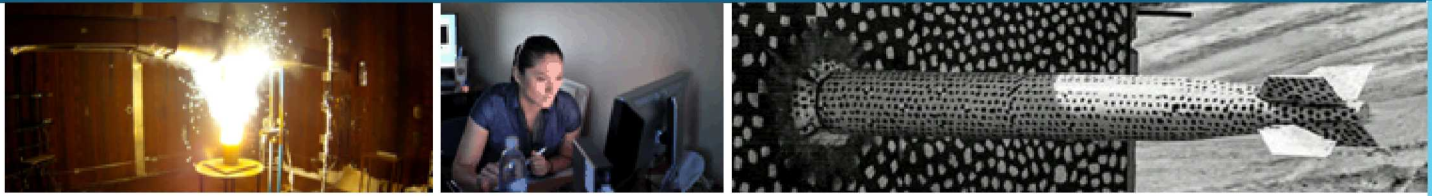
SAND2019-14707PE

ATA/1558 Interchange

Brittle fracture: Drivers, capabilities, and needs



DRAFT version, not for public release

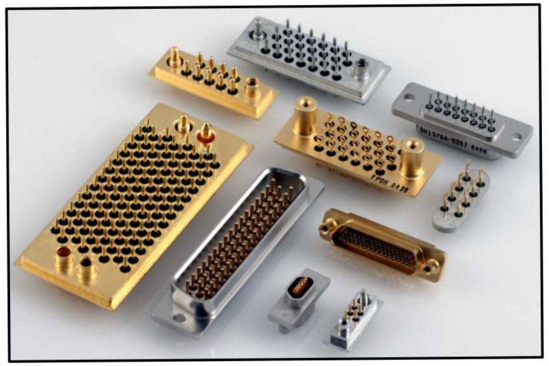
Anticipated UUR status after R&A approval

PRESENTED BY

Scott Grutzik

Demonstrative example: hermetic connectors

Credit: Brenton Elisburg (1556)



Barrier to gas/liquid transfer between environments

- Allow electrical transmission

Designed for extreme conditions

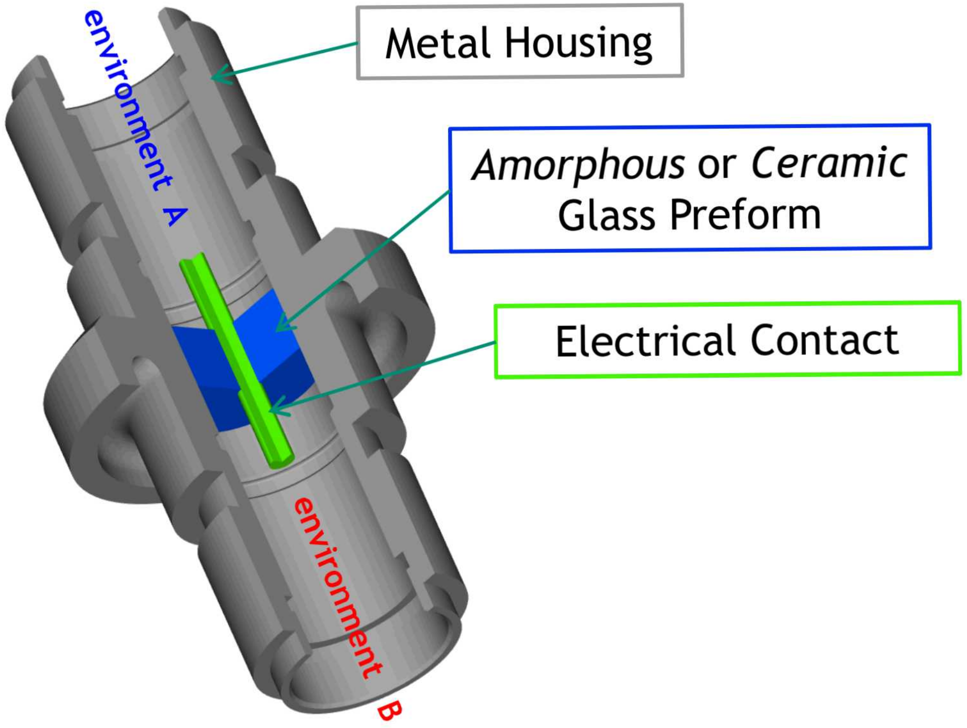
- Thermal
- Pressure
- Shock/vibration

Many applications

- Satellites, submarine vehicles, medical, telecommunications, fuel cells, etc

Types of hermetic connectors

- Matched seals (minimize residual stress, rely on bonding at interfaces)
- Compression seals (minimal interfacial bonding, rely on compressive residual stress for hermeticity)



Creating a hermetic seal

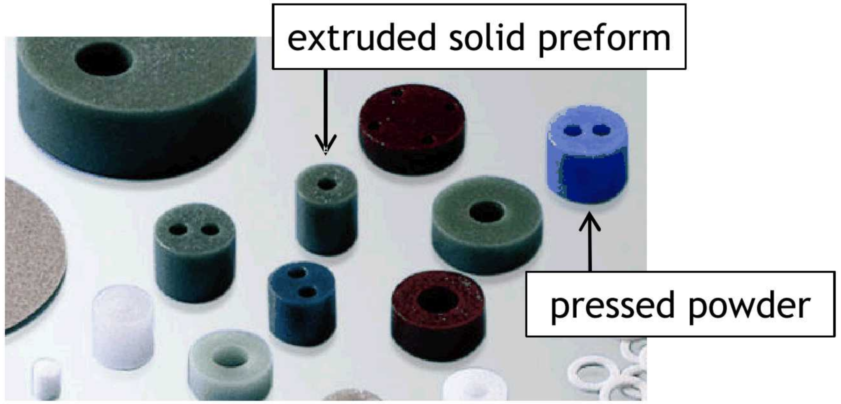
Credit: Brenton Elisburg (1556)

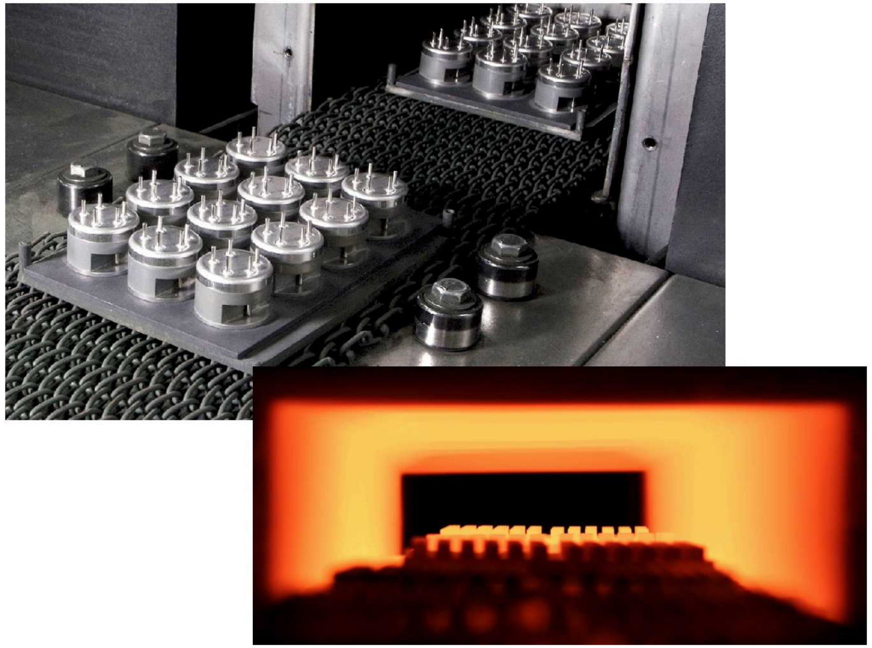
Piece part assembly
- Fixture holds preform and contact(s) in shell

Glass melt and flow
- Belt fed furnace with multiple chambers
- Exceed melt temperature
- Glass flows and fills all gaps

Compression from shell as connector cools
- SS 304L CTE = 17 ppm/°C
- Glass CTE = 10 ppm/°C

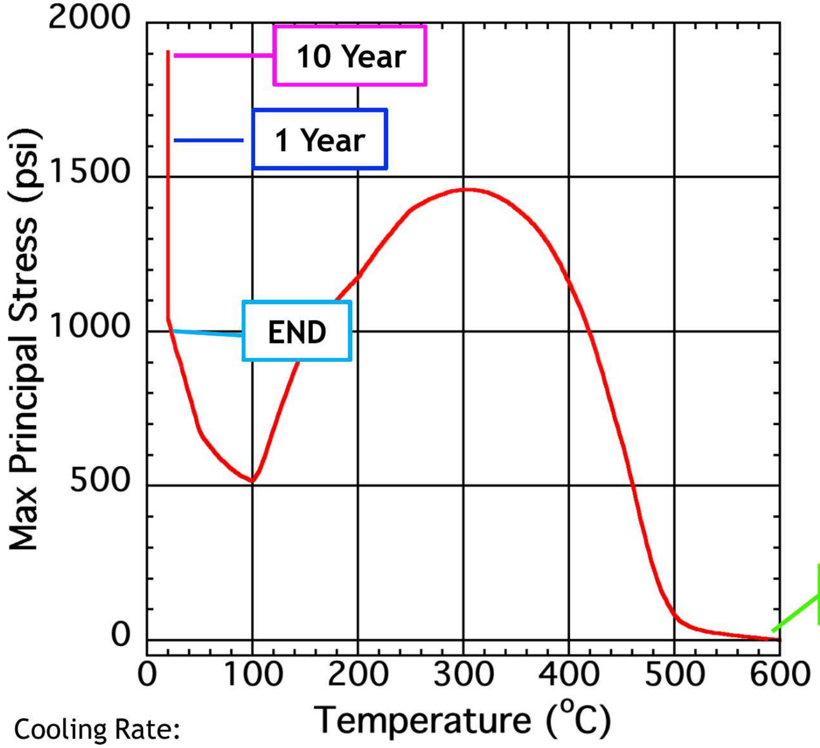
Matched seals usually made with glass-ceramics
- Crystalline phases precipitate from starting glass
- By controlling growth of various phases CTE can be matched to SS shell
- GC seals tend to be more reliable but have many technical open questions





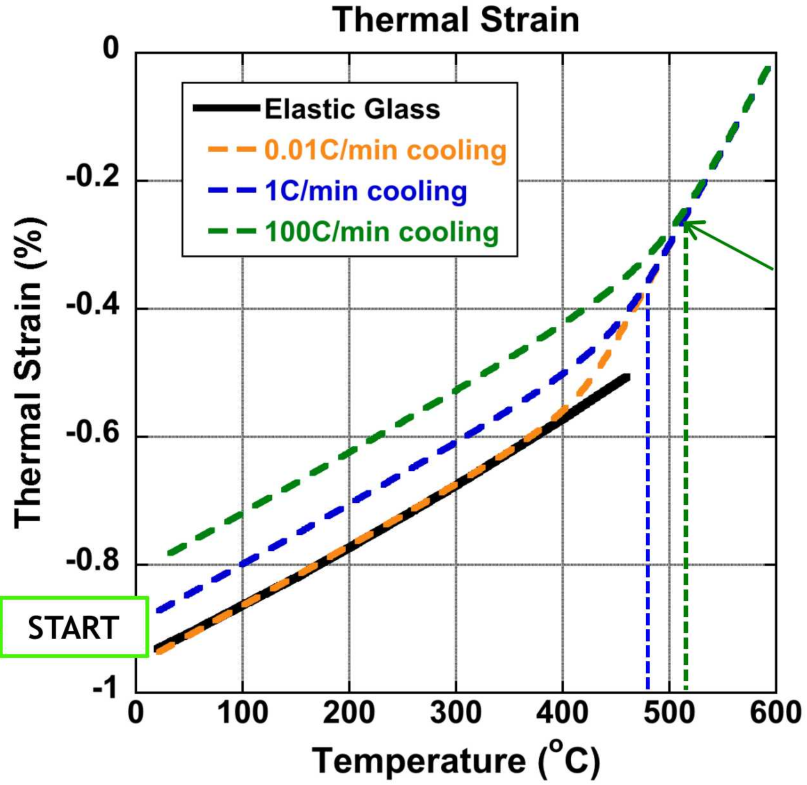
Constitutive model predictions

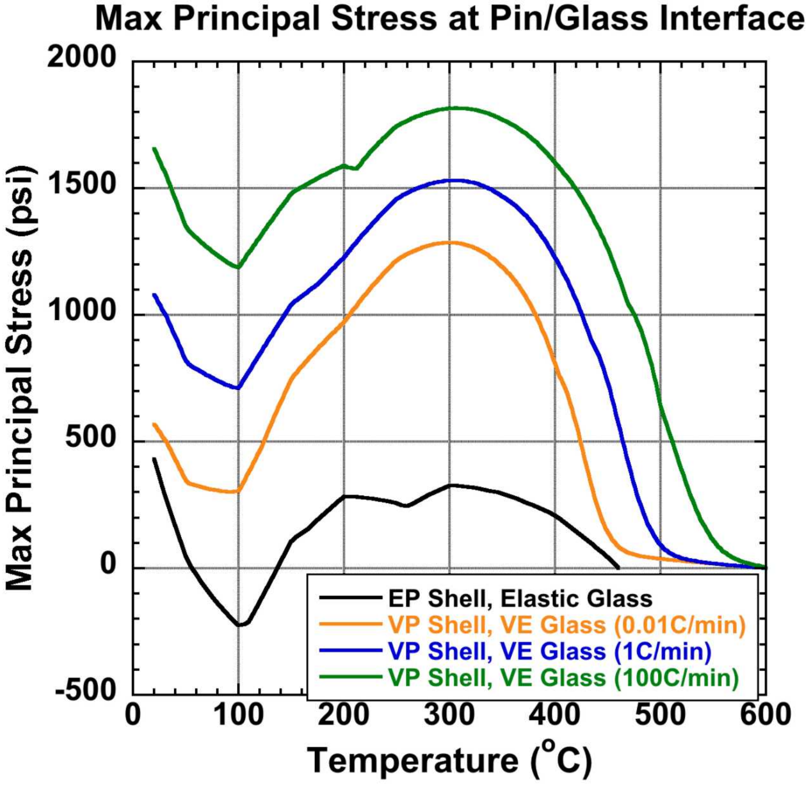
Credit: Brenton Elisburg (1556)



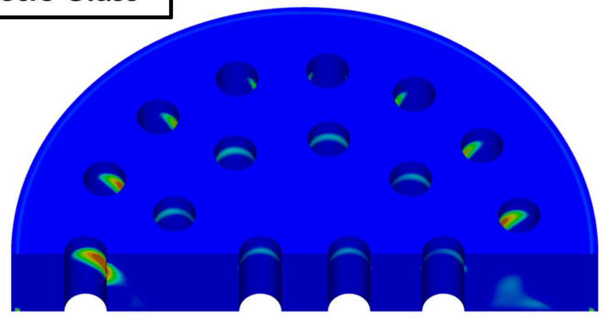
START

Cooling Rate: 1C/min

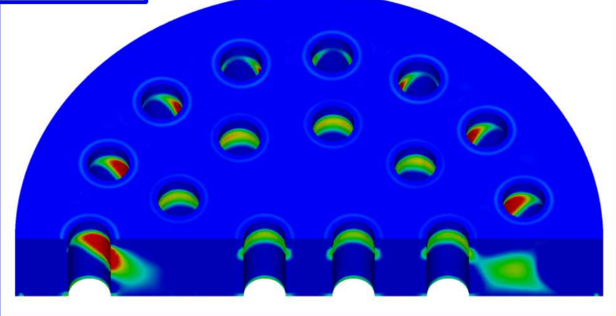


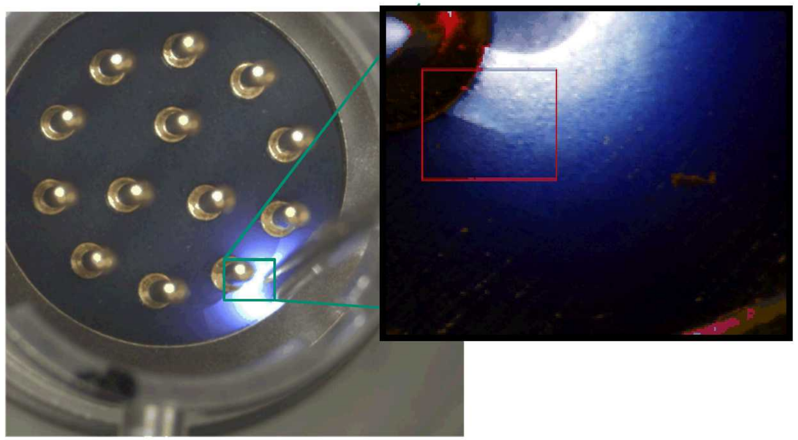


EP Shell, Elastic Glass



VP Shell, VE Glass





Challenges for predicting brittle failure in Sandia components

Accurate prediction of stress state requires constitutive models beyond linear elasticity

- How to combine constitutive model with LEFM tools which assume elasticity?
- Is LEFM an appropriate theoretical framework?

Cracks are often difficult to detect, geometry is uncertain

Cracks are often small, maybe on similar size as process zone or microstructure

Often require decades long lifetime prediction for materials that do not significantly age

- We must account for aging of flaw population and statistical variation of environment/loading

How to relate microstructural features to failure?

How to predict failure when there is no pre-existing dominant flaw?

- Use engineering approach of assuming largest undetectable flaw in worst location and orientation
- Use stochastic failure methods like Weibull analysis
- Similitude of Weibull specimens to component flaw populations is often questionable (in seals cracks often initiate at pin/glass interface whereas Weibull specimens are bend bars with a free surface)

Interfaces are often important

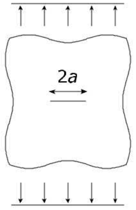
- Requires different theory, analysis methods, toughness data

Fatigue is often important

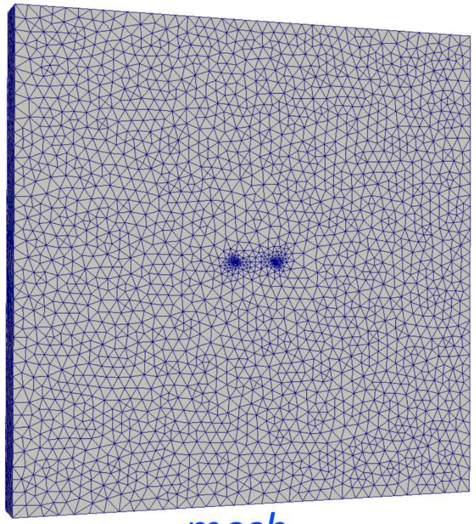
- Near threshold UHC fatigue is challenging
- Fatigue in welds has lots of complications

Current capability: LEFM modeling with FRANC3D/Sierra

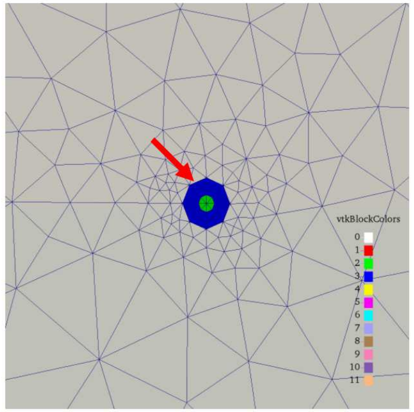
Interior crack in plate



$$K_I = \sigma_0\sqrt{\pi a}$$
$$K_I = \sqrt{\pi} = 1.77245$$



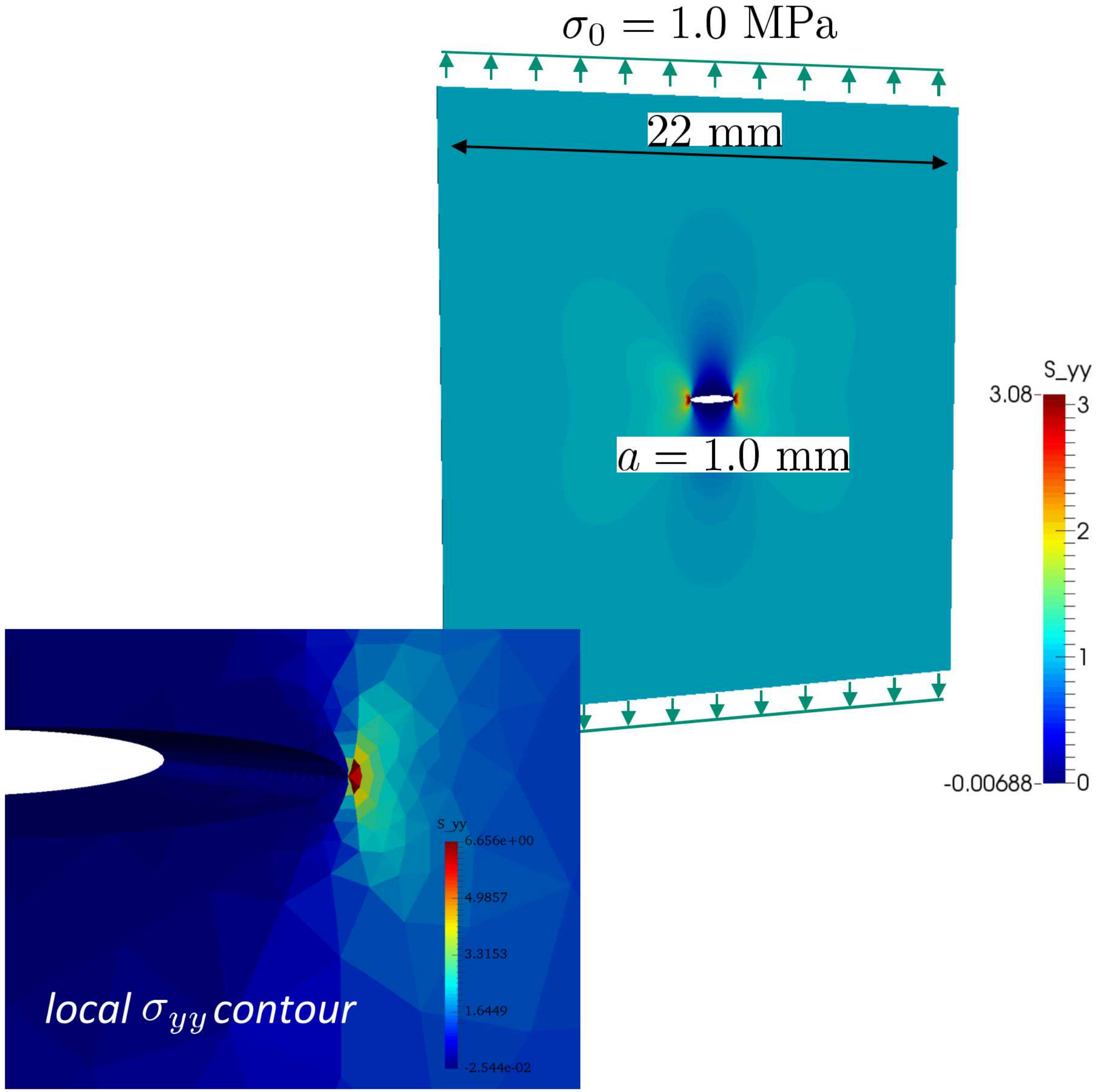
mesh



local mesh

method	K_I MPa$\sqrt{\text{mm}}$	% error
disp correlation	1.7961	-1.33
M-integral	1.7848	-0.70

Note: exact solution is for infinite plate

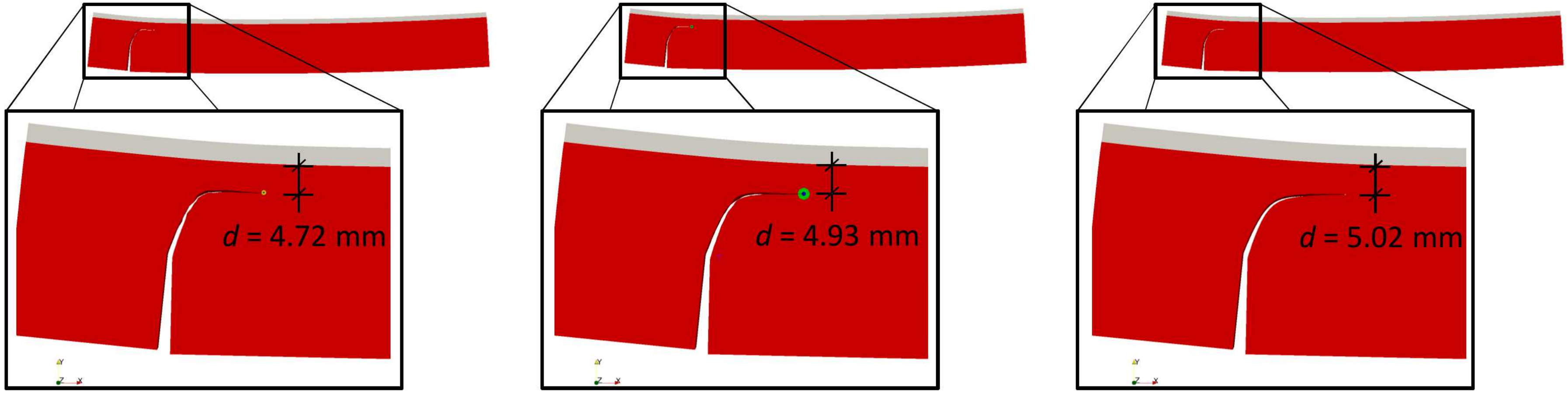


local σ_{yy} contour

Credit: John Emery (1558)

Current capability: LEFM modeling with FRANC3D/Sierra

Code validation calculations with a bi-material beam were conducted and compared with a known analytical solution and experiments. The analytical solution predicts a distance of 4.89 mm from the interface to the steady-state crack front and agrees reasonably with experiments. We investigated convergence with three user-specified median crack growth increments and obtained reasonable accuracy with all crack growth increments. The best accuracy of 4.93 mm was achieved for the intermediate increment. The close agreement with analytical solution and experiment provides strong validation evidence to support the effort.



Δa = 1.0 mm Δa = 0.5 mm Δa = 0.25 mm

Crack increment	**Δa = 1.0 mm**	**Δa = 0.5 mm**	**Δa = 0.25 mm**
Growth steps	22	44	88
Distance from interface	4.72 mm	4.93 mm	5.02 mm

Credit: John Emery (1558)

Current capability: other fracture methods

XFEM/GFEM

- Element shape functions include Heaviside step function which accounts for crack separation
- Evolves a "separation parameter" from 0 to 1, requires characteristic length scale, lacks singular crack tip fields
- Not a production capability

Phase field

- Includes strain energy release from fracture in weak form
- Crack is "smeared" to regularize integration
- Evolves a phase parameter from whole to cracked, only works with elastic materials, requires characteristic length scale, requires mesh which can resolve fracture zone
- Not a production capability

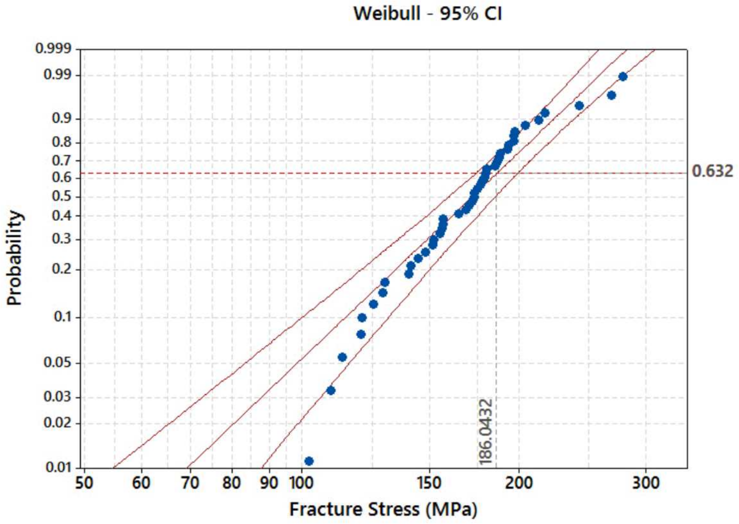
Cohesive zone methods

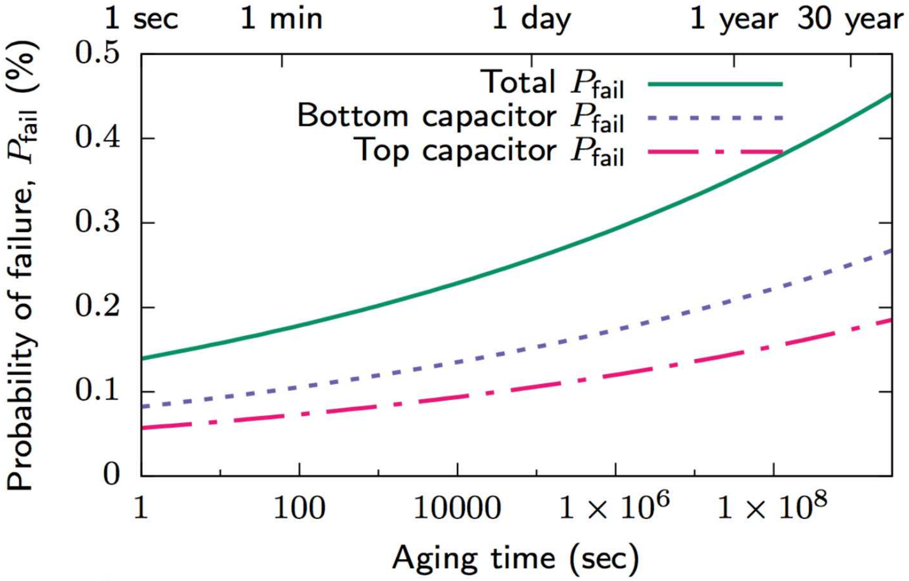
- Good for interfaces and elastic-plastic fracture
- Need to know where crack will go
- How to partition energy dissipation between cohesive zone and bulk material?

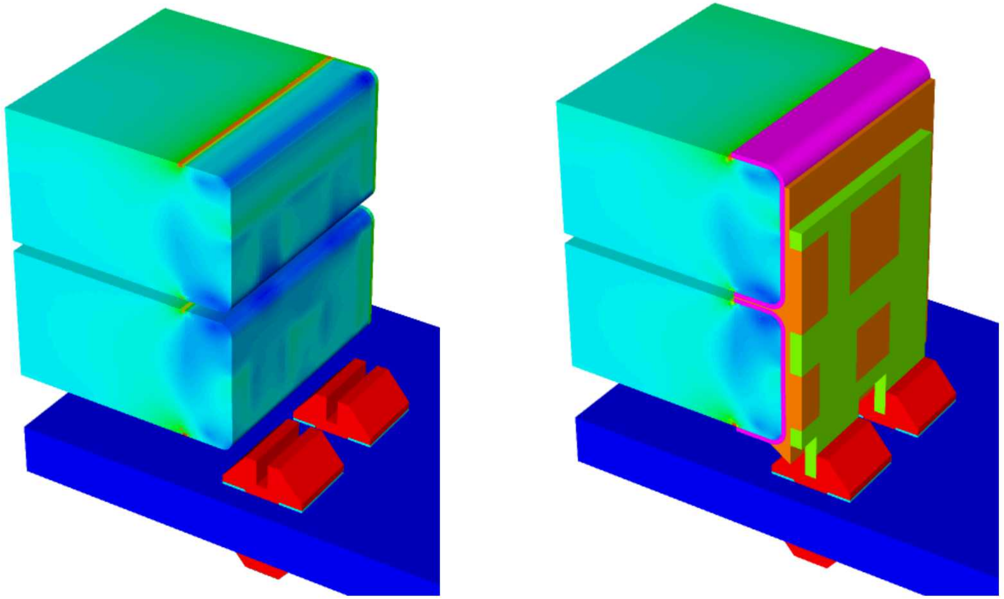
Native Sierra J-integral implementation

- Can calculate driving force for arbitrary constitutive models
- Interpretation of elastic-plastic J-integral is difficult due to material R-curve effects
- Current implementation requires linear hex elements → Not directly compatible with FRANC3D

Current capability: Weibull stochastic strength analysis







Credit for SM model:
Mike Neilsen(1558)

Current capability: Weibull stochastic strength analysis

Python post-processing tools implemented in agreement with ASTM standards

Measure strength of set of strength specimens

- Usually 4 point bend bars or ring-on-ring
- Try to match test type to dominant stress state in component

Fit strength data to Weibull distribution

$$P_{fail} = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^{\rho}\right]$$

Scale to size and stress state from FEA model

Weibull is weakest link failure

- When one element fails the model fails
- Model failure probability is 1 – (probability all elements survive)

Can combine with subcritical propagation rules to "age" the flaw population and calculate failure probability over time (below equation for environmentally assisted crack growth, similar to Paris law for cyclic fatigue)

$$v(a) = A(K/K_{Ic})^{n}$$

Potential for ATA collaboration (PLEASE ADD ANY SUGGESTIONS)

Generate “look up tables” for common Sandia geometry that are not in standard handbooks

Act as an additional SME resource for consultation with customers and other analysts regarding fracture and brittle failure

Improve implementation of existing Weibull post-processing tools

- More general lifetime prediction for non-constant loads/environments
- More complete documentation and code stability/unit testing
- Upgrade to python3 compatibility

Collaborate on development of modeling capabilities and material effects

Does ATA have a standard approach for analysis with fracture and fatigue? We are looking for ways to make Sandia fracture expertise more cohesive and resistant to staff change/turnover.