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Predicting Thermal Stress in Diesel Particulate Filters

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Abstract: A diesel particulate filter (DPF) thermal stress model is described and used to approximate stresses generated during filter regeneration.

The model, intended to aid in the evaluation of DPF materials and designs, is based on a continuum approach that employs effective mechanical properties accounting for both the base material and particular geometric details.

As an initial step in the model validation procedure, model generated failure predictions are compared to experimental results.

Outline

- Goals
- Approach
- Verification
- Failure Criterion
- Summary

Today I will describe a method of predicting thermal mechanical stress in ceramic diesel particulate filters.

I will describe the problem to be solved, the information that must be known to do so, the methods used, some checks I used to find out if my answers are any good, and some detail about using the predicted stress to answer the real question. Which is, of course, will the part break in service and fail to filter enough soot from the exhaust?

Although my focus is on filters, also known as DPFs, the method can be applied to other cellular ceramic structures used in emission control systems in internal combustion engines, such as diesel oxidation catalyst supports.

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

We want to predict the thermal stress in the part, as it can be used for the more useful prediction of the probability of failure from this stress. By failure I mean fracture from thermal stress.

We need to know some things to do this; the geometry, material properties, temperatures in service, and some way to know if the predicted stress is enough to fracture the part.

Measurement is usually the source of the material properties. If the product is a composite (that is, coated), it is important to measure the properties of the composite, as they may be different from the bare extruded part.

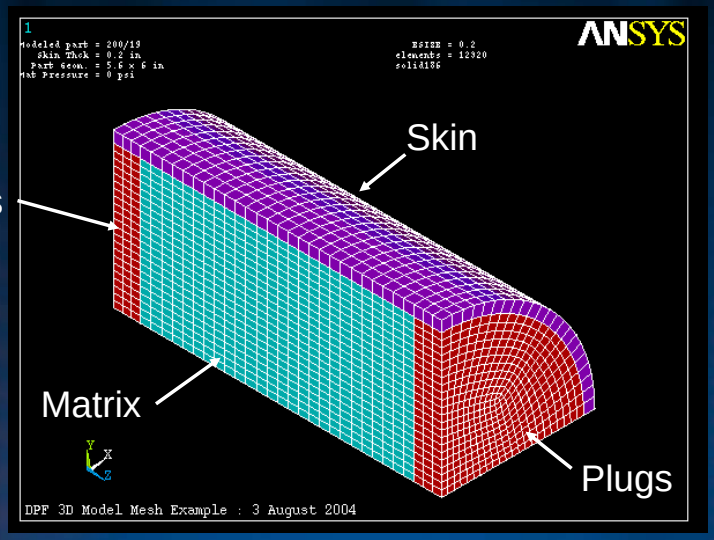
Temperatures come from instrumentation of a test or a physics based regeneration prediction model, which I will not cover here.

The failure criterion is from measurements; this *will* have a spread.

The properties, temperatures, and failure criterion are all sources of uncertainty in the prediction.

This prediction is useful for screening product concepts before making samples; exploring the structural consequences of regeneration strategies; post mortem analysis of failures, to understand how to prevent them in the future; and estimating product life before the completion of long term tests

Approach
Model Geometry

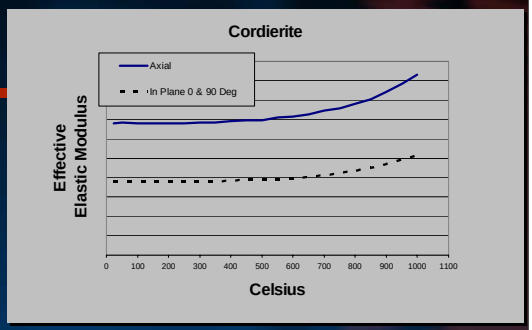


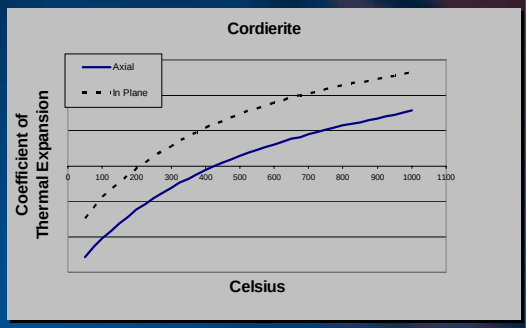
We predict stress using the finite element method. This is a plot of a 3D model mesh (there is a 2D model as well). We take advantage of symmetry and construct one quarter of the cylindrical part. Filters have three regions of differing material properties; the skin, plugs, and matrix or core, which the model accounts for.

For all the fans of FEA in the audience, I have found that higher order (or quadratic) finite element formulations give “smoother” strain and stress fields for these types of problems, so I use them in this model.

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





For practical reasons the model described here is limited to monoliths. Segmented structures can be modeled using similar methods (if you know the properties of the segment cement, and add the joints to the model geometry).

The material behavior model is linear elasticity, with temperature dependence. The plots on the right show this dependence. The second curve in each plot also shows the anisotropy, or directional dependence, of the properties. If there is any temperature hysteresis in the material, it is neglected.

The part is modeled as being stress free at room temperature. We neglect any affect of aging, from exposure to service conditions, on the properties. The properties within each of the three model regions (skin, plugs, & matrix) are considered to be uniform.

The real part is full of holes, channels actually. We must account for this, but want to do so without representing the geometric detail. One way is to treat the part as an effective continuum. This lets us simplify the geometry to a solid. That is, we account for the channels by treating the part as a solid with properties equivalent to the cellular structure. Therefore the model predicts equivalent stresses, not cell wall stress.

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

There's nothing novel about using a continuum approximation. It is commonly used for porous ceramics, as well as metals. Most applications of stress analysis don't need details about the grains in metals or about pores in ceramics.

Methods of measuring the equivalent properties of cellular ceramic structures are well understood. Corning has lots of historical equivalent properties for them.

The number of finite elements needed to model an entire part using the continuum approximation is small enough to allow for reasonably short solution times.

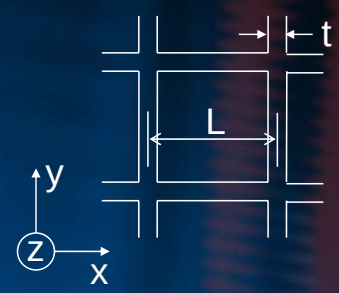
However, we are pushing the limits by using this assumption for cellular ceramics. Its acceptable use depends on the specific problem.

It can capture thermal stresses that vary smoothly over a few cell spacings, but, for example, not stresses caused by a sharp temperature spike in a small cluster of cells.

It does abstract the model material elastic properties, which become anisotropic or directionally dependent.

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

The anisotropic effective properties depend on the wall material, and structure repeat distance L and wall thickness t.

Anisotropic, homogeneous, linear elastic solids have at most 21 independent elastic constants. The symmetry of the square cell structure reduces the number of independent constants to 6.

These equations, which are for 3D Cartesian coordinates, get us from measurement to model material property input.

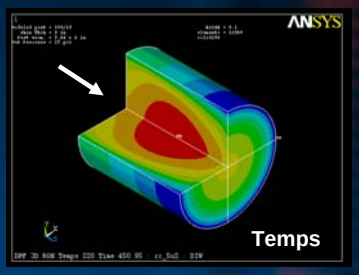
The effective axial and in plane elastic moduli, E sub z and E sub x, are obtained directly from measurement, as are the coefficients of thermal expansion.

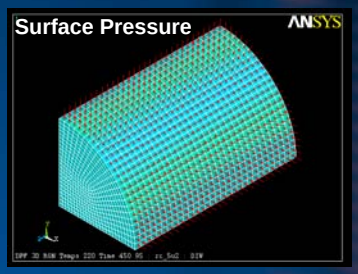
The shear moduli, the G's, are also anisotropic. They can be estimated using Chen's analysis, although direct measurement is preferable. The repeat distance and wall thickness need to be measured if the shear moduli are estimated. It's good to do this anyway, to characterize the structure.

Note that this structure has low resistance to forces along the diagonals because the cell walls bend. This is a source of the elastic anisotropy in the structure.

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

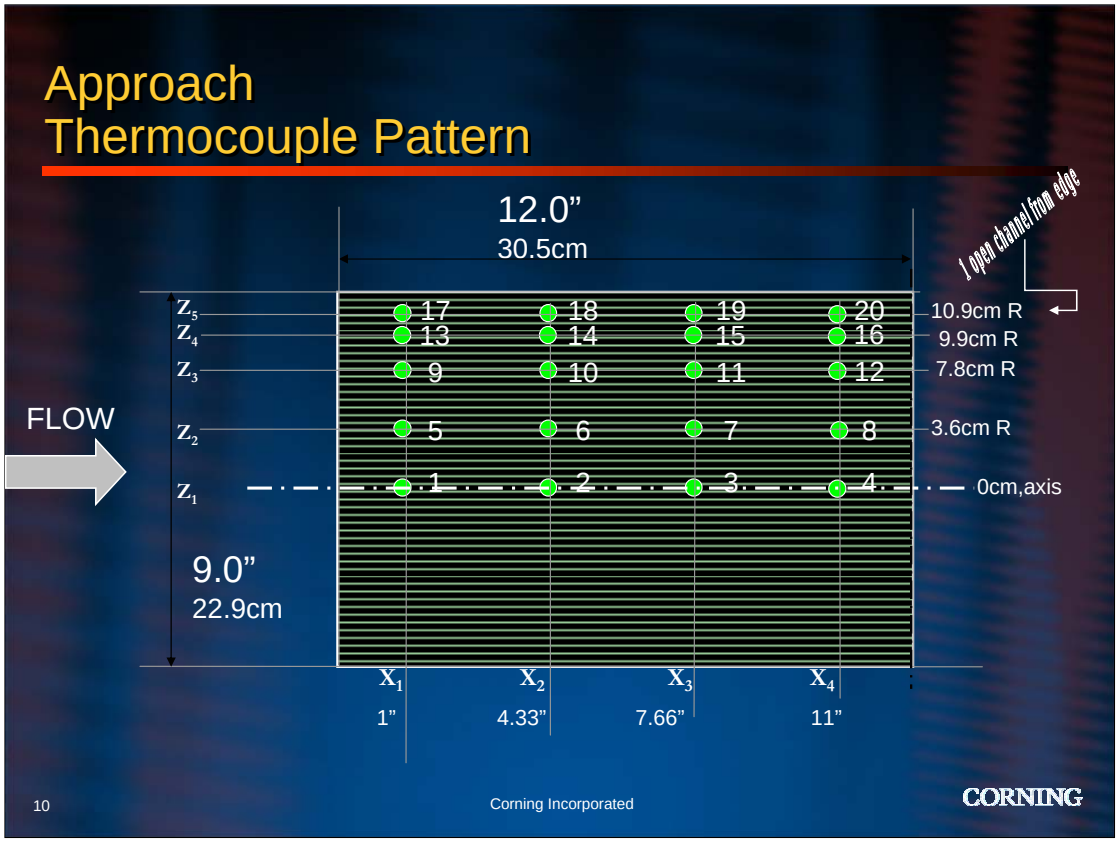




The part temperature distribution, on the upper right, is the load that causes the model predicted stress. In the plot, red indicates the highest temperature and dark blue the lowest. The arrow shows the direction of exhaust flow. Part temperatures can come from prediction, engine test measurement, lab simulation measurement, or a combination of measurement and prediction.

The package, that is, the mat & can, is not included in the model geometry, but is represented by a pressure boundary condition applied to the part surface, shown on the lower right. The model currently neglects the axial traction of the mat on the filter surface, caused by the relatively high thermal expansion of the can.

The symmetry planes of the mesh are constrained to remain in the plane. A single point on the line of intersection of the symmetry planes is also fixed to prevent rigid body motion.



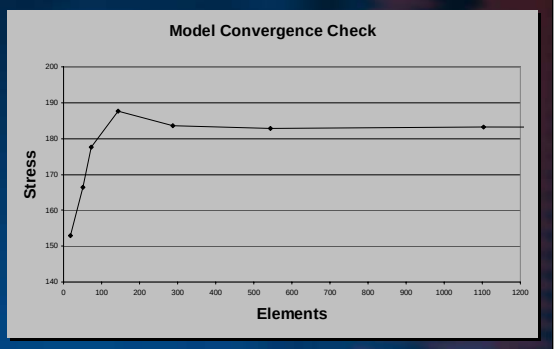
This is a typical thermocouple layout. They are not all on one plane, but distributed around the part, at various angular positions.

Lots of temperature measurement points are better for stress prediction. However, there is a practical limit to this. At some point, the mass of the thermocouples and wire must affect the thermal mass of the filter, and therefore the regeneration temperatures. They may also affect the distribution of exhaust gas flow through the filter.

The model assumes that the temperature distributions are axisymmetric, even for the 3D version. It interpolates and extrapolates from the thermocouple data to assign temperatures to the finite elements.

Verification

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



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

It's a good idea to test finite element models, as we need to know if our predictions are correct.

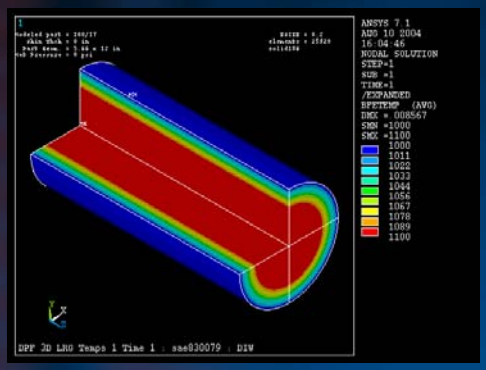
First, I did a mesh convergence check to ensure that the element size is fine enough. It's wise to use enough elements so moderate changes in the element size won't affect the prediction. This check does require changing the element size enough to get about a 2X change in the number of elements with each step.

Next, I also solved a problem I could check with an independent prediction method. For this I choose a problem with an approximate analytical solution.

Finally, although this is an indirect check, I compared the model predicted stress to experimental observation of filter integrity.

Verification
Comparison to Theory

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



Temperatures

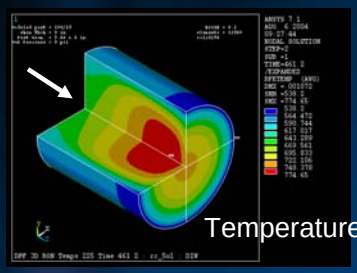
Tcore	Tskin	Theory 2D	FEA 2D	FEA 3D
Celsius	Celsius	Axial psi	Axial psi	Axial psi
1100	1000	134	124	107
900	800	126	119	104
700	600	106	95	83
500	400	73	67	58
300	200	28	26	22

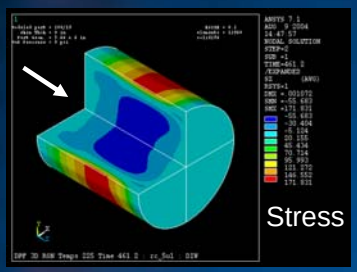
The model shows reasonable agreement between two dimensional analytical theory and 2D FEA for this simple linear radial temperature distribution. The agreement to three dimensional FEA is less good, but keep in mind that the 2D theory and 2D FEA can't account for the complete anisotropic behavior of the structure.

The predicted stress increases with temperature because of the material property temperature dependence.

The tangential (or hoop) stress comparison is similar for the 2D theory & 2D FEA. The 3D FEA tangential stress prediction is much lower, as we expect from the low in plane elastic modulus along the direction of the square cell diagonals, which 2D analysis doesn't account for.

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%

For the comparison to experiment, I used temperatures from a fit of regeneration prediction model to engine test measurement of an uncoated filter subjected to a drop to idle regeneration control strategy. A single bare 5.66”D by 6”L filter was tested by repeated loading and regeneration. After completing 50 load and regeneration cycles, the soot load was increased, and the cycle repeated until the filtration efficiency decreased significantly.

A contour plot of the predicted axial stress near the peak stress time during regeneration with 5 gm/L soot load is shown on the lower left. Red indicates tensile stress. The darker blues indicate compression.

The implication is that increased soot load increased the stress, as predicted by the model, until it became high enough to cause a fracture, allowing soot to bypass the filter. A ring off crack was observed during the post mortem analysis of this filter, supporting this hypothesis.

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**

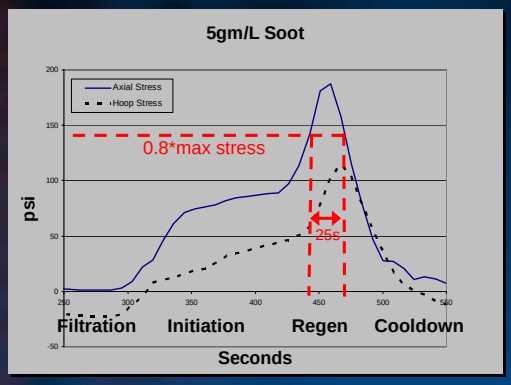
Another way of checking this hypothesis is to use some quantitative failure criterion. The FEA model predicts stress. We want to know if the part will break. We could just compare the peak stress prediction to the average measured strength. However, the strength of ceramics is not a single number. It has some spread, or distribution.

If we use the method described earlier today by my colleague Jim Webb, we can determine the probability of failure occurring from the predicted stress.

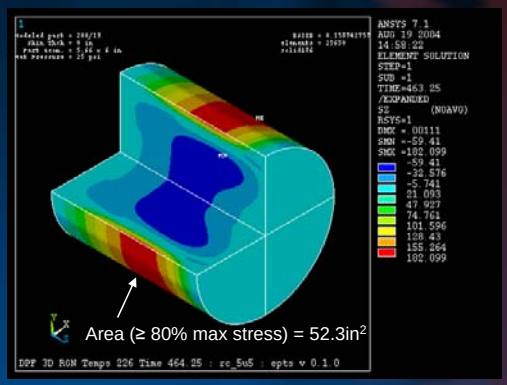
For this we need a prediction of more than just the peak stress. Fortunately the FEA also gives predictions that help determine the Stress Duration Factor, which accounts for slow crack growth fatigue, and the Size Factor, which accounts for the reduction of ceramic strength with increasing specimen size.

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

From a prediction of the peak stress as a function of regeneration time (plotted on the left), we see that the part is exposed to 80% of the maximum stress for 25 seconds during a single regeneration. Multiply this by the number of regeneration and we get t sub r, the regen stress duration time, used in the Stress Duration Factor equation on the previous slide.

From the plot of the axial stress at the regeneration time of the peak stress, we can determine that the area of the filter surface predicted to experience over 80% of the peak stress is about 52 square inches. This is A, the filter high stress surface area, used in the Size Factor equation.

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_0) = 820psi

We use these factors, along with the predicted peak regeneration axial stress from the experimental case, and calculate a predicted failure probability.

I considered just the axial stress because the predicted radial and hoop stresses are too low to be of concern. Plus, the tested part experienced a ring off crack, which is caused by axial stress.

The predicted failure probability agrees with the observation of a ring off crack occurring during the 15 gm/L cycles. This also gives us the idea that soot loads of around 5 gm/L are better for filter durability than those over 10 gm/L.

The failure probability of a more realistic number of regenerations is:

10 g/L, 500 x 30 sec regens (SDF=0.618), Pf = 0.09% (1:1100)

10 g/L, 1000 x 30 sec regens (SDF=0.597), Pf = 0.16% (1:625)

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

To summarize, we have a model that predicts stress in DPFs, using a continuum approach. It accounts for anisotropy, and the core, plug, and skin regions of the part.

It has been used to guide the development of base materials and coatings; to guide soot mass limits; for post mortem analyses of failures; and for input to durability estimates.

Thank you for your attention. Are there any questions?

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