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Damage in Highly-Filled Composites

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September 2020

Background

What are Highly-Filled Composites

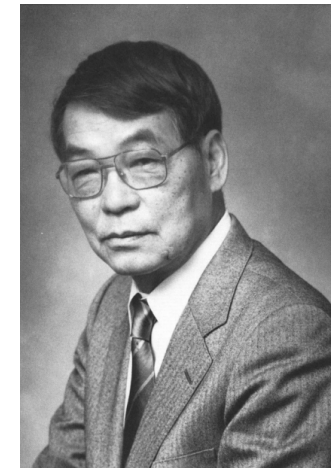
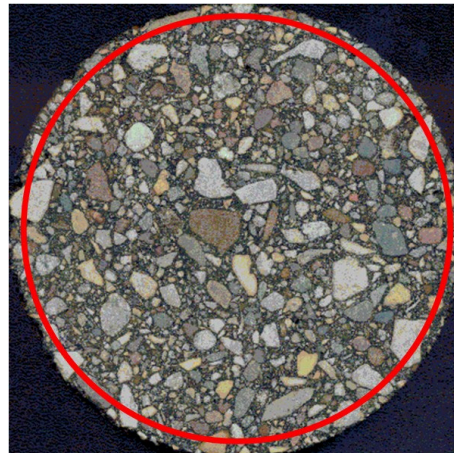
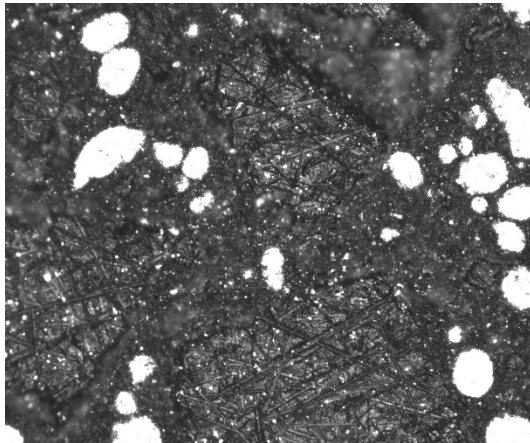
Many explosives, solid propellants, and some other materials (asphalt concrete) can be considered highly-filled composites.

The salient feature is that the "filler" material is a substantial volume fraction of the composite.

With solid propellants the volume fraction of the particles exceeds 60% (typical number is 75%).

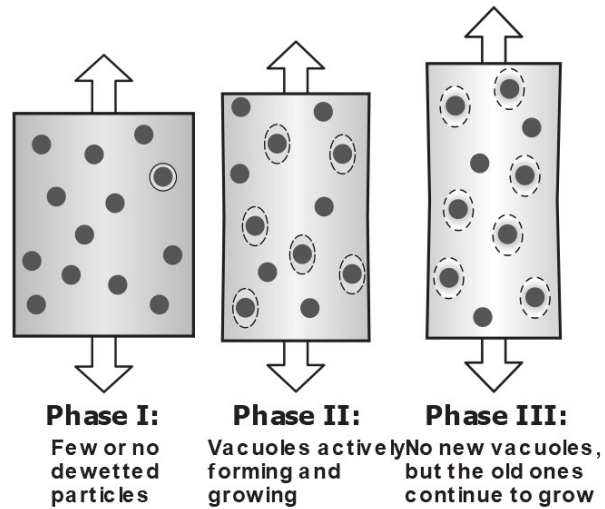
Implications:

- Micromechanics principles do not apply, since the "dilute concentration" assumption is stretched beyond its limit.
- Nonlinear viscoelasticity is the logical constitutive model, since particle/matrix separation will occur at very low strains (on the order of 1%)
- We illogically choose linear viscoelasticity, since the complexity of nonlinear viscoelasticity is too difficult to do well.
- Substantial damage may occur between initial damage and final failure.
- For predicting or improving mechanical properties, the strength of the particle/matrix interface is one of the most important features.

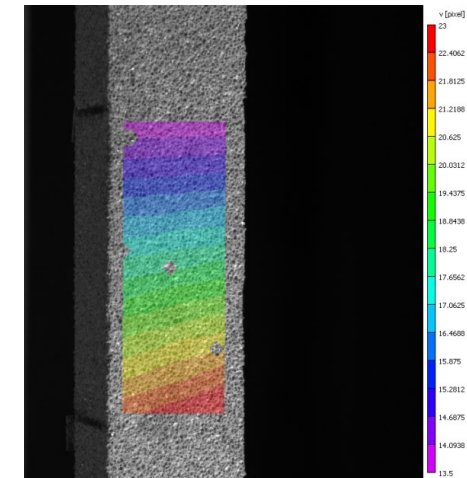
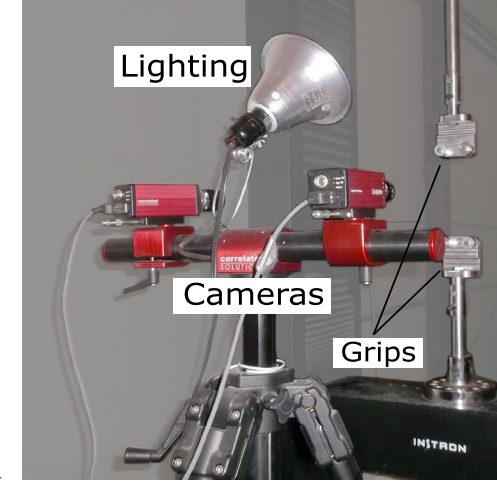
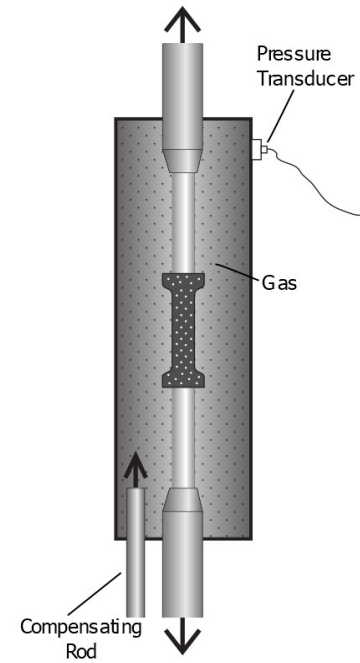
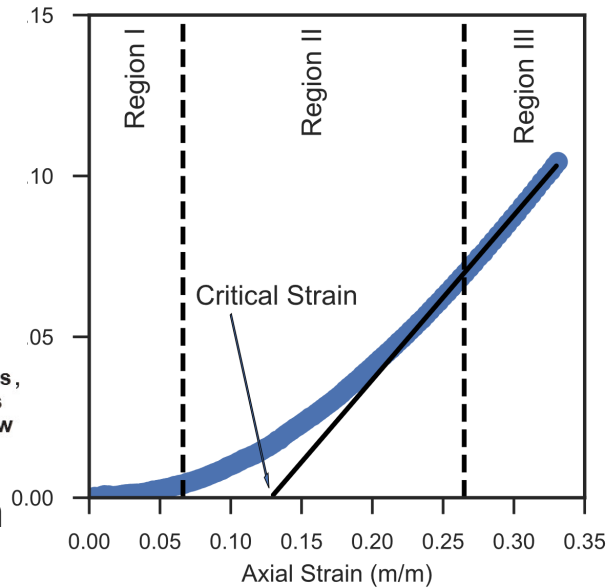


Do propellants experience damage?

- The particles do not change volume
- The matrix material does not, either
- All volume changes, therefore, come from holes that develop and grow.
- The volume change is indicative of a separation at the interfaces

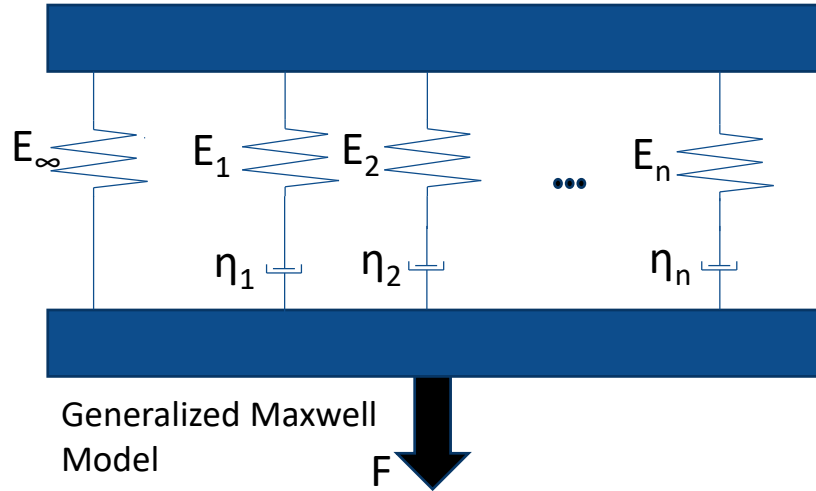


The separation of particles from the matrix in propellants is called **dewetting**.



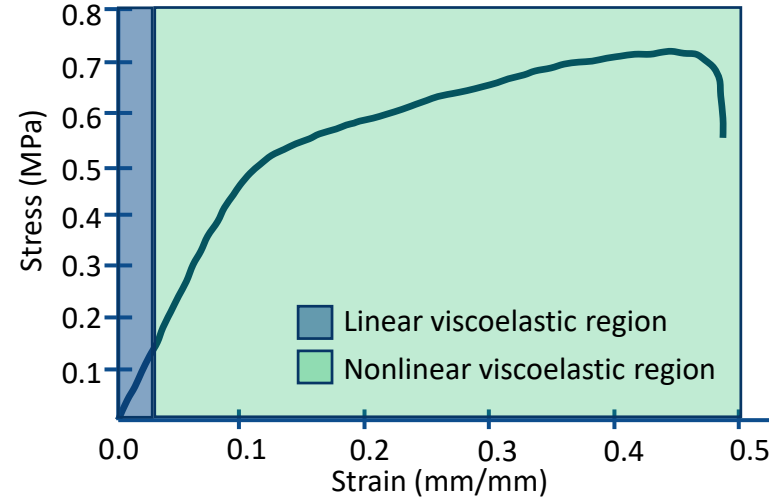
Miller, T. C., Damage and Dilatometry for Solid Propellants with Digital Image Correlation, *Propellants, Explosives, and Pyrotechnics*, 44(2), February 2019, p. 234-245. doi: 10.1002/prep.201800283

What are the appropriate constitutive equations?



$$E(t) = E_{\infty} + \sum_{i=0}^n E_i e^{-t/\tau_i}$$

$$\log(a_T) = -\frac{C_1(T - T_{ref})}{C_2 + (T - T_{ref})}$$



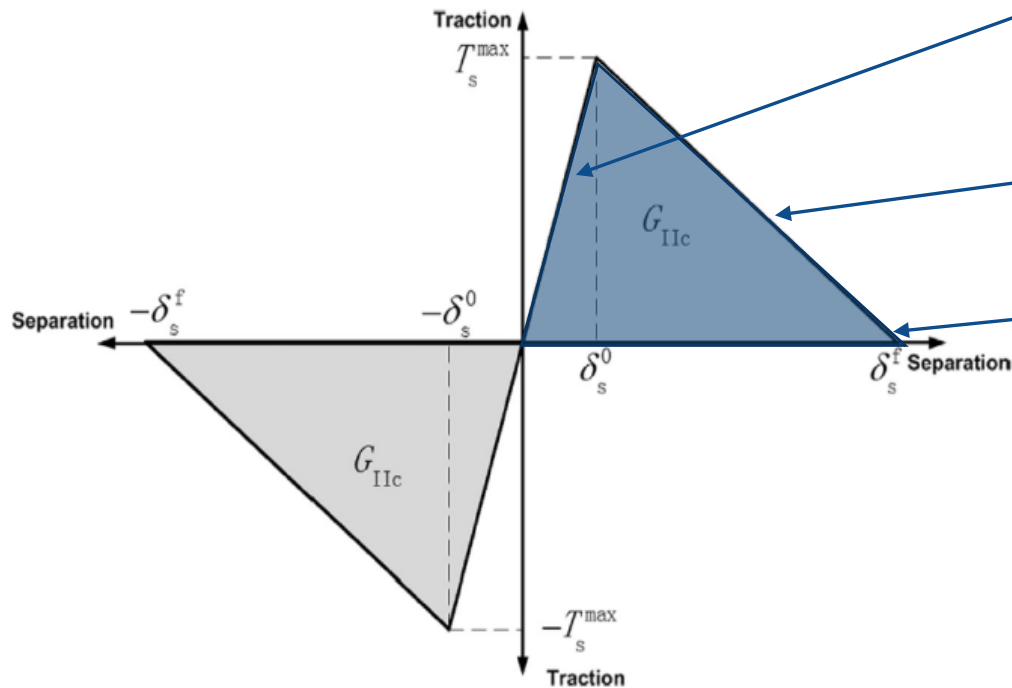
Linear viscoelasticity

- The mechanical properties are well characterized by simple uniaxial tests, such as stress-relaxation tests or DMA tests
- $E(t)$ is time and temperature dependent, but not strain level dependent
- Only applicable for low strain levels
- There's no such thing as damage

Nonlinear viscoelasticity

- Characterization of the mechanical properties require multiple tests with multiaxial stress states
- $E(t)$ is time, temperature, and strain dependent
- Applicable regardless of strain levels
- Requires a consideration of damage (primarily due to **dewetting**)

If the particle matrix interfacial strength is so important, how do you model that?

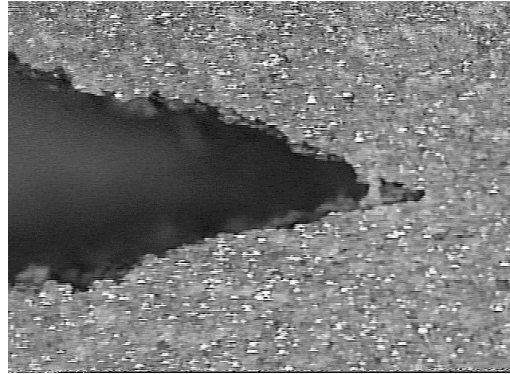


Simple traction separation law. The area shown in blue is equal to the critical energy release rate from fracture mechanics

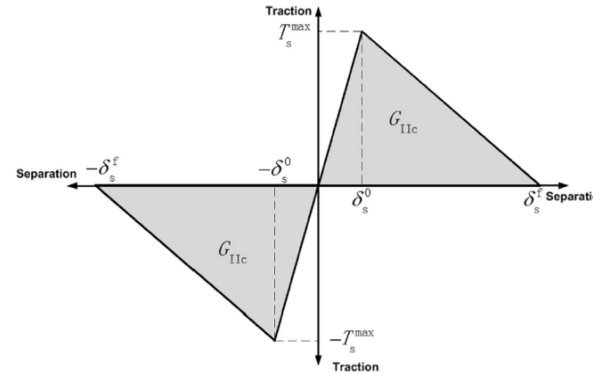
Cohesive zone modeling (CZM)

- The simplest traction separation law:
 - As you pull on an interface, it gets wider, but it also takes progressively more force to apply additional deformations.
 - After a certain point, the load reaches a peak, then begins to drop as damage takes place.
 - Once the load drops to zero, the two materials are separated.
- Separate sets of parameters will be needed for different modes of separation (tension vs. shear, for example)
- Getting the parameters from experimental data could prove difficult.
- More complex traction separation laws can be used if more fidelity is desired – a plateau can be implemented, for example.

What is the reason for using Cohesive Zone Modeling?



$$K_I > K_{IC}$$



Area under curve > G_{IIc}

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta)$$



Instead of $r^{-1/2}$, this becomes $r^{(-1/2+i\epsilon)}$, where $i = \sqrt{-1}$

Fracture Mechanics

- Analyzes an existing crack, but cannot predict the nucleation of one.
- Requires a singularity dominated zone, which requires small-scale yielding.
- Fracture mechanics on interfaces involves a complex number (square root of -1), which gives bizarre predictions

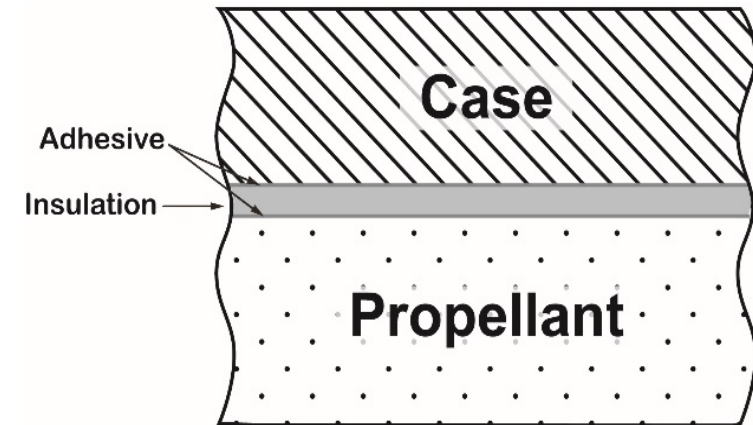
Cohesive Zone Modeling

- Can be used even without assumptions of an existing flaw.
- These assumptions are not required.
- This complication is avoided.

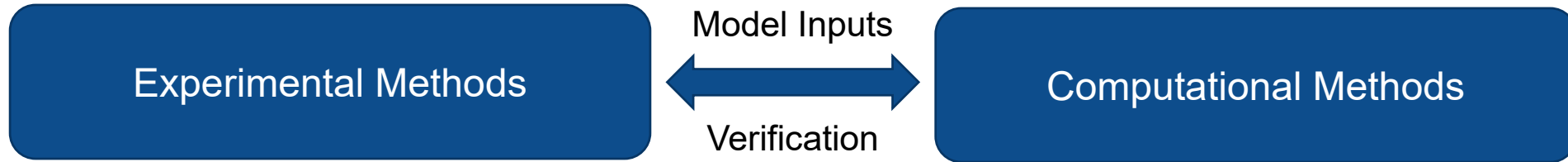
Goals and Objectives

A more fundamental understanding of the behavior of failure phenomena in highly-filled composites. This includes both the microstructural behavior in the bulk material and the delamination behavior along the composite/adhesive interfaces

- **Objective 1: Investigate the microstructural failure phenomena along particle/matrix interfaces in a highly filled composite**
 - What affects the onset of particle dewetting? (bonding agent, particle size, volume fraction, temperature, loading rate)
 - What are the appropriate traction-separation laws?
- **Objective 2: Investigate the special circumstances of a propellant-insulation delamination**
 - What makes a kissing debond propagate? (bond strength, material properties, mode-mixity, temperature, loading rate)
 - What are the appropriate traction-separation laws?



Approach



- Use two-dimensional digital image correlation in conjunction with an optical microscope to obtain strain fields in specimens.
- Vary experimental parameters (bonding agent, strain rate, particle size, etc.) and observe effects.
- Use strain fields to determine traction separation laws.

- Use Abaqus's conventional finite element analysis with built in cohesive zone models.
- Vary form of traction separation laws to optimize correlation with experimental data.

Technical Challenges

| Issue | Approach |
|--|---|
| Digital Image Correlation analyzes the displacements of speckle patterns. To work properly, the speckles must be much smaller than the objects that you are investigating. | Use non-conventional approaches to speckling, quantum dots or finely dispersed particulate matter, as a means of speckling. |
| The depth of field of the optical microscope prevents acquisition of good data. | Work with the digital image correlation vendor to determine proper optics and approaches for this work. |
| Too many variables to investigate in the given time frame. | Work incrementally, varying the most important parameters first. |

Payoffs



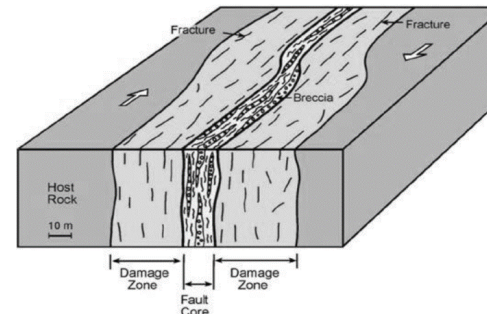
Improved propellant formulations



Civil engineering improvements



Reduced missile failure



Tectonic predictions

Questions?