FRACTURE IN PBX 9501 AT LOW RATES

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Tensile, or mode I, fractures in PBX 9501 have a very large process zone that runs well ahead of the visible fracture. This process zone is important in understanding dissipation from fractures that occur under accident conditions and in assessing density fluctuations in other conditions. A Model for process zone behavior is presented. We present images and load histories of fractures in three-point bending, modified compact tension, and Brazilian test configurations. The fracture conditions are measured using laser speckle interferometry, coherent gradient sensing (cgs), and digital correlation techniques. The application of the techniques is described and compared. These tests are all done at relatively slow rates. Brazil tests are done in both a pre-notched and un-notched configuration. The pre-notched experiments show effects of mixed fracture modes. The un-notched samples provide information on the statistical nature of the original material. Granular composites like PBX 9501 have a statistical distribution of local strength that interacts strongly with the growth and movement of macroscopic fractures. Intact larger particles tend to provide a reinforcing effect, while previously fractured large particles are initiators. Binder rich regions are relatively weak and provide a path for extended fracture. Correlating images with applied load provides insight into the detailed mechanics of the fracture process. These images are difficult to collect because of the safety requirements for testing on explosive materials. The Brazil tests show not only extended fractures, but very interesting details around the loading points. These seem to be the result of granular flow mechanics and we believe the measurements can be used to verify and develop improved mechanical constitutive equations.

FRACTURE TEST CONFIGURATION

Initial experiments were done using 4-point bend jigs, with both symmetric (Fig. 1) and asymmetric (Fig. 2) loading on samples about 25 mm thick, as well as Brazil tests (Figs. 4,5) on samples about 25 mm diameter. These are very standard configurations, however early on we noticed the existence of a very large process zone running ahead of any visible crack. Interpreting the data with classical Griffith crack theory is essentially impossible. One author, CL, developed a very special modified compact tension (CT) specimen (Fig. 3). The very long CT design uses a groove on the back to guide the developing crack. The long sample allows full imaging of a propagating fracture including undamaged material, the process zone, and a visible crack. Analysis of these images leads to a Stress-Bridging Law. The other author, RB, continued working on Brazil configurations examining the statistics of the unguided fractures and behavior under cyclic loading conditions.

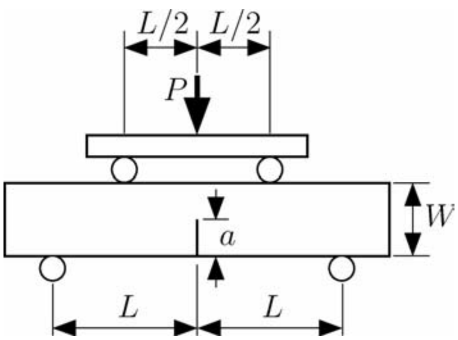

Figure 1 Symmetric beam loading

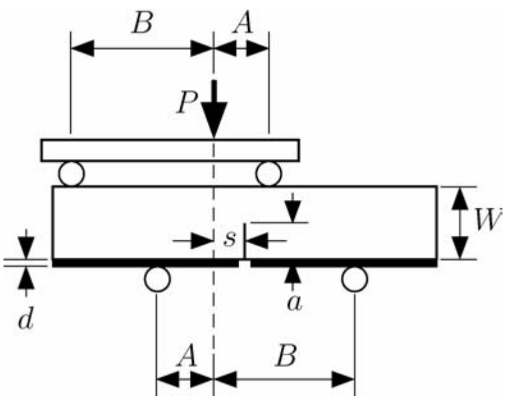

Figure 2 Asymmetric beam loading

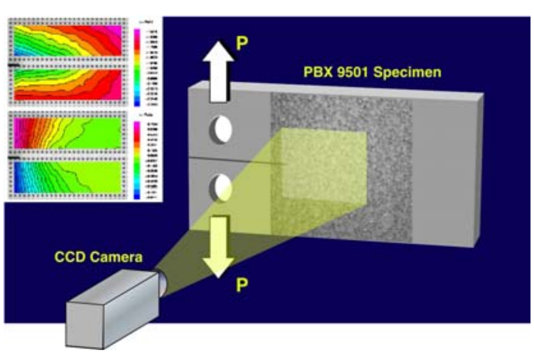

Figure 3 Modified compact tension

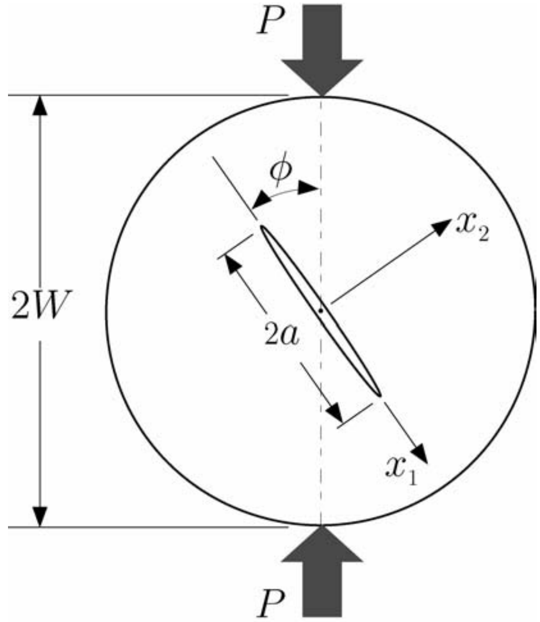

Figure 4 Brazil geometry with initial flaw

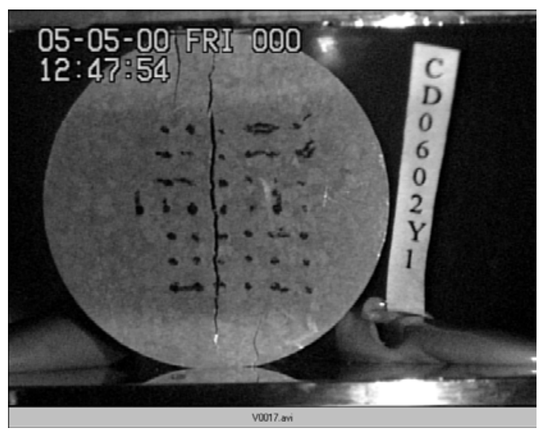

Figure 5 Frame from movie of convential Brazil test

LOAD DEFLECTION MEASUREMENTS QUANTIFY STIFFNESS

Most materials show a sharp failure in a fracture test. PBX 9501 shows a very extended softening behavior, as the process zone develops and eventually a visible crack emerges. Cyclic loading shows the residual strength and changes in stiffness.

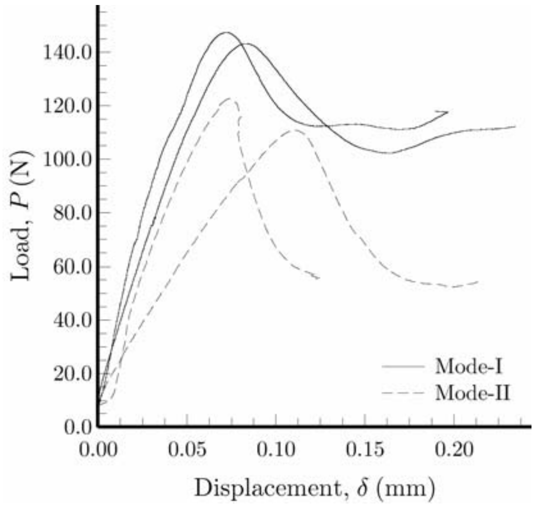

Figure 6 Initial fractures in mode 1 and 2 orientation.

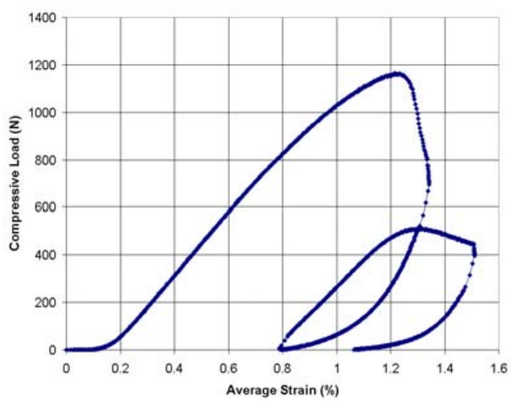

Figure 7 Cyclic loading in Brazil test shows changes in stiffness as crack develops.

FULL-FIELD DEFORMATION MEASURING TECHNIQUES

Speckle techniques are based on interference patterns resulting from minute surface irregularities when illuminated with coherent laser light. The speckles are imaged on photographic film, and image correlation techniques are used to find the motion of material points. The arrangement simply adds a laser illumination to the arrangement in Fig. 3. Coherent Gradient Sensing (CGS) uses gratings to directly form fringe patterns related to displacement gradients. The only drawback is that the gradients are needed in two directions to calculate the in-plane strain components.

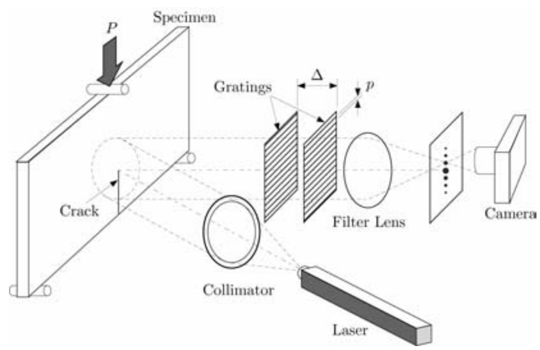

Figure 8 Coherent Gradient Sensing (CGS) test configuration.

In direct pattern matching (Fig. 3) the inherent texture of an illuminated surface and image correlation methods are used to track the movement of material points. Gradients in two directions are obtained by numerical differentiation. Marks can be applied to the surfaces freehand using a pencil or marking pen. Alternatively stencils can be used with spray or sputter coating methods. Although the stenciled patterns look tidy, hand applied marks tend to be very unique and allow easy matching by eye when multiple images are used. Computer matching works well on the natural surface texture and doesn't really need additional marks, as long as there is sufficient contrast in the image.

MODELS OF FRACTURE

The classical Griffith crack concept and associated linear elastic fracture mechanics concepts work well for most materials. The basic concept is an elastic material with an ideally sharp, completely separated, surface running to a crack tip or line. The process zone, where material separation occurs, is smaller than any characteristic length scale of the sample and is surrounded by the stress field with a square root singularity.

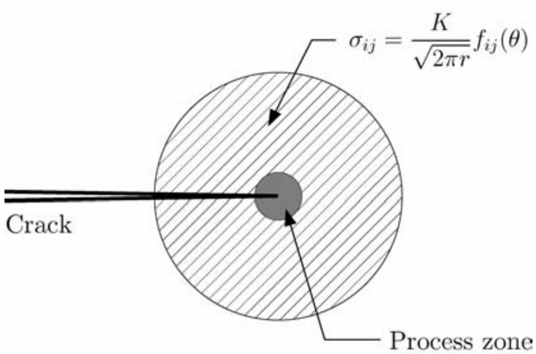

Figure 9 Idealized fracture configuration from conventional brittle fracture mechanics.

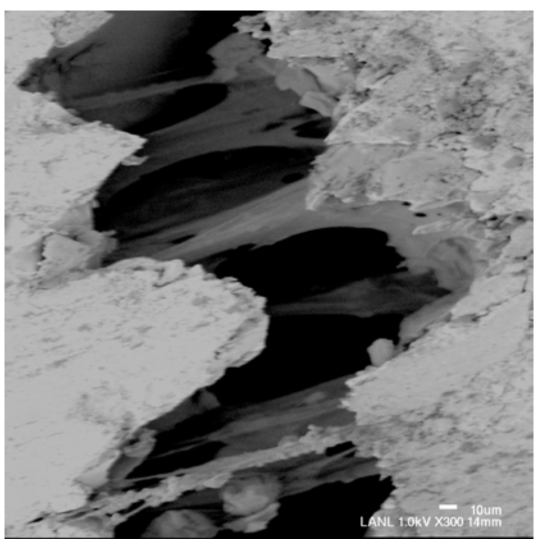

Figure 10 Electron micrograph shows taffy like binder bridging fracture surfaces.

In PBX materials, the crystal grain structure and relatively soft binder prevents this classical model from working at reasonable length scales due to the existence of large scale bridging. Micrographs (Figs. 10,11,17) show fractures meandering among and through crystals, and under certain conditions taffy like strings of binder bridging crack surfaces. Fracture models for PBX 9501 need to explicitly include the large-scale bridging mechanism and the bridging law needs to be determined experimentally.

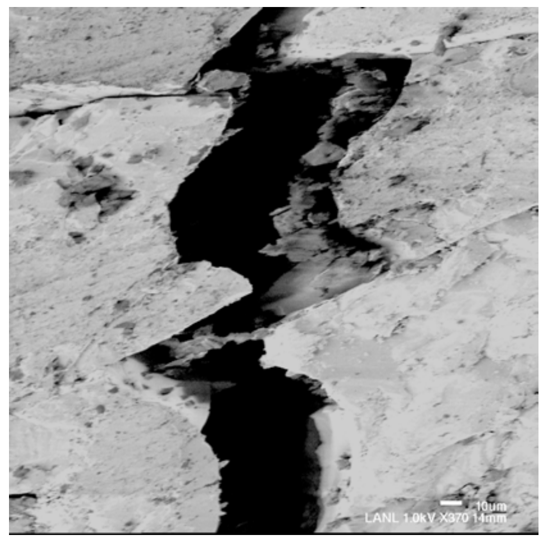

Figure 11 Electron micrograph shows fracture of crystalline HMX.

STRESS-BRIDGING (DE-COHESION) LAW EVALUATION

Using a digital image correlation (DIC) technique, sequences of images are converted to whole field deformation gradients and then to strain components as seen in Fig 17. Assuming elastic behavior the strains are converted to local stresses. The local stresses are interpolated into the process zone and plotted against the local deformation to generate the Stress-Bridging Law graph, Fig. 12. This graph shows the traction across an ideal gap that matches the observed local deflections, as a function of gap opening. In contrast to brittle materials, this bridging law exhibits a long descending tail.

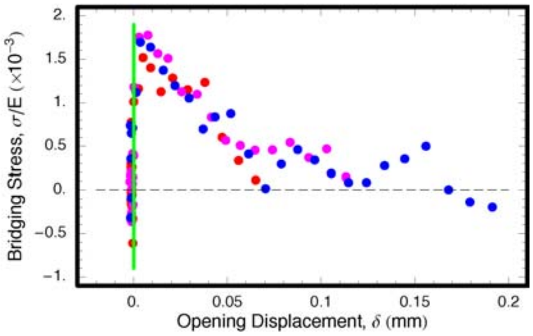

Figure 12 Bridging Stress Law quantifies the amount of bridging stress depending on separation of fracture surfaces.

CRACK PATH STATISTICS

Close examination of a crack path reveals information about the underlying granular nature of the material. By taking macrographs of Brazil specimens, after loading well into the failure regime and then unloading, we generate high resolution images that can be stitched together to cover an entire 25 mm diameter sample (Fig 16). The fracture path is then followed with a series of points. The slope is then obtained by differencing the incremental locations. Gathering cumulative lengths in slope bins produces the chart Fig 13. Note that although the mean slope is zero, the deviation is large with a substantial fraction of values above 45 degrees. We expect this to be strongly influenced by particle shape. A second statistical measure is the distance between slope sign changes. See Fig 14. This chart should be related to particle size, and the distribution of particle sizes. The distance the crack wanders from the centerline is related to the fluctuations in local strength. See Fig. 15.

PBX 9501 - PBS 9501

PBX 9501 is an explosive based on HMX (95%) and a binder comprised of Estane 5703 (2.5%) and a plasticizer (2.4%). PBX 9501 is an inert simulant made from cane sugar crystals and the same binder as PBX 9501. The simulant provides a good match in most mechanical properties although the density is low because of the difference between sucrose and HMX crystal density. The particle size distribution is matched using granulated and powdered material.

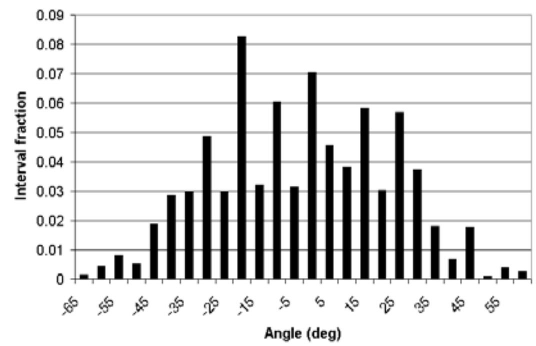

Figure 13 Slope distribution of fracture path.

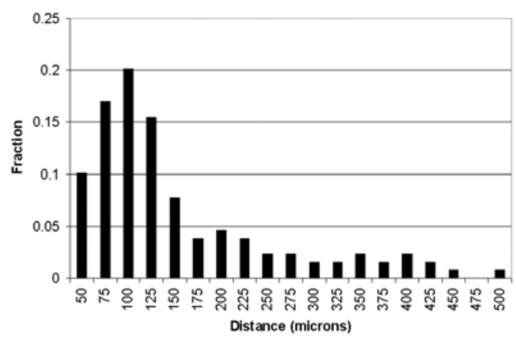

Figure 14 Run length before change in sign of slope also varies widely, should be related to particle size distribution.

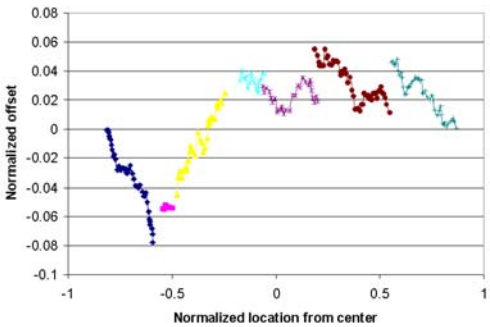

Figure 15 Offset from nominal centerline of crack path expressed as a fraction of the diameter.

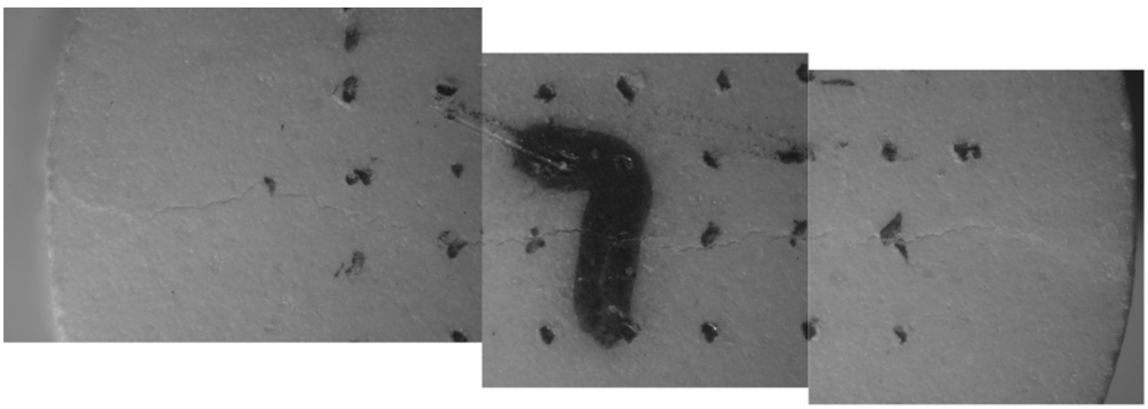

Figure 16 Optical micrograph of fracture across a Brazil sample shows the erratic path and wedge features at loading regions typical of these samples.

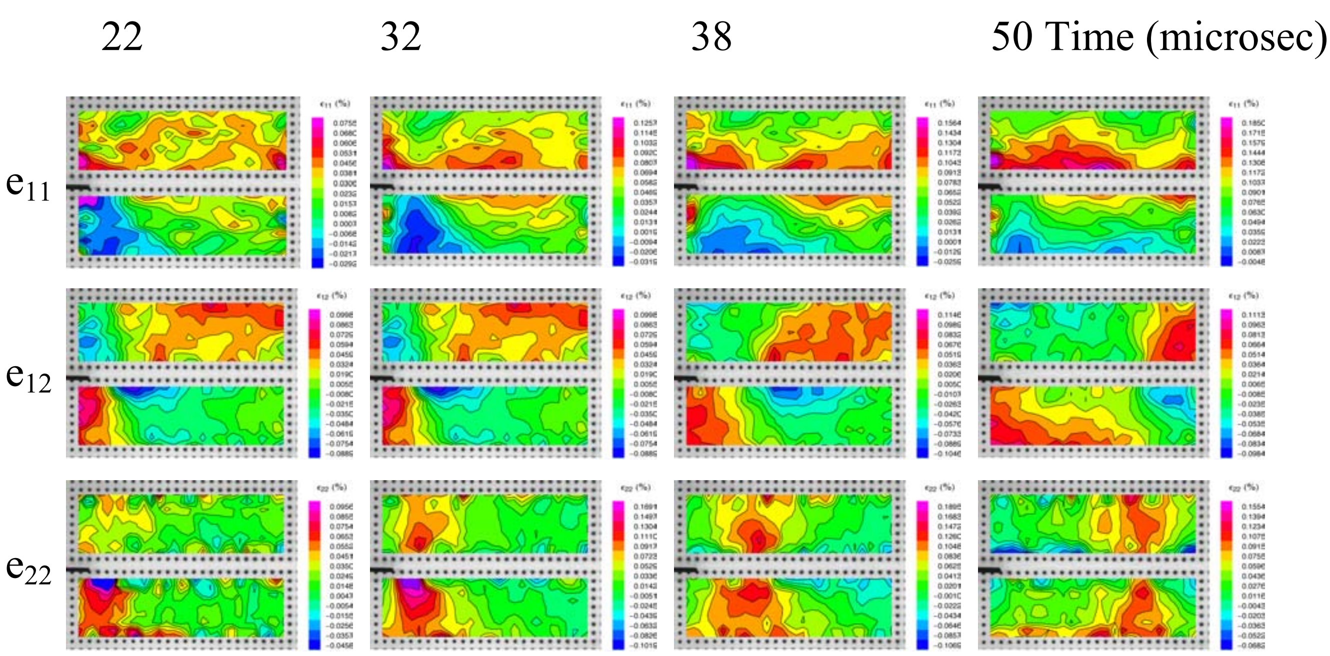

Figure 17 Contour plots of strain fields derived from digital image correlation, at a sequence of times, provide the basic information about the conditions around the bridging zone and crack tip.