Award Title: Fracture of Adhesive Bonds under Mixed Mode Loading: Experiments in a Dual Actuator Load Frame and Numerical Simulations

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Many of us have experienced the frustration of attempting to tear a perforated sheet of paper, only to find that the tear does not propagate along the row weakened by flaws. The path taken by a growing crack involves a complex interaction between two important aspects, namely, the spatially varying stress field induced by the applied loading and influenced by stress concentration regions, and the spatially (and sometimes directionally) dependent resistance of the material to fracture. At the intersection of these two aspects is the resulting path of failure and important metrics about the material strength in service. Although principles governing how failure occurs in single materials have been well established, much less is known about interactions and outcomes in bonded systems such as adhesive joints.

Technical Problems Addressed and Their Intellectual Merit

Because of the increasing importance of adhesives in the fabrication of so many products – from shoes to phones, cars to airplanes, and even building materials to civil construction projects - this research program was undertaken to advance our understanding of bonded joint failure. Specifically, this research effort has addressed how a flaw within adhesive layer may interact with weakened zones or defects at interfaces between the adhesive and the substrates that it bonds. The approach is conceptually illustrated in **Error! Reference source not found.**, where numerically simulated results for the stress state in a common fracture test method for characterizing adhesive joints (the double cantilever beam specimen) are depicted at the top, the spatially varying resistance to failure is shown at the bottom, and the resulting prediction for the crack path is exhibited in the middle. An improved understanding of this behavior will be important for the design and fabrication of bonded joints, and for estimating the strength, working life, and durability of adhesively bonded components in automotive, aerospace, microelectronic, and many other industries.

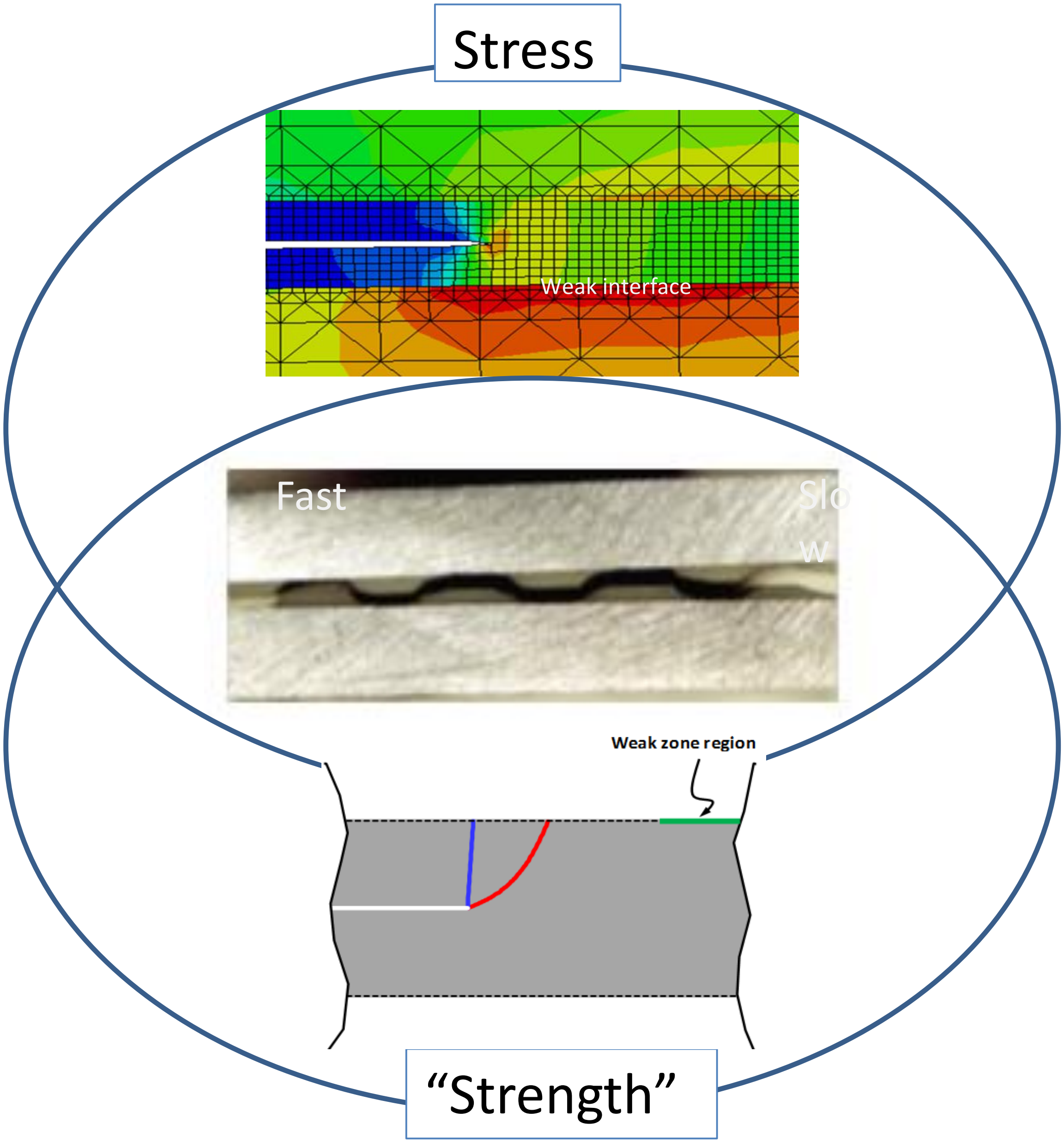


Figure 1. Numerical and experimental results

Although we do not often think of inanimate objects “communicating” with each other, the project essentially focuses on “communication” between the high stress states surrounding a crack tip and weakened regions that might be present at an interface between the adhesive and substrate. It attempts to address the following questions. Under what conditions does a crack-like flaw “sense” the presence of weak regions at adjacent interfaces, potentially leading to catastrophic failure? Are there critical sizes of weak regions, below which they have no effect on growing cracks, thereby reducing likelihood of failure? How weak does a local interface zone need to be for it to be “detected”, enabling rapid advance of a crack? Does the manner of loading affect whether weak regions will influence the growing crack potentially allowing cracks to be steered away from weak regions, maintaining higher fracture resistance and avoiding unwanted failure? Flaws are present in every structure, so an understanding of how these flaws propagate and how resistant the material is to failure is of critical importance in a wide range of engineering applications. Progress made in this research effort is providing insights and answers to these questions.

Research accomplishments have occurred in both numerical modeling and experimental developments and characterization. Experimentally, localized regions of an interface have been weakened by applying less than optimal chemical surface treatments or by contaminating small regions with graphite particles. One significant outcome has been that small changes in contact angles (a means to measure surface energy) induced by different silane treatments can noticeably affect whether cracks are steered towards the weakened interface or remain within the adhesive layer. A second significant result is that narrow bands of graphite contamination were “detected” by rapidly growing cracks but “ignored” by slowly growing cracks, suggesting significant time dependence to the interactions. This result is shown in **Error! Reference source not found.**.

An efficient computational method, the meshless method, was developed for analyzing crack propagation in two adhesively-bonded beams subject to simple or more complex loads. The meshless method dramatically simplifies crack propagation analysis. It is easy to build a model of complicated structures since only locations of nodes are needed as shown in **Error! Reference source not found.** comparing a traditional computational method (FEM, finite element method) with the meshless method.

Broader Impacts

This project and the Research Experiences for Undergraduates (REU) supplements have supported the education and professional development of four doctoral and eight undergraduate students from the U. S. and three other countries, and have included persons from underrepresented groups such as Hispanics and women. These students presented their research findings both in writing and orally in weekly group meetings as well as professional society conferences.

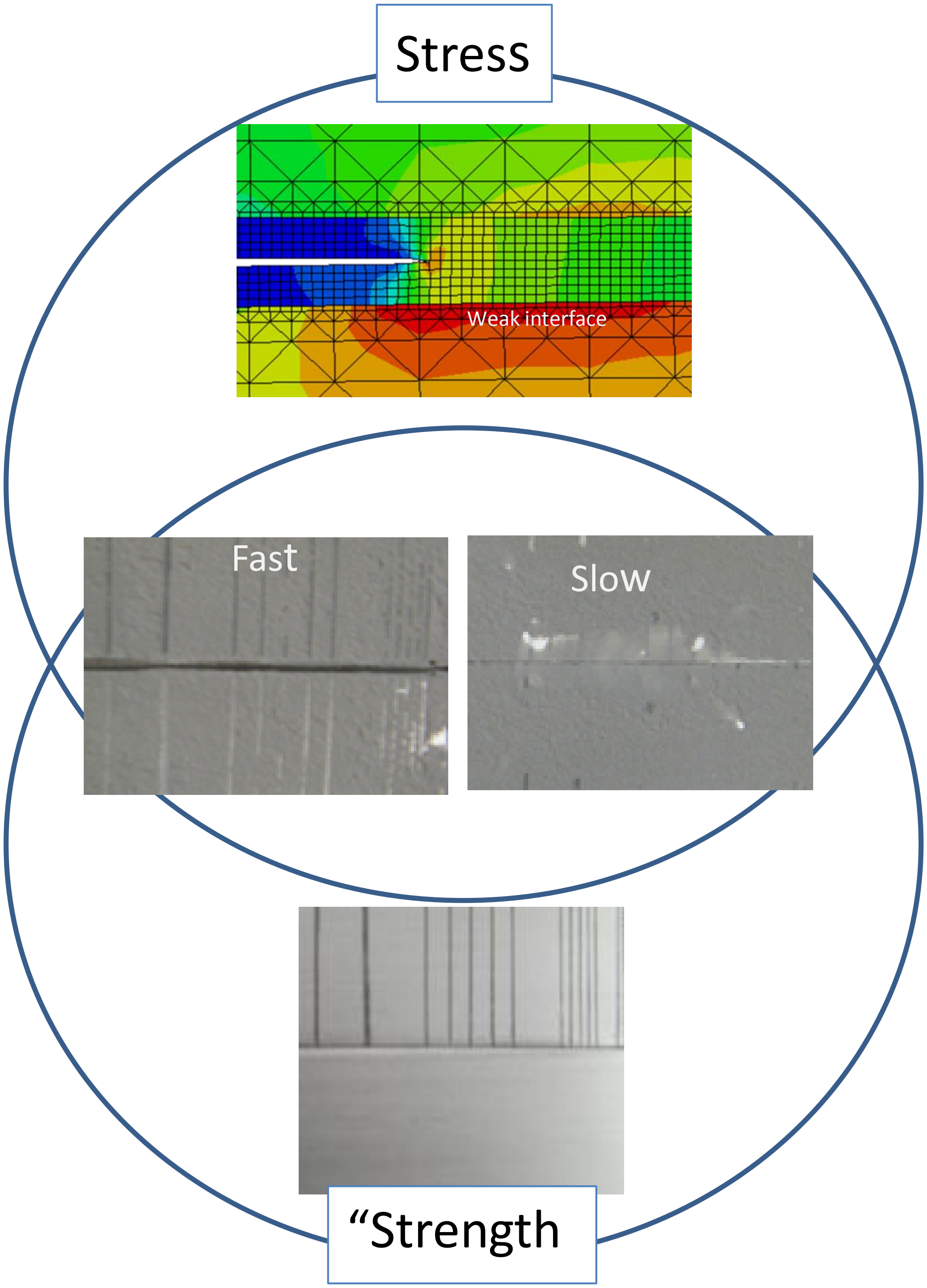
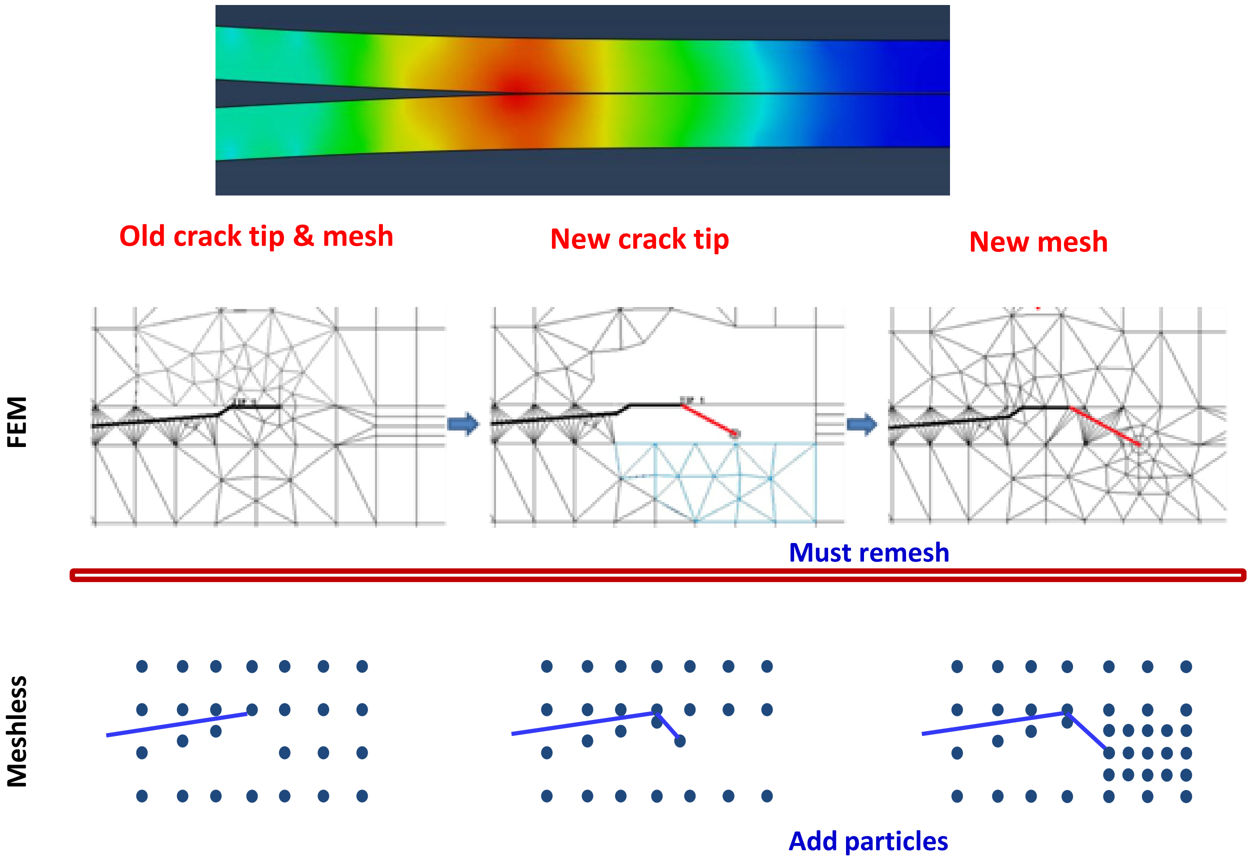


Figure 2. Rapidly growing cracks were more likely to "detect" and follow weakened zones on the adherend.



	Meshless	FEM
Assembly of equations	*Not required*	*Needed*
Add particles/elements	*Easy*	*Difficult*
Information of nodes	*Location*	*Location and connectivity*
Stresses/strains	*Smooth everywhere*	*Good at integration points*
Compute strain energy	*Difficult*	*Easy*

Figure 3. Differences between meshless method and traditional FEM method.