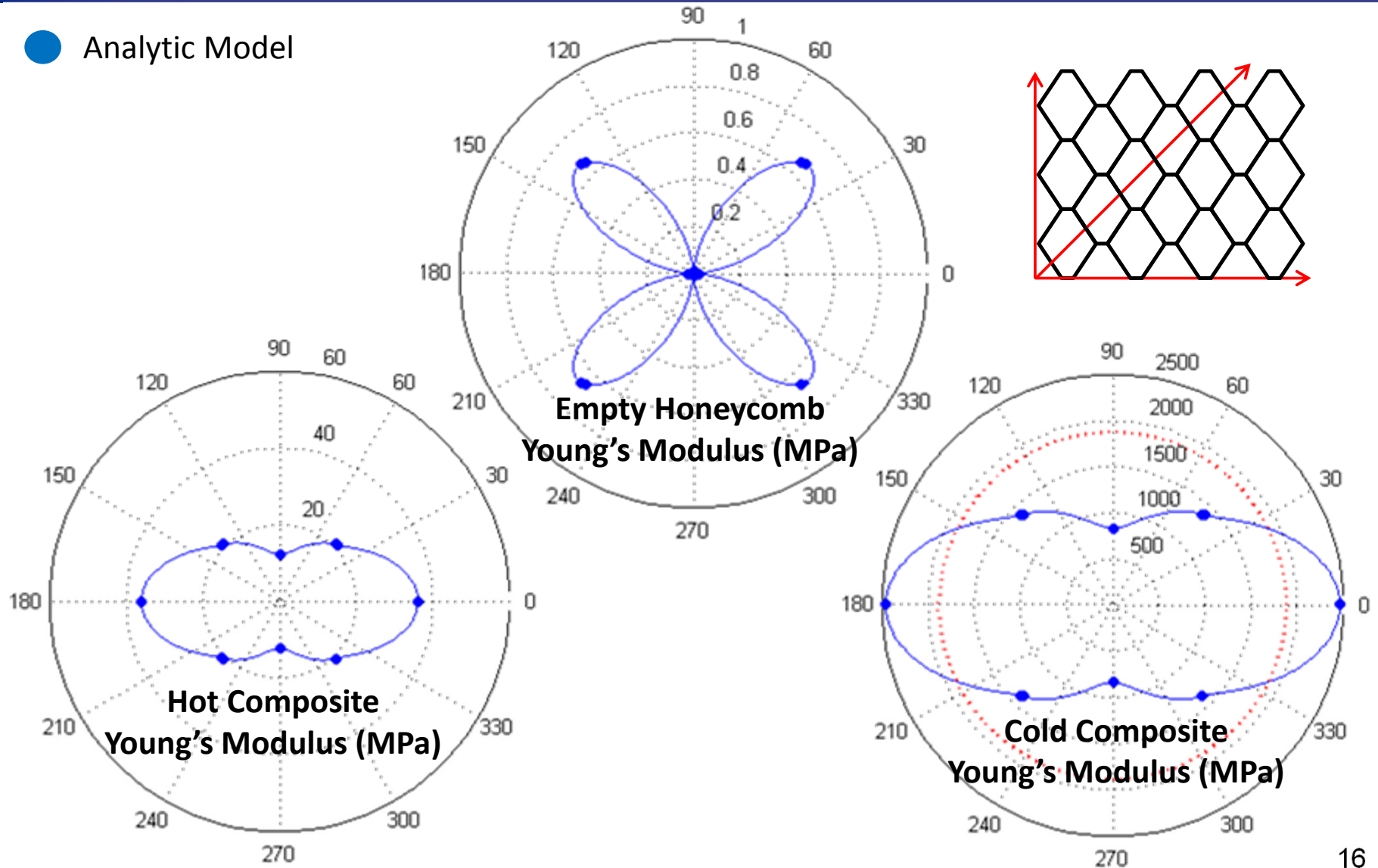
$$E_{c0} = \frac{F_{00}}{\delta_0} \frac{(a + x_0)}{2cy_0}$$



# Composite Analytic Model

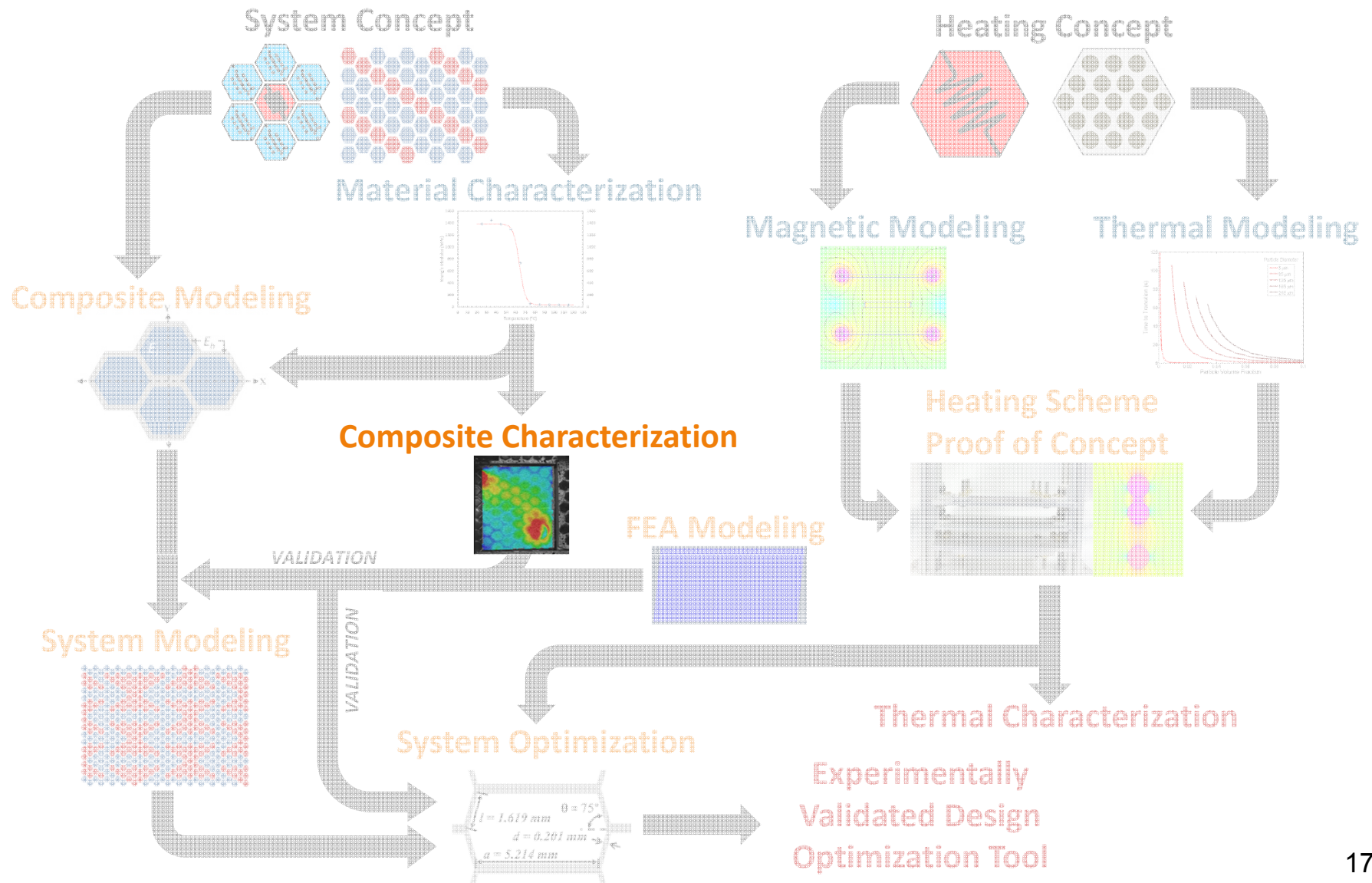


- Analytic Model



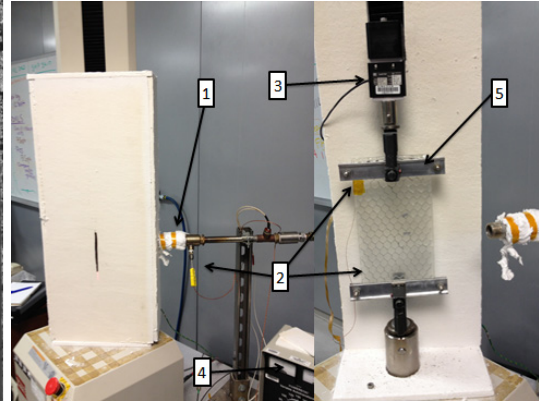
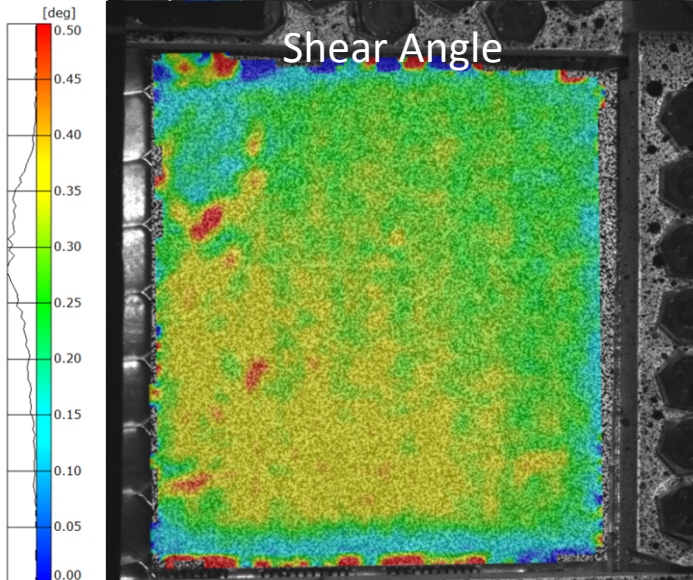
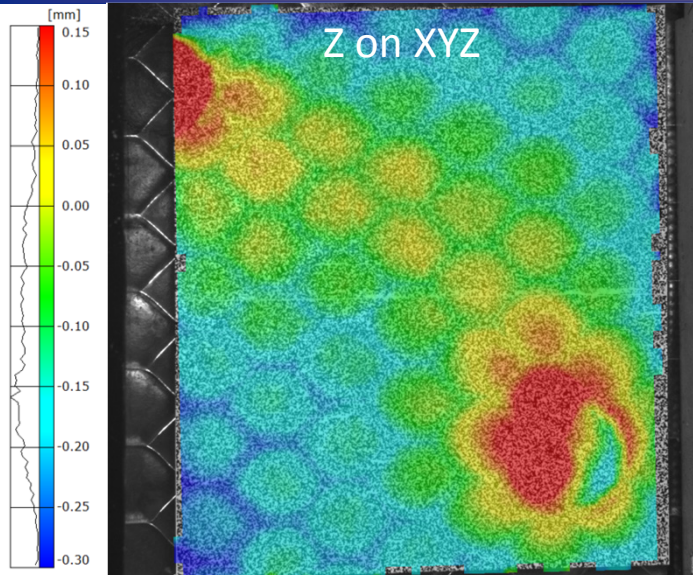


# Project Roadmap





# Composite Characterization



	23 °C	115 °C
$E_{\text{Epoxy}}$	1.3 GPa	19 MPa
$E_{\text{HX}}$	62.8 kPa	
$E_{\text{HY}}$	16.6 kPa	
$E_{\text{CX}}$	2.19 GPa	33.9 MPa
$E_{\text{CY}}$	2.04 GPa	11.8 MPa

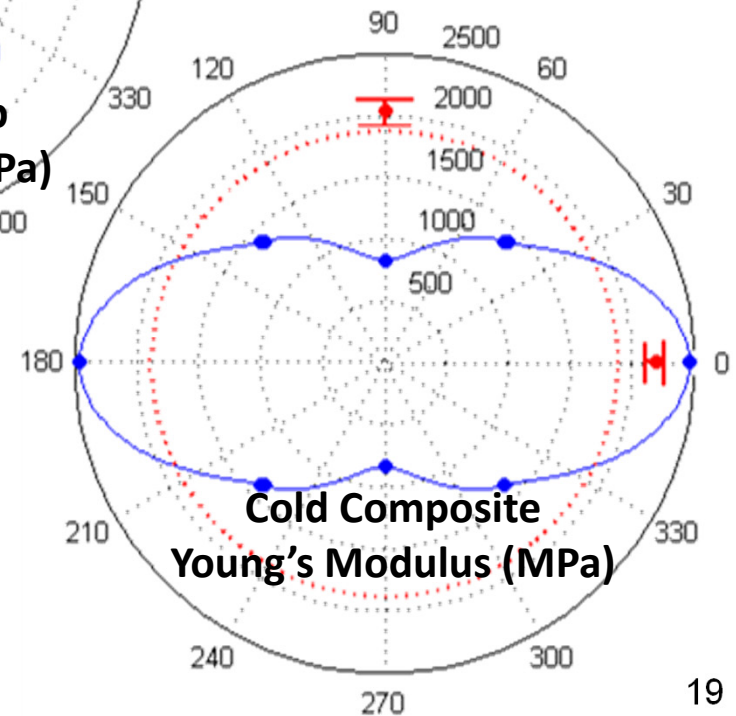
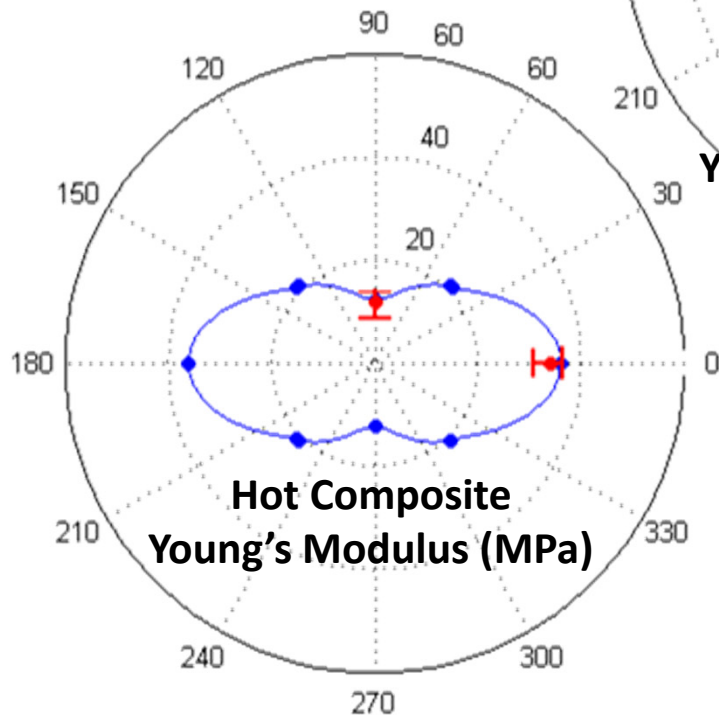
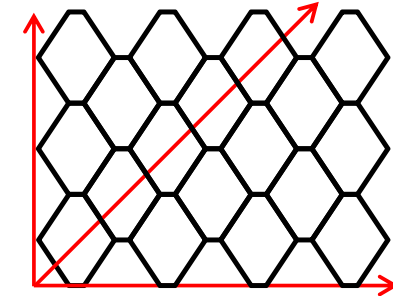
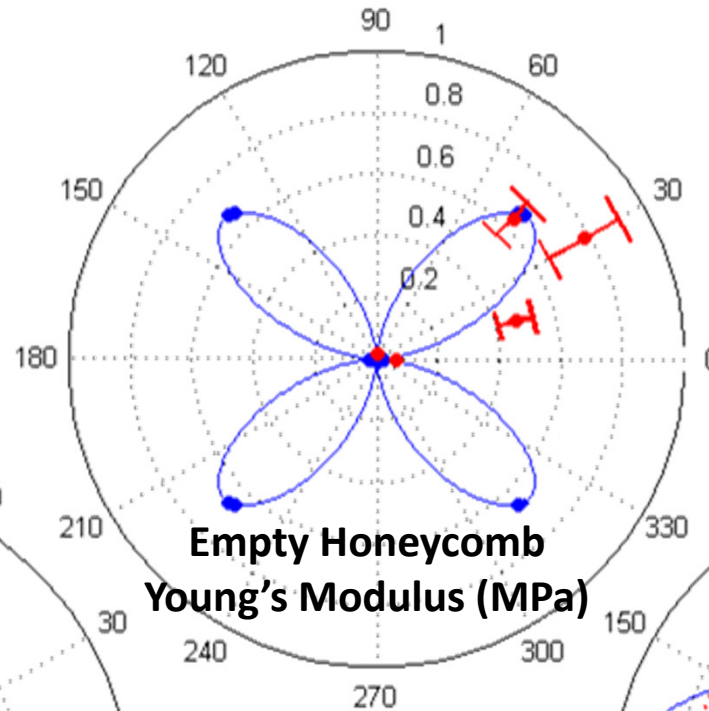
	23 °C	115 °C
$G_{\text{Epoxy}}$	1.27 GPa	1.06 MPa
$G_{\text{CXY}}$	1.19 GPa	13.9 MPa
$G_{\text{CYX}}$	1.13 GPa	13.0 MPa



# Composite Characterization

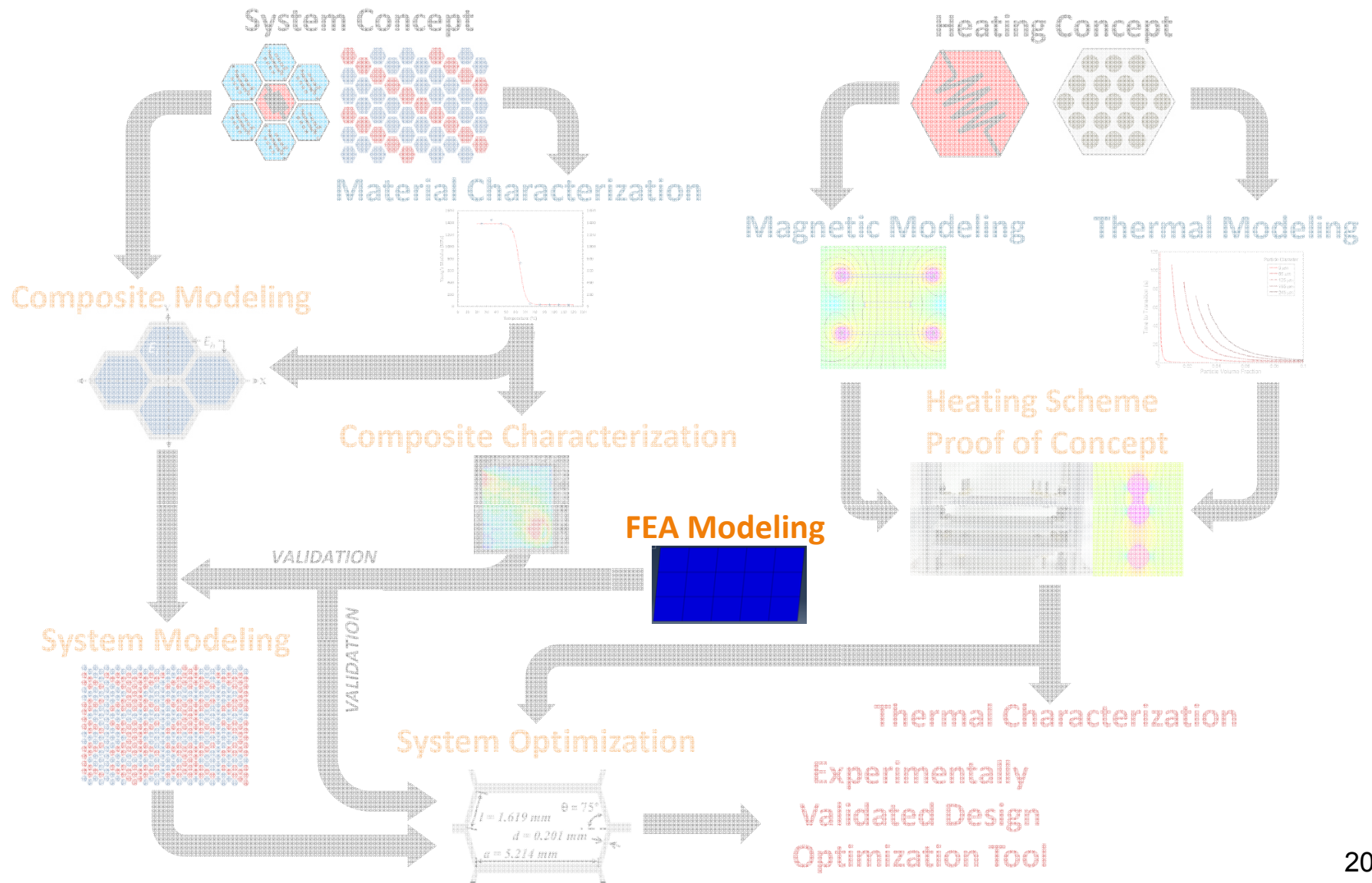


- Analytic Model
- Experimental Results



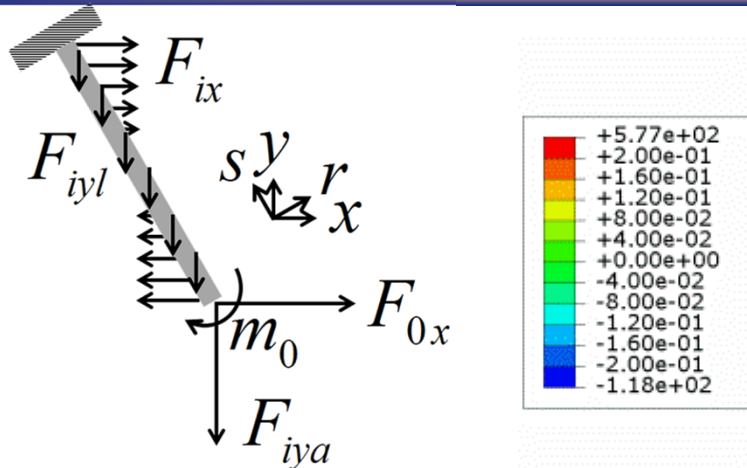


# Project Roadmap

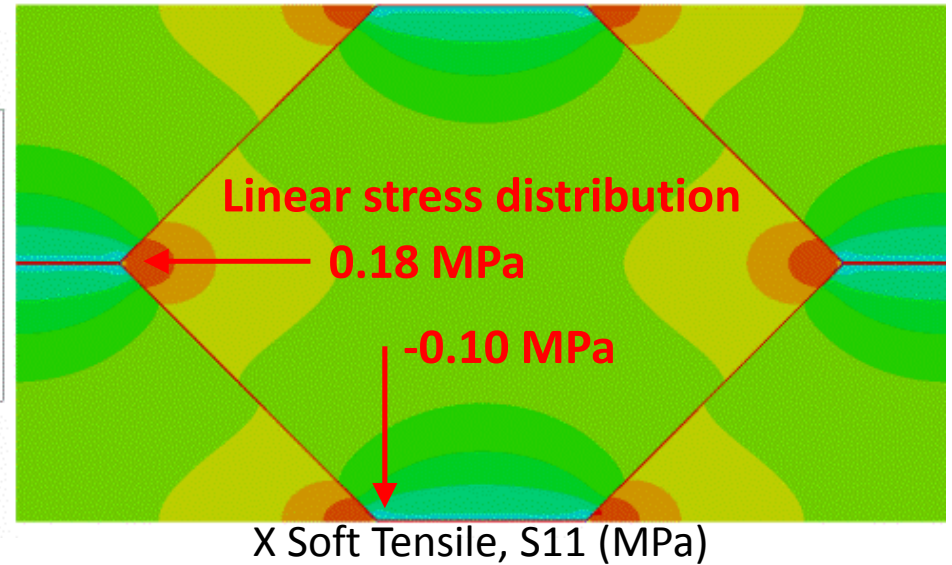




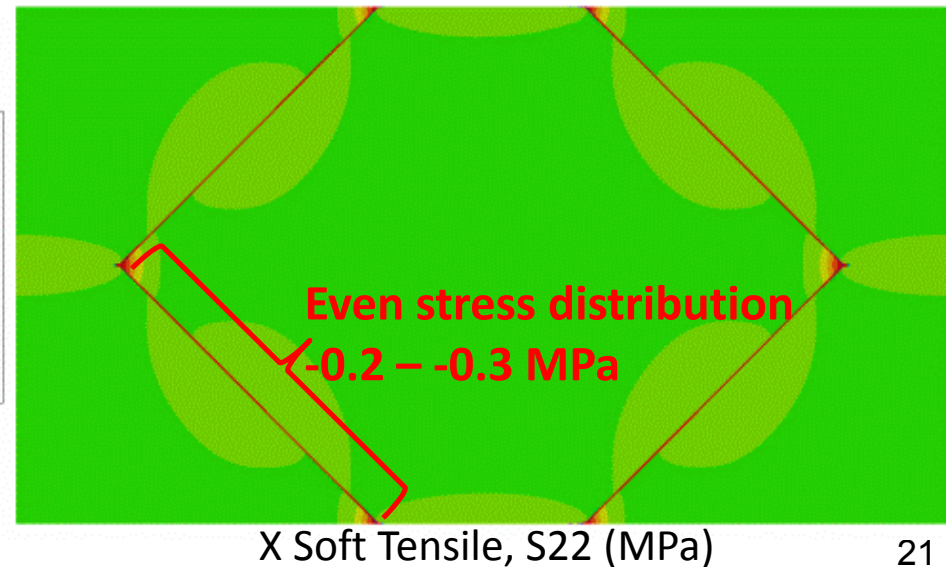
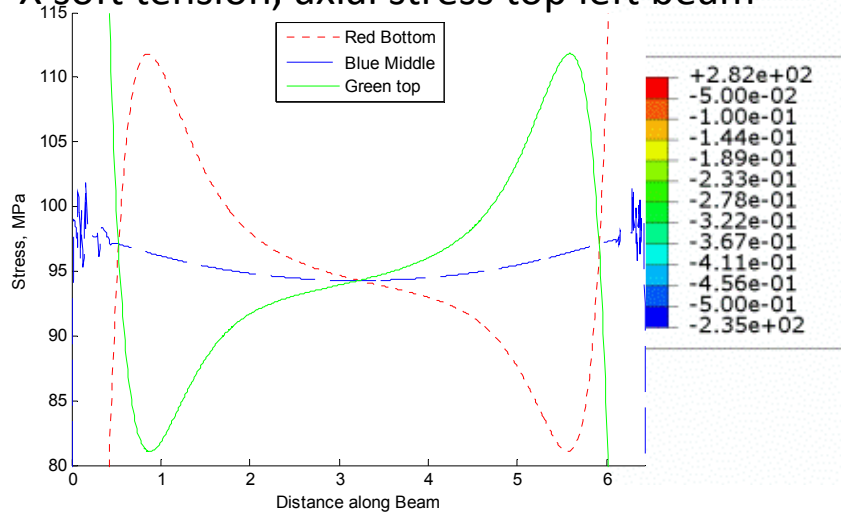
# Composite FEA Model



FEA supports force distribution assumption of analytic model



X soft tension, axial stress top left beam

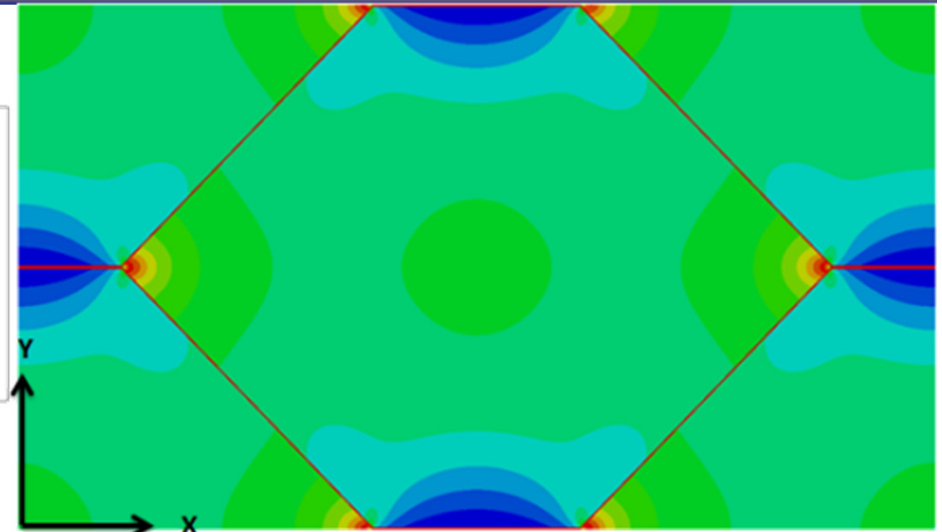
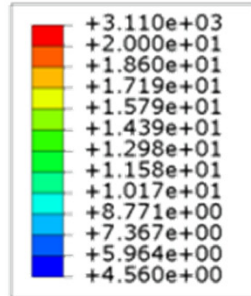




# Composite FEA Model

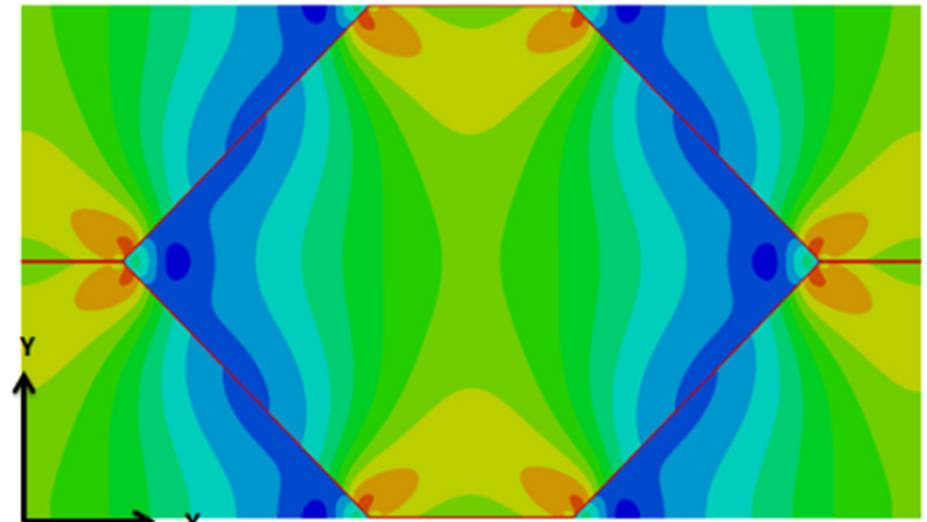
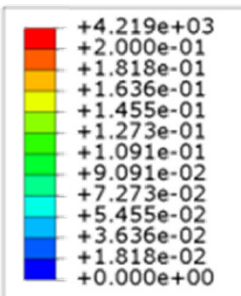
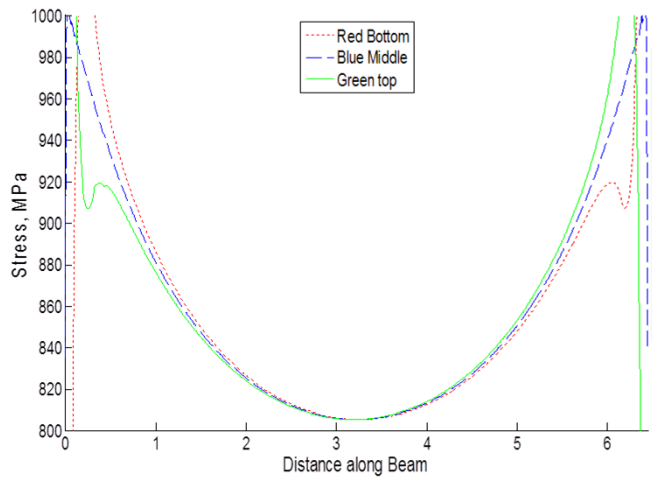


	23 °C	115 °C
$E_{CX}$	1.40 GPa	52.4 MPa
$E_{CY}$	1.08 GPa	17.9 MPa
$G_{CXY}$	0.81 GPa	16.3 MPa
$G_{CYX}$	0.81 GPa	16.4 MPa



X Hard Von-Mises Stress (MPa)

X hard tension, axial stress top left beam



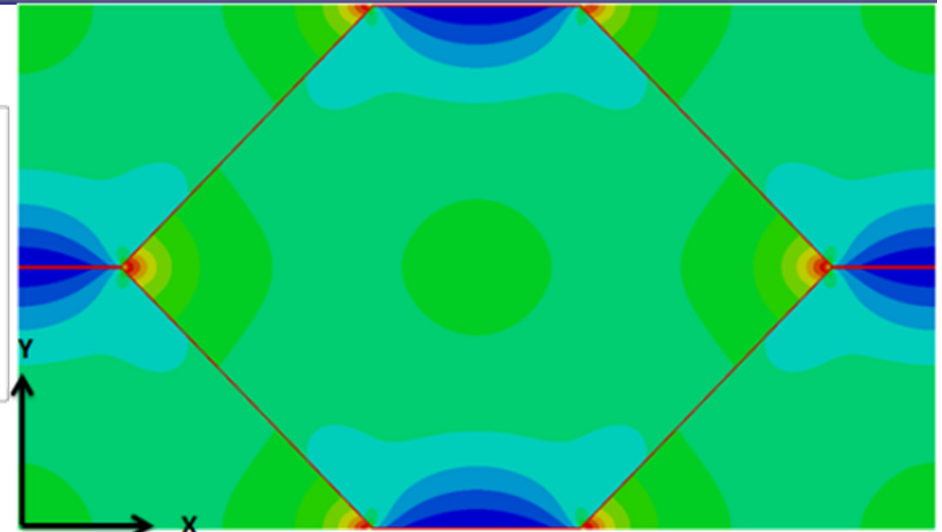
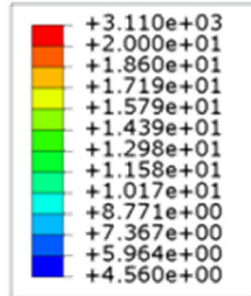
XY Hard Von-Mises Stress (MPa)



# Composite FEA Model

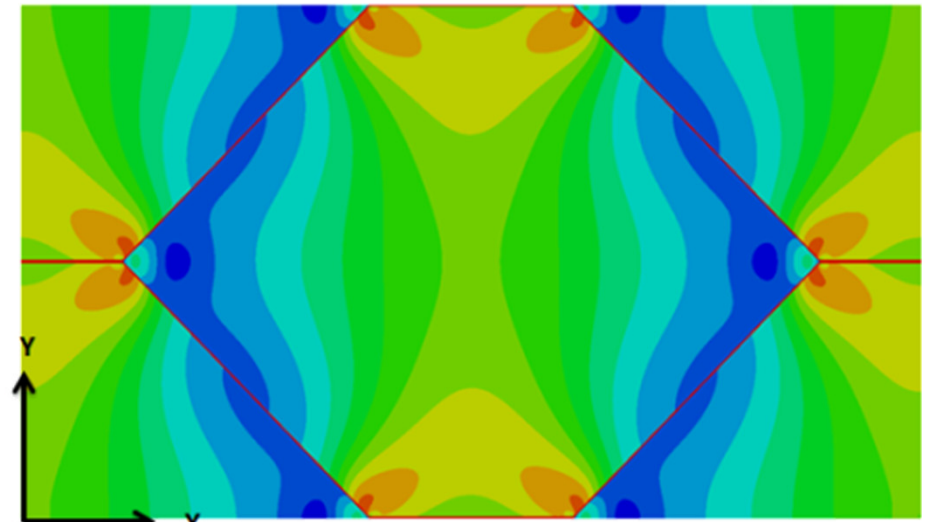
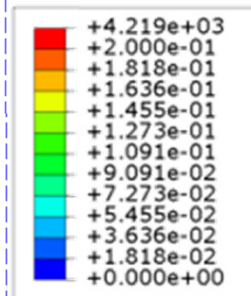
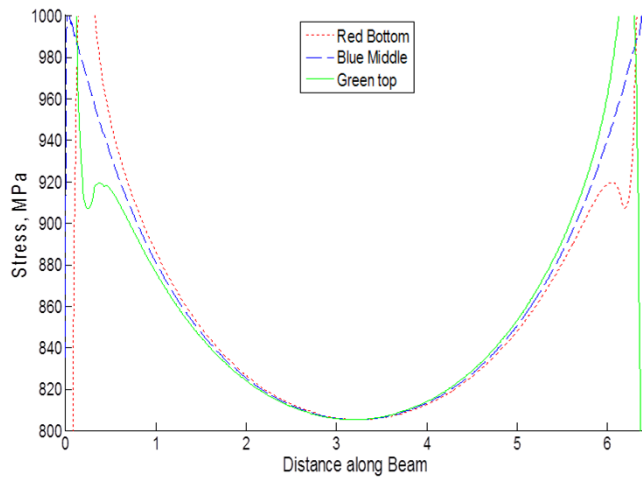


	23 °C	115 °C
$E_{CX}$	TBD	TBD
$E_{CY}$	TBD	TBD
$G_{CXY}$	TBD	TBD
$G_{CYX}$	TBD	TBD



X Hard Von-Mises Stress (MPa)

X hard tension, axial stress top left beam



XY Hard Von-Mises Stress (MPa)



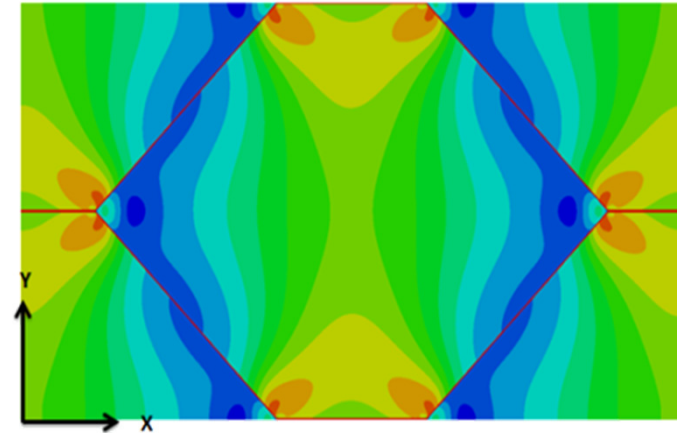
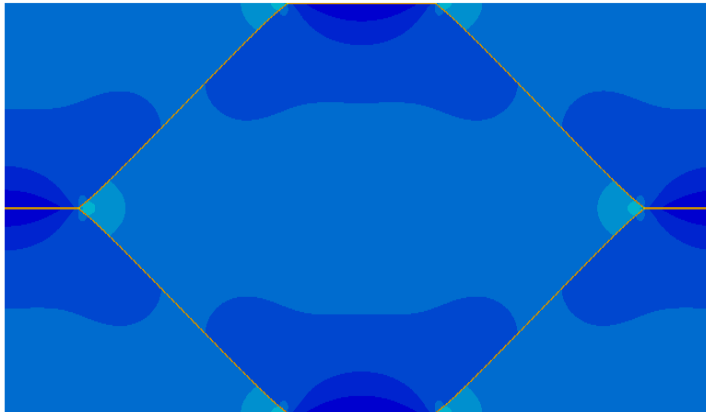
# Composite FEA Model



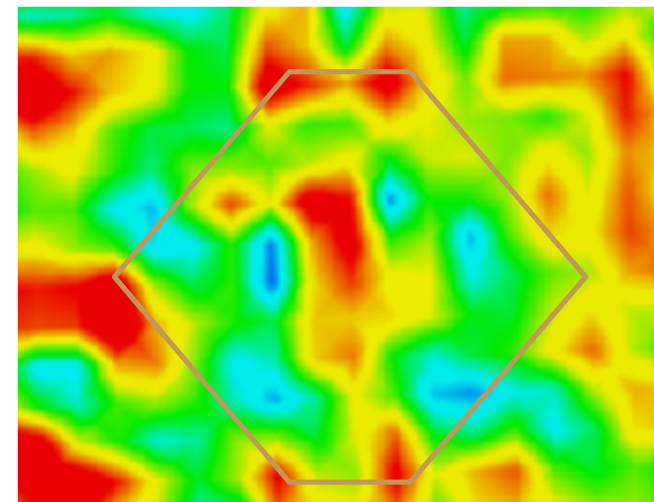
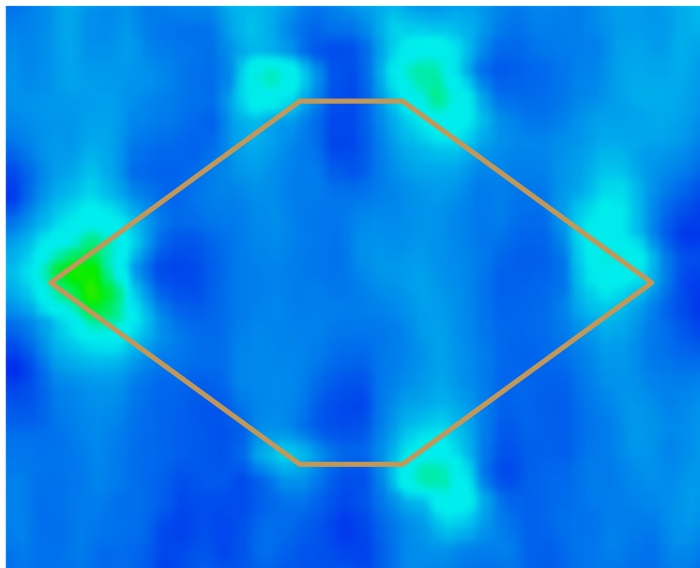
Tension (Von-Mises Stress)

Shear (Von-Mises Stress)

FEA



DIC

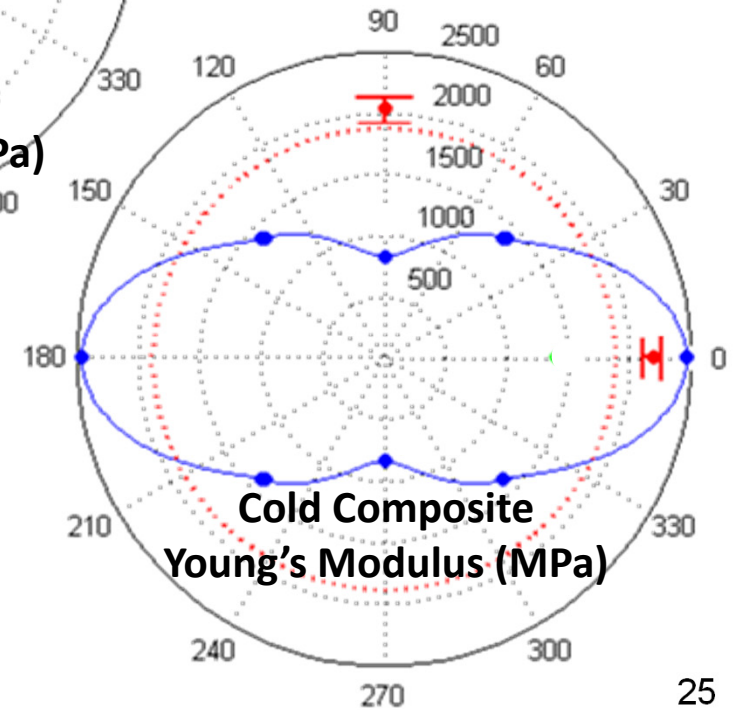
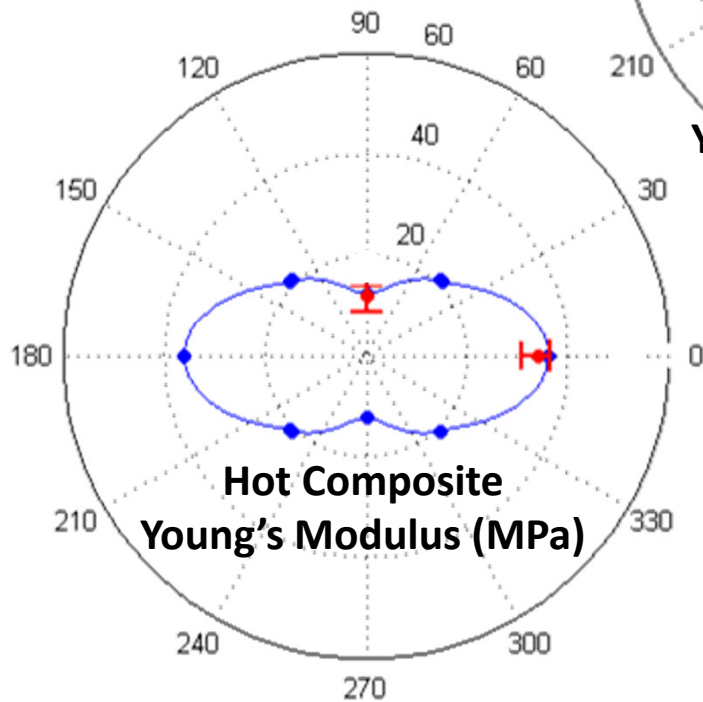
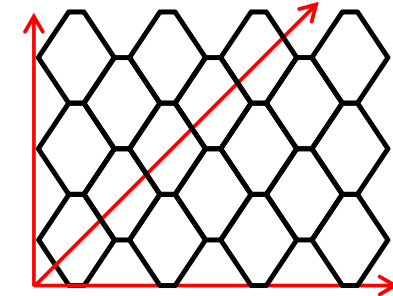
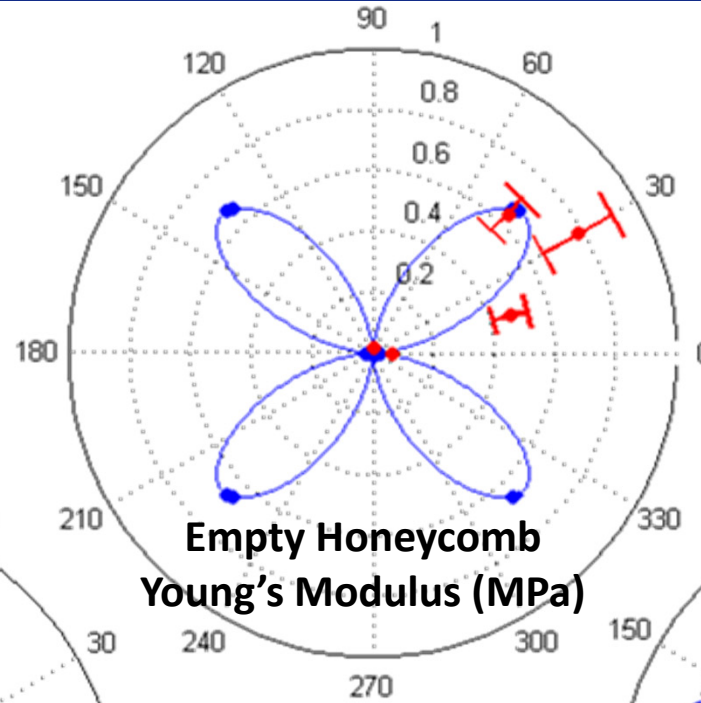




# Composite FEA Model

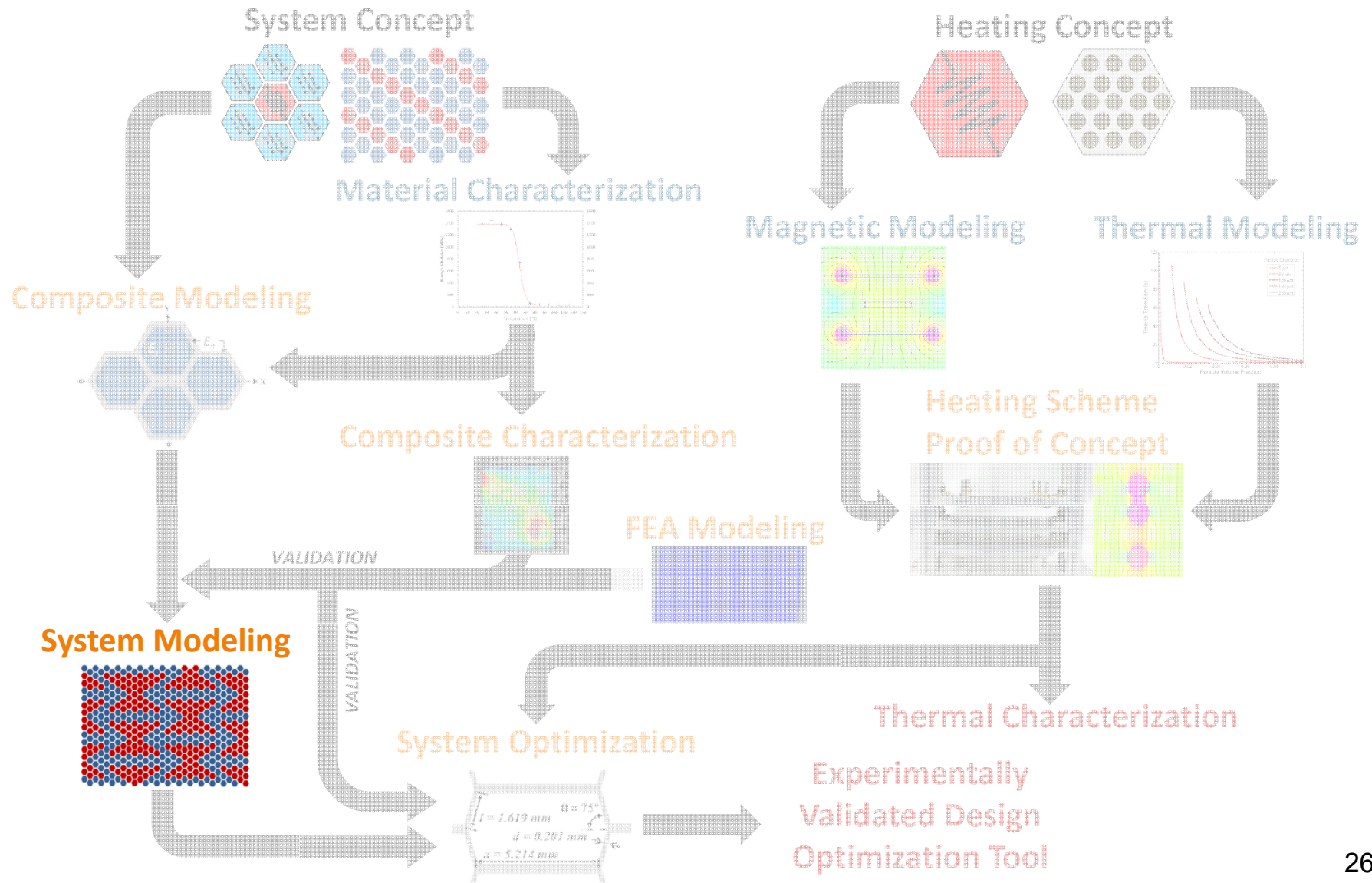


- Analytic Model
- Experimental Results
- FEA Results





# Project Roadmap





# System Modeling



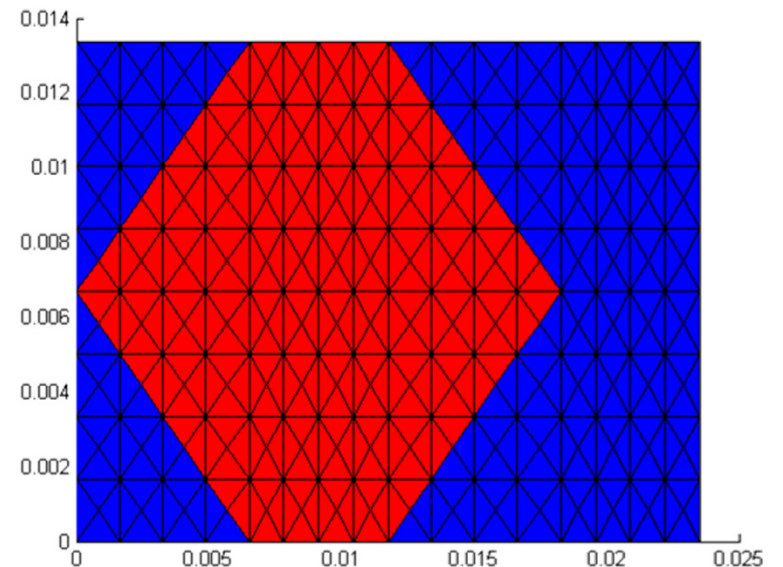
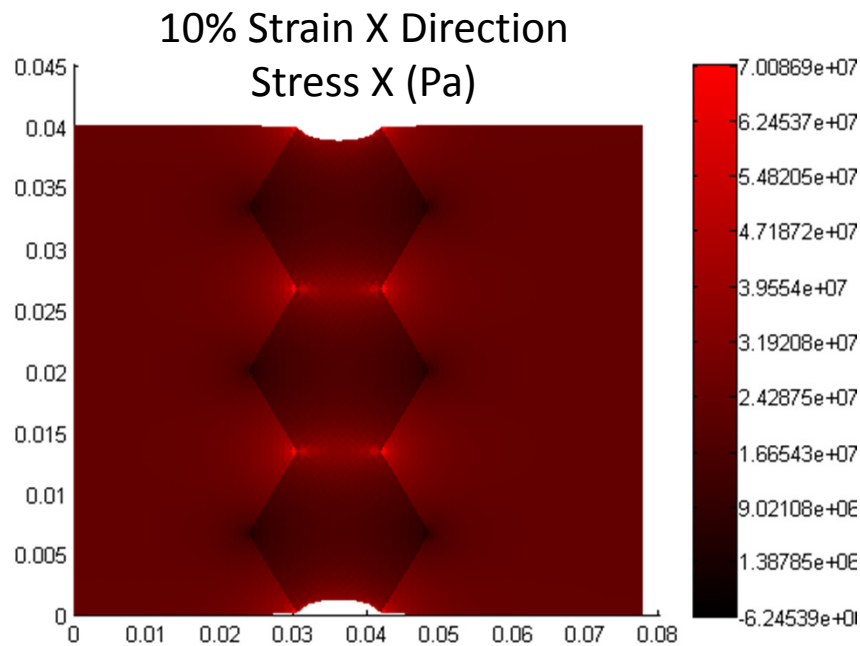
Low fidelity FEA  
 Homogenization scheme using  
 effective composite properties  
 Plane Stress (z direction neglected)  
 In-plane only  
 Calculates effective  $E_x$ ,  $E_y$ ,  $G_{xy}$ ,  $G_{yx}$   
 given heating pattern

## Material Stiffness Matrix

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \\ \varepsilon_{21} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & 0 & 0 \\ 0 & 0 & \frac{1}{G_{12}} \rightarrow \mu_{12,21} & \frac{1}{G_{21}} \\ 0 & 0 & \rightarrow \mu_{21,12} & \frac{1}{G_{21}} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \\ \sigma_{21} \end{bmatrix}$$

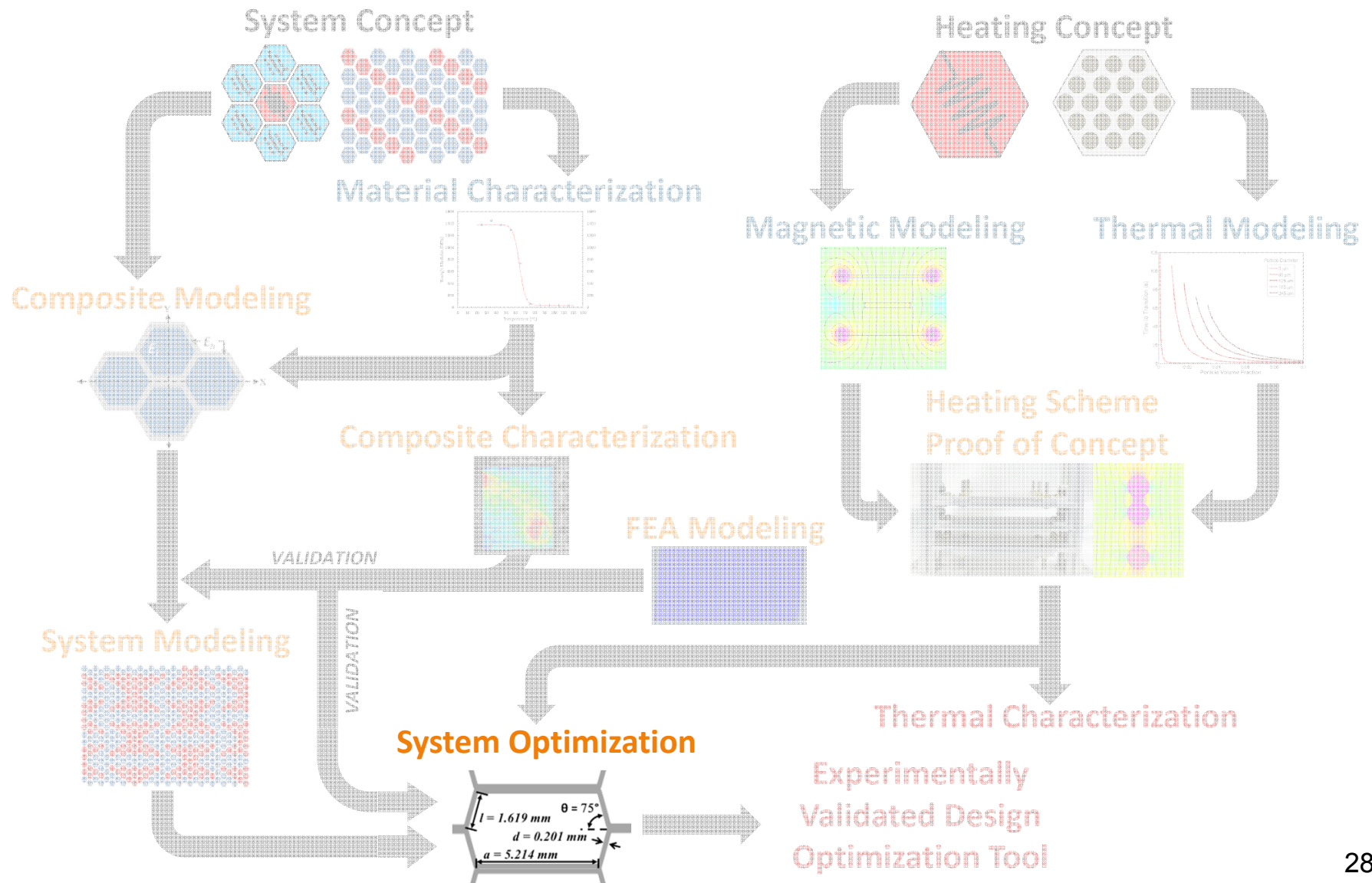
$$\mu_{12,21} = \frac{1}{\mu_{21,12}} = \frac{(l^3 + a^3 \cos^2(\theta))(a + x_0)}{2y_0 a^3 \cos(\theta) \sin(\theta)}$$

Non-zero shear coupling (Chentsov) coefficients





# Project Roadmap





# Honeycomb Geometry Optimization



## Design Variables

$$0 \leq l(m) < \infty$$

$$0.00005 \leq d(m) < \infty$$

$$0 \leq a(m) < \infty$$

$$0 \leq \theta \leq \frac{\pi}{2}$$

$$0 \leq h_{core}(m) < \infty$$

$$0 \leq t_f(m) < \infty$$

## Ex. Optimization Function

$$F_{ext} = ave(E_{call}) \varepsilon_{max} b_{panel} (h_{core} + 2t_f)$$

## MAS Program Constraints

$$\delta = \delta_{panel} + \delta_{cell} \leq 2.54 \text{ mm}$$

$$\delta_{panel} = \frac{C_0 w b_{panel}^4}{6 E_f h_{core}^2 t_f} \left( \frac{1 - \nu_f^2}{0.91} \right)$$

$$\delta_{cell} = \frac{C_0 w \min(2y_0, a + x_0)^4}{E_i t_f^2} \left( \frac{1 - \nu_i^2}{0.91} \right)$$

$$W_{skinmax} \leq 4.6 \frac{kg}{m^3} = \rho_{skin} (h_{core} + 2t_f)$$

$$\rho_{skin} = \rho_{core} \frac{h_{core}}{h_{core} + 2t_f} + \rho_f \frac{2t_f}{h_{core} + 2t_f}$$

## Self-Imposed Constraints

$$\varepsilon_{xmax} > 0.1$$

$$\varepsilon_{ymax} > 0.1$$

$$\frac{1}{2} < \frac{2y_0}{a + x_0} < 2$$

## Equation Constraints

Unit Cell Equations

$$\left\{ \begin{array}{l} \leq \frac{\sin(\theta)}{\sin(\theta)\cos(\theta)} \\ \leq \frac{2\sin(\theta) - \sin(2\theta)\cos(\theta)}{\sin(\theta)\cos(\theta)} \\ \frac{a}{l} \geq 0 \\ \geq \frac{\sin\left(\frac{3\pi}{2} + 2\theta\right)}{\cos(\theta)} \end{array} \right.$$

Thin Beam Theory

$$\left\{ \begin{array}{l} \leq \frac{a}{8} \\ \leq \frac{l}{8} \end{array} \right.$$

Sandwich Plate Deflection

$$\delta \leq (h_{core} + 2t_f)$$

$$\delta_{cell} \leq t_f$$

## Material Properties Constraints

$$\frac{C_1 w b_{panel}^2}{t_f h_{core}} = \sigma_{max} \leq \frac{1.0E7 (Pa)}{2} = \frac{\sigma_f}{FOS}$$

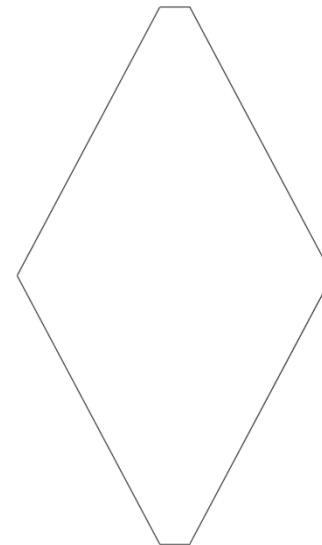
$$\varepsilon_{xmax} \leq \varepsilon_{yf} = \frac{l(\cos(\beta_x) - \cos(\theta))}{a + l \cos(\theta)}$$

$$\beta_x = \cos^{-1} \left[ \frac{\varepsilon_{yf} a}{l} + \cos(\theta) (\varepsilon_{yf} + 1) \right]$$

$$\varepsilon_{ymax} \leq \varepsilon_{yf} = \frac{\sin(\beta_y) - \sin(\theta)}{\sin(\theta)}$$

$$\beta_y = \cos^{-1} [\sin(\theta) (\varepsilon_{yf} + 1)]$$

$$\varepsilon_{yf} = 200\%$$

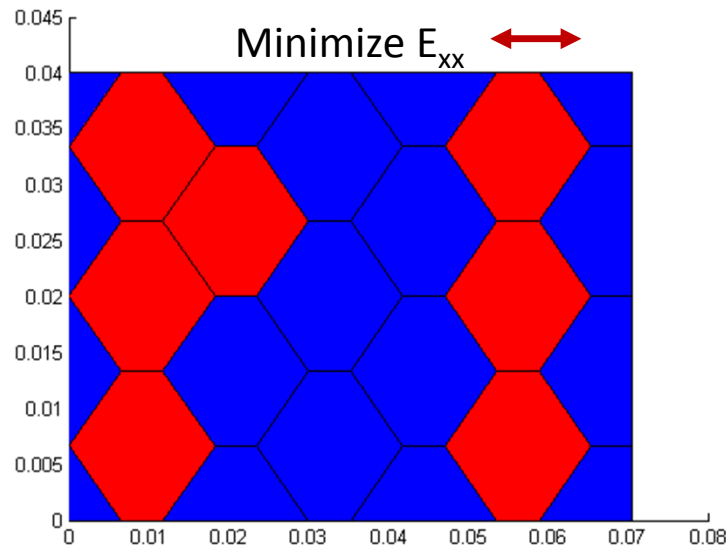


## Optimized Geometry

$l$	10 mm
$a$	1.0 mm
$d$	0.05 mm
$\theta$	62°
$h_{core}$	172 mm
$t_f$	2.5 mm



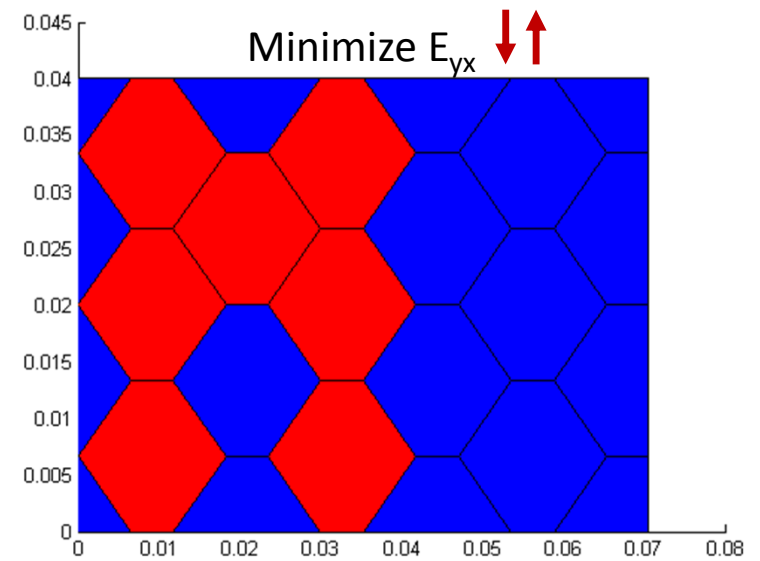
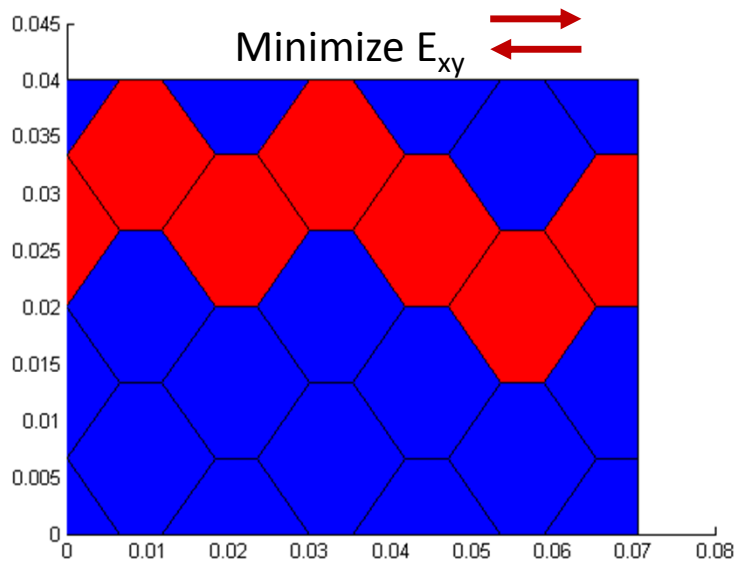
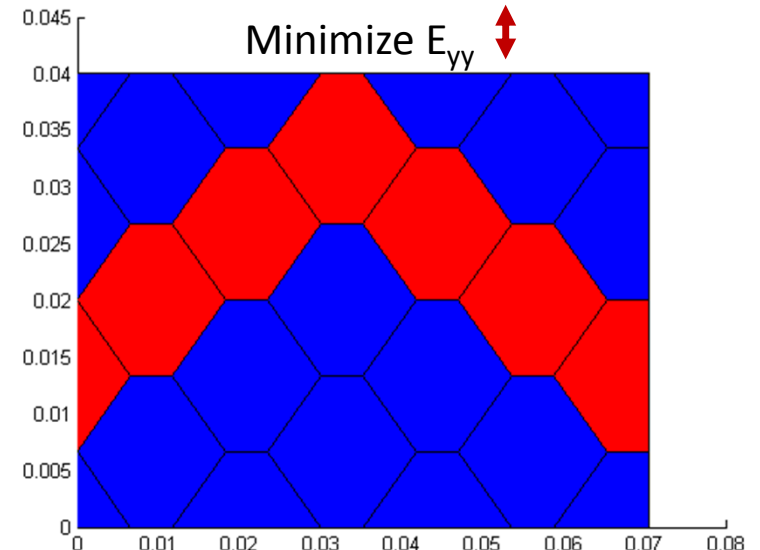
# Heating Pattern Optimization



Genetic Algorithm

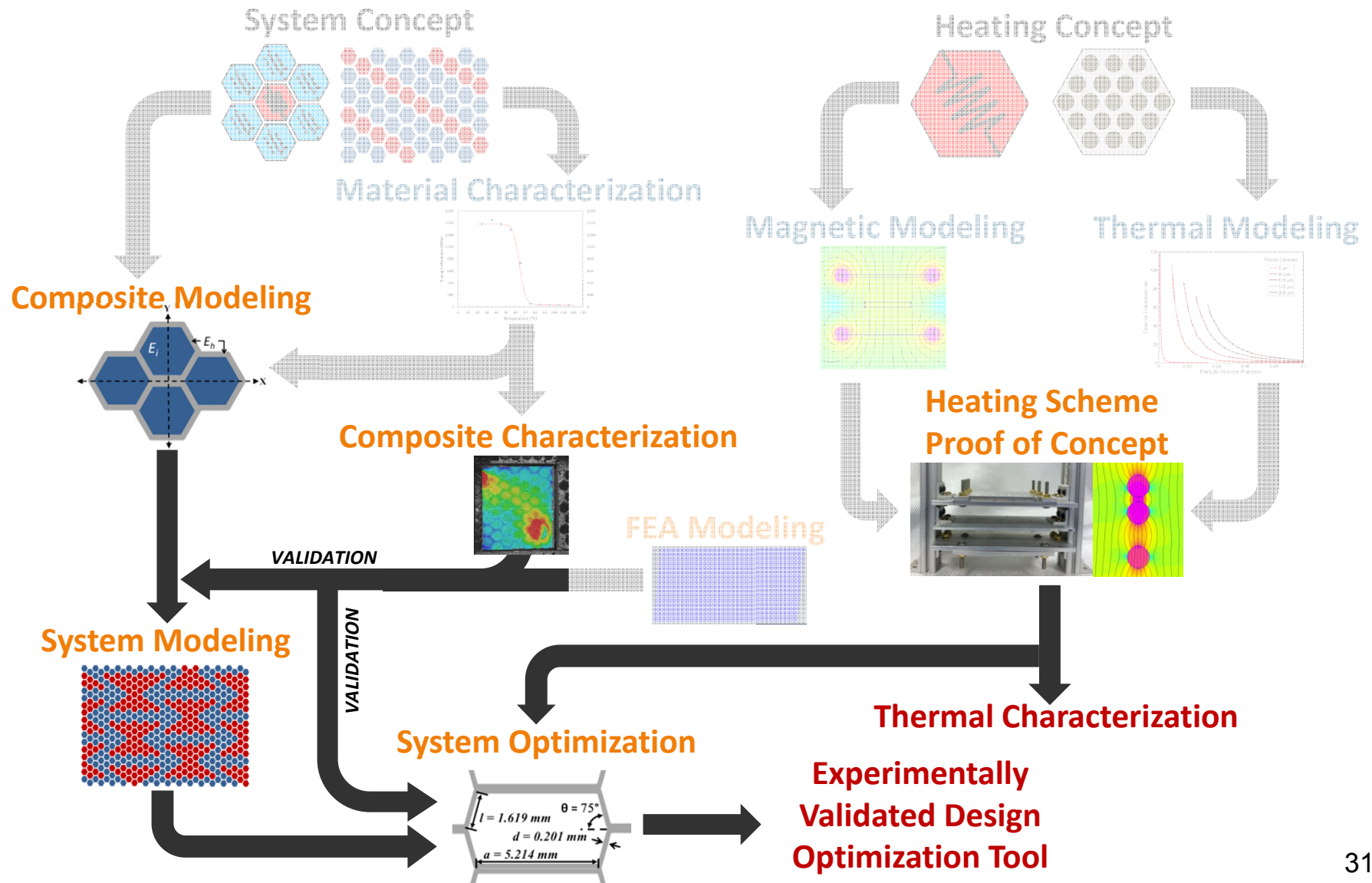
13 full cells  
12 partial cells  
7 hot cells  
18 cold cells

Not included:  
Out-of-plane def.  
Deformation req.





# Project Roadmap





# Future Work

## Future Work System Scheme

- Heating Pattern Optimization
- System Integration / Fabrication
- System Characteristics Envelope

## Future Work Heating Scheme

- Thermal characterization of heating scheme
- Thermal diffusion between cells
- Direct write electrodes (variable patterns)



# Conclusions



## Conclusions

- **Viable Option for Morphing Structures**
- **30-40% In-plane Strain Achievable**
- **Accurate Analytic Model of Filled Honeycomb**
- **Optimistic High Thickness SMP Heating Scheme**