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Discovering Beyond Imagination

Predicting Thermal Stress in Diesel Particulate Filters

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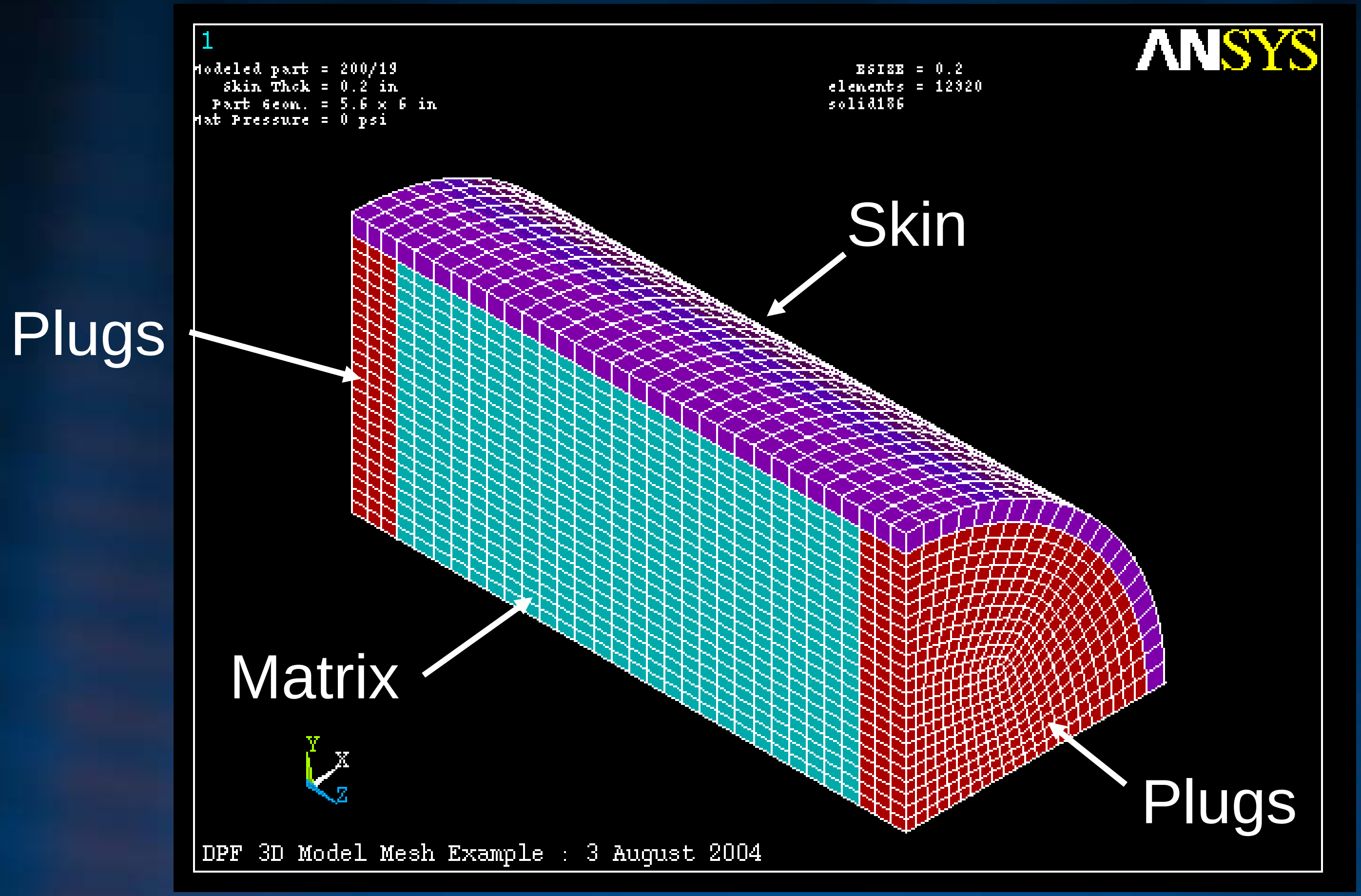
Outline

- Goals
- Approach
- Verification
- Failure Criterion
- Summary

Goals

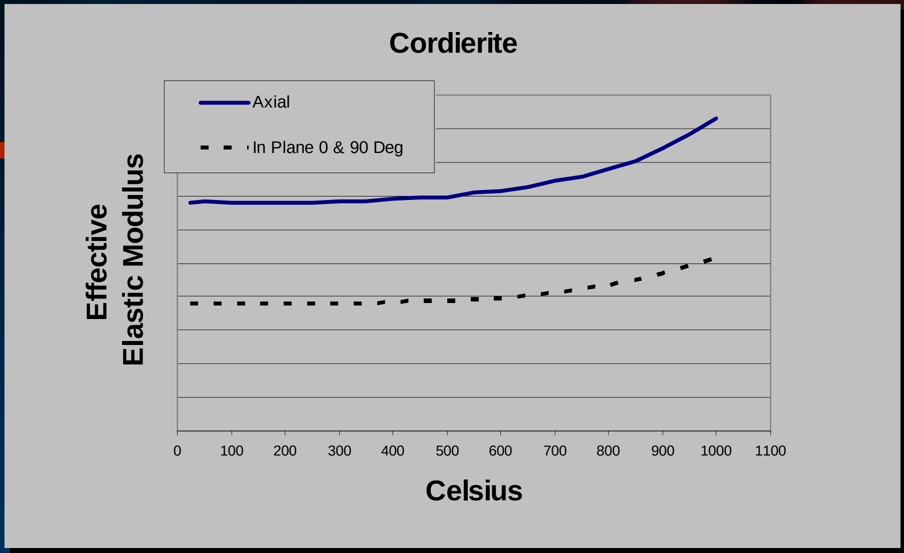
- **To predict**
  - Thermal stresses in DPFs
  - Likelihood of failure
- **Given**
  - Part geometry
  - Material properties
  - Temperature distribution
  - Failure criterion
- **Useful for**
  - Product concept screening
  - Consequences of regeneration strategies
  - Post mortem analysis
  - Life estimation

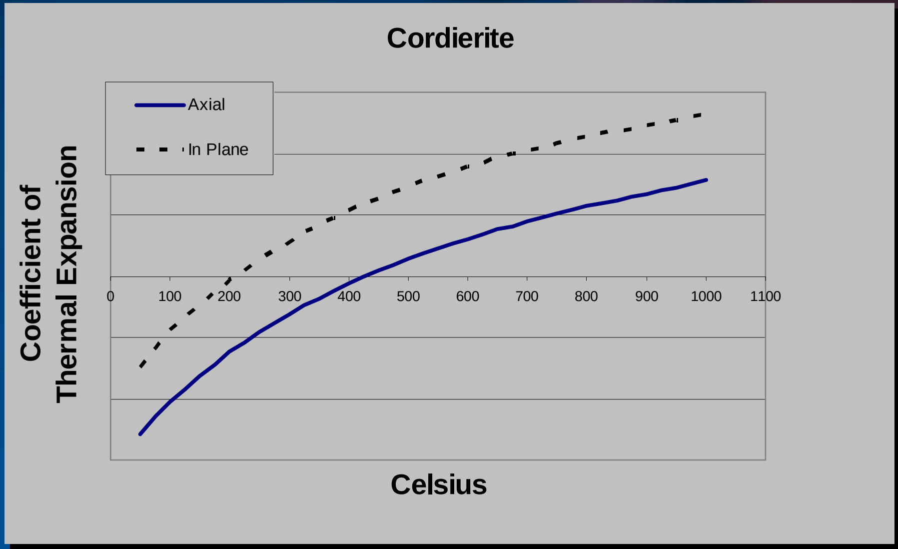
Approach
Model Geometry



Approach
Material Behavior

- Monolithic cellular structures
- Linear elastic material behavior
  - Include temperature dependence
  - Neglect temperature hysteresis
  - Stress free at room temperature
  - Neglect aging affect on properties
  - Neglect local property variation
- Continuum
  - Accounts for channels w/o needing geometric detail
  - Model simplifies to a solid
  - Equivalent properties
  - Therefore equivalent stresses



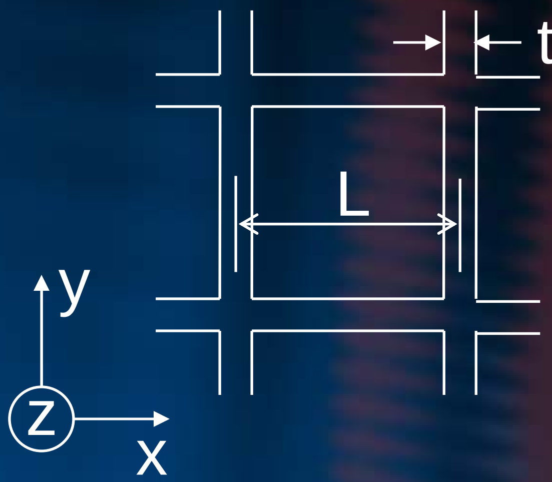


Approach
Continuum Assumption

- Pros
  - Routinely used for polycrystalline, composite, and porous materials
  - Well understood methods for measuring properties
  - Corning history of measured equivalent properties
  - Modeling entire filter practical
  - Appropriate considering the temperature measurement precision, and variability in strength and radii of cell wall intersection fillets
- Cons
  - Acceptable use depends on specific problem
  - Model material properties abstracted

Approach
Continuum Model – Square Cells[1]

- $(E)_{effective} = f((E)_{material}, L, t)$
  - E_z = Effective Axial EMOD
  - $E_x = E_y$ = Effective in plane (0° & 90°) EMOD
  - $G_{xy} = E_z\, t^2 / [(2\,L - t)(2\,L)]$ = Shear Modulus
  - $G_{zx} = G_{zy} = E_z\, L^2 / [2(1+\nu)(2\,L - t)(L-t)]$
  - $\nu_{xz} = \nu_{yz} = \nu = 0.25$ = Poisson's Ratio
  - $\nu_{xy} = \nu\,(t/L)$

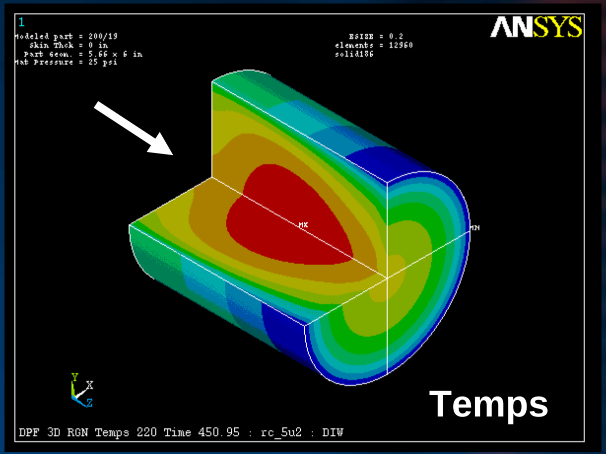


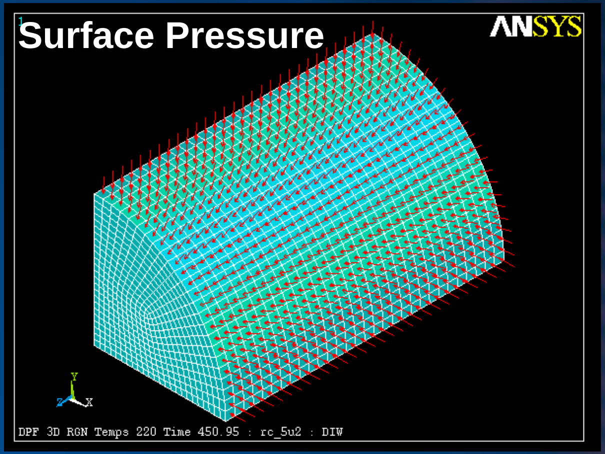
- E : Elastic moduli (anisotropic)
- Note: $G \neq E / [2\,(1 + \nu)]$: Shear moduli are anisotropic
- α_z , α_x, α_y : Coefficients of thermal expansion
  material anisotropy

[1] "Mechanical Behavior and Strength of Honeycomb Ceramic Cellular Substrates," D. K. S. Chen, ASME 90-WA/DE-5

Approach
Loads

- Temperatures
  - Regeneration prediction model
  - Engine test measurement
  - Lab simulation measurement
- Mat & can
  - Represented by boundary conditions
  - Pressure on surface
- Constraints
  - Symmetry & Rigid Body Motion

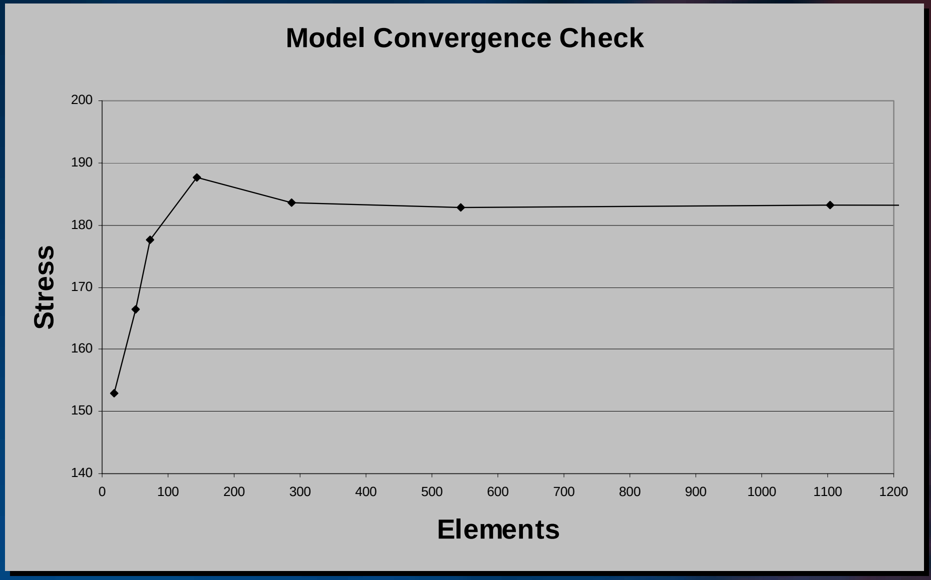




Approach
Thermocouple Pattern

Verification

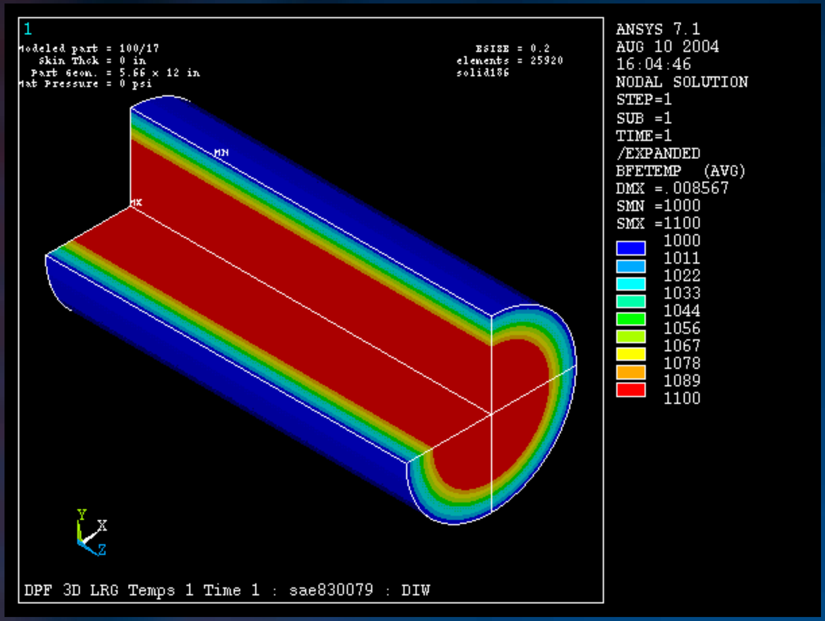
- Mesh convergence check[1]
- Comparison to theory
- Comparison to experiment



[1] "Estimating Errors in FE Analyses", A. R. Rizzo, Mechanical Engineering, May 1991

Verification
Comparison to Theory

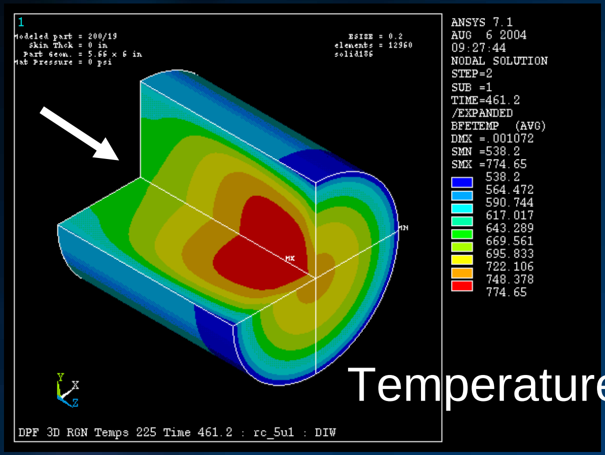
“Thermal Stresses in Ceramic Wall Flow Diesel Filters,” S. T. Gulati, SAE Technical Paper Series 830079

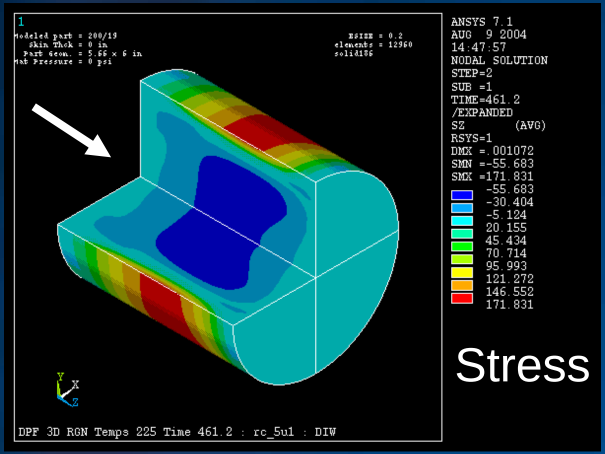


Temperatures

Tcore	Tskin	Theory 2D	FEA 2D	FEA 3D
Celsius	Celsius	Axial psi	Axial psi	Axial psi
1100	1000	134	124	107
900	800	126	119	104
700	600	106	95	83
500	400	73	67	58
300	200	28	26	22

Verification
Comparison to experiment – Uncoated DPF





Soot Load	Regens	Axial Stress 3D FEA	Filtration Efficiency
5 g/L	50	180 psi	> 90%
10 g/L	50	240 psi	> 90%
15 g/L	25	730 psi	~70%

Failure Criterion[1]

- Failure Probability P_f

$$P_f = 1 - \exp\left[-\left(\frac{\sigma_{\max,regen}}{S_o * SDF * SF} \right)^m \right]$$

- Stress Duration Factor   Size Factor

$$SDF = \left(\frac{t_o}{t_r} \right)^{\frac{1}{n}} \quad \& \quad SF = \left(\frac{A_o}{A} \right)^{\frac{1}{m}}$$

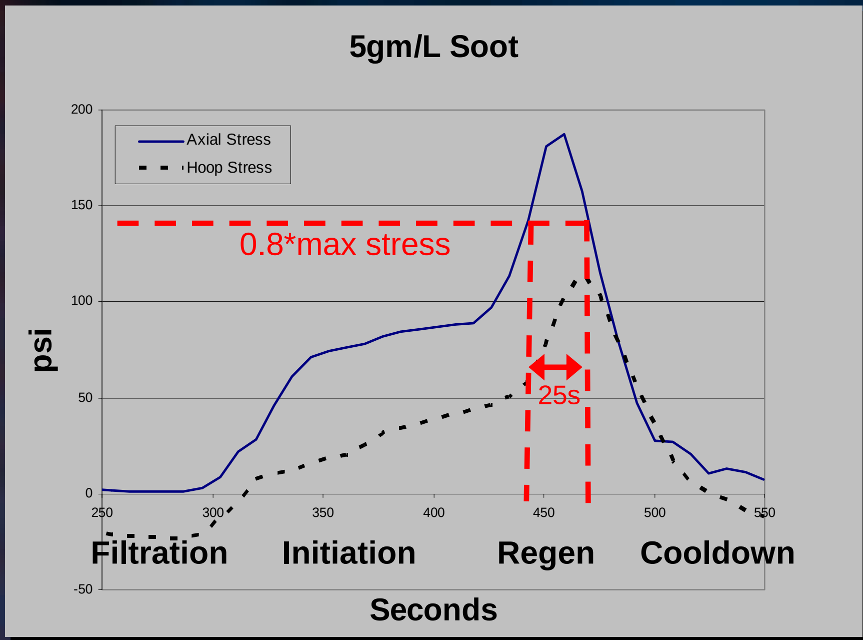
$\sigma_{max, regen}$ = maximum regeneration stress
S_o = Characteristic strength
t_o = MOR duration (1 sec)
t_r = regen stress duration
n = fatigue constant

m = Weibull modulus
A_o = MOR bar high stress surface area (0.75 sq in)
A = filter high stress surface area

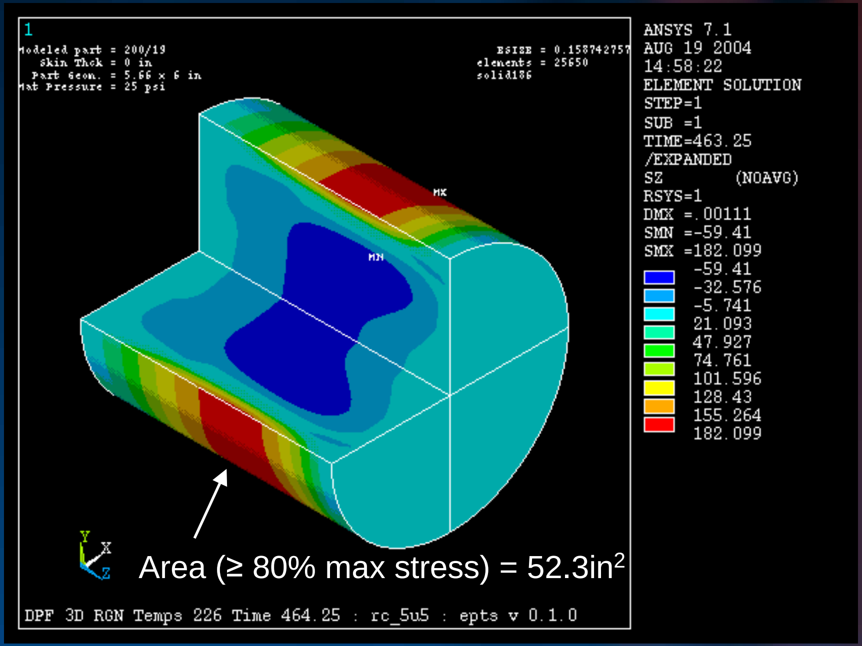
[1] **"Reliability and Design Strength Limit Calculations in DPFs," Jim Webb, DEER 04**

Failure Criterion Determination of SDF & SF

(1) Stress Duration Factor (SDF)



(2) Size Factor (SF)



- For this uncoated 5.66"Dx6"L example:
  - SDF = 70.0%*
  - SF = 75.4%*

*based on 80% max. stress level, Weibull modulus (m) = 15, fatigue constant (n) =20, and 50 regens at 25 seconds each

Failure Predictions
Verification Test Case – Uncoated DPF

Soot Load	Regens	Filtration Efficiency	Peak Axial Stress 3D FEA	SDF	SF	Failure Probability* P_f
5 g/L	50	> 90%	180 psi	0.700	0.754	0.0002%
10 g/L	50	> 90%	240 psi	0.700	0.754	0.014%
15 g/L	25	~70%	730 psi	0.725	0.754	100%

* Characteristic Strength (S_o) = 820psi

Summary

- FEA model created that predicts stress in DPFs
  - Continuum approach
  - Accounts for anisotropy, core, plugs, & skin
- Successfully used to guide research, development, and OEM design efforts
  - Development of base materials and coatings
  - Soot mass limits
  - Post mortem analyses
  - Input for durability estimates

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