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Title: Effect of Aging on Fracture Toughness: Using Digital Image Correlation on Polymers and Brittle Composites

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Effect of Aging on Fracture Toughness: Using Digital Image Correlation on Polymers and Brittle Composites

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Abstract

Previous work has shown that digital image correlation (DIC) can be used to quantitatively describe macroscopic cracks, both their location and extent, in various brittle and other materials that have limited ductility. Using this technique it is possible to describe quantities that have limited ductility. Using this technique it is possible to describe quantities that have limited ductility. Using this technique it is possible to describe quantities that characterize the material fracture process, like the crack-opening displacement and crack opening angle. These measurements can then be used to calculate fracture toughness. It is expected that fracture toughness is the material property that will be most effected by aging. In this study DIC will be used to find and measure crack growth rates and from these measurements determine the fracture toughness. Through careful evaluation of the fracture behavior of materials that have been artificially aged it is hoped that the fracture toughness can be used to show subtle differences in material deformation and damage.

Outline

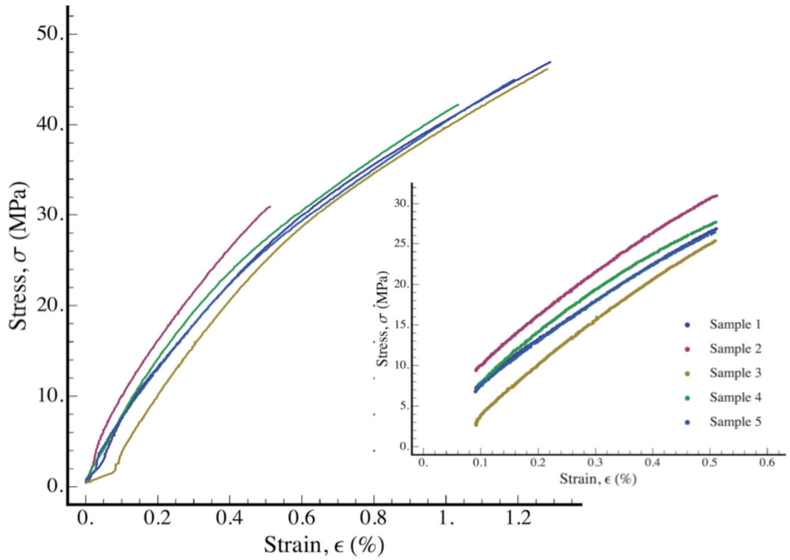
Objective of the work: To find an experimental technique that is statistically less random and sensitive to changes in the material properties.

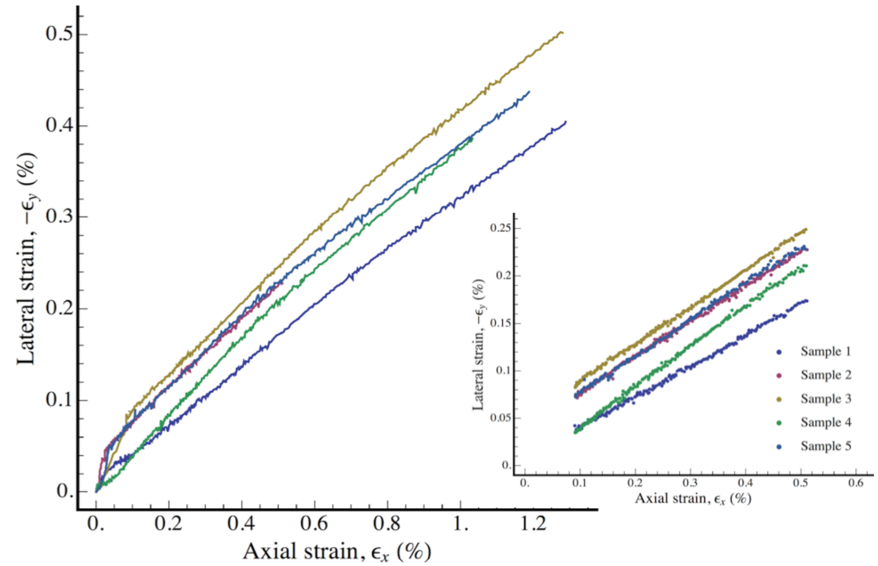
- Initial tensile work – large statistical variability

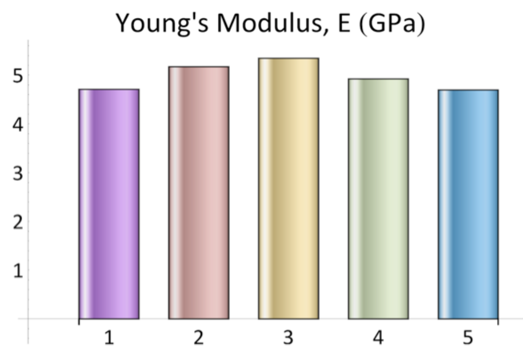
- Brazil tests – limitations in brittle materials

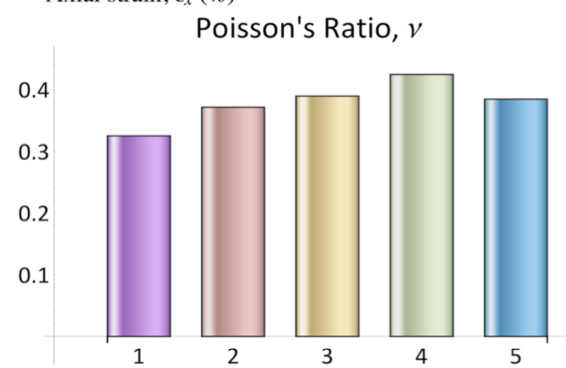
- "Compression – Fracture" – produces measurable crack growth even in brittle composites

Uniaxial Tension of Rigid Polymer



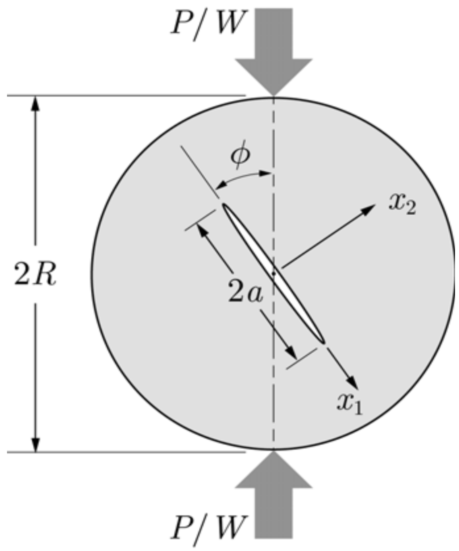


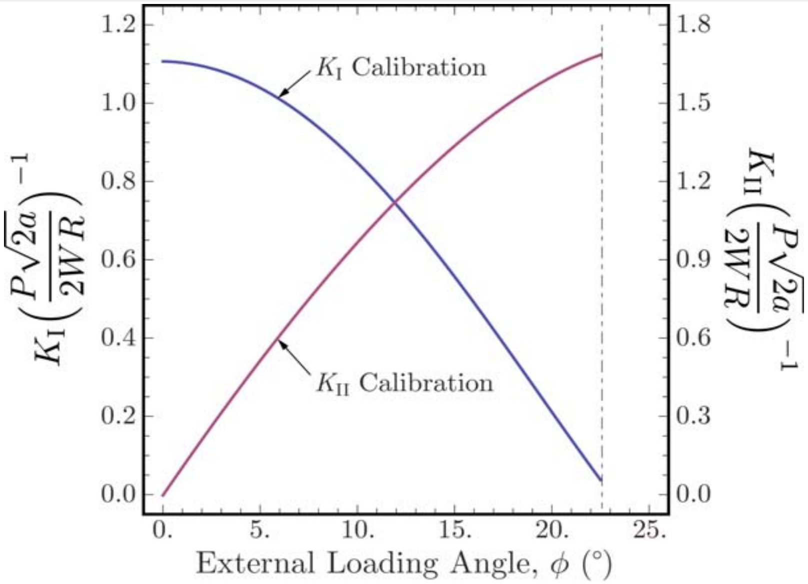




- **Materials show limited strain (< 1.5%).**
- **Large statistical variability in failure strength and strain**

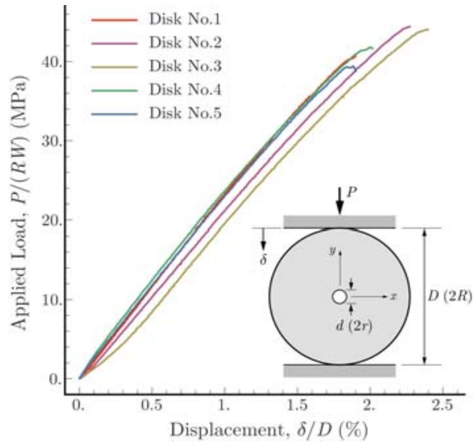
Brazilian Disk Fracture Sample Calibration

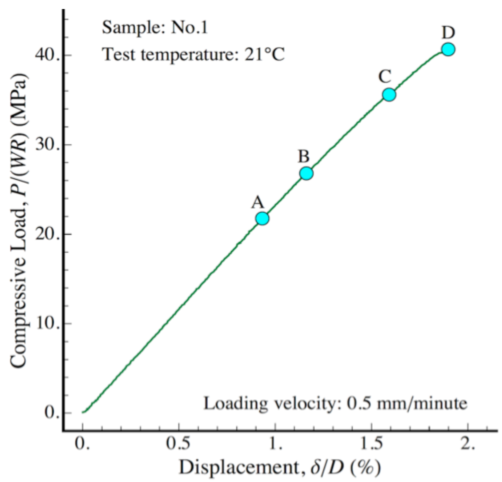




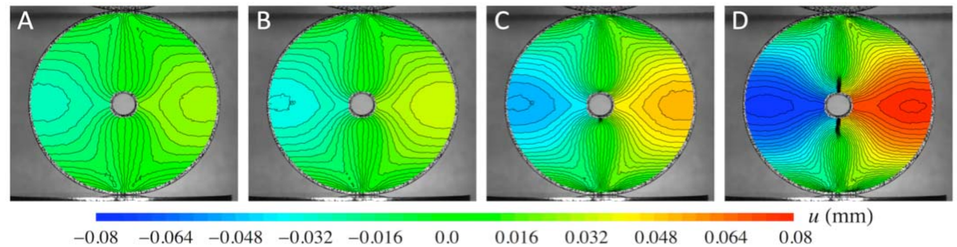
- Brazilian disk specimen with a center crack was calibrated for orthotropic materials (Huang, et al., Acta Mat 1996) for measuring mixed-mode fracture toughness of graphite composite (Liu, et al., Int J Fract 1997).
- The Brazilian disk specimen with a center crack was also used for studying mixed-mode fracture in epoxy resin (Liu, et al., Acta Mat 1998).
- The calibration curve shown is for $a/R = 0.5$ only. However, Huang et al. (1996) has shown that for given applied load, when $a/R < 0.5$, the crack tip stress field varies very little when crack length changes.
- We thus will use the calibration curve for isotropic solid, shown above, to estimate the mode-I fracture toughness of the rigid polymer disk specimens.

Rigid Polymer Disk Compression: Overall Response

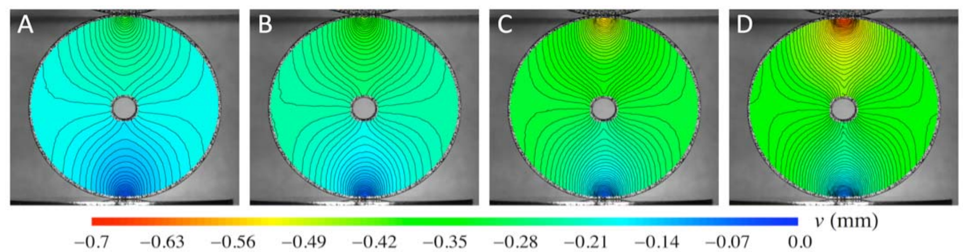




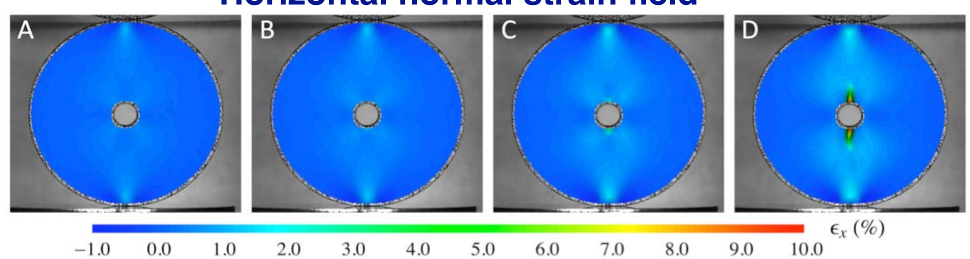
Horizontal displacement field



Vertical displacement field

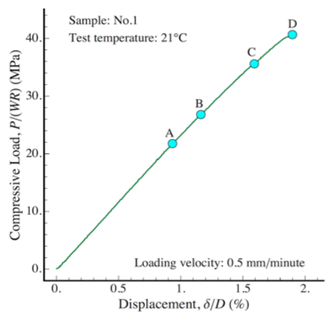


Horizontal normal strain field

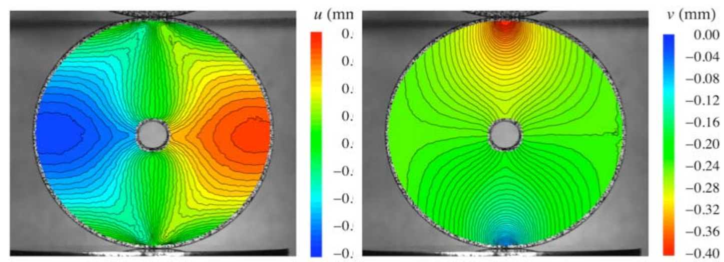


- Repeatable but rapid crack growth to failure.
- Large displacement gradient (strain) correlating to damage, cracking, and failure
- Quantitative analysis indicates that at “time” B Damage initiates in sample.

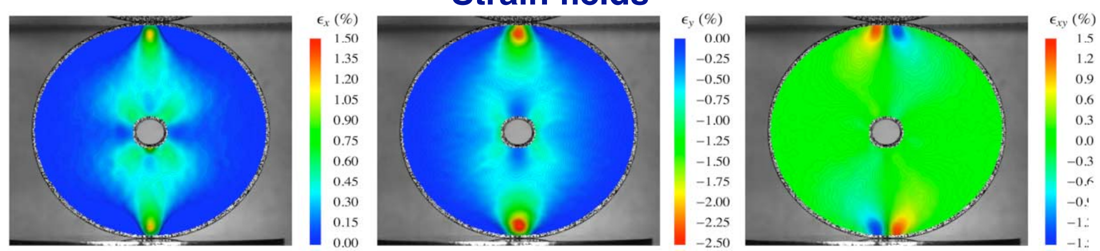
Deformation Field at the Critical Moment B

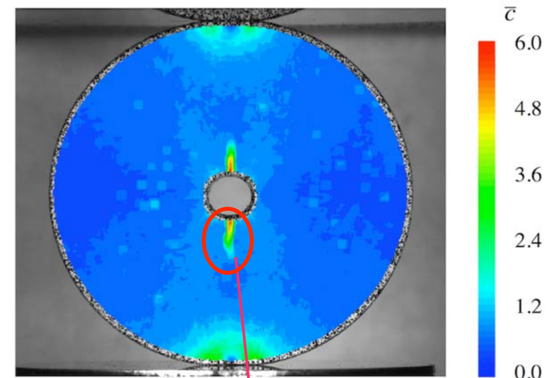


Displacement fields

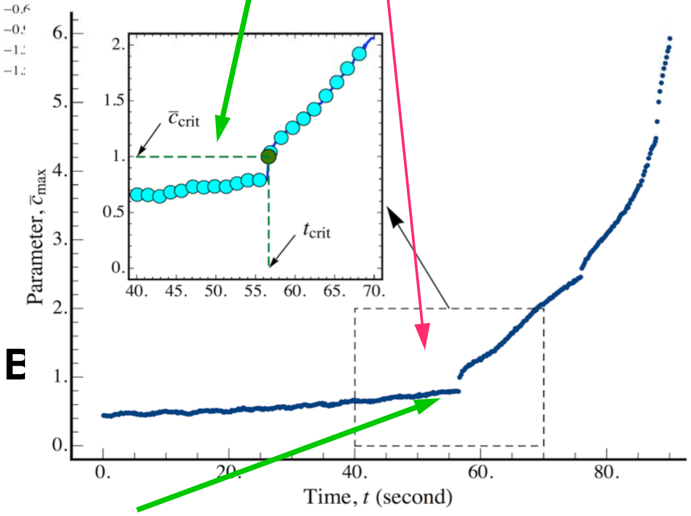


Strain fields





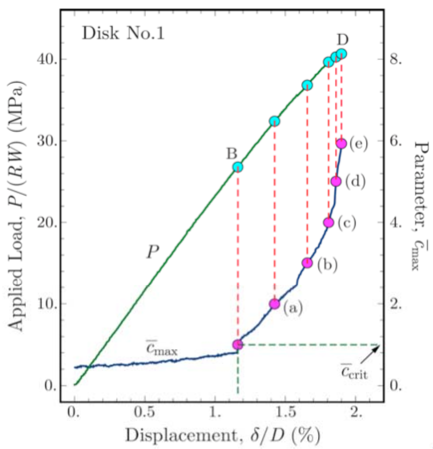
The critical value itself can be used to identify cracked regions

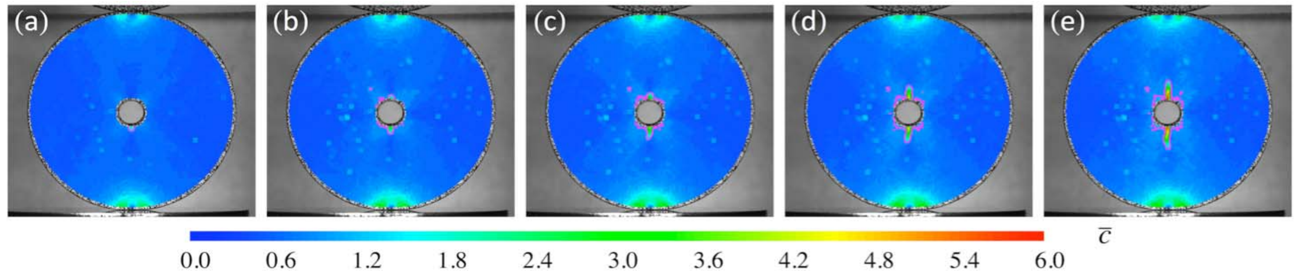


Macroscopic crack initiation is uniquely identified

- **Images at moment B whe damage initiates.**
- **Strain fields used to find elastic constantslike shear modulus and poissons ratio.**
- **From the overall response of the specimen, the deformation may well be linearly elastic up to moment B**
- **The critical correlation coefficient shows the value at which "damage" initiates.**

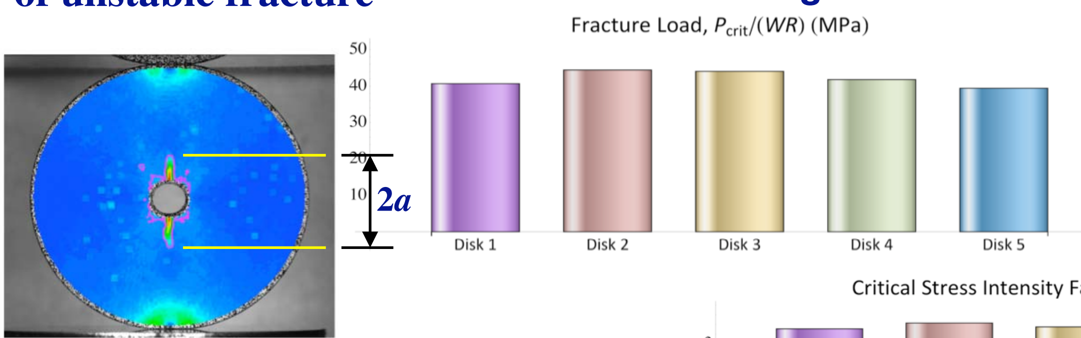
Damage/Cracking Evolution and Fracture Toughness

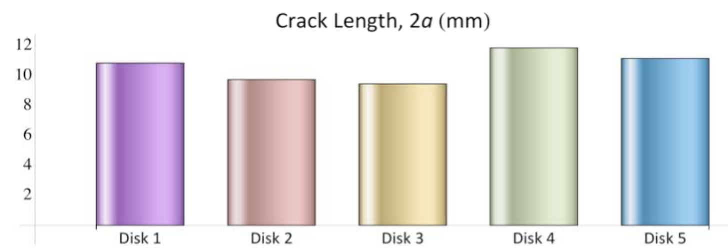




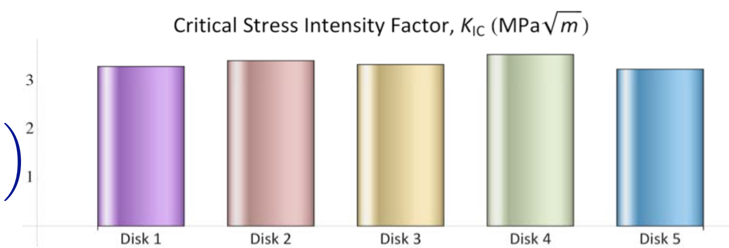
- The critical correlation coefficient is used to identify the boundary of the cracking.
- The growth rate of the crack can be determined by measuring crack extension from frame to frame, initially slow and increasing to failure.
- Near failure, the crack is extenging quite rapidly and is an indication on unstable crack growth.

Crack length at the onset of unstable fracture

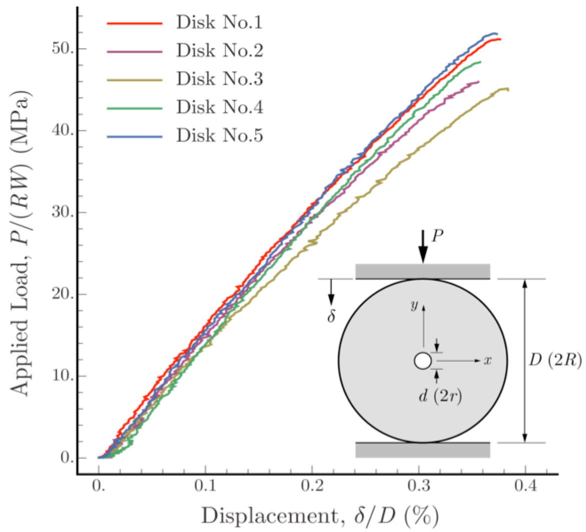


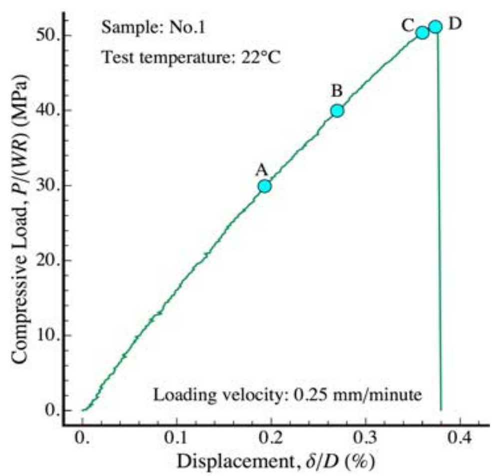


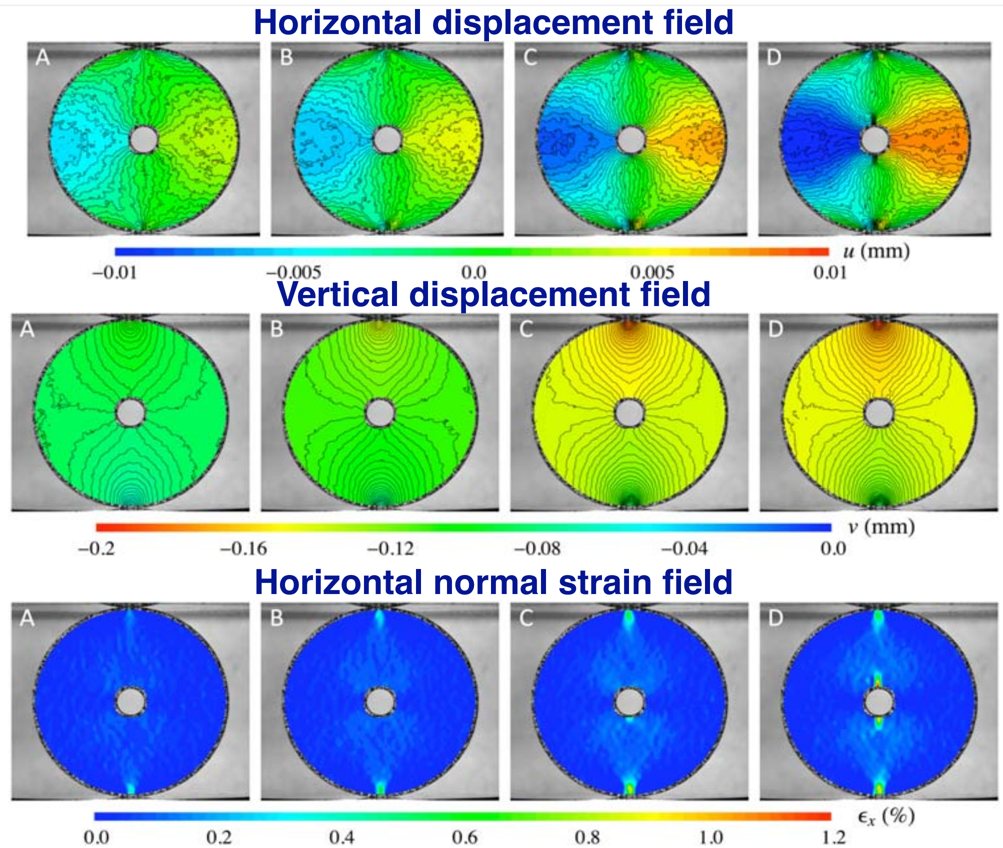
$$K_{\mathrm{IC}} = 1.1065\left(\frac{P_{\mathrm{crit}}}{WR} \cdot \frac{\sqrt{2a}}{2}\right)$$



Brittle Composite Disk Deformation

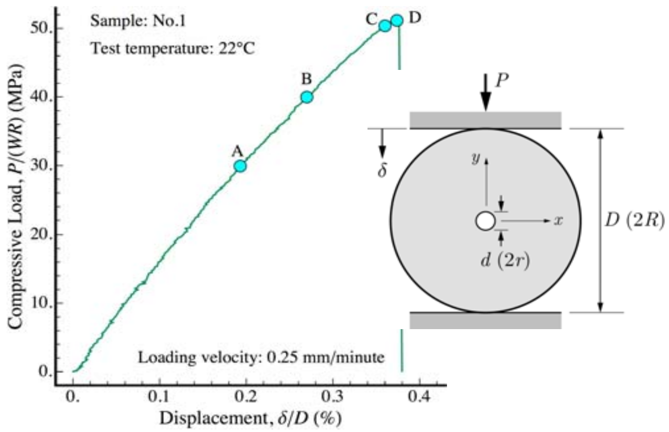


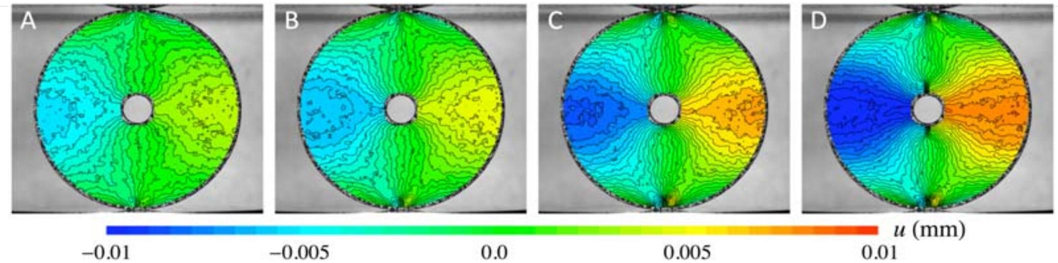


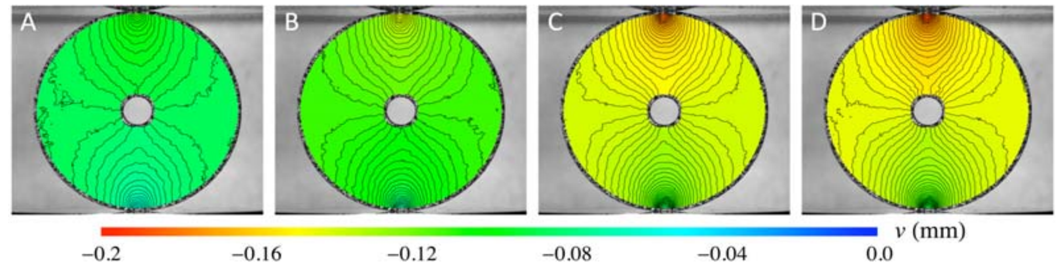


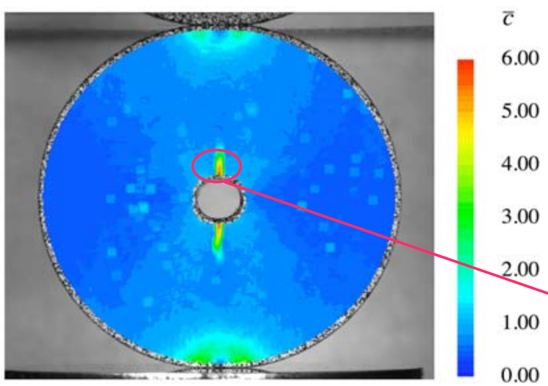
- The overall response of brittle composite and rigid polymer disk specimens show similar trends but the composite is much stiffer than the polymer.
- The overall deformation at the moment of failure is very small
- Failure is catastrophic and rapid with little chance to measure crack growth rates.

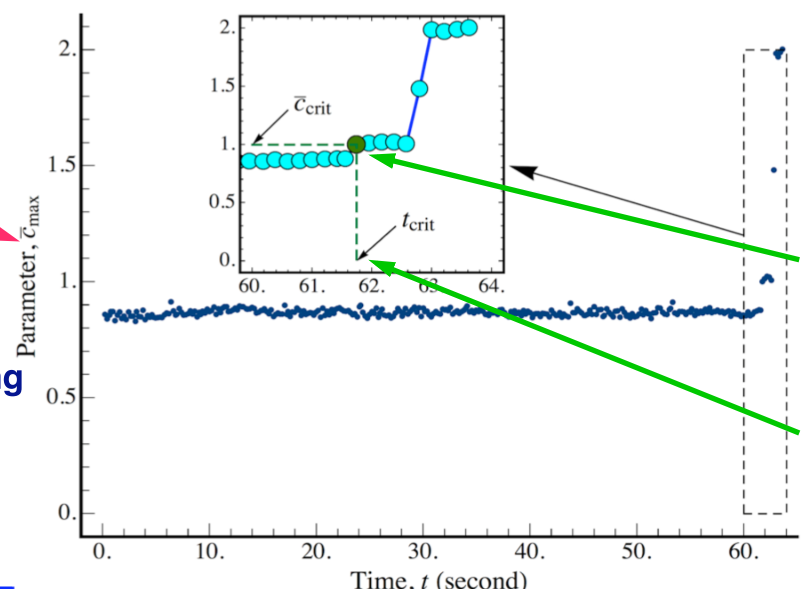
Limited Crack Growth in Brittle Composite Disk Samples











- **The normalized correlation coefficient as a function of time increases very rapidly proving little crack growth prior to the final failure.**
- **Fracture analysis cannot be applied to short cracks.**

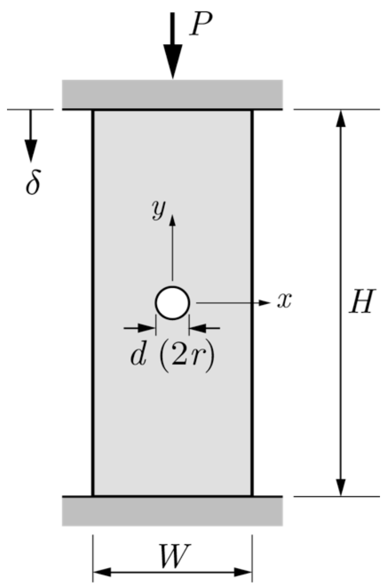
The critical value itself can be used to identify cracked regions

Macroscopic crack initiation is uniquely identified

"Compression – Fracture" sample: Unaged & Aged Polymer

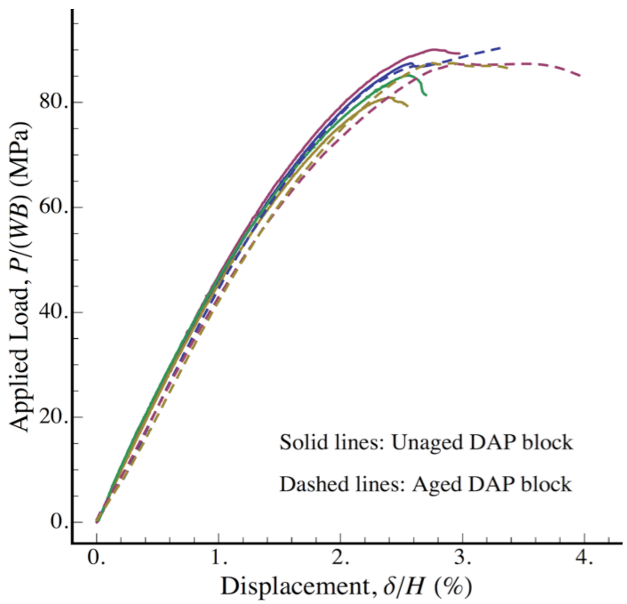
Based on work of Sammis and Ashby, "The Failure of Brittle Porous Solids Under Compressive Stres Sates" *Acta Metall.*, 34, 1 (1986) 511-526

- **The overall response of both unaged and aged rigid polymer specimens show similar trends for this geometry and they exhibit stable crack growth.**
- **Only slightly the stiffness of the aged samples is lower than the unaged specimens.**
- **For aged polymer samples, the load drop after the peak load is not as drastic as the unaged specimens.**

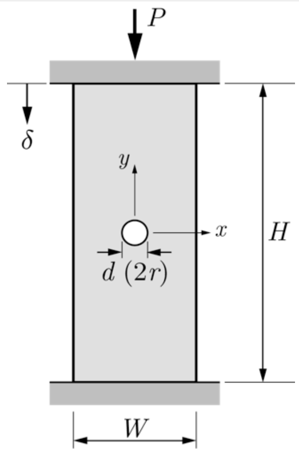


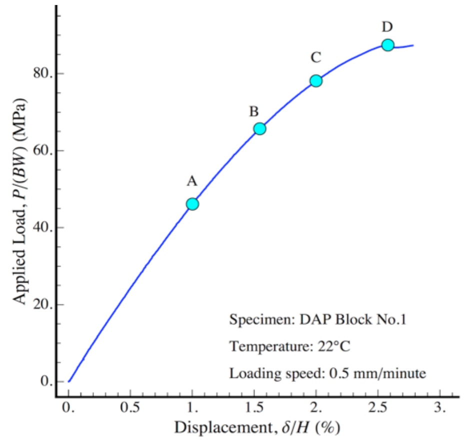
$$K_{\mathrm{IC}} = -\left(\frac{l}{a}\right)^{1/2}\left\{\frac{1.1}{\left(1+\frac{l}{a}\right)^{3.3}}\right\}\sigma_1\sqrt{\pi a}$$

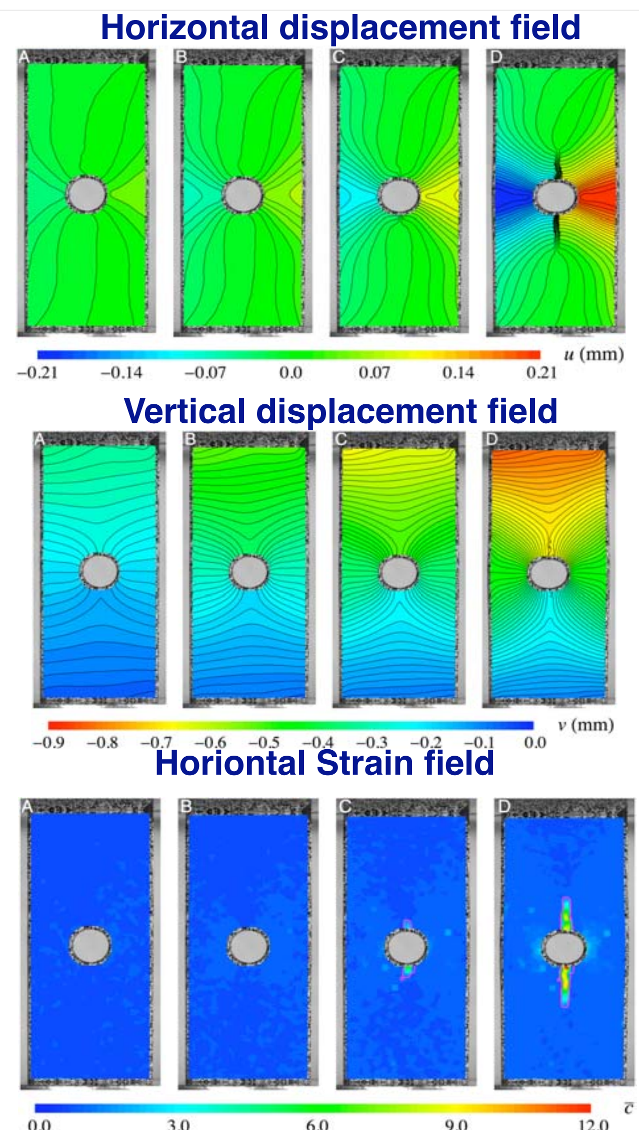
l = crack length, a = hole radius,
σ_1= load / far field area = P/WxT
(from figure r=a)



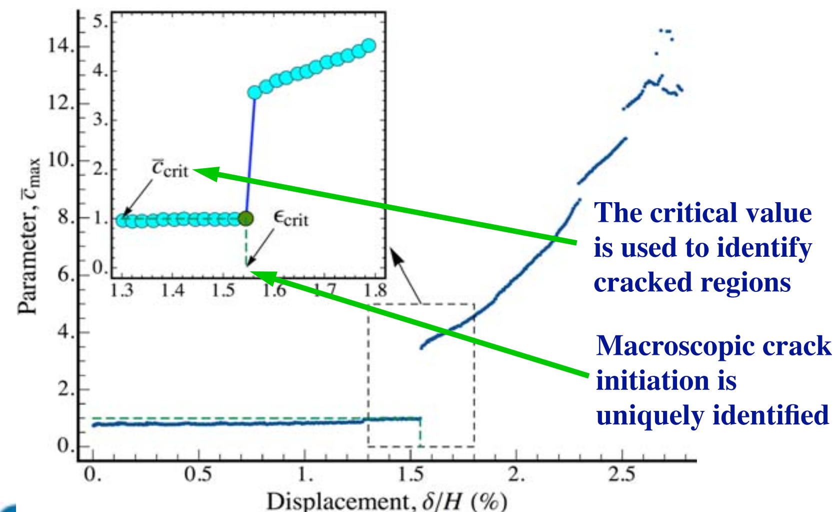
Deformation and Crack Growth in Unaged polymer



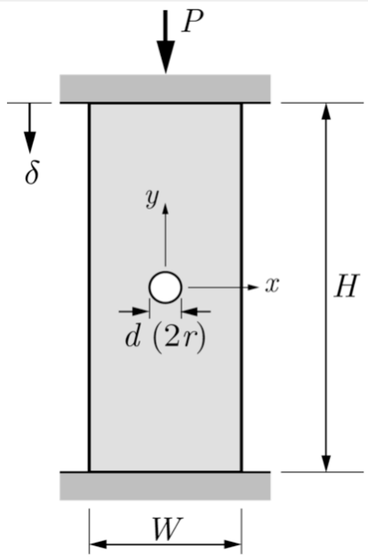


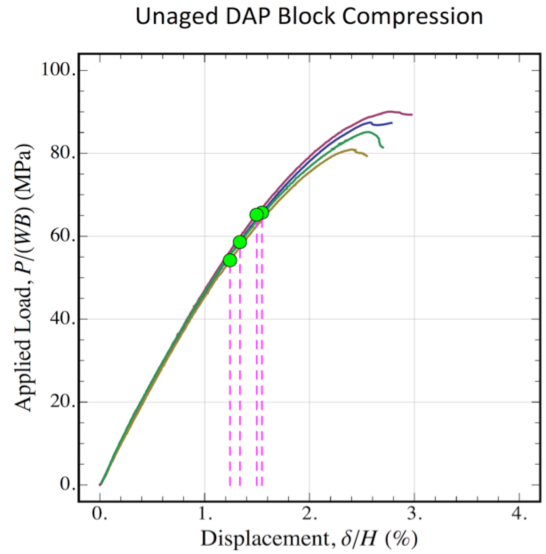


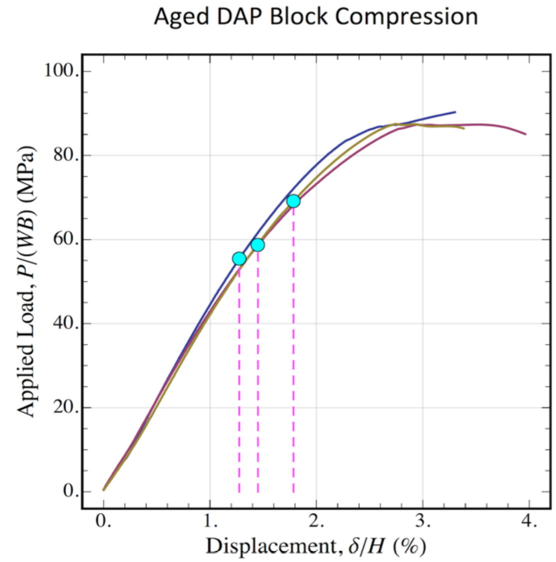
- **Crack growth is much slower for this geometry..**
- **Measured crack length and the applied load suffice to calculate the stress intensity factor, thus the fracture toughness, at a given moment.**



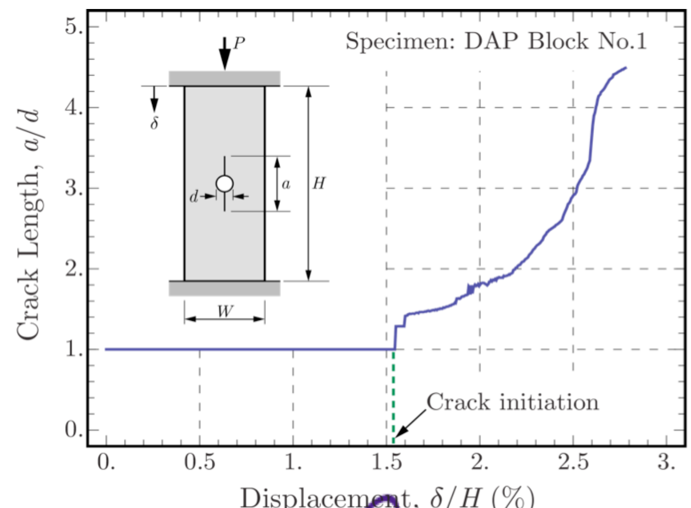
Unaged & Aged Rigid Polymer Compression- Fracture







- The overall response of both unaged and aged polymer specimens show similar trends.
- All specimens exhibit stable crack growth.
- The stiffness of the aged samples is slightly lower than the unaged specimens.
- For aged polymer samples, the load drop after the peak load is not as drastic as the unaged specimens.
- There appears to be more variability in the critical correlation coeficient relating to damage initiation.



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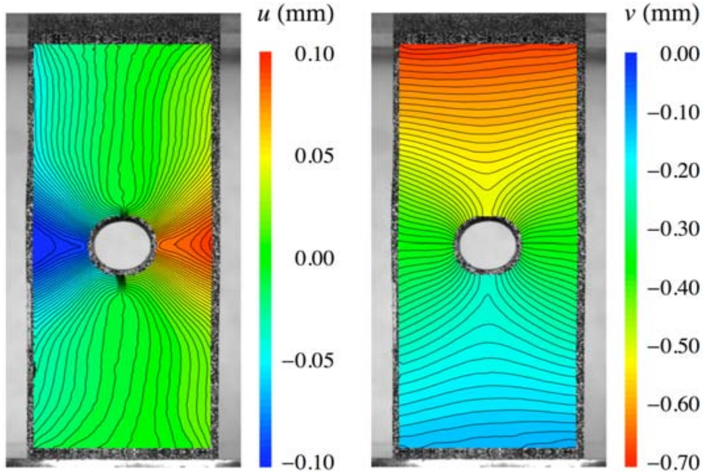
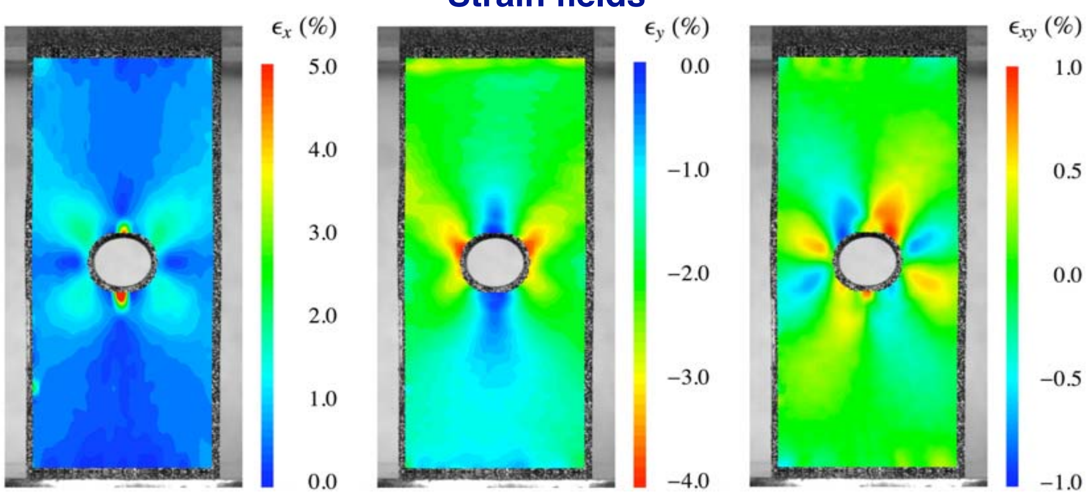
Identifying Damage Initiation (Aged Polymer)

Displacement fields

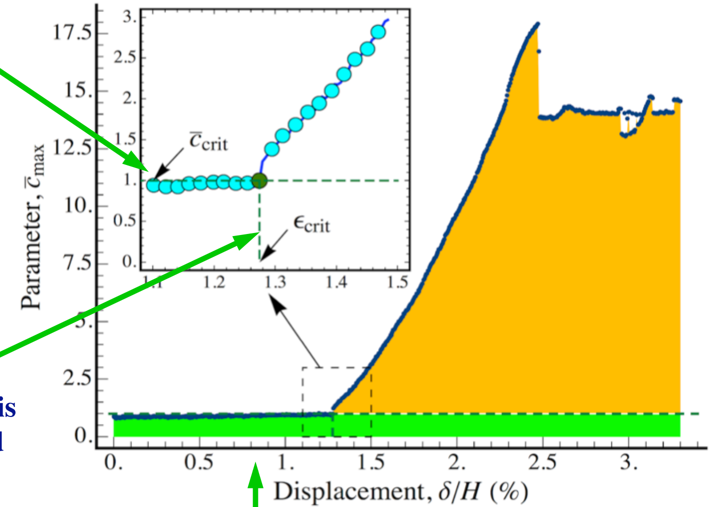


Strain fields

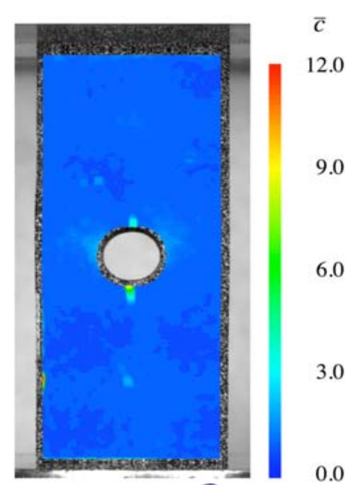


The critical value is used to identify damaged/cracked regions

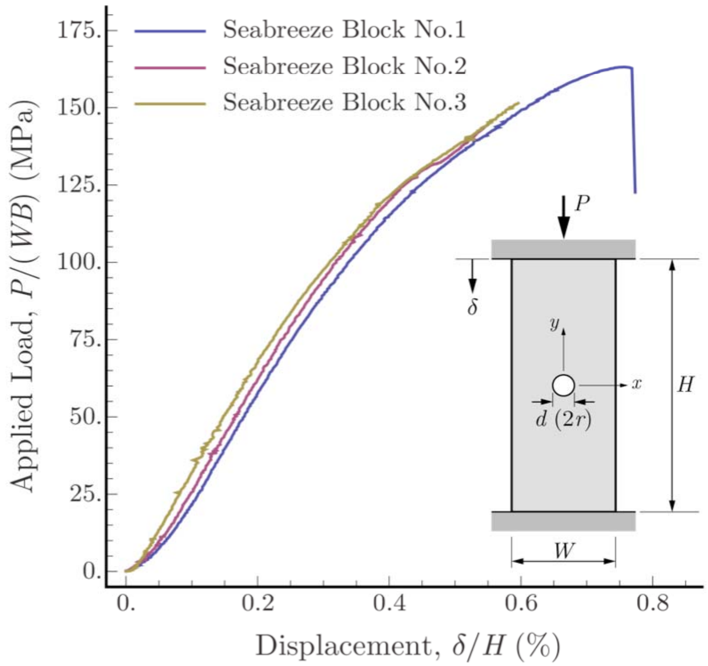
Macroscopic damage initiation is uniquely identified

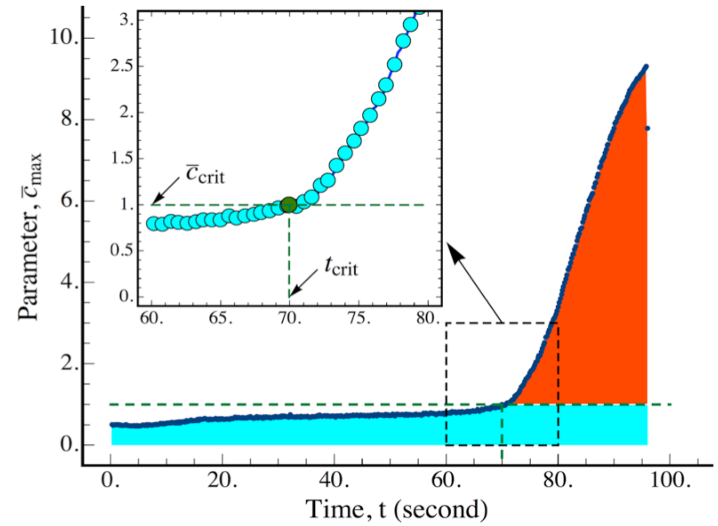


Correlation coefficient field



Brittle Composite Compression – Fracture Results





- **Tests of brittle composte show measurable crack growth rates and fracture toughness values.**
- **The overall response of the Brittle composite is much stiffer than the rigid polymer.**

Summary

- Digital image correlation (DIC) was used to capture the deformation and strain fields.
- Preliminary fracture toughness experiments on the two materials using the Brazilian disk with a center hole showed rapid crack growth and large statistical variation in the test results.
- The implementation of a “compression – fracture” tests generated stable crack growth on both the rigid polymer and the brittle composite.
- A scheme to measure damage initiation and crack growth was developed using the correlation coefficient.
- Combination of crack length measurement and applied load at a given moment will enable us to compute the stress intensity factor, thus the fracture toughness for the growing crack.

Future direction

- FE calculation simulating experiment to verify values for stress intensity factor and fracture toughness.
- Independent determination of Young’s modulus and Poisson’s ratio using uniaxial stress measurements (tension/compression).