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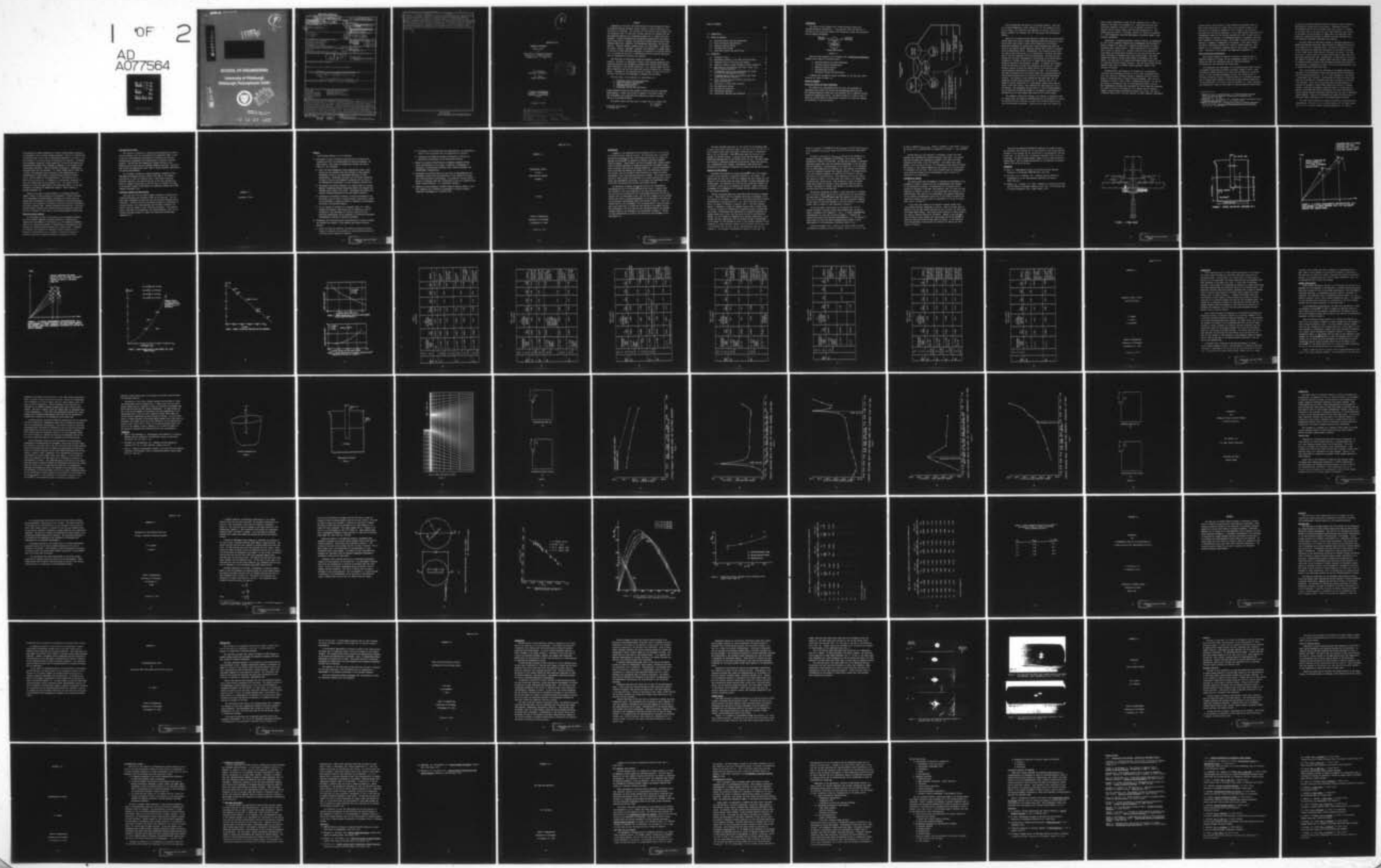

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research program is intended to explore and develop commonalities in fracture theory as applied to wide classes of differing materials at different scales - from the atomic to the continuum. Primary attention is focused upon analytical and experimental methods needed to analyze underlying and potentially common basic mechanisms controlling the fracture process, e.g. two and three dimensional stress singularities, effect of environment, etc. and to examine structure-property relationships, including the effect of the fabrication process upon the preparation of specimens made from standardized model materials representative of polymers

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) and metals. Secondary emphasis is focused upon numerical analysis methods needed at various scale levels, atomic to continuum, and instrumentation capability peculiarly suited to or needed for fracture studies. In later stages of the program, increasing attention will be devoted to technology transfer and engineering applications of the basic research. Major results during the first year include (1) the development of a test for measuring Mode II fracture toughenss, and(2) quantifying the effect of geometry in an embedded fiber or rod and the location of initial interfacial debonding from the matrix upon resulting adhesive fracture under load.

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SETEC-SF-79-51

SCIENCE OF FRACTURE

Annual Report
to
USAF Office of Scientific Research
Contract No. F 49620-78-C-0101
15 August 1978 - 14 August 1979

M.L. Williams
Principal Investigator

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Program Coordinator

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October 12, 1979

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PREFACE

Beginning in late 1978, the United States Air Force through the Office of Aerospace Research initiated a major science of fracture project at the University of Pittsburgh. The rationale for this special effort emerged from the recognition that, in some form, fracture analysis was becoming more and more generally employed as an engineering design tool to assess structural integrity. Fracture technology was increasingly sophisticated and complex. With the many static, fatigue, and spallation problems being attacked using different analytical, numerical, and experimental approaches, and the many theories - Griffith, Wiebull, maximum strain, and hydrodynamic - appropriate for metals, plastics, elastomers, ceramics, and composites, it seemed timely to inquire; is there sufficient experience to generalize the state-of-the-art, i.e., to provide the basis for a comprehensive fracture analysis discipline which is fundamentally consistent and complete?

The University of Pittsburgh program was designed to answer this question. The effort is organized in terms of five program categories each containing difficult but fundamental problems whose solution would significantly contribute to the desired unification. In a research sense, the program is high-risk, and for this reason was initially proposed for a five-year period. Consequently, the potential pay-off is great, not only for the U.S. Air Force, but also for the Department of Defense and the Nation.

The five areas, to be construed in a broad sense, are

1. Analytical efforts and basic mechanism
2. Structure-property relationships
3. Numerical analysis methods
4. Instrumentation science
5. Technology transfer and applications

Primary emphasis during the early phases is upon the first two categories. Simultaneously, a lower level effort is devoted to the latter three, so that development can be monitored and preparation be made to increase effort as the program develops.

This report covers the first year, 15 August 1978 to 14 August 1979.

M.L. Williams
C.C. Yates

Pittsburgh, Pennsylvania
14 October 1979

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3.0 APPENDICES

INTRODUCTION

The thrust of this program is not toward materials science nor continuum mechanics individually. It is directed toward the analysis of fracture and the structural integrity as influenced by these two disciplines and the loading environment.

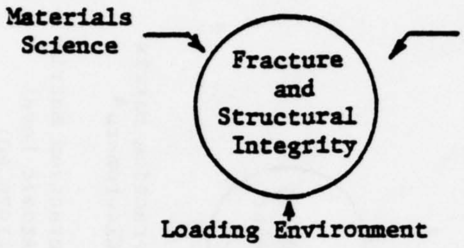

Figure 1.1

There are five components of the program plus a Data Base and Repository category which supports the entire project.

1. Analytical Efforts and Basic Mechanisms
2. Structure-Property Relationships
3. Numerical Analysis Methods
4. Instrumentation Science
5. Technology Transfer and Applications

A summary work statement is given in Appendix 3.1 and the major interrelations are shown in Figure 1.2.

STATUS OF RESEARCH

Analytical Efforts and Basic Mechanisms

The keystone for understanding fracture rests upon knowledge of mechanisms which control the process and accompanying analytical work. This approach generally proves more cost-effective than an unguided testing program and engineering history. The method chosen is to study a class of idealized problems which are analytically tractable yet reveal key elements and mechanisms of fracture behavior.

SCIENCE OF FRACTURE
PROGRAM

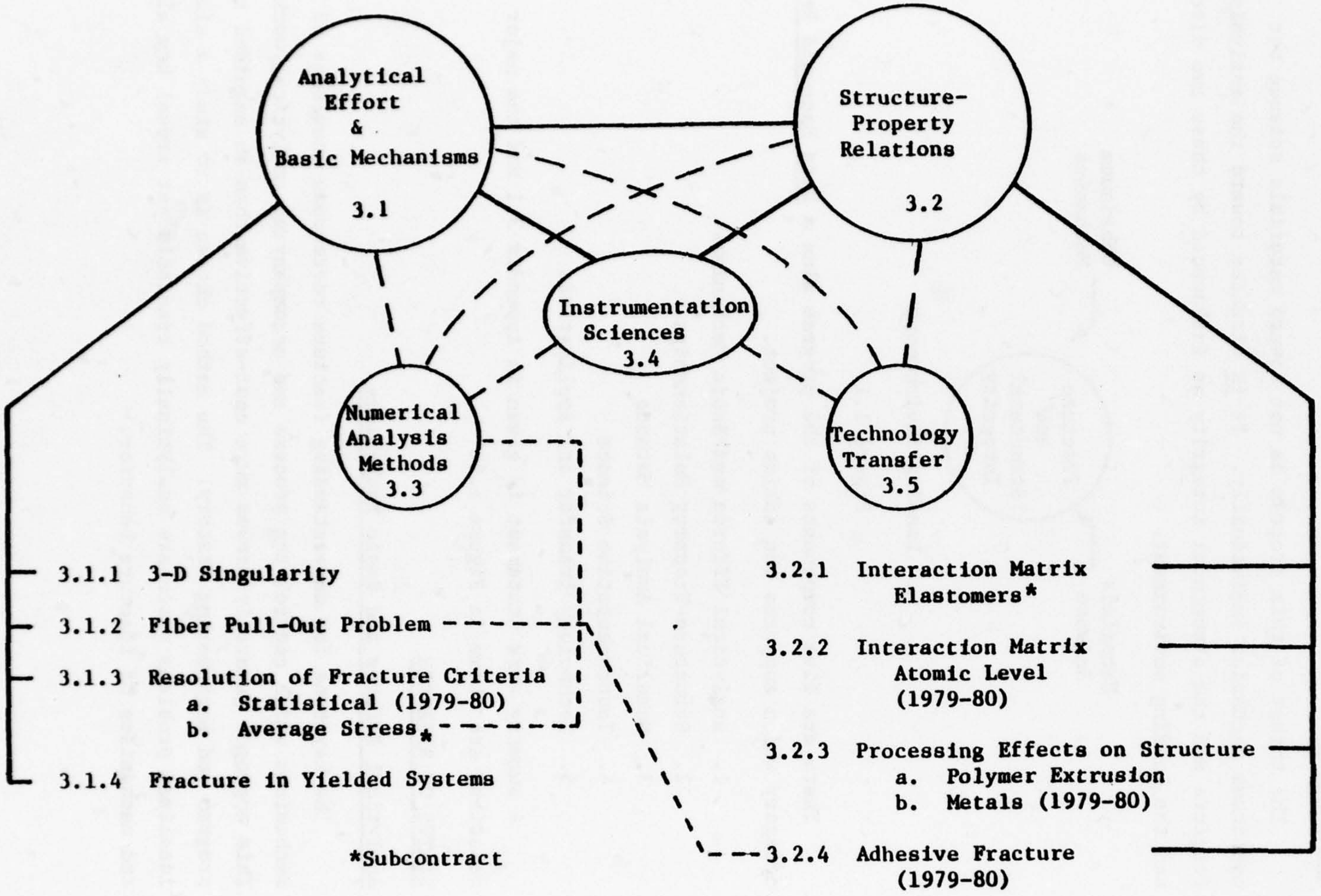

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Figure 1.2.

Four illustrations were given in the original proposal. They were (i) the three-dimensional stress singularity, (ii) the elemental "tooth-pick" problem, (iii) resolution and comparison of fracture criterion for metals, polymers, and ceramics, and (iv) crack growth and environmental effects.

Nearly all of modern fracture analysis is based upon the characteristic inverse square root elastic stress singularity which was deduced for plane stress (thin plate stock) or plane strain (infinitely thick plates). Practically speaking, all plates have a finite thickness and when they fracture they usually exhibit important features which cannot be predicted using two-dimensional theory. Consequently, with success obtained using the simple plane stress result, it is appropriate to encourage continuing work on the still unsolved 3-D stress distribution. Our group has been working with the major investigator of this problem in the United States, Professor E.S. Folias, as well as Dr. T. Kawai from the Institute of Industrial Science of the University of Tokyo. It appears that Professor Folias has been able to reduce this problem to the solution of a single integral equation in which the unknown function is the surface crack opening geometry—approximately elliptical in shape. The formulation now seems satisfactory but the solution hinges upon overcoming numerical difficulties associated with the solution for the opening displacement function. The solution of this problem may shed some light upon the singularity problem being attacked by Dr. C. Atkinson, that of the change in elastic singularity at a right-angled, bonded corner when and after a crack first occurs, thus converting the right angle into one of 180 degrees. The fundamental obstacle here is a lack of understanding of how to construct the limiting process of the change in strain energy of deformation as the crack length jumps from zero to a finite length.

The elemental "tooth-pick" problem, (ii) pertains to cylindrical rods of various shape, and degree of debonding when they are embedded in a matrix. The problem has direct relevance to glass fiber reinforced plastics and other multi-material composites. During the past year, this subject has been our major experimental thrust and was conducted by Dr. E. Betz. A summary of the report is in Appendix 3.2. Supporting analytical work, along with parametric variations of the rod geometry in terms of the adhesive fracture energy release rate have been assembled by Dr. John Fleming and his students. Preliminary results are collected in Appendix 3.3. The Fleming-Betz analytical-experimental correlation seems to show internal consistency.

Preparatory to comparing different fracture criteria, as contemplated in (iii) we have completed administrative arrangements with Professor E. Becker, University of Texas, for a numerical stress analysis of highly deformable media (rubber sheets). A brief description of the proposed work is given in Appendix 3.4. Suitable codes have been completed to treat Mooney and Mooney-Rivlin materials for both plain strain and plane stress stretching of specimens with finite length cracks. The codes compute the change of (large) strain energy of deformation with crack length. The next step is to compute the cohesive energy transfer for use in a modified Griffith fracture criterion. Very few large strain fracture analyses, other than for uniaxial tensile specimens, appear in the technical literature.

Serendipitously, what began as an alternate way to investigate controlled crack propagation turned out to be a most interesting result which also resolves a different problem of immediate practical value—a method for measuring Mode II (shear) fracture toughness. Most fracture toughness is quoted in terms of Mode I (symmetrical-opening). No one has yet devised a satisfactory test for (antisymmetrical-shear) fracture. Most experimental specimens have some small but finite mixed mode component. Our results to date, as developed by Dr. R. Smelser and his students, suggest a direct method for deducing the Mode II K_{Ic} value. The test is a modified "Brazil test" (circular cylinder rod under diametral compression) as first used to test concrete.* Later Libatskii and Kovchik** used its plane stress analog and put a small crack in the specimen aligned in the direction of the diametral compressive load (0 degrees), and calculated and tested for the fracture threshhold. We and some Japanese investigators,*** independently tested for the fracture threshhold but with the small crack at various angles to the load. At intermediate angles it is apparent that both Mode I and Mode II conditions exist. As the Mode I distribution passes from tension at 0 degrees to compression at 90 degrees, it must pass through a zero Mode I contribution leaving only a Mode II (shear) condition. This happens at 20 to 30 degrees, depending upon the crack length to diameter ratio. The details of the analysis are summarized in Appendix 3.5

Structure-Property Relationships

The relation between the chemical structure of a material and its mechanical behavior is perhaps the most fundamental problem of all. It affects not only the constitutive law, but controls processing characteristics, and prescribes the failure mode.

We contemplated the development of an Interaction Matrix which relates to parameters describing the material structure, (Burger's vector, cross-link density, Weibull modulus, etc.) with those describing its properties. So far, we have concluded arrangements with Dr. F.N. Kelley and Dr. P. Dreyfuss, University of Akron, to begin synthesis of a "standard elastomer" and a "standard epoxy" having a controlled and known chemical composition. A brief description of the work is given in Appendix 3.6. After consistency and repeatability checks we shall begin the physico-mechanical measurements.

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*Carniero, F.L.L.B., and Barcellos, A., "Concrete Tensile Strength" Union of Testing and Research Laboratories for Materials and Structures, No. 13, 1953.

**Libatskii, L.L., and Kovchik, S.E., "Fracture of Discs Containing Cracks", Soviet Materials Science, Vol. 3, pp. 334-339, 1967.

***Awaji, H., and Sato, S., "Combined Mode Fracture Toughness Measurement by the Disk Test", Journal of Engineering Materials and Technology, Vol. 100, pp. 175-182, 1978.

We intend to synthesize materials which are chemically clean systems as environmentally insensitive as practicable. (Subsequent doping for environmental effects will be valuable under Task 1, Part 4.) Because of the high stress at the crack tip (and large deformation which should be calculable via the University of Texas work), the conditions there should be a sensitive indicator of chemical structure influences upon the mechanical properties, especially near fracture.

The epoxy resin has been chosen because of increased importance of bonded and composite structures, which can fail by adhesive fracture such as we observe in our "tooth-pick test". The epoxy, in addition to the usual strain-rate and temperature dependence, is non-linear in behavior so that normal linear stress analysis techniques are suspect. The same point can of course be made for the more ductile metals, which also have non-linear stress-strain laws. Nevertheless, it seems that for the epoxy, and plastics in general, the working stress level may be higher relative to ultimate stress in plastics than the metals and hence non-linearity is more important. Consequently we expect to begin some consideration of how to handle non-linear constitutive laws.

One of the important factors affecting our "standard" materials is the effect of the fabrication process and precursor material variability upon the resulting properties. Dr. J.T. Lindt (Appendix 3.7) has begun to investigate "melt fracture". Historically this term was adopted some time ago to describe the "cracking" sound made by polymers at the mouth of an extruder. Since then, the term has been used more generally to describe the formation of macro-flaws during the extrusion or forming process. Aside from providing an important assist in calibrating the quality of elastomer and plastic fabrication, the Lindt study should be able to explain unstable processing conditions which can lead to unintended product defects. While our rod diameters are larger than those used in fiber and textile technology, there is phenomenological similarity.

Two other topics complete our present activities in structure-property relationships. The first, by Dr. H. Kuhn (Appendix 3.8) is related somewhat to Dr. J.T. Lindt's polymer processing experiment. Dr. Kuhn is investigating the strain threshhold at fracture during forming, especially in compression, such as during forging operations. While it is coupled with a processing step, he will also be making micro-analyses of the metal to see what features of its structure may be initiating the fractures. At present the preliminary conclusion, rather simplified, is that any microstructural discontinuities promote early cracking as compared to the stronger of the two materials separately. While intuitively acceptable, a quantitative characterization will be important. If a small enough scale is viable for a control, the analytical work on relative stress singularities and concentrations at metal-crystal interfaces being conducted in Task I, Part 1, could be useful in the interpretation. The second by Dr. R. Porter with the help of Dr. J. Blachere is a quantitative evaluation of metal and ceramic powder stocks (Appendix 3.9). The quality of base powders as to size and shape affects the presintered density, or at least the amount of pressure and temperature required. Their proposal is appended (Appendix 3.9).

Finally as an area of future potential, we initiated during the summer a series of talks internally with Professor G. Jeffrey, Chairman of the Department of Crystallography, regarding the current status of making direct experimental or analytical deductions of physico-mechanical properties, such as modulus of elasticity, directly from lattice parameters and atomic potential laws. Similar discussions were held with a few other national experts, because this problem area--while numerically obstructed now--is in principle a direct part of the structure-property problem area.

Numerical Analysis Methods

At the present our work in this area is one of becoming acquainted with the technical community in various fields and of supporting as required the other members of the project, e.g., the numerical parametric study of the "tooth-pick problem" or coordinating our knowledge with the University of Texas specialized capability in finite strain. Internally, we coordinate with Professor W. Rheinboldt, Mellon Professor at the University of Pittsburgh, who is an expert in theoretical aspects of numerical computation, keeping him generally informed of our work.

Instrumentation Science

This subject is construed to include how instrumentation is used in fracture analysis, such as in non-destructive examination (NDE), as well as what new instrumentation requirements are projected and what new instrumentation techniques can be appropriated or applied to fracture analysis. The NDE work most immediately relevant has been at the Rockwell Science Center and the Southwest Research Institute. Both have been visited and appropriate action taken to obtain technical publications and meeting announcements.

Dr. M. Simaan, an expert in signal processing, attended the last ARPA/AFML NDE Symposium and made contacts with some of the Rockwell participants to study the technical level of NDE signal processing knowledge compared to the state-of-the-are in this fast growing area. While Dr. Simaan's conclusions are not yet final, it appears that there is an excellent target of opportunity for technology transfer to the NDE community (Appendix 3.10).

Technology Transfer and Applications

This task has so far not been formally activated, although all the program participants are continually aware of the objective. For the time being, attainments in this area rely upon informal observations and deductions. Insofar as effective technology transfer is accomplished by personal contact, the various meetings and briefings attended by the project staff have added to their collective knowledge. A few specific topics, collected in the Appendices, have been addressed as part of our internal Data Bank activity to support our analytical and NDE tasks (Appendix 3.11).

APPENDIX 3.1

Statement of Work

Research

The following research is to be conducted:

a) Investigate a class of idealized problems which are analytically tractable but key to the understanding of fracture mechanisms and their control. This class of problems will include, but not be limited to, the following:

   1) Study the three dimensional stress singularities along a crack surface and its interface with free surfaces or other material interfaces, as well as the engineering importance of these singularities. Investigate the nature of this stress singularity in terms of typical crack geometric parameters and the nature of the mathematical discontinuity as these parameters approach zero.

   2) Investigate the fracture behavior of an elastic fiber in a matrix material considering typical interfacial defects and uniaxial and combined stress states on the fiber. Investigate the adhesive and cohesive strength mechanisms of the fiber matrix interface.

   3) Investigate the extension of models of fracture mechanisms of the micro/macro scale in order to predict fatigue crack growth, including as appropriate, strain rate effects, temperature, environmental conditions, and nonlinear behavior.

   4) For the classes of problems to be addressed under "a" - metals, polymers and ceramics, individually and in combination, will be considered in the development of fracture criteria in which particular significance can be attributed to constitutive equations, thermodynamics, kinetics or material processing.

b) Investigate the structure-property characteristics of metals, polymers and ceramics with respect to both adhesive and cohesive fracture behavior.

   1) Review the existing literature and develop an interaction matrix between the chemical and crystalline or noncrystalline structure of a material and its mechanical properties.

2) Investigate, both theoretically and experimentally, the quantitative nature of this interaction and its significance to fracture.

3) Coordinate with AFOSR the planned investigation to develop the quantitative relationship of the interaction matrices.

c) Review the current state-of-the-art in numerical analysis methods which are applicable to the science of fracture, considering, in particular, the micro/macro modeling levels, kinetic phenomena, and thermodynamic considerations.

d) Investigate the state-of-the-art in the field of instrumentation and measurement science which has application to the science of fracture and structure/property relationships. In particular, include investigation of techniques which may be developed to study in a nondestructive manner internal material, i.e., nonsurface, behavior.

e) Develop an active program to transfer fracture reserach results to the user community and to maintain as assessment of critical fracture technology requirements on a national level.

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APPENDIX 3.2

Experimental Studies
of the
Fibre Pull-Out Problem
(Summary)

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October 12, 1979

INTRODUCTION

A summary of the experimental work performed by Betz (1) in the study of the fibre pull-out problem is given. The objectives were to establish the failure processes that take place during the pull-out of a glass rod imbedded in Solithane®, and measure the specific interfacial adhesive fracture energies. These results can then be compared with computer simulations on failure predictions of adhesive fracture from the energy release rates at various flaw sizes and specimen geometries. Previous experimental work by Williams and Anderson was thought not to be sufficiently accurate and reliable, and was considered useful primarily as a guide for future improvement, rather than supplying definitive answers. The state-of-the-art reached in their studies was considered to be a good starting point, and by using their experimental techniques, it was hoped that improvements would evolve that can produce more accurate and reliable results.

An innovation of making a movie film record of the isochromatics surrounding the rod in the Solithane® matrix was tried. A digital clock was included so that the photographs of the crack front position along the rod could be correlated with the displacements applied to the rod (for constant rate of displacement input), and the force response by the specimen. Efforts were made to overcome misalignment of the specimen in the load cage by introducing a self-aligning gimbal type platform, Figure 1. The 50 ml beakers used for the containment of the solithane matrix - glass rod specimens, were ground flat to provide an even seating on the gimbal platform. The positioning of the load cage was also constrained against any movement sideways caused by the overhang of the displacement transducer. Details of these modifications are given in the section on test equipment in the Betz Report (1).

The major problems found were (i) the control of an advancing crack, to give a crack front orientated normal to the axis of the rod, and (ii) to find a debond release agent which would reliably produce a satisfactory flaw at the rod interface. Frekote® release agent was tried for this purpose, but without success. A special cutter was developed which functioned satisfactorily at the surface end of the rod. The major effect was directed at improving reliability and accuracy, rather than carrying out a comprehensive test program. Nevertheless, some results were obtained and are presented in graphical and tabular form and may be useful.

ANALYSIS OF TEST RESULTS

Specimens were prepared by pouring Solithane® 113 into 50 ml beakers. A glass rod was inserted in a position concentric to the beaker. The quartz glass rod was 0.50 ± 0.005 cm in diameter and had a ground flat end squared to the rod axis which was flame polished to produce smoothness and rounded edges. The opposite end of the rod had a glass knob formed on it to provide a load stop in the aluminum load ferrule. Figure 2 shows the arrangement of the components of a specimen and also defines the notation of the leading dimensions.

Typical cross-plots taken from visicorder charts are given in Figures 3 and 4. These depict the force response versus the displacement of the rod relative to the beaker. A summary of test results are given in Table 1. An explanation of values given for u, γ_a, t and P (critical) listed in Table 1 is given by reference to Figures 3 and 4. The first diagram, Figure 3, represents a failure by adhesive fracture when a debond starts at the tip, and later is followed by the complete failure by debond from the surface. Difficulties were experienced in accurately measuring the energy release rate, $\partial U/\partial A$, over the tip of the rod for any flaw size. However, for the purposes of comparison with computer simulations, it was thought that good comparisons could be obtained through the measurement of the energy U in the specimen at point A, the critical condition for the formation of a small spherical bubble at the end surface of the rod, prior to crack growth over the whole end and some distance a_0 down the rod (Figure 2). This energy is represented in Figure 3 by area OAE. The value of $u_{critical}$ is represented by OE, $p_{critical}$ by AE and time $t_{critical}$ by the expression $u_{critical}/R$, where R here is the constant displacement rate.

In Table 1, the value of $(\gamma_a)_{critical}$ for end of rod debonds is an integrated average, incremented as the change in the elastic energy represented in Figure 3 by area OAF. The area AFB is thought to represent additional energy input from the continued displacement of the rod, modified by dissipation, occurring mainly at the crack tip. It is recognized that the above definition is inaccurate, but this quantity is convenient to use for comparison purposes with computer results. The energy release rate, $\partial U/\partial A$ changes throughout the debond and is related to critical conditions for a given flaw size. From observation of the test results, (as typified in Figure 3) the next event that occurs is the debond from the surface end, along the rod. This follows as a result of further energy input beyond B in Figure 3, which apparently does not induce critical conditions for further crack growth at a_o before failure by fracture occurs from the surface end.

The process represented in Figure 3, could take place in a similar way if a flaw is present at the tip or surface end of the rod interface. The application of Frekote® release agent was supposed to create such a flaw, but the adhesive strength was too high and the behavior resembled in most cases (as seen from reference to the test results) a two phase debond, which is similar to that described in Figure 3.

In the case where a flaw exists at the surface end, the rod becomes vunerable to failure at much lower energy levels, as seen in Table 1, specimens 25-27 compared to 1 and 3. A typical diagrammatical representation for this case is shown in Figure 4. A smaller δa_1 theoretically gives a more accurate approximation to γ_a. In practice it almost works the other way where averaging often provides a closer approximation to the hypothetical theoretical value for γ_a.

Rather than measure $\partial U/\partial A$ directly, the elastic lines to points representing increasing a_1/b shown in Figure 4 as A, B, C, D, etc., may be used to measure $U|_{A,B,C,D,etc.}$ versus u (constant, at any value $\leq u_{critical}$). The results for the various tests are summarized in Figure 5. (See reference 3).

Another method is also available to determine U versus a_1/b from separate test specimens with various initiation flaw sizes. The results from this procedure are illustrated in Figure 6 (for tests with flaws produced by the cutter at the free surface). This method could apply equally to the tip end of the rod, if a satisfactory flaw could be inserted. The accuracy of this method depends upon the location of a critical point of instability for the flaw. This can be obtained from the displacement - force curves and checked from the photographic record to detect the initiation of the flaw growth.

DISCUSSION OF RESULTS

The results given were instrumental in guiding the development of the equipment to render it suitable for use in comprehensive test program on the fibre-pullout problem. An appreciation of the results can be obtained by reference to Williams' and Anderson's work (2), which has been reproduced in Figures 7A and 7B. It was established from reference to the energy release rates that for both experimental and computer simulations, the tip debond is approximately twice that of the surface end debond (see comparisons between critical values for specimens 25 to 28 and for specimens 1 and 3, in Table 1).

It was shown that changes in the balance of energy release rates could promote different mechanisms of failure. When the release agent is applied to the tip end, debond took place at the tip first, but only along the release agent surface. Any further growth resulted in radial growth of the crack by cohesive fracture of the matrix. Because of the high bond that was shown to exist between the release agent and the Solithane®, (no debond was observed between release agent and glass), it was considered that the mechanisms of failure were in principle the same as the cases defined in Figure 3.

This work has improved experimental techniques for greater accuracy and reliability when carrying out the fibre-pullout tests through improved alignment of the specimen and the introduction of photographical recording of the test. As the next step, an extensive program of tests can now be undertaken. One major problem remains, namely to find a more satisfactory release agent. This is needed particularly for the insertion of suitable flaws at the tip end of the rod.

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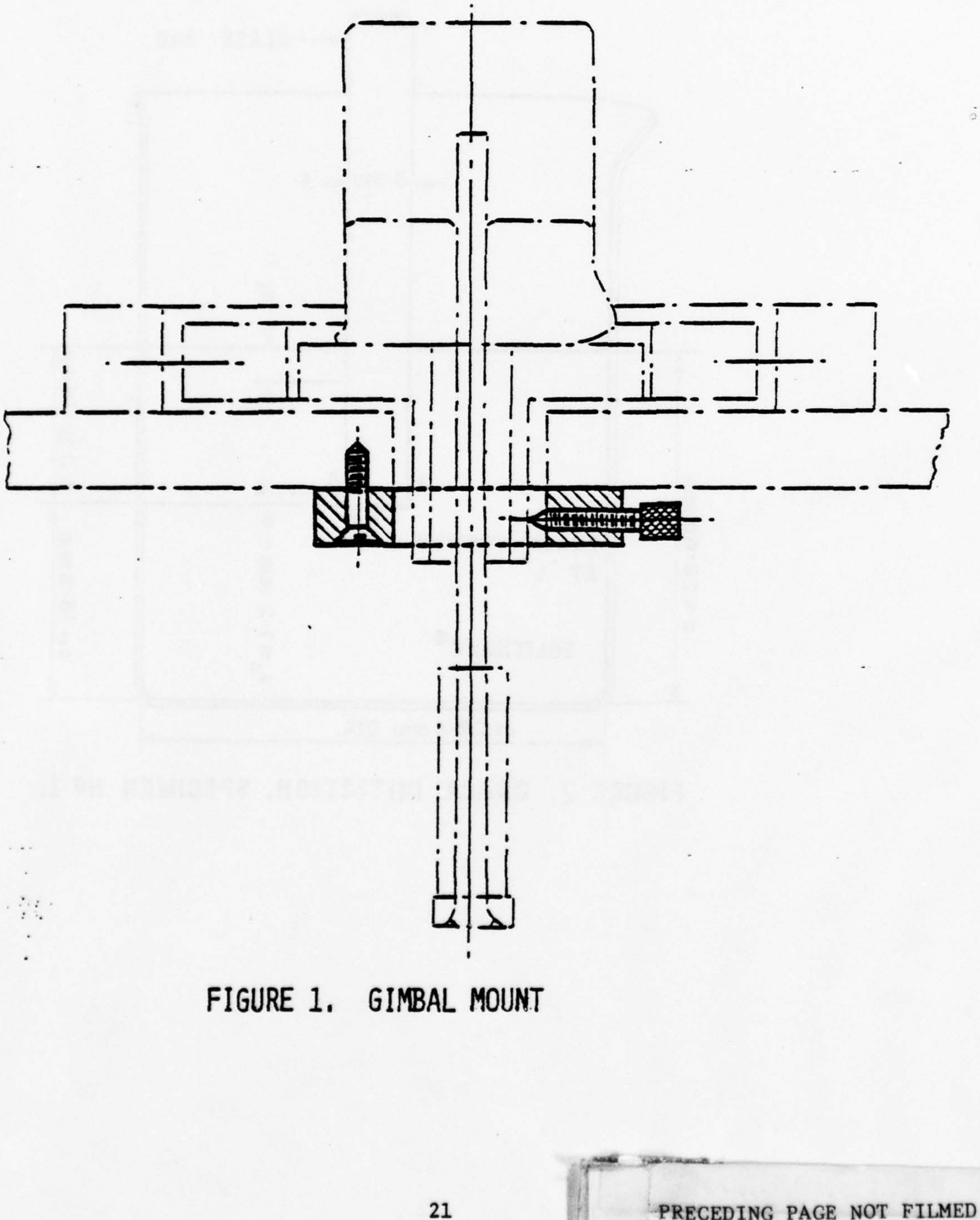

FIGURE 1. GIMBAL MOUNT

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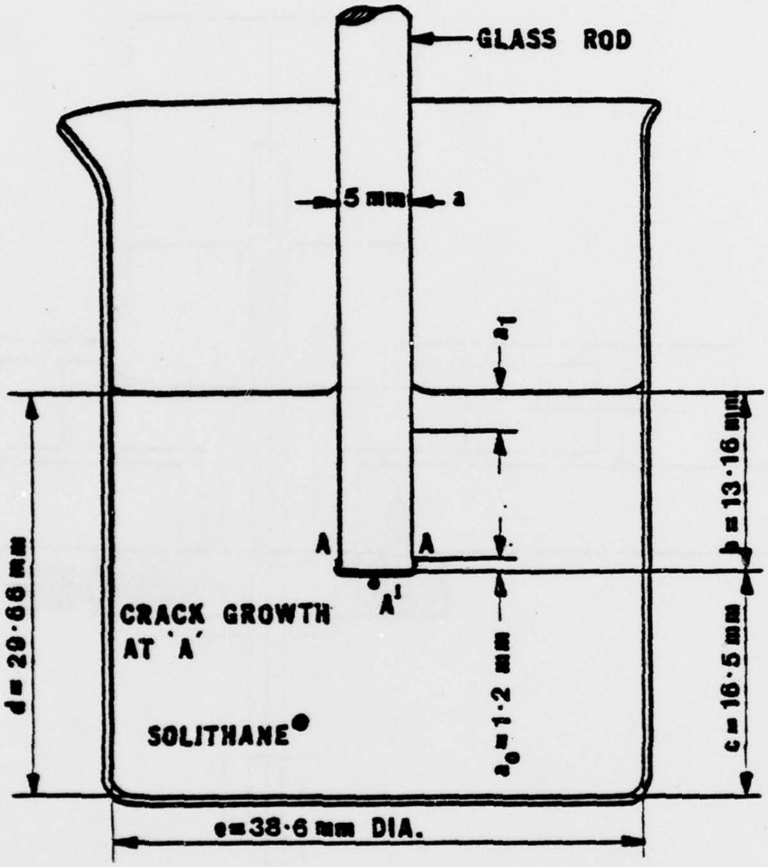
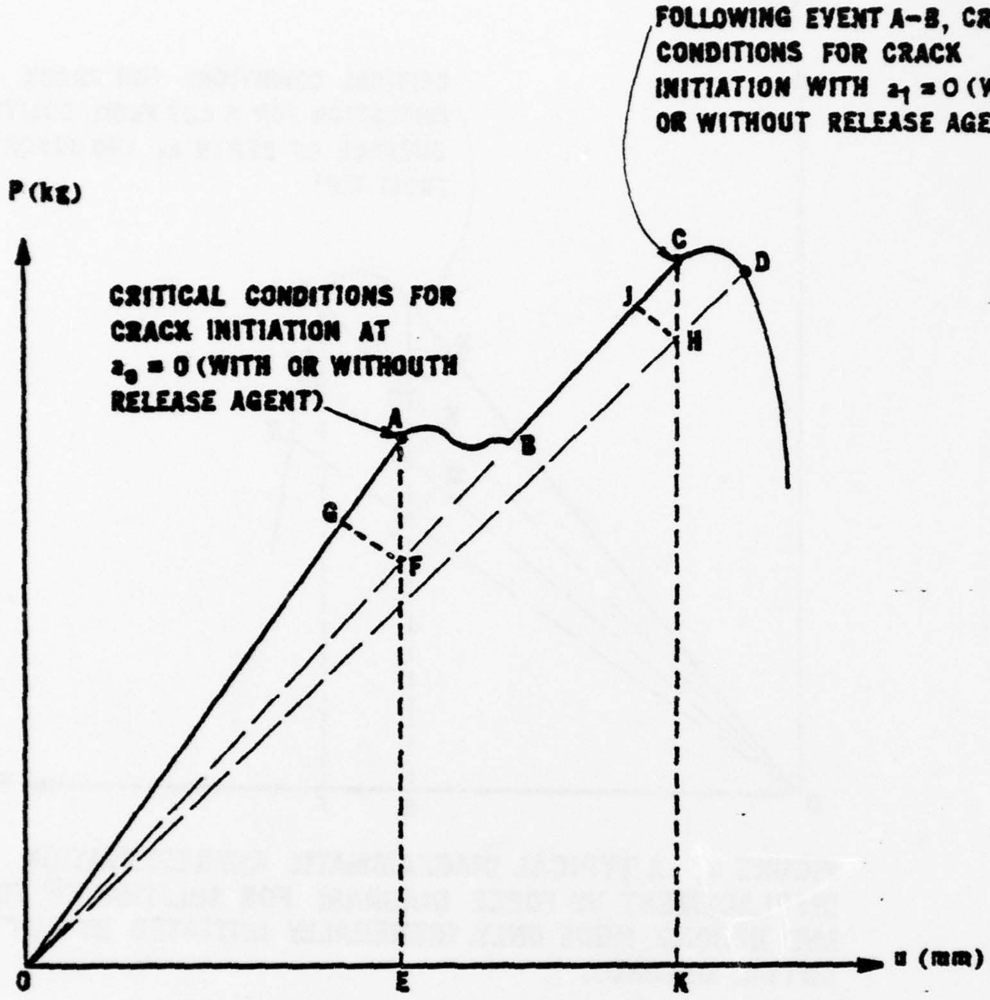


FIGURE 2. CRACK INITIATION, SPECIMEN Nº 1.


FOLLOWING EVENT A–B, CRITICAL CONDITIONS FOR CRACK INITIATION WITH $a_1 = 0$ (WITH OR WITHOUT RELEASE AGENT)

CRITICAL CONDITIONS FOR CRACK INITIATION AT $a_0 = 0$ (WITH OR WITHOUTH RELEASE AGENT)

FIGURE 3. A TYPICAL DIAGRAMMATIC REPRESENTATION OF A DISPLACEMENT VS FORCE DIAGRAM FOR A TIP, SOLITHANE® SURFACE END DEBOND MODE.

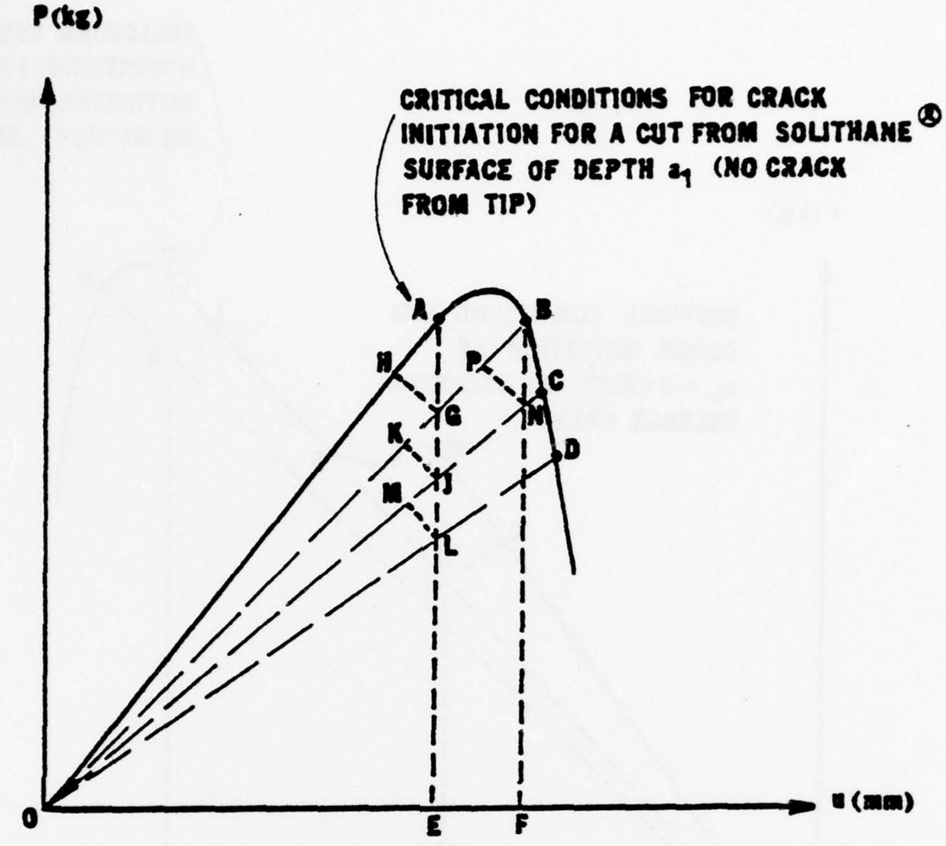


FIGURE 4. A TYPICAL DIAGRAMMATIC REPRESENTATION OF A DISPLACEMENT VS FORCE DIAGRAM FOR SOLITHANE® SURFACE END DEBOND MODE ONLY. (GENERALLY INITIATED BY CUTTING-IN INITIAL DEBOND).

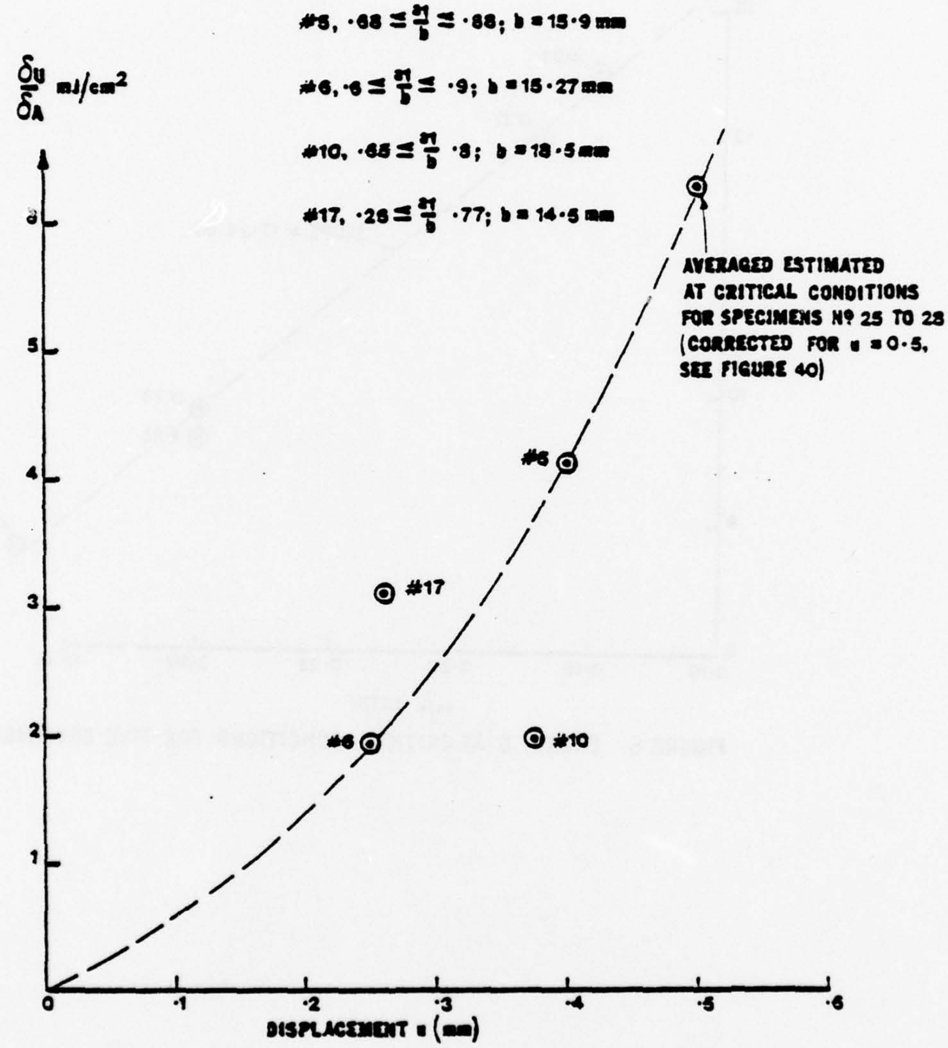


FIGURE 5. ENERGY RELEASE RATES VS DISPLACEMENT FOR CRACK GROWTH FROM a_1.

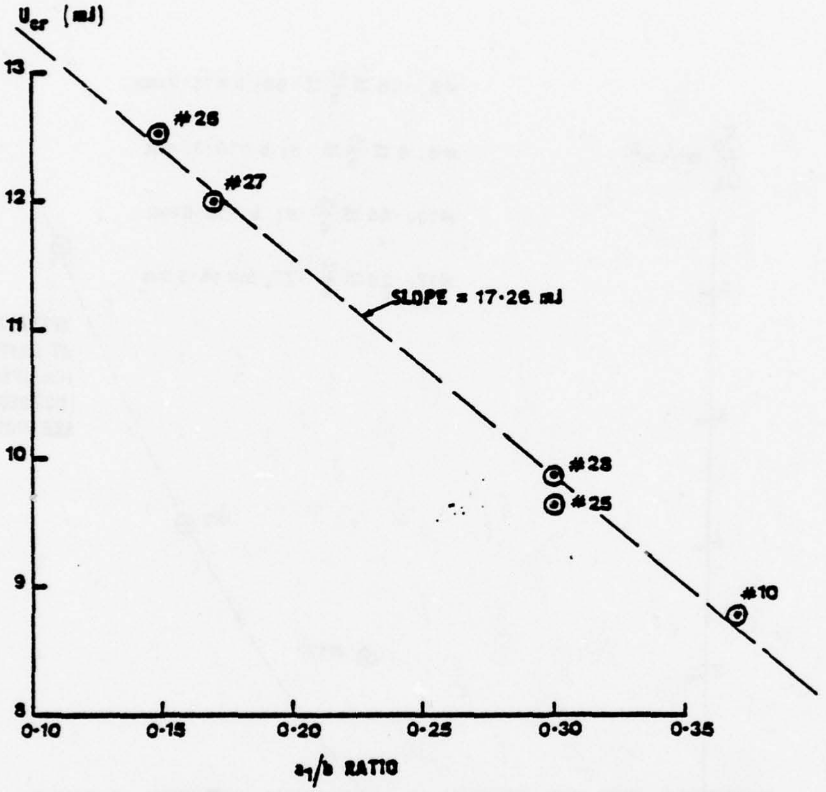


FIGURE 6. ENERGY U AT CRITICAL CONDITIONS FOR FIVE SPECIMENS.

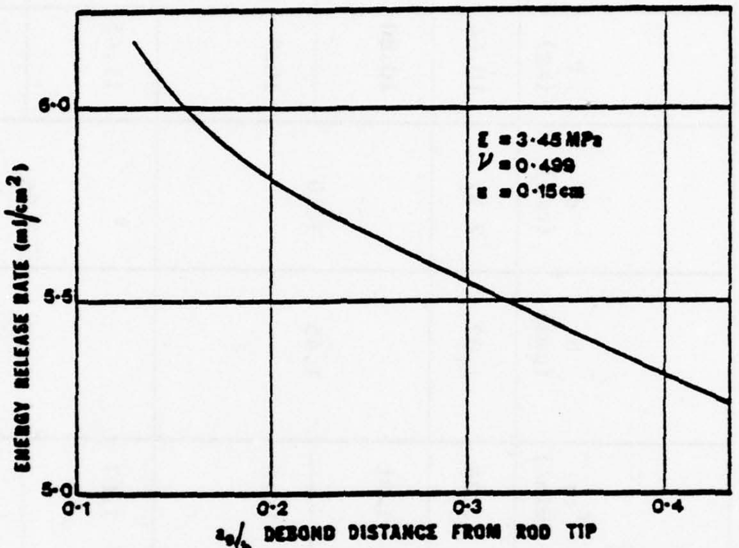


FIGURE 7A. ENERGY RELEASE RATE FOR ROD TIP INITIAL DEBOND. (AFTER WILLIAMS AND ANDERSON [1])

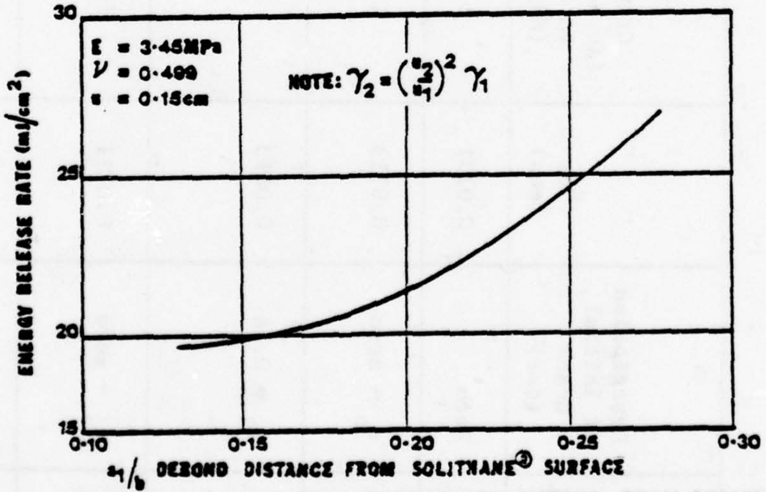


FIGURE 7B. ENERGY RELEASE RATE FOR DEBOND FROM SOLITHANE® SURFACE. (AFTER WILLIAMS AND ANDERSON [1])

Table 1

Test Results

Spec. No.	$\frac{a_o}{b}$ or $\frac{a_1}{b}$	Description of Initial Crack (cms)	u_{cr} (cms)	γ_a Critical (as defined) in text) (MJ/cm^2)	t_{cr} (mins)	b (cms)	d (cms)	P (kg)	Remarks
#1		Zero	0.0731	13.99	1.04	1.32	2.97	10.64	For tip CG
#3	$\frac{a_o}{b} = 0$	a_o = zero	0.0713	13.397	1.01	1.45	3.10	10.80	Tip crack growth
	$\frac{a_1}{b} = 0.1$	a_1 = 0.14	0.0813	5.749	1.16			10.9	Crack growth from free surface end
#4	$\frac{a_o}{b} = 0$	a_o = zero	0.0711	10.932	1.07	1.60	3.25	11.45	Tip crack growth
	$\frac{a_1}{b} = 0.24$	a_1 = 0.387	0.0813	9.293	1.18			11.66	Surface crack growth initiated release agent
#5	$\frac{a_1}{b} = 0.68$	a_1 = 1.08	0.0408	3.35	0.517	1.59	3.24	4.08	Crack growth from free surface end

Table 1 cont'd

Test Results

Spec. No.	$\frac{a_o}{b}$ or $\frac{a_1}{b}$	Description of Initial Crack (cms)	u_{cr} (cms)	γ_a Critical (as defined in text) (MJ/cm^2)	t_{cr} (mins)	b (cms)	d (cms)	P (kg)	Remarks
#6	$\frac{a_1}{b} = 0.60$	$a_1 = 0.92$	0.0265	2.643	0.40	1.53	3.18	3.13	Crack growth from free surface end
#10	$\frac{a_1}{b} = 0.37$	$a_1 = 0.678$	0.0377	2.112	0.50	1.85	3.50	4.75	Crack growth from free surface end
#13	$\frac{a_o}{b} = 0.34$	$a_o = 0$ to 0.5 (release agent surface)	0.0514	4.15 energy release rate for release agent and solithane adhesion	0.55	1.45	3.10	6.26	Tip crack growth only release agent surface
	$\frac{a_1}{b} = 0$	$a_1 =$ zero	0.072	5.738	0.78			6.26	Non-uniform crack growth from free surface
#14	$\frac{a_o}{b} = 0.34$	$a_o = 0$ to 0.5 (release agent surface)	0.0709	6.476	0.78	1.45	3.10	7.92	For tip crack growth only release agent surface

Table 1 cont'd

Test Results

Spec. No.	$\frac{a_o}{b}$ or $\frac{a_1}{b}$	Description of Initial Crack (cms)	u_{cr} (cms)	γ_a Critical (as defined in text) (MJ/cm^2)	t_{cr} (mins)	b (cms)	d (cms)	P (kg)	Remarks
#15	$\frac{a_o}{b} = 0.34$	$a_o = 0.5$ release agent surface	0.0592	4.996	0.617	1.45	3.10	6.08	Tip crack growth on release agent surface only
	$\frac{a_1}{b} = 0$	$a_1 = 0$ to 0.516	0.0881	10.00	2.433			5.606	Crack growth from free surface end
#17	$\frac{a_1}{b} = 0.26$	$a_1 = 0.371$	0.0614	2.852	0.59	1.45	3.10	4.80	Initiation of crack
			For further details see Figures 25 and 26						
#18		$a_1 = 0.340$	0.0748	7.482	0.817	1.45	3.10	6.10	Crack growth just beyond 0.3 cm release surface
		$a_o = 0$ (Initial debond at tip of rod)	0.034	10.09	0.35			2.69	Initial debond at extreme tip, see Fig. 26

Table 1 cont'd

Test Results

Spec. No.	$\frac{a_o}{b}$ or $\frac{a_1}{b}$	Description of Initial Crack (cms)	u_{cr} (cms)	γ_a Critical (as defined in text) (MJ/cm^2)	t_{cr} (mins)	b (cms)	d (cms)	P (kg)	Remarks
#19	$\frac{a_o}{b} = 0.14$	$a_o = 0$ to 0.2 (release agent surface)	0.0450	3.60	0.47	1.45	3.10	4.13	Tip crack growth on release agent surface only
		$a_1 = 0$	0.0939	7.60	1.0			7.74	Non-uniform crack growth from free surface
#20	$\frac{a_o}{b} = 0.21$	$a_o = 0$ to 0.3 (release agent surface)	0.0461	2.713	0.483	1.45	3.10	4.33	Tip growth on release agent surface only. Detail of further crack growth see Figure 28
		$a_1 = 0$	0.1553	Difficult to measure see Fig. 28	1.73			10.75	Crack growth from free surface

Table 1 cont'd

Test Results

Spec. No.	$\frac{a_o}{b}$ or $\frac{a_1}{b}$	Description of Initial Crack (cms)	u_{cr} (cms)	γ_a Critical (as defined in text) (MJ/cm^2)	t_{cr} (mins)	b (cms)	d (cms)	P (kg)	Remarks
#21	$\frac{a_o}{b} = 0.276$	$a_o = 0$ to 0.4 (release agent surface)	0.0447	6.225	0.467	1.45	3.10	4.68	Tip crack growth on release agent only
		$a_o = 0.42$	0.0678		0.8			6.00	Cohesive crack growth in radial direction
		$a_1 = 0$	0.1424		1.65			10.0	Crack growth from free surface

Table 1 cont'd

Test Results

Spec. No.	$\frac{a_o}{b}$ or $\frac{a_1}{b}$	Description of Initial Crack (cms)	u_{cr} (cms)	γ_a Critical (as defined in text) (MJ/cm^2)	t_{cr} (mins)	b (cms)	d (cms)	P (kg)	Remarks
#25	$\frac{a_1}{b} = 0.30$ actual	$a_1 = 0.42$ (cut in)	0.050	2.362	0.50	1.62	3.29	3.915	Crack growth from flaw cut in from free surface end
#26	$\frac{a_1}{b} = 0.148$ actual	$a_1 = 0.188$ (cut in)	0.056	3.120	0.58	1.57	3.22	4.581	Crack growth from flaw cut in from free surface end
#27	$\frac{a_1}{b} = 0.17$ actual	$a_1 = 0.206$ (cut in)	0.054	3.158	0.57	1.60	3.25	4.54	Crack growth from flaw cut in from free surface end
#28	$\frac{a_1}{b} = 0.3$ actual	$a_1 = 0.441$ (cut in)	0.048	3.87	0.52	1.63	3.28	4.17	Crack growth from flaw cut in from free surface end

Table 1 cont'd

Test Results

Spec. No.	$\frac{a_o}{b}$ or $\frac{a_1}{b}$	Description of Initial Crack (cms)	u_{cr} (cms)	γ_a Critical (as defined in text) (MJ/cm^2)	t_{cr} (mins)	b (cms)	d (cms)	P (kg)	Remarks
#29		$a_o = 0$	0.105	19.4	1.17	1.61	3.26	9.83	Tip crack growth from zero flaw
		$a_1 = 0$	1.401	8.31	1.55			10.36	Crack growth from zero flaw from free surface end
#30		$a_o = 0$	0.0845	11.08	0.90	1.76	3.41	8.854	Crack growth from zero flaw at tip which almost debonded whole rod

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APPENDIX 3.3

Parametric Study of Fiber Pull-Out Problem

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INTRODUCTION

A very important factor in fiber reinforced materials is the nature of the stress transfer between the individual reinforcing fibers and the surrounding media. In particular, if a proper factor of safety against failure is to be established, the stress conditions must be determined under which debonding of the fibers will occur. A first step in obtaining a solution to this problem is to determine the behavior of a single reinforcing fiber when isolated from the interaction effects of surrounding fibers. The particular situation which was initially considered was a partially embedded fiber of circular cross section in an elastic media, loaded by an axial tensile force, as shown in Figure 1. A number of different cases were investigated in which cracks of various lengths were present at various locations on the interface between the fiber and the surrounding media. The purpose was to establish the effect of crack size and location upon the bonding stresses along the boundaries of the fiber and in particular to determine the conditions for which the crack would propogate and cause either a total or partial failure.

Only a very few papers are available in the literature concerning this particular problem. An anlytical analysis of a partially embedded rod in a half-space has been presented by Muki and Sternberg (1). In this analysis the rod and surrounding media were assumed to be linear elastic and the rod was assumed to be bonded to the surrounding media over its entire length. A number of curves, obtained by a numerical solution technique, were presented which show the load transfer between the rod and the surrounding media for a wide range of problem variables. The results which are available show that the load falls off very rapidly in the rod and that the rate of load transfer is very sensitive to the embedment length to diameter ratio of the rod and also to the relative elastic properties of the rod and the surrounding media.

In another study, conducted by Williams and Anderson (2) using a finite element mathematical model, some information is presented concerning the effect of debonding of the rod at both the free surface and at the rod tip. In particular, the elastic strain energy release rate (i.e. change in elastic strain energy with crack extension) was investigated over a small range of crack lengths for one particular geometric configuration. The study was not carried far enough to establish any definite conclusions, however, it was demonstrated that a finite element mathematical model can be conveniently used to study this problem.

CURRENT INVESTIGATION

Since an exact analytical solution is not available for the case of an embedded rod with debonding, it was necessary to develop analysis procedures which were suitable for use in the present investigation. Two investigative techniques were used: an experimental approach, which is described in a University of Pittsburgh, School of Engineering Research Report (3); and a numerical approach, using a finite element mathematical model. The remainder of this discussion will be devoted to a description of the finite element analyses and the results available at the present time.

In the experimental investigation, the tests were performed on a glass rod embedded in Solithane®. In order to compare the numerical results to those obtained from the experimental investigation, the geometry used for the initial numerical studies was the same as that used for the experimental specimens, as shown in Figure 2.

Since the physical problem consists of a circular rod loaded by an axial force, the problem is amenable to being represented by an axisymmetric finite element mathematical model. The finite element computer program which was used represented the continuous system by a finite number of four node axisymmetric quadralateral elements which were generated by combining four constant strain axisymmetric triangular elements. To simplify the mathematical model, it was assumed that the glass rod was essentially rigid compared to the Solithane®, therefore, rather than modeling the rod it was assumed that its effect could be represented by introducing uniform displacements along the entire interface where the rod was bonded to the Solithane®. In later studies the effect of a variety of elastic properties for the rod and the surrounding media will be considered.

Figure 3 shows the form of a typical finite element mathematical model used in the initial numerical analyses. It was necessary to use very small elements in the region of the crack tip, or any other stress concentration point, in order to obtain an accurate solution. One way of circumventing this requirement is to use a special crack tip finite element, which contains a built-in singularity. Special elements of this type were not available in the specific computer program being used in these initial studies. The use of a special crack tip element might be considered later in the investigation. It was found from preliminary analyses that finite element grids containing approximately 1000 nodes and 900 quadralateral elements were required for the mathematical model being used.

As stated earlier, the initial numerical studies which will be discussed here were conducted on a mathematical model which represents the specimen used in an experimental investigation. The specific conditions which were investigated were the effects of debonding of the rod from the surrounding media starting at both the rod tip and at the free surface. Figures 4a and 4b define these two conditions, where B is the rod embedment length, R is the rod radius, A_o locates the crack tip for debonding from the rod tip, and A_1 locates the crack tip for debonding from the free surface.

Since considerable difficulty was encountered in the experimental investigation in manufacturing the specimens, controlling the crack length and applying a true axial load to the rod, the first finite element analyses which were performed were used to compare the experimental and analytical results for several different initial crack lengths extending from the free surface. Figure 5 shows a comparison of the experimental and analytical relationships for strain energy versus crack length. As can be seen the curves are essentially the same shape with a difference in ordinates of approximately 20 percent. The comparison gives an indication of the agreement which might be expected between the experimental and analytical studies. Since the curves are of the same shape it shows that the experimental specimens and mathematical models are behaving in the same general manner. The difference in the strain energy could be due to many accumulated effects in the experimental procedure ranging from the loading of the specimens and the actual symmetry of the debonding to the material properties of the Solithane®. In the mathematical model the material was assumed to be perfectly linear elastic while the Solithane does exhibit some non-linear time dependent behavior.

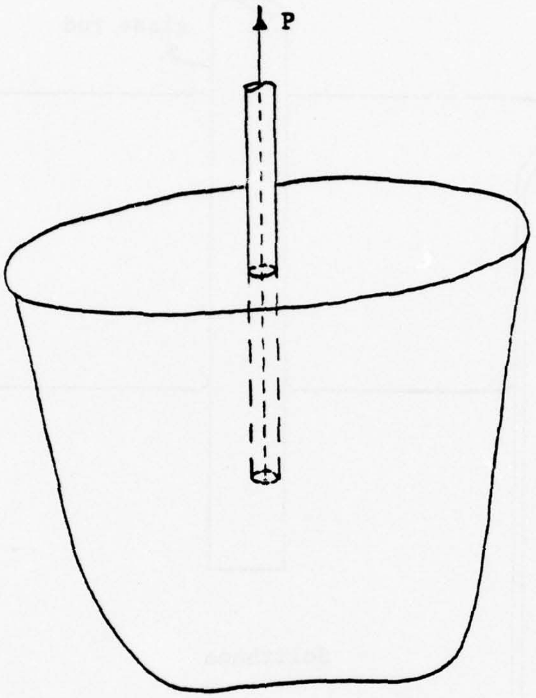
The majority of the finite element analyses were performed to obtain the relationships shown in Figures 6 and 7. These curves show the strain energy release rate as a function of crack tip position for debonding from the rod end and from the free surface respectively. In these studies the end of the rod was assumed to be perfectly flat and perpendicular to the longitudinal axis of the rod, with a perfectly square corner where the rod end surface intersected the side cylindrical surface. As can be seen there is a sharp increase in the strain energy release rate as the crack tip approaches this square corner due to the interaction of the singularities. Figures 8 and 9 show a set of curves for the same conditions except that the rod is now assumed to have a spherical tip as shown in Figure 10. The curved tip eliminates the discontinuities in the relationships.

REFERENCES

1. Muki, R. and Sternberg, E., "Elastostatic Load-Transfer to a Partially Embedded Axially Loaded Rod," International Journal of Solids and Structures, Vol. 60, 1970, p. 69

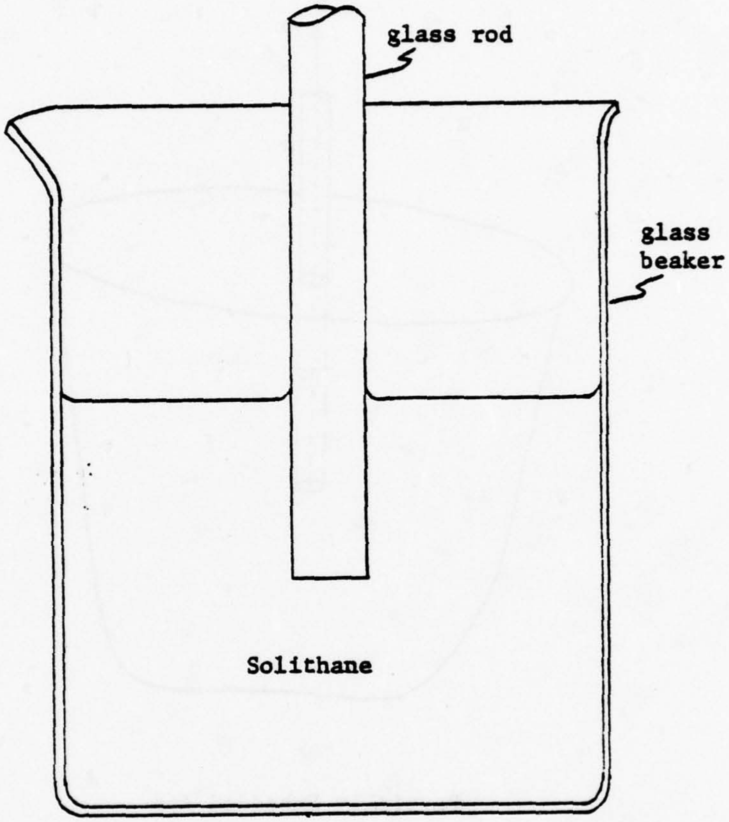
2. Williams, M.L. and Anderson, G.P., "Adhesive Fracture Mechanics," Fracture 1977, Vol. 1, ICF4, Waterloo, Canada, June 1977

3. Betz, E., "Report on Experimental Studies of the Fiber Pull-Out Problem," University of Pittsburgh, School of Engineering Research Report SETEC ME 79-34, June 1979



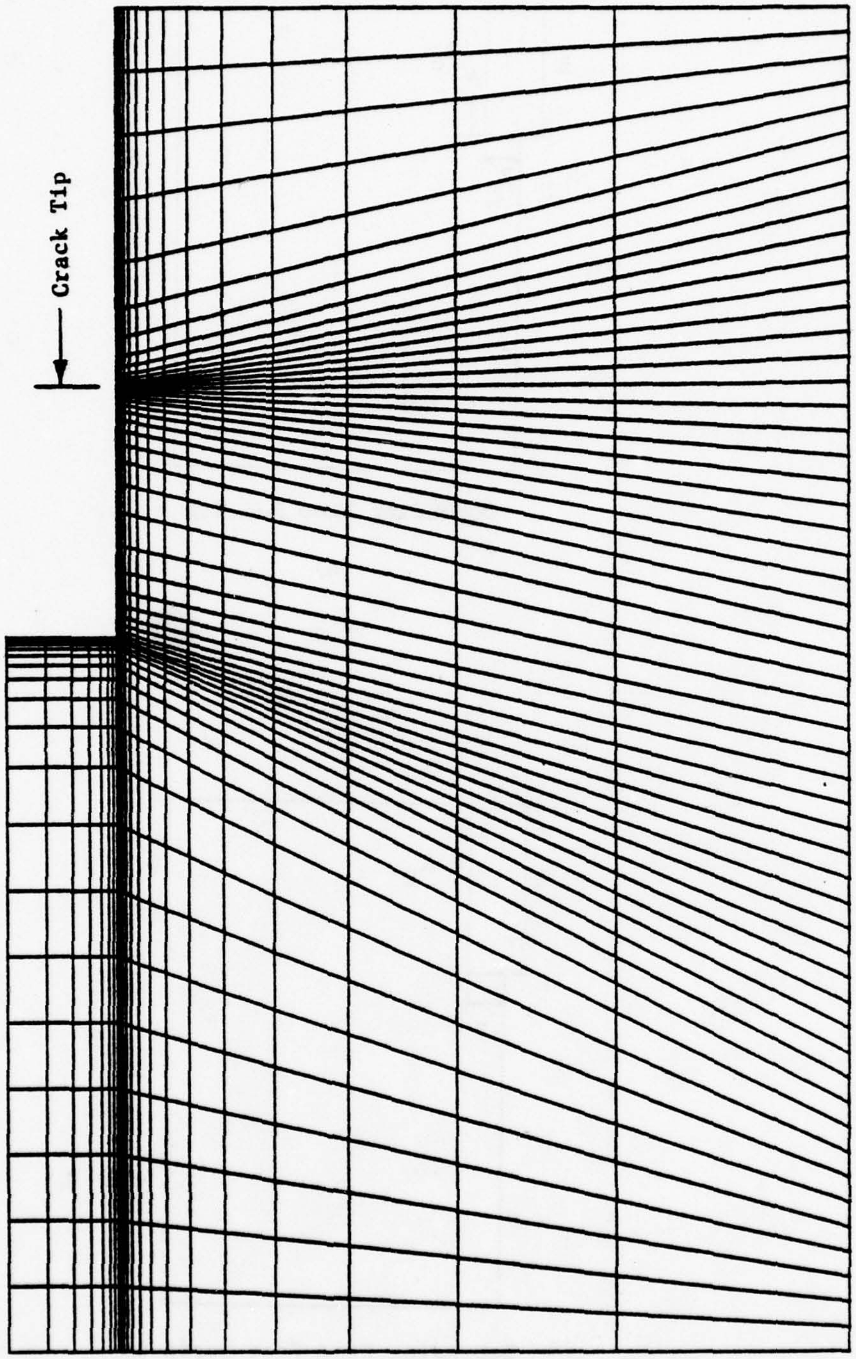
Partially Embedded Rod

Figure 1



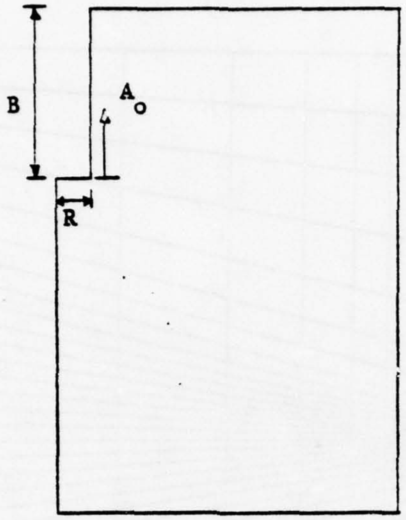
Experimental Specimen

Figure 2



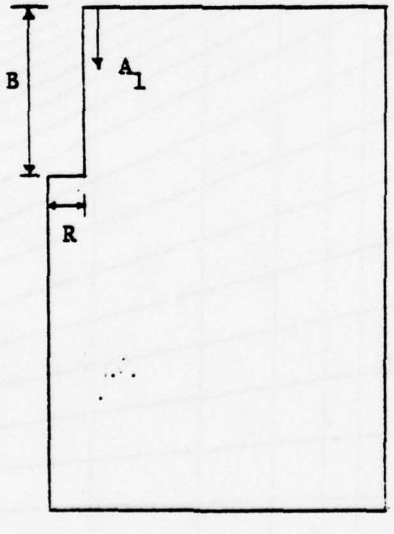
Finite Element Mathematical Model

Figure 3



Debonding From Rod Tip

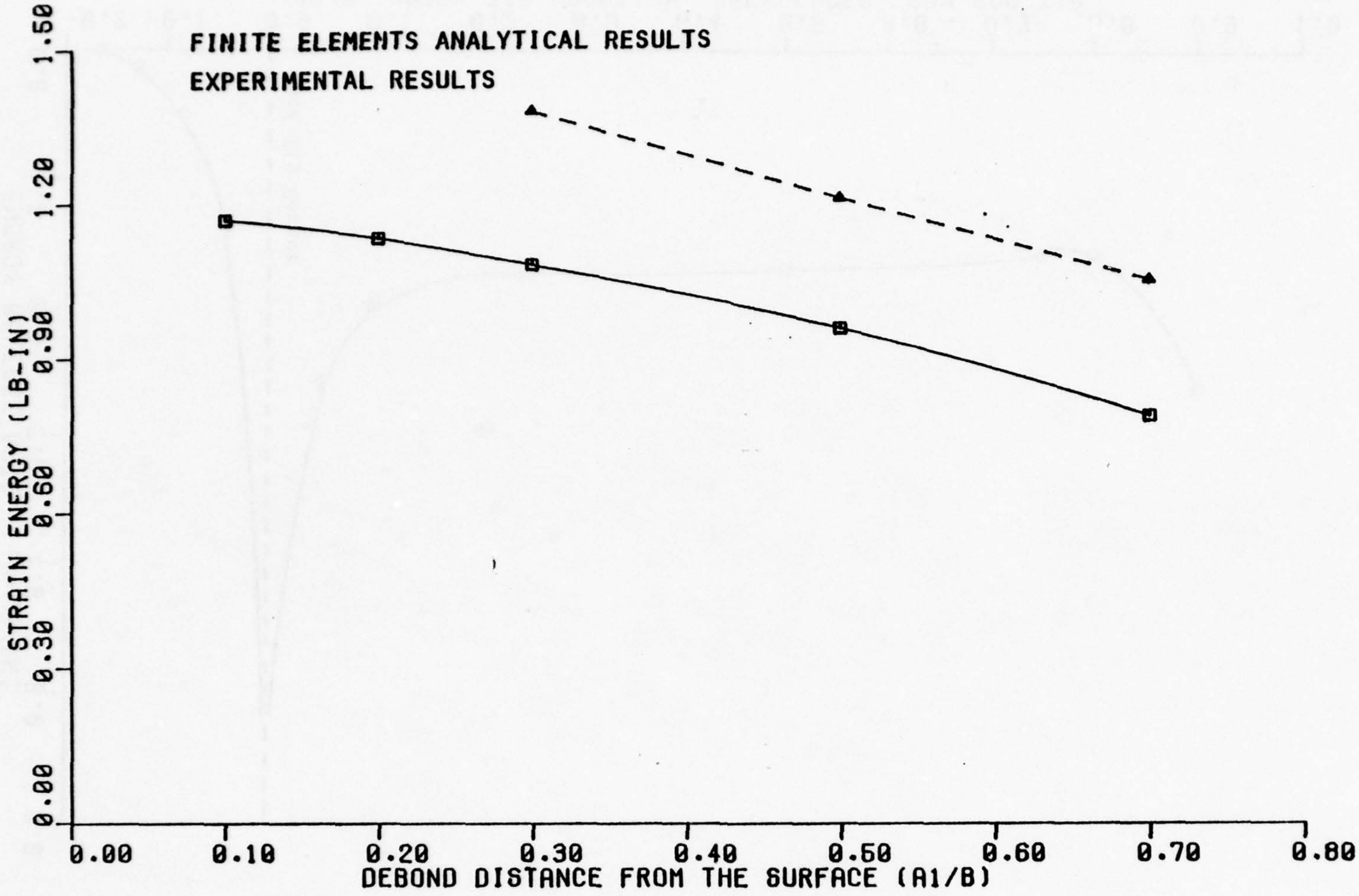
(a)



Debonding From Free Surface

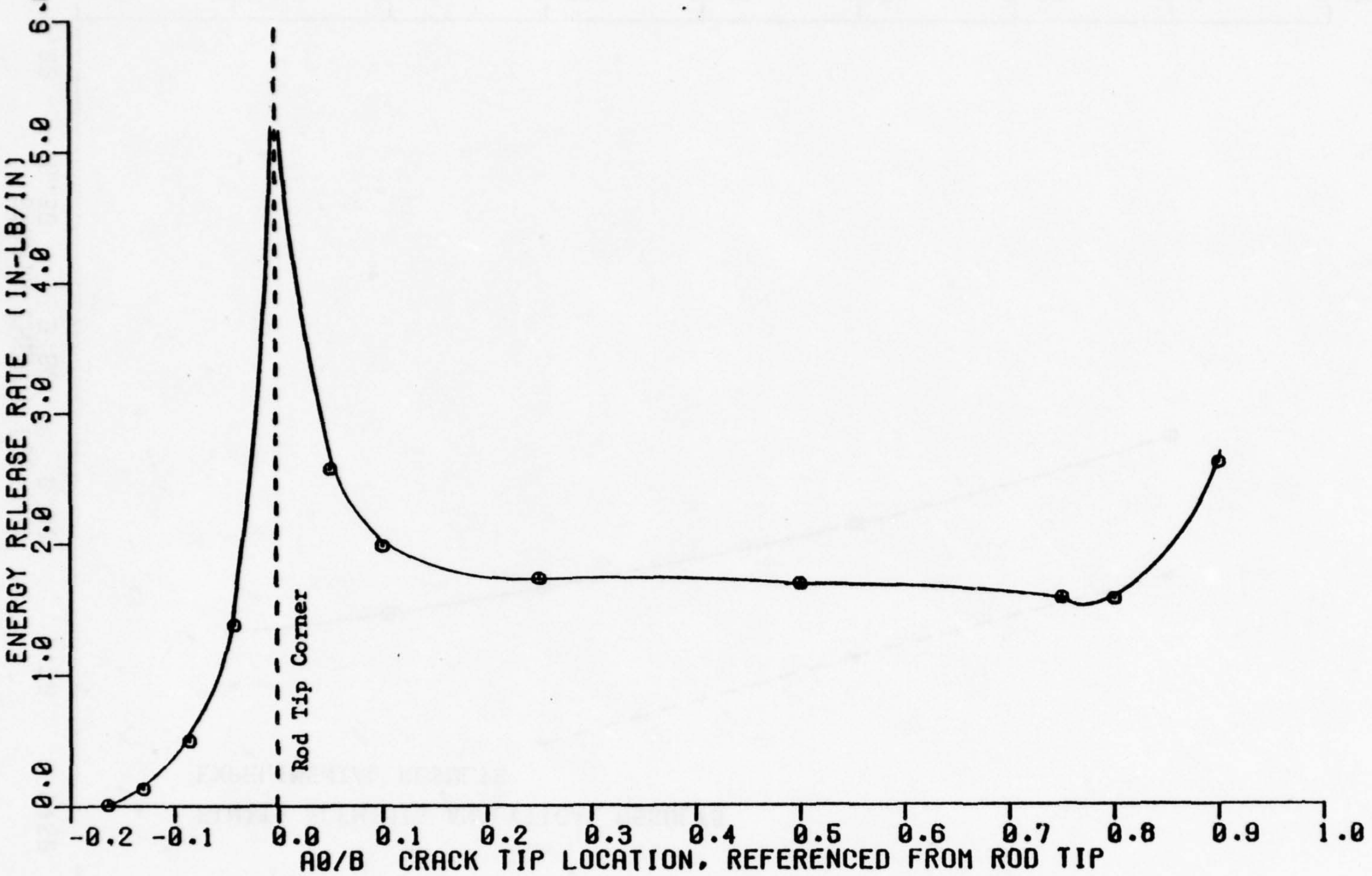
(b)

Figure 4



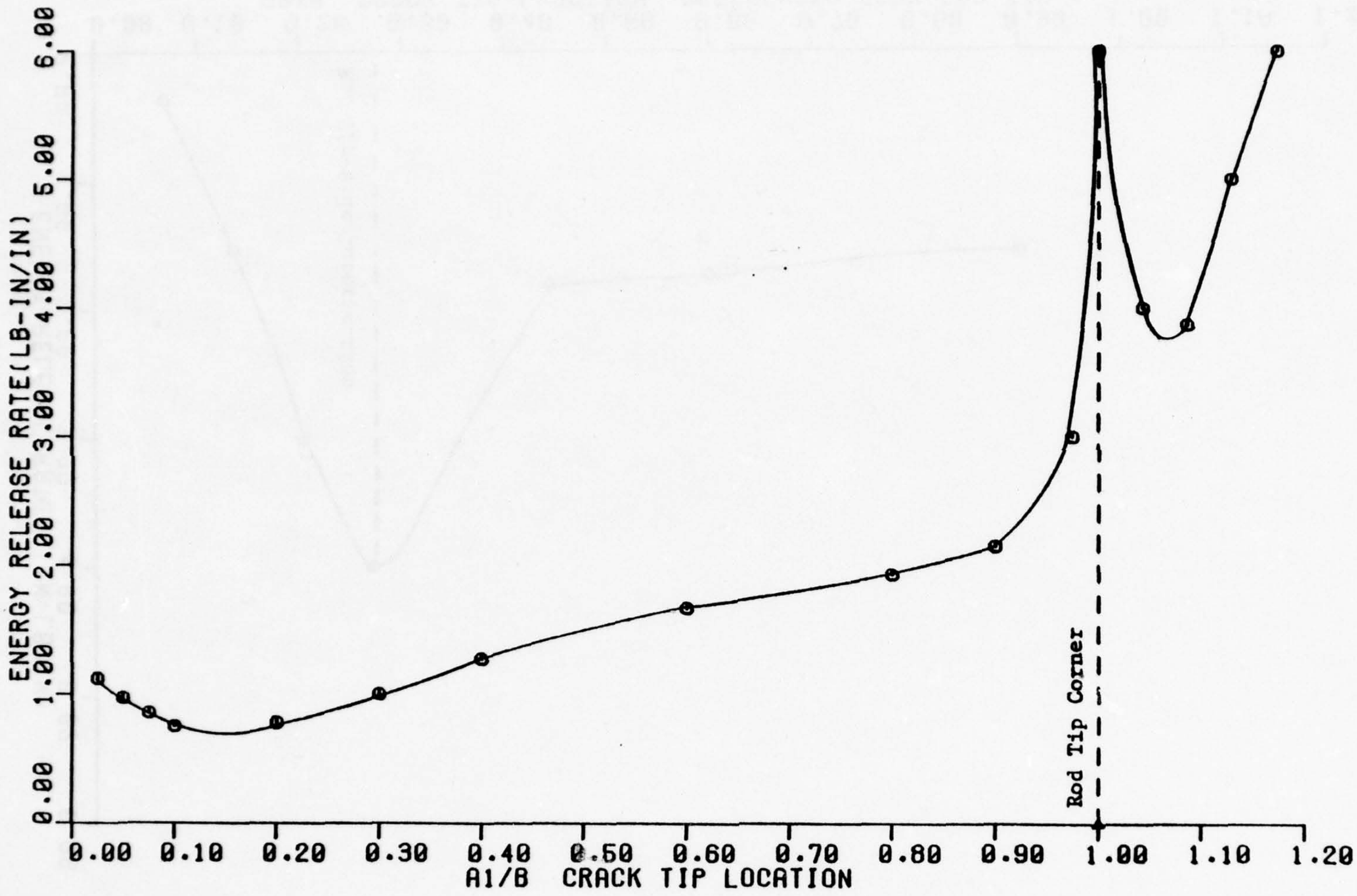
STRAIN ENERGY FOR DEBOND FROM THE SOLITHANE SURFACE

Figure 5



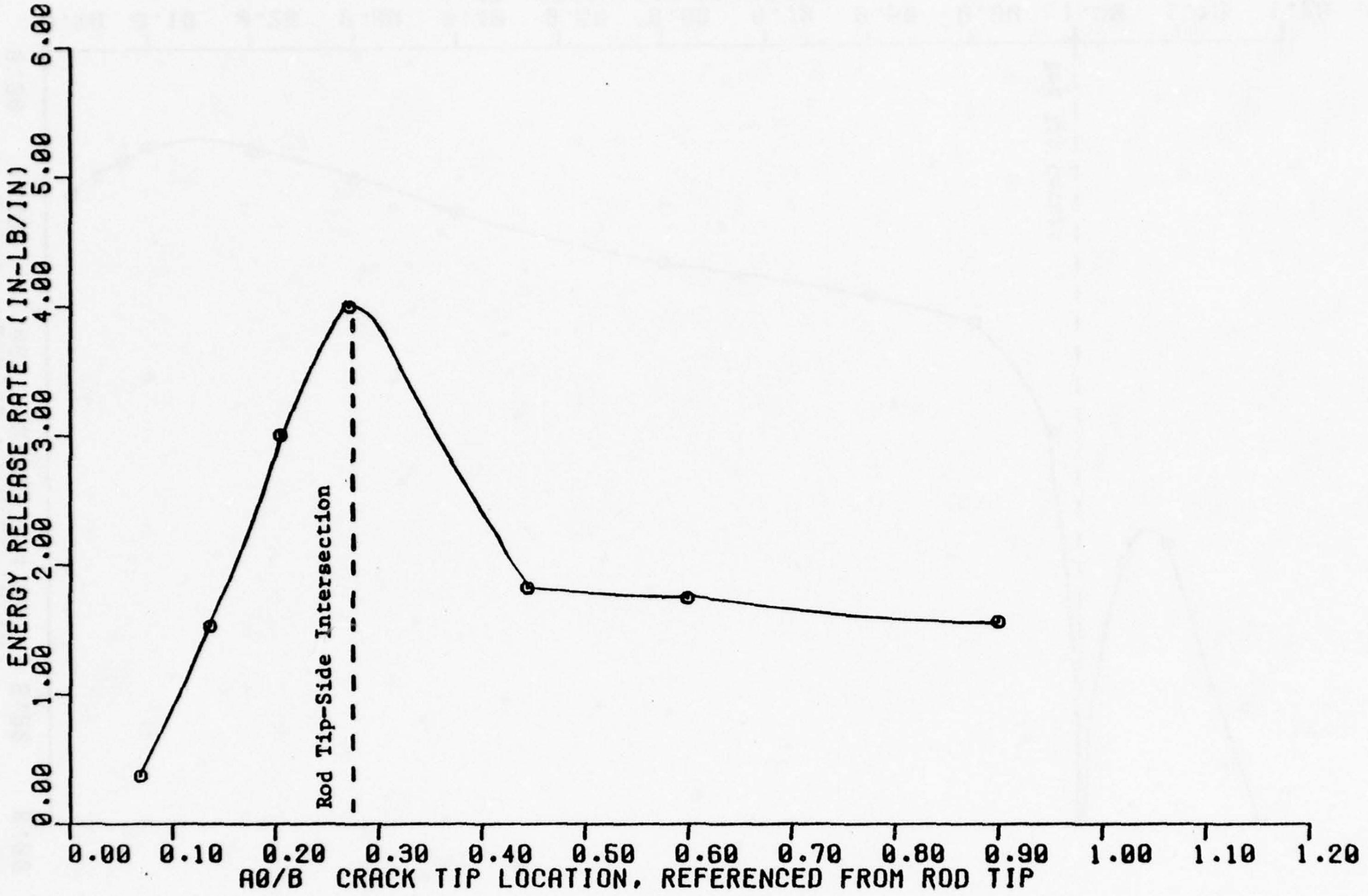
ENERGY RELEASE RATE FOR ROD TIP INITIAL DEBOND, FLAT-ROD

Figure 6



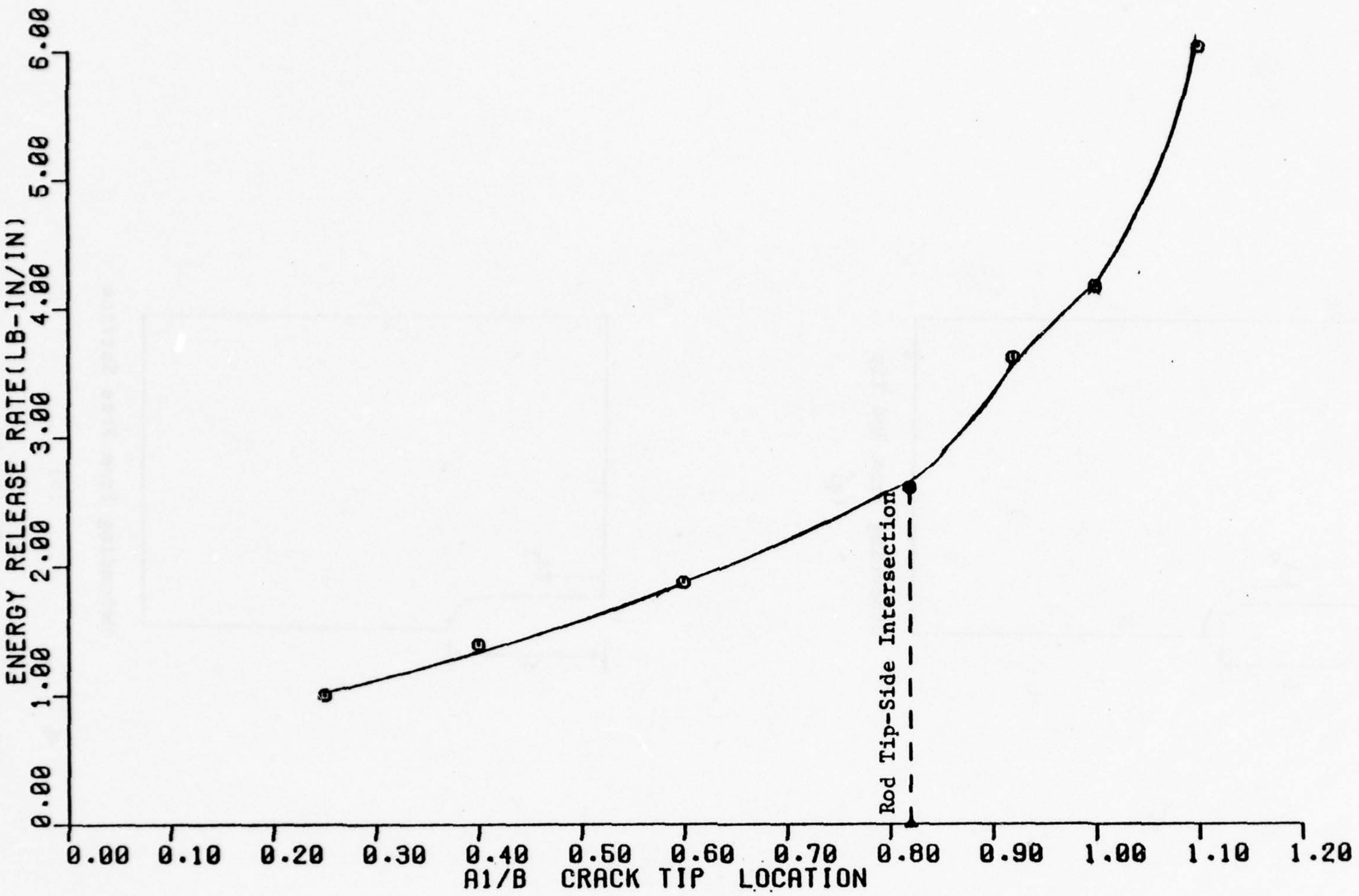
ENERGY RELEASE RATE FOR DEBOND FROM THE SURFACE FLAT TIP ROD

Figure 7



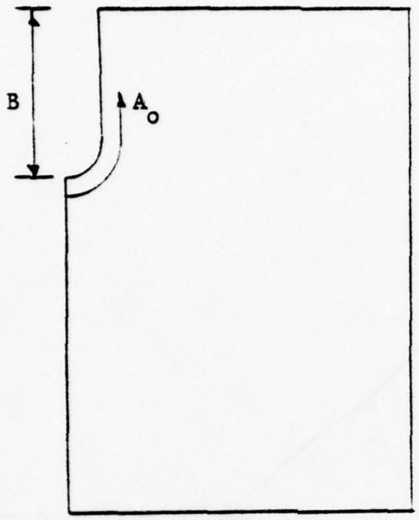
ENERGY RELEASE RATE FOR ROD TIP INITIAL DEBOND, SPHERICAL-TIP ROD

Figure 8



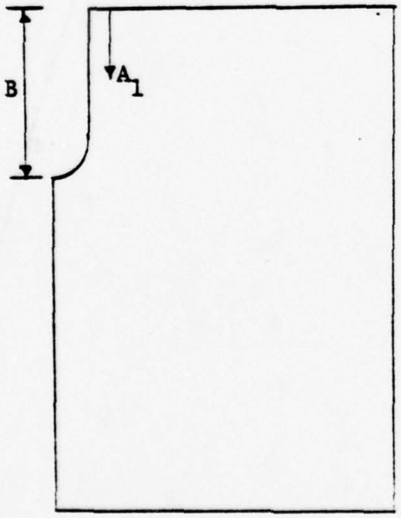
ENERGY RELEASE RATE (DEBOND FROM SURFACE) SPHERICAL TIP ROD

Figure 9



Debonding From Rod Tip

(a)



Debonding From Free Surface

(b)

Figure 10

APPENDIX 3.4

Subcontract
for
Numerical Studies of Crack Problems In Finite Elasticity

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INTRODUCTION

The linear theory of elasticity contains a variety of problems with singularities, the character of which is often attributed to the inadequacy of classical theories as a model of the behavior in the neighborhood of cracks, changes of boundaries conditions, and contact surfaces. Some investigators have felt that a better understanding of the behavior of elastic bodies near these points of high strain might be obtained from the more general theory of finite elastic deformations. However, owing to the complexity of the equations of nonlinear elasticity, it has been impossible to carry out such analyses except for some very simple cases. On the other hand, significant advances have been made in the numerical analysis of problems for finite elastic deformation and it seems possible that new computational methods could be used to investigate the characteristics of singularities in certain problems involving finite deformations.

This document is a proposal for a research project aimed at studying various singular problems of finite elasticity using finite element methods and modern computational techniques.

PROPOSED WORK

Formulation of problems involving finite elastic deformations, in terms suitable for finite element analysis, is straightforward and, in fact, many existing programs contain such formulations. The actual solution of boundary value problems is less straightforward -- many problems which involve very large stretches and/or regions of large strain gradients prove to be intractable for these programs. Failure of the usual algorithms for solving the (nonlinear) finite element equations is often observed.

Recent work at the University of Texas has been directed toward overcoming these computational difficulties. Various formulations, including penalty and Lagrange multiplier methods, are used to enforce the incompressibility constraints. These formulations, as well as various solution procedures, are incorporated in two new finite element programs which are in the final stages of development.

It is proposed that these codes be used to study several problems involving geometric singularities such as cracks. The primary objective of the study will be the prediction of such features of the solution as total strain energy, radius of curvature of the crack and maximum strain of the crack as functions of geometry, loading conditions, and constitutive equations. The ability to predict such features will allow studies of the correlations between these and the fracture. The particular problems to be studied will be determined by the University of Pittsburgh with consultation by the principal investigator.

A secondary objective of the studies will be to assess quantitative questions relative to the finite element modelling of the class of problems to be studied. Such questions as mesh requirements and adequacy of stress, strain, and strain energy density calculation in the neighborhood of the crack will be studied.

It is anticipated that some modifications of the finite element codes will be required during the course of this investigation. These modifications will be made as required during the course of the investigation and will not constitute a code development program.

SETEC SF 70-52

APPENDIX 3.5

Application of the Brazilian Disk Test To Mode I and Mode II Fracture Analysis

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A combined numerical, experimental investigation of the cracked Brazilian disk test has been conducted.* The specimen configuration consists of a disk containing a crack loaded in diametral compression, Figure 1a. The crack may also be oriented at any angle relative to the loading axis, Figure 1b. This orientation will produce any combination desired of Mode I and Mode II loading. It is this ease of producing combined mode loading which makes the specimen attractive for fracture studies.

A series of experiments were conducted to establish the validity of the test in Mode I loading conditions using PMMA as a model material. The results from the disk test were compared to standard ASTM three point bend tests. An ASTM proposed four point bend specimen was also tested. These results are shown in Figure 2, here the normalized critical load to fracture is plotted versus the normalized carck length. As can be seen, the results from the disk test and the three point bend specimens compare quite favorably with the thoretical curve. The results from the four point bend tests, however, show a systematic error. On the basis of this data, it is concluded that the critical stress intensity, K_{Ic} determined from the disk test is comparable to that determined using ASTM standard E-399.

Following completion of the Mode I experiments, a numerical investigation of the disk specimen was conducted using the finite element method. The analysis included a special crack tip element obviating the need for mesh refinement near the crack tip. The results of the analysis are presented in, Figure 3 and Tables 1a, 1b and 2. The normalized stress intensity factors N_I and N_{II} are given by

$$N_I = \frac{K_I}{K}$$

$$N_{II} = \frac{K_{II}}{K}$$

where

$$K = \frac{P\sqrt{L}}{\sqrt{\pi}\,Rh}$$

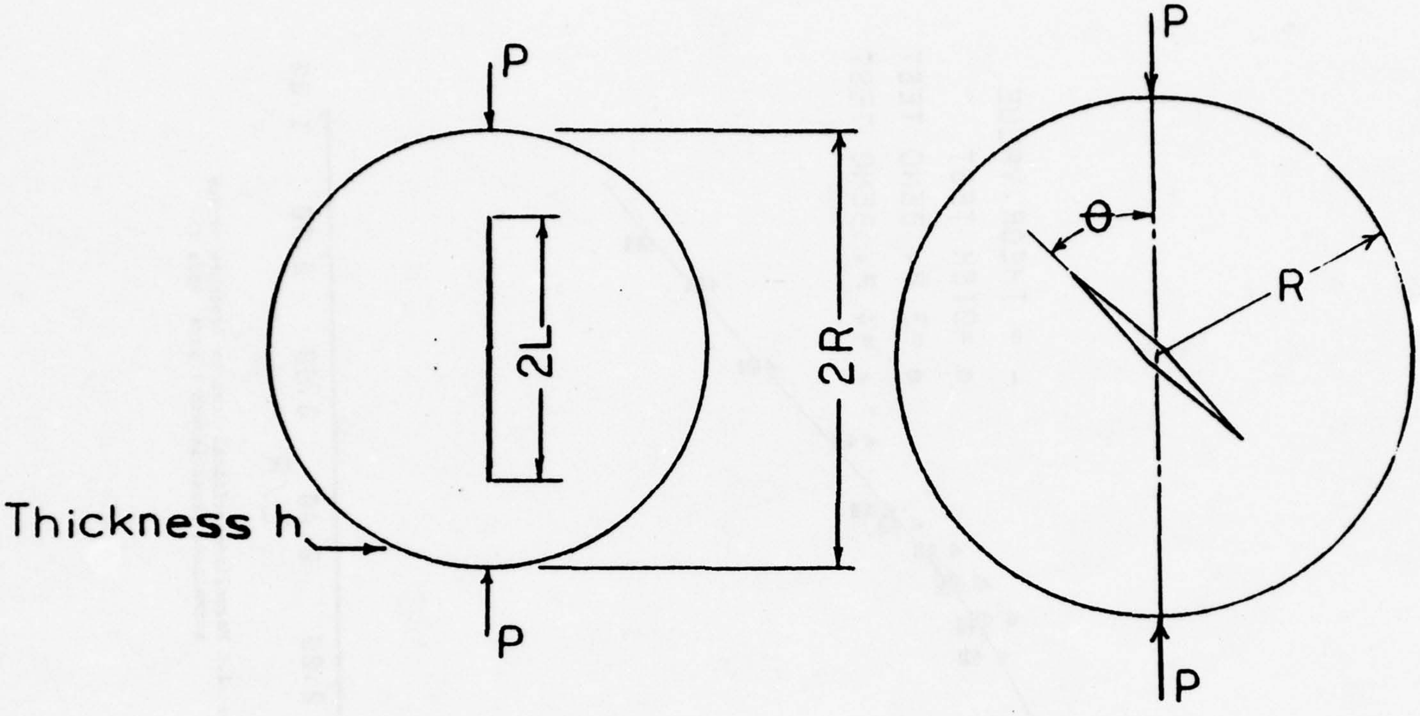
---

*J. Sanchez, "Application of the Disk Test to Mode I - II Fracture Analysis", Master of Science Thesis, August 1979.

As the crack orientation is changed from the load line, an angle is reached at which K_I becomes negative indicating crack closure. The point at which K_I equals zero produces a condition of pure Mode II loading. The angle at which this occurs decreases as the crack length (L) to radius (R) ratio increases. This angle ranges from 27.7 degrees at an $L/R = 0.3$ to 20.0 degrees at $L/R = 0.6$ (Table 2). These results agree with an independent analysis of Awaji and Sato (J. Eng. Mat'ls and Tech., Trans ASME, Vol. 100, 1978, pp. 175-182).

Using the results of the numerical analysis, experiments were conducted to measure the critical stress intensity factor under Mode II loading conditions. These results are presented in Figure 4. The scatter of this data is much larger than for the Mode I testing. This is most probably due to the imprecision of the measurement of crack orientation and/or crack length. The results of such experiments are presently not conclusive since an adequate independent experimental evaluation of K_{IIc} has not been found.

Currently, work is being carried out to investigate approximate schemes of stress analysis for the disk test. The approximate technique will allow the incorporation of friction in the model when the crack closes. This is not easily accomplished using the special crack tip element currently available. The use of a similar test for square specimens is also being examined. Once the transfer to a second specimen is completed, a test methodology will be available to rank materials using a combined mode fracture test for common production shapes.



(a) (b)

Figure 1. Cracked Brazilian Disk Specimen: (a) Mode I Loading.
(b) Combined Mode I-II Loading.

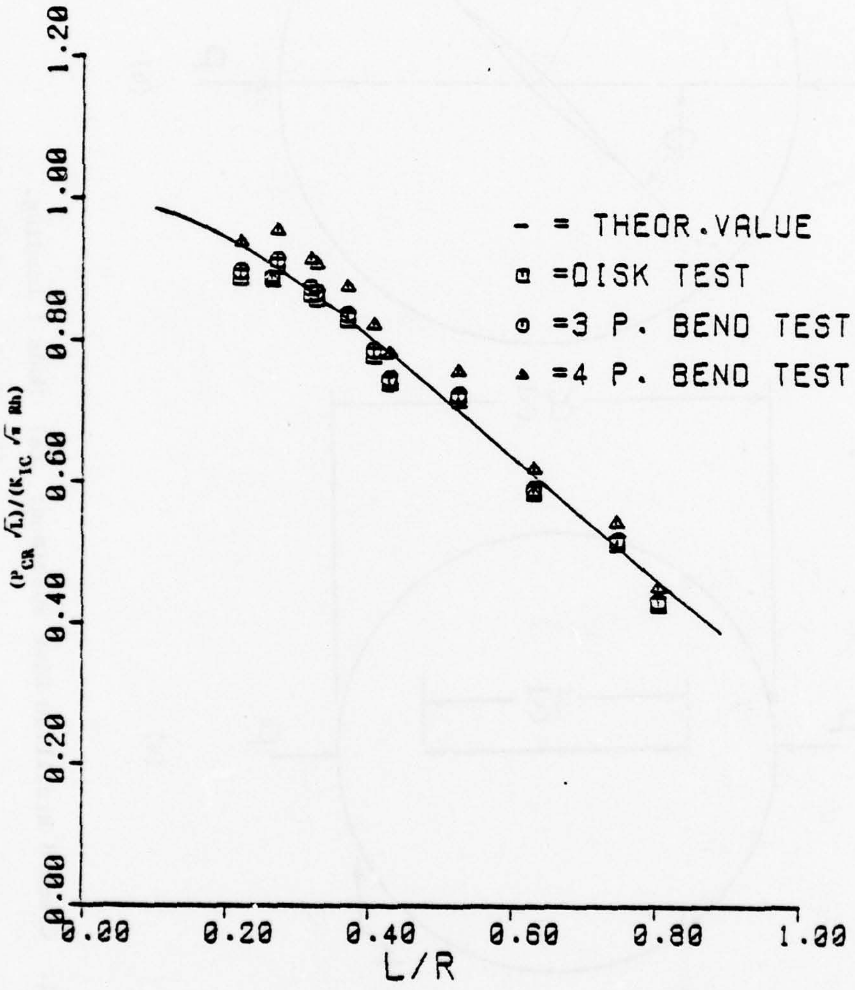


Figure 2. Normalized critical load to fracture versus normalized crack length ('pure' mode I)

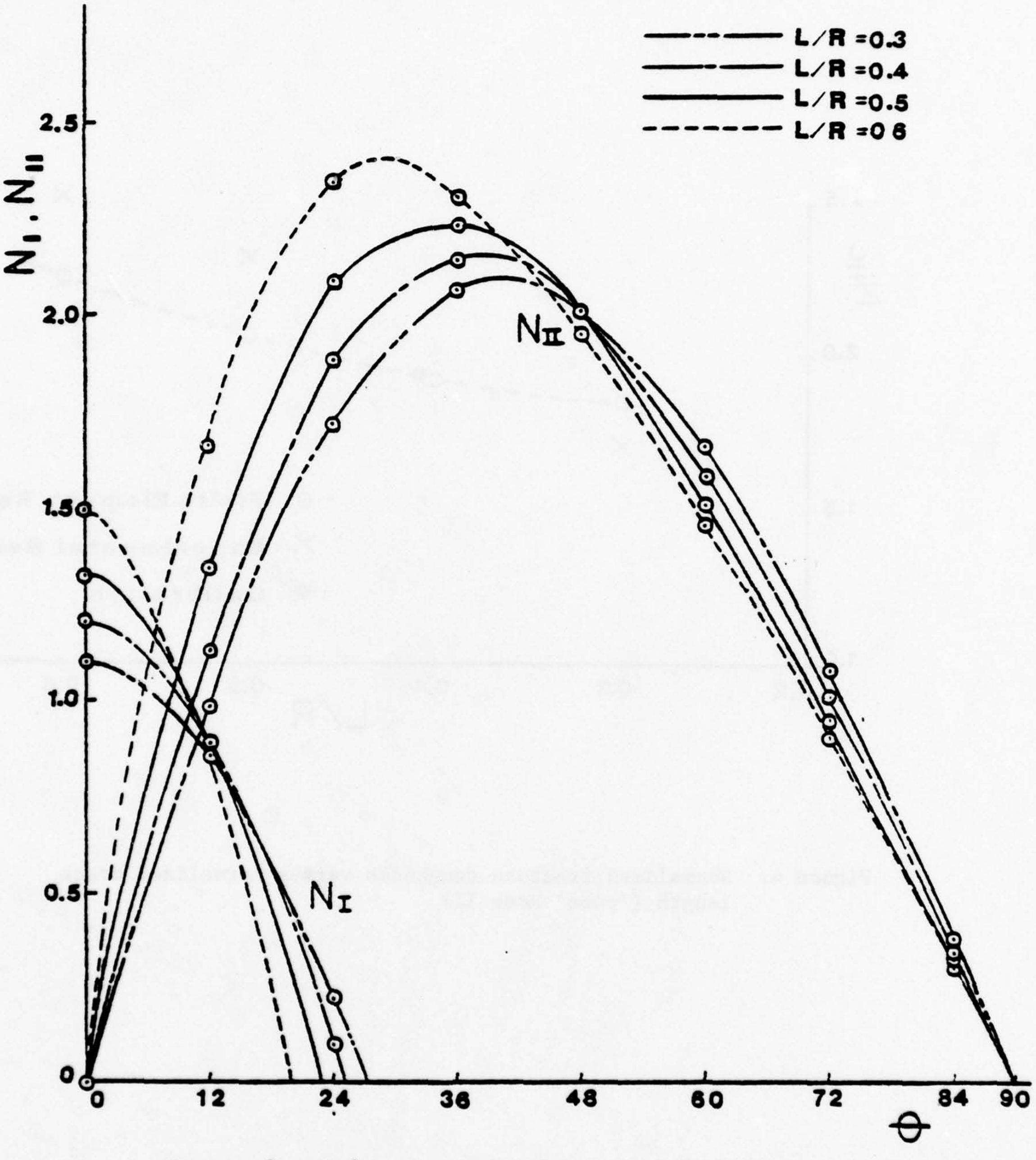


Figure 3. Stress intensity factors of disk subjected to concentrated loads (combined mode I-II loading)

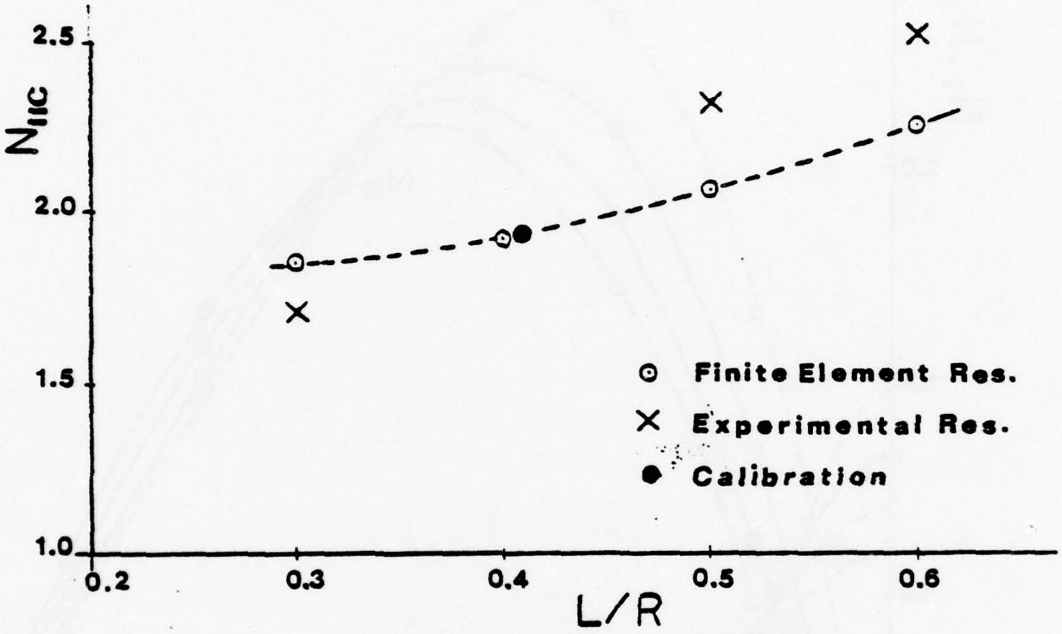


Figure 4. Normalized fracture toughness versus normalized crack length ('pure' Mode II)

Table 1a. Results for Combined Mode I-II Disk Analysis by Finite Elements (*)

	L/R = 0.3		L/R = 0.4		L/R = 0.5		L/R = 0.6	
	Load = 3289.7 lbs.		Load = 2602.5 lbs.		Load = 2086.4 lbs.		Load = 1676.3 lbs.	
θ	K_I	N_I	K_I	N_I	K_I	N_I	K_I	N_I
0°	1110 (**)	1.902	1110 (**)	1.195	1100 (**)	1.322	1090 (**)	1.488
12°	864	0.850	818	0.881	740	0.889	617	0.842
24°	222	0.218	96.5	0.104	-69.4	-0.083	-270	-0.369
36°	-634	-0.624	-776	-0.835	-	-	-	-
48°	-	-	-	-	-	-	-	-
60°	-	-	-	-	-	-	-	-
72°	-	-	-	-	-	-	-	-
84°	-	-	-	-	-	-	-	-

(*) Refer to Figure 1b

(**) K_{IC} value

Table 1b. Results for Combined Mode I-II Disk Analysis by Finite Elements (*)

	L/R = 0.3 Load = 3289.7 lbs.		L/R = 0.4 Load = 2602.5 lbs.		L/R = 0.5 Load = 2086.4 lbs.		L/R = 0.6 Load = 1676.3 lbs.	
θ	K_{II}	N_{II}	K_{II}	N_{II}	K_{II}	N_{II}	K_{II}	N_{II}
0°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12°	-996	0.980	-1040	1.120	-1110	1.334	-1210	1.652
24°	-1740	1.712	-1740	1.874	-1730	2.078	-1710	2.334
36°	-2090	2.077	-1980	2.132	-1850	2.223	-1680	2.293
48°	-2040	2.056	-1850	1.992	-1630	1.958	-1420	1.938
60°	-1680	1.653	-1460	1.572	-1250	1.502	-1060	1.447
72°	-1090	1.072	-929	1.000	-780	0.937	-656	0.895
84°	-377	0.371	-317	0.341	-365	0.318	-222	0.303

(*) Refer to Figure 1b

Table 2. Stress Intensity Factors for Pure Mode II and Angles of Crack for Various Crack Sizes (Finite Elements Solution)

L/R	N_{IIP}	θ_o (deg.)
0.3	1.85	27.7
0.4	1.92	25.2
0.5	2.06	23.2
0.6	2.25	20.0

APPENDIX 3.6

Subcontract

for

A Fundamental Study of the Relationships of Polymer Structure and Time-Dependent Fracture

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ABSTRACT

The Institute of Polymer Science proposes to undertake a one-year study of polymer structure-property relationships to complement a broad program in material fracture at the University of Pittsburgh, currently supported by the Air Force Office of Scientific Research. Particular emphasis will be placed on the time-dependent fracture behavior of cross-linked amorphous elastomers. A systematic investigation of the influence of variations in polymer backbone structure and network architecture on the threshold and rate-dependent fracture energy will be conducted. Insights gained from this study will provide a basis for extension of work to thermosetting resins above their glass transition temperatures. The Interaction Matrix format will be used to separate and categorize structure-property relationships.

OBJECTIVE

The objective of this program task will be to prepare and fully characterize polymer network and morphological structures to correlate with time-dependent fracture behavior of the resultant materials.

PROPOSED WORK

The Institute of Polymer Science will focus efforts on the preparation and characterization of model network polymer structures and some specific mechanical property measurements. The work will be coordinated and complementary with further mechanical characterization and fracture investigations of the same materials systems at the University of Pittsburgh. Initial polymer selection will probably be Solithane^R 113, a commercially available urethane based on castor oil and toluene diisocyanate. This polymer was used extensively in a previous Air Force contract at the California Institute of Technology and is easily prepared with variations in network density and architecture. A substantial data base exists for this material over a range of compositons. A second possibility is ARCO polymer R-45 HT. Extensions to more well-defined structures are possible through the precise control afforded by advance synthetic methods already established at the Institute. Termination-free anionic polymerization techniques with functionalization at predetermined sites along the polymer backbone or at chain ends, allows the degree of control necessary for systematic investigations of molecular structure and relationships to mechanical properties. The volume of effort devoted to these polymers in the initial year will be dependent on their availability, but as a minimum they will provide crucial checks on the conclusions reached from the more abundant materials studied.

The resultant elastomers will be thoroughly characterized by quasi-static and dynamic tests, swelling and sol-gel analysis to obtain information on network architecture, segmental mobility and a variety of viscoelastic parameters. The influence of backbone and network variations on viscous dissipation processes, as might be evidenced in the shear loss modulus "G," will be determined. A specific variation in network architecture expected to have a strong influence on dissipation will be the concentration and size of dangling chains. Effects of hard and soft segments, fillers and plasticizers will be studied as time permits in the initial year of work.

An eventual objective of this work will be an extension to highly cross-linked thermosetting polymers such as the epoxy resins used as composite matrix materials and structural adhesives. These materials have been largely intractable from a network or microstructural characterization viewpoint. However, preliminary efforts examining selected variations of these materials will be undertaken, specifically with regard to behavior in the plasticized state or above the glassy transition. Also investigations of domain structure and its characterization by electron microscopy will be undertaken.

In all cases the coordinated efforts of the University of Pittsburgh and the Institute of Polymer Science at the University of Akron will be directed to the further insights of polymeric material fracture as it relates to material composition and microstructure. An effective tool used by the principal investigators at each institution in the past has been the Interaction Matrix (1). An early attempt to discover first-order structure-property effects governing polymer time-dependent fracture (2) will be extended to include wider ranges of behavior and material variables. It is expected that the thermosetting materials will introduce a new set of compositional and structural variables, but that they will yield important information when systematically examined by the Interaction Matrix format.

APPENDIX 3.7

A Phenomenological Study
on
Oscillatory Melt Flows Associated with Melt Fracture

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PROPOSED WORK

Melt fracture is an instability which occurs beyond a critical flow rate at the outlet of a capillary or slit die. It often limits the capacity of polymer melt processing equipment.

The term "melt fracture" was coined by Tordella in 1956 because of audible tearing noises that accompany the extrusion of grossly distorted melt strands of fractured appearance.

The exact mechanism leading to the occurence of melt fracture has not been identified, as yet. Possible explanations offered in literature are based on a variety of flow effects (inlet and outlet effects, slip at the wall, rheological and flow instabilities, thermal effects). None of the mechanisms suggested has been generally accepted. The controversy that exists in the literature indicates that more basic information on melt fracture is required, in particular, experimental data.

Some of the previous work indicates that the flow instability giving rise to melt fracture originates in the die entry. The leading question of the experimental concept proposed here is how the flow disturbance is propagated throughout the flow system. In other words, if an oscillating vortex pair exists at the die entry, under what conditions is melt fracture going to occur? In fact, the present approach goes a step further; the melt fracture is a manifestation of instability of the entire flow system. Therefore, the whole flow pattern is proposed to be examined while melt fracture is observed at the exit.

The oscillatory stress field in the flowing polymer will be examined as a function of flow rate, temperature, polymer architecture, geometry, and die material. The measurements will be made in a series of "unidimensional" slit dies. The test cells will be fed with polymer using a 1" single-screw extruder.

The stress distribution will be examined using both optical and mechanical measurements. The use of two independent measuring techniques is necessitated by the uncertainty concerning the flow regime, e.g., slip at the die wall. A birefringence apparatus will be used to measure the normal and shear stresses; strain gauges will be used for pressure measurements.

A birefringence measurement of stresses is based on the stress-optical law making use of orientation effects in the melt exposed to flow induced stresses. The average stress levels along with the amplitude and frequency of the stress oscillations will be recorded. Also, a corresponding dynamic measurement of pressure will be made. The stress data will be evaluated throughout the stress field, and the propagation and dissipative mechanisms involved will be analyzed.

The analysis of the oscillatory stress field will be used to interpret the flow exit conditions. This information will be complemented by measurements of the periodic distortions in the extrudate geometry.

Once the controlling transport phenomena will be identified, a basis for theoretical analysis will be formulated.

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APPENDIX 3.8

Study of Ductile Fracture Criteria And Models For Fully Plastic Bodies

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INTRODUCTION

Elastic-plastic fracture mechanics centers on analysis of the plastic zone at the crack tip in a ductile material. The primary objectives are to describe crack blunting and crack growth rates in terms of material properties and microstructure. As in all fracture mechanics analyses, a flaw is assumed to be present initially. Initiation of the flaw, such as a void at an inclusion boundary, however, has largely been overlooked. Modification of microstructure to limit flaw initiation is a valid approach to improving the usefulness of alloys.

In metalworking processes, ductile fracture is a major limiting factor. In this case, initiation of a flaw and early stages of growth are much more important than crack growth rate since the existence of minor flaws is cause for rejection, with consequent material loss. Fracture initiation and growth in fully plastic bodies has been relatively unexplored in terms of fracture mechanics, with macroscopic, experimental observations taking the place of detailed mechanistic understanding.

An empirical criterion for ductile fracture in metalworking processes has been established previously through experimental measurements of strains at fracture in upset compression and bending tests. The criterion is most conveniently expressed in the form of a fracture strain locus, modified by the hydrostatic component of stress. In this form, the process parameters and the material influence can be conveninetly separated, so the criterion may be used readily for design of a material-process system against fracture. An entire system for workability analysis of metalworking processes has been built around this empirical fracture criterion.

For each of the wide variety of materials tested, the empirical fracture locus has the same shape; only the intercepts with the strain axes change with material, temperature, and material condition. (The fracture locus is similar, then, to a yield surface, where the yield strengths constitute the stress axes' intercepts.) Determination of the fracture strain locus intercepts in terms of the material structural characteristics remains as the critical problem for enhanced understanding of workability and improved processing of difficult-to-work materials.

Previous attempts to model the ductile fracture process (e.g. McClintock, Marciniak-Kuczynski, Cockcraft) lead to reasonably accurate predictions of the shape of the empirical fracture locus, but extremely incorrect predictions of the fracture locus intercepts. Each of these models considers primarily the ductile fracture process as a growth and coalescence of holes, without regard for the initiation of holes. The latter factor is the focus of the proposed study. It is expected that improved understanding of fracture initiation will permit accurate prediction of the fracture strain locus intercepts.

A combined mechanics/metallurgy study of the fracture initiation process at points of inhomogeneity (most notably, precipitate particles and inclusions) will be conducted. Simultaneously, a two-pronged study would be carried out, involving (i) a metallurgical study of fracture initiation of a controlled particle-matrix system, and (ii) a micromechanics and dislocation model of fracture initiation. The results would then be combined for evaluation of the models, interpretation of the experimental observations, and identification of the initiation mechanism.

Internally-oxidized Cu-Ti alloys will be used for the metallurgical study. Copper alloys are selected because of their known wide range of interface strengths, high strain-rate sensitivity, and rigid behaviors of the TiO_2 particles. Control of the particle size, shape, volume fraction, and interface strength can be exercised through proper selection of composition and heat treatment.

Prepared specimens of the alloy will be subjected to bending and upset compression tests. The deformation will be applied in small increments so that the progress of deformation and structural damage in the vicinity of the oxide particles can be traced. Characteristics of the initial separation surfaces will also be determined. Optical microscopy, scanning electron microscopy, and transmission electron microscopy will be used for these studies. It is expected that the observations will identify the initiation process (e.g. particle fracture, shear separation, delamination due to tensile stress), as well as the nature of the growth process in a fully plastic body.

Mechanical analysis of the fracture initiation process will include finite element analysis for large deformations (the Matrix Method of Kobayashi used in metalworking analysis) and dislocation mechanics (e.g. that due to Ashby for particle strengthening). Individual precipitates will be analyzed with different assumed values of interface strength and particle strength. Two precipitate particles at various separation distances and orientations to the pricnipal stress directions will also be analyzed to determine the interaction effects. These analytical results will give a description of the stress distributions at and near the particle/matrix interfaces for the various global stress states applied in the experimental tests.

Comparison of the analytical results and experimental observations will indicate the nature of the initiation process. Fractography of the initiation surfaces will reveal the characteristics of the process (i.e. particle fracture, interface shear, interface cleavage, etc.). Results of the mechanical analysis, in combination with these observations, will give the critical values of stress and/or strain for fracture initiation. The relationships between applied global stress state, localized stress states, and the fracture initiation process, will then permit prediction of the fracture locus intercepts. These results would also give the relative importance of particle, matrix, and interface properties on the fracture initiation process.

CURRENT STATUS

Work was initiated on physical modeling of the ductile fracture process through a simulated matrix/inclusion system. Plasticene was used as the matrix material with small spheres or wire sections acting as inclusions. Deformation was carried out by upset compression tests on cylindrical specimens with the inclusions placed at the equator of the bulging free surface. This subjects material in the region of interest to known biaxial tension/compression plane stress states.

Figure 1 is a sequence of photographs showing the evolution of a crack from a single inclusion. Separation of the matrix from the inclusion occurs after about 25% height reduction, and shear bands become evident after 30%

height reduction with severe shear bands and crack propagation after 50% reduction. The shear bands form intiially at the top and bottom contact points with the inclusion (Fig. 1c), and later at the tips of the lenticular voids (Fig. 1d). Similar results are obtained if two inclusions are arranged at various angles to the compression axis, Fig. 2.

All of the results shown previously were carried out at a compression rate of 0.1 cm/min. In tests performed at 10 cm/min, however, the lenticular voids formed but no shear bands developed, Fig. 3. In Fig. 1, the shear bands were responsible for crack propagation in the low strain rate tests, but their absence in the high strain rate tests (Fig. 3) meant that no cracking occurred.

The startling result that shear bands form in the amorphous material (Plasticene) and that shear band formation is strain rate dependent, makes Plasticene an ideal material for study of ductile fracture initiation and propagation in strain rate sensitive materials. Future work will focus on determination of the effects of stress state, strain rate, and inclusion pair orientation on fracture.

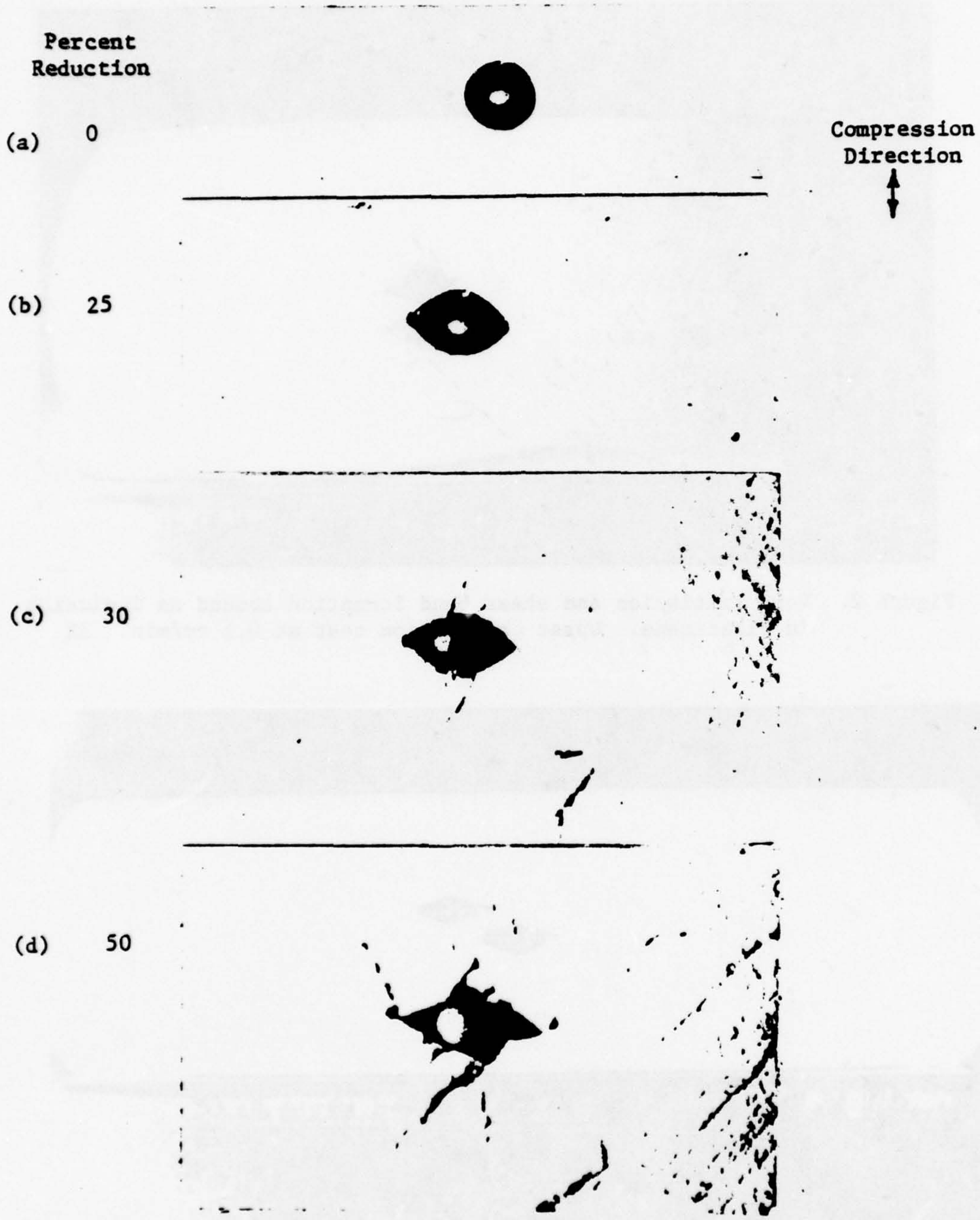

Figure 1. Void initiation and shear band formation leading to cracking around an inclusion. 6X.

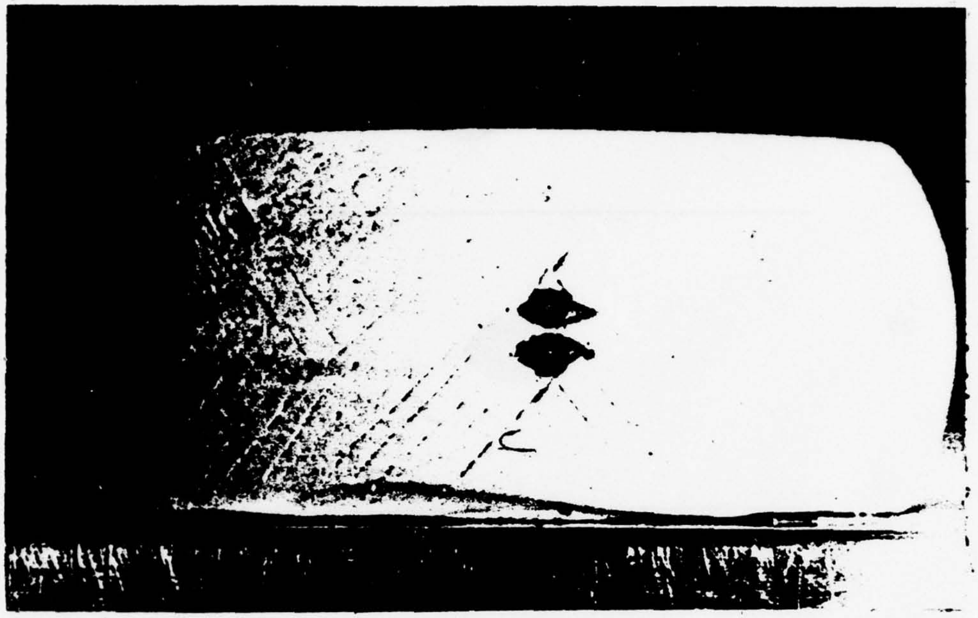

Figure 2. Void initiation and shear band formation around an inclusion in plasticene. Upset compression test at 0.1 cm/min. 3X

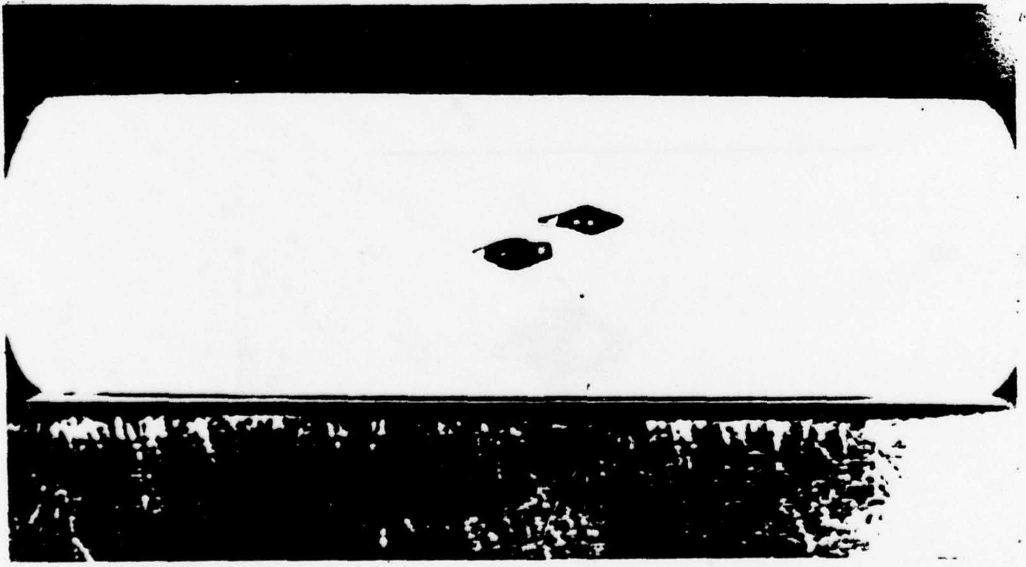

Figure 3. Void initiation around inclusions in plasticene. Upset compression test at 10 cm/min. 3X

APPENDIX 3.9

Evaluation
of
Silicon Based Ceramics

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ABSTRACT

The goal of this work is to study the influence of silicon carbide and silicon nitride powder characteristics on the reproducibilty of final fabricated shapes. To date, work has centered on fabrication and sintering of alpha-silicon carbide without the usual sindering aids. Submicron powder (Lonza Co., 1200 mesh) has been compacted into discs which have been sintered at 1600-1900 C. No sintering aids were added. Initial runs were made using powder compacts 0.50 in. diam. and 0.18 in. thick compacted at 118,000 psi. which yielded a starting density of approximately 58% theoretical. Several runs have been made to isolate difficulties in the experimental design prior to making any comparative runs or preparing sintered compacts suitable for fracture tests.

RESEARCH OBJECTIVES

The goal of this research is to study the influence of the preparation of simple shaped products of silicon based ceramics on the reproducibility of the final product using fracture mechanics as the major indicator. It is not intended to study the final product. Powders that are on hand include carborundum's alpha-silicon carbide premix and Lonza Co. silicon carbide available in a wide range of particle sizing. Silicon nitride powder, although commercially available, will be produced internally using a method developed in this laboratory that yields high purity powder of controlled structure. Efforts will be made to maintain consistency of the samples and not to optimize their properties.

Silicon carbide is normally consolidated by solid state sintering with sintering aids added to the base material. The carborundum material contains sintering aids whereas the Lonza material is not as highly processed and contains no additives. Variables that will be considered include initial particle size, initial compact density, sintering temperatures, additives, and powder activity.

Silicon nitride is normally consolidated by hot pressing. The process is less dependent on additives but small amounts are added industrially to enhance the densification rate.

This work will investigate the preparation of simple geometric shapes of both silicon carbide materials that will be suitable for later measuremental fracture studies.

STATUS OF RESEARCH EFFORT

Sintering of silicon carbide requires high temperatures (1700-2100 C) which varies depending on the variables mentioned in the objectives. An induction furnace has been assembled that allows sintering in vacuum to greater than 2200C. The work to date was centered on trial runs utilizing the Lonza Co. silicon carbide of the same particle size used commercially (5-6 micrometers) and an initial compact density of 58% theoretical. Scanning electron microscopy has been utilized to check any changes in the powder topography and any consolidation that has occurred. Small shrinkages have been measured in the initial runs (less than 2%) but should increase as the temperature is raised and held for longer times.

Efforts are being made to influence the surface activity of the powder during the sintering process by creating a glow discharge around the compact.

APPENDIX 3.10

Instrumentation Science

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INSTRUMENTATION SCIENCE

The thrust of our research in Instrumentation Science during the first year of the Fracture Mechanics program has been towards the development of a current awareness capability of recent developments in the fields of instrumentation with the following three main objectives in mind:

1) to emphasize awareness in the area of Nondestructive Evaluation for detecting inherent flaws in materials;
2) to monitor research activities in other related fields such as medical electronics, geophysics, digital speech, and image signal processing in order to provide an input to our technology transfer team on the applicability to fracture mecahnics of new instrumentation techniques developed in these fields; and
3) to provide advisory support for our research efforts, within the "Science of Fracture" project on the subject of the relationships between the chemical structure of various materials and their mechanical properties.

In order to achieve these objectives, it was initially necessary to focus on instrumentation science in as much as the area of Nondestructive Evaluation (NDE) is concerned. The main problem of concern to the NDE community is how to determine nondestructively whether a certain material has inherent flaws in it, which could affect its useful lifetime. If such flaws exist, the determination of their characteristics becomes a problem of major importance. Recent research in this area has mostly emphasized the development of techniques whose ultimate objective is to determine as accurately as possible the type of flaw (whether it is a crack or an inclusion), its location and its shape and size. In the last decade or so, techniques such as Eddy currents, Acoustic emissions, Acoustic microscopy, Ultrasonics and others have been considerably explored towards meeting this objective. The most recent results on these techniques have been reported (1) at the "ARPA/AF Review of Progress in Quantitative NDE" meeting which was held at the Scripps Institution of Oceanography, July 9-13, 1979.

Although, as pointed out at this meeting, the potential benefits of any successful NDE technique are tremendous; the cost of the associated

a) Transducers Configuration

The main requirements for NDE ultrasonic transducers are high efficiency and broadband impulse response. If the system is designed to detect the presence or absence of a flaw, typically one transducer is sufficient. If however, the objective is to determine the flaw characteristics, then an array of transducers is, in most cases, required. Although, at present, most flaw characterization research is based on single-transducer data, we feel that ultimately arrays of transducers need to be investigated more thoroughly. Besides the capability of two and three dimensional imaging, array data has the advantages of increased resolution, improved signal to noise ratio after preprocessing and sharper focusing. These advantages have been demonstrated in other engineering fields such as radar, sonar and biomedical as well as through recent NDE research on hexogonal arrays (1). We feel that additional emphasis should be placed on the use of arrays in NDE systems so that the full potential of possible transducer configurations can be exploited.

b) NDE Signal Processing

In any NDE system, the acquisition of data is only one step towards the final objective of flaw characterization. The other step is that of processing the data in order to extract the desired information. Despite the complexity of this step, it seems that it has received the least attention in NDE research. In its simplest form, the mathematical model of the measured signals can be represented as a convolution of the emitted pulse and the structural characteristic function of the material including its front and back surfaces and the flaws if any. Because of the band limited nature of the emitted pulse, interference among all the scattered waves almost always occurs. This makes it impossible to differentiate among the reflections due to the boundaries of the flaw and the boundaries to the material. For this reason, special processing instrumentation is needed to remove this interference and separate the various signals. The majority of NDE processing techniques are presently limited to simple filtering and analysis in time and frequency domains by comparisons with synthetically generated data obtained from materials having flaws of known characteristics. While these techniques have been successful in some special cases, as experiments have already demonstrated (1), their usefulness in practice is unfortunately very limited. The reason being that flaws in general, seldom have characteristics that coincide, even roughly, with synthetic flaws for which NDE data can be generated. It is our opinion that if accurate information about flaw characteristics is needed, then more sophisticated processing of the signals, requiring perhaps more complicated hardware, needs to be performed. In particular, it may be worthwhile to mention that the fields of image processing (2), speech processing (3), and geophysical processing (4) have all exploited the most recent advances in the area of digital signal processing (5,6). Techniques such as digital Weiner filtering, predictive filtering and homomorphic filtering have all been successfully implemented to solve a wide spectrum of signal processing problems in these fields. Because NDE problems are similar in nature to those associated with image, speech and geophysical data, it is our belief that the effectiveness of future NDE systems can only be improved if these techniques were to be exploited in the context of processing ultrasonic data.

In conclusion, we feel that NDE systems can be more effective in meeting future requirements of flaw detection and characterization if more emphasis is placed on (i) the development of transducer arrays for source and receiver systems, and (ii) the incorporation of recent advances in the area of digital signal processing at the hardware level of ultrasonic systems.

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APPENDIX 3.11

Data Base and Repository

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A summary of data sources investigated during the past year is given below.

THE INTERFACE CRACK PROBLEM

Fracture surfaces occur as a separation in similar material or along an imaginary surface between two different materials. The first case is denoted by the term cohesive fracture and has been the subject of extensive investigation. The literature for the latter one, especially when treated by continuum mechanics, is not as extensive. One of the key problems is the fundamental difference between cohesive and adhesive behavior when viewed as a classical elasticity problem.

Using retrospective literature search techniques, "benchmark" papers were tabulated (Section 3.11.1) using generally available journals. Apparently the first stress analyses were contributed by Volkersen (1938) and Goland and Reissner (1944), the first theoretical treatment of the problem, as a singular stress problem in elasticity by Williams (1959) and the first extensive engineering tests for lap shear joints by Ripling, Mostovoy and Patrick (1964).

The recent (1970-1980) contributions to the interface crack problem are presented in 3.11.2. Several new items appear as references although they have not as yet appeared in print. The articles were accepted for publication in the International Journal of Fracture, which has its editorial office at the University of Pittsburgh. The feature article "Stress Singularities and Fracture Mechanics" by Colin Atkinson appearing in Applied Mechanics Reviews (1) proved to be extremely useful. Dr. Atkinson included an extensive list of references, (not included in 3.11.2), many of which were not only pertinent but led to others of interest.

THE FIBER PULL-OUT PROBLEM

The fundamental "building block" in composite materials, e.g. glass fiber reinforced plastic, is a single, finite, cylindrical rod embedded in an infinite matrix. The rod, or fiber, may be either partially or totally embedded in the matrix. Both problems are of interest, and the former has been the subject of an experimental study by Betz (2) under this project. For this reason, a survey of the recent literature (3.11.3) was conducted as well as a retrospective search to identify the significant papers in this area (3.11.4). Only 6 historical papers were included, dating from what appears to be one of the first important papers (in English) in the field, published in the Proceedings of the Royal Society, London in 1964.

NON-DESTRUCTIVE TESTING

One of the major areas of endeavor under this project's current awareness effort is Instrumentation Science. This category includes new instrumentaion of possible general interests for new or more efficient measurement of basic materials behavior, and in particular techniques to examine the structural integrity of components or assemblies, the latter including the quality of adhesive bonding between similar or different materials. Generally, this subject has been called non-destructive testing (NDT), non-destructive examination (NDE), or non-destructive inspection (NDI).

Among others, the Department of Defense has been vitally concerned with the NDE effort, currently sponsoring a relatively large program at the Rockwell Science Center, Thousand Oaks, California, ARPA/USAF supervision. In addition, the Army supports the Non-Destructive Testing Information Analysis Center (NTIAC), at the Southwest Research Institute, San Antonio, Texas. The former has been mainly concerned with ultrasonic methods and sponsorship of the annual conference on NDE, and the latter has tended to emphasize acoustic emission, but also publishing newsletters of more general coverage. The NTIAC newsletters of December 1978 (3) and August 1979 (4) are of particular interest because of their state-of-the-art nature. Both installations have been visited by University of Pittsburgh representatives. Dr. M. Simaan of the University of Pittsburgh attended the ARPA/AFML meeting for review of Progress in Quantitative NDE at the Scripps Institution of Oceanography in LaJolla, California, July 8-13, 1979 in order to "get acquainted with the latest research results that have been generated by the Science Center, Rockwell International, for the Advanced Research Projects Agency and the Air Force Materials Laboratory." (5) For completeness a list of present methods employed for instrumentation at both the research and the development stages can be a severely limiting factor. Because of the large effort being spent in this area and the many approaches and systems presently under investigation, the need for centralized awareness in NDE techniques and instrumentation developments as well as similar developments in other engineering fields which could be used in NDE work can be of substantial benefit in minimizing duplication in research efforts and in determining what can be transferred in terms of instrumentation technology.

Regardless of the application, typically an NDE system consists of a source (except for acoustic emissions) and receiver combination and signal processing hardware which ultimately extracts from the measured signals, the necessary information for characterization of the flaw. The development of such a system must take into consideration the following factors:

1) Source and Receiver Characteristics
    - Transducers configuration
    - Transducers type
    - Transducers location and coupling mechanism
2) Processing Techniques for NDE Signals
    - Time domain analysis
    - Spectral analysis
    - Deconvolution methods
3) Flaw Characterization
    - Signal interpretation
    - Flaw type, location, shape and size.

These factors have all received a considerable degree of attention in the development of recent NDE systems. Nevertheless, we feel that two of these factors: the transducer configurations and signal processing techniques as related to ultrasonics, need to be considered at a higher level of intensity than what the present literature indicates. Ultrasonic systems, because of their high resolution, are probably the most promising for future applications and unless new advances related to transducers configurations and signal processing are made, the development of such systems will, in most likelihood, not be able to meet the stringent requirements of future NDE specifications.

NDT and NDE include:

- A. Conventional non-destructive examination
  1. Radiography (x-ray and neutron)
  2. Radiographic enhancement dyes
  3. Ultrasonics
  4. Visual
  5. Dye penetrants
- B. Emerging techniques
  1. Radioactive gas
  2. High frequency ultrasonics - defect detection
  3. Microwave
  4. Laser acoustic microscopy
  5. Acoustic emission
  6. Laser photoacoustic spectroscopy
  7. Acoustic property measurement - environmental effects.

For our internal purposes, concern has tended to be focussed mainly upon signal recognition and processing due to our Pattern Recognition Laboratory. Hence, a general bibliography on acoustic emission used in non-destructive testing was prepared and followed by another of selected references on characterization, propagation and processing of acoustic signals (3.11.5 and 3.11.6). The following areas of interest were used as the guidelines for both bibliographies.

- A. Source and receiver characterization of acoustic signals for non-destructive testing
  - 1) Source and receiver location coupling
  - 2) Source and receiver mechanism
- B. Processing techniques for non-destructive signals
  - 1) Spectral analysis
  - 2) Inverse method
  - 3) Deconvolution
  - 4) Interpretation
- C. Flaw and adhesive bond characteristics by acoustic techniques
  - 1) Flaw location, size and shape
  - 2) Bond strength

D. Propagation properties of acoustic signals in materials

1) Velocity
2) Dispersion
3) Scattering

DISLOCATION ANALYSIS OF FRACTURE

While most fracture analyses are conducted using elasticity or elastoplasticity as formulated in terms of continuum mechanics, there is another approach which consists of constructing, say, along a line which turns out to be the (mathematical) crack, a density distribution of dislocation adjusted in such a way that the faces of the crack are stress-free as physically required. This approach is well understood by most metallurgists, and insofar as equivalent results are obtained by either method, it was thought worthwhile to make at least a cursory check of the fracture mechanics literature to verify how frequently the metallurgist's approach was published there.

Hence a retrospective search of the index of the International Journal of Fracture produced a list of authors with papers on dislocations that have appeared in the Journal since 1965. Their geographic location was determined with approximately half located in North America (3.11.7).

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3.11.5 ACOUSTIC EMISSION

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1974

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3.11.7 DISLOCATION PAPERS

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1966

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1968

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1974

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1975

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1977

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1978

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1979

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APPENDIX 3.12

Professional Personnel

University of Pittsburgh

Faculty, School of Engineering

Max L. Williams, Jr.	Professor & Dean, School of Engineering
Jean R. Blachere	Assoc. Prof., Met/Mat. Engineering
John F. Fleming	Assoc. Prof., Civil Engineering
Howard A. Kuhn	Professor, Met/Mat. Engineering
Jan T. Lindt	Visiting Assoc. Prof., Met/Mat. Engr.
Richard L. Porter	Asst. Prof., Met/Mat. Engineering
Marwan Simaan	Assoc. Prof. Elec. Engineering
Shan Somayaji	Asst. Prof., Civil Engineering
Campbell C. Yates	Professor & Chairman, Mech. Engineering

Faculty, Other Schools, (Advisory)

Werner C. Rheinboldt	Andrew Mellon Professor, Math. Depart.
George A. Jeffrey	University Professor, Crystallography

Graduate Students

Jaime' Sanchez	M.S., Spring Term 1978-79
Jose' Avila	
Mary Jane Kleinosky	

Visiting Professors at University of Pittsburgh

Eric Betz	Dept. of Mech. Engr., Univ. of Newcastle
Colin Atkinson	Math. Dept., Imperial College, London

University of Akron

Frank N. Kelley	Dir. of Institute of Polymer Science
Patricia Dreyfuss	Res. Assoc., Institute of Polymer Science

Graduate Students

Long-Ji Su

Brian Swetlin

University of Texas, Austin

Eric Becker	Prof., Aerospace Engr. & Engr. Mech.
J. T. Oden	Prof., Aerospace Engr. & Engr. Mech.

Graduate Students

Amin Aly

Patrick LeTallec

APPENDIX 3.13

Interactions, Meetings and Conferences

Person(s)*		Place & Date	Subject
P. Cannon, D. O. Thompson Rockwell Science Center M.L. Williams, U. of Pgh.	**	Thousand Oaks California 5/18,19/78	NDE Data Center
R. M. Christensen, Lawrence Livermore Lab. M. L. Williams, U. of Pgh,	**	Livermore, Calif.	Fiber Pull-Out Problem
S. Batdorf, UCLA M. L. Williams, U. of Pgh.	**	Los Angeles California 5/18,19/78	Statistical Fracture Analysis
C. Atkinson, Imperial College, London	**	Pittsburgh 5/23,26/78	Fiber Pull-Out Problem
E. S. Folias, Univ. of Utah	**	Pittsburgh 7/15,16/78	3- Stress Singularity
S. Batdorf, UCLA		Pittsburgh 1/18,19/79	Weibull Fracture Analysis
A. G. Evans, UCB M.L. Williams, U. of Pgh.		UCB	Micro-Macro Characterization
J. T. Oden, U. of Texas W. Rheinboldt, Dept. of Math., U. of Pgh.		Pittsburgh 2/15/79	Finite Element Methods
Garron P. Anderson, Thiokol Corp.		Pittsburgh 2/23,24/79	Finite Elements Rod Pull-Out Problem
A. T. Oden, E. Becker, Univ. of Texas, Austin M.L. Williams, U. of Pgh.		Austin Texas 3/14,15/79	Non-Linear FEM
P. Francis, Southwest Research Institute M.L. Williams, U. of Pgh.		Albuquerque N.M. 3/15/79	NDE Data Center
E. S. Folias, U. of Utah T. Kawai, U. of Tokyo R. Smelser, U. of Pgh.		Austin, Texas 3/29/79	3-D Problem Coord. Conf.
A. E. Atkins, Delta Materials Research, Suffolk, England		Pittsburgh 4/15/79	Adhesive Fracture
M.L. Williams, M15/515 Briefing		Annapolis, MD 4/25,26/79	Fracture Applications

*Pittsburgh conferences and meetings attended by faculty working on the project and by other interested faculty.

**Planning conferences and meetings prior to award of contract.

Person(s)*	Place & Date	Subject
F. N. Kelley, U. of Akron M. L. Williams, R. Smelser U. of Pgh.	Cincinnati Ohio 5/1-4/79	Structure-Property Relation for Polymers
J. Morgan, AFOSR M.L. Williams, U. of Pgh.	Cincinnati Ohio 5/1-3/79	Progress Reports
M. Gomey, J. L. Kardos Washington Univ. M.L. Williams, U. of Pgh.	St. Louis MI 5/14,15/79	Polymer Characterization and Numerical Methods
R. C. Phoenix, Carborundum Corp. M.L. Williams, U. of Pgh. (no charge to contract)	Niagara Falls 5/22/79	Inspection of new Powder Metallurgy Lab.
F. N. Kelley, U. of Akron M. L. Williams	Akron, Ohio 5/29,30/79	Structure-Property Relationships
M. Simaan, D. Reynolds U. of Pgh. Visit to Alcoa Research Center	New Kensington, PA 6/4/79	NDE Methods for Metals
J. Morgan, AFOSR M.L. Williams, C. C. Yates U. of Pgh,	Wash. DC 6/14/79	Progress Reports
F. N. Kelley, U. of Akron M.L. Williams, U. of Pgh.	Akron, Ohio 6/15,16/79	Structure Property Relationships
M. Simaan, C. C. Yates U. of Pgh.	San Diego, California 7/8-13/79	ARPA/AF Progress Review, NDE
J. Morgan, AFOSR M.L. Williams, U. of Pgh.	Washington, DC 8/10/79	Progress Report
C. A. Rau Failure Analysis Associates M.L. Williams	Palo Alto CA 8/17/79	NDE Methods
E. S. Folias, U. of Utah M.L. Williams, U. of Pgh.	San Diego Calif. 8/23,24/79	3-D Stress Singularity
G. F. Anderson, Thiokol Corp. M.L. Williams, U. of Pgh.	Salt Lake City, Utah 8/27,28/79	Fiber Pull-Out Problem Parametric Study

Person(s)*	Place & Date	Subject
K.L. DeVries, U. of Utah M.L. Williams, U. of Pgh.	Salt Lake City 8/29/79	Polymer Micro-Fracture
Smithsonian Information Exchange, M. C. Williams	Wash. DC 9/4-7/79	Data Base and Repository Visit
ONR Fracture Conference M.L. Williams	Wash. DC 9/4-7/79	National Fracture Conference