MEASURING/PREDICTING THE ADHESION
OF POLYMERIC COATINGS

by

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ABSTRACT

Critical to the performance and reliability of microelectronic structures is the adhesion between the various constituent materials. Since most devices are fabricated with many different materials, large thermal stresses develop during processing. These can lead to interfacial failures; thus, to design reliable parts it is necessary to have a true measure of the interfacial integrity. To this end, the Edge Delamination Test (EDT) has been developed. The EDT measures the energy required to cause a thin film, under biaxial tensile stress, to debond from a rigid substrate. Circular holes are etched through the films and if the stress is large enough, stable debond rings grow radially around the holes. A finite element analysis is used to find the applied strain-energy release rate as a function of debond crack length, hole radius and side-wall angle. To facilitate widespread use of the test, tables of reduced debond energy values, $G_r$, are presented. With observed EDT results, $G_r$ is extrapolated from the tables and then the critical debond energy is calculated by multiplying $G_r$ by the maximum strain energy. Also, $G_r$ is fit with a semi-empirical equation, which is in good agreement over a broad range of geometries. Experimental EDT results are presented. The results demonstrate the usefulness of the test for measuring the effect of processing and material selection on interfacial debond energies.

A method to predict the ultimate adhesion performance of coating materials subjected to biaxial, tensile stress is also presented. A set of equations are developed to predict the onset of failure when the locus of failure is cohesive in the coating. These compare the stress to the coating's ultimate strength and fracture toughness; when the stress surpasses a critical point failure is predicted. Since this stress is due typically to thermal expansion mismatches between the coating and the substrate, one can predict the temperature at which a coating will debond. The equations also have been extended to predict fatigue lifetime when a coating is cycled from a low temperature to room temperature.

To validate these, the Edge Lift-off Test (ELT) was developed. It consists of fabricating coatings of various heights on a rigid substrate and dicing the latter, so the edges are $90^\circ$ to the interface. The parts are cooled and the
temperature of debonding is recorded. For the thermal fatigue validation, the parts are cycled between low and room temperatures. The number of cycles at which the first debond is observed is recorded. ELT results have been collected for a typical epoxy for both monotonic and cyclic cooling. The results are in good agreement with the predictions.

Thesis Supervisor: Prof. F. J. McGarry
Title: Professor of Polymer Engineering
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CHAPTER 1: INTRODUCTION

1.1 Background

More and more, the microelectronics industry is pushed to increase the density of components to meet the performance and cost requirements demanded by customers. One technology that promises to meet this need is thin-film packaging [1,2]. Thin-film packages are processed with methods similar to those used for integrated-circuit chips, thus, yielding a high density of interconnects. Both use photolithography to define electronic elements and interconnects into the package. Thin-film packaging consists of three classes of constituent materials: substrate, conductor and insulating dielectric layers [3,4]. An illustration of a typical thin-film multichip module (MCM-D) is shown in Figure 1-1. MCM-D’s range from 2 to 6 dielectric layers each 5 to 25 μm thick on a silicon or ceramic substrate. The dielectric layers are polymeric because of their electrical and processing properties [5,6]. A schematic of a via interconnect used to connect the various signal levels in a thin-film package is shown in Figure 1-2. Thin-film packaging is one of the fastest growing technologies and is predicted continue into the 21st century [7].

One area of concern to both customers and MCM-D manufacturers is the reliability and service life of the module. For the customer, these failures manifest themselves as changes in the electrical characteristics of the package, consequently, most reliability testing consists of monitoring the electronic signals as a function of some prescribed test [7]. For example, one can monitor the change in resistance across a chain of vias as a function of thermal cycling.
If the resistance increases too much the part is said to have failed. These tests are repeated for numerous samples in order to build a distribution of failures. Other tests include accelerated aging at high temperature, high humidity (85°C/85%) and high temperature voltage bias testing [7].

![Diagram of a typical thin-film multichip module](image)

Figure 1-1: Illustration of a typical thin-film multichip module [7]. An MCM consists of multilayers of metal lines built on a rigid substrate with a polymer as the dielectric passivation between layers.

For the manufacturer, these tests provide statistics for the likelihood of failure for that module, but any modification either to the materials or to the processes used to fabricate the device requires a new set of data to construct the reliability distribution. This is because the tests do not focus on the sources of failure, only their manifestation. So, the design engineer is left with nothing more than historical data to assist in the selection of materials and processes for optimizing reliability.

One reason for the popularity of the above test is that the sources for failure in a multichip module are numerous. MCM's are complicated composites made of metal, ceramic and polymer, which undergo large temperature ranges during fabrication. These changes generate large thermal stresses due to the mismatch in coefficients of expansion between the
materials. They can cause adhesive and cohesive failures in the module. High temperatures also increase the potential for side reactions between the materials that can yield corrosive environments and lead to degradation.

Figure 1-2: Illustration of metal via interconnects in a MCM. The metallizations and dielectric layers are built sequentially. Interconnects can span one to all of the layers.

Of concern to this research are adhesive failures due to the large thermal stresses that develop during processing. The magnitude of these stresses is a function of the material properties, the processing temperature and the geometry of the module. The stress fields are complex; to achieve reliability, the engineer must be able to calculate the stresses and compare them to an experimentally determined critical property of the interface. One method used to calculate stress is finite element analysis (FEA) as done in references [8-11]. FEA has the advantage of being able to model complex geometries, material non-linearities and a variety of loading conditions. Then, based on the relative intensities of stress and previous observations of module failure, one can judge the probability of failure for the given geometry. However, to predict the reliability of a design, failure criteria must
be available to compare to the calculated stress fields. Such criteria can be based on the ultimate strength or the fracture toughness for cohesive failure, or, on the critical debond energy for adhesive failure. The criteria must be measurable for a variety of experimental conditions including thermal shock, thermal fatigue, and humidity testing.

The challenge for an adhesion test is twofold. First, it must be performed within certain limitations of the device. For example, four-point bend tests [12] are commonly used to measure the adhesion of thin coatings, but because of the high stiffness of silicon substrates this test method is not practical. Second, the results should measure a critical parameter such as the adhesion energy, $G_C$. The critical parameter should reflect an intrinsic property of the interface and not be a function of test geometry and material non-linearities.

1.2 Current Adhesion Tests

Available in the literature are numerous methods for measuring adhesive strengths of thin film coatings [13] and reviews of the subject [14-18]. The selection of an adhesion test is based on several requirements dictated by the application and material limitations, however, the goal of all of them is to extract a meaningful measure of adhesion. It should be comparable between systems and be able to guide in future module designs. In microelectronics, peel tests and blister tests are used predominately. Other tests commonly used include the scratch test and indentation test. In many of these tests, the measured critical parameter is a force, which is confounded by extrinsic effects such as test geometry and material properties. Thus, the critical force cannot
be used as a predictive tool for failure in other more complicated geometries. Also, it is impossible to relate it to any cohesive fracture or strength measurement of the coating, so, it is not useful to predict the lifetime of an interface in a thermal fatigue experiment. Descriptions of the tests with their advantages and disadvantages are given in the following sections.

1.2.1 Peel Tests

The most common method for characterizing the performance of a coating is the peel test [19-22]. The peel test is illustrated in Figure 1-3. It consists of applying a load to the free end of the coating that is partially debonded from the substrate. When the load reaches a critical level, the debond grows. The test is quantified by the load required to propagate the crack reduced by the width of the film. The adhesion energy, \( \gamma_a \), can be calculated in an elastic system by dividing the critical load by the width of the film. The limit of the elastic analysis is:

\[
\frac{6EP}{h\sigma_y^2} < 1 \tag{1-1}
\]

where \( E \) is the modulus of the coating, \( P \) is the critical load, \( h \) is the coating thickness and \( \sigma_y \) is the yield stress of the coating [23,24]. For polyimides on copper coatings this condition requires film thicknesses greater than 500 \( \mu m \), which is well above typical film thicknesses in microelectronic applications.

To increase the applicability of the peel test a "Universal Peel Diagram" concept was developed by Kim et. al. [23]. From the thickness and the peel measured force, the adhesion energy, \( \gamma_a \), is calculated, but to use the diagram requires an exact description of the stress-strain behavior of the coating and
the substrate. For most systems used in microelectronics the adhesion energy is 1 - 2% of the total applied energy. Hence, use of the peel diagram is difficult since large errors can arise.

![Diagram of the peel test](image)

**Figure 1-3:** Schematic of the 90° Peel Test. The rigid substrate is mounted to a sliding stage such that as the coating is peeled the angle of the peel force remains 90°.

Because of the ease of sample fabrication and testing the peel test is still used extensively. Although the analysis for the true adhesion energy is difficult, the test can be used quite effectively for measuring relative changes in the work to debond an interface. Work at MIT [25] to calculate the strain energy release rate for the interface from measured peel forces using FEA, has shown the complexity of the problem.
1.2.2 Blister Tests

The blister test consists of applying a uniform pressure across a membrane [26]: when the pressure reaches a critical level debonding, along the edge will occur. Many blister geometries are used, as illustrated in Figure 1-4. Early analyses used continuum mechanics to relate critical pressures to the adhesion energy [27-29]. Later improved energy balance methods were used to derive a more accurate adhesion energy fracture criterion [30,31], but these ignored large scale dissipative mechanisms, residual stress and did not account for fracture mode mixity. Jensen [32,33] used linear elastic theory developed for bimaterial interfaces [34] to account for mode mixity and the residual stress effects on the blister analysis. More recent integral equations have been developed that relate the strain energy release rate to critical pressures and volumes of debonding [35].

In the standard blister test, most of the energy applied is used in large scale deformation of the blister instead of being applied to the interface. As a result, cohesive ruptures are likely to occur in the blister before debonding does. To reduce the likelihood of ruptures, Senturia and Allen [36-38] developed the island blister test (IBT). Finite element methods analyze the plastic energy dissipated in the test and to directly measure the adhesion energy. [39,40] The IBT is effective for measuring the debond energy of strongly adhered films. However, the test is very difficult to fabricate, perform and analyze. Other modifications to the blister test include the peninsula blister test [41-44], which reduces the ratio of the rupture stress to the debonding stress ratio further improving the efficiency of the test.
Figure 1-4: Illustrations of blister test geometries: (a) Standard Blister Test, (b) Constrained Blister Test, (c) Island Blister Test and (d) Peninsula Blister Test.
However, the full analysis of the peninsula blister test has not been completed.

1.2.3 Scratch Tests

Scratch testing, Figure 1-5, consists of dragging a stylus across the film while applying large normal and longitudinal forces, until the film fails, resulting in a clear channel [45-47]. This is easy to perform and requires only a small area of the coating, but the fracture process is very complicated, so no analysis of the adhesion energy is possible [48]. Recent modifications to the scratch test include the micro-wedge test [49]; again, determination of true adhesion energies is confounded by material and geometry factors.

![Diagram of Scratch Test]

Figure 1-5: Illustration of the scratch test.

1.3 The Edge Delamination Test

As noted, electronic assemblies can develop large residual stresses after thermal processing; the edge delamination test (EDT) uses these to induce
delamination from the substrate [50-54]. Thus, it avoids many of the complications of other tests which apply external loads for debonding.

Previous work has shown that the strain energy density is sufficient to delaminate coatings when it is released by an interfacial crack. In 1988, Farris and Bauer [52] used large circular geometries to debond polyimide from glass. They analyzed the debond energy assuming plane stress through the thickness of the film and then solving the stress equations for a large hole. They found values of 3.1 N/m for \( r/h = 200 \) and 3.4 N/m for \( r/h = 157 \) where \( r \) is the radius and \( h \) is the film height. Hu, Thouless and Evans studied the delamination and cracking of chrome on glass substrates for plane strain geometries. Similarly, Choi and Kim [53] studied the delamination of polyimide from glass by cutting slits in the coating. With a finite slit they measured the mode I and mode III energies for delamination. Jensen, Hutchinson and Kim [57] also tested polyimide/glass adhesion using a large circular geometry and a slit for a single sample. Although these previous approaches are limited in scope, they demonstrate the usefulness of such geometries.

Illustrated in Figure 1-6, the EDT has circular holes etched into the coating adhered to a rigid substrate. The geometry is characterized by the hole radius, \( r \); the debond length, \( a \); and the side-wall angle, \( \theta \). A biaxial tensile stress, \( \sigma_0 \), arises from the differential thermal expansion and, in the simplest case, is given by:

\[
\sigma_0 = \frac{E\Delta\alpha\Delta T}{(1-v)}
\]

where \( E \) and \( v \) are the Young’s modulus and the Poisson’s ratio of the film, \( \Delta\alpha \) is the difference in thermal expansion coefficients of the film and the
substrate, and ΔT is the change in temperature for linear elastic materials. An analysis of $\sigma_0$ versus ΔT for linear viscoelastic materials has been done by Margaritis [55]. The relationship between $\sigma_0$ and ΔT also can be measured: the Tencor Flexus measures the curvature of the wafer as a function of temperature and time, which permits the calculation of the stress. In the EDT, the stress can be increased by cooling the part below room temperature.

![Diagram](image)

**Figure 1-6:** Illustration of the Edge Delamination Test. The results are characterized by the radius of the hole, r; the length of the debond a, the height of the film h; and the via angle $\theta$.

The EDT has several advantages. First, the dimensions of the hole are small compared to the radius of a typical silicon wafer, so, hundreds of tests can be performed with a single sample. Second, different portions of the wafer may have different surface treatments, allowing the experimenter to evaluate several variables with a single sample. Third, the features can be incorporated in an actual microelectronic device and monitored during
processing as a means of quality control. Finally, many of the complications of fabricating, testing and handling films or test pieces are avoided since no external loads are applied, but since the test relies on the residual stress to induce delamination it is limited to those cases where either sufficient film thickness or residual stress can be generated. It also cannot handle films of high fracture toughness; currently it is limited to brittle materials.

1.4 Edge Lift-Off Test

A simplified version of the EDT is the Edge Lift-Off Test, ELT, which is the plane-strain limit of the EDT. The advantage of the ELT is that the edge can be fabricated by scoring the coating and the substrate and cleaving the sample. This avoids the necessity of exposing the sample to harsh processing environments. The disadvantage of the ELT is that fewer samples are yielded per wafer.

1.5 Objectives and Goals

In this dissertation, methods for measuring and predicting the adhesive reliability of polymer coatings are presented. The failure criterion used is based on the energy required to cause debonding, or, the critical strain energy release rate. Although most of this dissertation applies these techniques to microelectronic applications, they can be used anywhere coatings are under biaxial, tensile stress.
In Chapter Two, a finite element analysis characterizes the applied strain energy release rate for the EDT as a function of debond length, hole radius and side wall angle. The results are compared to previous analytical solutions of simpler geometries to validate the accuracy of the model. To simplify the analysis, an equation is developed to calculate the debond energy for EDT results. The equation is in good agreement with the numerical results over a broad range of geometries. The effect of introducing a compliant layer between the coating and substrate also is investigated.

In Chapter Three, these techniques are applied to surface mounted assemblies such as leadless interconnects and Flip Chips, to demonstrate their use in real applications. The complication of the Flip Chip is that the adhesive is triaxially constrained. The maximum debond energy for a plane strain steady state crack for such a system is found, then (as for the EDT) the debond energy is solved numerically for a variety of geometries and materials used in the leadless interconnects.

In Chapter Four experimental results from the EDT are presented. These experimental data are collected for materials and substrates used currently in the MCM-D industry. The usefulness of the EDT for measuring the effects of processing on the interfacial strength is presented. Also presented are humidity results that demonstrate its utility for tracking adhesion exposed to moisture.

The Edge Lift-Off Test is analyzed in Chapter Five. From this, several rules for predicting the adhesive reliability of a coating are developed. The predictions assume the existence of an intrinsic flaw in the coating near the interface. When the applied debond energy there exceeds the fracture
resistance of the coating, debonding occurs. To validate the predictions, the Edge Lift-Off Test is applied to several epoxy resins. Predicted adhesion and experimental ELT results are presented. Next, these rules are extended to predict cyclic lifetimes of an interface that is thermally cycled. Again, experimental results are compared to the predicted lifetimes; they are in good agreement. Reliability rules are also derived from the Flip Chip analysis done in Chapter 3. Finally, in Chapter 6 conclusions and recommendations for future work are presented.
2.1 Introduction

Previous analyses of interfacial cracks have been performed using linear-elastic fracture mechanics, as described in Section 2.2. However, these results are limited to very specific geometries. To analyze the fracture of the EDT, numerical methods are used, described in section 2.3. The results from the numerical analysis are presented in section 2.4. Comparison to the analytical solutions is used to confirm the validity of the analysis. The effect of geometry on the applied debond energy for the EDT is analyzed. In section 2.5 tables of reduced debond energy values, $G_r$, are presented to facilitate the use of the EDT. With observed EDT results, $G_r$ is extrapolated from the tables and then the critical debond energy is calculated by multiplying $G_r$ by the maximum strain energy. Also, $G_r$ is fit with a semi-empirical equation, which is in good agreement over a broad range of geometries. In Section 2.6 the effect of a compliant interlayer between the polymer coating and the rigid substrate is studied.

2.2 Linear-Elastic Fracture Mechanics

One parameter characterizing the durability of an interface is the critical strain-energy release rate, $G_c$, or debond energy. This is the work required to cause an existing flaw to propagate over a unit area of the interface. The strain energy release rate is defined [56]:

$$G = \frac{\partial W_a}{\partial A} = \frac{\partial (W_{ex} - U - W_{pl})}{\partial A}$$  \hspace{1cm} 2-1
where \( W_a \) is the fracture energy, \( A \) is the crack surface area, \( W_{ex} \) is the applied external energy, \( W_{pl} \) is the plastic energy of deformation and \( U \) is the elastic-strain energy of the system given by:

\[
U = \int \frac{\sigma_{ij} \varepsilon_{ij}}{2} dV
\]

2-2

where \( \sigma_{ij} \) are the stresses and \( \varepsilon_{ij} \) are the strains. Assuming that the substrate is rigid, the integration is done over the volume element, \( dV \), of the film. In a linear-elastic system, \( W_{pl} \) is zero and \( W_{ex} = 2U \). Thus, \( G \) becomes:

\[
G = \frac{\partial U}{\partial A}
\]

2-3

When \( G \) exceeds \( G_c \) of the interface, the crack will propagate.

2.2.1 Plane-Strain Steady-State Interfacial Crack

\( G \) has been calculated analytically for two interfacial crack geometries that are relevant to the EDT. The first is a long, two-dimensional, plane-strain crack, which is the limit of a hole with an infinite radius. The steady-state energy release rate is [57]:

\[
G = \frac{1}{2} \frac{\sigma_0^2 h(1 - \nu^2)}{E}
\]

2-4

where \( h \) is the film thickness, \( \sigma_0 \) is the biaxial tensile stress, \( E \) is the Young's modulus, and \( \nu \) is the Poisson's ratio of the film. Equation 2-4 defines the maximum energy that can be applied by the EDT.

2.2.2 Axisymmetric, Large Radius Interfacial Crack

A second geometry that has been solved analytically is the large radius hole. For \( r >> h \) (i.e., a thin film), the strain-energy release-rate is [54,58]:

34
\[ G = \frac{2\sigma_0^2 h(1 - \nu^2)}{E[1 + \nu + (a / r + 1)^2(1 - \nu)]^2} \]  

2-5

Structures with \( r/h \) greater than 100 are not practical to fabricate, so, most EDT cases cannot be analyzed with this expression. Also, Equation 2-5 does not account for other geometry effects such as side-wall angle. To accommodate more varied cases and to validate the finite element model against Equations 2-4 and 2-5, finite element methods are used.

2.2.3 Mode Mixity at Interfacial Cracks

In fracture mechanics the fracture energy, \( G \), involves three modes [56]. The peeling mode (mode I), \( G_I \), arises from stresses applied normal to the interface. The shear mode (Mode II), \( G_{II} \), is produced by the shear stresses applied parallel to the interface and parallel to the direction of crack propagation. The antiplane mode (mode III), \( G_{III} \), is produced by shear stresses parallel to the interface but perpendicular to the direction of crack propagation. For the axisymmetric and plane-strain problems considered here, the tearing mode is absent. Thus, \( G \) is composed of:

\[ G = G_I + G_{II} \]  

2-7

When both mode components are present the problem is characterized as mixed mode. This mixity is quantified by the angle \( \psi \) where:

\[ \psi = \tan^{-1}((G_{II}/G_I)^{0.5}) \]  

2-8

The mixity influences the direction of interfacial cracks [50]; in homogeneous elastic bodies, a crack turns toward and propagates along the plane where \( \psi \) equals zero, or, \( G_{II} \) is equal to zero. An interfacial crack with positive mixity may turn into the film if along that plane normal to \( \psi \) the \( G_{lc} \)

35
of the film is exceeded. Alternatively, if the mixity is negative, the crack may turn into the substrate.

Previous studies of such interfacial cracks postulate that the fracture is mixed [50,34]; for the steady-state plane-strain crack situation, both analytical and numerical solutions indicate the mixity angle is a function of the ratio of the materials elastic properties as described by the Dundar's equations [34]. The Dundar's equations relate the relative stiffness of the coating to the substrate. For an infinitely thick substrate, Suo and Hutchinson find $\psi$ to range from 45° to 65° depending on the Dundar's ratio $\alpha$. For $\alpha$ equal to zero $\psi$ is 52.14° [34]. From numerical analysis Thouless found $\psi$ to be 52.08° [59]. Other results show that for a coating on a rigid substrate which is infinitely thick and stiff $\psi$ is near 46° [60]. This means in the steady-state plane-strain crack $G_{IC}$ is less than 40% of the total applied energy. If $G_{IC}$ of the interface determines failure then it is necessary to consider both the total energy and the mixity factor, as previous studies have shown [40,62].

The linear-elastic solutions used to predict mixity for the above cases have some discrepancies. They predict the existence of an oscillating stress singularity at the crack tip which produces oscillating crack opening displacements near the tip and interpenetration of the crack faces. This is unrealistic physically.

To avoid this complication, Suo and Hutchinson solve the linear elastic problem at a reference length $\bar{\ell}$ away from the crack tip [60]. The choice of $\bar{\ell}$ can be made on geometry or material considerations. With respect to geometry a typical $\bar{\ell}$ for coating problems would be the coating thickness, $h$. On the other hand, $\bar{\ell}$ may be the zone size of $K$-field dominance when
considering material properties. The results discussed in the previous paragraphs are consistent with the choice of \( \bar{I} \) equal to the film height. The FEA model will be used to resolve the mixity angle and compare with both analytical and experimental results.

2.3 Finite Element Analysis of the EDT

Abaqus® [61] finite element software was used to model the deformation of various polymeric films adhered to a rigid substrate. The mesh is generated from a FORTRAN program, Appendix A, where the user specifies various geometry parameters, material properties and boundary conditions. A generic illustration of the coating geometry is shown in Figure 2-1. An interlayer may be introduced between the coating and the rigid substrate. When the interlayer is not present the coating is pinned to the rigid substrate. Also, a backing layer may be added to the model. The various input parameters are listed in Table 2-1.

This geometry is meshed with eight noded reduced integration elements. These can be either axisymmetric or plane-strain elements. The right edge of the model in Figure 2-1 has \( X \)-symmetry. The coating is long enough such that stress distributions at this right edge do not influence the stresses near the crack tip. An example of the mesh is shown in Figure 2-2, with more detail near the crack tip shown in Figure 2-3. The inputs allow the user to vary the mesh density and the element size near the crack tip. Details of the mesh geometry are given in Appendix A.
Table 2-1: Input Parameters for EDT FEA

<table>
<thead>
<tr>
<th>GEOMETRY</th>
<th>BOUNDARY</th>
<th>MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating Thickness</td>
<td>Initial Temperature</td>
<td>Modulus</td>
</tr>
<tr>
<td>Crack Length</td>
<td>Final Temperature</td>
<td>Poisson's Ratio</td>
</tr>
<tr>
<td>Hole Radius</td>
<td>Residual Stress</td>
<td>Coef. of Therm. Exp.</td>
</tr>
<tr>
<td>Interlayer Height</td>
<td>Axisymmetric or</td>
<td>Yield Strength</td>
</tr>
<tr>
<td>Back Height</td>
<td>Plane Strain</td>
<td>Hardening Coeff.</td>
</tr>
<tr>
<td>Via Angle</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Residual stress is applied either by cooling the part from an initial temperature to a final temperature or by specifying the stress as an input. To account for the thermal deformation of the substrate the coefficient of thermal expansion of each layer is reduced by the substrate's CTE. Also, in those cases where the metal layer is only a few 1000 Å thick, it is ignored.

The user can specify which of the above inputs to use, to vary the input range, and the number of increments. The variable can be incremented linearly, logarithmically, geometrically or entered manually. Then the code will then generate the input decks; submit the jobs; collect the data and calculate $G_I$ and $G_{III}$; and store the results in a specified output file.
Figure 2-1: Illustration of Finite Element Model for Coatings on a rigid substrate. The crack is between the coating and the interlayer when it is present, else, the crack is at the Coating/Substrate interface.
Figure 2-2: Finite element mesh geometry: (a) undeformed mesh; (b) deformed mesh with 4x displacement magnitude.
A variation of the modified crack closure method is used to obtain the different modes of the strain energy release rate \([62, 63]\). For eight-noded quadrilaterals under axisymmetric conditions, the mode I and II components of the strain energy release rate for an interfacial crack between a linear elastic material and a rigid substrate are given by:

\[
G_I = \frac{1}{\pi((r_i - \Delta a)^2 - r_i^2)} (F_{z,i}u_{z,i+2} + F_{z,i-1}u_{z,i+1}) \tag{2-9}
\]

and

\[
G_{II} = \frac{1}{\pi((r_i - \Delta a)^2 - r_i^2)} (F_{r,i}u_{r,i+2} + F_{r,i+1}u_{r,i-1}) \tag{2-10}
\]
Referring to Figure 2-4, $i$ is the crack tip node, $F_{Z,i}$ and $F_{Z,i-1}$ are the nodal forces of nodes $i$ and $i-1$ along the $z$ axis; $u_{Z,i+2}$ and $u_{Z,i+1}$ are the displacement of nodes $i+2$ and $i+1$ along the $z$ axis; $F_{r,i}$ and $F_{r,i-1}$ are the nodal forces of nodes $i$ and $i-1$ along the $r$ axis; $u_{r,i+2}$ and $u_{r,i+1}$ are the displacement of nodes $i+2$ and $i+1$ along the $r$ axis; $\Delta a$ is the length of each of the two adjacent elements and $r_i$ is the radial distance of the crack tip.

For linear elasticity the work, which is the area under the force-displacement curve, is one-half the force times the displacement. However, for non-linear cases, such as plasticity, this procedure is not valid. In order to calculate the work, the load is applied incrementally and the load versus displacement curve is integrated directly. The numerical integration scheme sums the areas under each consecutive trapezoid. An example of a non-linear force displacement curve is shown in Figure 2-5.

2.4 Results of the Finite Element Analysis

2.4.1. Comparison to Linear-Elastic Results

The FEA model is applied to the two-dimensional plane strain interfacial geometry. To insure steady-state conditions the crack is five times longer than the thickness of the film. A reduced debond energy parameter, $G_r$, is defined as:

$$G_r = \frac{2GE}{\sigma_0 h^2 (1 - \nu^2)} \quad 2-11$$
Figure 2-4: Modified crack closure method: (a) Undeformed state, (b) deformed state before crack propagation and (c) after propagation.
Figure 2-5: Force Displacement curve for a non-linear coating.

According to Equation 2-4 $G_r$ equals unity in the plane-strain case. The model found $G_r$ to be unity for element sizes ranging from 0.1 to 0.00001 times the film height.

Next the axisymmetric case for large $r/h$ is considered. The reduced strain energy, $G_r$, as a function of crack length for two different Poisson's ratios, $v$, is shown in Figure 2-6, accompanied by the values predicted from Equation 2-6. The data nearly superpose. The model and the analytical results are in excellent agreement. For smaller $r/h$ ratios, $G_r$ is reduced (see Figure 2-7). Equation 2-6 cannot account for this effect, hence, the model is necessary to analyze EDT results, where, $r/h$ ranges from 1 to 10. In Section 2.5, a semi-empirical equation is presented to account for the effect of $r/h$ and side wall angle.
Figure 2-6: Plot of reduced debond energy, $G_r$, for an axisymmetric internal crack as a function of crack length, $a$, from the numerical model and the analytical solution. The radius of the hole, $r$, is 100 times the film thickness. $v$ is the Poisson's ratio.
Figure 2-7: Plot of reduced debond energy, $G_r$, for an axisymmetric internal crack as a function of crack length, $a$, from the numerical model and the analytical solution for various $r/h$.

2.4.2 Mixity Calculations

In the model the mode I and II components can be resolved using Equations 2-9 and 2-10. Equation 2-8 defines the mixity angle, $\psi$. The plot of $\psi$ as a function of element size, $\Delta a$, for the steady-state, plane-strain case is shown in Figure 2-8. As the size of the element approaches zero, the mixity angle does the same: at the crack tip the fracture process is mode I. Similar results are found for the axisymmetric crack geometry.

Previous analytical results showed that the mixity angle is $46^\circ$ [60] for the plane-strain steady state case when the characteristic length, $\bar{1}$, is equal to
the film thickness. Shown in Figure 2-8, as the element size, $\Delta a$, approaches $h$ the mixity approaches $47^\circ$, which is in agreement with the analytical solution.

![Graph](image)

**Figure 2-8:** Mixity angle, $\psi$, vs. element size/film thickness, $\Delta a/h$ for a steady-state ($a>>h$), plane-strain, interfacial crack of a thin film on a rigid substrate.

The question arises as to which limit of $\bar{I}$, zero or $h$, describes the actual fracture process. Here, $\bar{I}$ is defined as the size of the fracture process zone, which can be for example the plastic zone size. In a purely elastic system $\bar{I}$ is equal to zero. The derivations of reliability and experimental results from the ELT discussed in Chapter 5 support the assumption that the fracture process is Mode I for residually stressed brittle coatings debonding from a rigid substrate.

47
One issue that does arise from the assumption of a mode I fracture process is crack trajectory. It has been observed that a crack will deviate from the interface [54]. To resolve this apparent contradiction, we propose that the crack trajectory is controlled by the traction forces which precede the crack. The finite element model calculates these forces. The normal, $F_z$, and parallel, $F_r$, forces versus distance from the crack tip, $x$, are plotted in Figure 2-9. The results show that $F_z$ is much larger than $F_r$ in the limit of $x$ approaching zero, as $x$ increases the ratio of $F_r$ to $F_z$ increases. At $x/h$ near 0.01 the forces are equivalent. At large distances, the parallel forces are greater than the normal forces. Thus, as the crack propagates along the interface, any small flaw ahead of it will experience these forces prior to the arrival of the crack front. If these forces are sufficiently intense, the flaw will initiate another crack and when the main crack front arrives it will deflect from its original plane and path.

2.4.3 Plasticity Effects

The previous sections have considered only elastic coatings. However, most coatings will exhibit some limited plasticity. To determine its effect on the applied debond energy the finite element model discussed in Section 2.2 is used. The effect of yielding on the total applied debond energy and its mixity is considered; and the limits of small-scale yielding within which elasticity can be used to describe the Edge Delamination Test are explored.
Figure 2-9: Forces, $F$, along interface reduced by the area of the element, $A$, and residual stress, $\sigma_0$, versus distance from the crack tip, $x$, reduced by film height, $h$.

As in the elastic case, the mixity at different lengths from the crack tip is calculated by varying the element size. Unfortunately, when finite plasticity is present the elements at the crack tip collapse when they are small compared to the plastic zone size. Hence, the numerical model cannot converge. Essentially, the longitudinal stress present in the coating causes the yielded material at the crack tip to flow. Since the coating is assumed to remain pinned to the rigid substrate, the crack tip rolls over itself. As a result the elements to the right of the crack tip are collapsed. In order to avoid the
complication the Hutchinson characteristic length, $\bar{I}$, is used to describe the mixity for a virtual crack with length $a$ plus the plastic zone size, $r_p$.

An elastic perfectly-plastic coating is considered. In Figure 2-10 the reduced debond energy as a function of the residual stress reduced by the yield stress of the material is plotted. Here, the mesh size is large, $\Delta a = 0.1h$, to avoid the collapsed elements. The reduced debond energy using the modified crack closure method, Section 2.2.3, is used. The total debond energy does not decrease significantly until $\sigma_o / \sigma_y > 0.4$. Even at $\sigma_o / \sigma_y$ equal to one the reduced debond energy is 0.89. This result is in agreement with established ASTM requirements [64]. The requirements compare yield values to the geometry of the specimen. For this case:

$$h > 2.5 \left( \frac{K}{\sigma_y} \right)^2$$  \hspace{1cm} 2-12

From Equation 2-4 $K = \sigma_o \sqrt{h/2}$ and by substituting into 2-12 one finds:

$$\sigma_y > 1.12 \sigma_o$$  \hspace{1cm} 2-13

to meet the small scale yielding requirement of ASTM. From Figure 2-10 it is seen that at this stress level the total $G$ is 93% of the elastic debond energy.

The above analysis shows that the total energy is relatively insensitive to yield stress but it does not account for the mixity. Recall from the elastic analysis that mixity was a function of element size, $\Delta a$, Figure 2-11. This $\Delta a$ corresponds to the Hutchinson characteristic length $\bar{I}$. The mixity as a function of $\bar{I}/h$ is fit with:

$$\Psi = \pi \ln(\bar{I}/h) + 46.5^\circ$$  \hspace{1cm} 2-14
Figure 2-10: Effect of Yield Stress on the reduced debond energy, $G_r$.

If a new sharp crack is defined by extrapolating it to a distance $\bar{I}$ equal to the plastic zone size blunting problems are circumvented, Figure 2-12. In doing so, the mixity defined at $\bar{I}$ has been extrapolated to the new crack tip. Since the mixity as a function of $\bar{I}/h$ is known, then the mixity as a function of plastic zone size is known.

The plastic zone size is found by determining the von Mises stress as a function of distance in front of the crack tip. The numerical model is used to solve the von Mises stress, $\sigma_v$, at a distance $r$ in front of a plane-strain steady-state crack. Using linear elasticity and numerical fitting parameters, the von Mises stress is represented by:
\[
\frac{\sigma_v}{\sigma_o} = \sqrt{\frac{3}{4\pi \frac{r}{h} (1 + \tan^{-2}(\phi)) + 1}}
\] 2-15

where \( \sigma_o \) is the residual stress and \( \phi \) is determined by fitting the above expression to the numerical results:

\[
\phi = \frac{3\pi}{2} \ln(r/h) + 90^\circ
\] 2-16

The calculated \( \sigma_v \) and the fit of Equation 2-15 are shown in Figure 2-13.

Figure 2-11: Mixity as a function of element size reduced by film thickness for an elastic coating.
Figure 2-12: Diagram of assumed crack tip where the new crack length is extended by the plastic zone radius.

Figure 2-13: von Mises Stress in front of a Plane-Strain Steady-State interfacial crack calculated numerically and the semi-empirical fit of it.

For a given yield stress, $\sigma_y$, the yield zone size, $r_y$, is found from Equation 2-15; then from a redistribution integral [56] one finds that $r_p$ is $2r_y$. 

53
As stated, mixity is defined where $\bar{I} = r_p$. From numerical analysis the mixity is:

$$\psi = \pi \ln(\bar{I}/h) + 46.5^\circ$$

2-17

By definition, the mode I strain energy reduced by the total strain energy is:

$$\frac{G_1}{G_{tot}} = \frac{1}{1 + \tan^2(\psi)}$$

2-18

See Figure 2-14 for the results of Equation (2-17) and (2-18): Limited plasticity significantly reduces the applied mode I fracture energy.

![Graph](image)

Figure 2-14: $G_1/G_{tot}$ and the Mixity angle versus the ratio of residual stress/yield stress. For an elastic system the problem is pure mode I.
2.4.4 Edge Effects on the Edge Delamination Test

The model was run for a variety of crack lengths and hole radii. The results are shown in Figure 2-15. In the limit, zero crack length, the applied debond energy is zero. It then rises reaching a maximum near $a/h$ equal to 0.025, followed by a shallow minimum at $a/h$ equal to 0.20. Beyond that point, the reduced debond energy reaches steady-state for the plane-strain case or decreases for the axisymmetric case.

For plane strain conditions, as the crack grows away from the edge, the stress distribution in front of it increases due to the development of the one-half singularity at the crack tip. However, as the crack grows the film peels back slightly which causes a reduction in the stress distribution at the crack tip. The cantilever effect becomes more pronounced as the crack lengthens, leading to the minimum in the reduced debond energy. As the crack proceeds further the effect diminishes because the crack is moving away from the edge; and traction forces are no longer supported behind the crack tip. For the plane-strain case the stress distribution in front of the crack becomes constant: the steady-state condition. The cantilever effect is minimized by removing material from the edge with a side wall angle less than $90^\circ$. In Figure 2-16 is shown the reduced debond energy as a function of crack length for the plane strain geometry with different side-wall angles. As the angle decreases the rise in debond energy becomes slower and the minimum disappears. Similarly, the Poisson’s ratio of the material is varied to produce the same effect: decreasing it increases the stiffness of the cantilever, thus reducing the amount of stress dip. Figure 2-17 shows this for various values of Poisson’s ratio.
2.5 Numerical Results for Reduced Debond Energy

In this section tables of reduced debond energy values, $G_r$, which facilitate the use of the EDT are presented. With observed EDT results, $G_r$ can be found from the tables and then the critical debond energy can be calculated by multiplying $G_r$ by the maximum strain energy. Also, $G_r$ is expressed by a semi-empirical equation, which is in good agreement over a broad range of geometries.
Figure 2-16: Effect of side-wall angle on the plane-strain reduced debond energy for small cracks.

Figure 2-17: Effect of Poisson’s Ratio on the plane-strain reduced debond energy for small cracks.
Tables 2-2 and 2-3 list the numerical values of $G_r$ for $75^\circ$ and $90^\circ$ sidewall angles. They cover a large range of $a/h$ and $r/h$. To use the table, one measures the debond length, the film height, the hole radius and the sidewall angle in the experiment. The value of $G_r$ is found from the appropriate table using linear interpolation if necessary. Then, the critical strain-energy release rate for the interface is given by:

$$G_c = \frac{G_r \cdot \sigma_o^2 h(1-\nu^2)}{2E} \tag{2-19}$$

An alternative approach uses the fracture toughness, $K_c$, to describe the integrity of the interface. This eliminates the need to know the modulus and the Poisson's ratio of the film. As before, reduced fracture toughness, $K_r$, is defined so:

$$K_r = \frac{\sqrt{2}K_{app}}{\sigma_o \sqrt{h}} \tag{2-20}$$

Since $K = \sqrt{GE'}$, where $E'$ is the plane-strain modulus, it can be shown that $K_r = \sqrt{G_r}$. Hence, the critical fracture toughness is calculated as:

$$K_c = \sigma_o \sqrt{\frac{G_r h}{2}} \tag{2-21}$$

The following is an example of how $K_c$ is calculated. In the EDT specimen assume the debond length is 40 $\mu$m around a 100 $\mu$m radius hole, in a 10 $\mu$m film with a side-wall angle of $75^\circ$. From Table 2-2, $G_r$ is interpolated to be 0.493. If the residual stress in the coating is 30 MPa then, using Equation 2-21, the fracture toughness of the interface is 0.047 MPa-\sqrt{m}.

To further simplify the analysis of the EDT, an equation to calculate $G_r$ for the various geometries has been developed. It is a hybrid of the analytical solution in Equation 2-5 multiplied by a fitted function to account for finite
hole radii and non-90° side-wall angles. The equation was determined by fitting the numerical results using a minimum residual error method. It applies to values of a/h greater than 0.1 and less than 100 and r/h greater than 1 and less than 100. The best fit is:

\[ G_r = \text{erfc}(Bh/r) \left( \frac{2}{(1 + v^2 + (1 - v)(a/r + 1)^2} \right)^2 \]

where \( \text{erfc} \) is the complimentary error function and \( B \) is a function of the side-wall angle. Figures 2-18 and 2-19 show how Equation 2-22 relates to the numerical values of \( G_r \) at side wall angles of 75° and 90°. The percent difference between Equation 2-22 and the numerical data is listed in Tables 2-4 and 2-5.

Table 2-6 presents the values for \( B \) as a function of side-wall angle; it depends linearly on the angle and is given by:

\[ B = 0.0126 \theta - 0.605 \]

where \( \theta \) is the side-wall angle in degrees. The correlation factor for the linear fit is 0.9922.

As before, the interfacial fracture toughness can be determined by calculating \( G_r \) with Equation 2-22 then using Equation 2-21 to calculate \( K_c \). Equation 2-22 requires the Poisson's ratio value; if this is assumed to be 0.40, the error introduced is listed in Table 2-7. As shown, it becomes very small for larger values of \( r/a \).
Table 2-2: Numerically Calculated Reduced Strain Energy ($G_r$) Values for a 75° Side Wall Angle

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Table 2-3: Numerically Calculated Reduced Strain Energy ($G_r$) Values for a 90° Side Wall Angle

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Table 2-4: % Error between Numerical Results and Semi-Empirical Fit for a 75° Side Wall Angle

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Table 2-5: % Error between Numerical Results and Semi-Empirical Fit for a 90° Side Wall Angle

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Table 2-6: Parameter B as a Function of Side Wall Angle

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Table 2-7: Percent Error in $K_r$ assuming Poisson's Ratio equal to 0.40 in Equation 2-22

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62
Figure 2-18: Numerical and semi-empirical reduced debond energy, $G_r$, for 75° Side wall angle.
Figure 2-19: Numerical and semi-empirical reduced debond energy, $G_r$, for $90^\circ$ Side wall angle.
2.6 Effect of a Compliant Interlayer

The applied debond energy can exceed the critical debond energy of an interface. In this section, the use of a compliant interlayer to reduce the applied debond energy to preserve the coating is illustrated. A rubber material is coated on the wafer, then the coating atop it can shrink and the thermal stress is relieved.

In Figure 2-20, the base layer is modeled with rubber properties and a top coating layer with epoxy properties. These are listed in Table 2-8. The ratios of the base height to the coating height and the base modulus to the coating modulus are varied. Both layers are assumed to be linear-elastic materials. Introducing the compliant interlayer is an effective way to enhance the adhesive reliability of the coating. This is especially true when the modulus of the interlayer is a factor of a 1000 less than the coating modulus.

<table>
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<tr>
<th>Property</th>
<th>Coating</th>
<th>Base</th>
</tr>
</thead>
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<td>Varied</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
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<td>0.499</td>
</tr>
<tr>
<td>Coef. Therm. Exp.</td>
<td>50 PPM/°C</td>
<td>300 PPM/°C</td>
</tr>
<tr>
<td>Height</td>
<td>20 μm</td>
<td>Varied</td>
</tr>
</tbody>
</table>
Figure 2-20: Reduced Debond Energy versus Reduced Base Layer Modulus for various base height to coating height ratios.
CHAPTER 3: ANALYSIS OF LEADLESS INTERCONNECTS AND FLIP CHIP ASSEMBLIES

3.1 Introduction

The use of surface-mount technology increases the number of interconnects per unit area by decreasing the size of the interconnect. [7] Here a component is mounted onto the substrate rather than into it. Typically, this consists of a leadless-chip carrier with metallized contacts at its periphery which are soldered to a metallized contact on the substrate, Figure 3.1. A Flip Chip is an example of a SMT in which a chip is bonded to the substrate, face down by metal connections. This was introduced by IBM in the 1960's as Controlled Collapse Chip Connection, C4, where solder bumps were used to bond the chip to the substrate. Polymer encapsulants such as epoxies, have improved the thermal fatigue life of leadless interconnections, especially C4 assemblies [65-68].

A simplified geometry of the leadless interconnection is shown in Figure 3.2. Large stresses develop because of thermal expansion mismatches among the constituent materials. Much work has been done to understand the effects of the stresses on the solder used in the assemblies [7, 69,70], but little attention has centered on the encapsulant, which can fail either cohesively or adhesively. Here an analysis of the stress in the coating is presented for the situation where the chip and substrate are perfectly rigid and the geometry is plane-strain. This includes the steady-state plane-strain strain energy release rate for a crack propagating along the polymer substrate interface, as shown in Figure 3-2.
Numerical analysis is used to find the applied strain energy release rate for axisymmetric geometries. The effect of polymer/post adhesion on the polymer/substrate adhesion is examined. It is also used to study the effect of the chip's compliance on the applied debond energy.

Figure 3-1: Generalized Illustration of a Leadless Interconnect. The metal post can be either a pin, e.g. gold, or a solder bump as in C4 packages.

3.2 Analytical Solutions for Flip Chip Debond Energies

In the illustration in Figure 3-2 the silicon chip is assumed to be perfectly rigid, so, there are no shear forces. The Hooke's equation [71,72] for the coating is:
Figure 3-2: Model Geometry used for Leadless Interconnect. Either it is plane-strain or axisymmetric about the centerline of the post, with a mirror symmetry plane at the far right edge.

\[
\begin{pmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z
\end{pmatrix} = \frac{E_c(1-v_c)}{(1+v_c)(1-2v_c)} \begin{pmatrix}
1 & v_c/(1-v_c) & v_c/(1-v_c) \\
v_c/(1-v_c) & 1 & v_c/(1-v_c) \\
v_c/(1-v_c) & v_c/(1-v_c) & 1
\end{pmatrix} \begin{pmatrix}
\varepsilon_x + \Delta \alpha_c \Delta T \\
\varepsilon_y + \Delta \alpha_c \Delta T \\
\varepsilon_z + \Delta \alpha_c \Delta T
\end{pmatrix} \tag{3-1}
\]

where $\Delta \alpha_c$ is $(\alpha_c - \alpha_s)$. Since the polymer is rigidly constrained in the $x$-direction by the rigid substrate, $\varepsilon_x$ and $\varepsilon_z$ are zero. For the unconstrained case $\sigma_y$ is zero and 3-1 becomes:

\[
\begin{pmatrix}
\sigma_x \\
0 \\
\sigma_z
\end{pmatrix} = \frac{E_c(1-v_c)}{(1+v_c)(1-2v_c)} \begin{pmatrix}
1 & v_c/(1-v_c) & v_c/(1-v_c) \\
v_c/(1-v_c) & 1 & v_c/(1-v_c) \\
v_c/(1-v_c) & v_c/(1-v_c) & 1
\end{pmatrix} \begin{pmatrix}
\Delta \alpha_c \Delta T \\
\varepsilon_y + \Delta \alpha_c \Delta T \\
\Delta \alpha_c \Delta T
\end{pmatrix} \tag{3-2}
\]

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The in-plane stress and the strain in the y direction, $\varepsilon_y$ are:

$$\sigma_x = \frac{E_c \Delta \alpha_c \Delta T}{(1-\nu_c)} \quad \text{and} \quad \varepsilon_y = \frac{-\Delta \alpha_c \Delta T (1+\nu_c)}{(1-\nu_c)}$$  \hspace{1cm} (3-3)

In the Flip Chip, the coating is constrained in the y-direction by the post. Since the post is finitely stiff, the coating will be able to shrink by a strain $\varepsilon_y + \Delta \alpha_c \Delta T$. It is possible to solve for $\varepsilon_y$ because the forces in the y-direction must balance and the post and the coating are constrained to displace equally. From force balance one obtains:

$$F_{y,\text{post}} = -F_{y,\text{coat}}$$

or,

$$\sigma_{y,p} A_p = -\sigma_{y,c} A_c$$  \hspace{1cm} (3-4)

where $A$ is the area. From Equation 3-1 $\sigma_y$ in either material is given by:

$$\sigma_y = \frac{E(1-\nu)}{(1+\nu)(1-\nu)} \left( \frac{\Delta \alpha \Delta T (1+\nu)}{(1-\nu)} + \varepsilon_y \right)$$  \hspace{1cm} (3-5)

To simplify the results, two reduced parameters are defined:

$$\alpha = \frac{\Delta \alpha_p (1+\nu_p)(1-\nu_c)}{\Delta \alpha_c (1+\nu_c)(1-\nu_p)} \quad \text{and} \quad \beta = \frac{E_c A_c (1+\nu_p)(1-2\nu_p)}{E_p A_p (1+\nu_c)(1-2\nu_c)}$$  \hspace{1cm} (3-6)

Then $\varepsilon_y$ is:

$$\varepsilon_y = -\Delta T \Delta \alpha_c \frac{(1+\nu_c)}{(1-\nu_c)} \frac{\alpha + \beta}{1 + \beta}$$  \hspace{1cm} (3-7)

In the limit of $\Delta \alpha_p$ and $\Delta \alpha_c$ and $\nu_p$ and $\nu_c$ being equivalent, the results in Equation 3-3 are obtained. To solve for the x and y stresses in the coating using Equations 3-2 and 3-7:

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\[ \sigma_x = \frac{E_c \Delta \alpha_c \Delta T}{(1 - 2v_c)} \left( 1 - \frac{v_c (\alpha + \beta)}{(1 + v_c)(1 + \beta)} \right) \text{ and } \sigma_y = \frac{E_c \Delta \alpha_c \Delta T}{(1 - 2v_c)} \left( \frac{1 - \alpha}{1 + \beta} \right) \]

The stored energy for the constrained polymer is defined:

\[ W_T = \frac{1}{2} \{ 2\sigma_x \Delta \alpha_c \Delta T + \sigma_y (\Delta \alpha_c \Delta T + \varepsilon_y) \} \]

However, when a crack propagates between the substrate and coating not all of the work is released; the coating goes from triaxially constrained to biaxially constrained. The change in work as a plane-strain steady-state crack is released in the Flip Chip is:

\[ \Delta W = W_T - W_b = \sigma_x \Delta \alpha_c \Delta T + \frac{1}{2} \sigma_y (\varepsilon_y + \Delta \alpha_c \Delta T) - \sigma_o \Delta \alpha_c \Delta T \]

Using these, an expression for the energy release rate in the Flip Chip, \( G_{FC} \) is derived:

\[ G_{FC} = \frac{E_c (\Delta \alpha_c \Delta T)^2 h}{2(1 - v_c)(1 - 2v_c)} \left\{ 2v - 2v \left( \frac{\alpha + \beta}{1 + \beta} \right) + (1 - v_c) \left( \frac{1 - \alpha}{1 + \beta} \right) \left( 1 - \frac{(1 + v_c)(\alpha + \beta)}{(1 - v_c)(1 + \beta)} \right) \right\} \]

or,

\[ G_{FC} = \frac{G_b}{(1 - 2v_c)(1 + \beta)} \left( 1 - \alpha \right)^2 \]

where \( G_b \) is the biaxial strain energy release rate given by Equation 2-4.

Tables 3-1 through 3-3 list values for \( x \) and \( y \) stresses divided by the unconstrained stress, \( \sigma_o \), and \( G_{FC} \) divided by \( G_b \). The values in the tables can be used to estimate the maximum stress and debond energy encountered in the Flip Chip. To use the tables one calculates \( \alpha \) and \( \beta \) from Equation 3-6, then from the table with the appropriate Poisson's ratio, find the reduced stresses and energies. For example, assume the posts are gold and the coating
is a standard epoxy with a modulus of 3 GPa, a Poisson’s ratio of 0.4 and an expansion coefficient of 57 PPM/°C. If the substrate and the chip are silicon then $\alpha$ is 0.2. If the posts are 50 $\mu$m wide and spaced 200 $\mu$m apart then $\beta = 0.2$. Also let the coating thickness be 10 $\mu$m and the part cooled to -65°C. If the $T_g$ of the coating is 125°C then the biaxial stress, $\sigma_o$, is 51.3 MPa and the biaxial debond energy is 3.68 J/m$^2$. Using values from Table 3-2 the longitudinal stress is 119.5 MPa, the vertical stress is 102.6 MPa and the applied debond energy is 8.17 J/m$^2$. This would be a severe condition for a typical epoxy to withstand.

3.3 Finite Element Model of the Flip Chip

Abaqus [61] is used to model the Flip Chip. The meshing scheme is similar to the EDT mesh with the additional constraint of the post added. The chip can be included in the model or it can be treated as a rigid substrate. Eight-noded reduced integration, axisymmetric or plane-strain elements are used. The modified crack closure method is used to calculate the mode I and mode II energies, (See section 2.3.) A FORTRAN program interfaces between the user and Abaqus to create a series of input decks, submit the jobs and collect the data. This is listed in Appendix B.
Table 3-1: Values for Reduced Stress and Energy at $v_c = 0.35$ for Plane-Strain Geometry for Flip Chip Assemblies.

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Gfc/Gb
Table 3-3: Values for Reduced Stress and Energy at \( v_c = 0.45 \) for Plane-Strain Geometry for Flip Chip Assemblies.

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75
Table 3-4: Input Parameters for Flip Chip FEA

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3.4 Finite Element Results for Flip Chip Geometry

This section gives the results from the finite element analysis described in Section 3.2. First the model was run for plane-strain, to compare to the analytical solution. Then it was run for various axisymmetric cases. Last, the effect of finite chip stiffness on the results was analyzed.

3.4.1 Plane Strain FEA Results

The code was run for the plane-strain case. The post length, \( l_p \), was twice the film height, \( h \), and the coating length, \( l_c \), was 50\( h \). The coating has properties similar to epoxy: \( E_c = 3 \) GPa, \( v = 0.40 \) and \( \alpha_c = 53 \) PPM/°C; the post was similar to gold: \( E_p = 80 \) GPa, \( v = 0.33 \) and \( \alpha_p = 14.8 \) PPM/°C. The reduced parameters \( \alpha \) and \( \beta \) are 0.20 and 1.36, so, \( G_{FC}/G_b \) is 0.575. For these cases the chip was assumed to perfectly rigid, as in the analytical solution. Two cases were studied. In the first, the coating was adhered to the post; in the second it was not.

The calculated energy release rate, \( G \), reduced by \( G_{FC} \) (Equation 3-12) versus crack length reduced by \( h \) is plotted in Figure 3-3. Here the coating is
adhered to the post. For small cracks, the reduced debond energy is less than 1/10th of the steady state value. Then it rises to one at $a/h$ equal to one. As the crack proceeds the reduced energy continues to increase. This is because the length of the polymer over which force can be supported is being decreased. As a result $\beta$ decreases. Correction for this finite length can be made by defining the area of the polymer from the crack tip to the end of the part. The corrected reduced debond energy then does reach a plateau value, Figure 3-3.

![Graph showing the relationship between $G_{num}/G_{fc}$ and $a/h$.]

**Figure 3-3:** Numerically calculated debond energy reduced by the analytical solution for plane strain geometry as a crack grows away from the post. When the analytical solution is corrected to account for the changing coating area the reduced energy plateaus. The polymer is adhered to the post.
The next case removes the adhesion of the coating to the post. The reduced debond energy with and without the crack length correction are plotted in Figure 3-4. Compared to the adhered case, $G$ is large for small $a/h$. It also reaches its first maximum sooner, at $a/h$ equal to 0.0167, with a value of $1.4G_{FC}$. As the crack continues, a second, larger maxima develops: 1.53 $G_{FC}$. This second peak is due to edge effects. In the limit of a long crack the debond energy plateaus at the same level as the adhered case.

![Graph showing debond energy vs. a/h](image)

**Figure 3-4:** Numerically calculated debond energy reduced by the analytical solution for plane strain geometry as a crack grows away from the post. The polymer is not adhered to the post.

The edge effects for this geometry are more complex; since the effect is not present for the adhered case it is not due to errors in the finite element model. The non-adhered case was run for two additional post side-wall
angles. The results for 90°, 70° and 50°, are shown in Figure 3-5. Similar to the EDT results, reducing the side-wall angle causes the first maximum to shift, but it also increases it from $1.40G_{FC}$ for 90° to $1.60G_{FC}$ for 50°.

The mechanics of the oscillatory debond energy are not fully understood at this time.

![Graph showing the effect of sidewall angle on debond energy](image)

Figure 3-5: Effect of sidewall angle on the numerically calculated debond energy reduced by the analytical solution for plane strain geometry as a crack grows away from the post. The polymer is not adhered to the post.

The effect of the Poisson's ratio on the reduced debond energy, corrected for crack length, is plotted in Figure 3-6 for the adhered case. Increasing Poisson's ratio increases the magnitude of the applied $G$ for small
cracks, but the rise in debond energy for larger cracks is independent of the it: 
the curves reach the same plateau at a/h equal to one.

![Graph](image)

Figure 3-6: Effect of Poisson’s ratio on the numerically calculated debond energy reduced by the analytical solution for plane strain geometry as a crack grows away from the post. The polymer is adhered to the post.

3.4.2 Axisymmetric Finite Element Analysis Results

The model was run for the axisymmetric geometry. The same geometry and material properties as in the plane strain case were used. The results for the adhered and non-adhered cases are shown in Figure 3-7. The
applied debond energy is higher for the non-adhered case. For this geometry, both cases are stable; that is, the energy decays as the crack proceeds.

![Debond energy graph](image)

**Figure 3-7:** Numerically calculated debond energy for axisymmetric geometry reduced by the analytical solution for plane strain geometry as a crack grows away from the post.

The model was run for various post radii, \( l_p \), with the coating adhered to the post; all other variables were held constant. The results are shown in Figure 3-8. As the post diameter increases the total energy at long cracks increases; the functional form approaches the plane strain case. However, the debond energy as a function of crack length changes dramatically as the diameter of the post changes. For small diameters, the energy is similar to the EDT case where it decreases with increasing crack lengths, but as the diameter...
increases the energy for small cracks decreases and then increases to a plateau for large cracks. The maximum of the plateau is proportional to the diameter of the post.

![Graph showing debond energy as a function of post diameter](image)

**Figure 3-8:** Numerically calculated debond energy for axisymmetric geometry as a function of post diameter. The coating is adhered to the post.

To illustrate this more fully the reduced energy is plotted in Figure 3-9, where it is clear that the functional form of $G$ is changing from a stable fracture process, small diameter post, to an unstable fracture process, large diameters. This occurs near $\beta$ equal to 0.20. The cause of this change is not understood. The results suggest three conditions are influencing the debond energy. First, the stress distribution in front of the crack tip is increasing as the one-half singularity develops for small cracks. Second, this stress is dissipated over a
larger surface area as the crack grows radially. These two factors yield the stable crack results for the small diameter posts. As the post size increases, a third effect causes the stress distribution to increase. Since the energy plateaus for large diameter the rise in stress may be proportional to the increase in the debonded area.

![Graph showing the relationship between Gnum/Gpe and a/h for different values of lp.]

Figure 3-9: Numerically calculated reduced debond energy for axisymmetric geometry as a function of post diameter. The coating is adhered to the post.

The challenge for the design engineer is to select the appropriate post size. Larger posts reduce the debond energy for small cracks, so, small flaws due to processing are less likely to grow. The disadvantage of larger posts is that if larger flaws do exist, they will be unstable leading to catastrophic failure. Smaller posts avoid this catastrophic behavior since the debond
energy decays with increasing crack length. However, smaller posts apply larger debond energies for small flaws which may cause them to propagate to an observable distance.

3.4.3 Finite Stiffness Effect of the Silicon Chip

The plane strain case described in Section 3.3.1 was run again, with a less rigid 525 μm thick silicon chip. The results are shown in Figure 3-10; the coating is adhered to the post. The more flexible chip deflects similarly to a three-point bend test, which reduces the stresses in the center of the coating. The debond energy is less than the predicted plane strain energy for large cracks, but its consequence is higher stress near the post because not all of the coating is acting to shrink the post. As a result the debond energy rises to a maximum much greater than the predicted plane strain condition. Also shown in Figure 3-10 are the results for a silicon chip where the coating is not adhered to the post. This leads to high debond energies at very small crack lengths, so, a small flaw is more likely to propagate.

3.5 Summary

The applied debond energy for a simplified leadless interconnect geometry has been analyzed. The solution also is applicable to Flip Chip geometries. In the plane-strain, large crack case, the energy is a function of two reduced parameters, α and β. where α is essentially the ratio of the thermal coefficients and β is the ratio of the stiffnesses of the coating to the post. The applied stresses for this case also are found. The results are very
dependent on the Poisson’s ratio of the coating due to the triaxial stress state. As the ratio approaches 0.50 the stresses become infinite.

A numerical model confirms the analytical solution and was applied to the small crack plane strain case. It showed that loss of adhesion between the post and coating increases the applied energy for small cracks by an order of magnitude. The model then was used to find the debond energy for the axisymmetric case. Here the applied energies as functions of crack length are complicated and strongly dependent on $\beta$. For small post diameters, i.e. small $\beta$, the functional form of the debond energy is similar to the EDT results.
where $G$ increases with crack length, reaches a peak and then decreases to zero. However, for large posts, large $\beta$, the debond energy rises to a maximum and then plateaus near the plane strain value.

The model was used to analyze the effect of finite chip stiffness for the plane strain case. Because of its compliance, the chip bows, thereby relieving the stresses in the center of the polymer coating. This results in the applied energy decreasing with crack length, however, it also causes a rise in the initial maximum for small cracks since the post is not competing with the entire length of polymer in order to shrink. The maximum debond energy for a Si chip is more than twice the energy for the rigid chip.
CHAPTER 4: EDGE DELAMINATION TEST RESULTS

4.1 Introduction

The EDT has been applied to several materials of interest to the microelectronics industry. Three commercially available polymer coatings were tested: Cyclotene™ 3022, Ultradel™ 4212 and Pyralin™ 2545: also known as divinylsiloxane - bisbenzocyclobutene (DVS-BCB), hexafluorodianhydride - aminophenoxybiphenylin (HFDA-APBP), pyromellitic dianhydride-oxydianiline (PMDA-ODA). The substrate used for all cases was 525 μm thick 100 silicon wafers. These were metallized with either copper, aluminum or chrome.

In certain cases the stress-temperature profile was measured directly using curvature methods. If this was not possible, the properties in Table 4-1 were used to calculate the stress using Equation 1-2. For those cases where delamination was limited by the total applied energy, the samples are cooled using a thermal stage to increase the residual stress. The lowest temperature obtainable was liquid nitrogen (-196°C).

The effects of adhesion promoters on the interfacial fracture toughness was tested for Cyclotene 3022. Also, the EDT was used to monitor the degradation of interfacial strength when Cyclotene 3022/silicon and Ultradel 4212/silicon were exposed to 85°C/85% humidity for extended periods.

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™ Cyclotene is a registered trademark of The Dow Chemical Company
™ Ultradel is a registered trademark of Amoco Chemical Company
™ Pyralin is a registered trademark of E. I. DuPont de Nemours Company

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Table 4-1: Material Properties for Pyralin 2545, Cyclotene 3022, Ultradel 4212, and Silicon. [69]

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4.2 Experimental Procedure

This section details the procedures used to fabricate and test the EDT specimens. For certain samples there will be modifications in the fabrication procedure. If so, this will be noted in the results and discussion section.

4.2.1 Sample Fabrication

EDT specimens were fabricated using standard microelectronic techniques. A schematic of the standard process is shown in Figure 4-1. Single crystal silicon substrates of {100} orientation approximately 525 µm thick and 100 mm in diameter were used. One side was polished to a mirror finish. The wafer was then plasma cleaned by exposure to a 225 W oxygen plasma for 15 minutes. A metal layer, of thickness near 3000 Å, was either sputter deposited or evaporated. In some cases an additional metal layer was placed between the silicon and the test metal layer to promote adhesion.

When adhesion promoters were used, they were spun-cast onto the wafer and processed according to the recommended practice. Then the
polymer was spun-cast onto the wafer. The polymer was cured according to the manufacturers recommended practice, see Table 4-2.

The features were plasma etched into the polymer by a microlithographic process. First, an aluminum or copper hardmask was sputtered onto the polymer. Then a photoresist layer was spun and exposed using the EDT test mask. Hole diameters range from 50 μm to 1000 μm (one wafer contains about 600 holes). The hardmask pattern was defined by exposure to a phosphoric, acetic and nitric acid bath (PAN) at 50°C for Al masks or ferric chloride at 40°C for Cu masks. The polymer was etched with a 300 W oxygen plasma at 50 - 100 millitorr pressure. After etching the holes into the polymer, the wafer was placed in the appropriate acid bath to remove the hardmask.

Table 4-2: Cure Schedules for Cyclotene 3022, Ultradel 4212 and Pyralin 2545.

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</tbody>
</table>
1. Metallize Si, e.g. with Cu.

2. Spin coat and cure polymer layer (PY).

3. Metallize with hardmask (HM).

4. Spin coat photoresist (PR) layer, pattern and develop as per manufacturers directions.

5. Etch pattern into hardmask using standard etchant.

6. Reactive ion etch polymer layer.

7. Soak in etchant to remove hardmask. Dump rinse in DI water. Spin rinse dry.

Figure 4-1: Schematic of EDT sample fabrication using photolithography.
It was subsequently found that many interfaces were sensitive to the etch. A second fabrication scheme was used to avoid acid. It consists of the above process with the addition of a photoresist layer between the polymer and the hardmask. The pattern in the mask was defined as before and the polymer was plasma etched. To remove the hardmask the sample was placed in acetone which dissolves the first photoresist layer releasing the hardmask.

4.2.2 Optical Microscopy

Optical microscopy was used to measure the debond rings around the various diameter holes. For each diameter size, the debond lengths on three to five different holes were measured, then averaged for the range of hole sizes for error analysis. A micrograph of a debond ring is shown in Figure 4-2. The thickness of the film was determined using profilometry. The via wall angle was estimated by measuring the difference of the hole radius at the top and bottom, then dividing by the film height to get the arctangent. The hole diameter, the via angle and the debond length were inputs to the finite element model. An example data spreadsheet for EDT results is shown in Appendix C.

4.2.3 Stress-Temperature Measurements

The residual stress in the film was determined by the Flexus™ method, which measures the radius of curvature, $R_f$, of the coated wafer. It consists of measuring the deflection of a laser beam off the substrate. The beam is translated across the diameter of the wafer. The stress in the film is calculated from the curvature using the Stoney equation [73]. For silicon substrates the Young's modulus is 130 GPa and the Poisson's ratio is 0.28.
4.2.4 Humidity Effects

Thin films of both Ultradel and Cyclotene were spin-coated onto silicon wafers and then etched with the standard EDT process given above. Both wafers showed initial debonding after processing which has been characterized.

For the humidity exposure, only a portion of each wafer was used. The wafers were quartered, taking advantage of silicon’s crystal orientation. Then one of the quarters was tested by placing it in a wafer holder, which was placed into the oven.

A high humidity and high temperature environment was created in a Blue-M Electric Co. Humid-Flow® temperature and humidity cabinet. The test conditions were set at 85% relative humidity at 85°C. Although the
chamber is designed to provide constant humidity and temperature levels, some fluctuation occurred when opening and closing the chamber doors.

When the wafers were removed from the humidity chamber for measurements, the wafer was allowed to cool to room temperature before any measurements were made. The hole diameter and the debond rings measurements were made prior to the start of the test as well as during various intervals of the test. The exposure time intervals increase in length during the test. This was designed so that any initial changes in the behavior of the film's adhesion could be observed. As the experiment proceeded, the wafer was exposed at longer intervals.

4.3 Results and Discussion

The results for several EDT interfaces are given. The results are listed by polymer coating type and then subcategorized by the metal. The details for each interface are described. An example of the EDT optical measured data and the calculated debond energy is given in Appendix C.

4.3.1 Cyclotene 3022

This lists the collected data for Cyclotene 3022 on various metals; aluminum, silicon, copper and chrome. The humidity results for Cyclotene on silicon are also given.

4.3.1.a Cyclotene 3022 on Aluminum

The first set of samples, C-AL-01, were three wafers fabricated using the MIT clean room facilities. Table 4-3 summarizes their results. The thickest
sample, C-AL-01 #1 at 33 μm, was debonded at room temperature. The \( G_c \)
was a function of the hole radius but did plateau at larger radii. From this
sample \( G_c = 5.43 \pm 0.55 \text{ J/m}^2 \). The other two samples, C-AL-01 #2 & #3, were
18.7 μm and 13.5 μm thick. Sample 2 had debond rings, but from the
calculations no plateau region was found. Sample 3 had no debonding at
room temperature. It was then cooled to -90°C. Debonds were measured.
The average \( G_c \) for this sample is 5.28±0.25 J/m\(^2\) which is in agreement with
the results from C-AL-01 #1.

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Height, μm</th>
<th>Temp., °C</th>
<th>Stress, MPa</th>
<th>( G_c ), J/m(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33</td>
<td>20</td>
<td>36</td>
<td>5.43±0.55</td>
</tr>
<tr>
<td>2</td>
<td>18.7</td>
<td>20</td>
<td>36</td>
<td>&gt; 3.7</td>
</tr>
<tr>
<td>3</td>
<td>13.5</td>
<td>-90</td>
<td>52.5</td>
<td>5.28±0.25</td>
</tr>
</tbody>
</table>

The second set of samples fabricated were D-CR-12-49. These were
made at Dow in June, 1993. The Dow aluminum sputter target has 1% Cu.
The MIT target is pure Al. The results are summarized in Table 4-4. For
wafer 1, a 1.5% MOPSTMS* adhesion promoter was applied prior to the
Cyclotene coat. Wafers 2 and 3 had no promoter. Wafers 1 and 2 were
completely delaminated after the copper hardmask etch.

To avoid the corrosion failure, wafer 3 was fabricated using a
photoresist release layer under the hardmask. It was removed by soaking the
sample in acetone which dissolved the photoresist, releasing the mask. No

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* MOPSTMS is Metharyloxypropyl trimethoxysilane
debonding was observed in the sample. At room temperature the maximum applied debond energy is 3.94 J/m² which is less than the $G_c$ from C-AL-01.

Table 4-4: Summary of D-CR-12-49 Samples: Cyclotene 3022 on Aluminum

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Height, µm</th>
<th>Temp., °C</th>
<th>Stress</th>
<th>$G_c$, J/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>20</td>
<td>36</td>
<td>&lt; 7.33*</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>20</td>
<td>36</td>
<td>&lt; 7.33*</td>
</tr>
<tr>
<td>3</td>
<td>14.5</td>
<td>20</td>
<td>36</td>
<td>&gt; 3.94</td>
</tr>
</tbody>
</table>

* Samples debonded after acid etch of hardmask.

D-CR-12-63 wafers 1-3 are Cyclotene 3022 on Al-1% Cu with thicknesses of 20.3 µm, 12.4 µm and 13.7 µm. All three samples completely debonded during the final DI water rinse after acid etching. The maximum debond energies were 5.54, 3.36 and 3.72 J/m². Exposure to acid caused catastrophic failure even for low applied debond energies.

D-CR-13-22 was received from Dow Chemical in November 1993. Most samples were destroyed in the acid bath, however, wafer #4 was processed without exposure to acid. The results were independent of hole radius, Figure 4-3. This confirms the analysis of the EDT and shows the test can be used to gather adhesion data over a large range of hole sizes. The average $G_c$ was 4.88±0.47 J/m². This is slightly lower than the results from C-AL-01; possibly due to the difference in sputter targets.
4.3.1.1 Cyclotene 3022 on Silicon

D-CR-12-43 samples #1 - #4 were the first Cyclotene/Silicon samples fabricated by Dow on 6/23/93. These were made using an aluminum hardmask; so, they were exposed to PAN etch at 50°C for 3 minutes. Table 4-5 lists the samples. 1 and 3 had 1.5% MOPSTM adhesion promoter applied prior to the Cyclotene. Only wafer 2 had debonding at room temperature. Wafer 1, 3 and 4 were exposed to -196°C; no debonding was observed. So, from wafer 1, the \( G_c \) was greater than 29.4 J/m². Therefore, \( K_{IC} \) for the Cyclotene must be greater than 0.26 MPa-√m in order to have prevented cohesive delamination from the edge. This is in agreement with the reported \( K_{IC} \) for Cyclotene of 0.28 MPa-√m.[62]

A second group of wafers was fabricated at Dow, D-CR-12-43 #5 - #8. No adhesion promoter was used. A copper hard mask was used instead of
aluminum. Ferric Chloride at 50°C was used to etch the hardmask. The results are plotted in Figure 4-4; They show no plateau value for G_c at large holes. Wafer 6 was diced and undercooled to -50°C and then to -95°C. The debond rings did not increase. The results for wafers 5-8 are in good agreement, but they are much less than the wafer 2 energies. Possibly, this is due to the difference in hardmask etchants.

Table 4-5: Summary of D-CR-12-43 Sample: Cyclotene 3022 on Silicon

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Height, µm</th>
<th>Promoter</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.5</td>
<td>Yes</td>
<td>no debonds</td>
</tr>
<tr>
<td>2</td>
<td>30.8</td>
<td>No</td>
<td>debonded</td>
</tr>
<tr>
<td>3</td>
<td>15.4</td>
<td>Yes</td>
<td>no debonds</td>
</tr>
<tr>
<td>4</td>
<td>15.4</td>
<td>No</td>
<td>no debonds</td>
</tr>
</tbody>
</table>

To account for the various adhesion results, it is proposed that the adhesion strength of Cyclotene to silicon is greater than the toughness of the Cyclotene. Debonding is due only to the combination of stress and acid. This stress-corrosion occurs when the debond energy is sufficient to peel the corroded interface, thereby exposing fresh interface to the acid. For wafer #2 the applied debond energy is 6.4 J/m² at 50°C (the acid bath temperature), whereas, for #4 it is 3.2 J/m². Since no debonding was observed for wafer #4 one can assume that the G_c of the PAN corroded interface is between 6.4 and 3.2 J/m². The adhesion promoter increases its G_c above 5.9 J/m². The G_c of the corroded interface will be a function of the acid type and concentration and soak time.
Figure 4-4: D-CR-12-43 Cyclotene 3022 on Silicon. Wafer 5-8 were processed together, wafer 2 was processed separately. All samples show dependence on the acid etch.

A third group of samples, listed in Table 4-6, was fabricated at Dow, D-CR-12-85. These also used PAN etch to remove the Al hardmask. Only wafer 18 had debonds. It was subsequently cooled to -20°C, -50°C and -90°C and the debonding did not increase. This supports the hypothesis that failure is a stress-corrosion process. For these samples G applied for wafer 18 at 50°C is 5.7 J/m² and for #11 is 4.0 J/m². Since #11 did not debond, the $G_c$ of the corroded interface is between 5.7 J/m² and 4.0 J/m² which is in agreement with the previous results.
Table 4-6: Summary of D-CR-12-85 Samples: Cyclotene 3022 on Silicon

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Height, µm</th>
<th>Stress@RT</th>
<th>Adh. Prm.</th>
<th>Debonds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.4</td>
<td>29.6</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>8</td>
<td>35.9</td>
<td>35.2</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>15</td>
<td>46.0</td>
<td>26.5</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>4</td>
<td>26.6</td>
<td>26.7</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>11</td>
<td>35.0</td>
<td>26.7</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>18</td>
<td>48.6</td>
<td>26.8</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Stress measured using Flexus. Adhesion promoter information not available.

The effect of 85°C/85% humidity on the Cyclotene/Silicon interface was studied. Sample D-CR-12-43 #6 was diced and one part was then exposed to the humidity chamber. The results are shown in Figure 4-5: after 2500 minutes the debond energy is only slightly decreased and appears to be stable.

4.3.1.3 Cyclotene on Copper

Table 4-7 lists the first set of Cyclotene Copper samples. To promote copper adhesion to the silicon substrate a 300Å aluminum layer is first sputtered onto the silicon followed by 1 µm of copper. All wafers had an Al hardmask, which was removed with a 50°C PAN etch. Wafers 1 and 2 failed completely during the acid etch. The results for wafers 3-5 & 7 are plotted in Figure 4-6. The samples with the 1% MOPSTMS adhesion promoter had higher G values than those without. However, all samples had high sensitivity to the PAN etch.
Figure 4-5  Effect of 85°C/85% Humidity on Cyclotene 3022/Silicon interfacial debond energy. The test was stopped at 2500 minutes.

Table 4-7:  Summary of D-CR-11-93 Samples: Cyclotene 3022 on Copper

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Height, μm</th>
<th>Adh. Prm.</th>
<th>Observ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>yes</td>
<td>Fail</td>
</tr>
<tr>
<td>2</td>
<td>25.1</td>
<td>no</td>
<td>Fail</td>
</tr>
<tr>
<td>3</td>
<td>20.4</td>
<td>yes</td>
<td>debond</td>
</tr>
<tr>
<td>4</td>
<td>20.4</td>
<td>no</td>
<td>debond</td>
</tr>
<tr>
<td>5</td>
<td>17.1</td>
<td>yes</td>
<td>debond</td>
</tr>
<tr>
<td>6</td>
<td>20.4</td>
<td>yes</td>
<td>debond</td>
</tr>
<tr>
<td>7</td>
<td>15.6</td>
<td>no</td>
<td>debond</td>
</tr>
</tbody>
</table>
Figure 4-6: D-CR-11-93 Cyclotene on Copper Results. The promoter is 1.0% MOPSTMS. All samples were exposed to PAN etch.
To verify that the acid was diffusing at the via edge, a second set of samples D-CR-12-32, listed in Table 4-8, was fabricated. These were exposed to the PAN etch for various times. Wafers 5 and 6 failed in the acid bath. The results for wafers 1-4, which have adhesion promoter, are shown in Figure 4-7. As the acid etch time increased the amount of degradation increased. This confirms the sensitivity of the interfacial strength to the acid etch. The results for samples with and without adhesion promoter are shown in Figure 4-8. Without adhesion promoter the samples were even more susceptible to acid damage.

Table 4-8: Summary of D-CR-12-32 Samples: Cyclotene 3022 on Copper. All samples are 14.2 μm thick.

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Adh. Prm.*</th>
<th>Time in Etch, min</th>
<th>Observ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>yes</td>
<td>0.5</td>
<td>debond</td>
</tr>
<tr>
<td>2</td>
<td>yes</td>
<td>1.0</td>
<td>debond</td>
</tr>
<tr>
<td>3</td>
<td>yes</td>
<td>2.0</td>
<td>debond</td>
</tr>
<tr>
<td>4</td>
<td>yes</td>
<td>3.0</td>
<td>debond</td>
</tr>
<tr>
<td>5</td>
<td>no</td>
<td>3.0</td>
<td>fail</td>
</tr>
<tr>
<td>6</td>
<td>no</td>
<td>2.0</td>
<td>fail</td>
</tr>
<tr>
<td>7</td>
<td>no</td>
<td>1.0</td>
<td>debond</td>
</tr>
<tr>
<td>8</td>
<td>no</td>
<td>0.5</td>
<td>debond</td>
</tr>
</tbody>
</table>

* Adhesion promoter was 3-APS (3-aminopropyl-triethoxysilane)
Figure 4-7: D-CR-12-32 #1 - #4, Effect of acid etch time on Cyclotene/Copper interface with 3-APS promoter. As the acid bath time increases the strength of the interface degrades of larger radii vias.
Figure 4-8: D-CR-12-32 1, 2, 8, & 7, Effect of acid etch time on Cyclotene/Copper interface with and without 3-APS promoter. Without the adhesion promoter the degradation is much more rapid.
The effect of acid was studied with three more samples D-CR-12-70 #4, D-CR-12-71 #10 and #11, all about 14.5 μm thick. Wafer 4 was fabricated using a copper hardmask which was removed by a 30 second etch in copper etchant. The results for D-CR-12-70#4 are plotted in Figure 4-9. Wafers 10 and 11 used the photoresist release method described earlier. These had no debonding at room temperature. They were undercooled to -196°C and still no debonding was evident. To initiate debonding they were exposed to the copper etchant for 5 seconds and the results are plotted in Figures 4-10 and 4-11. Although the effect of the acid was diminished it was still present. The data appear to plateau near 2.5 J/m² which may be the G_c of the corroded interface.

Recently, a set of wafers (D-CR-13-69) with no features etched into them was received from Dow Chemical. These had blanket coatings cured with the standard schedule for Cyclotene. A variety of thicknesses and adhesion promoters were used, see Table 4-9. They were diced and undercooled to -196°C. No wafers, even at 40 μm thickness, failed. The maximum G applied was 24 J/m². After, they were exposed to PAN at 50°C for less than 30 seconds; all samples with no promoter failed, demonstrating that the interfacial strength of Cyclotene on copper is extremely high but also is extremely sensitive to acid. Similar results were found with samples on Copper using the MOPSTMS adhesion promoter, however, the APS samples did not delaminate after a 30 second acid etch.
Figure 4-9: D-CR-12-70 #4 14.7 μm Cyclotene 3022 on Copper with a 30 second copper etch at 50°C. Five holes are averaged at each radius; the solid squares are the average with the dash lines representing the lower and upper standard deviation.
Figure 4-10: D-CR-12-71 #9 14.3 μm Cyclotene 3022 on Copper with no acid etching during fabrication; afterwards no debonding was observed. To initiate debonding the sample was soaked for 5 seconds in 50°C copper etchant. Three holes are averaged at each radius; the solid squares are the average with the dash lines representing the lower and upper standard deviation.
Figure 4-11: D-CR-12-71 #10 14.5 µm Cyclotene 3022 on Copper with no acid etching during fabrication; afterwards no debonding was observed. To initiate debonding the sample was soaked for 5 seconds in 50°C copper etchant. Three holes are averaged at each radius; the solid squares are the average with the dash lines representing the lower and upper standard deviation.
Table 4-9: D-CR-16-39 Cyclotene 3022 on Copper. Blanket coatings with no features etched into them.

<table>
<thead>
<tr>
<th>Wfr ID</th>
<th>Slope MPa/°C</th>
<th>Intrcpt MPa</th>
<th>(MPa) @23°C</th>
<th>Metal</th>
<th>Adhes. Prom.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.117</td>
<td>29.336</td>
<td>26.65</td>
<td>Si</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>-0.121</td>
<td>30.046</td>
<td>27.26</td>
<td>Si</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>-0.121</td>
<td>29.660</td>
<td>26.88</td>
<td>Si</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>-0.117</td>
<td>28.989</td>
<td>26.30</td>
<td>Si</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>-0.119</td>
<td>30.078</td>
<td>27.34</td>
<td>Si</td>
<td>MOPS</td>
</tr>
<tr>
<td>6</td>
<td>-0.120</td>
<td>30.004</td>
<td>27.24</td>
<td>Si</td>
<td>MOPS</td>
</tr>
<tr>
<td>7</td>
<td>-0.118</td>
<td>29.346</td>
<td>26.63</td>
<td>Si</td>
<td>MOPS</td>
</tr>
<tr>
<td>8</td>
<td>-0.120</td>
<td>29.866</td>
<td>27.11</td>
<td>Si</td>
<td>MOPS</td>
</tr>
<tr>
<td>9</td>
<td>-0.121</td>
<td>30.360</td>
<td>27.58</td>
<td>Si</td>
<td>3-APS</td>
</tr>
<tr>
<td>10</td>
<td>-0.119</td>
<td>29.669</td>
<td>26.93</td>
<td>Si</td>
<td>3-APS</td>
</tr>
<tr>
<td>11</td>
<td>-0.118</td>
<td>29.862</td>
<td>27.15</td>
<td>Si</td>
<td>3-APS</td>
</tr>
<tr>
<td>12</td>
<td>-0.128</td>
<td>31.179</td>
<td>28.24</td>
<td>Si</td>
<td>3-APS</td>
</tr>
<tr>
<td>13</td>
<td>27*</td>
<td>Cu</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
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<td>Cu</td>
<td>No</td>
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<td></td>
</tr>
<tr>
<td>15</td>
<td>27*</td>
<td>Cu</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>27*</td>
<td>Cu</td>
<td>APS</td>
<td></td>
<td></td>
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<td>MOPS</td>
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<td>27*</td>
<td>Cu</td>
<td>APS</td>
<td></td>
<td></td>
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<tr>
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<td>27*</td>
<td>Cu</td>
<td>MOPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>27*</td>
<td>Cu</td>
<td>MOPS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Based on average of Wafers 1-12

4.3.1.d Cyclotene on Chrome

Set D-CR-13-11 is described in Table 4-10. These were fabricated using an aluminum hardmask removed with 50°C PAN. Some of the samples had through the thickness cracking at room temperature when they were
received. By the analysis of Margaritis [62] the $K_{IC}$ value is between 0.26 and 0.30 MPa-√m which agrees with previously reported values [62].

Table 4-10: D-CR-13-11 Cyclotene 3022 on Chrome

<table>
<thead>
<tr>
<th>#</th>
<th>Thickness, $\mu$m</th>
<th>Cracking Observed</th>
<th>Debond Observed</th>
<th>$K_I$ applied, MPa-√m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.7</td>
<td>no</td>
<td>no</td>
<td>0.181</td>
</tr>
<tr>
<td>2</td>
<td>19.2</td>
<td>(a)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>27.2</td>
<td>no</td>
<td>yes (b)</td>
<td>0.238</td>
</tr>
<tr>
<td>4</td>
<td>32.0</td>
<td>no</td>
<td>yes</td>
<td>0.258</td>
</tr>
<tr>
<td>6</td>
<td>42.1</td>
<td>yes</td>
<td>yes</td>
<td>0.296</td>
</tr>
<tr>
<td>7</td>
<td>53.5</td>
<td>yes</td>
<td>yes</td>
<td>0.335</td>
</tr>
<tr>
<td>8</td>
<td>66.3</td>
<td>yes</td>
<td>yes</td>
<td>0.371</td>
</tr>
</tbody>
</table>

(a) Sample 2 broke during processing.
(b) On edge of wafer slightly.

The results from the debond measurements for wafers 4, 6 and 8 are plotted in Figure 4-12, and the acid influence is evident. Wafer 3 was undercooled in liquid nitrogen, where the stress was 69 MPa and the maximum applied debond energy was 27 J/m². The debonds did not proceed. Fine hair-line cracks were observed through the thickness of the Cyclotene, which indicates that the cohesive strength of the coating was exceeded.

Wafer 6 was cooled until it reached -196°C; debonding was observed only along the cleaved edge near -130°C. Hairline cracks were observed at -196°C. The applied debond energy at -130°C was 31 J/m² which is near the fracture toughness of Cyclotene (33 J/m²). Thus, cohesive failure in the plane of the coating was expected.
Wafer 8 was cooled in liquid nitrogen; it cohesively cracked through the thickness with catastrophic debonding occurring at the silicon chrome interface. The applied debond energy was 66 J/m². Therefore, the $G_{ic}$ of the silicon-chrome interface is between 42 and 66 J/m².

Figure 4-12: D-CR-13-11 Cyclotene 3022 on Chrome at room temperature. Samples exposed to PAN etch during fabrication. The values have not reached steady state; they are limited by the maximum applied $G$ at each of the respective heights.
4.3.2. ULTRADEL 4212

This section reports the collected EDT results for Ultradel 4212. Due to the high toughness of Ultradel 4212 only a limited number of cases were studied.

4.3.2.a Ultradel 4212 on Aluminum

U-AL-02-01 was 110 μm of Ultradel 4212 spun coated on 0.5 μm of evaporated aluminum. The sample was exposed to PAN etch. The room temperature results are shown in Figure 4-13. The debond energy was influenced by corrosion effects, but when the sample was diced, debonding at the free edge occurred. From the plane-strain calculations \( G_C \) was estimated to be 23.4 J/m\(^2\). The part was cooled while monitoring a single debond ring; the debond ring did grow but at -196°C the film completely lifted-off the wafer. Upon examination, the remains of aluminum around the via holes could be seen. From these tests the \( G_C \) was measured to be 24±2 J/m\(^2\), which is in good agreement with debond energies measured using the IBT (\( G_{IC} = 30 \text{ J/m}^2 \)) [39].

The failure then turned into the aluminum-silicon interface and the debond energy at this temperature was 66.4 J/m\(^2\). The applied \( K_I \) is 0.46 MPa-\( \sqrt{\text{m}} \). This is close to the \( K_{IC} \) of silicon oxide.

4.3.2.b Ultradel 4212 on Copper

Ultradel, 28 μm thick, was cured onto sputtered copper. The sample was exposed to PAN etch. The results from the debonding at room temperature are shown in Figure 4-14. They plateau at 2.99±0.12 J/m\(^2\). When the sample was undercooled it completely debonded at -50°C, so, no further
data could be taken. This behavior was with the low debond energy measured at room temperature.

Two additional samples, D-CR-12-65-7 and D-CR-12-70-7, were fabricated; both were 38.5 μm thick. They were fabricated using the photoresist release method, but the edge profiles of the via sidewalls were very shallow. To initiate debonding they were exposed to 45°C PAN etchant for 30 seconds. The results for D-CR-12-65-7 are shown in Figure 4-15. The average $G_c$ was $5.18 \pm 0.72$ J/m$^2$. The average for D-CR-12-70-7 was $5.57 \pm 0.75$ J/m$^2$.

Figure 4-13: 110 μm Ultradel 4212 on evaporated aluminum at room temperature. The sample was etched with PAN to remove the hardmask. The interface is sensitive to the acid.
4.3.2.3 Ultradel 4212 on Silicon

Figure 4-16 shows the results collected for a 33 μm and a 42 μm thickness Ultradel coatings on silicon. The results are limited by the maximum applied energy for these thicknesses. The debonds measured were due to acid etching effects. Undercooling to liquid nitrogen temperature did not increase the debonding or cause any failure. Then, they were exposed to 85°C/85% humidity and measured periodically. The results are plotted in Figure 4-17. By 176 minutes #2 failed. #1 survived to 1100 min. These data demonstrate the usefulness of the EDT for tracking the adhesion as influenced by exposure to moisture.

![Graph showing Gtot vs Radius, μm]

Figure 4-14: D-CR-12-57 #4 28.5 μm thick Ultradel 4212 on Copper.
Figure 4-15  D-CR-12-65 #7 39.4 µm Ultradel 4212 on Copper after 30 seconds exposure to PAN at 45 °C.

Figure 4-16: Ultradel 4212 on Silicon. The applied energy plateaus at high radii since it limited by the maximum energy at this thickness. Further undercooling did not increase the debonding.
4.3.2. c Ultradel 4212 on Chrome

A coating of Ultradel 4212 83 μm thick was spun on chrome and the sample was processed using the standard fabrication method. No debonds were observed at room temperature. The sample was undercooled to -196°C. No debonding occurred. The maximum G applied at -196°C was 46 J/m². This result is in agreement with data from the IBT [39] where G_c for this interface was 102 J/m².

4.3.3. Pyralin 2545 on Aluminum

Other results from the EDT and the IBT have been compared for samples of PI 2545 coated on evaporated aluminum processed similarly. [74]. Table 4-11 shows the results from the island blister test where the critical Mode I adhesion energies of 17 J/m² and 19 J/m² were measured. (For each IBT sample four to five adhesion measurements are made.) Table 4-12 lists the results from the edge delamination test. Initially, Sample C showed no debonding at room temperature, where the applied energy was 8.89 J/m², which is below the G_{IC} measured by the IBT. Cooling the sample to liquid nitrogen increased the stress in the film. The stress was extrapolated from the room temperature residual stress using reported elastic constants. The average G_{IC} was 16.0±0.7 J/m².

To avoid the necessity for cooling below 20°C and extrapolating the residual stress, thicker samples were made. For sample D, the critical debond energy was 13.8±1.7 J/m². (The scatter was due to small through the thickness cracks which grew radially from the hole edge; these complicated the measurement of debond length). Sample E, a repeat of D, showed no through the thickness cracking. The measured G_{IC} for sample E was 18.2±0.7 J/m².
Figure 4-17: Effect of 85°C and 85% humidity on the interfacial strength of Ultradel 4212 on silicon. By 176 min sample 2 failed and by 1100 minutes the sample 1 failed.

Table 4-11: Island Blister Adhesion Data for PI2545 on Aluminum

<table>
<thead>
<tr>
<th>Sample</th>
<th>Film Height, µm</th>
<th>Gl, J/m²</th>
<th>GIl, J/m²</th>
<th>Gtot, J/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>19.7</td>
<td>19±2.0</td>
<td>28</td>
<td>47</td>
</tr>
<tr>
<td>B</td>
<td>23.3</td>
<td>17±1.8</td>
<td>27</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 4-12: Edge Delamination Adhesion Data for PI2545 on Aluminum

<table>
<thead>
<tr>
<th>Sample</th>
<th>Film Height, µm</th>
<th>$\sigma_0$, MPa</th>
<th>Max. Applied G</th>
<th>Glc, J/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>105</td>
<td>39.5‡</td>
<td>20.5</td>
<td>16.0±0.7</td>
</tr>
<tr>
<td>D</td>
<td>168</td>
<td>40.5</td>
<td>38.6</td>
<td>13.8±1.7</td>
</tr>
<tr>
<td>E</td>
<td>170</td>
<td>35.0</td>
<td>25.2</td>
<td>18.2±0.7</td>
</tr>
</tbody>
</table>

‡Extrapolated residual stress.
4.4 SUMMARY

Edge delamination tests were performed for three polymers: Cyclotene 3022, Ultradel 4212 and Pyralin 2545. Several metal interfaces were tested: silicon, aluminum, copper and chrome. The results for Ultradel and Cyclotene show that the interfacial strength is extremely sensitive to the acid etchant used during fabrication. Table 4-13 summarizes the data collected. The listed values are practical limits of adhesion defined by plateau values of $G_c$ at large radii holes.

Table 4-13: Critical Strain Energy Release Rate, $J/m^2$ for Polymer metal interfaces after fabrication with acid etchants.

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Bare Si</th>
<th>Al 1%Cu</th>
<th>Al</th>
<th>Chrome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclotene 3022</td>
<td>2.4±0.25</td>
<td>4.8</td>
<td>4.9±0.4</td>
<td>5.4±0.5</td>
<td>12.8</td>
</tr>
<tr>
<td>Ultradel 4212</td>
<td>5.5±0.7</td>
<td>6.1</td>
<td>-</td>
<td>24±2</td>
<td>&gt;46b</td>
</tr>
<tr>
<td>Pyralin 2545</td>
<td>-</td>
<td>-</td>
<td>17±2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(a) Sample debonded and cracked.  Debond energy may be influenced by cracking.
(b) Sample did not debond at this thickness.

Accelerated aging studies at 85°C/85% humidity show that the Ultradel silicon interface is very sensitive to moisture: the critical debond energy is nearly constant until a critical time is reached. Then the critical debond energy drops to zero. One sample completely failed by 176 minutes; another survived to 1100 minutes. Cyclotene 3022 showed little sensitivity to moisture: after 2500 minutes exposure the sample had not debonded.
CHAPTER 5: ADHESIVE RELIABILITY OF COATINGS

5.1 Introduction

One challenge for coating manufacturers is to screen candidate materials quickly to meet rigorous adhesion requirements. For microelectronic packages reliability tests include thermal shock to -65°C and thermal fatigue from -65°C to 150°C [74]. As discussed in Chapter 1, reliability is assessed by testing components and then building a probability of failure distribution [7]. This is expensive and time consuming. It would be more efficient to determine the reliability of the coating a priori based on an easily measured failure criterion.

To this end, a set of equations that predict the reliability of a coating [75] is developed. They analyze the Edge Lift-Off test. To assess its maximum use limit, strong interfacial bonding is assumed, so the adhesion is limited by the coating's strength. The equations predict failure by comparing the coating's strength and fracture toughness to the biaxial residual stress, which develops during thermal cooling. For monotonic cooling, a failure map is made, with coating thickness versus temperature showing the safe and fail regimes. For thermal fatigue, sets of curves are drawn to predict the lifetime of a coating as a function of thickness when cycled to various low temperatures.

In this chapter, an analysis of the Edge Lift-Off test is presented and reliability equations for monotonic and cyclic cooling are derived. Also, a similar set of equations to predict coating reliability for Flip Chip assemblies, discussed in Chapter 3, is developed. To validate the equations, ELT
experiments were performed. Bulk samples were fabricated to collect strength and fracture toughness data; and strength versus cycles behavior was measured from tensile-tensile fatigue. The stress versus temperature behaviors for the coating were measured. From these data, predictions for monotonic and cyclic thermal reliability were made. These predictions were compared to data collected using the ELT.

5.2 Reliability Analysis of the Edge Lift-Off Test

5.2.1 Monotonic Cooling

For a biaxially stressed coating on a rigid substrate the applied strain energy, $G_b$, for a long, two-dimensional, plane-strain crack is:

$$G_b = \frac{\sigma_o^2 h(1-v^2)}{2E} \quad 5-1$$

where $h$ is the film thickness, $\sigma_o$ is the residual stress in the coating, and $E$ and $v$ are the coatings Young's modulus and Poisson's ratio. From the EDT numerical analysis, $G_b$ can be approximated with a linear equation as a function of crack length, $a$, where $a/h < 0.025$:

$$G_b = \frac{\sigma_o^2 h(1-v^2)}{2E} \cdot \frac{40a}{h} = \frac{20\sigma_o^2 a(1-v^2)}{E} \quad 5-2$$

and is Equation 5-1 for $a/h > 0.025$ for a crack propagating away from an edge which has a 90° angle to the substrate.

The difficulty in using Equation 5-2 is selecting the appropriate crack length. Griffith showed fracture properties can be related to the strength by
assuming the presence of an intrinsic flaw [76]. Its size for an interfacial crack is:

\[
a_{\text{in}} = \frac{G_c E}{\pi \sigma_u^2 (1 - \nu^2)}
\]  

5-3

where \( G_c \) is the critical strain energy release rate and \( \sigma_u \) is the ultimate strength of the coating. As stated, the condition for failure is \( G > G_c \). Using Equations 5-2 and 5-3 the failure criteria for \( a/h < 0.025 \) becomes:

\[
\sigma_o > \frac{\sigma_u}{2.52} = \frac{\sigma_u}{S}
\]  

5-4

The S-factor is a dimensionless parameter used to predict failure by interfacial cracks in polymer coatings. For thinner films, when \( a/h > 0.025 \):

\[
\sigma_o > K_{IC} \sqrt{\frac{2}{h}}
\]  

5-5

where \( K_{IC} \) is the fracture toughness of the coating.

Using Equations 5-4 and 5-5, and knowing the ultimate strength and the fracture toughness, one can predict the onset of adhesive film failure as a function of residual stress and thickness. An example failure map is given in Figure 5-1 for a material with an ultimate strength, \( \sigma_u \), of 80 MPa, and a fracture toughness, \( K_{IC} \), of 0.25 MPa-\( \sqrt{m} \). There are two regimes in the failure map. For thicker films, the boundary between fail and safe is a horizontal line (Equation 5-4) while for thinner films it is a curved one (Equation 5-5). Both refer to the same kind of failure: a crack in the coating which propagates very close and parallel to the interface.
If the stress-temperature relationship for the coating is known (for this case assume $\sigma_0 = -0.12T(\degree C) + 35$ MPa) then the map as a function of coating thickness and temperature, can be constructed, Figure 5-2.

Figure 5-1: An example of a failure map for a coating with a strength of 80 MPa and a fracture toughness of 0.25 MPa-$\sqrt{m}$ using Equations 5-4 and 5-5.

In Section 2.3.2 it was shown that the angle of the side wall changes the strain energy release rate as a function of crack length, Figure 5-3. Thus, the S-factor is a function of side wall angle. $S$ can be determined for each angle plotted in Figure 5-3, using Equations 5-1 through 5-4. The results are shown
in Figure 5-4. As the side wall angle decreases $S$ decreases; at $64^\circ$ the S is one. For smaller angles the coating will crack through its thickness before delaminating because $\sigma_o$ will have exceeded $\sigma_u$.

![Graph showing failure map]

**Figure 5-2:** Failure map constructed as a function of temperature and coating thickness where the stress temperature relationship of the coating is known. For this example, $\sigma_u = 80$ MPa, $K_{ic} = 0.25$ MPa-$\sqrt{m}$ and $\sigma_o = -0.12T + 35$ MPa.
Figure 5-3: $G_r$ as a function of $a/h$ for various side wall angles in the ELT geometry.

5.2.2 Thermal Fatigue

Fatigue lifetime estimates have been derived from tensile fatigue test results and the above analysis. From mechanical fatigue testing, the fatigue life data are fit with the following equation:

$$\sigma_u(N) = m\log(N) + \sigma_u$$  \hspace{1cm} (5-6)

where $m$ is the slope, $\sigma_u$ is the single cycle strength and $\sigma_u(N)$ is the strength after $N$ cycles. From the monotonic analysis of thicker films, when $a/h < 0.025$, failure occurs when Equation 5-4 is satisfied. Thus, for the cyclic strength:
Figure 5-4: The dependence of the S-factor on the side wall angle. Below 64° the coating will fail through its thickness before debonding.

$$\sigma_0 > \frac{\sigma_u(N)}{2.52} = \frac{m\log(N) + \sigma_u}{2.52}$$  \hspace{1cm} 5-7

The residual stress-temperature curve is fit by:

$$\sigma_0 = T_S \cdot T + T_i$$  \hspace{1cm} 5-8

where $T$ is the temperature in °C, $T_S$ is the slope in MPa/°C, and $T_i$ is the intercept in MPa. To predict the number of cycles, $N_f$, to failure for thick film samples, which are cycled to a low temperature, $T_l$, Equation 5-8 is substituted into 5-7 and solved:
\[
\log(N_f) = \frac{[2.52(T_1 \cdot T_2) + T_1]}{m} - \sigma_u
\]  

For thinner samples, when \(a/h > 0.025\), failure occurs when Equation 5-5 is satisfied. Now the Griffith equation is used:

\[
K_{IC} = \sigma_u \sqrt{a_{in}}
\]  

where \(a_{in}\) is the inherent flaw size. To represent how \(K_{IC}\) varies with cycles, \(a_{in}\) is assumed to be independent of \(N\), which leads to the expression:

\[
\frac{K_{IC}(N)}{K_{IC}} = \frac{\sigma_u(N)}{\sigma_u}
\]  

Incorporating Equation 5-6 into this provides:

\[
K_{IC}(N) = K_{IC} \left( \frac{m \log(N)}{\sigma_u} \right) + 1
\]  

Using Equations 5-5 and 5-8 in Equation 5-12 and solving for the number of cycles, \(N_f\), to failure when cycling from 20°C to 71°C gives:

\[
\log(N_f) = \frac{\sigma_u}{m} \left( \sqrt{\frac{h}{K_{IC} \sqrt{2} (T_1 T_2 + T_1)} - 1} \right)
\]  

The fatigue failure map has two regions; one for thick films and the other for thin ones, an example is shown in Figure 5-16. For thick films, the number of cycles to debond, when cycling to a given temperature, is independent of the film thickness, so the curve is flat. In this region, the reliability is controlled by the rate of decay of the coating strength under fatigue loading. As the low temperature is decreased, the applied stress increases which leads to shorter lives. Eventually, when the low cycle temperature is equal to or below the critical temperature predicted for
monotonic cooling the part will delaminate in the first cycle. For thin films
the log of the number of cycles to failure is inversely dependent on the square
root of the film height: slight decreases in film thickness lead to large
increases in lifetime.

5.3 Reliability Analysis of the Flip Chip

A reduced debond energy for Flip Chip geometries, $G_{F_{Cr}}$ is defined as:

$$G_{F_{Cr}} = \frac{G}{G_{FC}} = \frac{G(1-2v)}{G_b} \left(\frac{1-\alpha}{1+\beta}\right)^2$$  5-14

where $G_{FC}$ is given in Equation 3-12, $G_b$ is given in Equation 5-1 and $\alpha$ and $\beta$
are given in Equation 3-6. Using the analysis of Section 3-2 $G_{F_{Cr}}$ is calculated
as a function of crack length for the plane strain Flip Chip geometry when the
coating is adhered to the post and when it is not.

5.3.1 Post/Coating Adhesion Case

For the adhered case $G_{F_{Cr}}$ is approximated as one when $a/h > 0.75$ and
as $1.33a/h$ when it is less. From Equation 5-14 the debond energy is:

$$G = G_{F_{Cr}} \cdot G_{FC} = \frac{G_{F_{Cr}} \sigma_o^2 h(1-v^2) \left(\frac{1-\alpha}{1+\beta}\right)^2}{2E(1-2v)}$$  5-15

As done in Section 5.2.1 the Griffith criterion is used to define failure for the
coating. Then for $a/h < 0.75$:

$$\sigma_o > \frac{\sigma_u}{S}; \quad S = \sqrt{\frac{1.33(1-v^2)(1-\alpha)}{2\pi(1-2v)\left(1+\beta\right)}}$$  5-16
The worst case geometry is $\alpha$ and $\beta$ equal zero; then $S$ is a function of the Poisson's ratio. The relation is plotted in Figure 5-5. For $\nu$ less than 0.41, $S$ is less than one so debonding will not occur before through the thickness cracking takes place.

![Graph](image)

**Figure 5-5:** The effect of Poisson's ratio on the S-Factor for plane strain Flip Chip geometry with $\alpha$ and $\beta$ equal to zero.

For thin films, $a/h > 0.75$:

$$
\sigma_o \geq K_{IC} \frac{(1+\beta)}{(1-\alpha)} \sqrt{\frac{2(1-2\nu)}{h}}
$$

5-17

Again for $\alpha$ and $\beta$ equal zero, the predicted failure maps can be drawn for the material described in Section 5.2 for various Poisson's ratio: Figure 5-6. The ELT failure predicted by Equation 5-5 also is plotted. As the Poisson's ratio increases it is more probable the sample will break.
Recall that the stress in the coating is much higher than in the ELT case, so, this must be added to the failure criterion. From Chapter 3, the stress in the plane of the film is:

\[
\sigma_x = \frac{\sigma_0 (1 - \nu)}{(1 - 2\nu)} \left( 1 - \frac{\nu (\alpha + \beta)}{(1 - \nu)(1 + \beta)} \right) \tag{5-18}
\]

Figure 5-6: Reliability map for Plane Strain Flip Chip adhered to post with $\alpha$ and $\beta$ equal to zero predicted from Equation 5-17 and using the properties of the example material in Section 5.2.
Again for $\alpha$ and $\beta$ equal to zero, the temperature at which $\sigma_x$ exceeds $\sigma_u$ can be calculated. Including this in Figure 5-6, adds an additional regime to the reliability map, Figure 5-7. For small a/h, a plateau defined by the longitudinal stress exceeding the strength of the material defines failure. This is independent of thickness. For larger a/h, a curved function defined by Equation 5-17 defines failure; this is inversely proportional to the $\sqrt{h}$.

Figure 5-7: Reliability predictions for monotonic undercooling for $\alpha$ and $\beta$ equal to zero. The coating's $\sigma_u$ is 80 MPa, its $K_{IC}$ is 0.25 MPa-m and the stress, $\sigma_D$, is -0.12T, °C + 35 MPa. The results are plotted for various Poisson's ratios and for the ELT case.
5.3.2 Post/Coating with No Adhesion Case

In Section 3.2 the relationship between $G_{FCr}$ and $a/h$ was found to be complex because of the presence of two maxima. In order to assess fits reliability the relationship is simplified. Assume for $a/h$ less than 0.0167 $G_{FCr}$ is equal to $60a/h$ and is 1.4 when $a/h$ is greater than 0.0167. Then for $a/h$ less than 0.0167:

$$\sigma_0 > \frac{\sigma_u}{S}; \quad S = \sqrt{\frac{30(1 - v^2)(1 - \alpha)}{\pi(1 - 2v)^2(1 + \beta)}}$$  \hspace{1cm} (5-19)

In Figure 5-8 $S$ versus $v$ for $\alpha$ and $\beta$ equal to zero is plotted. At $v = 0.4$ $S$ is 6.33; so, for the example material, when adhesion to the post is lost the temperature below which debonding occurs would increase from -208°C to 186°C. The results clearly show the importance of good adhesion between the post and the coating.

For thin films, $a/h > 0.0167$, assume $G_{FCr}$ is constant at 1.40. Then:

$$\sigma_0 \geq K_{IC} \frac{(1 + \beta)}{(1 - \alpha)} \sqrt{\frac{1.43(1 - 2v)}{h}}$$  \hspace{1cm} (5-20)

The analyses from Sections 5.2.1 and 5.2.2 can be applied to a realistic Flip Chip module. Assume Cyclotene 3022 is the coating and gold is the post. The material properties used are listed in Table 5-1. For this case the posts are 100 μm wide and spaced 100 μm apart; so, $\alpha$ and $\beta$ are 0.23 and 0.03. The predicted failure map is plotted in Figure 5-9. First, Equation 5-18 is used to define the operable limit for all coating heights. This determines the lowest use temperature because beyond this $\sigma_x$ exceeds $\sigma_u$. Then Equations 5-16 and 17 are solved for the adhered case. As seen in Figure 5-9, it does not affect the coatings performance since at these thicknesses the predicted failure
Figure 5-8: S-Factor versus Poisson’s ratio for the Flip Chip when the post and coating are not adhered. $\alpha$ and $\beta$ are zero.

Temperatures are less than the temperature established by Equation 5-18. Next Equations 5-19 and 5-20 are plotted for the non-adhered failure case. Here the failure temperature increases in accordance with Equation 5-20 until it plateaus at the thick film limit defined by Equation 5-19.

Table 5-1: Properties of Cyclotene 3022 and Gold

<table>
<thead>
<tr>
<th></th>
<th>$E$, GPa</th>
<th>$\nu$</th>
<th>CTE*, PPM/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>80</td>
<td>0.33</td>
<td>12</td>
</tr>
<tr>
<td>Cyclotene</td>
<td>2.08</td>
<td>0.35</td>
<td>49</td>
</tr>
</tbody>
</table>

*Offset by the silicon substrate’s CTE
Figure 5-9: Predicted reliability map for Flip Chip having a Cyclotene 3022 coating and gold posts. Cyclotene's strength is 85 MPa and $K_{IC}$ is 0.28 MPa $\sqrt{m}$.

These results can be compared to another coating material with properties recommended in the literature [66,67]; modulus of 9 GPa, CTE of 30 PPM/°C, $K_{IC}$ greater than 1, and $T_g$ equal to 125°C. Assume the strength is equal to Cyclotene's, 85 MPa, a Poisson's ratio of 0.40, and identical post geometry. The results are shown in Figure 5-10. Here the reliability is limited by the longitudinal stress, (Equation 5-18) both for the adhered and non-adhered conditions. Comparing to the Cyclotene map, failure will occur here
at higher temperatures for the recommended coating. This is because the high modulus causes the residual stress to increase more rapidly.

5.3.3 Thermal Fatigue Analysis for Flip Chip

As demonstrated in the previous sections, the longitudinal stress exceeding the strength of the coating is the predominate failure mechanism. From Equations 5-6, 5-8 and 5-18 one obtains:

$$\log N_f = \frac{\sigma_u}{m} \left( \frac{(T_i + T_j)(1 - v)}{(1 - 2v)} \left( 1 - \frac{v(\alpha + \beta)}{(1 - v)(1 + \beta)} \right)^{-1} \right)$$ 5-21

$N_f$ is independent of film thickness and increases with strength.

Figure 5-10: Predicted reliability map for Flip Chip with gold posts and a coating with literature recommended properties. Both curves are identical.
5.4 Experimental Procedures for ELT

Two epoxy resins were used to validate the ELT reliability analysis. One was Epon 828™ the other, an experimental resin labeled Resin A. Both are linear elastic materials but differ in the magnitudes of their physical properties. These were chosen because of their availability and their ease of fabrication.

5.4.1 Sample Fabrication

EPON 828 was formulated with Ancamine K61B curing agent in a 9 to 1 ratio for all samples. The cure schedule consisted of one hour at 90°C followed by 10 hours at 150°C. Resin A needed no additional curing agent added. Its cure schedule was one hour at 177°C followed by four hours at 220°C.

Bulk mechanical samples were fabricated by casting and curing 6 mm thick plaques of the resins. The plaques were machined into the shapes required by the ASTM standards. For uniaxial tensile testing and uniaxial tensile-tensile fatigue testing, the M-III modified version of ASTM specification D 638M-91a was used to make microtensile specimens. For the plane-strain fracture toughness (KIC) test, ASTM specification D5045-91a was used with compact tension specimens. To eliminate any defects, such as nicks and other stress concentrators, the gauge length of the microtensile specimens was hand polished with 320 grit silicon carbide paper. Compact tension specimens were cracked by clamping the sample and tapping with a fresh razor blade.

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Coated specimens for ELT and curvature testing were fabricated by adding 4 weight percent toluene to the resins to lower their viscosity. This mixture was then spin-coated onto degreased glass substrates for ELT and silicon for the curvature tests. The coating thickness was controlled by varying the spin speed. After curing, the glass coated samples were diced into 2 cm square specimens. Optical microscopy was used to measure the coating thickness on each of the four sides of the ELT specimen. Profilometry was used to measure the thickness of the silicon coated sample.

5.4.2 Mechanical Testing

Instron testing was done at room temperature. A 1/2" extensometer was used to measure the strain. The strain rate was 0.1 mm/mm-min. The maximum tensile stress, strain, and Young's modulus were calculated. The Instron also was used for Mode I fracture toughness testing on the machined compact tension specimens; $K_{IC}$ was calculated from the peak load. All specimens met the linearity requirement. A minimum of seven specimens was used per test. Fatigue testing was done at a constant crosshead speed of 10 mm/min. The stress cycle went from 10 MPa minimum to the upper stress.

5.4.3 Curvature Testing

The Tencor FLX 2320 machine was used to measure the stress in the coating at various temperatures. For Resin A the temperature cycle went from 20°C to 250°C, then down to -50°C, and back to 20°C. For Epon 828 the cycle went from 20°C to 150°C, then to -50°C and back to 20°C. The controlled rate was 3°C/min for both heating and cooling.
5.4.4 ELT Procedure

ELT specimens were cooled using a cold stage under a dry nitrogen purge. The stage can control to -196°C. It also can be programmed for ramp/soak or thermal fatigue. For monotonic undercooling failure was observed visually. The temperature of adhesive failure is recorded. Thermal fatigue experiments are also done with the cold stage. The temperature is cycled between the low limit and room temperature with 5 minutes at the low temperature. The cycle time was varied to maintain a constant cooling rate for each test. The cooling rate was 4°C/minute. Optical microscopy was used to monitor the onset of debonding. The debond was easily identifiable under cross-polarized light with a 5X objective. Care was taken to record any defects or debonds that may have occurred during fabrication.

5.5 RESULTS AND DISCUSSION

5.5.1 Mechanical Testing Results

From uniaxial tensile testing the $\sigma_u$ of Epon 828 is $70 \pm 2$ MPa. From compact tension tests the $K_{IC}$ is $0.33\pm0.09$ MPa.m. The fatigue results are shown in Figure 5-11; plotted is the maximum cycle stress divided by the ultimate strength versus log(cycles to failure). The data are fit with:

$$\frac{\sigma}{\sigma_u} = -0.10\log(N_t) + 1.00$$  \hspace{1cm} 5-22

Residual stress versus temperature was measured for the silicon/Epon samples. From the best fit $T_S$ was $-0.235^\circ$C/MPa and $T_i$ was 19 MPa.

For Resin A the ultimate strength was $57\pm7$ MPa and $K_{IC}$ was $0.49\pm0.2$ MPa-$\sqrt{m}$. From its fatigue data the best fit was:
Residual stress versus temperature was measured for the silicon/Resin A sample, Figure 5-12. From the best fit $T_S$ was $-0.314^{\circ}C/MPa$ and $T_i$ was 54.6 MPa.

Figure 5-11: Normalized tensile-tensile fatigue results of Epon 828 samples. Three sets of samples were fabricated from different plaques. The solid line is the best fit.
Figure 5-12: Stress-Temperature measurements for Resin A on silicon.

5.5.2 Monotonic ELT Results

From the stress-temperature and the tensile results, the critical temperature can be predicted for adhesive failure versus film thickness for Epon 828, Figure 5-13 and Resin A, Figure 5-14. The ELT results are plotted. From the Epon 828 ELT data it is possible to calculate the strength 72±2 MPa and the fracture toughness: 0.34±0.06 MPa√m, which are in excellent agreement with the other measurements. From the ELT results for Resin A, $K_{IC}$ was calculated to be 0.50±0.09 MPa-√m; in excellent agreement with the compact tension results. Several samples, denoted as solid squares in Figure 5-14, had already debonded when the oven door was opened after the cure finished at 25°C, which is in agreement with the predicted failure. Also note that for Resin A there is no S regime at these thicknesses.
Ellipsometry was done to identify the locus of failure. For both the Epon 828 and Resin A ELT specimens residual epoxy was found on the glass fractured side ranging in thickness from 250 to 500Å. The fractures were cohesive in the epoxy layer.

The agreement between the compact tension $K_{IC}$ values and the ELT results reinforce the assumption that the mixity for the ELT and EDT is mode I for linear elastic materials. Had it been mixed mode the ELT $K_{IC}$ values would have been different by 60%, which was not the case.

![Graph](image)

Figure 5-13: Failure Map for Epon 828 Epoxy Coatings on Glass. The solid line is the predicted failure locus. The experimental results (diamond data points) are failures; they correlate well with the predictions.
Figure 5-14: Failure Map for Resin A Epoxy Coatings on Glass. The solid line is the predicted failure locus. The experimental results (square data points) are failures; they correlate well with the predictions. The solid square data were samples that had failed when the oven was opened at 25°C after cooling from the cure temperature.

5.5.3 Cyclic ELT Results

From the measured values of $m$, $T_s$, $T_i$, $\sigma_U$ and $K IC$ and Equations 5-9 and 5-13, the lifetimes can be predicted as a function of coating thickness and low cycle temperature. In Figure 5-15 the predicted lifetimes for resin A as a function of film height for several low cycle temperatures is plotted. Because the predicted results are extremely sensitive to film height, cyclic ELT testing was not done with Resin A. The same predictions are made for Epon 828 in,
Figure 5-16. Here the curves are less sensitive to film height so the experiments were performed.

![Graph showing lifetime cycles vs. film height for different low cycle temperatures.]

Figure 5-15: Lifetime cycle predictions for Resin A on glass as a function of film thickness cycled to various low temperatures from 20°C.

Three low cycle temperatures were chosen: -22°C, -32°C and -45°C. These tend to distinguish the experimental results. The -22°C, -32°C and -45°C cycled results for Epon 828 are plotted in Figures 5-17 - 19, with the predicted error; the latter were constructed from a one standard deviation associated with the measured input values. Nearly all of the ELT fatigue results are within the error bands. From this agreement, the assumption that the intrinsic Griffith flaw, \(a_{in}\), is not a function of cycling appears to be valid.
Figure 5-16: Lifetime cycle predictions for EPON 828 on glass as a function of film thickness cycled to various low temperatures from 20°C.
Figure 5-17: ELT thermal fatigue results for EPON 828 on glass as a function of film thickness cycled to -22°C. The solid line is the predicted lifetime. The dashed lines are error curves of the prediction determined by the standard deviation of the input material properties.
Figure 5-18: ELT thermal fatigue results for EPON 828 on glass as a function of film thickness cycled to -32°C. The solid line is the predicted lifetime. The dashed lines are error curves of the prediction determined by the standard deviation of the input material properties.
Figure 5-19: ELT thermal fatigue results for EPON 828 on glass as a function of film thickness cycled to -45°C. The solid line is the predicted lifetime. The dashed lines are error curves of the prediction determined by the standard deviation of the input material properties.
5.6 Modified ELT

The ELT can be modified to measure the fracture toughness of very brittle materials or ones that do not generate a large $G$ sufficient to induce debonding. This is done by applying a backing layer to the test resin; the backing layer must have a higher strength than the test coating and must be adhered well enough that the crack remains cohesive in the test layer. (If the thickness of the test layer is much thinner than the backing layer the applied $G$ is approximately that stored in the backing layer alone.) The advantage of this test is that the properties of the test layer are not required; only the height and stress-temperature profile of the backing need to be known.

The Modified ELT also can be used to enhance the ELT. For example, in Figure 5-20 the predicted failure map for Cyclotene 3022 and for a thin layer of it backed with Epon 828™ are shown. The ELT can be applied for Cyclotene 3022 only over film heights from 50 to 130 $\mu$m, but, the backing layer extends the range to 400 $\mu$m. It also allows the strength of the coating to be measured since the $S$ temperature is less than 20°C.

Currently the modified ELT is being applied to measure the fracture toughness and strength of a new experimental silicone resin [77] that cannot be tested alone because of its low toughness. The resin is backed with DER 332. The results are shown in Figure 5-21; $K_{IC}$ is 0.20±0.02 MPa-$\sqrt{m}$. Next the neat resin was filled with rubber and tested again. The measured $K_{IC}$ increased to 0.31±0.04 MPa-$\sqrt{m}$.

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™ DER is an epoxy resin supplied by The Dow Chemical Company.
Figure 5-20: Effect of DER 332 backing layer on the reliability map for Cyclotene 3022.

5.6 SUMMARY

A set of equations have been developed to predict the adhesive reliability of a coating as a function of thermal cooling and thermal fatigue. Equations also have been derived to predict failure for a simplified Flip Chip geometry. The Edge Lift-off Test has been used to collect experimental data and compare it to the predictions for an Epon 828 epoxy/glass system and an experimental epoxy Resin A/glass system. The predictions and experimental data are in good agreement both for monotonic and cyclic cooling. This agreement confirms that the ELT and EDT produce a mode I fracture with linear elastic materials. It also supports the assumption that the Griffith flaw size is not a function of cycling.
Figure 5-21: Modified ELT results for an experimental neat silicone resin. The sample is backed with DER 332 epoxy.

Figure 5-22: Modified ELT result for the experimental silicone resin with a rubber toughening agent added. Again the sample is backed with DER 332.
CHAPTER 6: CONCLUSIONS

The goal of this research was to develop methods to measure and predict the adhesion of polymer coatings on rigid substrates, while bearing stress. The source stress is either a thermal mismatch or a volumetric change in the coating during processing. Microelectronic devices are used as the vehicle to illustrate the methods; but the results are applicable to any application where a coating is subjected to biaxial tensile stress.

To predict adhesive reliability, one must be able to use a material property (strength, energy, toughness...) and compare it to the required parameter (stresses, forces, energies...) encountered in an application. Fracture mechanics analysis describes the debonding process, so, the critical strain energy release rate, $G_c$, describes the interface's integrity. The material property $G_c$, is then compared to the applied strain energy release rate, $G$, for various geometries. To calculate $G$ finite element analysis (FEA) is used. From the analysis of simple geometries, adhesion tests to measure $G_c$ were developed. Expressions to predict reliability also were established.

A summary of the major tasks includes the refinement and application of the Edge Delamination Test; analysis of stresses and applied fracture energies in leadless interconnects and Flip Chips; the derivation of equations to predict adhesive failure as a function of monotonic cooling and thermal fatigue for coatings; its extension for Flip Chip geometries; and development and application of the Edge Lift-Off test to validate the reliability equations for coatings.
Chip geometries; and development and application of the Edge Lift-Off test to validate the reliability equations for coatings.

*Edge Delamination Test*

The EDT takes advantage of the thermal residual stress present in the coating to induce delamination from the substrate. As a result the EDT is a self-contained test requiring no external loads to be applied. The edge delamination test (EDT) measures the energy required to cause a thin film, under biaxial tensile stress, to debond from a rigid substrate. Circular holes are etched through the films and if the stress is large enough, stable debond rings grow radially around the holes.

Finite element analysis was used to find the applied strain energy release rate as a function of debond crack length, hole radius and side-wall angle. The mode mixity of the fracture process was modeled. The results were used to address the effects of non-linear materials. For materials where the yield stress is less than 80% of the residual stress the total debond energy applied does not significantly change. However, the fracture mechanism changes from a pure mode I (peeling) process to mixed mode I and mode II (shearing) process. The relationship between the mixity angle and the yield stress for a perfectly-plastic material was established.

To facilitate the use of this test, tables of reduced debond energy values, $G_r$, were presented. With observed EDT results, $G_r$ is extrapolated from the tables and then the critical debond energy is calculated by multiplying $G_r$ by the maximum strain energy. To simplify it use further, we fit $G_r$ with a semi-empirical equation, which is in good agreement over a broad range of geometries.
The EDT was then applied to several interfaces of interest to the microelectronics industry. The coatings included Cyclotene 3022, a benzocyclobutene; Pyralin 2545, a polyimide; and Ultradel 4212, a fluorinated polyimide. The substrates included silicon and silicon coated with either aluminum, copper or chrome. The trends showed better adhesion to chrome than to aluminum than to copper. This is in agreement with previously observed results. The results also quantified the effect of acid etchants on the polymer/metal interface demonstrating the utility of the EDT to optimize processing conditions to minimize debonding. Lastly, the effects of humidity on the interface were measured with the EDT. The results showed that the polyimide/silicon interface is very sensitive to moisture, whereas, the benzocyclobutene/silicon interface was not.

*Analysis of Leadless Interconnects and Flip Chips*

We have analyzed the applied debond energy for a simplified leadless interconnect geometry. This solution is also applicable to Flip Chip geometries. First, the applied debond energy and stress for the plane-strain, large crack case is solved analytically. The energy and stress is a function of two reduced parameters, α and β. α compares the thermal coefficients and β compares the stiffnesses of the coating to the post. The results are very dependent on the Poisson's ratio of the coating due to the triaxial stress state. As the Poisson's ratio approaches 0.50 the stresses rise to infinity.

Next, FEA is used to confirm the analytical solution and solve for the small crack plane strain case. The model shows that loss of adhesion between the post and coating increases the applied debond energy for small cracks by an order of magnitude. The FEA was then used to solve the debond energy
for the axisymmetric case. Here the applied energies as a function of crack length are complicated and strongly dependent on $\beta$. For small post diameters, i.e. small $\beta$, the functional form of the debond energy is similar to the EDT results where $G$ increases with crack length, reaches as maxima and the decreases to zero. However, for large posts, the debond energy rises to a maxima and then plateaus near the plane strain value.

Lastly, the model was used to analyze the effect of finite chip stiffness for the plane strain case. Due to the compliance of the chip, it bows thereby relieving the stresses in the center of the polymer coating. This results in the applied debond energy decreasing with crack length. However, it also leads to a rise in the initial maxima for small cracks since the post is not competing with the entire length of polymer in order to shrink. The maximum debond energy for a Si chip is more than twice the energy for the rigid chip.

*The Edge Lift-Off Test and Reliability Rules for Coatings*

The ELT is a simplified version of the EDT in the plane strain limit of the EDT. The ELT is the maximum applied energy case for a coating on the substrate. we use the FEA of the EDT to calculate the applied debond energy as a function of crack length. $G$ can be modeled as a linear function of crack length to a certain length where it then plateaus at its maximum value.

As stated previously, reliability can be predicted *a priori* if the applied energy and the critical debond energy is known. When designing reliable coatings, the ultimate adhesion limit is set by the cohesive properties of the coating. So, we can compare the applied $G$ for the ELT geometry to the $G_{IC}$ of the coating and predict failure. The complication is that the applied $G$ is a
function of crack length which is unknown. To avoid this, we assume the presence of an intrinsic flaw as described by Griffith.

Using this, a set of equations was developed to predict the adhesive reliability of a coating. For monotonic cooling, a failure map is drawn with coating thickness versus temperature showing the safe and fail regimes. For thermal fatigue, sets of curves are drawn predicting the lifetime of a coating as a function of thickness when cycled to various low temperatures. Equations were also derived to predict failure for a simplified Flip Chip geometry based on the earlier analysis.

To validate these, experiments were performed on epoxies. Bulk samples are fabricated to collect strength and fracture toughness; and strength versus cycles behavior was collected from tensile-tensile fatigue. The stress versus temperature behavior was measured. From these data, predictions for monotonic and cyclic reliability were made. These predictions were compared to data collected using the Edge Lift-off Test (ELT). The predictions and experimental data are in good agreement for both monotonic and cyclic cooling. This agreement confirms that the ELT and EDT is a mode I fracture process for linear elastic materials. It also supports the introduction of the Griffith flaw as the initial crack.

**Future Work**

Although a model for the fracture of ductile coatings has been posited the actual application and validation still needs to be performed. One could design a set of experiments wherein the coating's yield stress is a function of temperature. Then by building a matrix of EDT samples of various heights and tested at various temperatures one could establish whether the model for
APPENDIX A: FORTRAN PREPROCESSOR CODE FOR EDT FEA

A set of programs are used to create the Abaqus input decks to calculate the applied debond energy for various EDT geometries. First, the program create_session asks the user to input which variable he wants to change and for the other input parameters. It then generates a series of temporary input files and also the session report file which will summarize all the results. Next the program create_com.24.com directs the Unix workstation to set up the work directory. It then submits input files generated by create_session to create_mesh. The program create_mesh reads the inputs from the create_session output file and writes the Abaqus input deck. Create_com.com continues by running Abaqus, wait until the job is finished, and then direct the program post to the Abaqus data file. The program post collects the data needed to calculate the applied debond energy. It then adds this results the session report.

Create_Session

Program create_session

C
C   Version 2.4
C   COPYRIGHT ED SHAFFER 1994
C
C   6/17/93  add inittype (initial condition)
C   6/21/93  add sessionrpt
C   9/20/93  for new create mesh. add da
C   11/5/93  Use one step method to calc G's.
C   4/11/94  Add backing layer
C   12/29/94 Add strain hardening to calculation

IMPLICIT DOUBLE PRECISION(A-H,O-Z)
character*1 type, inctype, holtype, crltype, datype, fctype, geotype,
        plast, inittype, basepla, backpla, back, base
character*3 prefix !Starting three letters
character*13 variable !To output to session report
character*80 header

dimension holes(25), cracks(25), varis(100)

open(unit=10, file='session')
open(unit=7, file='sessionrpt')

c Read in data for this session

write(*,*) 'Is this a Hole (h) or an Edge (e),'#
read(*,10) geotype
if (geotype.eq.'e') rhole = 0.0
write(*,*) 'Do you want a Base Layer?'
read(*,10) base
write(*,*) 'Do you want a Backing Layer?'
read(*,10) back
write(*,*) 'Which Variable do you want to Vary?: ' 
write(*,*)
write(*,*) '  a = Film Height' 
write(*,*) '  b = Crack Length' 
write(*,*) '  c = da Length' 
if (geotype.ne.'e') write(*,*) '  d = Hole Radius' 
write(*,*) '  e = Via Angle' 
if (base.eq.'y') write(*,*) '  f = Base Film Height' 
if (back.eq.'y') write(*,*) '  g = Back Film Height' 
write(*,*) '  h = Film Modulus' 
if (base.eq.'y') write(*,*) '  i = Base Modulus' 
if (back.eq.'y') write(*,*) '  j = Back Modulus' 
write(*,*) '  k = Film Yield Stress' 
if (base.eq.'y') write(*,*) '  l = Base Yield Stress' 
if (back.eq.'y') write(*,*) '  m = Back Yield Stress' 
write(*,*) '  n = Both hole radius and crack length' 
write(*,*) '  o = Film Strain Hard. Coeff.' 
write(*,*)
read(*,10) type
10 format(a1)
101 format(a3)

write(*,11)
11 format('Geometric(g), logarithmic(l), linear(s) or enter(e): ') 
read(*,10) inctype

if (((inctype.eq.'e').and.(type.ne.'n'))) then
  write(*,*) 'Please enter the number of steps: ' 
  read(*,*) inc 
  nodecks = inc + 1 
  write(*,*) 'Please enter variables: ' 
  read(*,*) (varis(i),i=0,inc)
endif

if (((type.ne.'n').and.(inctype.ne.'e'))) then
  write(*,*) 'Please enter variables Low and High: ' 
  read(*,*) rlow, rhigh
endif
  write(*,*) 'Please enter the number of steps: ' 
  read(*,*) inc 
  nodecks = inc + 1

999 if (type.ne.'a') then
  write(*,*) 'Enter in Film Height: ' 
  read(*,*) fheight
endif

if (type.ne.'b') then
  if (type.ne.'n') then
    write(*,*) 'Enter in Crack Length: ' 
    read(*,*) crlength
  else
    write(*,*) 'Please enter in crack data set' 
    read(*,*) (cracks(I),I=1,nodecks)
  endif
endif
if (type.ne.'c') then  
  write(*,'(a)') 'Keep da constant (c) or keep as ratio (r): '  
  read(*,10) datatype  
if (datatype.eq.'r') then  
  write(*,'(a)') 'Enter in da: '  
  read(*,*) daT  
endif  
endif  
if ((type.ne.'d').and.(geotype.ne.'e')) then  
  if (type.ne.'n') then  
    write(*,'(a)') 'Enter in Hole Radius: '  
    read(*,*) rhole  
  else  
    write(*,'(a)') 'Please enter in radius data set'  
    read(*,*) (rholes(I),I=1,nodecks)  
  endif  
endif  
if (type.ne.'e') then  
  write(*,'(a)') 'Enter in Via Angle: '  
  read(*,*) viaaang  
endif  
if ((base.eq.'y').and.(type.ne.'f')) then  
  write(*,'(a)') 'Enter in Base Height'  
  read(*,*) baseht  
else  
  baseht = 0.0  
  NVAE = 1  
endif  
if ((back.eq.'y').and.(type.ne.'g')) then  
  write(*,'(a)') 'Enter in Back Height'  
  read(*,*) backht  
else  
  backht = 0.0  
  NVCE = 1  
endif  
if (type.ne.'h') then  
  write(*,'(a)') 'Enter in Film Modulus, GPa:'  
  read(*,*) fmodulus  
  fmodulus = fmodulus*1.e10  
endif  
write(*,'(a)') 'Enter in Film Poisson Ratio'  
read(*,*) frnu  
if (type.ne.'k'.and.type.ne.'o') then  
  write(*,'(a)') 'Do you want Film plasticity, y or n:'  
  read(*,10) filmpla  
else  
  filmpla = 'y'  
endif  
if (filmpla.eq.'y') then  
  if (type.ne.'k') then  
    write(*,'(a)') 'Enter Yield Stress, MPa: '  
    read(*,*) fyield  
  endif  
endif
fyield = fyield*1.0E7
endif
if (type.ne.'o') then
  write(*,*) 'Film Str. Hard. Coef (0-Perf. Plast, 1-Elas.):'
  read(*,*) fhard
endif
fstrainmax = 1.0
if (type.ne.'k'.and.type.ne.'h'.and.type.ne.'o')
  fstressmax = fmodulus*fhard + fyield
endif
write(*,*) 'Enter Film Expansion Coef, PPM/C: '
read(*,*) fexpansion
fexpansion = fexpansion*1.0e-6

if (base.eq.'y') then
  if (type.eq.'i') then
    write(*,*) 'Enter in Base Modulus, GPa: '
    read(*,*) bmodulus
    bmodulus = bmodulus*1.e10
  endif
  write(*,*) 'Enter in Base Poisson Ratio'
  read(*,*) brnu
  write(*,*) 'Do you want Base plasticity, y or n: '
  read(*,10) basepla
  if (basepla.eq.'y') then
    if (type.eq.'l') then
      write(*,*) 'Enter Yield Stress, MPa: '
      read(*,*) byield
      byield = byield*1.0e7
    endif
    write(*,*) 'Base Str. Hard. Coef (0 - Perf. Plast, 1 - Elastic):'
    read(*,*) bhard
    bstrainmax = 1.0
    if (type.eq.'l'.and.type.eq.'i')
      bstressmax = bhard*bmodulus + byield
    else
      byield = 0.0
      bstressmax = 0.0
      bstrainmax = 0.0
      bhard = 0.0
    endif
    write(*,*) 'Enter Base Expansion Coef, PPM/C: '
    read(*,*) bexpansion
    bexpansion = bexpansion*1.0e-6
  else
    brnu = 0.0
    byield = 0.0
    bstressmax = 0.0
    bstrainmax = 0.0
    bhard = 0.0
    bmodulus = 0.0
    bexpansion = 0.0
  endif
endif

if (back.eq.'y') then
  if (type.eq.'j') then
    write(*,*) 'Enter in Back Modulus, GPa: '
    read(*,*) cmodulus
  endif
endif
cmodulus = cmodulus*1.e10
endif
write(*,*) 'Enter in Back Poisson Ratio'
read(*,*) crnu
write(*,*) 'Do you want Back plasticity, y or n: '
read(*,10) backpla
if (backpla.eq.'y') then
   if (type.ne.'m') then
      write(*,*) 'Enter Yield Stress, MPa: '
      read(*,*) cyield
      cyield = cyield*1.0e7
   endif
   write(*,*) 'Back Str.Hard.Cof (0-Perf.Plast, 1-Elas):'
   read(*,*) chard
   cstrainmax = 1.0
   if (type.ne.'m'.and.type.ne.'j')
      cstressmax = chard*cmodulus + cyield
   endif
   write(*,*) 'Enter Back Expansion Coef, PPM/C: '
   read(*,*) cexpansion
   cexpansion = cexpansion*1.0e-6
else
   crnu = 0.0
   cyield = 0.0
   cstressmax = 0.0
   cstrainmax = 0.0
   chard = 0.0
   cmodulus = 0.0
   cexpansion = 0.0
endif
write(*,*) 'Please enter # vertical elements in coating '
read(*,*) NVBE
NVAE = 1
write(*,*) 'Please enter the # horiz elements near crack tip '
read(*,*) NEH
if (base.eq.'y') then
   write(*,*) 'Please enter # vertical elements in base '
   read(*,*) NVAE
endif
if (back.eq.'y') then
   write(*,*) 'Please enter # vertical elements in backing '
   read(*,*) NVCE
endif
write(*,*) 'Please enter file prefix: '
read(*,101) prefix
write(*,*) 'Please enter starting model number: '
read(*,*) model
write(*,*) 'Which initial condition Temperature(t) or Stress(s): '
read(*,10) inittype
write(*,*) 'Please enter the initial stress or the Dtemp: '
read(*,*) tinitial
write(*,*) 'Please enter in a header: '
read(*,135) header
if (type.eq.'a') variable = 'Film Height'
if (type.eq.'b') variable = 'Crack Length'
if (type.eq.'c') variable = 'da Length'
if (type.eq.'d') variable = 'Hole Radius'
if (type.eq.'e') variable = 'Via Angle'
if (type.eq.'f') variable = 'Base Height'
if (type.eq.'g') variable = 'Back Height'
if (type.eq.'h') variable = 'Film Modulus'
if (type.eq.'i') variable = 'Base Modulus'
if (type.eq.'j') variable = 'Back Modulus'
if (type.eq.'k') variable = 'Film Yield'
if (type.eq.'l') variable = 'Base Yield'
if (type.eq.'m') variable = 'Back Yield'
if (type.eq.'n') variable = 'CrckRadius'
if (type.eq.'o') variable = 'Str.Hard.'

write(7,*),'SESSION REPORT'
write(7,*)
write(7,135) header
write(7,21) prefix,model,prex3,model+inc

21 format('Input Files: ',a3,'_',i3,' to ',a3,'_',i3)
if (type.ne.'n') write(7,210) variable,rlow,rhigh
if (type.eq.'n') write(7,209)

209 format('Crack & Radius entered')
210 format(a3,' ranges from ',F9.4,' to ',F9.4)
if (type.ne.'a') write(7,211) fheight
211 format('Film Height is: ',t20,f8.2,' um')
if (type.eq.'f') and (base.eq.'y') write(7,211) baseht
211 format('Base Height is: ',t20,f8.2,' um')
if (type.eq.'g') and (base.eq.'y') write(7,211) backht
2112 format('Back Height is: ',t20,f8.2,' um')
if (type.eq.'b') and (type.ne.'n') write(7,212) crlength
212 format('Crack Length is: ',t20,f8.2,' um')
if (type.ne.'c') then
  if (datype.eq.'c') then
    write(7,213) datT
  else
    write(7,213)
  endif
endif

213 format('da Length is: ',t20,f8.3,' um')
2131 format('da Length is plastic zone size')
if (type.ne.'d' and type.ne.'n') write(7,214) rhole
214 format('Hole Radius is: ',t20,f8.2,' um')
if (type.ne.'e') write(7,215) viaang
215 format('Via Angle is: ',T20,F5.1)
if (intype.eq.'t') write(7,216) tinitial
216 format('d Temperature is: ',T20,F5.1)
write(7,217)
217 format('Film Material Properties: ')
if (type.ne.'h') write(7,218) fmodule/1.e10
218 format(' Modulus = ',T20,F8.2,' GPa')
write(7,219) fnmu
219 format(' Poisson = ',T20,F8.2)
write(7,220) fexpansion*1.e6
220 format(' CTE = ',T20,F8.2,' PPM/C')
if (filmpl.eq.'y') then
  if (type.ne.'k') write(7,221) fyield/1e7
  format( ' Yield = ',T20,F8.2,' MPa' )
  if (type.ne.'h'.and.type.ne.'o') write(7,222) fstressmax/1e7
  format( ' Ult. Stress = ',T20,F8.2,' MPa' )
  if (type.ne.'o') write(7,223) fhard
  format( ' Str. Hard. = ',T20,F4.2 )
endif

if (base.eq.'y') then
  write(7,227)
  format('Base Material Properties: ')
  if (type.ne.'i') write(7,228) bmodule/1.e10
  format( ' Modulus = ',T20,F8.2,' GPa' )
  write(7,229) brnu
  format( ' Poisson = ',T20,F8.2 )
  write(7,230) bexpansion*1e6
  format( ' CTE = ',T20,F8.2,' PPM/C' )
  if (basepla.eq.'y') then
    if (type.ne.'l') write(7,231) byield/1e7
    format( ' Yield = ',T20,F8.2,' MPa' )
    if (type.ne.'i') write(7,232) bstressmax/1e7
    format( ' Ult. Stress = ',T20,F8.2,' MPa' )
    write(7,233) bhard
    format( ' Str. Hard. = ',T20,F4.2 )
  endif
endif

if (back.eq.'y') then
  write(7,237)
  format('Coat Material Properties: ')
  if (type.ne.'j') write(7,238) cmodule/1.e10
  format( ' Modulus = ',T20,F8.2,' GPa' )
  write(7,239) crnu
  format( ' Poisson = ',T20,F8.2 )
  write(7,240) cexpansion*1e6
  format( ' CTE = ',T20,F8.2,' PPM/C' )
  if (backpla.eq.'y') then
    if (type.ne.'m') write(7,241) cyield/1e7
    format( ' Yield = ',T20,F8.2,' MPa' )
    if (type.ne.'j') write(7,242) cstressmax/1e7
    format( ' Ult. Stress = ',T20,F8.2,' MPa' )
    write(7,243) chard
    format( ' Str. Hard. = ',T20,F4.2 )
  endif
endif

if (type.ne.'g'.and.type.ne.'a'.and.type.ne.'h') then
  if ((inittype.eq.'t').or.(inittype.eq.'T')) then
    farfield = 1.0E-7*tinitial*(fexpansion)*
      fmodule/(1.0-frnu)
  else
    farfield = tinitial
  endif
  gexp = 0.5e7*(1.0-frnu**2)*fheight*farfield**2/fmodule
  write(7,244) farfield
  format('Far-Field Stress: ',T20, f9.3,' MPa' )
  write(7,245) gexp

161
c Write out data for each inc t, fort.*
do 20 i = 0, inc
   if (inctype.eq.'e') then
      var = varis(i)
   endif
   if (inctype.eq.'s') then
      rm = real(inc)
      step = (rhigh-rlow)/rm
      var = rlow + i*step
   endif
   if (inctype.eq.'g') then
      rm = 1.0/real(inc)
      x = (rhigh/rlow)***rm
      var = rlow*x**i
   endif
   if (inctype.eq.'l') then
      step = real((log10(rhigh/rlow))/inc)
      var = 10**(log10(rlow) + real(step*i))
   endif
   ifil = model + i
   if (type.eq.'a') then
      fheight = var
   endif
   if (type.eq.'b') then
      crlength = var
   endif
   if (type.eq.'c') then
      da = var
   endif
   if (type.eq.'d') then
      rhole = var
   endif
   if (type.eq.'e') then
      viaang = var
   endif
   if (type.eq.'f') then
      baseht = var
   endif
   if (type.eq.'g') then
      backht = var
   endif
   if (type.eq.'h') then
      fmodulus = var*1.0e10
      fstressmax = fmodulus*fhard + fyield
   endif
   if (type.eq.'i') then
      bmodulus = var*1.0e10
      bstressmax = bmodulus*bhard + byield
   endif
   if (type.eq.'j') then
      cmodulus = var*1.0e10
      cstressmax = cmodulus*chard + cyield
   endif
   if (type.eq.'k') then
      fyield = var*1.0e7
fstressmax = fmodulus*fhard + fyield
endif
if (type.eq.'l') then
  byield = var*1.0e7
  bstressmax = bmodulus*bhard + byield
endif
if (type.eq.'m') then
  cyield = var*1.0e7
  cstressmax = cmodulus*chard + cyield
endif
if (type.eq.'n') then
  crlength = cracks(i+1)
  rhole = rholes(i+1)
endif
if (type.eq.'o') then
  fhard = var
  fstressmax = fmodulus*fhard + fyield
endif

c
rplength = 10.0*(fheight+backht)
rplength = crlength + 10.0*(fheight+backht)

if (type.ne.'c') then
  da = daT
  if (datatype.eq.'r') then
    da = 1.05*fheight*0.6203776*(1.0E7*farfield/fyield)**2
    if ((da/fheight).lt.1.0E-4) da = 1.0E-4*fheight
  endif
endif
if (0.5*NVBE*da.GT.fheight) da = 0.5*fheight/NVBE

iunit = 11 + i
write(10,121)
121 format('T')
write(10,122) iunit
write(iunit,123) prefix, ifil
write(iunit,124) iunit
122 format('create_com.2.4.com < fort.'',I2)
123 format(a3,'_',I3)
124 format(I2)
write(iunit,1001) rplength
write(iunit,1001) crlength
write(iunit,1001) baseht
write(iunit,1001) fheight
write(iunit,1001) backht
write(iunit,1001) rhole
write(iunit,1001) viaang
write(iunit,1001) da
write(iunit,*) NVBE
write(iunit,*) NVAE
write(iunit,*) NVCE
write(iunit,*) NEH
write(iunit,1001) fmodulus
write(iunit,1001) frnu
write(iunit,1001) fyield

163
write(iunit,1001) fstrainmax
write(iunit,1001) fstressmax
write(iunit,1001) fexpansion
write(iunit,10)ofilm
write(iunit,1001) bmodulus
write(iunit,1001) bnu
write(iunit,1001) byield
write(iunit,1001) bstrainmax
write(iunit,1001) bstressmax
write(iunit,1001) bexpansion
write(iunit,10) basepl
write(iunit,1001) cmodulus
write(iunit,1001) crnu
write(iunit,1001) cyield
write(iunit,1001) cstrainmax
write(iunit,1001) cstressmax
write(iunit,1001) cexpansion
write(iunit,10) backpl
write(iunit,10) geotype
write(iunit,10) init
write(iunit,1001) tinitial
write(iunit,10) base
write(iunit,10) back
if (type.ne.'n') then
  write(iunit,*), 1
  write(iunit,1001) var
else
  write(iunit,*), 2
  write(iunit,*), cracks(i+1), rholes(i+1)
endif
write(iunit,92) header
continue

format(a80)

format(D18.8)
if (type.ne.'n') then
  write(7,*),
  write(7,22) variable
format(' File ','a3',' GI GII Gtot ',
1            ' Wse GfromJ Mixity G/Gmax')
write(7,23)
format(108(' - '))
else
  write(7,*),
  write(7,24)
format(' File ',' Crack ',' Radius ',' GI ','
1             ' GII ',' Gtot ',' Wpl ',' GfromJ ')
write(7,25)
format(108(' - '))
endif
write(10,35) prefix, model
format('cp sessionrpt ','a3','_','-',i3,'.rpt')
write(10,30)
format('rm -f fort.*')
write(10,36)
format('rm -f session')
end
Create_Com

# 7/28/94: modified for ABAQUS 5.3, SGI IRX 5.2, f77 v4.0.1 (YJL)
# 8/4/94: upgraded to Version2.4
#
# CREATE AN ABAQUS INPUT DECK USING A VIRTUAL SESSION
#
# Read from fort.* (input file) name of input deck and unit number
set abqinp = $<
set iunit = $<
set edhome = /usr/people/eshaffer/EDT_FEA
set scr = /usr/people/eshaffer/scratch
#
cp $edhome/fort.$iunit $scr
cd $scr
mkdir $abqinp
#
f77 -o create_mesh.x $edhome/create_mesh.2.4.f
createmesh.x < fort.$iunit > $abqinp.tmp
#rm -f create_mesh.x
cut -c2-99 $abqinp.tmp > $abqinp.inp
mv $abqinp.inp $abqinp
cp fort.9 $abqinp/$abqinp.pst
rm -f $abqinp.tmp fort.9
if (! -e edpost.x) then
   abaqus make job=edpost user=$edhome/post.2.4.f
endif

cd $abqinp
abaqus job=$abqinp
# sleep 5
RECHECK:
( echo checking)
if (-e /tmp/eshaffer$_abqinp) then
   sleep 5
   goto RECHECK
else
   sleep 5
   if (-e /tmp/eshaffer$_abqinp) then
      goto RECHECK
   else
      goto GOTIT
   endif
endif
GOTIT:
( echo GotIt)
sleep 5

../edpost.x < $abqinp.pst
cat REPORT >> $edhome/sessionrpt
program Create_Mesh

Version 2.4

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Update August 4, 1994 finish backing layer for small crack case
and also square up refined mesh at crack tip.
Update March 16, 1994 Add Backing layer
Updated November 5, 1993. Use one step crack closure method

Creates an Abaqus input deck for bimaterial cracks.
The geometry is basically:

|<------------------- Part Length ---------------->|
|/__ Backing RCT____|
| /____________________|
| / Via Ang. RBT |
| RH / Film |
|____/......|
|-> RA <-|
| Base RAT |

Update create_mesh 6/18/93. Add initial condition type=stress
to start run instead of thermal stepping.

Change mesh at crack tip to simple square CPE8. No singularity
bias.

Add Backing Layer

IMPLICIT DOUBLE PRECISION(A-H,O-Z)
integer topA, botB
Character*8 Name
Character*1 base, backing, inittype, basepla, filmpla, backpla,
mattype, geotype

Dimension topA(999), botB(999)

read(*,1) Name
format(a8)
read(*,*) iunit
read(*,*4) RL !Part Length
read(*,*4) RA !Crack Length
read(*,*4) RAT !A layer Height
read(*,*4) RBT !B layer Height
read(*,*4) RCT !C layer Height
if (RA.eq.RBT) RA = 0.95*RA
read(*,*4) RH !Hole Radius
read(*,*4) ANGLE !Via wall Angle
read(*,*4) DA !Crack release length
read(*,*) IEVA
read(*,*) IEVB
read(*,*) IEVC
read(*,*) IEHB
read(*,*) bmodulus  !!}Film Layer B Properties
read(*,*) brnu
read(*,*) byield
read(*,*) bstrainmax
read(*,*) bstressmax
read(*,*) bexpansion
read(*,2) filmpla
read(*,*) amodulus  !!}Base Layer A Properties
read(*,*) arnu
read(*,*) ayield
read(*,*) astrainmax
read(*,*) astressmax
read(*,*) aexpansion
read(*,2) basepla
read(*,*) cmodulus  !!}Back Layer C Properties
read(*,*) crnu
read(*,*) cyield
read(*,*) cstrainmax
read(*,*) cstressmax
read(*,*) cexpansion
read(*,2) backpla
read(*,2) geotype
read(*,2) inittype
read(*,*) rinitial  !!}Initial delta Temp or Stress
read(*,2) base
read(*,2) backing
read(*,*) irpt  !!}# of variables on report 1-4
if (irpt.eq.1) read(*,*) var1
if (irpt.eq.2) read(*,*) var1,var2
format(1)
if ((inittype.eq.'t').or.(inittype.eq.'T')) then
  farfield = rinitial*(bexpansion)*bmodulus/(1-brnu)
else
  rinitial = rinitial*1.0E7
  farfield = rinitial
endif
geexpected = 0.5e-7*(1.0 - brnu**2)*RBT*farfield**2/bmodulus
if ((filmpla.eq.'y').or.(backpla.eq.'y').or.(basepla.eq.'y'))
mattype = 'p'
c
Convert units of length

RL = RL*1.0E-4
RA = RA*1.0E-4
RAT = RAT*1.0E-4
RBT = RBT*1.0E-4
RCT = RCT*1.0E-4
RH = RH*1.0D-4
DA = DA*1.0D-4
DANGLE = ANGLE
ANGLE = 90.0 - ANGLE
ANGLE = ANGLE*0.017453293
Estimate # of Horz Increments for IEH, IEH2, IEH3 and IINC

IF (RA.GT.RBT) then

First estimate IINC
r1 = 0.5*DA
rtot=RB-T-IEHB*DA
b=1.25
RIINC = log((rtot/r1)*(B-1.0)+1)/log(B)
IINC = int(RIINC)
if (IINC.LE.1) IINC = 1

Now do IEH
r1 = rrot*(B-1)/(B**IINC-1.0)
rlst = r1*B**(IINC-1)
rl = rlst
rtot = RL-RA-RBT
B=1.25
RIEH = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH = int(RIEH)
if (IEH.LE.1) IEH = 1

Do IEH2
rtot=RB-T-IEHB*DA
r1 = rrot*(B-1)/(B**IINC-1)
rlst = r1*B**(IINC-1)
rl = rlst
rtot = RA-RBT
B = 1.25
RIEH2 = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH2 = nint(RIEH2)
if (IEH2.LE.1) IEH2 = 1

now do IEH3
if (RH.ne.0.0) then
r1 = rrot*(B-1)/(B**IEH2-1)
rlst = r1*B**(IEH2)
rl = rlst
rtot = RH
B = 1.25
RIEH3 = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH3 = nint(RIEH3)
if (IEH3.LE.1) IEH3 = 1
else
IEH3 = 1
endif
else

First estimate IINC
r1 = DA*0.5
rtot=RA-IEHB*DA
B = 1.25
RIINC = log((rtot/r1)*(B-1.0)+1)/log(B)
IINC = int(RIINC)
if (IINC.LE.1) IINC = 1

Now do IOTC
\begin{verbatim}
r1 = rtot*(B-1)/(B**IINC-1)
rlst = r1*B**(IINC-1)
rl = rlst
rtot = RBT
RIOTC = log((rtot/r1)*(B-1.0)+1)/log(B)
IOTC = int(RIOTC)
if (IOTC.LE.1) IOTC = 1

c Now do IEH
r1 = rtot*(B-1)/(B**IOTC-1)
rlst = r1*B**(IOTC-1)
rl = rlst
rtot = RL-RA-RBT
B=1.25
RIEH = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH = int(RIEH)
if (IEH.LE.1) IEH = 1

c now do IEH3
if (RH.ne.0.0) then
r1 = rtot*(B-1)/(B**IINC-1)
rlst = r1*B**(IINC)
rl = rlst
rtot = RH
B = 1.25
RIEH3 = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH3 = nint(RIEH3)
if (IEH3.LE.1) IEH3 = 1
else
    IEH3 = 1
endif

c Also, for the mesh not to collapse we must have:

if (real(IEHB*DA).GT.(0.5*(RA-real(DA*IEHB))/TAN(ANGLE+0.0001)))
    da = 0.5*(RA-real(DA*IEHB))/(TAN(ANGLE)*real(IEHB))
endif

IINC = int(IINC/2.0)
if (IINC.LE.1) IINC = 1
IOTC = int(IOTC/2.0)
if (IOTC.LE.1) IOTC = 1
IEH2 = int(IEH2/2.0)
if (IEH2.LE.1) IEH2 = 1
IEH3 = int(IEH3/2.0)
if (IEH3.LE.1) IEH3 = 1
IEH = int(IEH/2.0)
if (IEH.LE.1) IEH = 1

c Define Node Numbers for Large Crack Case

if (RA.GT.RBT) then
    N0A = 1
    N1A = N0A + 2000*IEVA
\end{verbatim}
N2A = N1A + 1000
N3A = N2A + 2000*IEVB
N5A = N3A + 1000 + 2000*IINC
N6A = N5A + 2000*IEVC

N0B = N0A + 2*IEH
N1B = N1A + 2*IEH
N2B = N2A + 2*IEH
N3B = N3A + 2*IEH
N5B = N5A + 2*IEH
N6B = N5B + 2000*IEVC

N0D = N0B + 2*IINC
N1D = N1B + 2*IINC
N2D = N2B + 2*IINC
N3D = N3B + 2*IINC
N4D = N3D + 2000*IINC

N0E = N0D + 2*IEHB
N1E = N1D + 2*IEHB
N2E = N2D + 2*IEHB
N3E = N3D + 2*IEHB
N4F = N3F + 2000*IINC

N0H = N0F + 2*IINC
N1H = N1F + 2*IINC
N2H = N2F + 2*IINC
N3H = N3F + 2*IINC
N5H = N5B + 4*IEHB
N6H = N5H + 2000*IEVC

N0I = N0H + 2*IEH2
N1I = N1H + 2*IEH2
N2I = N2H + 2*IEH2
N3I = N3H + 2*IEH2
N5I = N5H + 2*IEH2
N6I = N5I + 2000*IEVC

N0J = N0I + 2*IEH3
N1J = N1I + 2*IEH3
N3J = N3I + 2*IEH3

else

!Small Crack Case

N0A = 1
N1A = N0A + 2000*IEVA
N2A = N1A + 1000
N3A = N2A + 2000*IEVB
N5A = N3A + 1000 + 2000*IINC
N6A = N5A + 2000*IEVC

N0B = N0A + 2*IEH
N1B = N1A + 2*IEH
N2B = N2A + 2*IEH
N3B = N3A + 2*IEH
N5B = N5A + 2*IEH
N6B = N5B + 2000*IEVC

N0C = N0B + 2*IOTC
N1C = N1B + 2*IOTC
N2C = N2B + 2*IOTC
N3C = N3B + 2*10TC

N0D = N0C + 2*IINC
N1D = N1C + 2*IINC
N2D = N2C + 2*IINC
N3D = N3C + 2*IINC
N4D = N3D + 2000*IINC
N5D = N4D + 2000*IOTC

N0E = N0D + 2*IEHB
N1E = N1D + 2*IEHB
N2E = N2D + 2*IEHB
N3E = N3D + 2*IEHB

N0F = N0E + 2*IEHB
N1F = N1E + 2*IEHB
N2F = N2E + 2*IEHB
N3F = N3E + 2*IEHB
N4F = N3F + 2000*IINC
N5F = N4F + 2000*IOTC

N0H = N0F + 2*IINC
N1H = N1F + 2*IINC
N2H = N2F + 2*IINC
N3H = N3F + 2*IINC
N5H = N5B + 4*IEHB
N6H = N5H + 2000*IEVC

N0J = N0H + 2*IEH3
N1J = N1H + 2*IEH3
N3J = N3H + 2*IEH3

dendif

C Define Node Y Positions

YLEV0 = 0.0
YLEV1 = RAT
YLEV2 = RAT
YLEV3 = RAT + RA
YLEV4 = RAT + IEVB*DA
YLEV5 = RAT + RBT
YLEV6 = RAT + RBT + RCT

C Define Node X Positions

XLEVA = RH + RL
XLEVB = RH+RA+RBT
XLEVC = RH+2.0*RA
XLEVD = RH+RA+IEHB*DA
XLEVE = RH+RA
XLEVF = RH+RA-IEHB*DA
XLEVH = RH+RA-RBT
XLEVI = RH
XLEVJ = 0.0

For Post Processing Data Retrieval
open (9, status='unknown')
write(9, '(a)') name
write(9, 2) geotype
write(9, *) irpt
if (irpt.eq.1) write(9, *) var1
if (irpt.eq.2) write(9, *) var1, var2
if (RA.GT.RBT) then
    NLAST = N2I
else
    NLAST = N2H
endif
IBASE = 0
if (base.eq.'y') IBASE = 1
write(9, *) N1E, N2E, RH, NLAST, gexpected, N2H, IBASE

Start with Headings etc

write(*,*) 'HEADING'
write(*,92) Name
format(1x, 'EDT2.4:', a8)
if (backing.eq.'y') then
    write(*,*) 'BACKING PROPS'
    write(*,*) E = ',', CMODULUS
    write(*,*) v = ',', CRNU
    write(*,*) A = ',', CEXPANSION
    write(*,*) So = ',', CYIELD
endif
write(*,*) 'COATING PROPS'
write(*,*) E = ',', BMODULUS
write(*,*) v = ',', BRNU
write(*,*) A = ',', BEXPANSION
write(*,*) So = ',', BYIELD
if (base.eq.'y') then
    write(*,*) 'BASE PROPS'
    write(*,*) E = ',', AMODULUS
    write(*,*) v = ',', ARNU
    write(*,*) A = ',', AEXPANSION
    write(*,*) So = ',', AYIELD
endif
write(*,*) 'Calc FarField = ', farfield
write(*,*) 'GI Max = ', gexpected
if (geotype.eq.'e') then
    write(*,*) 'PLANE STRAIN'
else
    write(*,*) 'AXISYMMETRIC'
endif
write(*,*) 'Film Height = ', RBT*1E4
if (base.eq.'y') write(*,*) 'BASE Height = ', RAT*1E4
if (backing.eq.'y') write(*,*) 'BACK Height = ', RCT*1E4
write(*,*) 'Crack Length = ', RA*1E4
write(*,*) '*** Part Length = ',RL*1E4
write(*,*) '*** Hole Radius = ',RH*1E4
write(*,*) '*** Via Wall Angle = ', DANGLE
write(*,*) '*** Da of element = ', DA*1E4
write(*,*) 'RESTART, WRITE,FREQUENCY=10'
write(*,*) 'PREPRINT, MODEL=NO, HISTORY=NO, ECHO=NO'

! Write out Defined Nodes and Positions

write(*,*) '***NODE'

IF (RA.GT.RBT) THEN 
  !! LARGE CRACK

if (base.eq.'y') then
  write(*,10) 99992, 0.0, 0.0
  write(*,10) 99991, 0.0, 0.0
endif

write(*,10) N0A, XLEVA, YLEV0
write(*,10) N1A, XLEVA, YLEV1
write(*,10) N2A, XLEVA, YLEV2
write(*,10) N3A, XLEVA, YLEV5
write(*,10) N5A, XLEVA, YLEV5
write(*,10) N6A, XLEVA, YLEV6

write(*,10) N0B, XLEVB, YLEV0
write(*,10) N1B, XLEVB, YLEV1
write(*,10) N2B, XLEVB, YLEV2
write(*,10) N3B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N5B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N6B, XLEVB+(RH/XLEVB)*(RBT+RCT)*TAN(ANGLE), YLEV6

write(*,10) N0D, XLEVD, YLEV0
write(*,10) N1D, XLEVD, YLEV1
write(*,10) N2D, XLEVD, YLEV2
write(*,10) N3D, XLEVD, YLEV4
write(*,10) N4D, XLEVD+(RH/XLEVD)*RBT*TAN(ANGLE), YLEV5

write(*,10) N0F, XLEVF, YLEV0
write(*,10) N1F, XLEVF, YLEV1
write(*,10) N2F, XLEVF, YLEV2
write(*,10) N3F, XLEVF, YLEV4
write(*,10) N4F, XLEVF+(RH/XLEVF)*RBT*TAN(ANGLE), YLEV5

write(*,10) N0H, XLEVH, YLEV0
write(*,10) N1H, XLEVH, YLEV1
write(*,10) N2H, XLEVH, YLEV2
write(*,10) N3H, XLEVH+(RH/XLEVH)*RBT*TAN(ANGLE), YLEV5
write(*,10) N5H, XLEVH+(RH/XLEVH)*RBT*TAN(ANGLE), YLEV5
write(*,10) N6H, XLEVH+(RH/XLEVH)*(RBT+RCT)*TAN(ANGLE), YLEV6

write(*,10) N0I, XLEVI, YLEV0
write(*,10) N1I, XLEVI, YLEV1
write(*,10) N2I, XLEVI, YLEV2
write(*,10) N3I, XLEVI+RBT*TAN(ANGLE), YLEV5
write(*,10) N5I, XLEVI+RBT*TAN(ANGLE), YLEV5
write(*,10) N6I, XLEVI+(RCT+RBT)*TAN(ANGLE), YLEV6

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write(*,10) N0J, XLEVJ, YLEV0
write(*,10) N1J, XLEVJ, YLEV1

ELSE

!! SMALL CRACK NODE DEFINITION

write(*,10) N0A, XLEVA, YLEV0
write(*,10) N1A, XLEVA, YLEV1
write(*,10) N2A, XLEVA, YLEV2
write(*,10) N3A, XLEVA, YLEV5
write(*,10) N5A, XLEVA, YLEV5
write(*,10) N6A, XLEVA, YLEV6

write(*,10) N0B, XLEVB, YLEV0
write(*,10) N1B, XLEVB, YLEV1
write(*,10) N2B, XLEVB, YLEV2
write(*,10) N3B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N5B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N6B, XLEVB+(RH/XLEVB)*RBT+RCT)*TAN(ANGLE), YLEV6

write(*,10) N0C, XLEVC, YLEV0
write(*,10) N1C, XLEVC, YLEV1
write(*,10) N2C, XLEVC, YLEV2
write(*,10) N3C, XLEVC+(RH/XLEVC)*RA*TAN(ANGLE), YLEV3

write(*,10) N0D, XLEVD, YLEV0
write(*,10) N1D, XLEVD, YLEV1
write(*,10) N2D, XLEVD, YLEV2
write(*,10) N3D, XLEVD, YLEV4
write(*,10) N4D, XLEVD+(RH/XLEVD)*RA*TAN(ANGLE), YLEV3
write(*,10) N5D, XLEVD+(RH/XLEVD)*RBT*TAN(ANGLE), YLEV5

write(*,10) N0F, XLEVF, YLEV0
write(*,10) N1F, XLEVF, YLEV1
write(*,10) N2F, XLEVF, YLEV2
write(*,10) N3F, XLEVF, YLEV4
write(*,10) N4F, XLEVF*RA*TAN(ANGLE), YLEV3
write(*,10) N5F, XLEVF*RBT*TAN(ANGLE), YLEV5

write(*,10) N0H, XLEVH, YLEV0
write(*,10) N1H, XLEVH, YLEV1
write(*,10) N2H, XLEVH, YLEV2
write(*,10) N3H, XLEVH*RA*TAN(ANGLE), YLEV3
write(*,10) N5H, XLEVH*RBT*TAN(ANGLE), YLEV5
write(*,10) N6H, XLEVH+(RBT+RCT)*TAN(ANGLE), YLEV6

write(*,10) N0J, XLEVJ, YLEV0
write(*,10) N1J, XLEVJ, YLEV1

ENDIF
DEFINE NODE SETS FOR LARGE CRACK CASE

IF (RA.GT.RBT) THEN

C COATING LAYER
C *REGION 1B

write(*,*) '**FILM LAYER NODES'
write(*,*) '*NGEN,NSET=EDGEBA'
write(*,20) N2A, N3A, 1000
write(*,*) '*NGEN,NSET=EDGEBB'
write(*,20) N2B, N3B, 1000
write(*,*) '*NFILL,NSET=REG1B,BIAS=1.25'
write(*,30) 2*IIEH,1

30 format(2x,'EDGEBA, EDGEBB, ',I6,'','I4)

C *REGION 2B

write(*,*) '*NGEN,NSET=EDGEBD'
write(*,20) N2D, N3D, 1000
write(*,*) '*NFILL,NSET=REG2B,BIAS=1.25'
write(*,31) 2*IINC,1

31 format(2x,'EDGEBD, EDGEBD, ',I6,'','I4)

C *REGION 3B

write(*,*) '*NGEN,NSET=EDGEBF'
write(*,20) N2F, N3F, 1000
write(*,*) '*NFILL,NSET=REG3B'
write(*,32) 4*IIEHB,1

32 format(2x,'EDGEBD, EDGEBF, ',I6,'','I4)

C *REGION 4B

write(*,*) '*NGEN,NSET=EDGEBH'
write(*,20) N2H, N3H, 1000
write(*,*) '*NFILL,NSET=REG4B,BIAS=0.8'
write(*,33) 2*IINC,1

33 format(2x,'EDGEBF, EDGEBH, ',I6,'','I4)

C *REGION 5B

write(*,*) '*NGEN,NSET=EDGEBI'
write(*,20) N2I, N3I, 1000
write(*,*) '*NFILL,NSET=REG5B,BIAS=0.8'
write(*,34) 2*IIEH2,1

34 format(2x,'EDGEBF, EDGEBI, ',I6,'','I4)

C *REGION 6B

write(*,*) '*NGEN,NSET=EDGB63'
write(*,20) N3D,N3F,1
write(*,*) '*NGEN,NSET=EDGB64'
write(*,20) N4D, N4F,1
write(*,*) '*NFILL,NSET=REG6B,BIAS=0.8'
write(*,35) 2*IINC,1000

35 format(2x,'EDGB63, EDGB64, ',I6,'','I4)
*Extra node sets for equations and BCUs

write(*,*) 'NSET,NSET=NEXTB'
write(*,20) N2E, N2E=1,1
write(*,*) 'NSET,NSET=CRACK'
write(*,20) N2E,N2E,0
write(*,*) 'NSET,NSET=BOTLYB,GENERATE'
write(*,20) N2A,N2E,1
write(*,*) 'NSET,NSET=TOPLYB,GENERATE'
write(*,20) N3A,N3B-1,1
write(*,20) N4D+1, N4F-1,1
write(*,20) N3H+1, N3I, 1
write(*,*) 'NSET,NSET=RHTB,GENERATE'
if (backing.eq.'y') then
  write(*,20) N2A,N3A-1000,1000
else
  write(*,20) N2A,N3A,1000
endif

BASE LAYER NODE

if (base.eq.'y') then

*REGION 1A

write(*,*) '***BASE LAYER NODES'
write(*,*) 'NGEN,NSET=EDGEAA'
write(*,20) N0A, N1A, 1000
write(*,*) 'NGEN,NSET=EDGEAB'
write(*,20) N0B, N1B, 1000
write(*,*) 'NFILL,NSET=REG1A,BIAS=1.25'
write(*,36) 2*IEH,1
format(2x,'EDGEAA, EDGEAB, ',I6,','I4)

*REGION 2A

write(*,*) 'NGEN,NSET=EDGEAD'
write(*,20) N0D, N1D, 1000
write(*,*) 'NFILL,NSET=REG2A,BIAS=1.25'
write(*,37) 2*IEH,1
format(2x,'EDGEAB, EDGEAD, ',I6,','I4)

*REGION 3A

write(*,*) 'NGEN,NSET=EDGEAF'
write(*,20) N0F, N1F, 1000
write(*,*) 'NFILL,NSET=REG3A'
write(*,38) 4*IEHB,1
format(2x,'EDGEAF, EDGEAF, ',I6,','I4)

*REGION 4A

write(*,*) 'NGEN,NSET=EDGEAH'
write(*,20) N0H, N1H, 1000
write(*,*) ' *NFILL, NSET=REG4A, BIAS=0.8'
write(*,39) 2*IINC, 1

format(2x, 'EDGEAF, EDGEAH, ',I6, ' , ',I4)

C

*REGION 5A

write(*,*) ' *NGEN, NSET=EDGEAI'
write(*,20) NOI, N1I, 1000
write(*,*) ' *NFILL, NSET=REG5A, BIAS=0.8'
write(*,40) 2*IEH2, 1

format(2x, 'EDGEAH, EDGEAI, ',I6, ' , ',I4)

C

*REGION 6A

write(*,*) ' *NGEN, NSET=EDGEAJ'
write(*,20) NOJ, N1J, 1000
write(*,*) ' *NFILL, NSET=REG6A, BIAS=0.8'
write(*,41) 2*IEH3, 1

format(2x, 'EDGEAI, EDGEAJ, ',I6, ' , ',I4)

C

*Extra Node Sets for BC

write(*,*) ' *NSET, NSET=TOPLYA, GENERATE'
write(*,20) NI4A+1, N1E, 1

write(*,*) ' *NSET, NSET=BOTLYA, GENERATE'
write(*,20) NOA, NOJ, 1

write(*,*) ' *NSET, NSET=NEXTA'
write(*,*) N1E, ', ', N1E-1

write(*,*) ' *NSET, NSET=RghtA, GENERATE'
write(*,20) NOA, N1A-1000, 1000

endif

C

*BACKING LAYER NODE SETS

if (backing.eq.'y') then

*  

*REGION 1C

write(*,*) ' **BACKING LAYER NODES'
write(*,*) ' *NGEN, NSET=EDGECA'
write(*,20) N5A, N6A, 1000
write(*,*) ' *NGEN, NSET=EDGECB'
write(*,20) N5B, N6B, 1000
write(*,*) ' *NFILL, NSET=REG1C, BIAS=1.25'
write(*,42) 2*IEH, 1

format(2x, 'EDGECA, EDGECB, ',I6, ' , ',I4)

C

*REGION 2C

write(*,*) ' *NGEN, NSET=EDGECH'
write(*,20) N5H, N6H, 1000
write(*,*) ' *NFILL, NSET=REG2C'
write(*,43) 4*IEHB, 1

format(2x, 'EDGECB, EDGECH, ',I6, ' , ',I4)
C REGION 3C

write(*,*) 'NGEN,NSET=EDGECI'
write(*,20) N5I, N6I, 1000
write(*,*) 'NFILL,NSET=REG3C,BIAS=0.80'
write(*,44) 2*IEH2,1
format(2x,'EDGECH, EDGECI, ',i6,',',i4)
write(*,*) 'NSET,NSET=BOTLYC,GENERATE'
write(*,20) N5A, N5I, 1
write(*,*) 'NSET,NSET=RGHTC,GENERATE'
write(*,20) N5A,N6A,1000
endif

write(*,*) 'NSET,NSET=ALLNDS'
write(*,*) 'REG13,REG2B,REG3B,REG4B,REG5B,REG6B'
if (base.eq.'y') then
write(*,*) 'REG1A,REG2A,REG3A,REG4A,REG5A,REG6A'
write(*,*) '99991, 99992'
endif
if (backing.eq.'y')
+ write(*,*) 'REG1C,REG2C,REG3C'

C *****SMALL CRACK NODE SET DEFINITIONS*****
ELSE
C DEFINE LAYER B NODE SETS FOR SMALL CRACK CASE
C COATING NODE REGIONS
C *REGION 1B

write(*,*) '***COATING NODES'
write(*,*) 'NGEN,NSET=EDGEBA'
write(*,20) N2A, N3A, 1000
write(*,*) 'NGEN,NSET=EDGEBB'
write(*,20) N2B, N3B, 1000
write(*,*) 'NFILL,NSET=REG1B,BIAS=1.25'
write(*,130) 2*IEH,1
format(2x,'EDGEBA, EDGEBB, ',i6,',',i4)
C *REGION 2B

write(*,*) 'NGEN,NSET=EDGEBC'
write(*,20) N2C, N3C, 1000
write(*,*) 'NFILL,NSET=REG2B,BIAS=1.25'
write(*,131) 2*IOTC,1
format(2x,'EDGEBB, EDGEBC, ',i6,',',i4)
C *REGION 3B

write(*,*) 'NGEN,NSET=EDGEBD'
write(*,20) N2D, N3D, 1000

178
write(*,*) ' *NFIIL, NSET=REG3B, BIAS=1.25'
write(*,132) 2*IINC, 1
132 format(2x,'EDGEB, EDGEB, ',I6,',',I4)

c *REGION 4B

write(*,*) ' *NGEN, NSET=EDGEBF'
write(*,20) N2F, N3F, 1000
write(*,*) ' *NFIIL, NSET=REG4B'
write(*,133) 4*IEHB, 1
133 format(2x,'EDGEB, EDGEB, ',I6,',',I4)

c *REGION 5B

write(*,*) ' *NGEN, NSET=EDGEBH'
write(*,20) N2H, N3H, 1000
write(*,*) ' *NFIIL, NSET=REG5B, BIAS=0.8'
write(*,134) 2*IINC, 1
134 format(2x,'EDGEB, EDGEBH, ',I6,',',I4)

c *REGION 6B

write(*,*) ' *NGEN, NSET=EDGB63'
write(*,20) N3D, N3F, 1
write(*,*) ' *NGEN, NSET=EDGB64'
write(*,20) N4D, N4F, 1
write(*,*) ' *NFIIL, NSET=REG6B, BIAS=0.8'
write(*,135) 2*IINC, 1000
135 format(2x,'EDGB63, EDGB64, ',I6,',',I4)

c *REGION 7B

write(*,*) ' *NGEN, NSET=EDGB65'
write(*,20) N5D, N5F, 1
write(*,*) ' *NFIIL, NSET=REG7B, BIAS=0.8'
write(*,1361) 2*IOTC, 1000
1361 format(2x,'EDGB64, EDGB65, ',I6,',',I4)

C *Extra node sets for equations and BC's

write(*,*) ' *NSET, NSET=NEXTB'
write(*,20) N2E, N2E-1, 1
write(*,*) ' *NSET, NSET=CRACK'
write(*,20) N2E,N2E,0
write(*,*) ' *NSET, NSET=BOTLYB, GENERATE'
write(*,20) N2A,N2E,1
write(*,*) ' *NSET, NSET=TOPLYB, GENERATE'
write(*,20) N3A,N3B-1,1
write(*,20) N5D+1,N5F-1,1
write(*,*) ' *NSET, NSET=RCHTB, GENERATE'
if (backing.eq.'y') then
  write(*,20) N2A,N3A-1000,1000
else
  write(*,20) N2A,N3A,1000
endif

C BASE LAYER NODE SETS

if (base.eq.'y') then

C *REGION 1A

write(*,*) 'NGEN,NSET=EDGEAA'
write(*,20) N0A, N1A, 1000
write(*,*) 'NGEN,NSET=EDGEAB'
write(*,20) N0B, N1B, 1000
write(*,*) 'NFILL,NSET=REG1A,BIAS=1.25'
write(*,136) 2*IEH,1

136 format(2x,'EDGEAA, EDGEAB, ',I6,',',I4)

C *REGION 2A

write(*,*) 'NGEN,NSET=EDGEAC'
write(*,20) N0C, N1C, 1000
write(*,*) 'NFILL,NSET=REG2A,BIAS=1.25'
write(*,137) 2*IOTC,1

137 format(2x,'EDGEAB, EDGEAC, ',I6,',',I4)

C *REGION 3A

write(*,*) 'NGEN,NSET=EDGEAD'
write(*,20) N0D, N1D, 1000
write(*,*) 'NFILL,NSET=REG3A,BIAS=1.25'
write(*,138) 2*INC,1

138 format(2x,'EDGEAC, EDGEAD, ',I6,',',I4)

C *REGION 4A

write(*,*) 'NGEN,NSET=EDGEAF'
write(*,20) N0F, N1F, 1000
write(*,*) 'NFILL,NSET=REG4A'
write(*,139) 4*IEHB,1

139 format(2x,'EDGEAC, EDGEAD, ',I6,',',I4)

C *REGION 5A

write(*,*) 'NGEN,NSET=EDGEAH'
write(*,20) N0H, N1H, 1000
write(*,*) 'NFILL,NSET=REG5A,BIAS=0.8'
write(*,140) 2*INC,1

140 format(2x,'EDGEAF, EDGEAH, ',I6,',',I4)

C *REGION 6A

write(*,*) 'NGEN,NSET=EDGEAJ'
write(*,20) N0J, N1J, 1000
write(*,*) 'NFILL,NSET=REG6A,BIAS=0.8'
write(*,141) 2*IEH3,1

141 format(2x,'EDGEAH, EDGEAJ, ',I6,',',I4)

C Extra Node Sets for BCs
write(*,*) ' *NSET,NSET=TOPLYA,GENERATE'
write(*,20) N1A+1,N1E,1

write(*,*) ' *NSET,NSET=BOTLYA,GENERATE'
write(*,20) N0A,N0J,1

write(*,*) ' *NSET,NSET=NESTA'
write(*,*) N1E, ',', N1E-1

write(*,*) ' *NSET,NSET=RGHTA,GENERATE'
write(*,20) N0A,N1A-1000,1000

endif

C

* BACKING LAYER NODE SETS FOR SMALL CRACK CASE

if (backing.eq.'y') then

* REGION 1C

write(*,*) ' **BACKING LAYER NODES'
write(*,*) ' *NGEN,NSET=EDGECA'
write(*,20) N5A, N6A, 1000
write(*,*) ' *NGEN,NSET=EDGECB'
write(*,20) N5B, N6B, 1000
write(*,*) ' *NFILL,NSET=REG1C,BIAS=1.25'
write(*,242) 2*IEH,1

242 format(2x,'EDGECA, EDGECB, ','I6, ',', 'I4)

C

* REGION 2C

write(*,*) ' *NGEN,NSET=EDGECH'
write(*,20) N5H, N6H, 1000
write(*,*) ' *NFILL,NSET=REG2C'
write(*,243) 4*IEHB,1

243 format(2x,'EDGECH, EDGECH, ','I6, ',', 'I4)

write(*,*) ' *NSET,NSET=BOTLYC,GENERATE'
write(*,20) N5A, N5H, 1

write(*,*) ' *NSET,NSET=RGHTC,GENERATE'
write(*,20) N5A,N6A,1000

endif

write(*,*) ' *NSET,NSET=ALLNDS'
write(*,*) ' REG1B,REG2B,REG3B,REG4B,REG5B,REG6B,REG7B'
if (base.eq.'y')
  write(*,*) ' REG1A,REG2A,REG3A,REG4A,REG5A,REG6A'
+ write(*,*) ' REG1C,REG2C'

write(*,*) ' *NSET,NSET=DUMMY'
write(*,*) ' ', IDUM,','
write(*,*) '"NSET,NSET=CREDG,GENERATE'
write(*,20) N2E,NLAST,1

c Write Out Element Information

c Define Key Elements

if (geotype.ne.'e') then
  if (mattype.eq.'p') then
    write(*,*) '"ELEMENT,TYPE=CAX8R'
  else
    write(*,*) '"ELEMENT,TYPE=CAX8R'
  endif
else
  if (mattype.eq.'p') then
    write(*,*) '"ELEMENT,TYPE=CPE8R'
  else
    write(*,*) '"ELEMENT,TYPE=CPE8R'
  endif
endif

KEL0A = 1

if (base.eq.'y') then
  write(*,50) KEL0A, N0A+2, N0A, N0A+2000, N0A+2002, N0A+1,
               N0A+1000, N0A+2001, N0A+1002
endif

KEL5A = 1+(IEVA+IEVB+1)*1000

if (backing.eq.'y') then
  write(*,50) KEL5A, N5A+2, N5A, N5A+2000, N5A+2002, N5A+1,
               N5A+1000, N5A+2001, N5A+1002
endif

KEL2A = 1+(IEVA+1)*1000

write(*,50) KEL2A, N2A+2, N2A, N2A+2000, N2A+2002, N2A+1,
            N2A+1000, N2A+2001, N2A+1002

KEL3D = 90001

write(*,50) KEL3D, N3D+2, N3D, N3D+2000, N3D+2002, N3D+1,
            N3D+1000, N3D+2001, N3D+1002

format(2x,I6,',',I6,',',I6,',',I6,',',I6,',',I6,',',I6,',',I6,'
      ,I6,',',I6)

c Generate Elements

if (RA.GT.RBT) then
  if (geotype.eq.'e') then
    IELA = IEH + 2*IINC + 2*IEHB +IEH2
  else
    IELA = IEH + 2*IINC + 2*IEHB + IEH2 + IEH3
  endif
  IELB = IEH + 2*IINC + 2*IEHB + IEH2
  IELB2 = IINC
IELC = IEH + 2*IEBB + IEH2
else
  if (geotype.eq.'e') then
    IELA = IEH + IOTC + 2*IINC + 2*IEBB
  else
    IELA = IEH + IOTC + 2*IINC + 2*IEBB + IEH2
  endif
IELB = IEH + IOTC + 2*IINC + 2*IEBB
IELB2 = IOTC + IINC
IELC = IEH + 2*IEBB
endif

if (base.eq.'y') then
  write(*,*) '**ELGEN,ELSET=LYAELS'
  write(*,61) KEL0A,IELA,2,1,IEVA,2000,1000
endif

if ( backing.eq.'y') then
  write(*,*) '**ELGEN,ELSET=LYCELS'
  write(*,61) KEL5A,IELC,2,1,IEVC,2000,1000
endif

write(*,*) '**ELGEN,ELSET=LYBEL1'
write(*,61) KEL2A,IELB,2,1,IEVB,2000,1000
write(*,*) '**ELGEN,ELSET=LYBEL2'
write(*,61) KEL3D,2*IEBB,2,1,IELB2,2000,1000

61 format(2x,I6,'','I6','','I6','','I6','','I6','','I6','','I6')
write(*,*) '**ELSET,ELSET=LYBELS'
write(*,*) 'LYBEL1,LYBEL2,'
write(*,*) '**ELSET,ELSET=ALLELS'
write(*,*) 'LYBELS,'
if (base.eq.'y') then
  write(*,*) 'LYAELS,'
endif
if ( backing.eq.'y') then
  write(*,*) 'LYCELS,'
endif

c Material Information

write(*,*) '**SOLID SECTION,ELSET=LYBELS,MATERIAL=FLIM'
write(*,*) '**MATERIAL,NAME=FLIM'
write(*,*) '**ELASTIC,TYPE=ISOTROPIC'
write(*,64) b modulus, br nu
64 format(2x,0PD12.4,'','F9.4)
if (filmpla.eq.'y') then
  write(*,*) '**PLASTIC'
  write(*,64) byield, 0.0
  write(*,64) bstressmax, bstrainmax
endif
write(*,*) '**EXPANSION,TYPE=ISO'
write(*,65) bexpansion
65 format(2x,1PD12.4,'',')
if (base.eq.'y') then
  write(*,'**SOLID SECTION, ELSET=LYAELS, MATERIAL=BASE')
  write(*,'**MATERIAL, NAME=BASE')
  write(*,'**ELASTIC, TYPE=ISOTROPIC')
  write(*,64) amodulus, arnu
  if (basepla.eq.'y') then
    write(*,'**PLASTIC')
    write(*,64) ayield, 0.0
    write(*,64) astressmax, astrainmax
  endif
  write(*,'**EXPANSION, TYPE=ISO')
  write(*,65) aexpansion
endif

if (backing.eq.'y') then
  write(*,'**SOLID SECTION, ELSET=LYCELS, MATERIAL=BACK')
  write(*,'**MATERIAL, NAME=BACK')
  write(*,'**ELASTIC, TYPE=ISOTROPIC')
  write(*,64) cmodulus, crnu
  if (backpla.eq.'y') then
    write(*,'**PLASTIC')
    write(*,64) cyield, 0.0
    write(*,64) csstressmax, cstrainmax
  endif
  write(*,'**EXPANSION, TYPE=ISO')
  write(*,65) cexpansion
endif

c Boundary Conditions

write(*,'**MPC')
if (PA.GT.RBT) then !Tie Reg 6 & 7 to body
  do 201 i=0,2*IINC-1
    write(*,'(60I3)') N4D-i*1000,N3B+i
  continue
  do 202 i=1,2*IINC
    write(*,'(60I3)') N3F+i, N3F+i*1000
  continue
  if (backing.eq.'y') then !Tie top of Coat to Back
    do 203 i=0,2*IEH
      write(*,'(60I3)') N3A+i,N5A+i
    continue
    do 204 i = 1, 4*IEHB
      write(*,'(60I3)') N4D+i,N5B+i
    continue
    do 205 i = 1, 2*IEH2
      write(*,'(60I3)') N3H+i,N5H+i
    continue
  endif
  if (base.eq.'y') then !Tie top of Coat to Base
    do 206 i=0,2*IEH+2*IINC+2*IEHB-2
      write(*,'(60I3)') N1A+i,N2A+i
    continue
  endif
else !Small Crack BCs
  do 207 i=0,2*IINC+2*IOTC-1
    write(*,'(60I3)') N3B+i,N5D-i*1000
  continue
end
do 208 i=1,2*IINC
  write(*,'(" TIE",2(\',',',i9))') N3F+i,N3F+i*1000
continue
if (backing.eq.'y') then            !Tie top of Coat to Back
  do 209 i=0,2*IEH-1
    write(*,'(" TIE",2(\',',',i9))') N3A+i,N5A+i
  continue
  write(*,'(" TIE",2(\',',',i9))') N4D, N5B
  do 210 i = 1, 4*IEHB
    write(*,'(" TIE",2(\',',',i9))') N4D+i,N5B+i
  continue
endif
if (base.eq.'y') then               !Tie top of Coat to Base
  do 212 i=0,2*IEH+2*IINC+2*IEHB - 2
    write(*,'(" TIE",2(\',',',i9))') N1A+i,N2A+i
  continue
endif

! Need to Write Equation to Output RF's from Dummy Nodes

if (base.eq.'y') then
  write(*,*) '**EQUATION'
  write(*,*) ' 3'
  write(*,213) N2E, 1, -1, N1E, 1, 1, 99991, 1, 1
  write(*,*) ' 3'
  write(*,213) N2E, 2, -1, N1E, 2, 1, 99991, 2, 1
  write(*,*) ' 3'
  write(*,213) N2E-1, 1, -1, N1E-1, 1, 1, 99992, 1, 1
  write(*,*) ' 3'
  write(*,213) N2E-1, 2, -1, N1E-1, 2, 1, 99992, 2, 1
endif

format(1x,9(I5,',','))

! Enter Starting conditions

if ((inittype.eq.'t').or.(inittype.eq.'T')) then
  write(*,*) '**INITIAL CONDITIONS, TYPE=TEMPERATURE'
  write(*,*) ' ALLNDS, ',rinitial
else
  write(*,*) '**INITIAL CONDITION, TYPE=STRESS'
  write(*,('(\',',',',',e10.3))')
  1 rinitial,0.0,rinitial,0.0
endif

! Step Information COOL DOWN or STRESS

if (mattype.ne.'p') then
  write(*,*) 'STEP'
  write(*,*) 'STATIC'
else
  write(*,*) 'STEP, NLGEOM, MONOTONIC, INC=50'
  write(*,*) 'STATIC'
endif
write(*,*) '**BOUNDARY, OP=NEW'
write(*,*) ' TQFLYB, PINNED'
write(*,*) ' RGHTB, XSYM'
if (base.eq.'y') then
  write(*,*) ' BOTLYA, PINNED'
  write(*,*) ' RHGTA, XSYM'M
  write(*,*) ' 99991, PINNED'
  write(*,*) ' 99992, PINNED'
  if (geotype.eq.'e') then
    write(*,*) ' EDGEAI, XSYM'M
  else
    write(*,*) ' EDGEAJ, XSYM'M
  endif
else
  write(*,*) ' BOTLYB, PINNED'
endif
if (backing.eq.'y') then
  write(*,*) ' RGHTC, XSYM'M
endif
if ( (inittype.eq.'t').or.(inittype.eq.'T') ) then
  write(*,*) ' TEMPERATURE'
  write(*,*) ' ALLNDS, 0.0'
endif
write(*,*) ' J-INTEGRAL, COUNTOUR=7, OUTPUT= BOTH'
write(*,*) ' 0.,1.'
write(*,*) ' CRACK'
write(*,*) ' EL FILE,FREQ=1, POSITION=AVERAGED AT NODES'
write(*,*) ' S'
write(*,*) ' SINV'
write(*,*) ' EE'
write(*,*) ' EL PRINT, POSITION=NODES'
write(*,*) ' S, MISES'
write(*,*) ' NODE FILE,FREQ=1'
write(*,*) ' U'
write(*,*) ' RF'
write(*,*) ' ENERGY FILE,FREQ=1'
write(*,*) ' ALLEN'
write(*,*) ' ENERGY PRINT,FREQ=1'
write(*,*) ' ALLEN'
write(*,*) ' NODE PRINT,NSET=CREDG,FREQ=1'
write(*,*) ' COORD, U, RF'
write(*,*) ' NODE PRINT,NSET=BOTLYB,FREQ=1'
write(*,*) ' COORD, RF'
write(*,*) ' ENDSTEP'
end
PROGRAM POSTPROC
C ---- 7/29/94: modied for ABAQUS 5.3, J- INTEGRAL is extracted. (YJL)
C One step model
implicit double precision (a-h,o-z)
C
dimension ARRAY(513), JARRAY(2, 513), LRUNIT(2, 1)
dimension KEYS(513), KEYTOT(513)
dimension IREC(6), IARR(6), ITVAL(6), ICH(6), IVAL(6, 4000)
CHARACTER*1 GEOTYPE
CHARACTER*80 FNAME, FNAMES, FNAMEP, FNAMEQ
CHARACTER*80 OUTDIR, TMPDIR, RESNAM, FILNAM, INDIR
CHARACTER*80 SUPNAM(20)
C
DIMENSION VAL(6, 4000)
EQUIVALENCE (ARRAY(1), JARRAY(1, 1))
DOUBLE PRECISION DX1(40), DX2(40), DY1(40), DY2(40)
DOUBLE PRECISION DX1A(40), DX2A(40), DY1A(40), DY2A(40)
DOUBLE PRECISION DX1B(40), DX2B(40), DY1B(40), DY2B(40)
DOUBLE PRECISION RF1X(40), RF2X(40), RF1Y(40), RF2Y(40)
DOUBLE PRECISION TIM(40)
DOUBLE PRECISION RX(99999), RY(99999), UX(99999), UY(99999)
DOUBLE PRECISION SX(99999), SY(99999), SXY(99999), SZ(99999), VMIS(99999)

C COMMON BLOCK FOR VERSION 4.9
C COMMON/JOBPAR/FNAME
C
READ(5, 60) FNAME
READ(5, 61) GEOTYPE
READ(5, *) IRPT
IF (IRPT.EQ.1) READ(5, *) VAR1
IF (IRPT.EQ.2) READ(5, *) VAR1, VAR2

60 FORMAT(A)
61 FORMAT(A1)
NNU = 1
LRUNIT(1, NRU) = 8
LRUNIT(2, NRU) = 2
LOUTF = 0
C
OUTDIR= ' ' 
OPEN(UNIT=15, STATUS='unknown', FILE='REPORT')
OPEN(UNIT=16, STATUS='unknown', FILE='RFDISP')
OPEN(UNIT=17, STATUS='unknown', FILE='FORCES')
CALL INITPF (FNAME, NRU, LRUNIT, LOUTF)
C
INFO=1
ICOL=0
C
INITIALIZE LOTS OF VARIABLES
C
DO 10 I=1, 6
  IREC(I)=0
  IARR(I)=0
  ITVAL(I)=0
  ICH(I)=1
10 CONTINUE
DO 20 I=1, 200

187
KEYS(I)=0
KEYTOT(I)=0
20 CONTINUE
ISUM = 0
ITYP=1
KEYS(ITYP)=1921
IINC=0
JUNIT = 8
C
JUNIT = LRUNIT(1,NRU)
CALL DBRNU ( JUNIT )

C=================================================================================================================================================================

C READ DATA RECORD
C=================================================================================================================================================================

C
READ(5,*) NTIPA, NTIPB, Rhol, NLST, Gmax, NATH, IBASE
write(*,*) NTIPA, NTIPB, Rhole, NLST, Gmax, NATH
N1A = NTIPA + 1
N1B = NTIPB + 1
N2A = NTIPA + 2
N2B = NTIPB + 2
N3A = NTIPA - 1
N3B = NTIPB - 1
N0A = NTIPA
N0B = NTIPB
if (ibase.eq.1) then
   NDM1 = 99991
   NDM2 = 99992
else
   NDM1 = N0B
   NDM2 = N0B - 1
endif
NFST = 3001
C
**.fil
end of file1
DO 100 k1 = 1,999999
CALL DBFILE(0, ARRAY, JRCD)
IF (JRCD.NE.0) goto 999

! make sure not &t end of file
! Record Key See 10.1.1-1
KEY = JRAY(1,2)
if (KEY.eq.2000) then
   time = ARRAY(3)
   istep = JRAY(1,8)
   INCR = JRAY(1,9)
endif
if (KEY.EQ.1901.and.istep.eq.0) then
   NODAL COORDINATE in X of
   NEXT NODE
   NNODE = JRAY(1,3)
   if (NNODE.ge.NFST.and.NNODE.le.NLST) then
      X(NNODE) = ARRAY(4)
   endif
   if (NNODE.eq.NOB) then
      RX = ARRAY(4)
   endif

100 CONTINUE
999 WRITE(3,999)
STOP
END
endif
if (NNODE.eq.N1B) then
    RX1 = ARRAY(4)
endif
if (NNODE.eq.N2B) then
    RX2 = ARRAY(4)
endif
endif

if (KEY.eq.1999) then
    Wex1 = array(5)
    Wpl1 = array(6)
    Wsel1 = array(4)
endif

if (KEY.EQ.1) then
    NNODE = JARRAY(1,3)
endif
if (NNODE.ge.NFST.and.NNODE.le.N0B.and.time.eq.1.0) then
    if (KEY.eq.11) then
        SX(NNODE) = ARRAY(3)
        SY(NNODE) = ARRAY(4)
        SZ(NNODE) = ARRAY(5)
        SXY(NNODE) = ARRAY(6)
    endif
    if (KEY.eq.12) then
        VMIS(NNODE) = ARRAY(3)
    endif
endif

if (KEY.EQ.104) then
    NNODE = JARRAY(1,3)
    if (NNODE.ge.NFST.and.NNODE.le.N0B.and.time.eq.1.0) then
        RFX(NNODE) = ARRAY(4)
        RFY(NNODE) = ARRAY(5)
    endif
    if(NNODE.eq.NDUM1) then
        RF2X(INCR) = ARRAY(4)
        RF2Y(INCR) = ARRAY(5)
    endif
    if(NNODE.eq.NDUM2) then
        RF1X(INCR) = ARRAY(4)
        RF1Y(INCR) = ARRAY(5)
    endif
do 50 I=N2I,N3I,1000
    if(NNODE.eq.I) then
        FX = FX + ARRAY(4)
        FY = FY + ARRAY(5)
    endif
    continue
50
endif

c  Get J-Integral Energies

if (KEY.eq.1991) then
    nj = JARRAY(1,5) - 2
    GfromJ = 0.
end if
do i = 1,nj
   GfromJ = GfromJ + ARRAY(6+i)
end do
GfromJ = GfromJ/real(nj)
GfromJ = GfromJ*1.e-3
Gdev = 0.d0
do i = 1,nj
   Gdev = Gdev + (ARRAY(6+i)-GfromJ)**2
end do
Gdev = dsqrt(Gdev/5.)
Gdev = Gdev/GfromJ
end if

c get displacements

if (KEY.eq.101) then
   TIM(INCR) = TIME
   INCR1 = INCR
   NNODE = JRRAY(1,3)
   if (NNODE.le.NLST.and.NNODE.ge.N0B.and.time.eq.1.0) then
      UX(NNODE) = ARRAY(4)
      UY(NNODE) = ARRAY(5)
      endif
   if (NNODE.eq.N1A) then
      DX1A(INCR) = ARRAY(4)
      DY1A(INCR) = ARRAY(5)
      endif
   if (NNODE.eq.N1B) then
      DX1B(INCR) = ARRAY(4)
      DY1B(INCR) = ARRAY(5)
      endif
   if (NNODE.eq.N2A) then
      DX2A(INCR) = ARRAY(4)
      DY2A(INCR) = ARRAY(5)
      endif
   if (NNODE.eq.N2B) then
      DX2B(INCR) = ARRAY(4)
      DY2B(INCR) = ARRAY(5)
      endif
   endif

100 CONTINUE
999 CONTINUE

C computation
   SX1=0
   SX2=0
   SY1=0
   SY2=0
   DX1(0)=0
   DX2(0)=0
   DY1(0)=0
   DY2(0)=0
   RF1X(0)=0
   RF2X(0)=0
   RF1Y(0)=0
   RF2Y(0)=0
INCR=INCR1

do 300, I=1, INCR
   DX1(I)=DX1B(I)-DX1A(I)
   DX2(I)=DX2B(I)-DX2A(I)
   DY1(I)=DY1B(I)-DY1A(I)
   DY2(I)=DY2B(I)-DY2A(I)
   write(16,301) I, RF1X(I), RF1Y(I), DX1(I), DY1(I),
   + RF2X(I), RF2Y(I), DX2(I), DY2(I)
   FORMAT(I2,8(2x,1PE12.4))
   SX1 = SX1 + (RF1X(I)+RF1X(I-1))*(DX1(I)-DX1(I-1))/2.0
   SX2 = SX2 + (RF2X(I)+RF2X(I-1))*(DX2(I)-DX2(I-1))/2.0
   SY1 = SY1 + (RF1Y(I)+RF1Y(I-1))*(DY1(I)-DY1(I-1))/2.0
   SY2 = SY2 + (RF2Y(I)+RF2Y(I-1))*(DY2(I)-DY2(I-1))/2.0
   continue

do 320, I=N0B,NFST,-1
   write(17,321) I, 1.0E4*(X(I) - X(N0B)), -10*RFX(I), -10*RFY(I)
   format(1x,I5,1x,3(1PE16.8,1x))
   continue

write(17,*) 'Averaged Forces'
write(17,*) 'Node RX,um EL:width,um Fxavg,N Fyavg,N ',
   + ' Sxavg, MPa Syavg, MPa'
   do 325, I=N0B-1,NFST+1,-2
      RXavg = -10*RFX(I)*0.6666667 + RFX(I-1)/6.0 + RFX(I+1)/6.0
      FXYavg = -10*RFY(I)*0.6666667 + RFY(I-1)/6.0 + RFY(I+1)/6.0
      elw = (X(I-1) - X(I+1))*10000 ! in um
      area = elw*1.0e-4  ! in cm
      sxavg = 1.0E-8*RFXavg/area
      syavg = 1.0E-8*RFYavg/area
      write(17,326) I,1.0E4*(X(I)-X(N0B)),elw,RFXavg,RFYavg,sxavg,syavg
   continue
   format(1x,I5,1x,6(1PE16.8,1x))
write(17,*) 'Stresses Averaged at Nodes'
write(17,*) 'Node RX,um Sxavg, MPa Syavg, MPa'
   do 327, I=N0B,NFST,-1
      write(17,328) I,1.0E4*(X(I)-X(N0B)),Sx(I)*1.0E-7,Sy(I)*1.0E-7,
      + Sz(I)*1.0E-7,Sxy(I)*1.0E-7,Vmis(I)*1.0E-7
      continue
   format(1x,I5,1x,6(1PE16.8,1x))
write(17,*) 'Displacements of Crack Opening'
do 322, I=N0B,NLST,1
   write(17,323) I, (X(N0B)-X(I))*1.0E4, 1.0E4*ux(I),1.0E4*uy(I)
   format(1x,I5,1x,3(1PE16.8,1x))
   continue

   rad = RX
   da = RX2 - RX
write(*,*), 'da = ', da*1.0e4, RX*1.0e4
   rpi = 3.141592654
   if (geotype.eq.'e') rad = 0.159154943
   GI = (SY1+SY2)/(da*2000*rpi*rad)
   GII = (SX1+SX2)/(da*2000*rpi*rad)
Gtot = abs(GI) + abs(GII)
Wadh = 1.0E4*Wse1*1.0E-3
CTOD = 180*atan(UX*(NATH)/UY*(NATH))/3.141592654

rnx = atan(sqrt(GII/GII))*180.0/3.141592654

C put force in N (/m)

RF1X = RF1X*0.1
RF1Y = RF1Y*0.1
RF2X = RF2X*0.1
RF2Y = RF2Y*0.1

write(*,21) Gmax
write(*,*) 'Strain Energy = ', Wadh
rat = GTOT/Gmax
write(*,22) fname, GI, GII, GTOT, Wadh, GfromJ, rnx, rat
if (irpt.eq.1) write(15,23) fname, var1, GI, GII, GTOT, Wadh,
1       GfromJ, rnx, rat
if (irpt.eq.2)
   write(15,24) fname, var1, var2, GI, GII, GTOT, Wadh, GfromJ,
   +       rnx, CTOD
if (irpt.eq.3)
   write(15,25) fname, var1, var2, var3, GI, GII, GTOT
if (irpt.eq.4)
   write(15,26) fname, var1, var2, var3, var4, GI, GII, GTOT
write(*,22) 'Node1:', DX1, DY1, RF2X, RF2Y, GfromJ

21   FORMAT(' Calculated Maximum G = ',1PE12.4)
22   FORMAT(1x,a8,' ',5(' ',1PE10.3))
23   FORMAT(1x,a8,8(1x,1PE12.5))
24   FORMAT(1x,a8,9(1x,1PE9.2))
25   FORMAT(1x,a8,8(' ',1PE12.4))
26   FORMAT(1x,a8,7(' ',1PE12.4))

end
APPENDIX B: FORTRAN PREPROCESSOR CODE FOR FLIP CHIP FEA

A set of programs are used to create the Abaqus input decks to calculate the applied debond energy for various EDT geometries. First, the program create_session asks the user to input which variable he wants to change and for the other input parameters. It then generates a series of temporary input files and also the session report file which will summarize all the results. Next the program create_com24.com directs the Unix workstation to set up the work directory. It then submits input files generated by create_session to create_mesh. The program create_mesh reads the inputs from the create_session output file and writes the Abaqus input deck. Create_com.com continues by running Abaqus, wait until the job is finished, and then direct the program post to the Abaqus data file. The program post collects the data needed to calculate the applied debond energy. It then adds this results the session report.

Create_Session

Program create_session

C
C Version 2.4
C COPYRIGHT ED SHAFFER 1994
C
C 11/16/94 modify for Flip Chip Problem
C 6/17/93 add inittype (initial condition)
C 6/21/93 add sessionrpt
C 9/20/93 for new create mesh. add da
C 11/5/93 Use one step method to calc G's.
C 4/11/94 Add Chip layer

character*1 type, inctype, holtype, crltype, datype, fhtype, geotype,
+ plast, inittype, postpla, chippla, chip, post, adh
character*3 prefix !Starting three letters
character*13 variable !To output to session report
character*80 header

dimension rholes(25), cracks(25), varis(100)

open(unit=10, file='session')
open(unit=7, file='sessionrpt')

C Read in data for this session

write(*,*) 'Is this a Hole (h) or an Edge (e),'
read(*,10) geotype
post = 'y'

193
write(*,*) 'Do you want to add a Chip Layer?'
read(*,10) chip
write(*,*) 'Which Variable do you want to Vary?:'
write(*,*)
write(*,*) '  a = Film Height'
write(*,*) '  b = Crack Length'
write(*,*) '  c = da Length'
write(*,*) '  d = Post Width'
write(*,*) '  e = Via Angle'
write(*,*) '  g = Chip Film Height'
write(*,*) '  h = Film Modulus'
if (chip.eq.'y') write(*,*) '  i = Post Modulus'
write(*,*) '  j = Chip Modulus'
write(*,*) '  k = Film Yield Stress'
if (post.eq.'y') write(*,*) '  l = Post Yield Stress'
write(*,*) '  m = Chip Yield Stress'
write(*,*)
read(*,10) format(a1)
10 format(a1)
101 format(a3)
write(*,11)
format('Geometric(g), logarithmic(l), linear(s) or enter(e):')
read(*,10) inctype
if ((inctype.eq.'e').and.(type.ne.'n')) then
  write(*,*) 'Please enter the number of steps: '
  read(*,*) inc
  nodecks = inc + 1
  write(*,*) 'Please enter variables: '
  read(*,*) (varis(i),i=0,inc)
endif
if ((type.ne.'n').and.(inctype.eq.'e')) then
  write(*,*) 'Please enter variables Low and High in um: '
  read(*,*) rlow, rhigh
  write(*,*) 'Please enter the number of steps: '
  read(*,*) inc
  nodecks = inc + 1
endif
write(*,*) 'Do you want adhesion to the post: '
read(*,10) adh
write(*,*) 'Length of Polymer to Center Line: '
read(*,*) rplength
rplength = rplength
999 if (type.ne.'a') then
  write(*,*) 'Enter in Film Height: '
  read(*,*) fheight
endif
if (type.ne.'b') then
  if (type.ne.'n') then
    write(*,*) 'Enter in Crack Length: '
    read(*,*) crlength
  endif
else
    write(*,*) 'Please enter in crack data set'
    read(*,*) (cracks(I),I=1,nodects)
endif
endif

if (type.ne.'c') then
    write(*,*) 'Keep da constant (c) or keep as ratio (r): '  
    read(*,10) datype
    if (datatype.eq.'r') then
        write(*,*) 'Enter in da fraction of crack: ' 
    else
        write(*,*) 'Enter in da: ' 
    endif
    read(*,*) daT  
endif

if (type.ne.'d') then
    write(*,*) 'Enter in Post Width: ' 
    read(*,*) rhole  
endif

if (type.ne.'e') then
    write(*,*) 'Enter in Via Angle: ' 
    read(*,*) viaaang  
endif

if ((chip.eq.'y').and.(type.ne.'g')) then
    write(*,*) 'Enter in Chip Height'
    read(*,*) chipht
else
    chipht = 0.0  
endif

if (type.ne.'h') then
    write(*,*) 'Enter in Film Modulus, GPa:'
    read(*,*) fmodulus
    fmodulus = fmodulus*1.e10  
endif
write(*,*) 'Enter in Film Poisson Ratio'
read(*,*) frnu

write(*,*) 'Do you want Film plasticity, y or n:'
read(*,10) filmpla
if (filmpla.eq.'y') then
    if (type.ne.'k') then
        write(*,*) 'Enter Yield Stress, MPa: '  
        read(*,*) fyield
    endif
    write(*,*) 'Enter Maximum Plastic Strain: ' 
    read(*,*) fstrainmax
    write(*,*) 'Enter Maximum Ultimate Stress, MPa: ' 
    read(*,*) fstressmax
    fstressmax = fstressmax*1.0e7
    fyield = fyield*1.0e7  
endif
write(*,*) 'Enter Film Expansion Coef, PPM/C: ' 
read(*,*) fexpansion

195
fexpansion = fexpansion*1.0e-6

if (post.eq.'y') then
  if (type.ne.'i') then
    write(*,'') 'Enter in Post Modulus, GPa:'
    read(*,*) bmodulus
    bmodulus = bmodulus*1.0e10
  endif
  write(*,'') 'Enter in Post Poisson Ratio'
  read(*,*) brnu
  write(*,'') 'Do you want Post plasticity, y or n:'
  read(*,10) postpla
  if (postpla.eq.'y') then
    if (type.ne.'l') then
      write(*,*) 'Enter Yield Stress, MPa: '
      read(*,*) byield
    endif
    write(*,*) 'Enter Maximum Plastic Strain: '
    read(*,*) bstrainmax
    write(*,*) 'Enter Maximum Ultimate Stress, MPa: '
    read(*,*) bstressmax
    bstressmax = bstressmax*1.0e7
    byield = byield*1.0e7
  endif
  write(*,*) 'Enter Post Expansion Coef, PPM/C: '
  read(*,*) bexpansion
  bexpansion = bexpansion*1.0e-6
endif

if (chip.eq.'y') then
  if (type.ne.'j') then
    write(*,'') 'Enter in Chip Modulus, GPa:'
    read(*,*) cmodulus
    cmodulus = cmodulus*1.0e10
  endif
  write(*,'') 'Enter in Chip Poisson Ratio'
  read(*,*) crnu
  write(*,'') 'Do you want Chip plasticity, y or n:'
  read(*,10) chipla
  if (chipla.eq.'y') then
    if (type.ne.'m') then
      write(*,*) 'Enter Yield Stress, MPa: '
      read(*,*) cyield
    endif
    write(*,*) 'Enter Maximum Plastic Strain: '
    read(*,*) cstrainmax
    write(*,*) 'Enter Maximum Ultimate Stress, MPa: '
    read(*,*) cstressmax
    cstressmax = cstressmax*1.0e7
    cyield = cyield*1.0e7
  endif
  write(*,*) 'Enter Chip Expansion Coef, PPM/C: '
  read(*,*) cexpansion
  cexpansion = cexpansion*1.0e-6
endif

write(*,*) 'Please enter # vertical elements in coating'
read(*,*) NVBE
NVAE = 1
write(*,*) 'Please enter the # horiz elements near crack tip'
read(*,*) NEH
if (chip.eq.'y') then
   write(*,*) 'Please enter # vertical elements in chipping'
   read(*,*) NVCE
endif
write(*,*) 'Please enter file prefix: '
read(*,101) prefix
write(*,*) 'Please enter starting model number: '
read(*,*) model
write(*,*) 'Which initial condition Temperature(t) or Stress(s): '
read(*,10) inittype
write(*,*) 'Please enter the initial stress or the Dtemp: '
read(*,*) tinitial
write(*,*) 'Please enter in a header: '
read(*,135) header
format(a60)
c
c Comment out to session report
c
if (type.eq.'a') variable = 'Film Height'
if (type.eq.'b') variable = 'Crack Length'
if (type.eq.'c') variable = 'da Length '
if (type.eq.'d') variable = 'Post Width'
if (type.eq.'e') variable = 'Via Angle'
if (type.eq.'g') variable = 'Chip Height'
if (type.eq.'h') variable = 'Film Modulus'
if (type.eq.'i') variable = 'Post Modulus'
if (type.eq.'j') variable = 'Chip Modulus'
if (type.eq.'k') variable = 'Film Yield'
if (type.eq.'l') variable = 'Post Yield'
if (type.eq.'m') variable = 'Chip Yield'
if (type.eq.'n') variable = 'Crck&Radius'
write(7,*) ' ' SESSION REPORT'
write(7,*)
write(7,135) header
write(7,210) prefix,model, prefix, model+inc
format('Input Files: ','a3',_,'i3,' to ','a3',_,'i3)
write(7,210) variable,rlow, rhigh
format(a13,' ranges from ','F9.4,' to ','F9.4)
if (adh.eq.'y') then
   write(7,209)
   format('Adhered to Post')
else
   write(7,2091)
   format('Not Adhered to Post')
endif
if (geotype.eq.'e') write(7,*') 'Plane Strain Geometry'
if (geotype.ne.'e') write(7,*') 'Axisymmetric Geometry'
if (type.ne.'a') write(7,211) fheight
format('Film Height is: ','t20,f8.2,' um')
if ((type.ne.'g').and.(chip.eq.'y')) write(7,2112) chipht
format('Chip Height is: ','t20,f8.2,' um')
if ((type.ne.'b').and.(type.ne.'n')) write(7,212) crlength
format('Crack Length is:', t20, f8.2, ' um')
if (type.ne.'c'.and.type.ne.'n') then
  if (datype.eq.'c') then
    write(7,213) daT
  else
    write(7,2131) daT*100
  endif
endif

format('da Length is: ', t20, f8.3, ' um')
format('da Length is: ', t20, f8.3, '%')
if (type.ne.'d'.and.type.ne.'n') write(7,214) rhole
format('Post Width is: ', t20, f8.2, ' um')
write(7,2141) rlength
format('Post Spacing is: ', t20, f8.2, ' um')
if (type.ne.'e') write(7,215) viaang
format('Via Angle is: ', t20, f8.2)
if (inittype.eq.'t') write(7,216) tinitial
format('d Temperature is: ', T22, F6.2, ' C')
write(7,217)
format('Film Material Properties: ')
write(7,218) fmodulus/1.e10
format(' Modulus = ', T20, F8.2, ' GPa')
write(7,219) fnnu
format(' Poisson = ', T20, F8.2)
write(7,220) fexpansion*1.e6
format(' CTE = ', T20, F8.2, ' PPM/C')
if (filmpla.eq.'y') then
  if (type.ne.'k') write(7,221) fyield/1e7
  format(' Yield = ', T20, F8.2, ' MPa')
  write(7,222) fstressmax/1e7
  format(' Ult. Stress = ', T20, F8.2, ' MPa')
  write(7,223) fstrainmax*100
  format(' Ult. Strain = ', T23, F4.1, '%')
endif
if (post.eq.'y') then
  write(7,227)
  format('Post Material Properties: ')
  write(7,228) bmodulus/1.e10
  format(' Modulus = ', T20, F8.2, ' GPa')
  write(7,229) brnu
  format(' Poisson = ', T20, F8.2)
  write(7,230) bexpansion*1.e6
  format(' CTE = ', T20, F8.2, ' PPM/C')
  if (postpla.eq.'y') then
    if (type.ne.'k') write(7,231) byield/1e7
    format(' Yield = ', T20, F8.2, ' MPa')
    write(7,232) bstressmax/1e7
    format(' Ult. Stress = ', T20, F8.2, ' MPa')
    write(7,233) bstrainmax*100
    format(' Ult. Strain = ', T20, F4.1, '%')
  endif
endif
if (chip.eq.'y') then
  write(7,237)
  format('Coat Material Properties: ')
  write(7,238) cmodulus/1.e10
format(' Modulus = ',T20,F8.2,' GPa')
write(7,239) crnu
format(' Poisson = ',T20,F8.2)
write(7,240) cexpansion*1e6
format(' CTE = ',T20,F8.2,' PPM/C')
if (filmpla.eq.'y') then
  if (type.ne.'k') write(7,241) cyield/1e7
  format(' Yield = ',T20,F8.2,' MPa')
  write(7,242) cstressmax/1e7
  format(' Ult. Stress = ',T20,F8.2,' MPa')
  write(7,243) cstrainmax*100
  format(' Ult. Strain = ',T20,F4.1,'%')
endif
endif

if (type.ne.'g'.and.type.ne.'a'.and.type.ne.'h') then
  if ((inittype.eq.'t').or.(inittype.eq.'T')) then
    farfield = 1.0E-7*tinitial*(fexpansion)*
    fmodulus/(1.0-frnu)
  else
    farfield = tinitial
  endif
endif
pi = 3.141592654
if (geotype.eq.'e') then
  areaC = rplength
  areaP = rhole
else
  areaC = rplength
  areaP = rhole
  rlp = rplength*rhole
  areaP = pi*rhole**2
  areaC = pi*(rlp**2 - rhole**2)
endif

fbase = (1+frnu)*(1-2*frnu)
fmod = fmodulus/1E7
bbase = (1+brnu)*(1-2*brnu)
bmod = bmodulus/1E7

C Find the Strain Balance Between Post/Coat
Bc = areaC*fmod*(1-frnu)/fbase
Bp = areaP*bmod*(1-brnu)/bbase
Cc = (1+frnu)/(1-frnu)
Cp = (1+brnu)/(1-brnu)
Ap = bexpansion*tinitial*Cp
Ac = fexpansion*tinitial*Cc
Alpha = Ap/Ac
Beta = Bc/Bp
x1 = (1-alpha)/(1+beta)
x2 = (alpha+beta)/(1+beta)
write(*,*) 'Coat ',Ac,Bc,Cc
write(*,*) 'Post ',Ap,Bp,Cp
g = -(Bc*Ac + Bp*Ap)/(Bp + Bc)

C Now Solve for Stresses
strX = fexpansion*tinitial
strY = g+strX
\[
\text{str} = \text{strX} + \text{strY}
\]
\[
\text{write}(7,2440) \text{ farfield}
\]
\[
\text{format('Biaxial Unconstr Stress: ',T20, f8.2,' MPa')}
\]
\[
\text{fartriaY} = (\text{fmod} \times \text{strY}/(1-2*\text{frnu}))(1-\alpha)/(1+\beta)
\]
\[
\text{fartriaX} = (\text{fmod} \times \text{strX}/(1-2*\text{frnu}))(1-\text{r2*frnu}/(1-\text{frnu}))
\]
\[
\text{write}(7,2441) \text{ fartriaX}
\]
\[
\text{format('Constrain. PE X Stress: ',T20, f8.2,' MPa')}
\]
\[
\text{write}(7,2442) \text{ fartriaY}
\]
\[
\text{format('Constrain. PE Y Stress: ',T20, f8.2,' MPa')}
\]
\[
\text{c Solve for Energies}
\]
\[
\text{Gbiax} = 0.5\times\text{farfield}^{2}\times\text{fheight}^{2} \times (1-\text{frnu}^{2})/\text{fmod}
\]
\[
\text{write}(7,245) \text{ Gbiax}
\]
\[
\text{format('Biaxial Energy Applied = ',T25,F9.3,' J/m^2')}
\]
\[
\text{workT} = 0.5\times(2\times\text{fartriaX} \times \text{strX} + \text{fartriaY} \times \text{strY})
\]
\[
\text{workB} = \text{farfield} \times \text{strX}
\]
\[
\text{gtriax} = \text{fheight} \times (\text{workT} - \text{workB})
\]
\[
\text{write}(7,246) \text{ gtri ax}
\]
\[
\text{format('Flip Chip PE Energy = ',T25,F9.3,' J/m^2')}
\]
\[
\text{write}(7,248) \text{ Gtriax/gbiax}
\]
\[
\text{format('Triaxial/Biaxial = ',T25,F9.3)}
\]
\[
\text{write}(7,247) \text{ g, Alpha, Beta}
\]
\[
\text{format('Triaxial Const g, Alph & Beta: ', 3(1PE12.4))}
\]
\[
\text{c Reduced Equations}
\]
\[
\text{Gtred} = \text{Gbiax} \times (1-\text{r2})^{2}/(1-2*\text{frnu})
\]
\[
\text{write}(7,249) \text{ gtri ed}
\]
\[
\text{format('Gfc from Reduced= ',T25,F9.3,' J/m^2')}
\]
\[
\text{c Write out data for each inc to fort.}
\]
\[
\text{do 20 } i = 0, \text{inc}
\]
\[
\text{if (inctype.eq.'e') then}
\]
\[
\text{var} = \text{varis(i)}
\]
\[
\text{endif}
\]
\[
\text{if (inctype.eq.'s') then}
\]
\[
\text{rm} = \text{real(inc)}
\]
\[
\text{step} = (\text{rhigh} - \text{rlow})/\text{rm}
\]
\[
\text{var} = \text{r low} + i \times \text{step}
\]
\[
\text{endif}
\]
\[
\text{if (inctype.eq.'g') then}
\]
\[
\text{rm} = 1.0/\text{real(inc)}
\]
\[
\text{x} = (\text{rhigh} / \text{rlow})^{2} \times \text{rm}
\]
\[
\text{var} = \text{r low}^{2} \times x\times i
\]
\[
\text{endif}
\]
\[
\text{if (inctype.eq.'l') then}
\]
\[
\text{step} = \text{real}((\text{log10(rhigh/rlow)})/\text{inc})
\]
\[
\text{var} = 10^{2} \times (\text{log10(rlow)} + \text{real(step}\times i))
\]
\[
\text{endif}
\]
\[
\text{ifil} = \text{model} + i
\]
\[
\text{if (type.eq.'a') then}
\]
\[
\text{fheight} = \text{var}
\]
\[
\text{endif}
\]
\[
\text{if (type.eq.'b') then}
\]
\[
\text{crlength} = \text{var}
\]
\[
\text{endif}
\]
\[
\text{if (type.eq.'c') then}
\]

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da = var
endif
if (type.eq.'d') then
    rhole = var
endif
if (type.eq.'e') then
    viaang = var
endif
if (type.eq.'g') then
    chipht = var
endif
if (type.eq.'h') then
    fmodulus = var*1.e10
endif
if (type.eq.'i') then
    bmodulus = var
endif
if (type.eq.'j') then
    cmodulus = var*1.e10
endif
if (type.eq.'k') then
    fyield = var*1.0e7
    fstressmax = fyield !Perfectly plastic
endif
if (type.eq.'l') then
    byield = var*1.0e7
    bstressmax = byield
endif
if (type.eq.'m') then
    cyield = var*1.0e7
    cstressmax = byield
endif
if (type.eq.'n') then
    crlength = cracks(i+1)
    rhole = rholes(i+1)
endif
if (type.ne.'c') then
    da = daT
    if (datype.eq.'r') then
        da = daT*crlength
    endif
endif

if (0.5*NVBE*da.GT.fheight) da = 0.5*fheight/NVBE

iunit = 11 + i
write(10,121)
format('#')
write(10,122) iunit
write(iunit,123) prefix, ifil
write(iunit,124) iunit

122 format('create_com.2.4.com < fort.',I2)
123 format(a3,'_',I3)
124 format(I2)

write(iunit,*) rplength
write(iunit,*) crlength
write(iunit,*) fheight
write(iunit,*) xchipt
write(iunit,*) rhole
write(iunit,*) viaang
write(iunit,*) da
write(iunit,*) NVAE
write(iunit,*) NVBE
write(iunit,*) NVCE
write(iunit,*) NEH
write(iunit,*) fmodulus
write(iunit,*) fnru
write(iunit,*) fyield
write(iunit,*) fstrainmax
write(iunit,*) fstressmax
write(iunit,*) fexpansion
write(iunit,10) filmpla
write(iunit,*) bmodulus
write(iunit,*) brnu
write(iunit,*) byield
write(iunit,*) bstrainmax
write(iunit,*) bstressmax
write(iunit,*) bexpansion
write(iunit,10) postpla
write(iunit,*) cmodulus
write(iunit,*) crnu
write(iunit,*) cyield
write(iunit,*) cstrainmax
write(iunit,*) cstressmax
write(iunit,*) cexpansion
write(iunit,10) chipla
write(iunit,10) geotype
write(iunit,10) iniittype
write(iunit,10) adh
write(iunit,*) tinitial
write(iunit,10) chip
if (type.ne.'n') then
  write(iunit,*) 1
  write(iunit,*) var
else
  write(iunit,*) 2
  write(iunit,*) cracks(i+1),rhols(i+1)
endif
write(iunit,92) header
continue
format(a80)

if (type.ne.'n') then
  write(7,*)
  write(7,22) variable
  format(' File ','al3', ' GI GII Gtot ',
1     ' Mix GfromJ')
  write(7,23)
  format(78('-'))
else
  write(7,*)
  write(7,24)
  format(' File ',' Crack ',' Radius ',' GI ','

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CII', 'Gtot', 'mix', 'GfromJ')
write(7,25)
  format(78(''))
endif
write(10,35) prefix, model
format('cp sessionrpt ',a3,'_','_','i3','.rpt')
write(10,30)
format('rm -f fort.*')
write(10,36)
format('rm -f session')
end

Create_Com

# 7/28/94: modified for ABAQUS 5.3, SGI IRIX 5.2, f77 v4.0.1 (YJL)
# 8/4/94: upgraded to Version2.4
#
# CREATE AN ABAQUS INPUT DECK USING A VIRTUAL SESSION
#
# Read from fort.* (input file) name of input deck and unit number
set abqinp = $<
set iunit = $<
set edhome = /usr/people/eshaffer/flip
set scr = /usr/people/eshaffer/flip/flipscratch
#
cp $edhome/fort.$iunit $scr
cd $scr
mkdir $abqinp
#
f77 -o create_mesh.x $edhome/create_mesh.2.4.f
create_mesh.x < fort.$iunit > $abqinp.tmp
rm -f create_mesh.x
cut -c2-99 $abqinp.tmp > $abqinp.inp
mv $abqinp.inp $abqinp
cp fort.9 $abqinp/$abqinp.pst
rm -f $abqinp.tmp fort.9
if (! -e edpost.x) then
  abaqus make job=edpost user=$edhome/post.2.4.f
endif

cd $abqinp

abaqus job=$abqinp
# sleep 10
RECHECK:
(echo checking)
if ( -e /tmp/eshaffer_$abqinp) then
  sleep 5
  goto RECHECK
else
  sleep 5
  if ( -e /tmp/eshaffer_$abqinp) then
goto RECHECK
else
goto GOTIT
endif
endif
GOTIT:
(echo GotIt)
sleep 10

./edpost.x < $abqinp.pst
cat REPORT >> $edhome/sessionrpt
#rm *

Create_Mesh

program Create_Mesh

Version 2.4

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Flip Chip Geometry

IMPLICIT DOUBLE PRECISION(A-H,O-Z)
integer topA, botB
Character*8 Name
Character*1 base, backing, inittype, basepla, filmpla, backpla,
    matttype, geotype
+ Dimension topA(999), botB(999)

read(*,1) Name
format(a8)
read(*,*), iunit
read(*,*) RL           !!Part Length
read(*,*) RA           !!Crack Length
read(*,*) RAT          !!A layer Height
read(*,*) RBT          !!B layer Height
read(*,*) RCT          !!C Layer Height
if (RA.eq.RBT) RA = 0.95*RA
read(*,*) RH           !!Hole Radius
read(*,*) ANGLE        !!Via Wall Angle
read(*,*) DA           !!Crack release length
read(*,*) IEVA         !!Film Layer A Properties
read(*,*) IEVB         !
read(*,*) IEVC         !
read(*,*) IEHB         !
read(*,*) bmodulus     !
read(*,*) brnu         !
read(*,*) byield       !
read(*,*) bstrainmax   !
read(*,*) bstressmax   !
read(*,*) bexpansion   !

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read(*,2) filmpla
read(*,*) amodulus  !!Base Layer A Properties
read(*,*) arnu
read(*,*) ayield
read(*,*) astrainmax
read(*,*) astressmax
read(*,*) aexpansion
read(*,2) basepla
read(*,*) cmodulus  !!Back Layer C Properties
read(*,*) crnu
read(*,*) cyield
read(*,*) cstrainmax
read(*,*) cstressmax
read(*,*) cexpansion
read(*,2) backpla
read(*,2) geotype
read(*,2) inittype
read(*,*) rinitial  !Initial delta Temp or Stress
read(*,2) base
read(*,2) backing
read(*,*) irpt  !# of variables on report 1-4
if (irpt.eq.1) read(*,*) varl
if (irpt.eq.2) read(*,*) varl,var2
format(a1)
if (((initype.eq.'t').or.(initype.eq.'T')) then
   farfield = rinitial*(bexpansion)*bmodulus/(1-brnu)
else
   rinitial = rinitial*1.0E7
   farfield = rinitial
endif
gexpected = 0.5e-7*(1.0 - brnu**2)*RBT*farfield**2/bmodulus

if ((filmpla.eq.'y').or.(backpla.eq.'y').or.(basepla.eq.'y'))
   matype = 'p'

C Convert units of length

RL = RL*1.0E-4
RA = RA*1.0E-4
RAT = RAT*1.0E-4
RBT = RBT*1.0E-4
RCT = RCT*1.0E-4
RH = RH*1.0D-4
DA = DA*1.0D-4
DANGLE = ANGLE
ANGLE = 90.0 - ANGLE
ANGLE = ANGLE*0.017453293

C Estimate # of Horz Increments for IEH, IEH2, IEH3 and IINC

IF (RA.GT.RBT) then

C First estimate IINC
r1 = 0.5*DA
rtot=RBT-IEHB*DA
b=1.25
RIINC = log((rtot/r1)*(B-1.0)+1)/log(B)
IINC = int(RIINC)
if (IINC.LE.1) IINC = 1

Now do IEH
r1 = rtot*(B-1)/(B**IINC-1.0)
rlst = r1*B**(IINC-1)
r1 = rlst
rtot = RL-RA-RBT
B = 1.25
RIEH = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH = int(RIEH)
if (IEH.LE.1) IEH = 1

Do IEH2
rtot=RBT-IEHB*DA
r1 = rtot*(B-1)/(B**IINC-1)
rlst = r1*B**(IINC-1)
r1 = rlst
rtot = RA-RBT
B = 1.25
RIEH2 = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH2 = nint(RIEH2)
if (IEH2.LE.1) IEH2 = 1

now do IEH3
if (RH.ne.0.0) then
r1 = rtot*(B-1)/(B**IEH2-1)
rlst = r1*B**(IEH2)
r1 = rlst
rtot = RH
B = 1.25
RIEH3 = log((rtot/r1)*(B-1.0)+1)/log(B)
IEH3 = nint(RIEH3)
if (IEH3.LE.1) IEH3 = 1
else
IEH3 = 1
endif!

else

First estimate IINC
r1 = DA*0.5
rtot=RA-IEHB*DA
B = 1.25
RIIINC = log((rtot/r1)*(B-1.0)+1)/log(B)
IINC = int(RIIINC)
if (IINC.LE.1) IINC = 1

Now do IOTC
r1 = rtot*(B-1)/(B**IINC-1)
rlst = r1*B**(IINC-1)
r1 = rlst
rtot = RBT
RIOTC = log((rtot/r1)*(B-1.0)+1)/log(B)
IOTC = int(RIOTC)
if (IOTC.LE.1) IOTC = 1

Now do IEH
r1 = rtot*(B-1)/(B**IOTC-1)
rlist = r1*B**(IOTC-1)
r1 = rlist
rrot = RL-RA-RBT
B=1.25
RIEH = log((rrot/r1)*(B-1.0)+1)/log(B)
IEH = int(RIEH)
if (IEH.LE.1) IEH = 1

    c    now do IEH3
    if (RH.ne.0.0) then
        r1 = rrot*(B-1)/(B**(IINC-1))
        rlist = r1*B**(IINC)
        r1 = rlist
        rrot = RH
        B = 1.25
        RIEH3 = log((rrot/r1)*(B-1.0)+1)/log(B)
        IEH3 = int(RIEH3)
        if (IEH3.LE.1) IEH3 = 1
        else
            IEH3 = 1
        endif
    endif

    c    Also, for the mesh not to collapse we must have:
        if (real(IEHB*DA).GT.(0.5*(RA-real(DA*IEHB))/TAN(ANGLE+0.0001)))
            da = 0.5*(RA-real(DA*IEHB))/TAN(ANGLE)*real(IEHB)
        endif

        IINC = int(IINC/2.0)
        if (IINC.LE.1) IINC = 1
        IOTC = int(IOTC/2.0)
        if (IOTC.LE.1) IOTC = 1
        IEH2 = int(IEH2/2.0)
        if (IEH2.LE.1) IEH2 = 1
        IEH3 = int(IEH3/2.0)
        if (IEH3.LE.1) IEH3 = 1
        IEH = int(IEH/2.0)
        if (IEH.LE.1) IEH = 1

    c    Define Node Numbers for Large Crack Case
        if (RA.GT.RBT) then
            N0A = 1
            N1A = N0A + 2000*IEVA
            N2A = N1A + 1000
            N3A = N2A + 2000*IEVB
            N5A = N3A + 1000 + 2000*IINC
            N6A = N5A + 2000*IEVC
            N0B = N0A + 2*IEH
            N1B = N1A + 2*IEH
            N2B = N2A + 2*IEH
            N3B = N3A + 2*IEH
            N5B = N5A + 2*IEH
N6B = N5B + 2000*IEVC
N0D = N0B + 2*IINC
N1D = N1B + 2*IINC
N2D = N2B + 2*IINC
N3D = N3B + 2*IINC
N4D = N3D + 2000*IINC
N0E = N0D + 2*IEHB
N1E = N1D + 2*IEHB
N2E = N2D + 2*IEHB
N3E = N3D + 2*IEHB
N0F = N0E + 2*IEHB
N1F = N1E + 2*IEHB
N2F = N2E + 2*IEHB
N3F = N3E + 2*IEHB
N4F = N3F + 2000*IINC
N0H = N0F + 2*IINC
N1H = N1F + 2*IINC
N2H = N2F + 2*IINC
N3H = N3F + 2*IINC
N5H = N5B + 4*IEHB
N6H = N5H + 2000*IEVC
N0I = N0H + 2*IEH2
N1I = N1H + 2*IEH2
N2I = N2H + 2*IEH2
N3I = N3H + 2*IEH2
N5I = N5H + 2*IEH2
N6I = N5I + 2000*IEVC
N0J = N0I + 2*IEH3
N1J = N1I + 2*IEH3
N3J = N3I + 2*IEH3

else

N0A = 1
N1A = N0A + 2000*IEVA
N2A = N1A + 1000
N3A = N2A + 2000*IEVB
N5A = N3A + 1000 + 2000*IINC
N6A = N5A + 2000*IEVC
N0B = N0A + 2*IEHB
N1B = N1A + 2*IEHB
N2B = N2A + 2*IEHB
N3B = N3A + 2*IEHB
N5B = N5A + 2*IEHB
N6B = N5B + 2000*IEVC
N0C = N0B + 2*IOTC
N1C = N1B + 2*IOTC
N2C = N2B + 2*IOTC
N3C = N3B + 2*IOTC

!Small Crack Case
N0D = N0C + 2*IINC
N1D = N1C + 2*IINC
N2D = N2C + 2*IINC
N3D = N3C + 2*IINC
N4D = N3D + 2000*IINC
N5D = N4D + 2000*IOTC

N0E = N0D + 2*IEHB
N1E = N1D + 2*IEHB
N2E = N2D + 2*IEHB
N3E = N3D + 2*IEHB

N0F = N0E + 2*IEHB
N1F = N1E + 2*IEHB
N2F = N2E + 2*IEHB
N3F = N3E + 2*IEHB
N4F = N3F + 2000*IINC
N5F = N4F + 2000*IOTC

N0H = N0F + 2*IINC
N1H = N1F + 2*IINC
N2H = N2F + 2*IINC
N3H = N3F + 2*IINC
N5H = N5B + 4*IEHB
N6H = N5H + 2000*IEVC

N0J = N0H + 2*IEH3
N1J = N1H + 2*IEH3
N3J = N3H + 2*IEH3

endif

c Define Node Y Positions

YLEV0 = 0.0
YLEV1 = RAT
YLEV2 = RAT
YLEV3 = RAT + RA
YLEV4 = RAT + IEVB*DA
YLEV5 = RAT + RBT
YLEV6 = RAT + RBT + RCT

c Define Node X Positions

XLEVA = RH + RL
XLEVB = RH+RA+RBT
XLEVC = RH+2.0*RA
XLEVD = RH+RA+IEHB*DA
XLEVE = RH+RA
XLEVF = RH+RA-IEHB*DA
XLEVH = RH+RA-RBT
XLEVI = RH
XLEVJ = 0.0

For Post Processing Data Retrieval
open (9,status='unknown')
write(9,'(a)') name

209
write(9,2) geotype
write(9,*) irpt
if (irpt.eq.1) write(9,*) var1
if (irpt.eq.2) write(9,*) var1, var2
if (RA.GT.RBT) then
    NLAST = N2I
else
    NLAST = N2H
endif
IBASE = 0
if (base.eq.'y') IBASE = 1
write(9,*) N1E, N2E, RH, NLAST, gexpected, N2H, IBASE

C Start with Headings etc

write(*,*) "**HEADING"
write(*,92) Name
92 format(1x, 'EDT2.4:', a8)
if (backing.eq.'y') then
    write(*,*) "** BACKING PROPS"
    write(*,*) " E = ", CMODULUS
    write(*,*) " v = ", CRNU
    write(*,*) " A = ", CEXPANSION
    write(*,*) " So= ", CYIELD
endif
write(*,*) "** COATING PROPS"
write(*,*) " E = ", BMODULUS
write(*,*) " v = ", BRNU
write(*,*) " A = ", BEXPANSION
write(*,*) " So= ", BYIELD
if (base.eq.'y') then
    write(*,*) "** BASE PROPS"
    write(*,*) " E = ", AMODULUS
    write(*,*) " v = ", ARNU
    write(*,*) " A = ", AEXPANSION
    write(*,*) " So= ", AYIELD
endif
write(*,*) "** Calc FarField = ", farfield
write(*,*) "** GI Max = ", gexpected
if (geotype.eq.'e') then
    write(*,*) "** PLANE STRAIN"
else
    write(*,*) "** AXISYMMETRIC"
endif
write(*,*) "** Film Height = ", RBT*1E4
if (base.eq.'y') write(*,*) "** BASE Height = ", RAT*1E4
if (backing.eq.'y') write(*,*) "** BACK Height = ", RCT*1E4
write(*,*) "** Crack Length = ", RA*1E4
write(*,*) "** Part Length = ", RL*1E4
write(*,*) "** Hole Radius = ", RH*1E4
write(*,*) "** Via Wall Angle = ", DANGLE
write(*,*) "** Da of element = ", DA*1E4
write(*,*) "**RESTART,WRITE,FREQUENCY=10"
write(*,*) "**PREPRINT,MODEL=NO,HISTORY=NO,ECHO=NO"

C Write out Defined Nodes and Positions

write(*,*) "**NODE"
IF (RA.GT.RBT) THEN

!! LARGE CRACK

if (base.eq.'y') then
    write(*,10) 99992, 0.0, 0.0
    write(*,10) 99991, 0.0, 0.0
endif

write(*,10) N0A, XLEVA, YLEV0
write(*,10) N1A, XLEVA, YLEV1
write(*,10) N2A, XLEVA, YLEV2
write(*,10) N3A, XLEVA, YLEV5
write(*,10) N5A, XLEVA, YLEV5
write(*,10) N6A, XLEVA, YLEV6

write(*,10) N0B, XLEVB, YLEV0
write(*,10) N1B, XLEVB, YLEV1
write(*,10) N2B, XLEVB, YLEV2
write(*,10) N3B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N5B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N6B, XLEVB+(RH/XLEVB)*(RBT+RCT)*TAN(ANGLE), YLEV6

write(*,10) N0D, XLEVD, YLEV0
write(*,10) N1D, XLEVD, YLEV1
write(*,10) N2D, XLEVD, YLEV2
write(*,10) N3D, XLEVD, YLEV4
write(*,10) N4D, XLEVD+(RH/XLEVD)*RBT*TAN(ANGLE), YLEV5

write(*,10) N0F, XLEVF, YLEV0
write(*,10) N1F, XLEVF, YLEV1
write(*,10) N2F, XLEVF, YLEV2
write(*,10) N3F, XLEVF, YLEV4
write(*,10) N4F, XLEVF+(RH/XLEVF)*RBT*TAN(ANGLE), YLEV5

write(*,10) N0H, XLEVH, YLEV0
write(*,10) N1H, XLEVH, YLEV1
write(*,10) N2H, XLEVH, YLEV2
write(*,10) N3H, XLEVH+(RH/XLEVH)*RBT*TAN(ANGLE), YLEV5
write(*,10) N5H, XLEVH+(RH/XLEVH)*RBT*TAN(ANGLE), YLEV5
write(*,10) N6H, XLEVH+(RH/XLEVH)*(RBT+RCT)*TAN(ANGLE), YLEV6

write(*,10) N0I, XLEVI, YLEV0
write(*,10) N1I, XLEVI, YLEV1
write(*,10) N2I, XLEVI, YLEV2
write(*,10) N3I, XLEVI+RBT*TAN(ANGLE), YLEV5
write(*,10) N5I, XLEVI+RBT*TAN(ANGLE), YLEV5
write(*,10) N6I, XLEVI+(RCT+RBT)*TAN(ANGLE), YLEV6

write(*,10) N0J, XLEVJ, YLEV0
write(*,10) N1J, XLEVJ, YLEV1

ELSE

!! SMALL CRACK NODE DEFINITION

write(*,10) N0A, XLEVA, YLEV0
write(*,10) N1A, XLEVA, YLEV1
write(*,10) N2A, XLEVA, YLEV2
write(*,10) N3A, XLEVA, YLEV5
write(*,10) N5A, XLEVA, YLEV5
write(*,10) N6A, XLEVA, YLEV6

write(*,10) N0B, XLEVB, YLEV0
write(*,10) N1B, XLEVB, YLEV1
write(*,10) N2B, XLEVB, YLEV2
write(*,10) N3B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N5B, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N6B, XLEVB+(RH/XLEVB)*(RBT+RCT)*TAN(ANGLE), YLEV6

write(*,10) N0C, XLEVC, YLEV0
write(*,10) N1C, XLEVC, YLEV1
write(*,10) N2C, XLEVC, YLEV2
write(*,10) N3C, XLEVC+(RH/XLEVC)*RA*TAN(ANGLE), YLEV3
write(*,10) N0D, XLEVD, YLEV0
write(*,10) N1D, XLEVD, YLEV1
write(*,10) N2D, XLEVD, YLEV2
write(*,10) N3D, XLEVD, YLEV4
write(*,10) N4D, XLEVC+(RH/XLEVC)*RA*TAN(ANGLE), YLEV3
write(*,10) N5D, XLEVB+(RH/XLEVB)*RBT*TAN(ANGLE), YLEV5
write(*,10) N0F, XLEVF, YLEV0
write(*,10) N1F, XLEVF, YLEV1
write(*,10) N2F, XLEVF, YLEV2
write(*,10) N3F, XLEVF, YLEV4
write(*,10) N4F, XLEVI+RA*TAN(ANGLE), YLEV3
write(*,10) N5F, XLEVI+RBT*TAN(ANGLE), YLEV5
write(*,10) N0H, XLEVI, YLEV0
write(*,10) N1H, XLEVI, YLEV1
write(*,10) N2H, XLEVI, YLEV2
write(*,10) N3H, XLEVI+RA*TAN(ANGLE), YLEV3
write(*,10) N5H, XLEVI+RBT*TAN(ANGLE), YLEV5
write(*,10) N6H, XLEVI+(RBT+RCT)*TAN(ANGLE), YLEV6

ENDIF

10 format(2X,I10,',' ,1PD18.8,',' ,1PD18.8)
20 format(2X,I10,',' ,I10,',' ,I10)

c DEFINE NODE SETS FOR LARGE CRACK CASE

IF (RA.GT.RBT) THEN

C COATING LAYER
C REGION 1B

write(*,*) '***FILM LAYER NODES'
write(*,*) '*GEN, NSET=EDGEBA'
write(*,20) N2A, N3A, 1000

212
write(*,*) ' *NGEN, NSET=EDGEBB'
write(*,20) N2B, N3B, 1000
write(*,*) ' *NFILL, NSET=REG1B, BIAS=1.25'
write(*,30) 2*IEH, 1
format(2x,'EDGEBA, EDGEBB, ',I6,',' ,I4)

C * REGION 2B

write(*,*) ' *NGEN, NSET=EDGEBD'
write(*,20) N2D, N3D, 1000
write(*,*) ' *NFILL, NSET=REG2B, BIAS=1.25'
write(*,31) 2*IINC, 1
format(2x,'EDGEBB, EDGEBD, ',I6,',' ,I4)

C * REGION 3B

write(*,*) ' *NGEN, NSET=EDGEBF'
write(*,20) N2F, N3F, 1000
write(*,*) ' *NFILL, NSET=REG3B'
write(*,32) 4*IEHB, 1
format(2x,'EDGEBD, EDGEBF, ',I6,',' ,I4)

C * REGION 4B

write(*,*) ' *NGEN, NSET=EDGEBH'
write(*,20) N2H, N3H, 1000
write(*,*) ' *NFILL, NSET=REG4B, BIAS=0.8'
write(*,33) 2*IINC, 1
format(2x,'EDGEBF, EDGEBH, ',I6,',' ,I4)

C * REGION 5B

write(*,*) ' *NGEN, NSET=EDGEBI'
write(*,20) N2I, N3I, 1000
write(*,*) ' *NFILL, NSET=REG5B, BIAS=0.8'
write(*,34) 2*IEHB, 1
format(2x,'EDGEBI, EDGEBH, ',I6,',' ,I4)

C * REGION 6B

write(*,*) ' *NGEN, NSET=EDGB63'
write(*,20) N3D,N3F,1
write(*,*) ' *NGEN, NSET=EDGB64'
write(*,20) N4D, N4F, 1
write(*,*) ' *NFILL, NSET=REG6B, BIAS=0.8'
write(*,35) 2*IINC, 1000
format(2x,'EDGB63, EDGB64, ',I6,',' ,I4)

C * Extra node sets for equations and BCUs

write(*,*) ' *NSET, NSET=NEXTB'
write(*,20) N2E, N2E-1, 1
write(*,*) ' *NSET, NSET=CRACK'
write(*,20) N2E,N2E, 0
write(*,*) ' *NSET, NSET=BOTLYB, GENERATE'
write(*,20) N2A,N2E, 1
write(*,*) 'NSET,NSET=TOPLYB,GENERATE'
write(*,20) N3A,N3B-1,1
write(*,20) N4D+1, N4F-1,1
write(*,20) N3H+1, N3I, 1

write(*,*) 'NSET,NSET=RGHTB,GENERATE'
if (backing.eq.'y') then
  write(*,20) N2A,N3A-1000,1000
else
  write(*,20) N2A,N3A,1000
endif

C BASE LAYER NODE

if (base.eq.'y') then
C
*REGION 1A

write(*,*) '**BASE LAYER NODES'
write(*,*) 'NGEN,NSET=EDGEAA'
write(*,20) NOA, N1A, 1000
write(*,*) 'NGEN,NSET=EDGEAB'
write(*,20) NOB, N1B, 1000
write(*,*) 'NFILL,NSET=REG1A,BIAS=1.25'
write(*,36) 2*IEH,1
36 format(2x,'EDGEAA, EDGEAB, ',I6,',' ,I4)

C
*REGION 2A

write(*,*) 'NGEN,NSET=EDGEAD'
write(*,20) NOD, N1D, 1000
write(*,*) 'NFILL,NSET=REG2A,BIAS=1.25'
write(*,37) 2*IEHC,1
37 format(2x,'EDGEAD, EDGEAD, ',I6,',' ,I4)

C
*REGION 3A

write(*,*) 'NGEN,NSET=EDGEAF'
write(*,20) NOF, N1F, 1000
write(*,*) 'NFILL,NSET=REG3A'
write(*,38) 4*IEHB,1
38 format(2x,'EDGEAD, EDGEAF, ',I6,',' ,I4)

C
*REGION 4A

write(*,*) 'NGEN,NSET=EDGEAH'
write(*,20) NOH, N1H, 1000
write(*,*) 'NFILL,NSET=REG4A,BIAS=0.8'
write(*,39) 2*INC,1
39 format(2x,'EDGEAH, EDGEAH, ',I6,',' ,I4)

C
*REGION 5A

write(*,*) 'NGEN,NSET=EDGEAI'
write(*,20) NOI, N1I, 1000
write(*,*) 'NFILL,NSET=REG5A,BIAS=0.8'
write(*,40) 2*1EH2,1

214
format(2x,'EDGECB', 'EDGECH', ',I6,', ',I4)

C

write(*,*) 'STOP'
write(*,*) 'END OF PROGRAM'

END

215
write(*,20) N5A, N5I, 1
write(*,*) '**NSET, NSET=RGHTC, GENERATE'
write(*,20) N5A,N6A,1000
endif
write(*,*) '**NSET, NSET=ALLNDS'
write(*,*) ' REG1B,REG2B,REG3B,REG4B,REG5B,REG6B'
if (base.eq.'y') then
  write(*,*) ' REG1A,REG2A,REG3A,REG4A,REG5A,REG6A'
  write(*,*) ' 99991, 99992'
endif
if (backing.eq.'y')
  write(*,*) ' REG1C,REG2C,REG3C'
C ****SMALL CRACK NODE SET DEFINITIONS****
ELSE
C DEFINE LAYER B NODE SETS FOR SMALL CRACK CASE
C COATING NODE REGIONS
C
*REGION 1B
write(*,*) '**COATING NODES'
write(*,*) '**NGEN, NSET=EDGEBA'
write(*,20) N2A, N3A, 1000
write(*,*) '**NGEN, NSET=EDGEBB'
write(*,20) N2B, N3B, 1000
write(*,*) '**NFILL, NSET=REG1B,BIAS=1.25'
write(*,130) 2*IEH,1
130 format(2x,'EDGEBA, EDGEBB, ',I6,'','I4)
C
*REGION 2B
write(*,*) '**NGEN, NSET=EDGEBC'
write(*,20) N2C, N3C, 1000
write(*,*) '**NFILL, NSET=REG2B,BIAS=1.25'
write(*,131) 2*IOTC,1
131 format(2x,'EDGEBB, EDGEBC, ',I6,'','I4)
C
*REGION 3B
write(*,*) '**NGEN, NSET=EDGEBD'
write(*,20) N2D, N3D, 1000
write(*,*) '**NFILL, NSET=REG3B,BIAS=1.25'
write(*,132) 2*INHC,1
132 format(2x,'EDGEBC, EDGEBD, ',I6,'','I4)
C
*REGION 4B
write(*,*) '**NGEN, NSET=EDGEBF'
write(*,20) N2F, N3F, 1000
write(*,*) '**NFILL, NSET=REG4B'
write(*,133) 4*IEHB,1
format(2x, 'EDGEBD, EDGEBF, ', i6, ',', i4)

*REGION 5B
write(*,*) 'NGEN, NSET=EDGEBH'
write(*,20) N2H, N3H, 1000
write(*,*) 'NFILL, NSET=REG5B, BIAS=0.8'
write(*,134) 2*IINC, 1
format(2x, 'EDGEBF, EDGEBH, ', i6, ',', i4)

*REGION 6B
write(*,*) 'NGEN, NSET=EDGB63'
write(*,20) N3D, N3F, 1
write(*,*) 'NGEN, NSET=EDGB64'
write(*,20) N4D, N4F, 1
write(*,*) 'NFILL, NSET=REG6B, BIAS=0.8'
write(*,135) 2*IINC, 1000
format(2x, 'EDGB63, EDGB64, ', i6, ',', i4)

*REGION 7B
write(*,*) 'NGEN, NSET=EDGB65'
write(*,20) N5D, N5F, 1
write(*,*) 'NFILL, NSET=REG7B, BIAS=0.8'
write(*,1361) 2*IOTC, 1000
format(2x, 'EDGB64, EDGB65, ', i6, ',', i4)

*Extra node sets for equations and BC's
write(*,*) 'NSET, NSET=NEXTB'
write(*,20) N2E, N2E-1, 1
write(*,*) 'NSET, NSET=CRACK'
write(*,20) N2E, N2E, 0
write(*,*) 'NSET, NSET=BOTLYB, GENERATE'
write(*,20) N2A, N2E, 1
write(*,*) 'NSET, NSET=TOPLYB, GENERATE'
write(*,20) N3A, N3B-1, 1
write(*,20) N5D+1, N5F-1, 1
write(*,*) 'NSET, NSET=RHTYB, GENERATE'
if (backing.eq.'y') then
  write(*,20) N2A, N3A-1000, 1000
else
  write(*,20) N2A, N3A, 1000
endif

BASE LAYER NODE SETS
if (base.eq.'y') then

*REGION 1A
write(*,*) 'NGEN, NSET=EDGEAA'

217
write(*,20) N0A, N1A, 1000
write(*,*) '*NGEN, NSET=EDGEAB'
write(*,20) N0B, N1B, 1000
write(*,*) '*NFILL, NSET=REG1A, BIAS=1.25'
write(*,136) 2*IEH, 1
format(2x,'EDGEAA, EDGEAB, ',I6,',',I4)

C  *REGION 2A

write(*,*) '*NGEN, NSET=EDGEAC'
write(*,20) N0C, N1C, 1000
write(*,*) '*NFILL, NSET=REG2A, BIAS=1.25'
write(*,137) 2*IOTC, 1
format(2x,'EDGEAB, EDGEAC, ',I6,',',I4)

C  *REGION 3A

write(*,*) '*NGEN, NSET=EDGEAD'
write(*,20) N0D, N1D, 1000
write(*,*) '*NFILL, NSET=REG3A, BIAS=1.25'
write(*,138) 2*IINC, 1
format(2x,'EDGEAC, EDGEAD, ',I6,',',I4)

C  *REGION 4A

write(*,*) '*NGEN, NSET=EDGEAF'
write(*,20) N0F, N1F, 1000
write(*,*) '*NFILL, NSET=REG4A'
write(*,139) 4*IEHB, 1
format(2x,'EDGEAF, EDGEAD, ',I6,',',I4)

C  *REGION 5A

write(*,*) '*NGEN, NSET=EDGEAH'
write(*,20) N0H, N1H, 1000
write(*,*) '*NFILL, NSET=REG5A, BIAS=0.8'
write(*,140) 2*IINC, 1
format(2x,'EDGEAF, EDGEAH, ',I6,',',I4)

C  *REGION 6A

write(*,*) '*NGEN, NSET=EDGEAJ'
write(*,20) N0J, N1J, 1000
write(*,*) '*NFILL, NSET=REG6A, BIAS=0.8'
write(*,141) 2*IEH3, 1
format(2x,'EDGEAH, EDGEAJ, ',I6,',',I4)

C  Extra Node Sets for BCs

write(*,*) '*NSET, NSET=TOPLYA, GENERATE'
write(*,20) N1A+1,N1E, 1

write(*,*) '*NSET, NSET=BOTLYA, GENERATE'
write(*,20) N0A, N0J, 1

write(*,*) '*NSET, NSET=NEXTA'
write(*,*) N1E,',',', N1E-1
write(*,*) '"NSET,NSET=RGHTA,GENERATE'
write(*,20) N0A,N1A-1000,1000
dend

C *BACKING LAYER NODE SETS FOR SMALL CRACK CASE
if (backing.eq.'y') then
*
*REGION 1C
write(*,*) '"BACKING LAYER NODES'
write(*,*) '"NGEN,NSET=EDGECA'
write(*,20) N5A, N6A, 1000
write(*,*) '"NGEN,NSET=EDGECB'
write(*,20) N5B, N6B, 1000
write(*,*) '"NFILL,NSET=REG1C,BIAS=1.25'
write(*,242) 2*IEH,1
242 format(2x,'EDGECA, EDGECB, ',I6,' ',I4)

C *REGION 2C
write(*,*) '"NGEN,NSET=EDGECH'
write(*,20) N5H, N6H, 1000
write(*,*) '"NFILL,NSET=REG2C'
write(*,243) 4*IEH,1
243 format(2x,'EDGECH, EDGECH, ',I6,' ',I4)
write(*,*) '"NSET,NSET=BOTLYC,GENERATE'
write(*,20) N5A, N5H, 1
write(*,*) '"NSET,NSET=RGHTC,GENERATE'
write(*,20) N5A,N6A,1000
dend
write(*,*) '"NSET,NSET=ALLNDS'
write(*,*) '"REG1B,REG2B,REG3B,REG4B,REG5B,REG6B,REG7B'
if (base.eq.'y')
+ write(*,*) '"REG1A,REG2A,REG3A,REG4A,REG5A,REG6A'
+ write(*,*) '"REG1C,REG2C'
write(*,*) '"NSET,NSET=DUMMY'
write(*,*) '", IDUM,'','
ENDIF
write(*,*) '"NSET,NSET=CREDG,GENERATE'
write(*,20) N2E,NLAST,1

C Write Out Element Information

C Define Key Elements
if (geotype.ne.'e') then
  if (mattype.eq.'p') then
    write(*,*) '"ELEMENT,TYPE=CAX8R'
else
  write(*,'*') '*ELEMENT,TYPE=CAX8R'
endif
else
  if (mattype.eq.'p') then
    write(*,'*') '*ELEMENT,TYPE=CPE8R'
  else
    write(*,'*') '*ELEMENT,TYPE=CPE8R'
  endif
endif
KEL0A = 1
if (base.eq.'y') then
  write(*,50) KEL0A, NOA+2, NOA, NOA+2000, NOA+2002, NOA+1,
              NOA+1000, NOA-2001, NOA+1002
endif
KEL5A = 1+(IEVA+IEVB+1)*1000
if (backing.eq.'y') then
  write(*,50) KEL5A, N5A+2, N5A, N5A+2000, N5A+2002, N5A+1,
              N5A+1000, N5A+2001, N5A+1002
endif
KEL2A = 1+(IEVA+1)*1000
write(*,50) KEL2A, N2A+2, N2A, N2A+2000, N2A+2002, N2A+1,
            N2A+1000, N2A+2001, N2A+1002
KEL3D = 90001
write(*,50) KEL3D, N3D+2, N3D, N3D+2000, N3D+2002, N3D+1,
            N3D+1000, N3D+2001, N3D+1002
50 format(2x,I6,'.',',',I6,'.',',',I6,'.',',',I6,'.',',',I6,'.',',',I6,'.',',',I6,'.',',',I6,'.',',',I6)
c Generate Elements
if (RA.GT.RBT) then
  if (geotype.eq.'e') then
    IELA = IEH + 2*IINC + 2*IEHB + IEH2
  else
    IELA = IEH + 2*IINC + 2*IEHB + IEH2 + IEH3
  endif
  IELB = IEH + 2*IINC + 2*IEHB + IEH2
  IELB2 = IINC
  IELC = IEH + 2*IEHB + IEH2
else
  if (geotype.eq.'e') then
    IELA = IEH + IOTC + 2*IINC + 2*IEHB
  else
    IELA = IEH + IOTC + 2*IINC + 2*IEHB + IEH2
  endif
  IELB = IEH + IOTC + 2*IINC + 2*IEHB
  IELB2 = IOTC + IINC
  IELC = IEH + 2*IEHB
endif

if (base.eq.'y') then
  write(*,*) '*ELGEN,ELSET=LYAELS'
  write(*,61) KEL0A, IELA, 2, 1, IEVA, 2000, 1000
endif

if (backing.eq.'y') then
  write(*,*) '*ELGEN,ELSET=LYCELS'
  write(*,61) KEL5A, IELC, 2, 1, IEVC, 2000, 1000
endif

write(*,*) '*ELGEN,ELSET=LYBEL1'
write(*,61) KEL2A, IELB, 2, 1, IEVB, 2000, 1000

write(*,*) '*ELGEN,ELSET=LYBEL2'
write(*,61) KEL3D, 2*IEHB, 2, 1, IELB2, 2000, 1000

61 format(2x,I6,','I6,','I6,','I6,','I6,','I6,','I6,','I6,'I6)

write(*,*) '*ELSET,ELSET=LYBELS'
write(*,*) 'LYBEL1, LYBEL2,'

write(*,*) '*ELSET,ELSET=ALLELS'
write(*,*) 'LYBELS,'
if (base.eq.'y') then
  write(*,*) 'LYAELS,'
endif
if (backing.eq.'y') then
  write(*,*) 'LYCELS,'
endif

c Material Information

write(*,*) '*SOLID SECTION,ELSET=LYBELS,MATERIAL=FLIM'
write(*,*) '*MATERIAL,NAME=FLIM'
write(*,*) '*ELASTIC,TYPE=ISOFRIC'  
write(*,64) bmodulus, brnu

64 format(2x,0PD12.4,','F9.4)
if (filmla.eq.'y') then
  write(*,*) '*PLASTIC'  
  write(*,64) byield, 0.0
  write(*,64) bstressmax, bstrainmax
endif

write(*,*) '*EXPANSION,TYPE=ISO'
write(*,65) bexpansion

65 format(2x,1PD12.4,'')

if (base.eq.'y') then
  write(*,*) '*SOLID SECTION,ELSET=LYAELS,MATERIAL=BASE'
  write(*,*) '*MATERIAL,NAME=BASE'
  write(*,*) '*ELASTIC,TYPE=ISOFRIC'  
  write(*,64) amodulus, arnu
if (basepl.eq.'y') then
  write(*,*) '*PLASTIC'  
  write(*,64) ayield, 0.0
  write(*,64) astressmax, astrainmax
endif
write(*,*) ' *EXPANSION,TYPE=ISO'
write(*,65) aexpansion
endif

if (backing.eq.'y') then
write(*,*) ' *SOLID SECTION,ELSET=LYCELS,MATERIAL=BACK'
write(*,*) ' *MATERIAL,NAME=BACK'
write(*,*) ' *ELASTIC,TYPE=ISOTROPIC'
write(*,64) cmodulus, crnu
if (backpla.eq.'y') then
write(*,*) ' *PLASTIC'
write(*,64) cyield, 0.0
write(*,64) cstressmax, cstrainmax
endif
write(*,*) ' *EXPANSION,TYPE=ISO'
write(*,65) cexpansion
endif

c Boundary Conditions

write(*,*) ' *MPC'
if (RA.GT.RBT) then    ! Tie Reg 6 & 7 to body
  do 201 i=0,2*IINC-1
    write(*,'(*** TIE',2('','',i9))') N4D-i*1000,N3B+i
  201 continue
  do 202 i=1,2*IINC
    write(*,'(*** TIE',2('','',i9))') N3F+i, N3F+i*1000
  202 continue
  if (backing.eq.'y') then    ! Tie top of Coat to Back
    do 203 i=0,2*IEH
      write(*,'(*** TIE',2('','',i9))') N3A+i,N5A+i
    203 continue
    do 204 i = 1, 4*IEHB
      write(*,'(*** TIE',2('','',i9))') N4D+i,N5B+i
    204 continue
    do 205 i = 1, 2*IEH2
      write(*,'(*** TIE',2('','',i9))') N3H+i,N5H+i
    205 continue
  endif if (base.eq.'y') then    ! Tie top of Coat to Base
    do 206 i=0,2*IEH+2*IINC+2*IEHB-2
      write(*,'(*** TIE',2('','',i9))') N1A+i,N2A+i
    206 continue
  endif else    ! Small Crack BCs
    do 207 i=0,2*IINC+2*IOTC-1
      write(*,'(*** TIE',2('','',i9))') N3B+i,N5D-i*1000
    207 continue
    do 208 i=1,2*IINC
      write(*,'(*** TIE',2('','',i9))') N3F+i,N3F+i*1000
    208 continue
    if (backing.eq.'y') then    ! Tie top of Coat to Back
      do 209 i=0,2*IEH-1
        write(*,'(*** TIE',2('','',i9))') N3A+i,N5A+i
      209 continue
      write(*,'(*** TIE',2('','',i9))') N4D, N5B
      do 210 i = 1, 4*IEHB
        write(*,'(*** TIE',2('','',i9))') N4D+i,N5B+i
  210 continue

continue
endif
if (base.eq.'y') then        !Tie top of Coat to Base
do 212 i=0,2*IEH + 2*IINC+2*IEHB - 2
    write(*,'('' TIE'','2('','','i9))') N1A+i,N2A+i
212 continue
endif
endif

c Need to Write Equation to Output RF's from Dummy Nodes
if (base.eq.'y') then
    write(*,'*EQUATION'
    write(*,' 3'
    write(*,213) N2E, 1, -1, N1E, 1, 1, 99991, 1, 1
    write(*,213) N2E, 2, -1, N1E, 2, 1, 99991, 2, 1
    write(*,' 3'
    write(*,213) N2E-1, 1, -1, N1E-1, 1, 1, 99992, 1, 1
    write(*,' 3'
    write(*,213) N2E-1, 2, -1, N1E-1, 2, 1, 99992, 2, 1
endif
213 format(1x,9(I5,',',''))
c Enter Starting conditions
if ((inititype.eq.'t').or.(inititype.eq.'T')) then
    write(*,'*INITIAL CONDITIONS,TYPE=TEMPERATURE'
    write(*,' ALLNDS',',',rinitial
else
    write(*,'*INITIAL CONDITION,TYPE=STRESS'
    write(*,'(ALLELS',',4(',','','e10.3),')
1 rinitial,0.0,rinitial,0.0
endif
c Step Information COOL DOWN or STRESS
if (matttype.ne.'p') then
    write(*,'*STEP'
    write(*,'*STATIC'
else
    write(*,'*STEP,NLGEOM,MONOTONIC,INC=50'
    write(*,'*STATIC'
endif
write(*,'*BOUNDARY,OP=NEW'
c write(*,'*TOPLYB, PINNED'
write(*,'*RGHTB, XSYM'
if (base.eq.'y') then
    write(*,'*BOTLYA, PINNED'
    write(*,'*RGHTA, XSYM'
    write(*,' 99991, PINNED'
    write(*,' 99992, PINNED'
else
    write(*,'*EDGEAI, XSYM'
endif
else
    write(*,*) ' BCTLYB, PINNED'
endif
if (backing.eq.'y') then
    write(*,*) ' RGHTC, XSYM'
endif
if ((inittype.eq.'t').or.(inittype.eq.'T')) then
    write(*,*) ' *TEMPERATURE'
    write(*,*) ' ALLNDS, 0.0'
endif
write(*,*) ' *J-INTEGRAL, COUNTOUR=7, OUTPUT=BOTH'
write(*,*) ' 0.,1.'
write(*,*) ' CRACK'
write(*,*) ' *EL FILE, FREQ=1, POSITION=AVERAGED AT NODES'
write(*,*) ' S'
write(*,*) ' SINV'
write(*,*) ' EE'
write(*,*) ' *EL PRINT, POSITION=NODES'
write(*,*) ' S, MISES'
write(*,*) ' *NODE FILE, FREQ=1'
write(*,*) ' U'
write(*,*) ' RF'
write(*,*) ' *ENERGY FILE, FREQ=1'
write(*,*) ' ALLEN'
write(*,*) ' *ENERGY PRINT, FREQ=1'
write(*,*) ' ALLEN'
write(*,*) ' *NODE PRINT, NSET=CREDG, FREQ=1'
write(*,*) ' COORD, U, RF'
write(*,*) ' *NODE PRINT, NSET=BCTLYB, FREQ=1'
write(*,*) ' COORD, RF'
write(*,*) ' *ENDSTEP'
end

Post
PROGRAM POSTPROC
C
C Copyright Ed Shaffer 1995
C implicit double precision (a-h,o-z)
C
dimension ARRAY(513), JRAY(2,513), LRUNIT(2,1)
dimension KEYS(513), KEYTOT(513)
dimension IREC(6), IARR(6), ITVAL(6), ICH(6), IVAL(6,4000)
CHARACTER*1 GEOTYPE
CHARACTER*80 FNAME, FNAMES, FNAMEP
CHARACTER*80 OUTDIR, TMPDIR, RESNAM, FILNAM, INDIR
CHARACTER*80 SUPNAM(20)
C
C DIMENSION VAL(6,4000)
EQUIVALENCE (ARRAY(1), JRAY(1,1))
data rx, rx2, dx1a, dx2a, dy1a, dy2a, dx1b, dx2b, dy1b, dy2b
1 /0.,0.,0.,0.,0.,0.,0.,0.,0.,0./
C
C COMMON BLOCK FOR VERSION 4.9
COMMON/JOBPAR/FNAME ! ABAQUS 4.9

READ(5,60) FNAME
READ(5,61) GEOTYPE
READ(5,*) IRPT
IF (IRPT.EQ.1) READ(5,*) VAR1
IF (IRPT.EQ.2) READ(5,*) VAR1,VAR2

60 FORMAT(A)
61 FORMAT(A1)
NRU = 1
LRUNIT(1,NRU) = 8
LRUNIT(2,NRU) = 2
LOUTF = 0

C
OUTDIR=''
OPEN(UNIT=15,STATUS='unknown',FILE='REPORT')
CALL INITPF (FNAME, NRU, LRUNIT, LOUTF )
C
INFO=1
ICOL=0

C C INITIALIZE LOTS OF VARIABLES
C
DO 10 I=1,6
  IREC(I)=0
  IARR(I)=0
  ITVAL(I)=0
  ICH(I)=1
10 CONTINUE
DO 20 I=1,200
  KEYS(I)=0
  KEYTOT(I)=0
20 CONTINUE
ISUM = 0
ITYP=1
KEYS(ITYP)=1921
IINC=0
JUNIT = 8
C
JUNIT = LRUNIT(1,NRU)
CALL DBRNU ( JUNIT )

C==============================================================================================================
C READ DATA RECORD
C==============================================================================================================
C
READ(*,*) NTIPA,NTIPB, Rhole, NLST, Gmax
write(*,*) NTIPA,NTIPB, Rhole, NLST, Gmax
N1A = NTIPA + 1
N1B = NTIPB + 1
N2A = NTIPA + 2
N2B = NTIPB + 2
N3A = NTIPA - 1
N3B = NTIPB - 1
N0A = NTIPA
N0B = NTIPB
DO 100 k1 = 1,99999
  CALL DBFILE(0, ARRAY, JRCD)
  IF (JRCD.NE.0)goto 999
   !make sure not at end of file
   !Record Key See 10.1.1-1
   KEY = JRRAY(1,2)
   if (KEY.eq.2000) then
      time = ARRAY(3)
      istep = JRRAY(1,8)
   endif
   if (KEY.eq.101) then
      NNODE = JRRAY(1,3)
   endif
   write(6,'(2(i5,1x),2(e12.5,1x))')
   k1,NNODE,ARRAY(4),ARRAY(5)
   if (NNODE.eq.N1A) then
      DX1A = ARRAY(4)
      DY1A = ARRAY(5)
   endif
   if (NNODE.eq.N1B) then
      DX1B = ARRAY(4)
      DY1B = ARRAY(5)
   endif
   if (NNODE.eq.N2A) then
      DX2A = ARRAY(4)
      DY2A = ARRAY(5)
   endif
   if (NNODE.eq.N2B) then
      DX2B = ARRAY(4)
      DY2B = ARRAY(5)
   endif
   if (NNODE.eq.N0B) then
      DX1TIP = ARRAY(4)
      DY1TIP = ARRAY(5)
   endif
   if (NNODE.eq.NLST) then
      DXLST = ARRAY(4)
      DYLST = ARRAY(5)
   endif
   endif
   if (KEY.EQ.104) then
      !Get Reaction Forces in Step 1
      if(NNODE.eq.N0B) then
         RF2X = ARRAY(4)
         RF2Y = ARRAY(5)
      endif
      if(NNODE.eq.N3B) then
         RF1X = ARRAY(4)
         RF1Y = ARRAY(5)
      endif
   endif
   if (KEY.EQ.1901) then
      !NODAL COORDINATE in X of NEXT NODE
      NNODE = JRRAY(1,3)
      if (NNODE.eq.N0B) then
RX = ARRAY(4),
endif
if (NNODE.eq.N1B) then
   RX1 = ARRAY(4)
endif
if (NNODE.eq.N2B) then
   RX2 = ARRAY(4)
endif
endif
if (KEY.eq.1991) then    ! J-INTEGRAL
   nj = JRAY(1,5) - 2
   Gf romJ = 0.
   do i = 1,nj
      Gf romJ = Gf romJ + ARRAY(6+i)
   end do
   Gf romJ = Gf romJ/real(nj)
   Gf romJ = Gf romJ*1.e-3
   Gdev = 0.d0
   do i = 1,nj
      Gdev = Gdev + (ARRAY(6+i)-Gf romJ)**2
   end do
   Gdev = dsqrt(Gdev/5.)
   Gdev = Gdev/Gf romJ
end if
100 CONTINUE
999 CONTINUE
rad = RX
da = RX2 - RX
if (geotype.eq.'e') rad = 0.159155
write(*,*) da, rad
DX1 = DX1B-DX1A
DX2 = DX2B-DX2A
DY1 = DY1B-DY1A
DY2 = DY2B-DY2A
GI = (RF1Y*DY1 + RF2Y*DY2)/(12566.4*da*rad)
GII = (RF1X*DX1 + RF2X*DX2)/(12566.4*da*rad)

rmix = atan(sqrt(GII/GI))*180.0/3.141592

da = da*1.0e4
DX1 = DX1*1.0e4
DY1 = DY1*1.0e4
DX2 = DX2*1.0e4
DY2 = DY2*1.0e4
RF1X = RF1X*0.1
RF1Y = RF1Y*0.1
RF2X = RF2X*0.1
RF2Y = RF2Y*0.1
GTOT = GI + GII
write(*,21) Gmax
write(*,22) fname, GI, GII, GTOT, rmix,Gf romJ
if (irpt.eq.1) write(15,23) fname, var1, GI, GII, GTOT,rmix,Gf romJ
1
   if (irpt.eq.2) + write(15,24) fname, var1,var2, GI, GII, GTOT,rmix,Gf romJ
   c   if (irpt.eq.3) c + write(15,25) fname,var1,var2,var3, GI, GII, GTOT
   c   if (irpt.eq.4) c
write(15,26) fname, var1, var2, var3, var4, GI, GII, GTOT
write(*,22) 'Node1: ', DX1, DY1, RF1X, RF1Y, GfromJ
write(*,22) 'Node2: ', DX2, DY2, RF2X, RF2Y, Gdev

21 FORMAT(' Calculated Maximum G = ',1PE12.4)
22 FORMAT(1x,a8,' ',5(' ',1PE10.3))
23 FORMAT(1x,a8,6(1x,1PE10.3))
24 FORMAT(1x,a8,7(1x,1PE9.2))
25 FORMAT(1x,a8,6(' ',1PE12.4))
26 FORMAT(1x,a8,7(' ',1PE12.4))

end
APPENDIX C: EXAMPLE ANALYSIS SHEET FOR EDT DATA

The measured optical data and the calculated debond energy, G, are listed for sample D-CR-12-71-10 Cyclotene 3022 on copper. The debond energy is calculated using the finite element model described in Chapter 2.

Film Height: 14.3 μm  
Young's Modulus: 2.08 GPa  
Poisson's Ratio: 0.35  
No Plasticity  
Via Angle is: 50.00  
Residual Stress: 36 MPa

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<th>File</th>
<th>Debond, μm</th>
<th>Radius, μm</th>
<th>G, J/m²</th>
<th>StDev</th>
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BIOGRAPHICAL NOTE

Edward Otto Shaffer II was born in Tampa, FL on May 4, 1964 to Ed and Bonnie Shaffer. In 1975, the Shaffer’s migrated north to the suburbs of Chicago after his father’s Ph.D. graduation. In the Shaffer family, both parents preached the power of education in both their words and deeds. Bonnie, a music teacher for over thirty years, has a masters degree and Ed, a superintendent of schools, has a Ph.D. With this backdrop, the younger Ed and his two brothers David and Philip were taught the true value of education. All three brothers obtained their bachelor’s of science degrees at the University of Illinois, Urbana.

Ed first started at the University of Illinois in 1982. He graduated in 1986 with a B.S. of Ceramic Engineering. While there, he took many polymer related courses which eventually led him to Northwestern University, Evanston, IL where he studied with Pr. Monica Olvera de la Cruz. His time their was spent pursuing his master’s of science degree on 'The Dynamics of Gel Electrophoresis'. And, while not pursuing that, he was pursuing the greatest love of his life - Linda Tranovich. Ed received his M.S. in Materials Science and Engineering in 1988. In 1989, he received his greatest award the hand of Miss Linda Tranovich. Ed and Linda were married on May 6, 1989. (A date conveniently chosen by his new wife so he could never forget it, as if he would).

Fresh out of Northwestern, Ed joined 'The Dow Chemical Company in August of 1988. He and Linda moved to the great metropolis of Midland and began to make a wonderful life for themselves - buying the house, getting a dog and most joyously having a son, Edward Otto Shaffer III, March 27, 1990 followed of course with a beautiful daughter, Elizabeth Anne Shaffer, April 23, 1991.

Ed continued to work for Dow in their Central Research Materials Science Group. His research spanned the spectrum of polymer science from rheological and phasic behavior of liquid crystalline polymers to ultrasonic testing of polymer engineering constants. However, Ed’s ambition to obtain a Ph.D. continued to grow. With the patience of a saint and the love of a good wife, Linda agreed to go east to find the families future. This move was facilitated by Linda’s growing career at Dow which allowed her to transfer to the Boston sales office. The Shaffer’s arrived in Boston in September of 1992. Without much fanfare and more than enough headaches, they transitioned the family to their new life. Ed set about with his studies and Linda made sure that the family was well tended. Nearing the completion of his dissertation Ed decided to go for broke (literally) with the birth of his third child Zachary Reed Shaffer, January 17, 1995. The stage is now set. With the Ph.D. soon in hand the Shaffer’s are headed back to Midland where they both can continue their careers for Dow and the family.