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Title: Effect of Aging on Fracture Toughness: Using Digital Image Correlation on DAP and Seabreeze

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Effect of Aging on Fracture Toughness: Using Digital Image Correlation on DAP and Seabreeze

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abstract

The primary reason for this investigation was to determine the most accurate means of measuring the effect of aging in these materials. Initial characterization was pursued to find the most sensitive, repeatable test that would have the least amount of scatter in the test results. Preliminary investigations let to the conclusion that the fracture toughness would likely be the property to show the greatest change in behavior for any intrinsic material property. Test configurations that were initially considered were tensile tests, 3 and 4 point bend tests, Brazil tests, Brazil tests with initial damage and finally a test geometry that is being called a "compression – fracture" test. The tensile test will continue to be done because it will be used to generate information about the Poisson's ratio, which can be used in simulations that would verify the test results presented in this report. The bend bar and Brazil test configurations were tried and determined to be unsuitable because they allowed for unstable crack growth in the materials. The result of these investigations on un-pedigreed materials leading to the selection and use of a test geometry that has subsequently been used on pedigreed materials is the focus of this presentation.

Outline

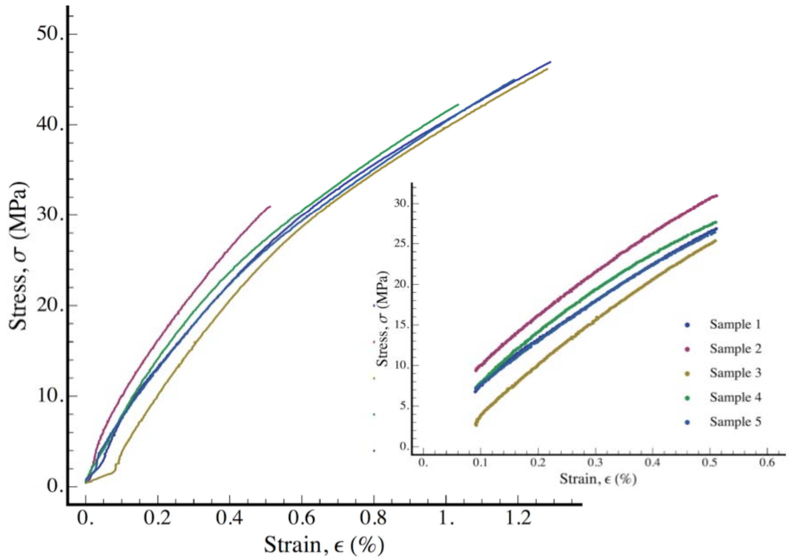
Objective of the work: To find an experimental technique that is statistically less random and sensitive to changes in the material properties.

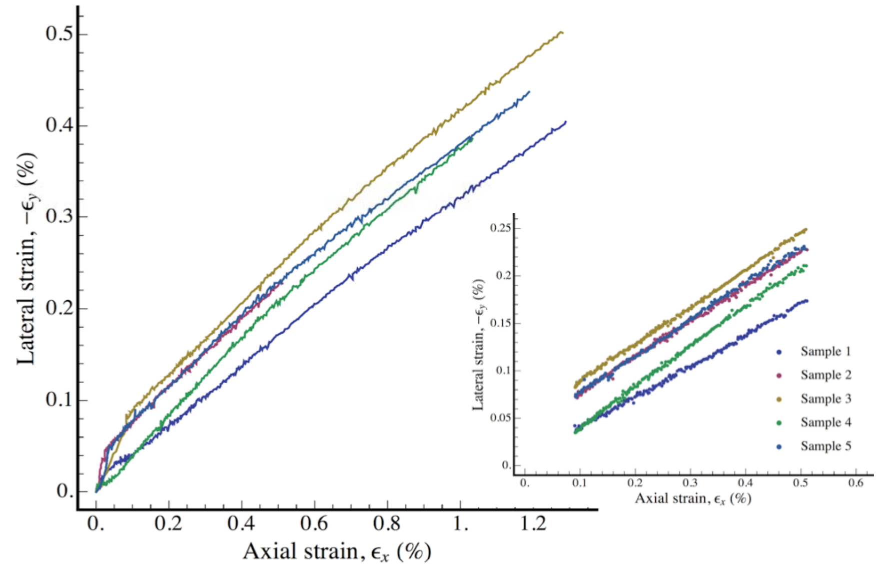
- Initial tensile work – large statistical variability

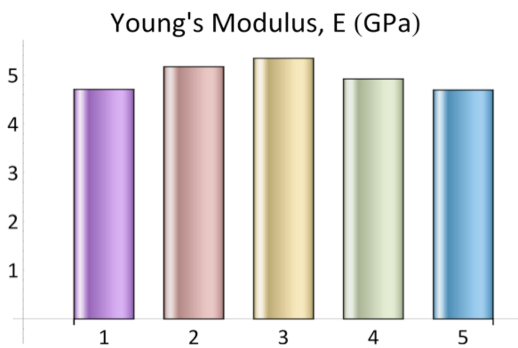
- Brazil tests – limitations in brittle materials

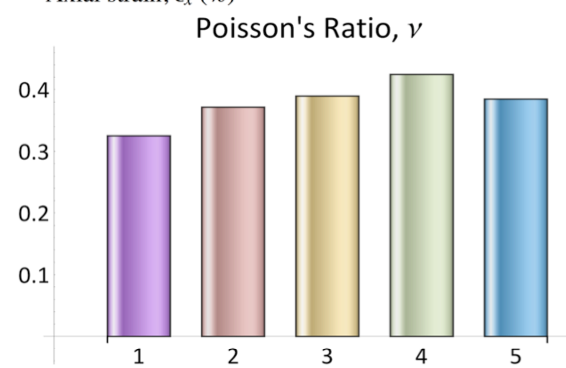
- “Compression – Fracture” – produces measurable crack growth even in brittle composites

Uniaxial Tension of DAP



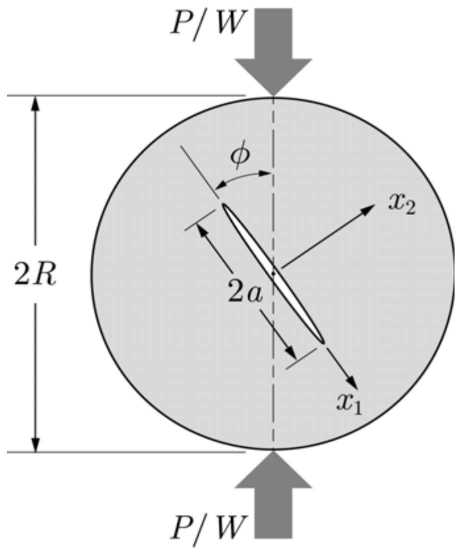


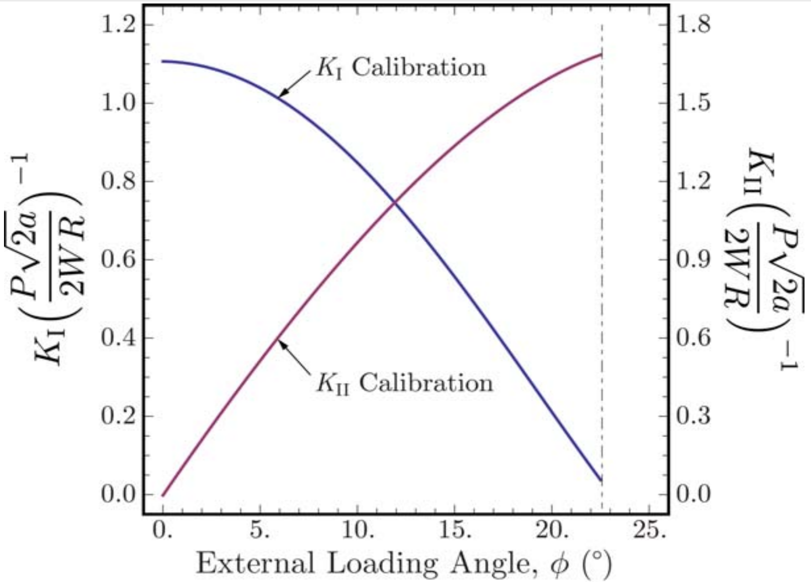




- **Materials show limited strain (< 1.5%).**
- **Large statistical variability in failure strength and strain**

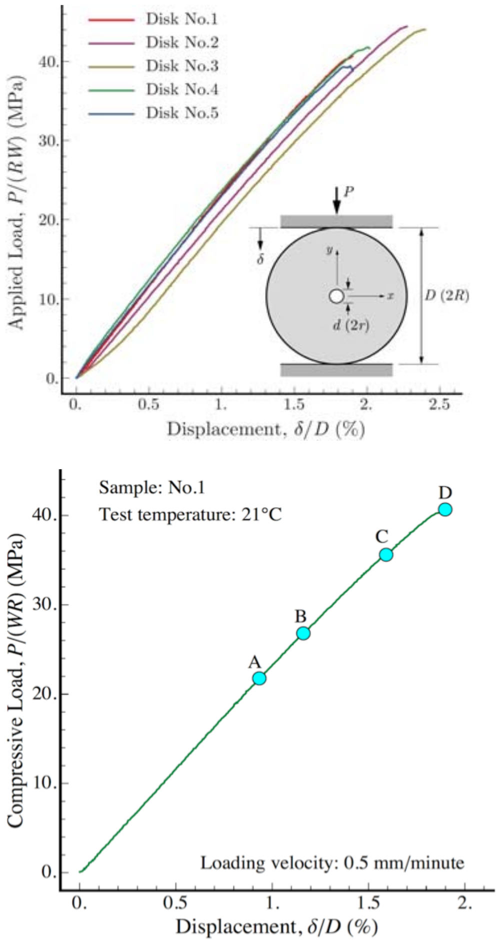
Brazilian Disk Fracture Sample Calibration

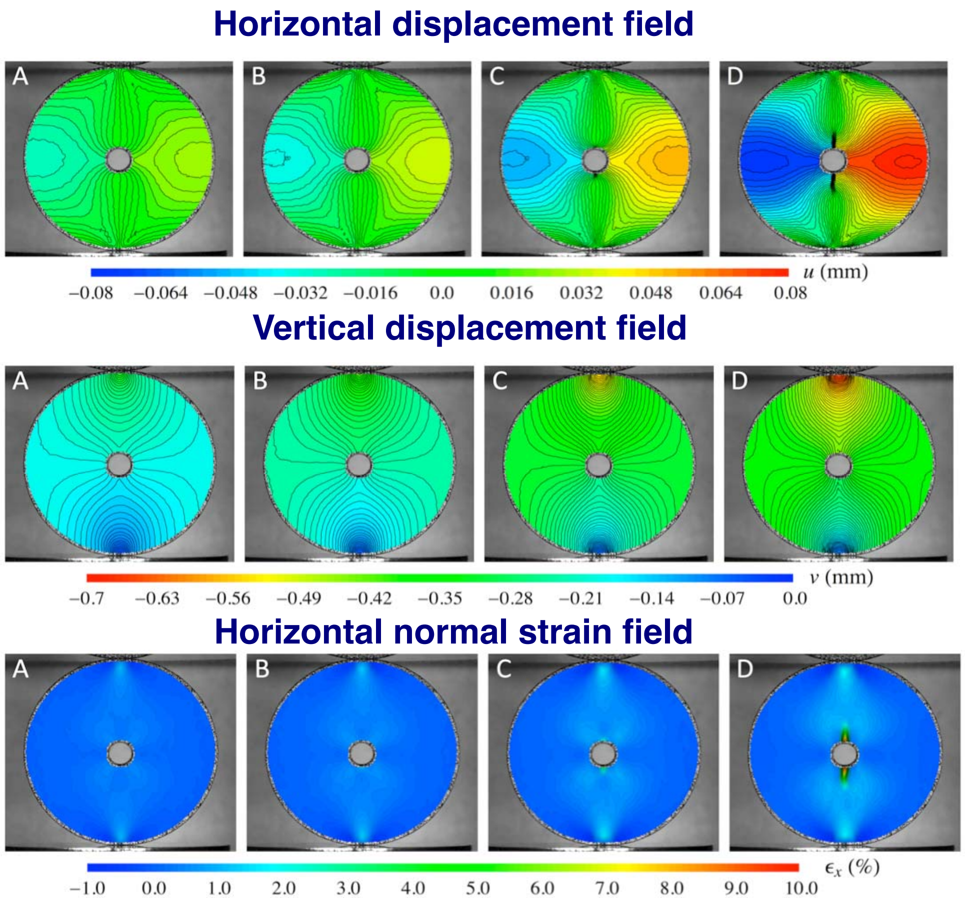




- **Brazilian disk specimen with a center crack was calibrated for orthotropic materials (Huang, et al., Acta Mat 1996) for measuring mixed-mode fracture toughness of graphite composite (Liu, et al., Int J Fract 1997).**
- **The Brazilian disk specimen with a center crack was also used for studying mixed-mode 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.**

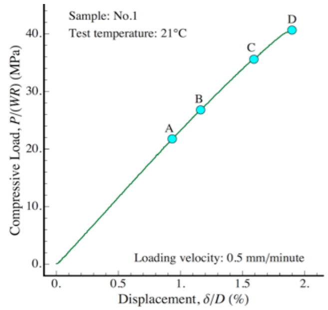
DAP Disk Compression: Overall Response



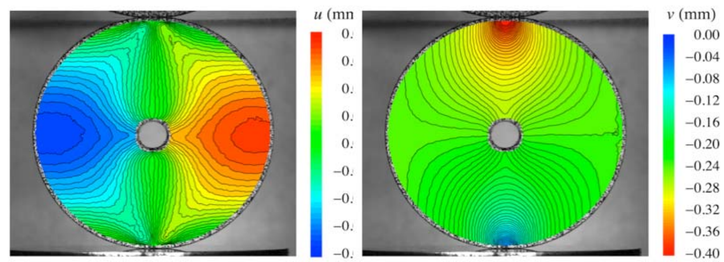


- **Repeatable but rapid crack growth to failure.**
- **Large displacement gradient (strain) correlating to damage, cracking, and failure**
- **Quantitative analysis indicates that at "time" B Damage initiates in sample.**

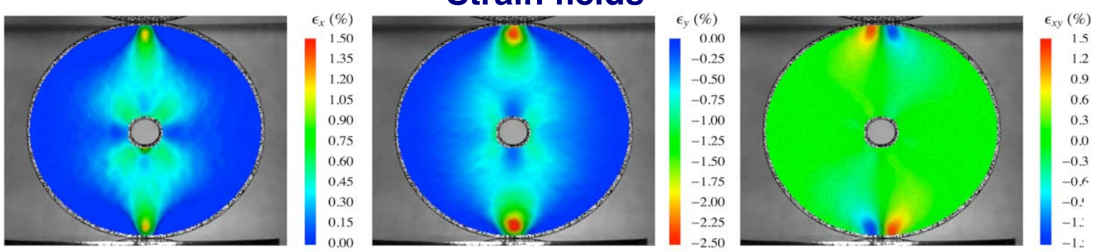
Deformation Field at the Critical Moment B

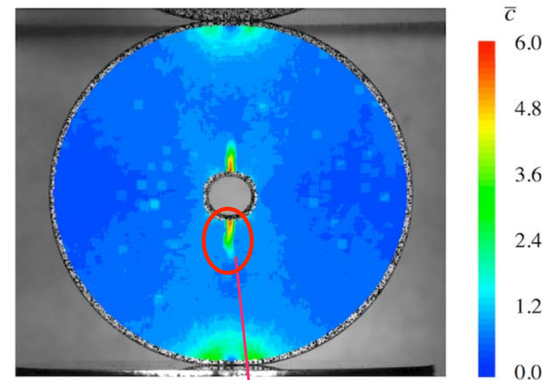


Displacement fields

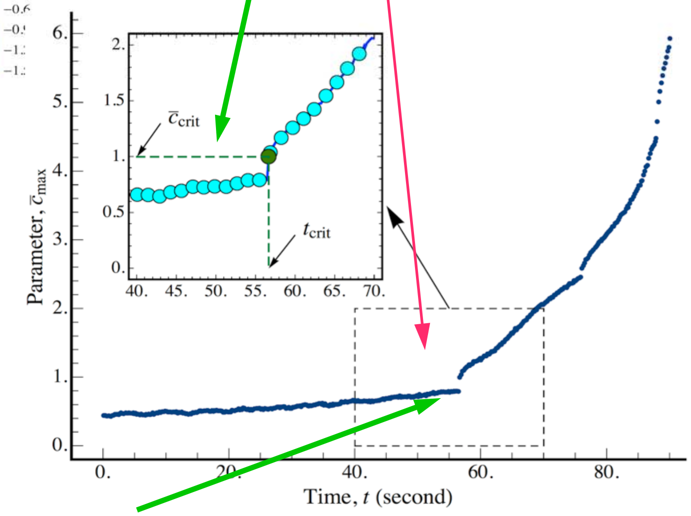


Strain fields





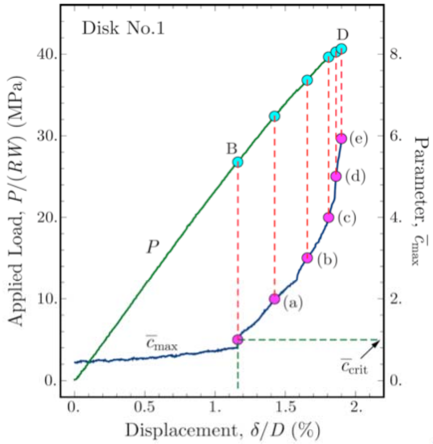
The critical value itself can be used to identify cracked regions

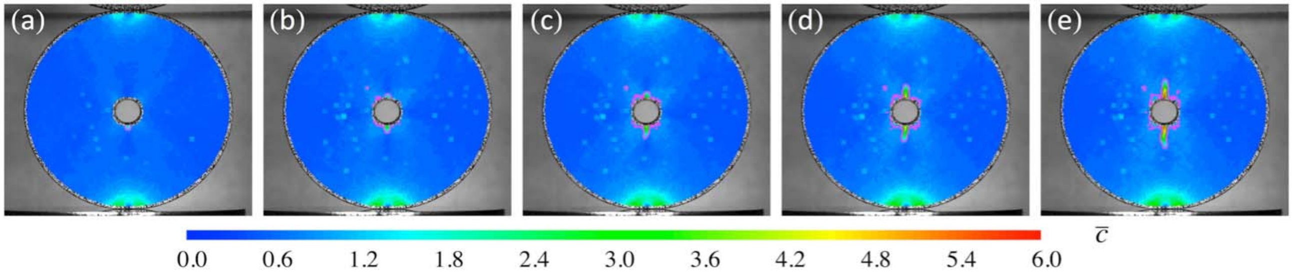


Macroscopic crack initiation is uniquely identified

- **Images at moment B when damage initiates.**
- **Strain fields used to find elastic constants like shear modulus and Poisson's 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.**

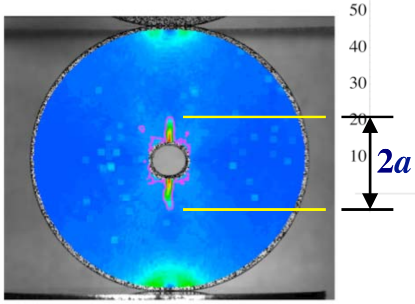
Damage/Cracking Evolution and Fracture Toughness

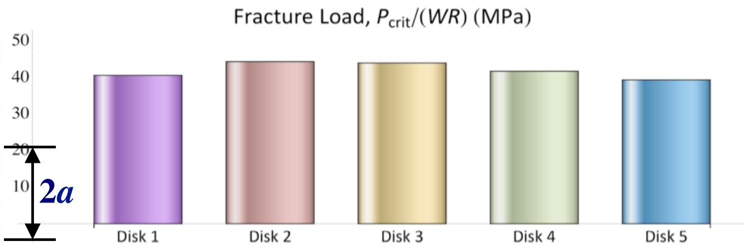


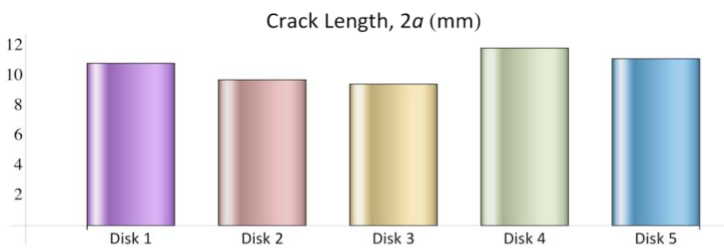


- The critical correlation coefficient is used to identify the boundary of the cracking.
- The growth rate of the crack can be determined by measuring crack extension from frame to frame, initially slow and increasing to failure.
- Near failure, the crack is extending quite rapidly and is an indication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

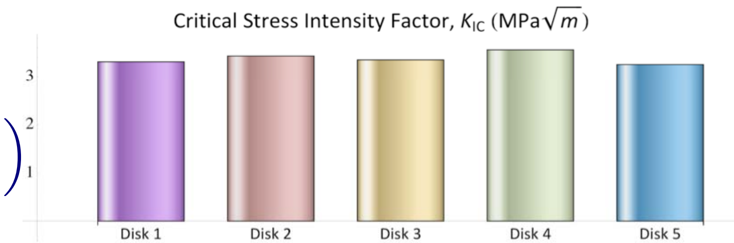
Crack length at the onset of unstable fracture



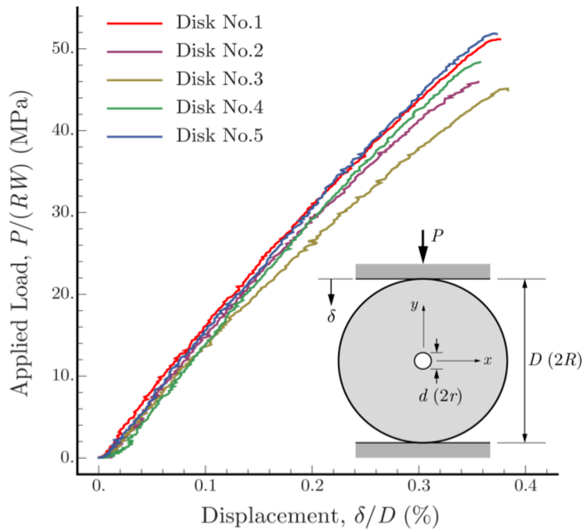


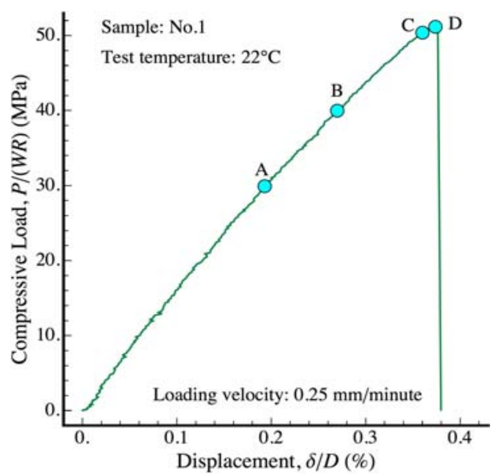


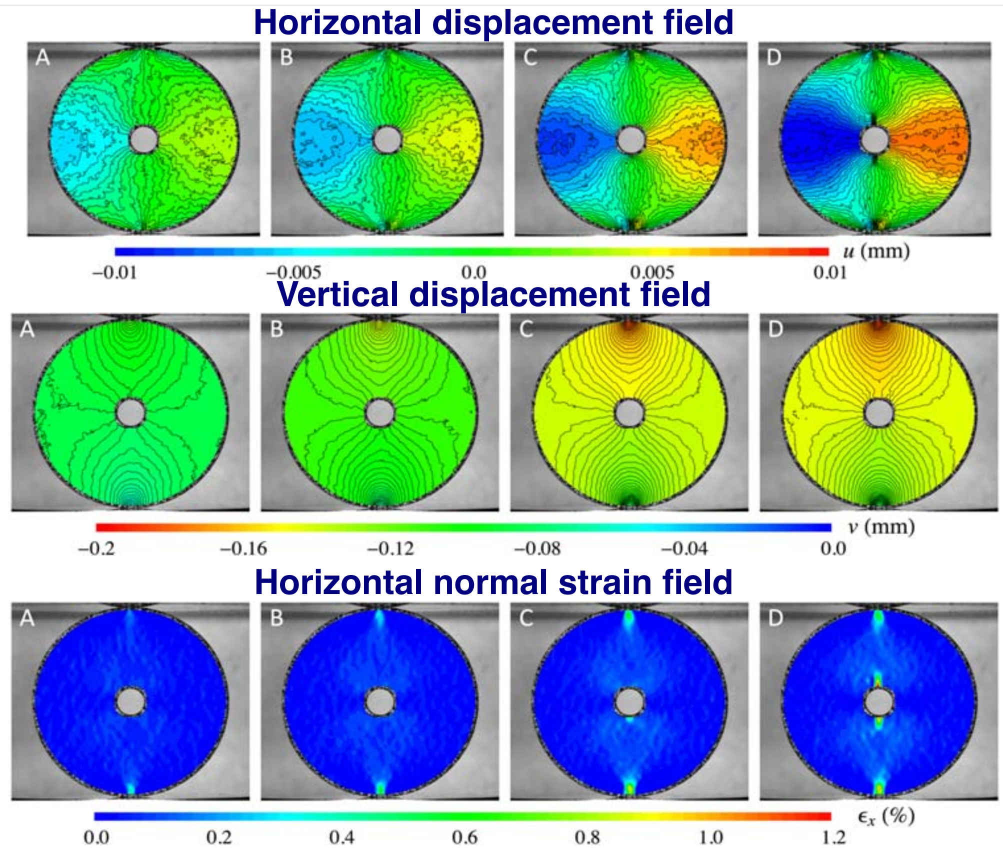
$$K_{IC} = 1.1065\left(\frac{P_{crit}}{WR}\cdot\frac{\sqrt{2a}}{2}\right)$$



Seabreeze Disk Deformation

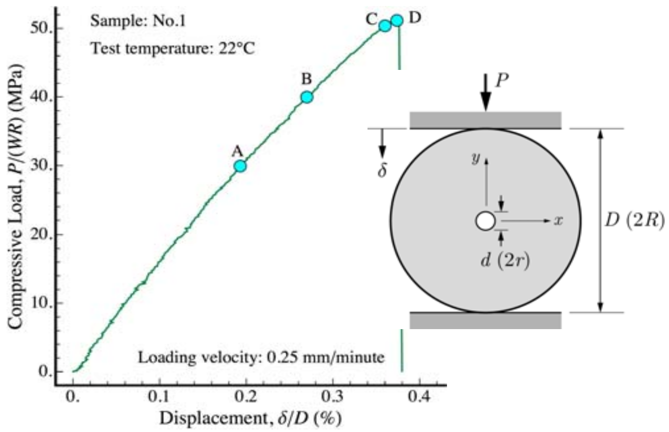


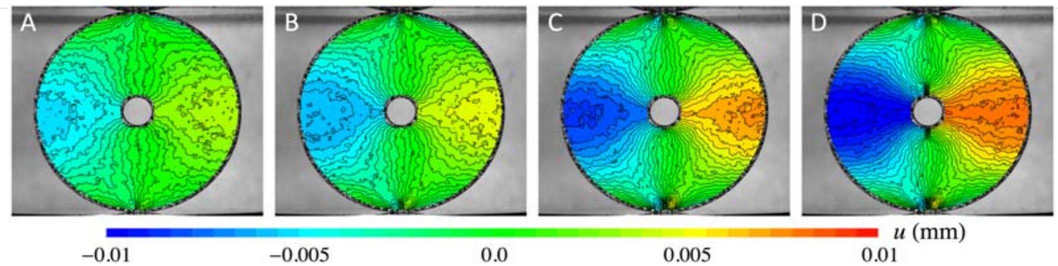


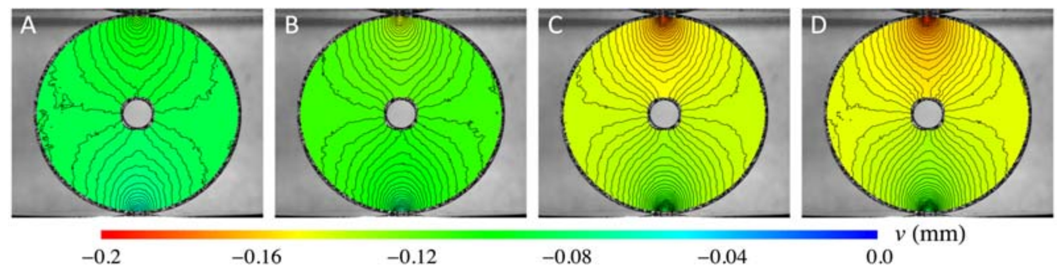


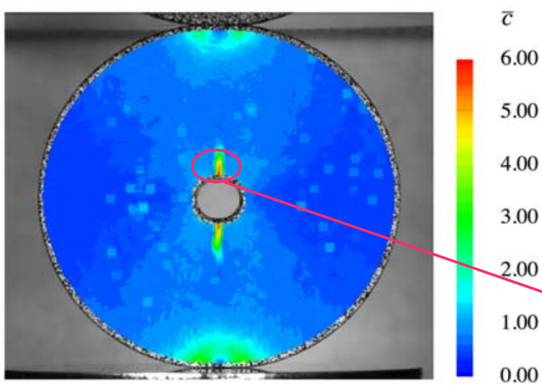
- The overall response of brittle composite and rigid polymer disk specimens show similar trends but the composite is much stiffer than the polymer.
- The overall deformation at the moment of failure is very small
- **Failure is catastrophic and rapid with little chance to measure crack growth rates.**

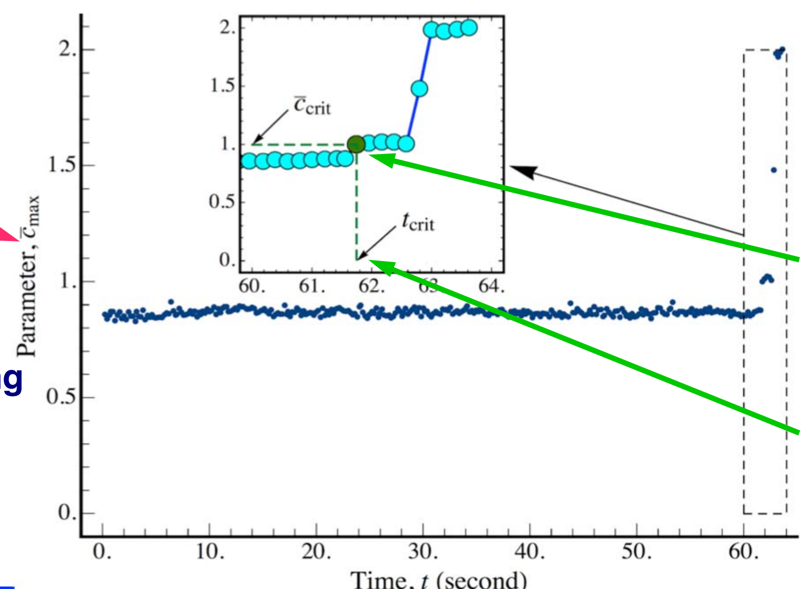
Limited Crack Growth in Seabreeze Disk Samples











The critical value itself can be used to identify cracked regions

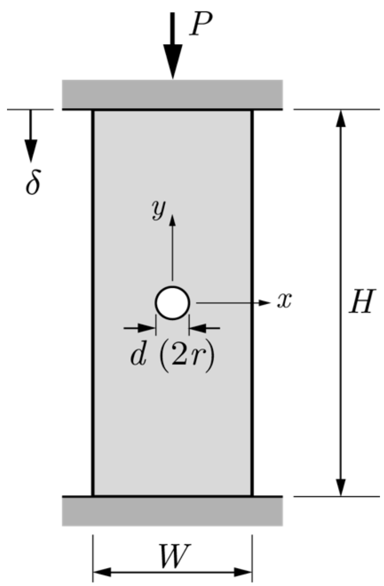
Macroscopic crack initiation is uniquely identified

- **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.**

"Compression – Fracture" sample: Unaged & Aged DAP

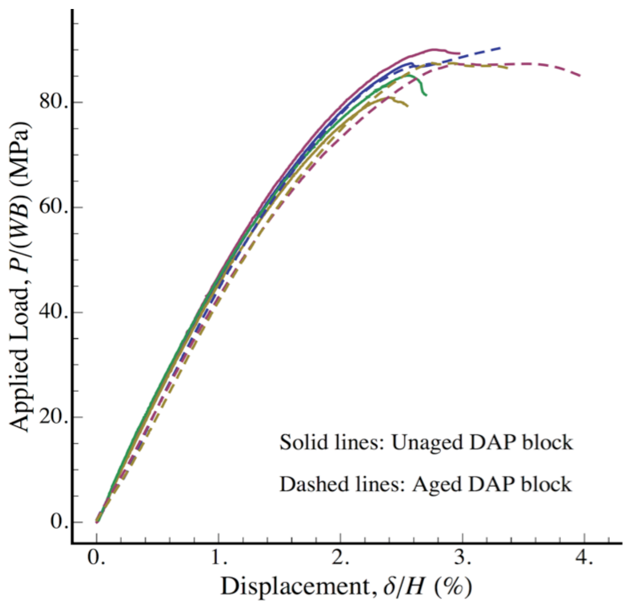
Based on work of Sammis and Ashby, "The Failure of Brittle Porous Solids Under Compressive Stress States" *Acta Metall.*, 34, 1 (1986) 511-526

- **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.**

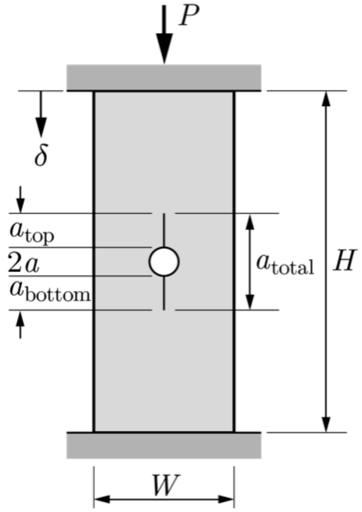


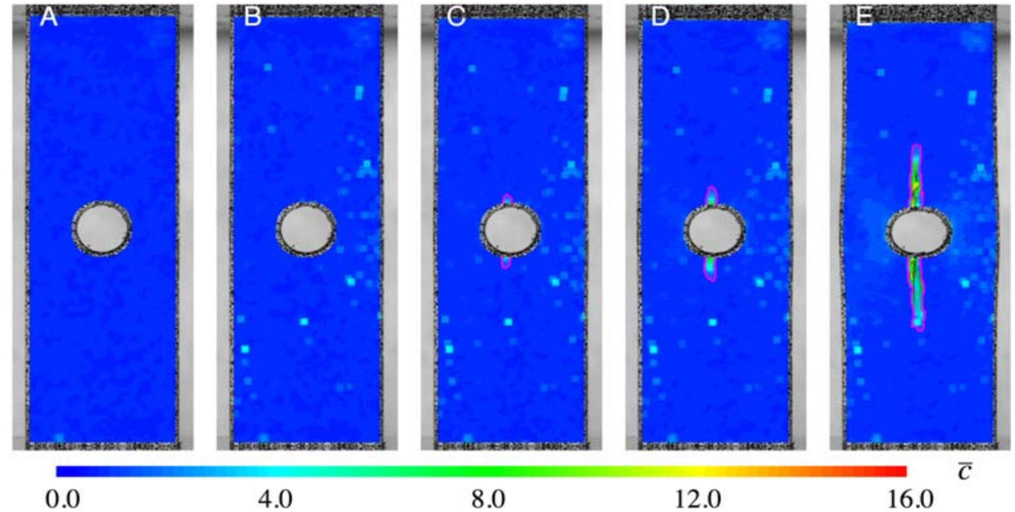
$$K_{IC} = -\left(\frac{l}{a}\right)^{1/2}\left\{\frac{1.1}{\left(1+\frac{l}{a}\right)^{3.3}}\right\}\sigma_1\sqrt{\pi a}$$

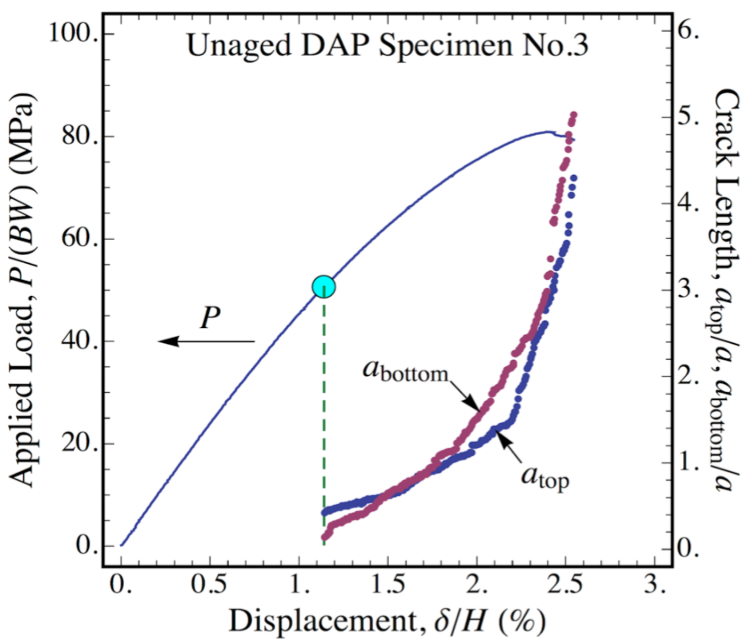
l = crack length, a = hole radius,
s_1 = load / far field area = P/WxT
(from figure r=a)

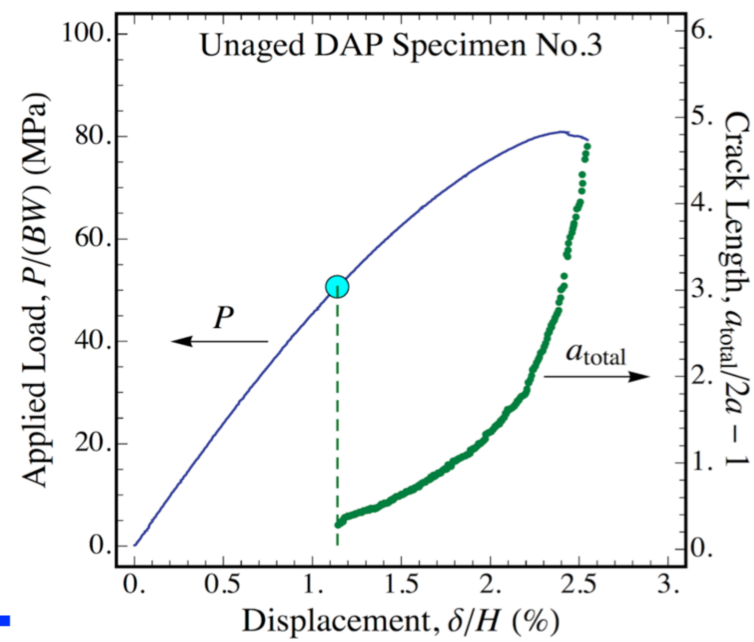


Crack Length Determination (Unaged DAP Block 03)

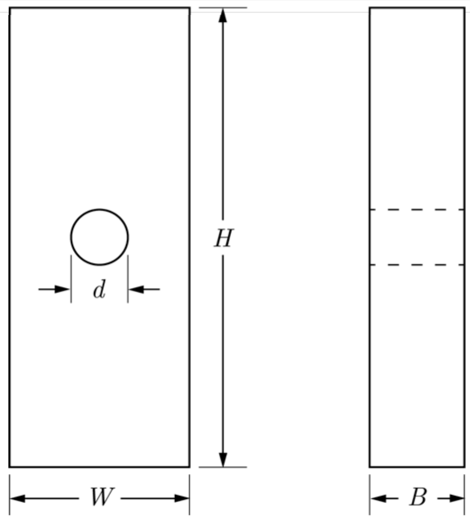








DAP Sample Summary

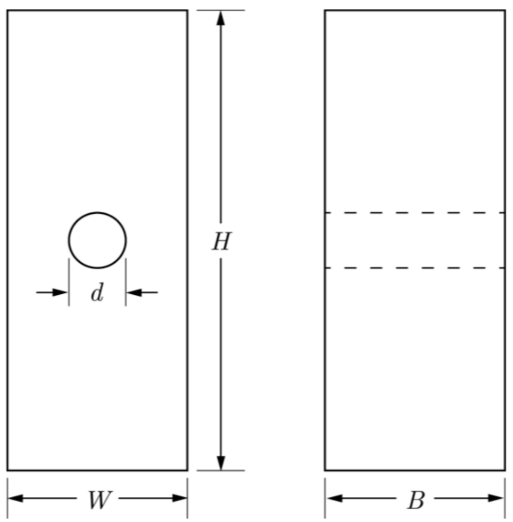


Sample Name	*H* (mm)	*W* (mm)	*B* (mm)	*d* (mm)
Block01	28.8531	12.7159	3.208	3.6690
Block02	28.8563	12.7921	3.218	3.6659
Block03	28.2296	9.5758	4.8622	3.1566
Block04	28.2264	9.5796	4.7663	3.1807
Test01	29.220	12.762	3.190	3.773
Test02	29.270	12.771	3.158	3.654
Test03	29.200	12.753	3.161	3.644
U-1	29.644	9.521	4.690	3.043
U-2	29.603	9.541	4.686	3.109
DPO-1-1	29.693	9.530	4.683	3.034
DPO-1-2	29.610	9.526	4.687	3.035
DPO-2-1	29.682	9.547	4.683	3.063
DPO-2-2	29.627	9.549	4.770	3.067
DPO-3-1	28.011	9.522	4.681	3.037
DPO-3-2	30.128	9.516	4.794	3.096

- To measure the fracture toughness of both unaged and aged DAP, we have proposed using the specimen with rectangular shape and with a circular hole at center.
- Compressive load is applied to the sample. Due to stress concentration near the boundary of the center hole, damage/cracking will start and propagate.
- Optical technique DIC (digital image correlation) is used to monitor the deformation field over the sample surface, and detect and monitor the initiation and propagation of growing crack.

Unaged samples are in green color, the rest are aged.

Sample Summary - Seabreeze



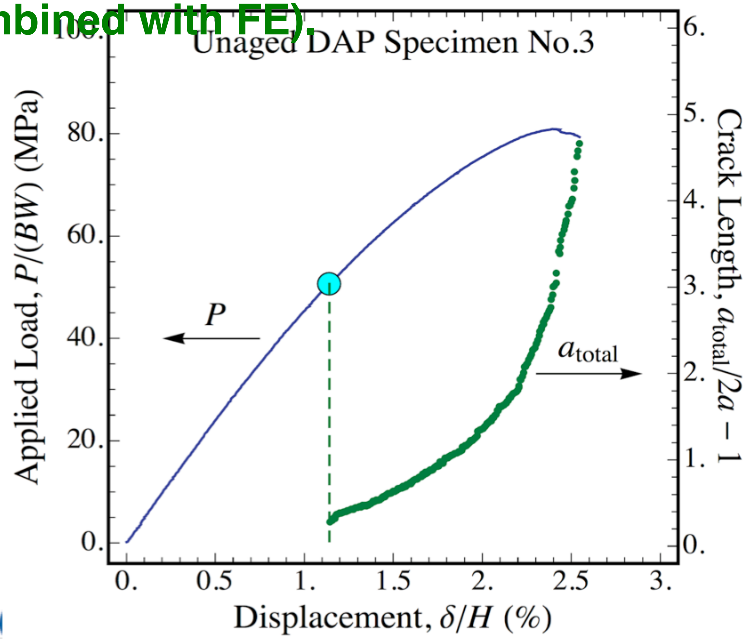
Sample Name	H (mm)	W (mm)	B (mm)	d (mm)
Block01	24.7447	9.5606	9.6514	3.0797
Block02	25.3740	9.5574	9.5898	3.0550
Block03	25.0234	9.5148	9.6342	3.0861
Block04	24.8844	9.4755	9.6234	3.2328
Block05	24.7910	9.5472	9.6279	3.2817
U-1	24.825	9.507	9.502	3.130
LBO-2-1	24.889	9.527	9.566	3.128
LBO-2-2	25.456	9.520	9.519	3.115
LBO-2-3	24.839	9.489	9.561	3.106
LBO-3-1	24.872	9.452	9.514	3.097
LBO-3-2	25.427	9.621	9.574	3.101
LBO-3-3	24.822	9.488	9.549	3.106

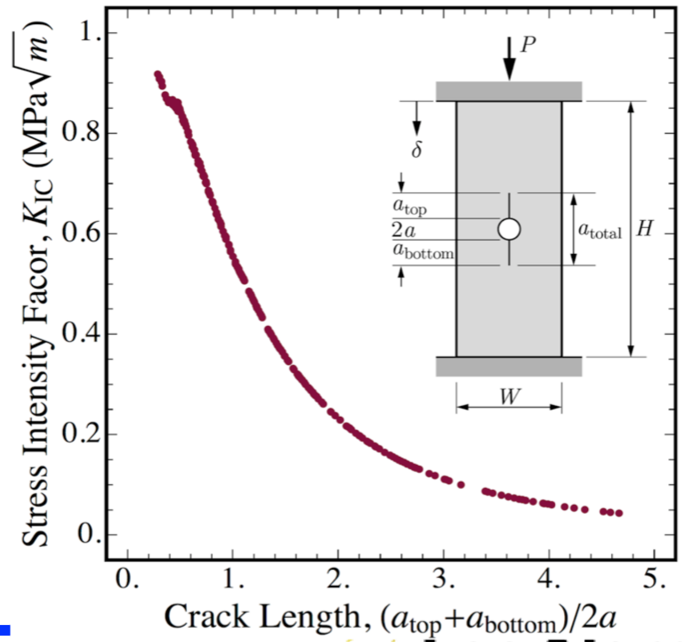
Fracture Toughness Measurement (Unaged DAP Block 03)

- **According to Sammis and Ashby (1986), applied load *P*/(*WB*) and the crack length a_{total} are sufficient for calculating the stress intensity factor at the crack tips:**

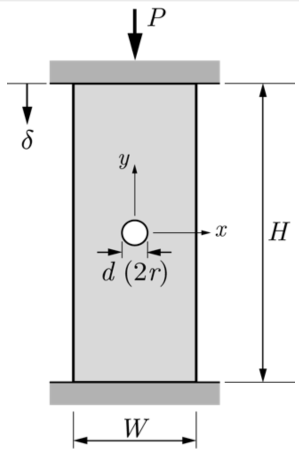
$$K_{\mathrm{IC}} = -\left(\frac{a_{\mathrm{top}} + a_{\mathrm{bottom}}}{2a}\right)^{1/2} \left\{ \frac{1.1}{\left(1 + \frac{a_{\mathrm{top}} + a_{\mathrm{bottom}}}{2a}\right)^{3.3}} \right\} \sigma\sqrt{\pi a}$$

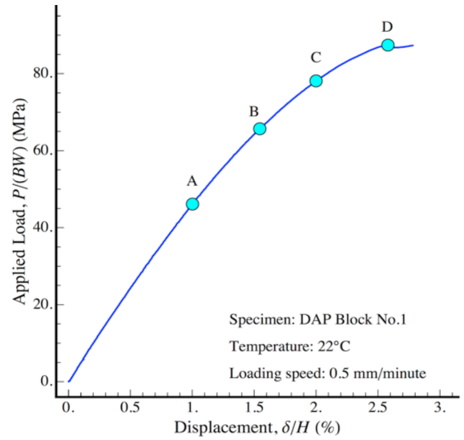
- **For growing crack, this stress intensity factor represents the fracture toughness of the material, K_{IC}.**
- **Caveat: The formula is semi-empirical, better options should and will be explored.**
- **The experimentally determined quantities are sufficient for better options (e.g., combined with FE).**



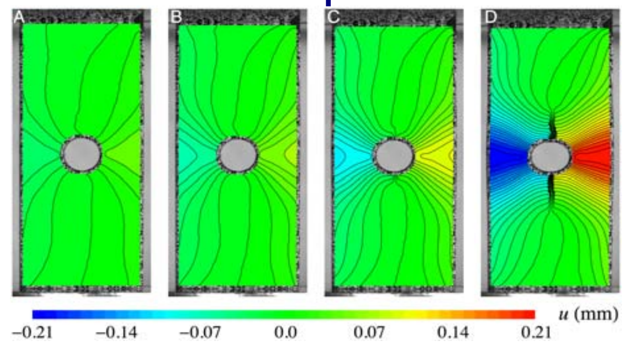


Deformation and Crack Growth in Unaged DAP

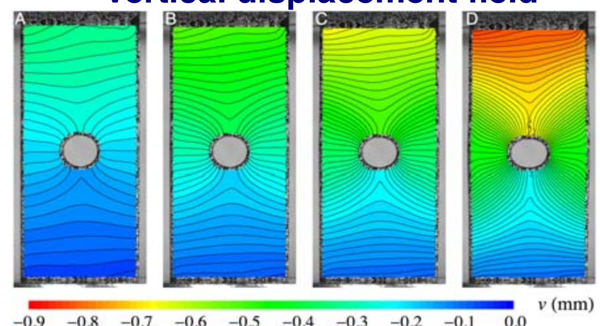




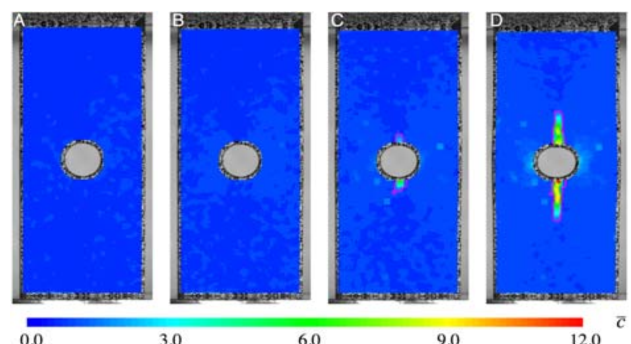
Horizontal displacement field



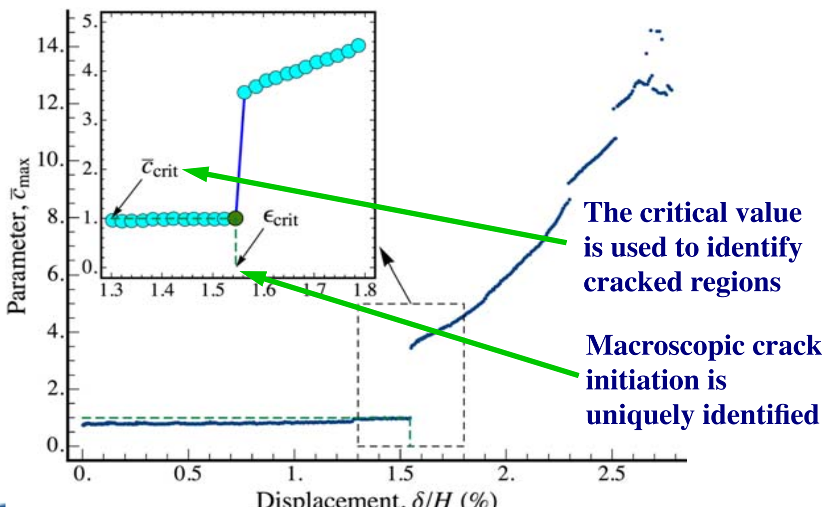
Vertical displacement field



Horizontal Strain field



- **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.**



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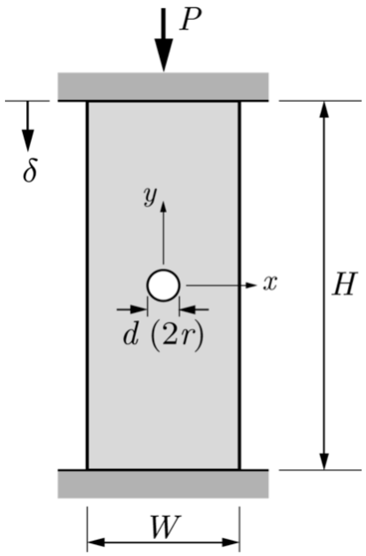
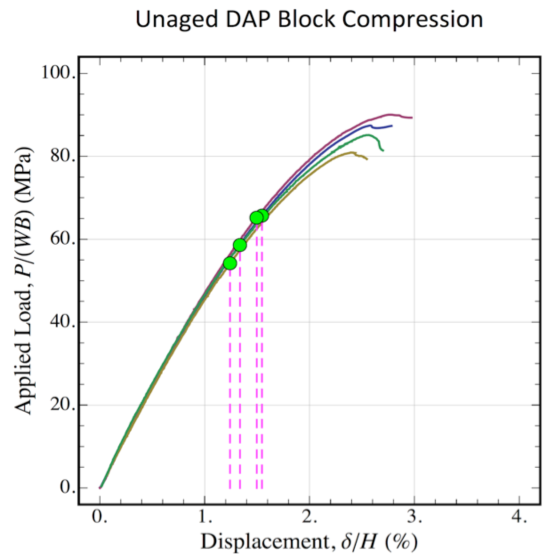
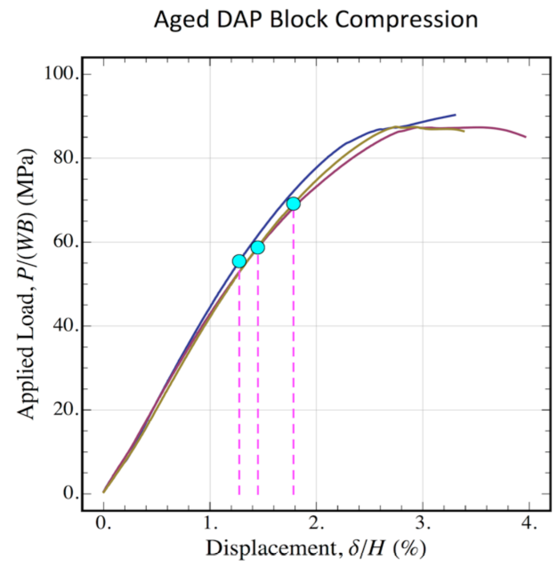
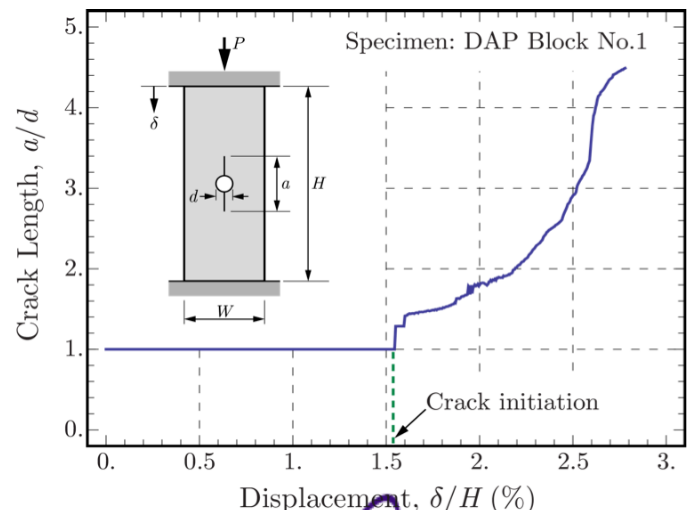
Unaged & Aged DAP Compression - Fracture





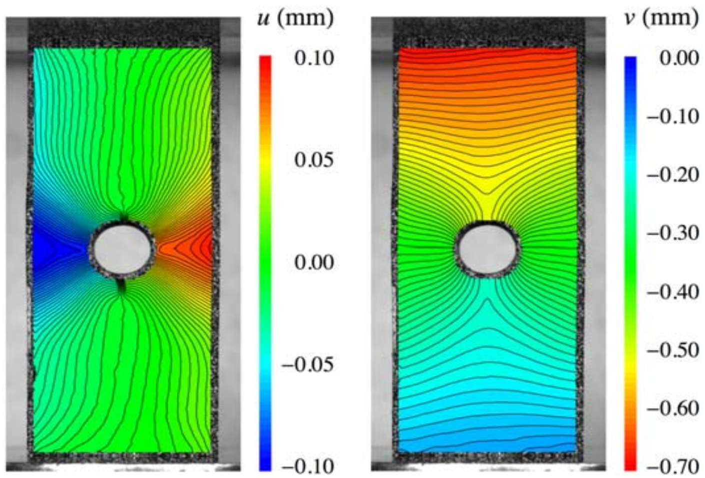


- **The overall response of both unaged and aged polymer specimens show similar trends.**
- **All specimens exhibit stable crack growth.**
- **The stiffness of the aged samples is slightly lower than the unaged specimens.**
- **For aged polymer samples, the load drop after the peak load is not as drastic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



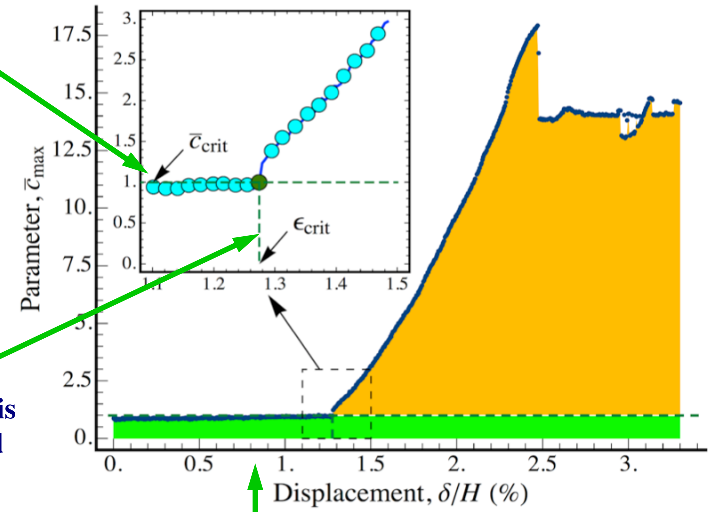
Identifying Damage Initiation (DAP)

Displacement fields

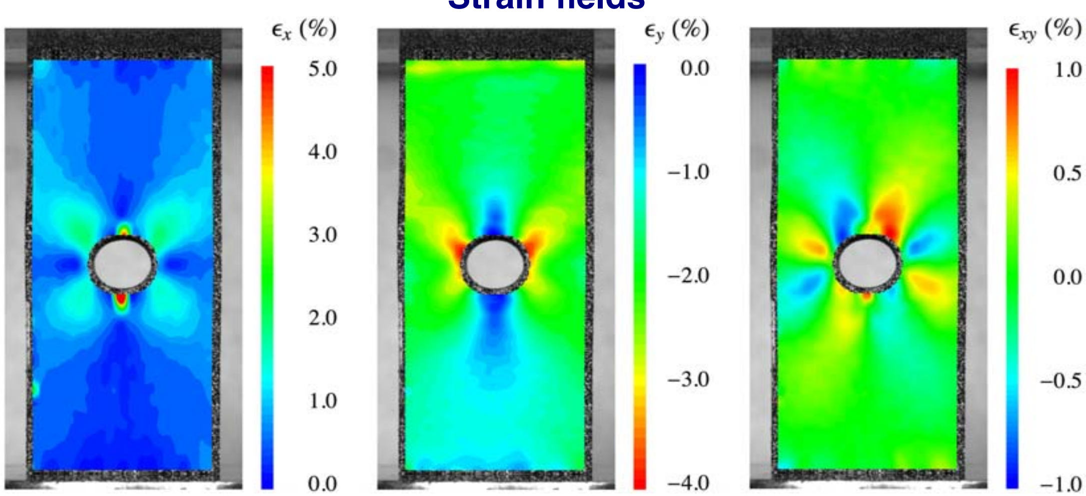


The critical value is used to identify damaged/cracked regions

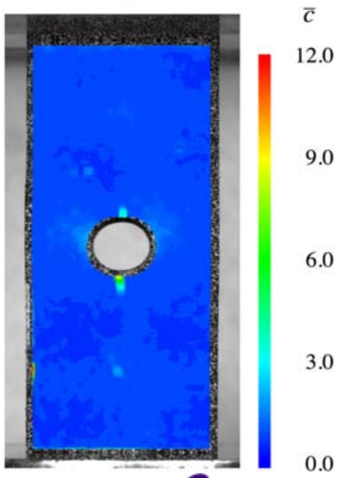
Macroscopic damage initiation is uniquely identified



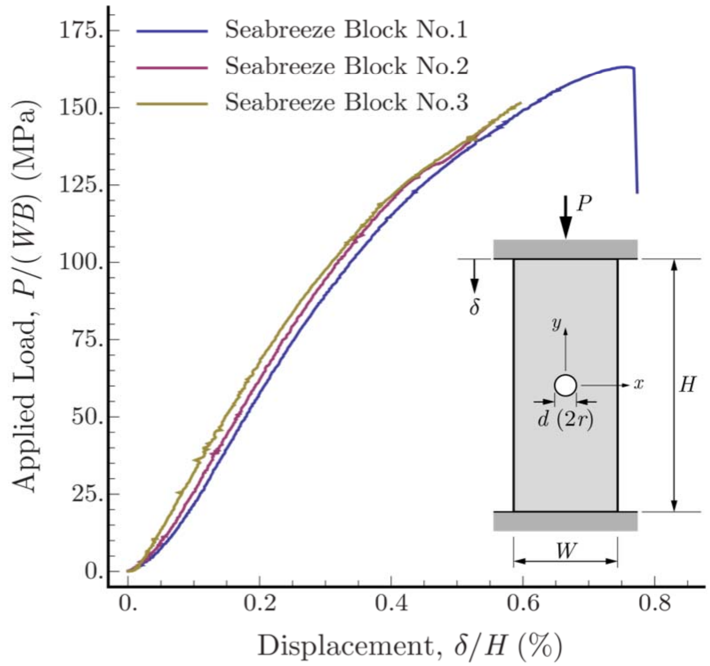
Strain fields

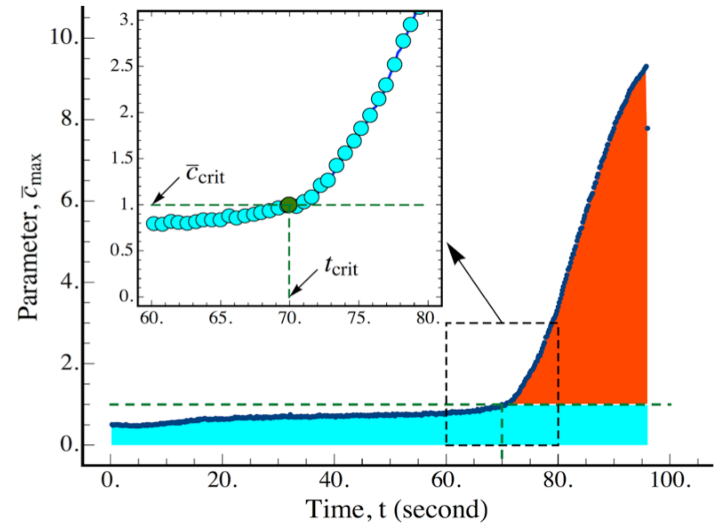


Correlation coefficient field



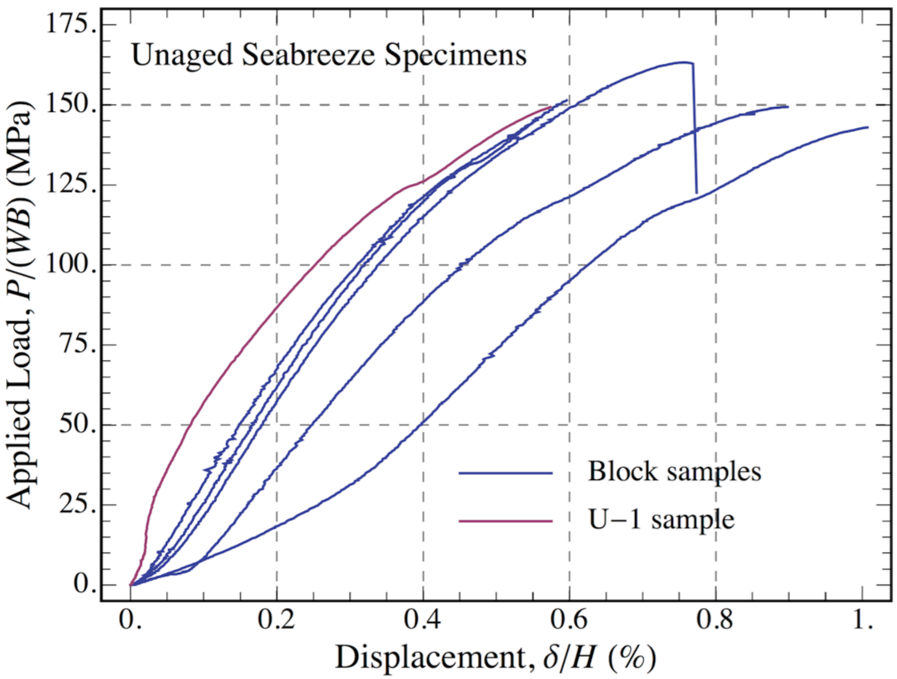
Seabreeze Compression – Fracture Results

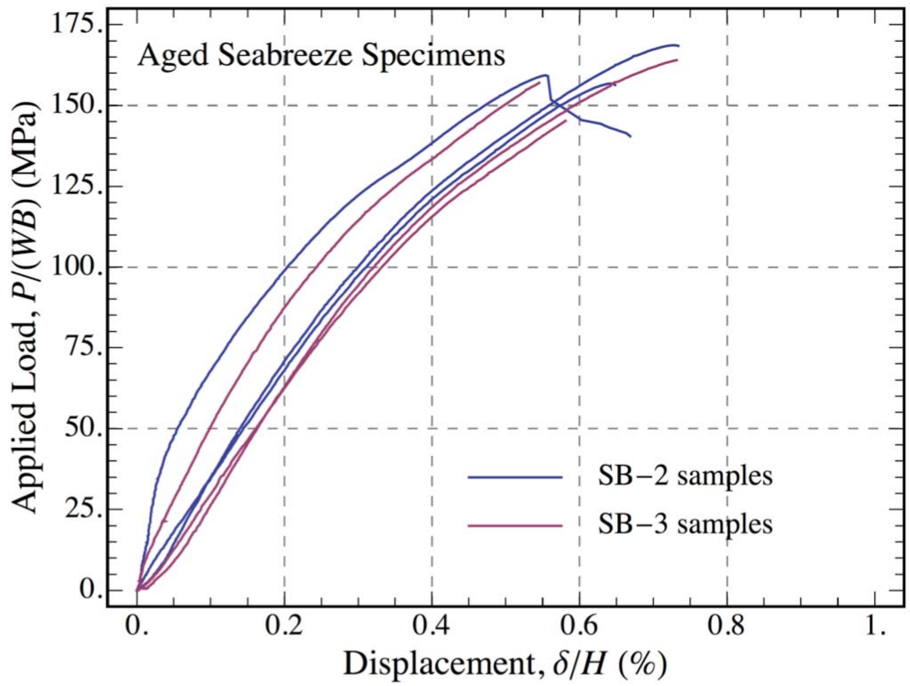




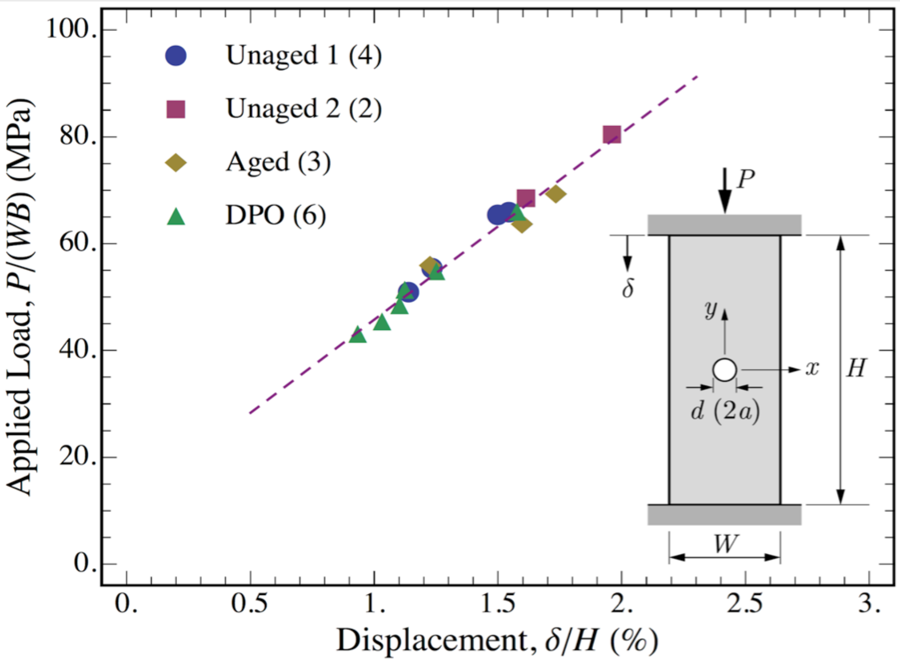
- **Tests of brittle composite show measurable crack growth rates and fracture toughness values.**
- **The overall response of the Brittle composite is much stiffer than the rigid polymer.**

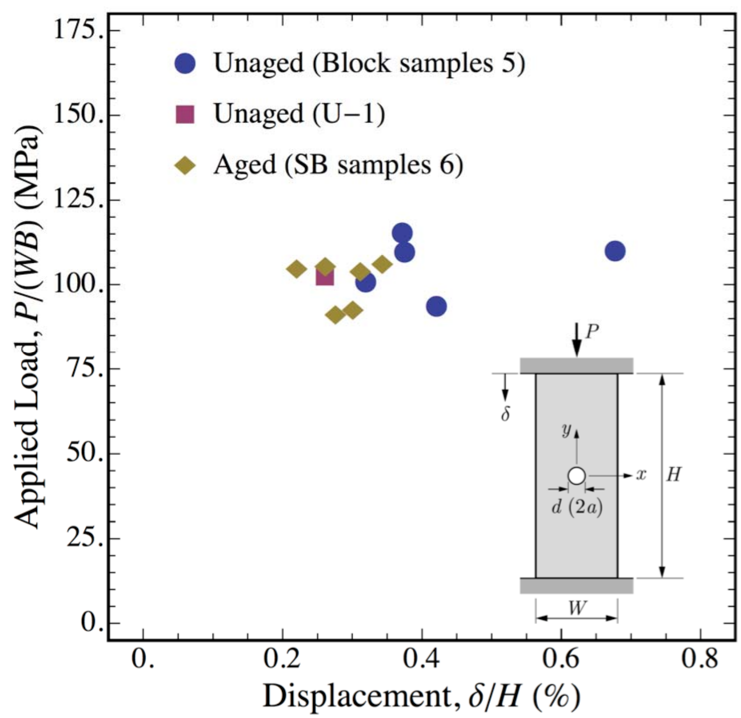
Overall Response of Unaged and Aged Seabreeze Samples



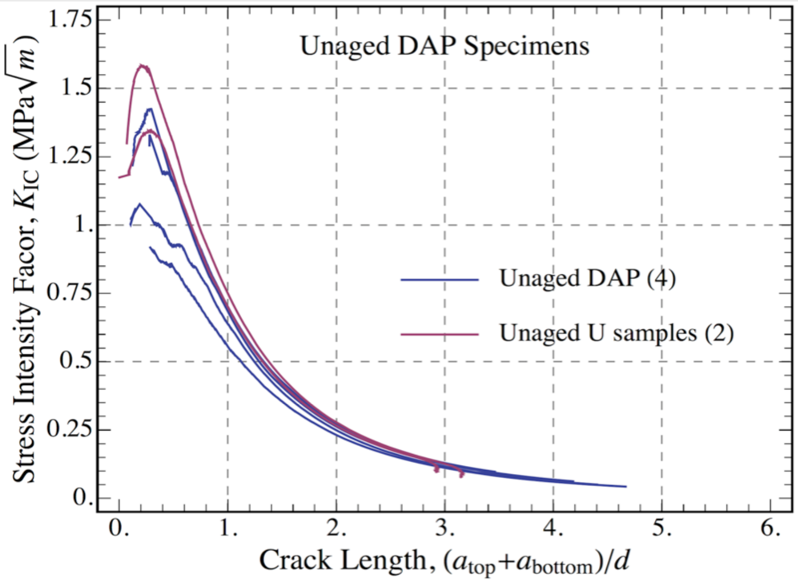


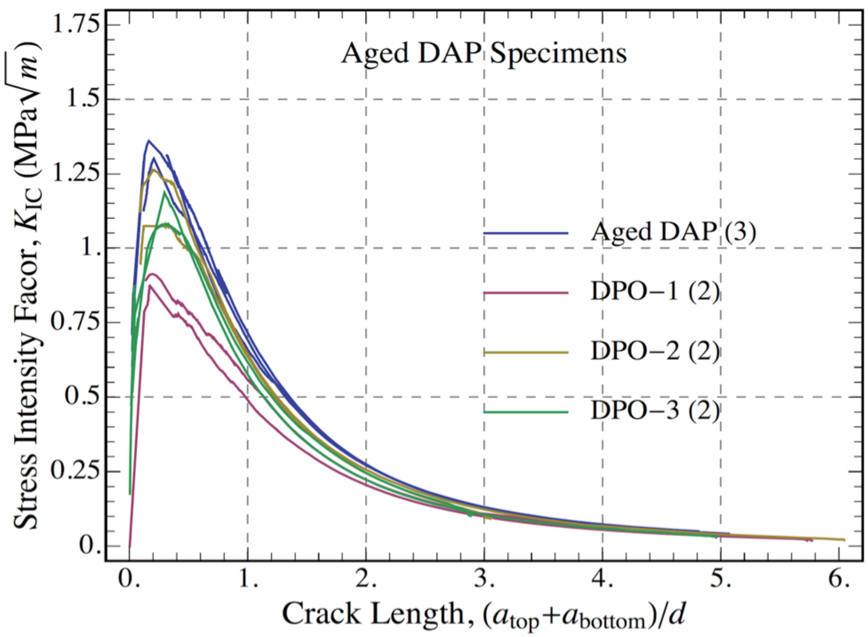
Damage/Cracking Initiation of DAP and Seabreeze Materials



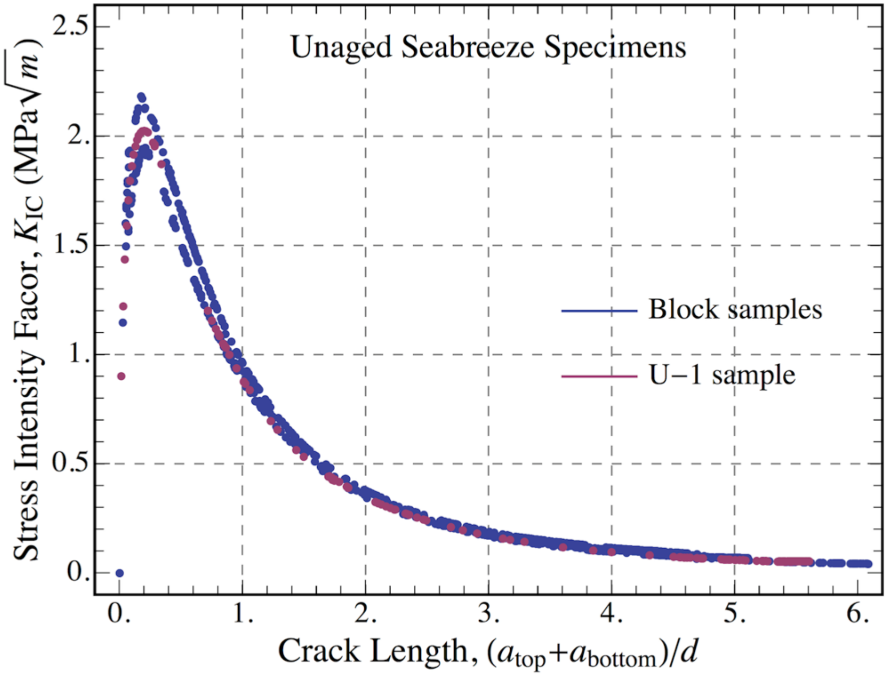


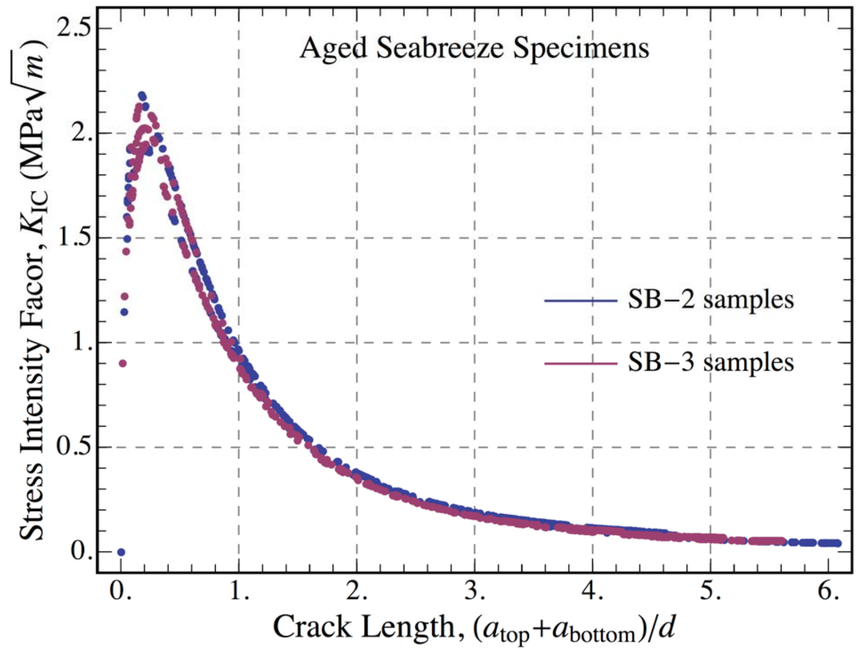
Fracture Toughness of Unaged and Aged DAP





Fracture Toughness of Unaged and Aged Seabreeze





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.
- Technique being used to put cracks in vitreous carbon where crack growth is rapid.

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).