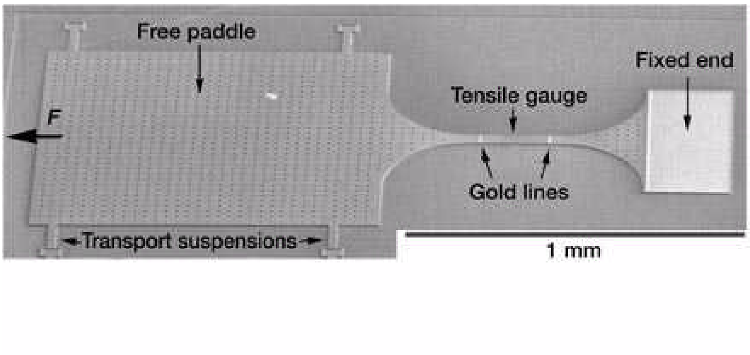
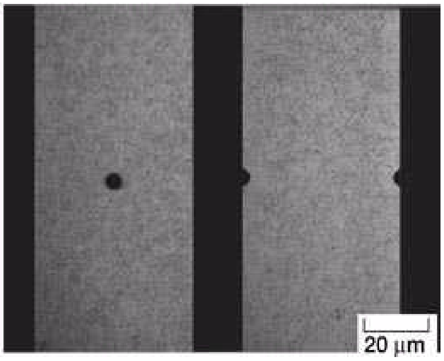
A Step Made Toward Designing Microelectromechanical System (MEMS) Structures With High Reliability

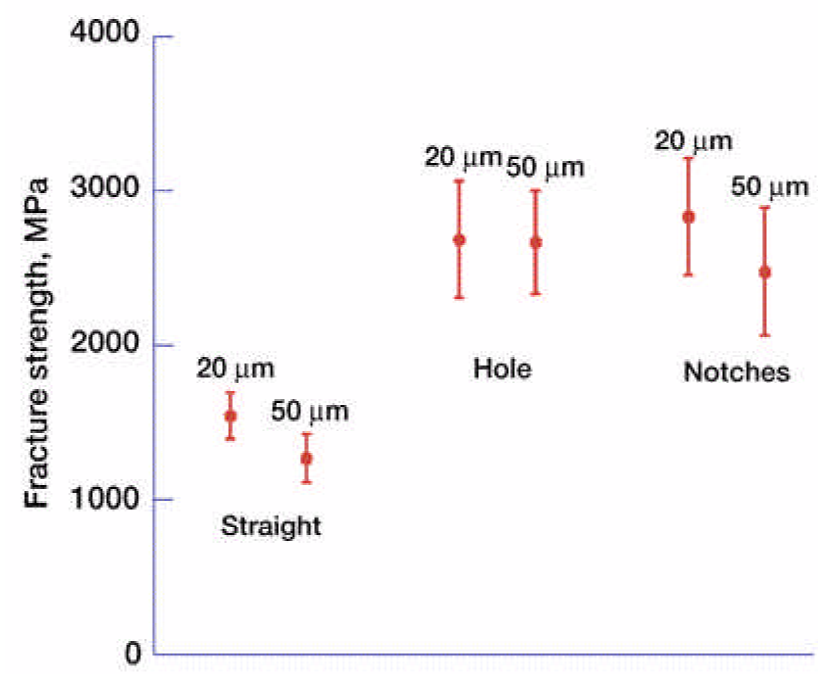
The mechanical design of microelectromechanical systems-particularly for micropower generation applications-requires the ability to predict the strength capacity of load-carrying components over the service life of the device. These microdevices, which typically are made of brittle materials such as polysilicon, show wide scatter (stochastic behavior) in strength as well as a different average strength for different sized structures (size effect). These behaviors necessitate either costly and time-consuming trial-and-error designs or, more efficiently, the development of a probabilistic design methodology for MEMS. Over the years, the NASA Glenn Research Center's Life Prediction Branch has developed the CARES/*Life* probabilistic design methodology to predict the reliability of advanced ceramic components. In this study, done in collaboration with Johns Hopkins University, the ability of the CARES/*Life* code to predict the reliability of polysilicon microsized structures with stress concentrations is successfully demonstrated.





Left: Scanning electron microscope image of a test specimen. Right: Photograph of gauge sections of 50-mm-wide hole and notch specimens.

The photograph on the left shows the microtensile specimen geometry used for the tests. Specimens were 3.5 µm thick with gross widths of either 20 or 50 µm. Fracture loads were measured for three shapes: a specimen with straight sides and a uniform cross section, a specimen with a central hole, and a specimen with symmetric double notches (see the photograph on the right). A total of 226 measurements were made to generate statistically significant information, with about 30 specimens fractured for each test geometry.

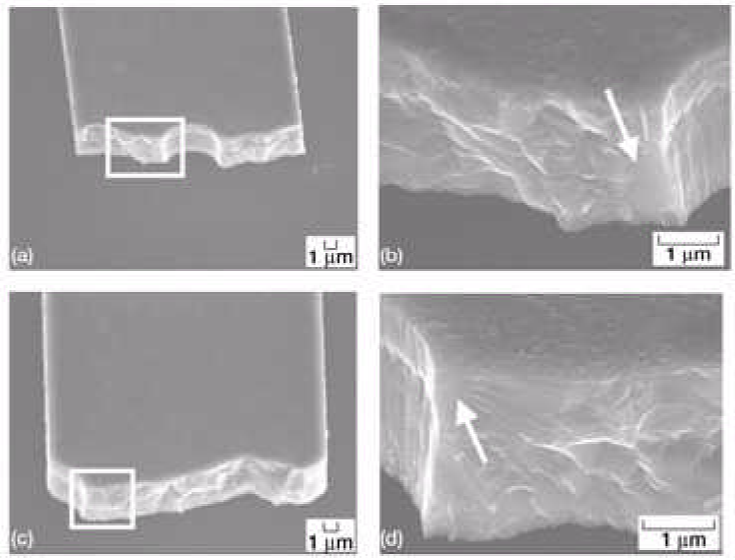


Measured local fracture strengths ±1 standard deviation.

This graph shows the results of the experiments. Average strengths are shown along with the scatter bands for a standard deviation of ±1. The strengths shown correspond to the peak average stresses found in the specimens. For example, for the notched specimen, the peak stress occurs at the notch root. The graph also shows that the fracture stresses for the holed and notched specimens are significantly higher than those for the straight-sided, uniform cross-section specimens. For bulk brittle materials, such as advanced ceramics, this difference in strength is termed the "size-effect." Size effect means that when the volume of material under high stress increases there is a higher likelihood of a weaker flaw being present. Hence, a component with a stress concentration would be expected to have a higher average strength than a component without a stress concentration because the amount of material under high stress is smaller with the specimen with the stress concentration. Although size effect is well known in bulk ceramics, its existence in MEMS is an active area of investigation. One can predict size effect by combining the Weibull distribution with integrating the stress state over the volume (or area) of the component. Showing the existence of size effect in MEMS and that it can be predicted using the Weibull distribution would establish the foundation for a MEMS structures probabilistic design methodology.

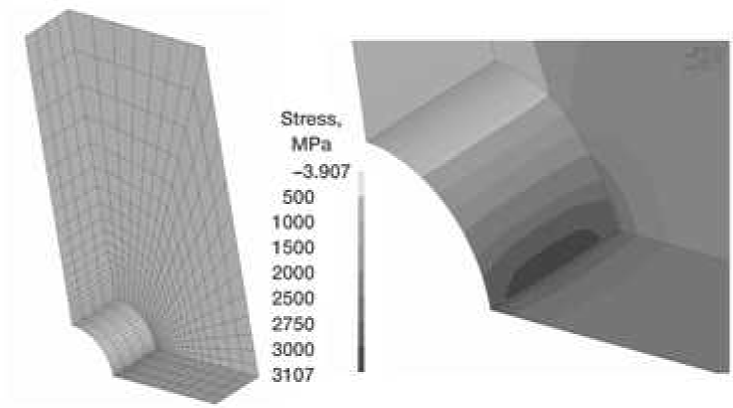
The fracture strengths of MEMS devices are known to be affected by surface defects and the resultant surface roughness from the manufacturing process. Such variability can directly affect the failure modes and, in turn, the reliability of the device. The following photomicrographs show the source of the defects responsible for the strength response. Typically, these flaws were located at or near the region of highest stress along the sidewalls of the specimen. Photographs (b) and (d) also show the considerable roughness of the sidewall in comparison to the upper and lower surfaces of the specimen.

Consequently, one would expect the strength response of the specimens to be controlled by the area and distribution of stresses along the sidewalls.

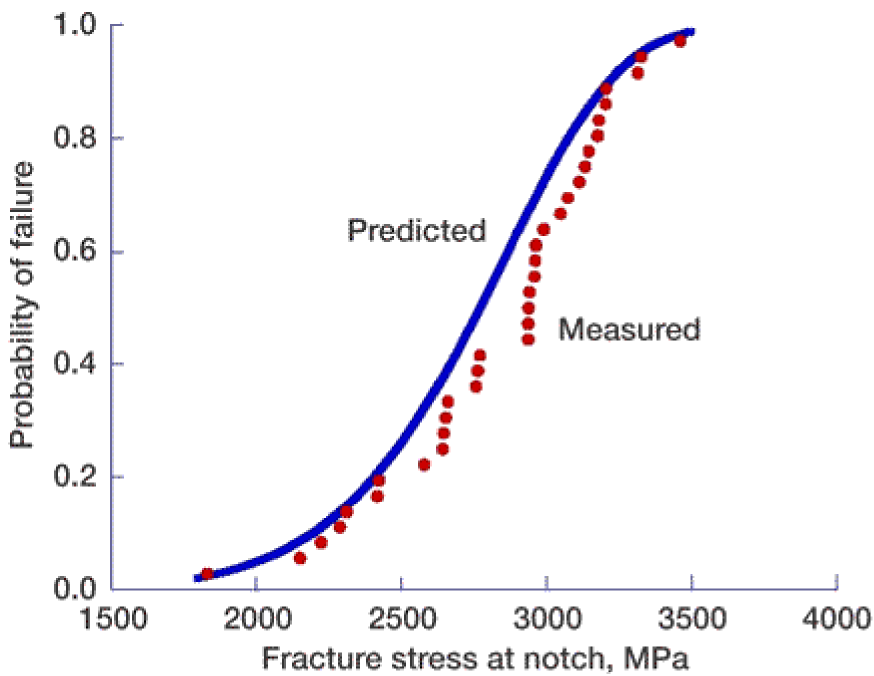


Overview of the fracture surfaces of a hole specimen (a) and a notch specimen (c). Both are 20 μm wide. Magnified views of the area within the white rectangles in (a) and (c) are shown on the right in (b) and (d), respectively. The white arrows point to the border between the mirror region and the mist-and-hackle region.

NASA's CARES/*Life* program was used to test if the baseline material properties from uniaxial (uniform cross section) tensile tests could predict the overall reliability response of the more complicated structures with the stress concentrators. CARES/*Life* requires results from finite element analysis in order to make component reliability predictions. The next figures show the finite element mesh and stress analysis results for the notched specimen. Reliability analysis was performed as a function of (1) specimen volume, (2) specimen surface area, and (3) specimen sidewall surface area. The final graph shows the CARES/*Life* predictions for failure probability versus stress at the notch root for the 20-μm-wide specimen. These results were within 3 percent of the experimental values when the analysis was based on the sidewall area. When the reliability analyses were performed as a function of the total surface area and volume, results differed by 21 and 51 percent, respectively. Similar trends were observed with the other notched and holed specimen geometries. These results, coupled with the fractographic observations of the origin of strength-controlling flaws, added confidence to the correctness of basing the reliability analysis on the sidewall surface area.



Left: Finite element mesh of a sample with an edge notch (quarter model). Specimen width, 20 mm; specimen thickness, 3.5 mm; notch radius, 2.5 mm. Right: Stress distribution at the root of the notch for a gross stress of 1000 MPa.



CARES/Life prediction of the sidewall failure probability versus the stress at the notch for the 20-mm-wide specimen.

Overall, Weibull statistics-on which CARES/*Life* is based-were quite successful in predicting the failure probability of MEMS components with stress concentrators. One can take baseline material properties from uniaxial tensile tests and use them in conjunction with finite element analysis to predict the overall strength of complicated components. This is commensurate with traditional mechanical design, but with the addition of Weibull statistics. This work is a confirmatory step toward the establishment of a comprehensive MEMS probabilistic design methodology.

Find out more about the research of Glenn's Life Prediction Branch

http://www.grc.nasa.gov/WWW/LPB/cares/.

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