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XIII SEM

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Crack Path Selection in Thermally Loaded Borosilicate/Steel Bibeam Specimen

Specimen development, validation, and application

S. J. Grutzik[1], E. D. Reedy[2]

[1]Material Mechanics and Tribology (1851)
[2]Component Science and Mechanics (1556)

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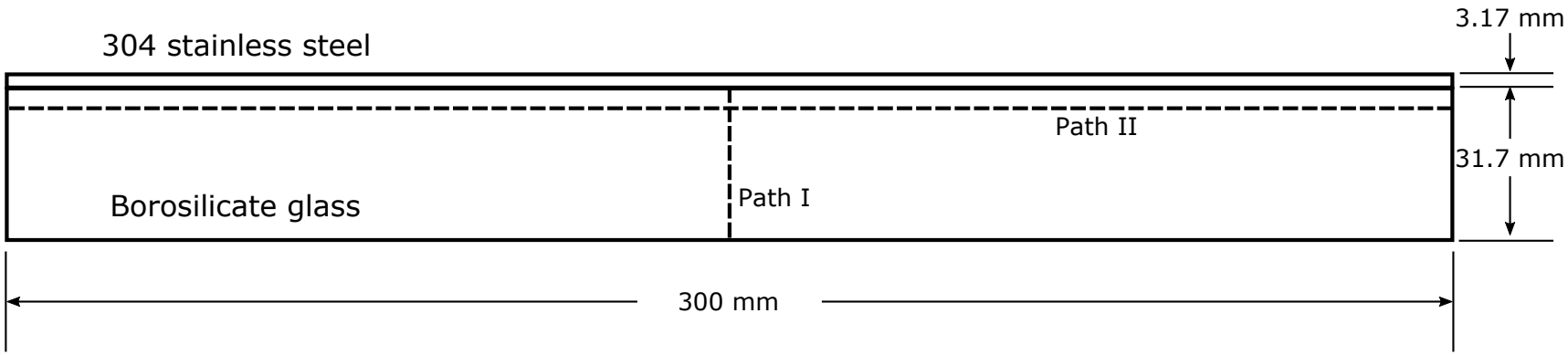
Albuquerque, New Mexico USA

Overview of bibeam fracture project

- Bibeam specimen is thermally loaded by uniform cooling from room temperature to $-10\,^{\circ}\mathrm{C}$.
- Two independent paths satisfy $K_{II} = 0$. A crack initiated along Path I (perpendicular crack) switches to Path II (parallel crack).
- This specimen is a good test case for crack path prediction codes like Franc3D.
- We are also interested in how geometry and other factors affect how the crack switches from Path I to Path II.



Notched bibeam experiments

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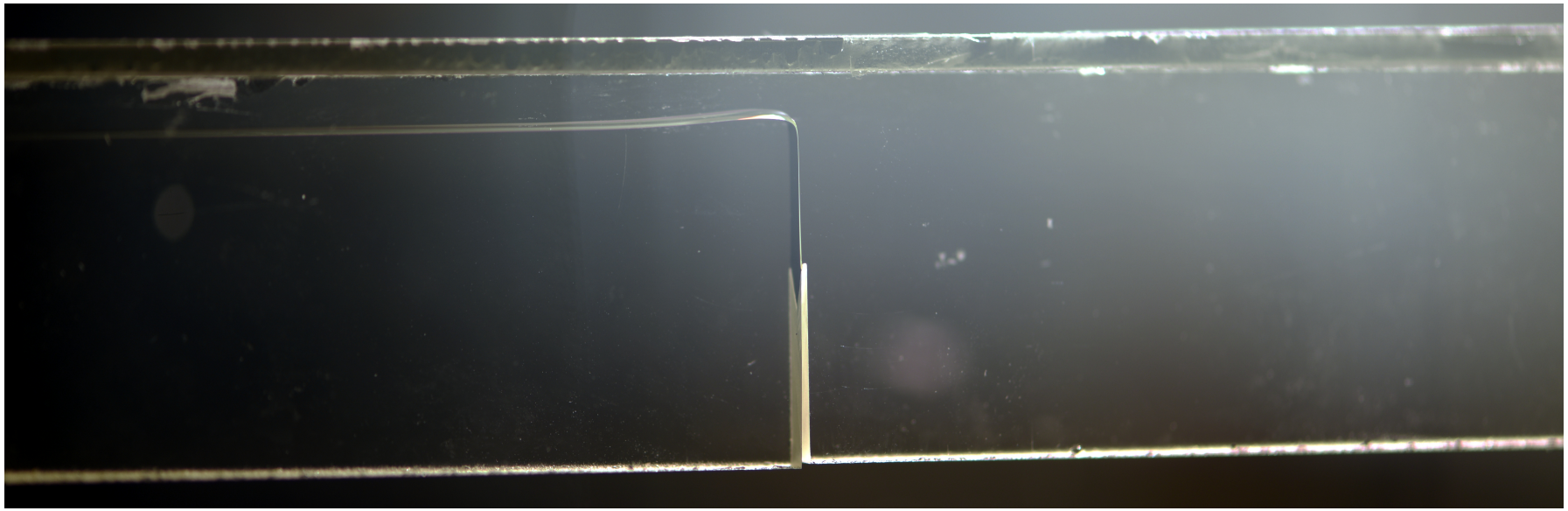
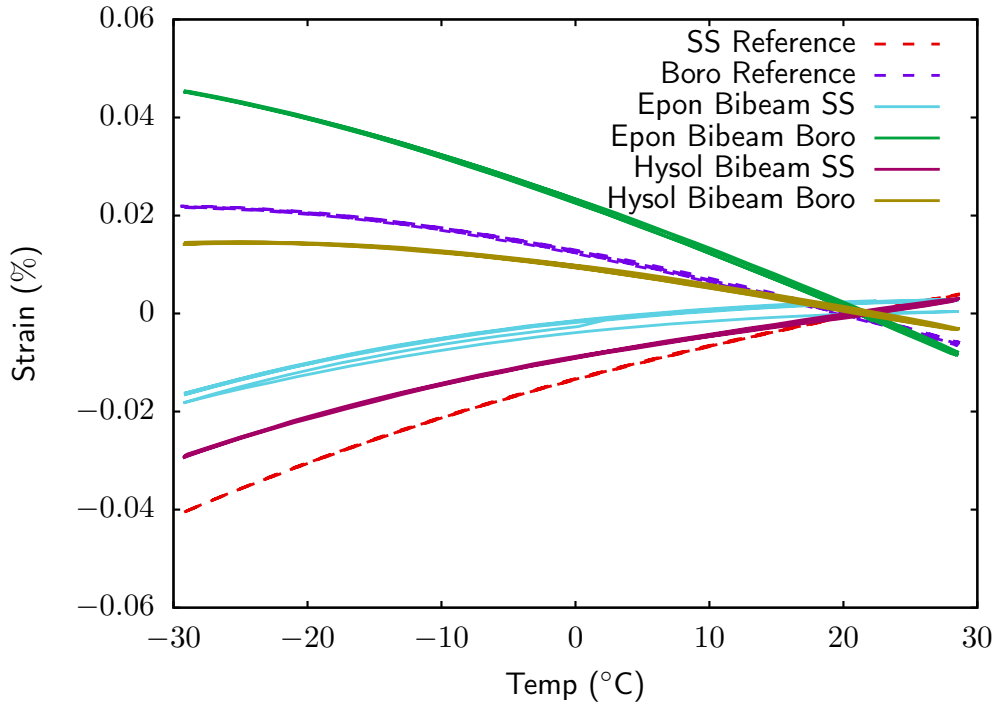
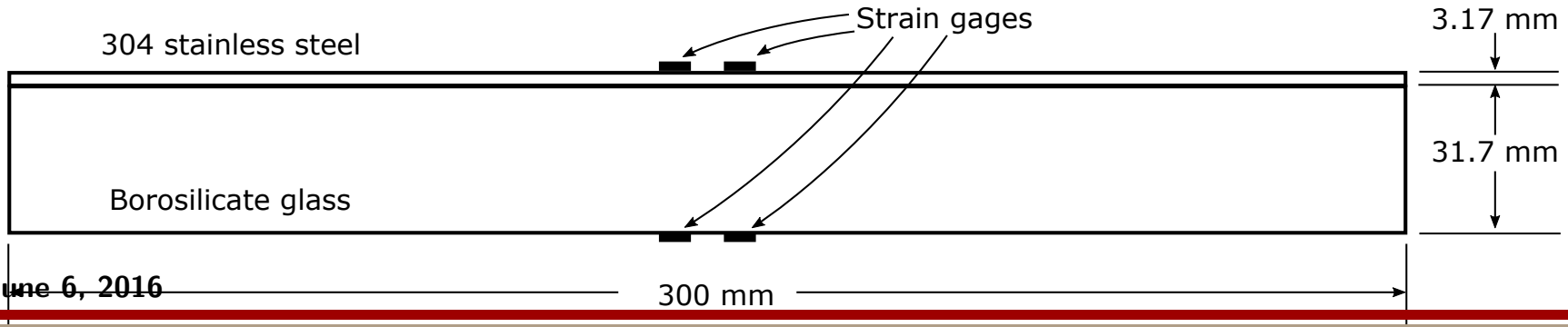
- If a perpendicular crack is initiated at the bottom, it initially propagates toward the interface.
- Near the interface, the fracture path turns, becoming a parallel crack.
- Whether the crack turns left or right appears to be random.
- Our interpretation is a bifurcation occurs, after which the initial path is unstable to perturbations in crack direction. The crack kinks to one of two stable kink angles.



Instrumented validation specimen

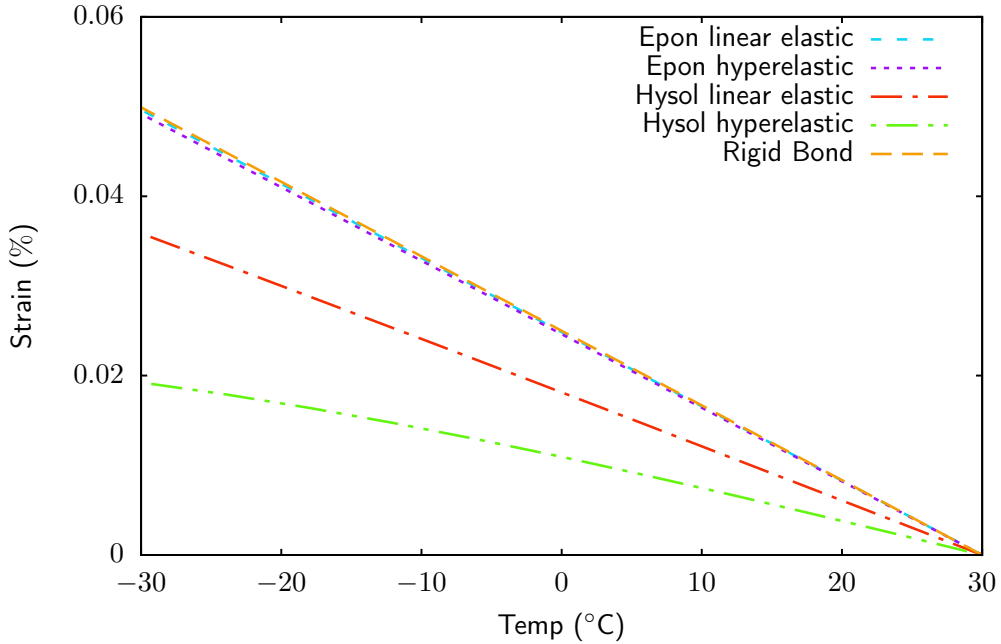
- Stresses in cracked specimen are calculated using a finite element model.
- An uncracked specimen instrumented with strain gages and thermocouples was used to validate the model.
- Two adhesive formulations were tested: Epon 828/Epikure 3140 epxoy and Hysol U-04FL urethane.





Effect of adhesive choice (FEA)

- Choice of adhesive has an obvious effect on resulting strain.
- Hysol urethane adhesive bonds well but is very compliant.
- Epon epoxy is much stiffer $\rightarrow$ can assume to be rigid

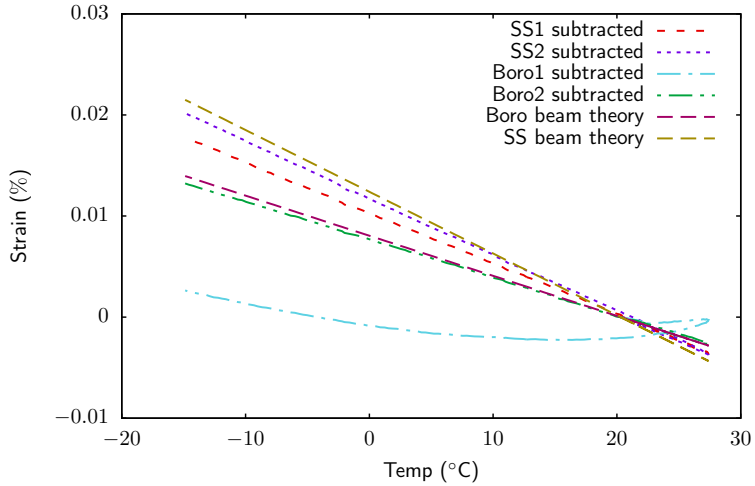


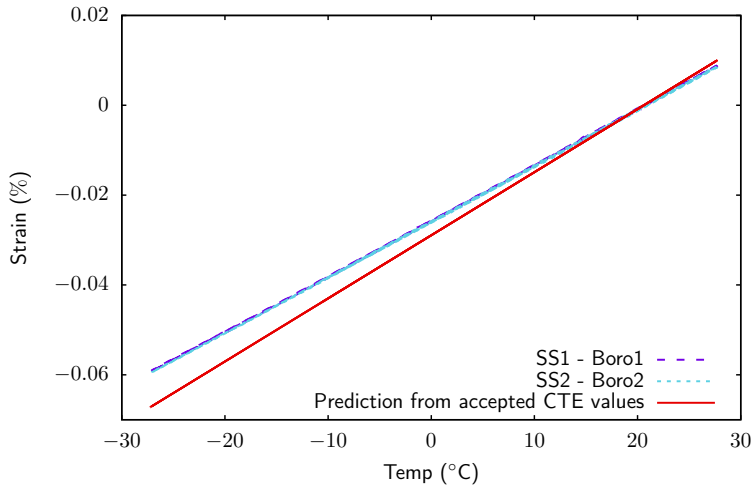
Elastic parameters	E (GPa)	ν	CTE (μm/m/°C)
Borosilicate Glass	64	0.2	3.25
304 Stainless Steel	193	0.29	17.3
Epon 828/Epikure 3140 epoxy	2.9	0.4	NA
Hysol U-04FL urethane adhesive	0.029	0.45	NA

Neohookean parameters	C_{10} (MPa)	D_1 (MPa)
Epon 828/Epikure 3140 epoxy	166	1660
Hysol U-04FL urethane adhesive	1.66	16.6

Strain gage measurement results

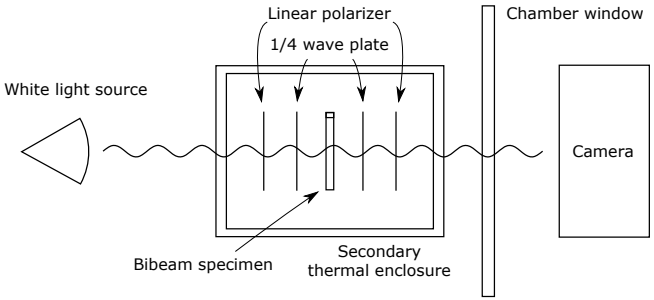
- Strain gage mismatch effects eliminated by using dummy gages
- Measured strains now roughly agree with beam theory predictions
  - 5.1 % difference between gages on steel
  - Average of 14.3 % difference between steel gages and beam theory
  - 5.3 % difference between glass gage and beam theory
- Difference in CTE calculated using the difference in strain of the reference materials
  - Measured CTE differences of 12.4 µm/m/°C and 12.6 µm/m/°C
  - Difference between accepted values is 14.1 µm/m/°C

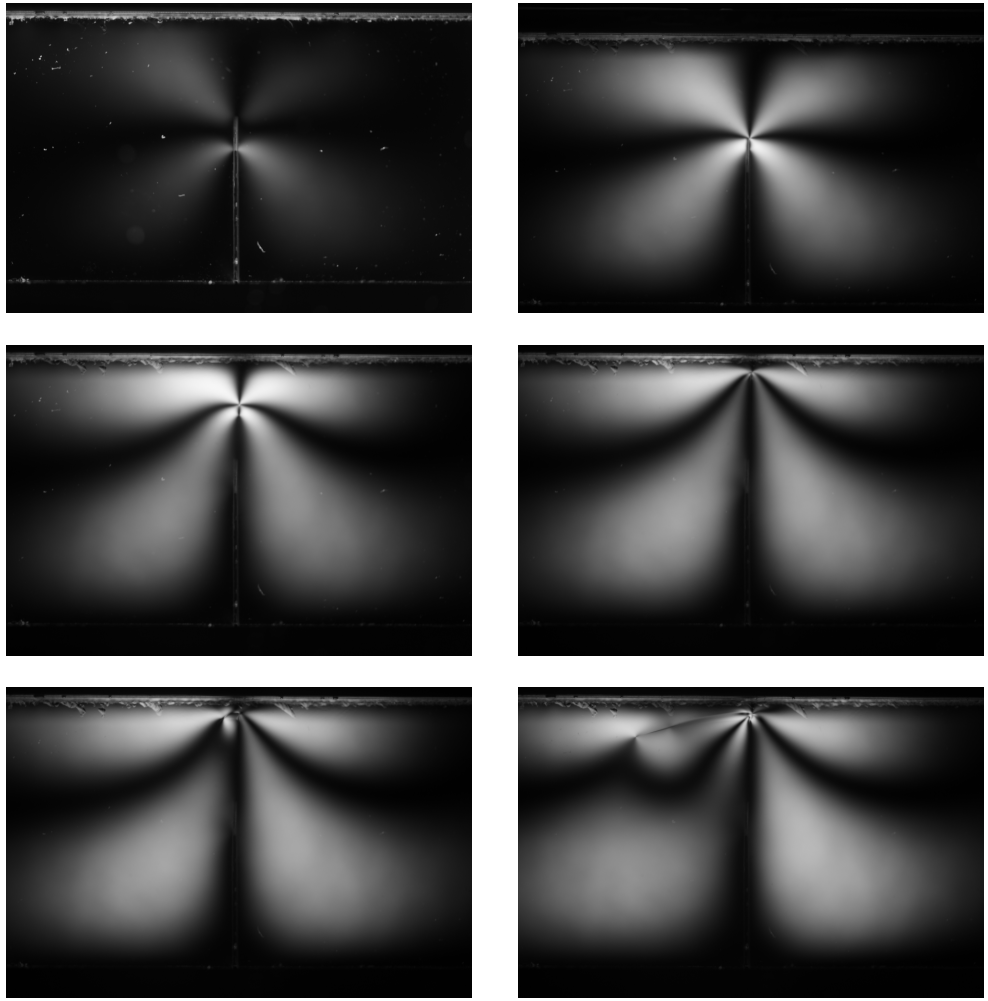




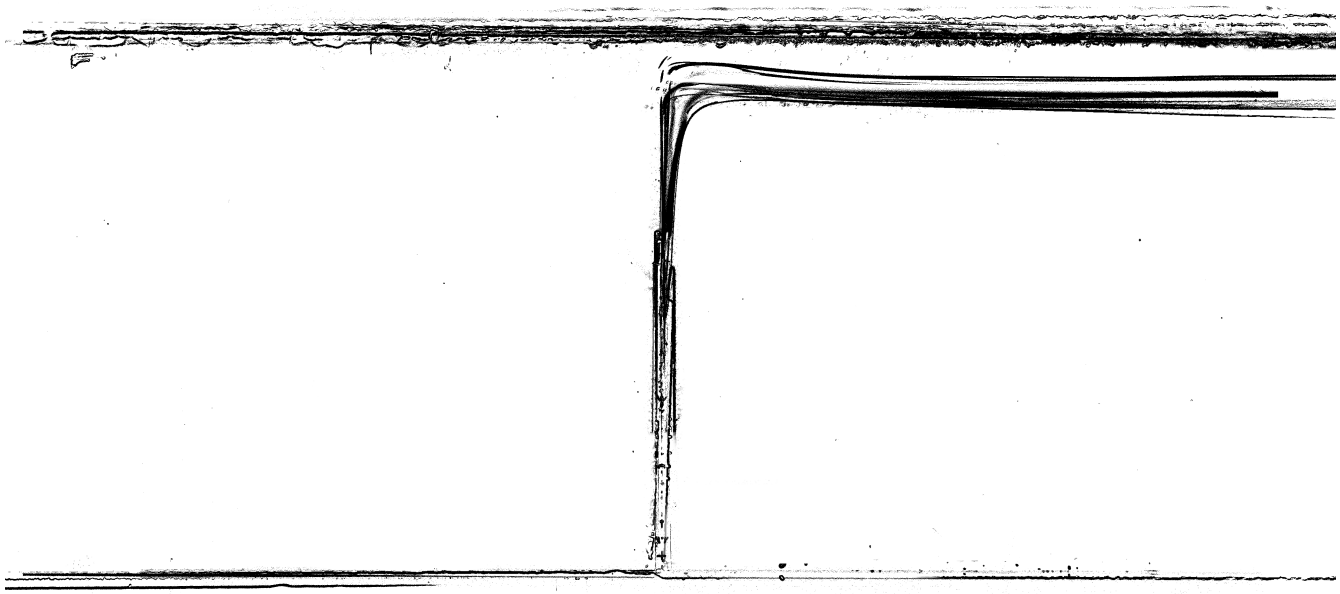
Crack detection with photoelasticity

- Crack tip is located with photoelasticity
- Normalized K_2 and T values extracted from photoelastic pattern





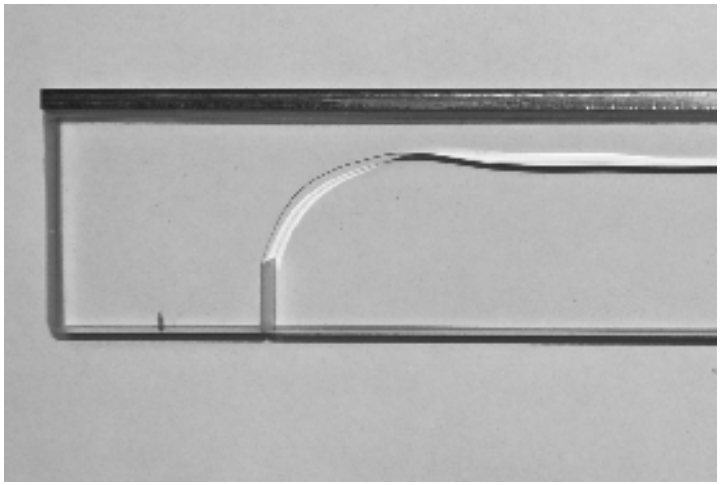
Crack path results

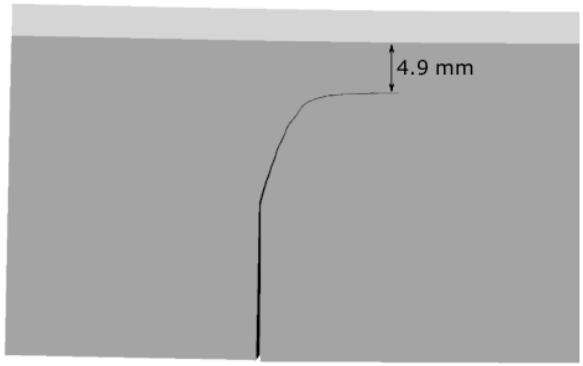


- 11 crack paths shown superimposed (all depicted as turning right for easier comparison)
- 7 turned right, 4 turned left
- Calculated K_{Ic} at notch filling is $0.806 \pm 0.04\,\text{MPa}\sqrt{\text{m}}$ (Corning published value is $0.77\,\text{MPa}\sqrt{\text{m}}$)

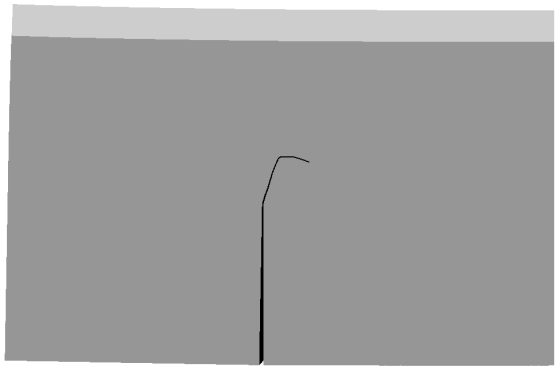
FEA: path prediction

- A perpendicular crack initiated near the end of the specimen turns gently toward the middle
- Numerical path prediction is difficult, even in this simple case





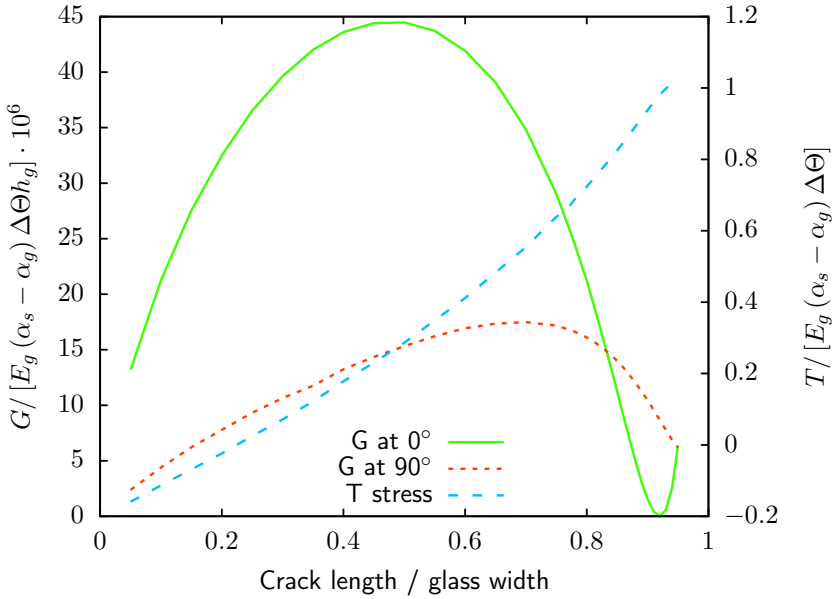
Path predicted by SIERRA/SM with Franc3D

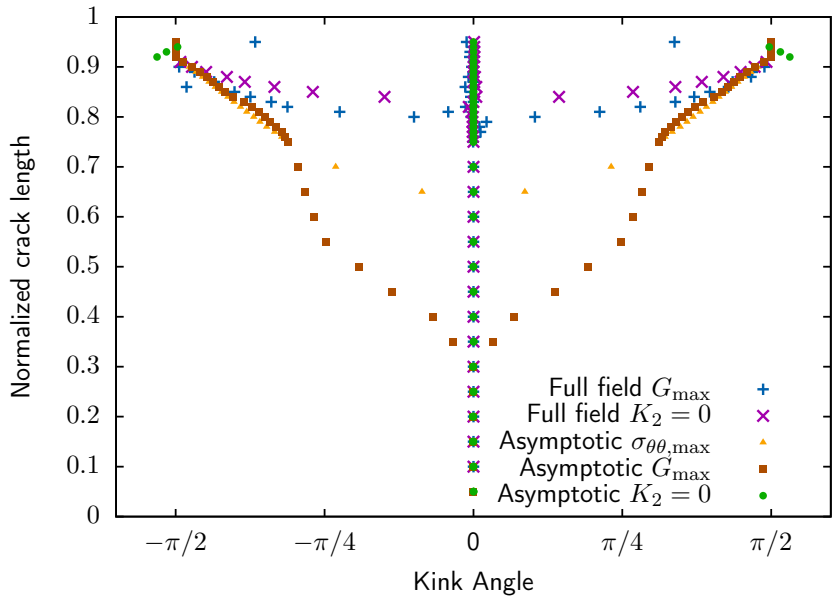


Path predicted by XFEM with Abaqus

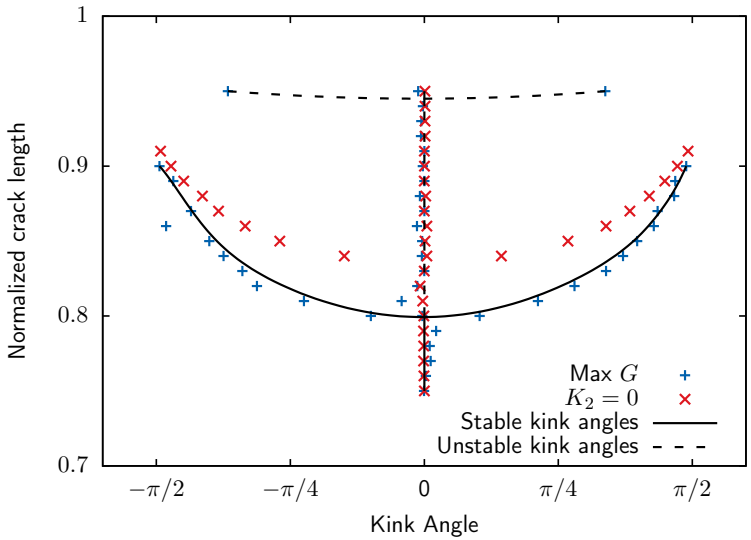
FEA: crack kinking studies

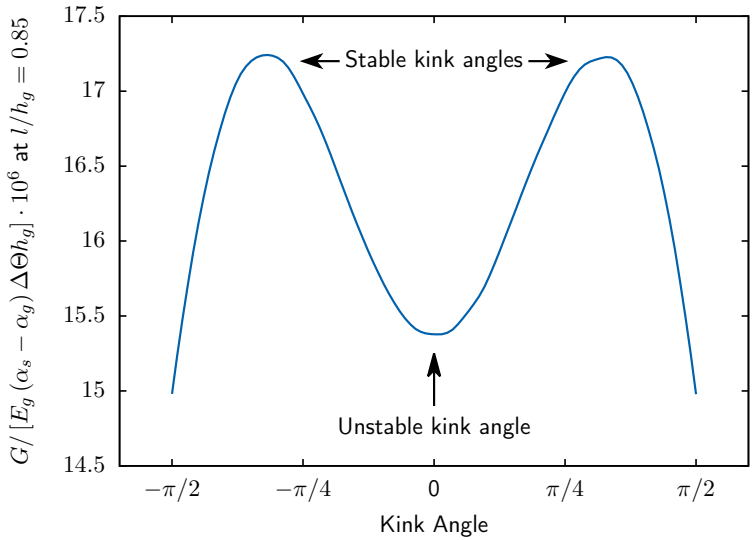
- Want to determine effect of crack kinking with full crack tip fields (not just low order terms).
- Use Abaqus to model bibeam with no adhesive, varying perpendicular crack position and length, and kink length $= 0.3\,\text{mm}$.
- G with no crack is maximum at crack length ≈ 0.5.
- At crack length ≈ 0.85 straight crack is no longer energetically favorable.
- T > 0 for all but very short cracks.
- Crack kinking not well predicted by low order asymptotic K and T terms.

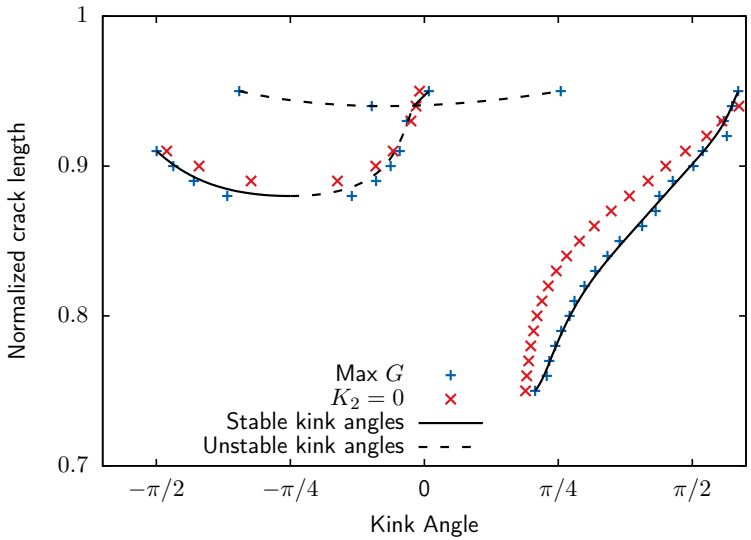


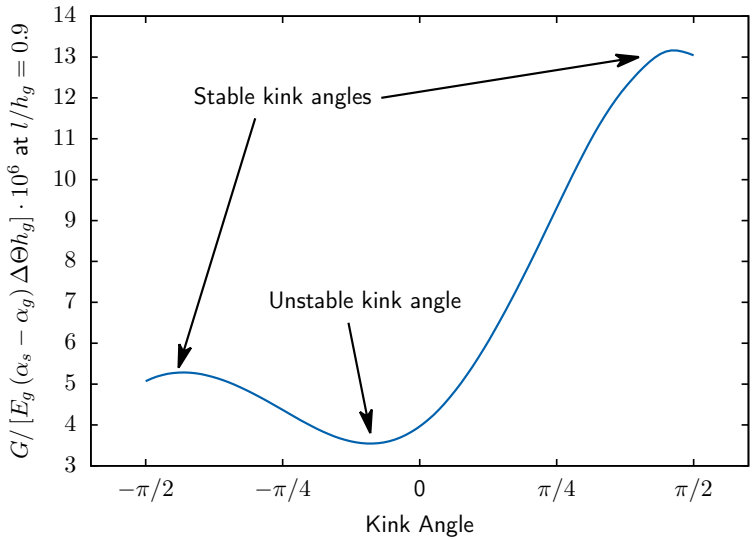


FEA: path stability



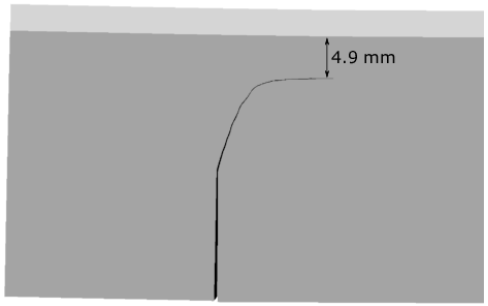


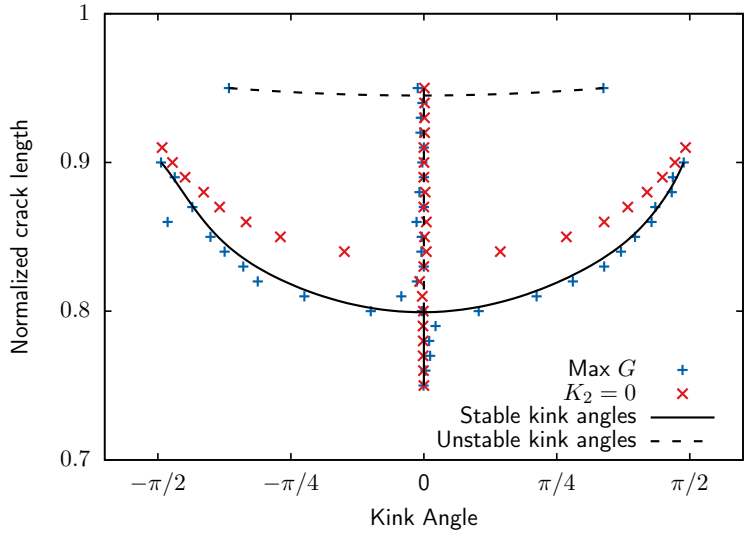


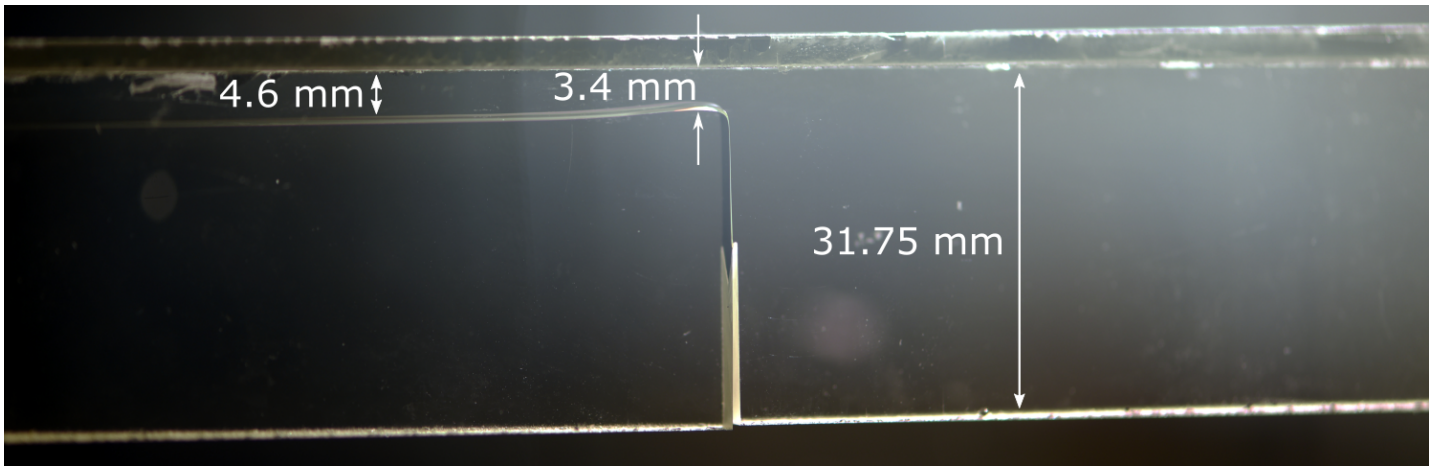


Theory/Experiment comparison

- Suo and Hutchinson[1] predict a steady-state parallel crack at 4.64 mm from interface
- Parallel crack and perpendicular crack with 90° kink occur at different locations







[1] Z. Suo and J. W. Hutchinson, *Int J Solids Struct*, vol 25, no 11, pp 1337–1353, 1989

Next steps

- Test repeated nominal identical specimens to determine intrinsic variability in crack path
- Vary notch preparation and other parameters to determine effect on crack path
- Apply lessons learned from behavior of crack near interface and path stability to numerical crack path calculations
- Currently developing a similar specimen self-loaded by residual stresses to study environmentally assisted crack growth
- Modify test so chevron notch fills under mixed mode loading and use this data to develop an improved crack kinking criterion

Questions?

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