11:47:45 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 09/05/96

Active

Project #: E-25-T75 Cost share #: Rev #: 2
Center # : 10/24-6-R8623-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: AGREEMENT DATED 950724 Mod #: ADMINISTRATIVE Document : AGR
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA:
Main project #: PE #:

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
SITARAMAN S K MECH ENGR (404)894-3405

Sponsor/division names: ARCHISTRAT TECHNOLOGIES / BOCA RATON, FL
Sponsor/division codes: 200 / 139

Award period: 950801 to 961231 (performance) 961231 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	39,920.00
Funded	0.00	39,920.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: THERMAL STRESS & FATIGUE LIFE PREDICTION FOR A VSPA PACKAGE

PROJECT ADMINISTRATION DATA

OCA contact: Anita D. Rowland 894-4820

Sponsor technical contact	Sponsor issuing office
MARIA M. PORTUONDO, VP ENGINEERING	SAME
(407)994-2300	(407)994-2300

ARCHISTRAT TECHNOLOGIES
A DIVISION OF THE PANDA PROJECT
5201 CONGRESS AVENUE, STE C-100
BOCA RATON, FL 33487

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A N/A supplemental sheet
Equipment title vests with: Sponsor GIT X
NONE PROPOSED
Administrative comments -
SPONSOR'S 9.5.96 NOTIFICATION AWARDS A NCE THRU 12.31.96 AT "FIXED PRICE"
(PAID IN FULL/ADVANCE)

PROJECT CLOSEOUT - NOTICE

Closeout Notice Date 10-MAR-1997

Project Number E-25-T75 Doch Id 37513

Center Number 10/24-6-R8623-0A0

Project Director SITARAMAN, SURESH

Project Unit MECH ENGR

Sponsor ARCHISTRAT TECHNOLOGIES/BOCA RATON, FL

Division Id 3666

Contract Number AGREEMENT DATED 950724 Contract Entity GTRC

Prime Contract Number

Title THERMAL STRESS & FATIGUE LIFE PREDICTION FOR A VSPA PACKAGE

Effective Completion Date 31-DEC-1996 (Performance) 31-DEC-1996 (Reports)

Closeout Action:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	02-JUN-1995
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory and Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments

Distribution Required:	
Project Director/Principal Investigator	Y
Research Administrative Network	Y
Accounting	Y
Research Security Department	N
Reports Coordinator	Y
Research Property Team	Y
Supply Services Department	Y
Georgia Tech Research Corporation	Y
Project File	Y

NOTE: Final Patent Questionnaire sent to PDPI

E-25-T75
#1,2
(New)

THERMAL STRESS AND FATIGUE LIFE PREDICTION FOR A VSPA PACKAGE

FIRST QUARTER REPORT

Submitted by

Dr. Suresh K. Sitaraman
Assistant Professor
and
R. Sean Murphy
Graduate Research Associate

Computer-Assisted Simulation of Packaging Reliability (***CASPaR***) Lab
Packaging Research Center
Georgia Institute of Technology
Atlanta, GA

Voice: 404-894-3405
FAX: 404-894-9342
e-mail: suresh.sitaraman@me.gatech.edu

Submitted to

Archistrat Division
The Panda Project
Boca Raton, Florida

January 30, 1996

1.0 Project Description

The goal of this project is to maximize the fatigue life of the solder joints of a VSPA package attached to PWB. The fatigue life of the solder joints is dependent on, among other factors, the thermo-mechanical stresses/strains induced due to the mismatch in Coefficient of Thermal Expansion (CTE) among dissimilar materials in the packaging assembly. The thermo-mechanical stresses/strains are a function of ΔT (increase in temperature due to operating or fabricating conditions of the package), material properties (Thermal Properties, Elastic/Plastic/Creep Properties, Expansion Coefficient, etc.), and geometric parameters.

This project proposes to use Finite-Element Technique to achieve its objectives. In particular, this project aims to (i) find a sufficiently accurate model of solder material properties under varying temperatures, (ii) build a finite-element model of the package and solder joint, (iii) determine the expected stresses and strains in the solder joint and make an estimate of the fatigue life, and (iv) make design suggestions to improve solder joint reliability.

2.0 Project Progress and Milestones Achieved

1. Toured the Panda Project design and prototyping facilities in October 1995. Met with industry contacts, gathered information on the current design, identified specific project goals, and obtained a first-hand exposure to the prototype manufacturing process.

2. Began an extensive literature review of related research (*Please see Section 4.0*). There is very little information available in the public-domain research literature on butt-type solder joints; most research is on J- or gull-wing type leads. However, two papers have been found that examine the reliability of solder joints, including butt-type, using analytic methods. The methods in these papers are being used to provide some initial estimates of the VSPA fatigue life.

   Of the papers that deal with J and gull-wing leads, there are several that study the fatigue life of quad flat pack designs using finite-element analysis. Some of this research is identical to the initial analysis to be performed on VSPA.

   Also, initial study has been done on identifying a suitable solder joint geometry.

3. Began collecting the material properties for the VSPA components. Most of the necessary thermo-mechanical properties for the Plastic Substrate (Liquid Crystal Polymer), Contact Leads (Phosphor Bronze), Ground Plate (Beryllium Copper), Die Attach (for example, Ablebond 84), and Encapsulation (for example, Hysol FP) have been obtained from the Manufacturers. The temperature dependent stress-strain curves for eutectic Pb-Sn solder was obtained through the CINDAS (Center for Information and Numerical Data Analysis and Synthesis) material database, Purdue University, Indiana.

4. Built a 2-D plane strain finite element model of the package, solder joint, and board assembly (excluding the silicon die). An initial linear elastic analysis of this assembly was performed to verify the model and confirm that plastic deformation was imminent.

3.0 Project Goals for Second Quarter

1. Find a sufficiently accurate temperature dependent, visco-plastic model of eutectic Pb-Sn solder. This is necessary to accurately predict plastic strain and hence fatigue life.

2. Complete the non-linear finite-element simulations of the 2-D plane-strain model.

3. Make a fatigue life prediction from the estimated plastic strain in the solder joint using the Coffin-Manson law.

4. Refine the solder joint geometry and build a 3-D model to more accurately model the lead deformations.

4.0 Related Research

J. Lau, D. Rice, and S. Erasmus: Thermal Fatigue Life of 256-Pin, 0.4 mm Pitch Plastic Quad Flat Pack (QFP) Solder Joints
This research uses finite element analysis to determine the thermal stresses and plastic strains in QFP type packages. The Coffin-Manson law is then used to compute a predicted fatigue life. This research is nearly identical to the initial analysis to be performed on VSPA.

J. Lau, S. Erasmus: Reliability of Fine Pitch Plastic Quad Flat Pack Leads and Solder Joints Under Bending, Twisting, and Thermal Conditions
This paper uses finite element analysis to examine the effect of thermal stress and strain, along with the effects of circuit board bending and twisting, on the solder joints of a quad flat pack.

W. Chen: Analyzing the Mechanical Strengths of SMT Attached Solder Joints
This paper predicts the pull and shear strength of surface mount solder joints and provides some design guidelines for optimum pad/lead configurations and solder volume.

A. Yasukawa: A New Index S for Evaluating Solder Joint Thermal Fatigue Strength
This paper provides an analytic solution to fatigue life for various package geometries, including butt-type joints, under thermal cycling.

E-25-T75
#3

Thermal Fatigue Life of the VSPA™ Package Solder Joints

R. Sean Murphy
Graduate Research Assistant
and
Suresh K. Sitaraman
Assistant Professor
Computer-**A**ided **S**imulation of **Pa**ckaging **R**eliability (CASPaR) Laboratory
The George Woodruff School of Mechanical Engineering
Packaging Research Center
Georgia Institute of Technology
Atlanta, GA 30332-0405
Voice: 404-894-3405
FAX: 404-894-9342
e-mail: suresh.sitaraman@me.gatech.edu

John Bartoszek
The Panda Project
5201 Congress Avenue #C100
Boca Raton, Florida 33487

ABSTRACT

The objective of this work is to determine the thermo-mechanical reliability of the butt solder joints of the novel VSPA™ package under thermal cycling. This study models the package/solder joint/FR-4 assembly using plane-strain finite elements. The FR-4 and various package/lead materials were modeled with constant, linear elastic properties while the eutectic solder was modeled with temperature-dependent, elastic-plastic properties. The model was subjected to a temperature increase of 85 °C after which the plastic strains in the solder joints were calculated. An estimate of the fatigue life was then made based on these strains using the Coffin-Manson law with some corrections. These life estimates were then compared to the estimated solder joint lives of standard QFP designs.

NOMENCLATURE

VSPA	Panda Project semiconductor package
CTE	Coefficient of Thermal Expansion, α
QFP	Quad Flat Pack
PGA	Pin Grid Array
$\Delta\varepsilon$	total strain range
$\Delta\varepsilon^p$	plastic strain range
σ_f'	fatigue strength coefficient
b	fatigue strength exponent
ε_f'	fatigue ductility coefficient
c	fatigue ductility exponent
N_f	fatigue life (cycles)
θ	fatigue life coefficient
η	fatigue life exponent
ε^p_{eqv}	equivalent plastic strain
ε^p_x	plastic normal strain, x direction
ε^p_y	plastic normal strain, y direction
ε^p_z	plastic normal strain, z direction
γ^p_{xy}	plastic shear strain, xy plane
γ^p_{yz}	plastic shear strain, yz plane
γ^p_{zx}	plastic shear strain, xz plane

INTRODUCTION

The increasing need for higher pin counts and smaller sizes has led the Technologies division of the Panda Project to develop a novel electronic package: VSPA. As shown in Figure 1, this square package is a periphery array design which provides, in the current design under study, 336 surface mounted butt-type leads in three rows. This design is low-cost, reworkable, and uses standard industry fabrication techniques and materials, as well as standard placement machines and board attach processes.

Thermal fatigue, due to temperature cycling and the mismatch of coefficients of thermal expansion (CTE) in the package/solder joint/FR-4 assembly, is one of the most commonly observed modes of solder joint failure. Much research has been done in determining the fatigue life of Quad Flat Pack (QFP) gull-wing, J-type, and leadless chip carrier solder joints [1, 2, 3, 8, 9, 10, 11, 12]. Most of the research on butt-type joints has been done on Pin Grid Array (PGA) solder joints [3, 4, 8, 11]. VSPA represents a new challenge as it is a combination of periphery and array designs.

Similar to the study of the thermal fatigue life of the 208-Pin QFP done by Lau, et al. [2], this work employs the finite element method to determine the plastic strains and estimate the fatigue life of a middle VSPA package solder joint. While the results presented here were obtained using plane-strain finite elements, efforts are under way to develop a comprehensive 3D model.

OVERVIEW OF THE VSPA PACKAGE

The VSPA package consists of a copper heat spreader bordered by a frame of Vectra™, a liquid crystal polymer. The copper leads, which provide the electrical and mechanical attachment of the package to the FR-4, are embedded in this polymer frame. In typical use, a silicon die would be mounted to the copper plate with a thermally conductive adhesive and electrical connections would be made from the die pads to the copper leads by wire bonding. The underside would then be encapsulated with an epoxy material, and the package could subsequently be surface mounted to a standard FR-4 printed wiring board.

Dimensions

The copper plate is 18.16 mm square and 0.25 mm thick. The Vectra liquid crystal polymer frame is 16.92 mm square at its smallest in the interior and 23.93 mm square at the exterior, with a maximum height of 2.92 mm. The stair case interior molding provides seats for the three rows of leads. The 336 leads are gathered in groups along the periphery: two 3-lead planar assemblies on a 0.5 mm pitch with 1.3 mm between groups. Each pin has a cross section of 0.2 mm by 0.4 mm. Including the lead frame, the package is 28.72 mm square in size and 3.43 mm high. The printed circuit board modeled in the study was 40 mm wide and 1.52 mm (0.06 in.) thick.

Material Properties

The various package and FR-4 material properties are shown in Table 1. All of the package materials and FR-4 properties, except solder, are modeled as constant and isotropic. Both Vectra and FR-4 have highly anisotropic material properties, such as CTE, but these are ignored for this study. The properties of several of the materials are also temperature dependent, but do not vary significantly over the temperatures of this study. Both anisotropic and temperature dependent properties will be included in future 3-D studies.

Table 1. Material Properties of VSPA Package

Component	Material	Young's Modulus (MPa)	Coefficient of Thermal Expansion (α) x 10^{-6} (mm/mm°C)	Poisson's Ratio (ν)
Heat Spreader/ Back Plate	Beryllium Copper	117,000	17.6	0.35
Frame	Vectra™	16,600	5	0.30
Leads	Phosphor Bronze	110,000	17.8	0.35
Encapsulant	Hysol™	11,720	18	0.30
Circuit Board	FR-4	22,000	17	0.28
Solder	63Sn/37Pb Eutectic	Temperature Dependent	21	0.40

Eutectic Sn-Pb solder is used to surface mount the VSPA package to the FR-4. Due to its low yield strength and high ductility, solder is typically modeled as a viscoplastic material [5]. The properties of solder are also known to be temperature, frequency, and strain rate dependent. For a truly accurate computation of strains and fatigue life, these factors should be accounted for. In addition, creep may play a significant role in solder joint fatigue life and several authors have studied methods of modeling this effect [8, 9, 11, 12]. In this study, most of these effects are ignored for simplicity and, as in [1] and [2], solder is modeled as an elastic-plastic material with temperature dependent stress/strain information (Figure 2) from [7].

CTE Mismatch

The coefficients of thermal expansion of the beryllium copper plate and phosphor bronze leads (17.6×10^{-6}/°C and 17.8×10^{-6}/°C) and the encapsulant (18.0×10^{-6}/°C) are comparable to an average CTE of FR-4 (17.0×10^{-6}/°C). However, the polymer frame of the package has a much lower CTE of 5.0×10^{-6}/°C. This low CTE frame constricts the expansion of the package with the board and is the source of large stresses and strains in the solder joints. Because of the geometry and composite design of the VSPA package, the net CTE of the package varies between 5 and 17 ppm/°C over the height of the package. Thus, a simple calculation of thermal expansion cannot be done; accordingly this study used the finite element model described below to predict true displacements.

Finite Element Model

The 2-D, plane strain, 8-node quadrilateral and triangle finite element model of a section of the package is shown in Figure 3. The plane strain model is not as rigorous as a 3-D model, but it was chosen for its simplicity and for short run times. Only half the assembly was modeled, using symmetry boundary conditions along center line. Also, modeling was confined to the innermost and outermost rows of pins which would experience the maximum strains in heating/cooling cycles. The geometries of the package and board were obtained from Panda Project design drawings. The geometry of the solder joint, Figure 4, was obtained from scanning electron micrographs similar to Figure 5. Studies have shown that convex or concave curvature of the solder bump does not greatly affect the mechanical performance of the joint [4], therefore a linear approximation of the curvature is made to model the solder bump. The stand-off height of the pin from the board is 0.075 rnm and it can be seen that a layer of solder, an average of 0.012 mm thick, wets up the pin.

To simulate a thermal cycle, all of the elements in the body were raised from a stress-free, uniform temperature of 20°C to 105°C (ΔT = 85°C). The 85°C range was chosen to match simulation conditions of research on a gull wing QFP solder joint [2]. This temperature was ramped up over 10 substeps with about 5 equilibrium iterations per substep.

Fatigue Life Equations

The fatigue life of a material is based on the total strain range which is composed of an elastic component, studied by Basquin, and a plastic component whose effects have been studied by Coffin and Manson [6]. The elastic and plastic components of strain can be related to fatigue life, N_f, by the following function:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

For high strains, the plastic component dominates, thus fatigue life is typically calculated using the Coffin-Manson power law function relating plastic strain range, $\Delta\varepsilon_p$, and life:

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f(2N_f)^c$$

Using this term, Solomon [5] has shown from experiments that

$$N_f = \theta\,(\Delta\varepsilon_p)^\eta$$

where θ = 1.2928 and η = -1.96 for eutectic solder between -50°C and 125°C. N_f here is the 50% pull strength reduction. These values were developed using isothermal experiments, so Solomon suggests dividing by 3 to account for the asymmetry of non-isothermal situations. To be conservative, it is also suggested that life data from 120°C tests be used which is achieved by dividing N_f by 5. This study will use a divisor of 4 in order to compare results with previous studies of QFP solder joints [2].

Determination of Plastic Strain Range

The fatigue life equations presented above are based on a plastic strain range. In a one-dimensional problem started from a stress-free state with a temperature change applied, this would be simply the maximum plastic strain. For a two dimensional problem such as the one presented here, a method must be used to combine the three independent strain components into one equivalent value. The equivalent plastic strain (ε^p_{eqv}) can be written, in general, as:

$$\varepsilon^p_{eqv} = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon^p_x - \varepsilon^p_y)^2 + (\varepsilon^p_y - \varepsilon^p_z)^2 + (\varepsilon^p_z - \varepsilon^p_x)^2 + \gamma^p}$$

where

$$\gamma^p = \frac{3}{2}(\gamma^{p\,2}_{xy} + \gamma^{p\,2}_{yz} + \gamma^{p\,2}_{zx}$$

In the specific case of plane strain, as is here, all z normal and shear strain components (ε_z, γ_{yz}, γ_{xz}) will be zero.

RESULTS AND DISCUSSION

The final displacements of the model are shown in Figure 6. A slight upward bow can be seen in the package body because the CTE of the encapsulant is slightly higher than that of the copper heat spreader.

Figure 7 shows the equivalent plastic strain in the outer solder joint (center of package to the left). The maximum strain occurs at the inboard edge of the joint and quickly falls off in magnitude. The inner solder joint shows a similar profile but with lower maximum strain.

Fatigue Life Estimate

The maximum equivalent plastic strain observed in the solder joint (ΔT = 85°C) was 0.00194. Applying the fatigue life equation yields a life of 268,000 cycles. Use of Solomon's suggestions (division by 4) yields a conservative fatigue life of 67,000 cycles. According to Solomon, this is life to a 50% reduction in pull strength. According to the Strain-Life theory, this "fatigue life" is life to crack initiation. In [2], "fatigue life" corresponded to 50% failure in a Weibull distribution.

It should be noted that in [9], a comparison between 2-D plane strain, 2-D plane stress, and a 3-D model, the plane stress model gave equivalent stress and strain values closer to the 3-D model which is assumed to be the most accurate of the models. If this study is performed with plane stress elements, as opposed to plane strain, the maximum equivalent plastic strain is 0.00489. This calculates to a "raw" fatigue life estimate of 43,700 cycles and, after the corrections, a conservative life estimate of 10,900 cycles.

CONCLUSIONS AND FUTURE WORK

1. This study used a 2-D plane strain model. It is a cost effective, easily implemented analysis method. Several variations of the VSPA package are under consideration. If this 2-D method proves to be sufficiently accurate, it will allow speedy trial and analysis of the effect of new package designs and pin geometries on fatigue life.

2. Based on the maximum equivalent plastic strains predicted by this model (0.00194) and the Coffin-Manson equation, the fatigue life of the 336 pin VSPA is about 268,000 cycles. Dividing by 4, in accordance with Solomon, yields a fatigue life of 67,000 cycles. [Plane stress analysis yields a maximum equivalent plastic strain of 0.00489 and fatigue lives of 43,700 and 10,900 cycles.] For comparison, [2] predicts a fatigue life of 12,300 cycles for a middle joint in a 208 pin QFP (50% failure).

3. The maximum equivalent plastic strain occurs at the inside edge of the outer lead's solder joint where the joint meets the FR-4. This is believed to be because of the greater distance from the neutral point of the package and the higher shear strain.

4. If a higher CTE ($5 < \alpha < 17$) material is used in place of the Vectra, even lower strains should result as all of the package materials will have CTEs close to that of FR-4. This change is easily accommodated in the model and should be studied.

5. As future work, these results must be compared to those of a 3-D finite element analysis and, most importantly, actual experimental testing. These results will hopefully be between the two extremes of plane stress and plane strain, allowing simpler 2-D models to be used with a knowledge of their accuracy.

6. Several other parametric studies are scheduled. Effects of the package size, the number of leads, the number of rows, and various lead shapes are of interest. These studies can be done using the 2-D method if it proves accurate. Strain at the corner leads should be higher than middle leads because of the out of plane displacement. This simulation, and studies of the full solder pad geometry, will require 3-D analysis.

ACKNOWLEDGMENTS

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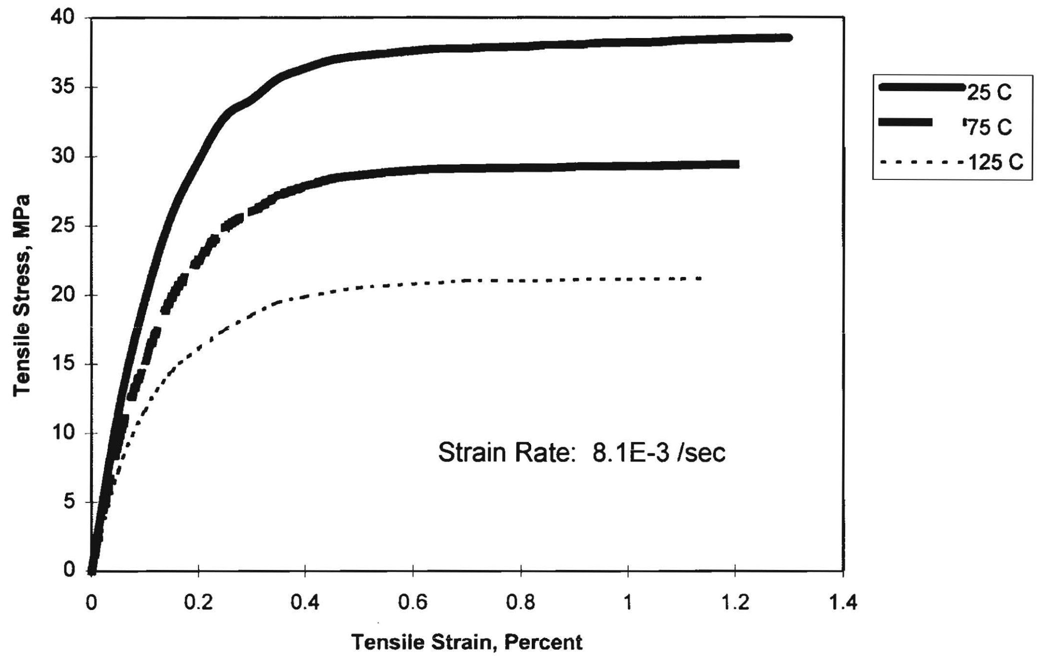

Figure 2. Tensile Stress-Strain Curve 38Pb-62Sn Alloy

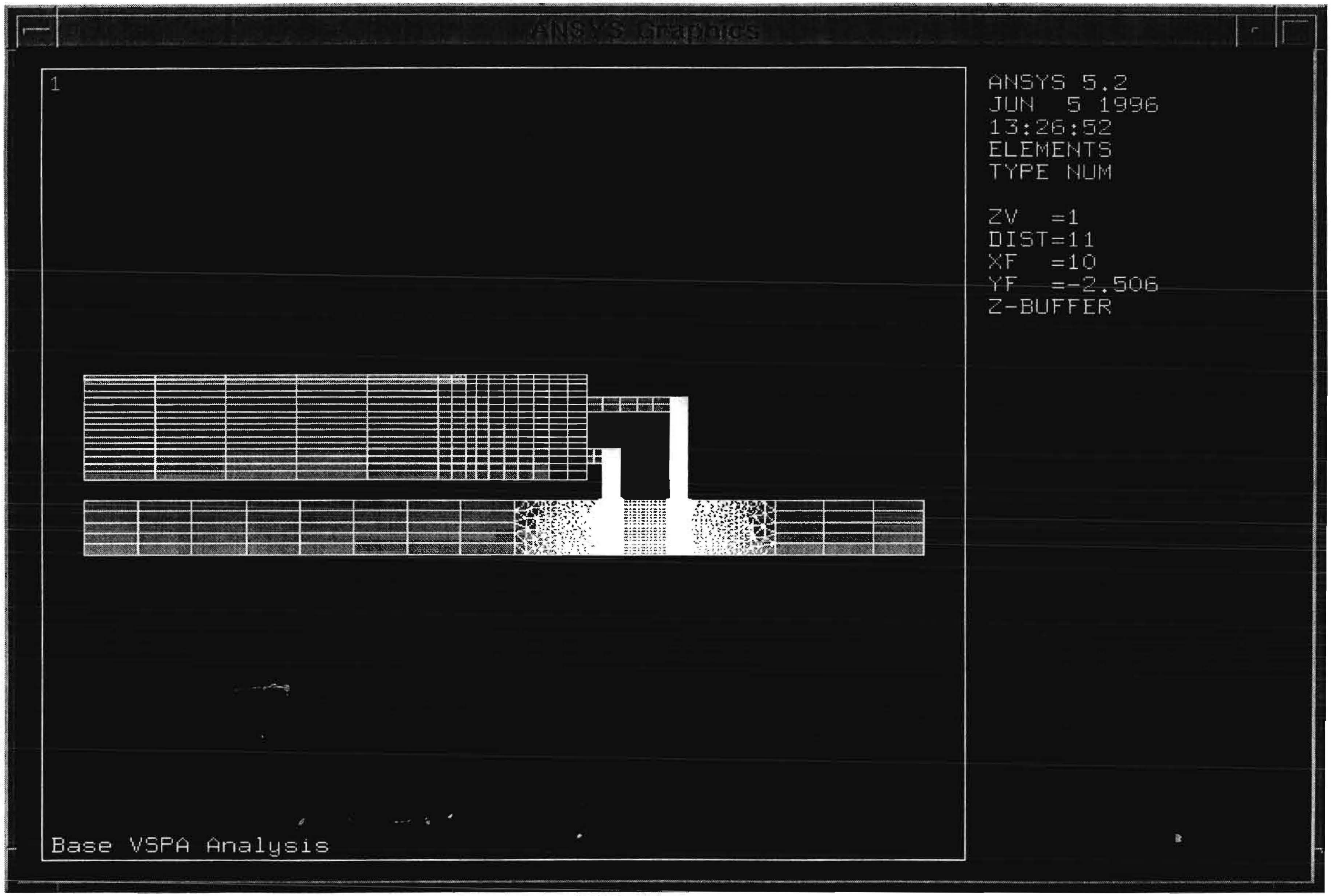
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Figure 3

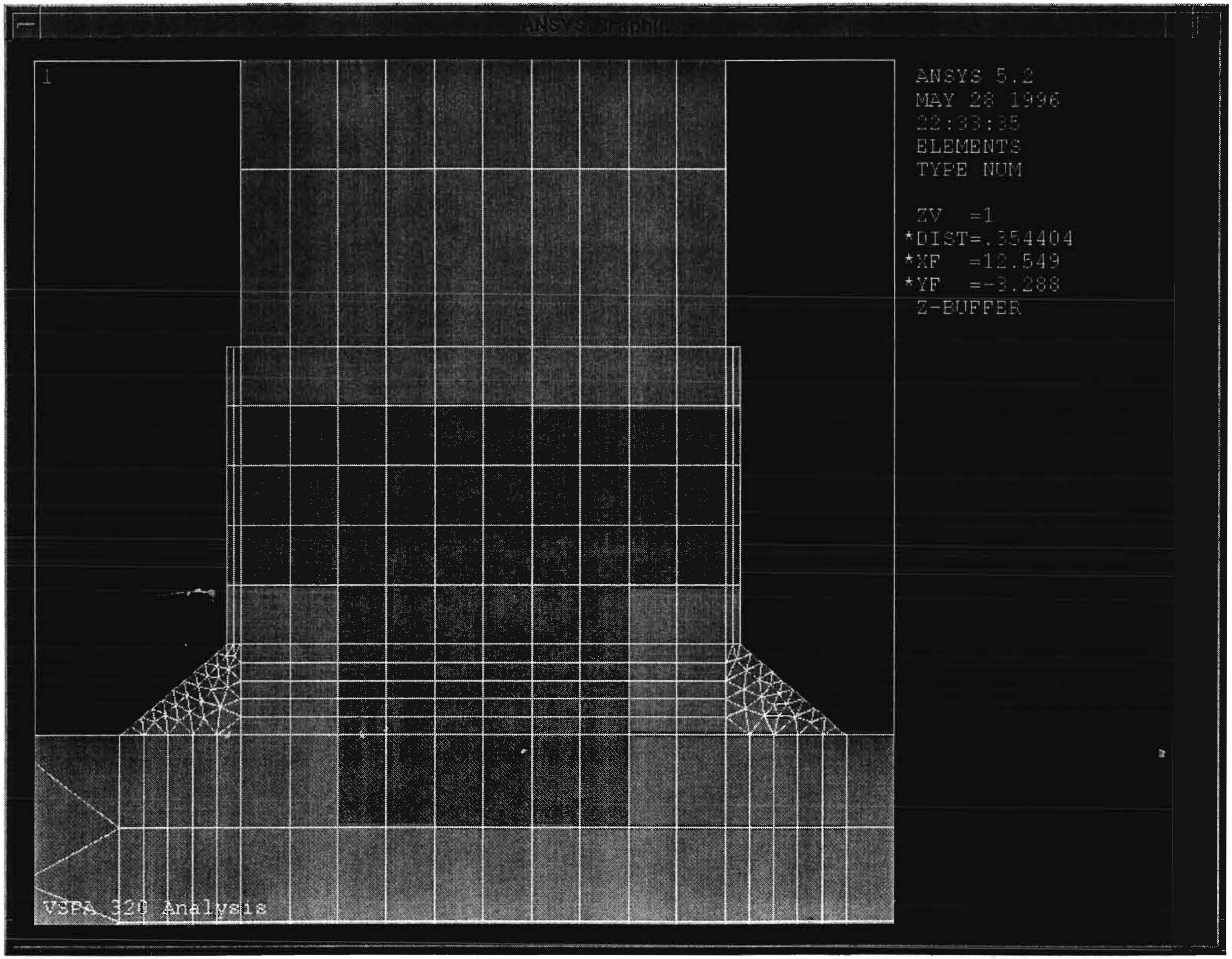
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Figure 4

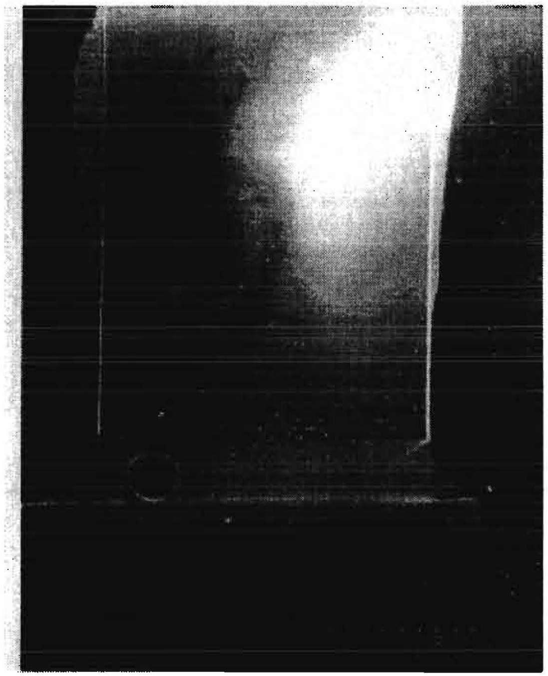

Figure 5

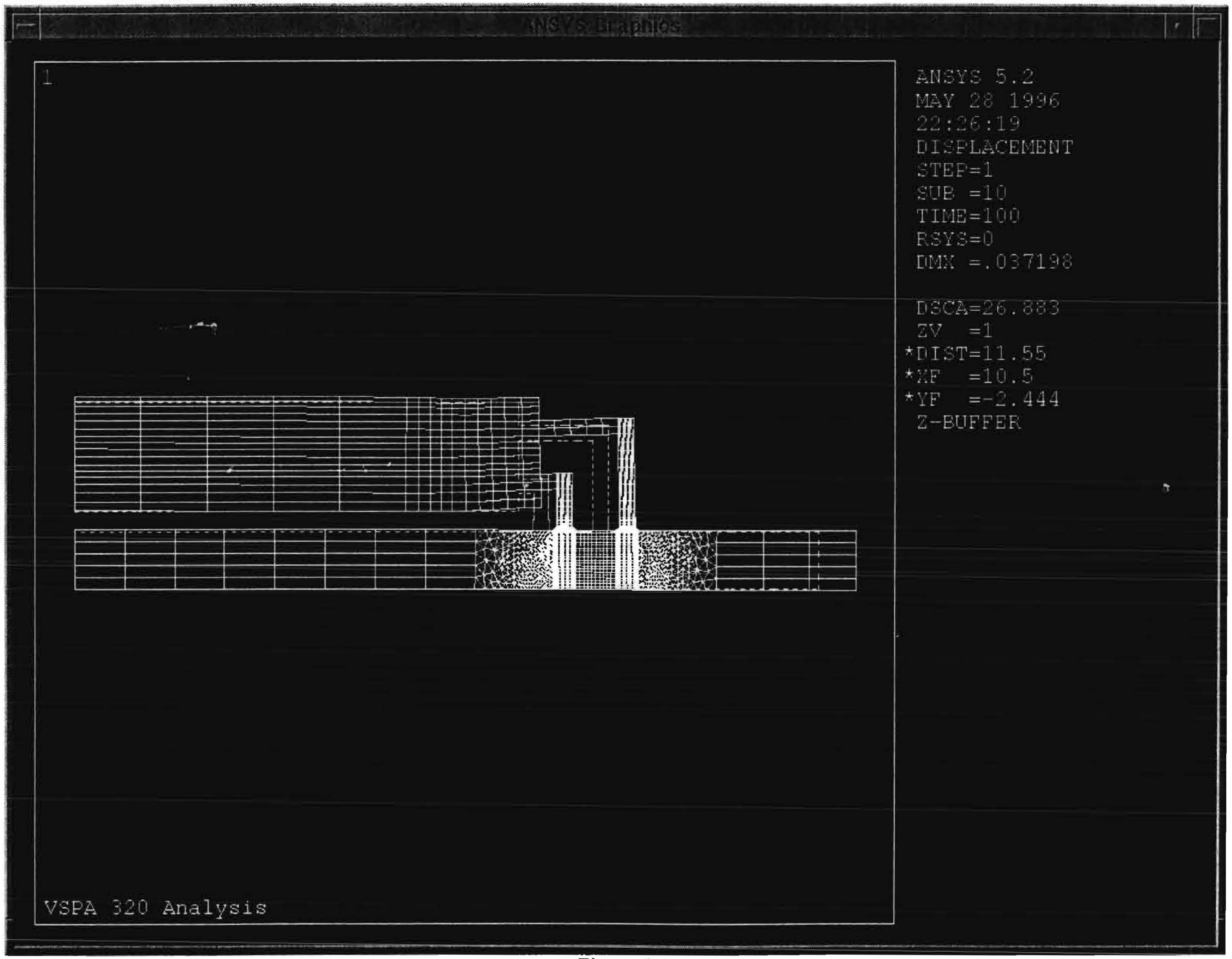
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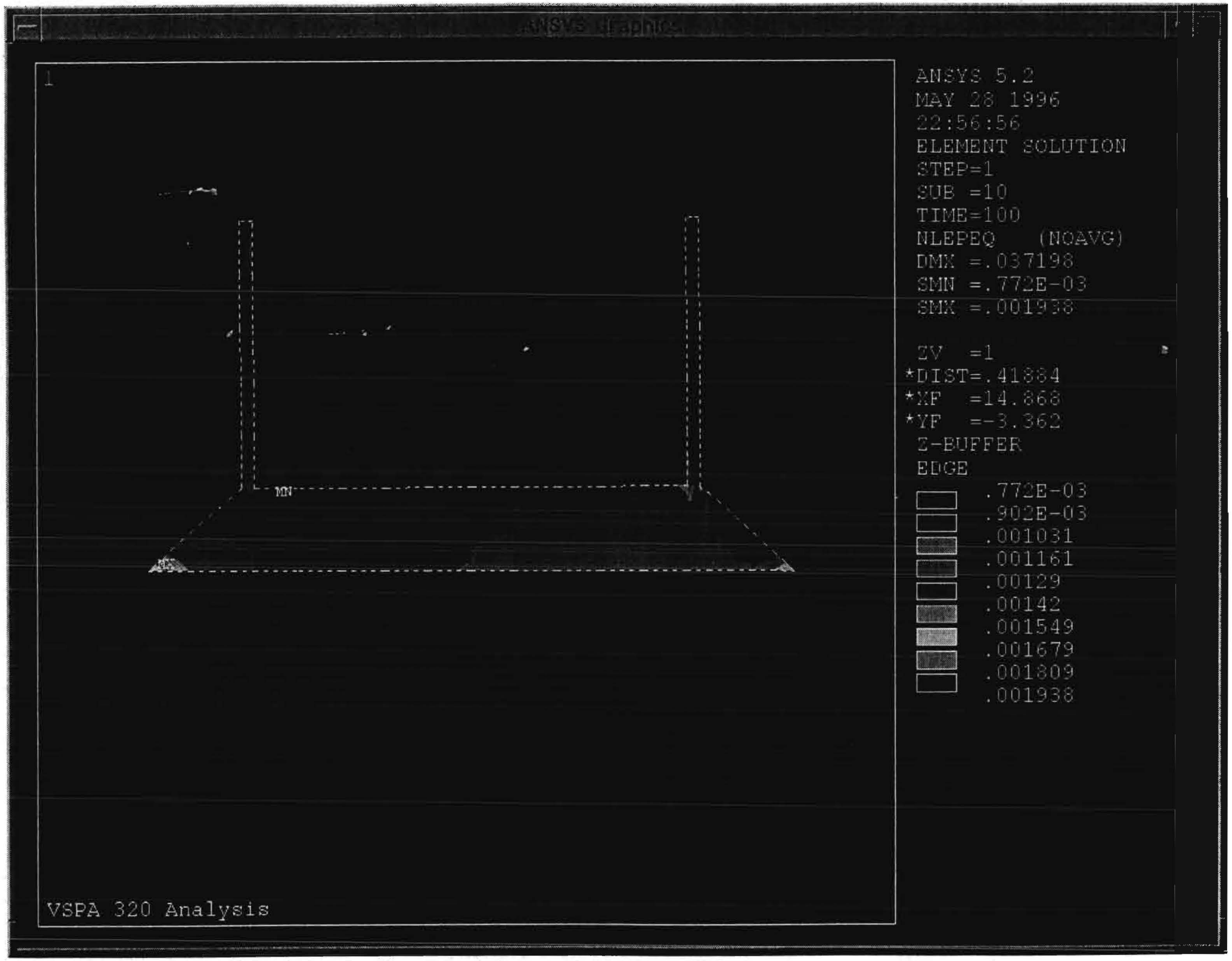
Figure 6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VSPA 320 Analysis

Figure 7

E-25-T75
#4

Two and Three-Dimensional Modeling of VSPA Butt Solder Joints

R. Sean Murphy
Graduate Research Assistant
and
Suresh K. Sitaraman
Assistant Professor

Computer-Aided Simulation of Packaging Reliability (CASPaR) Laboratory
The George Woodruff School of Mechanical Engineering
Packaging Research Center
Georgia Institute of Technology
Atlanta, Georgia 30332-0405

Voice: 404-894-3405
FAX: 404-894-9342
e-mail: suresh.sitaraman@me.gatech.edu

ABSTRACT

The objective of this work is to develop two- and three-dimensional numerical models of VSPA, a new peripheral array package, and study its solder joint reliability. VSPA has multiple rows of butt-type leads around its periphery and is surface mounted on a standard FR-4 printed circuit board. The FR-4 and various package materials were modeled as temperature-dependent and elastic while the eutectic solder was modeled as temperature-dependent, elastic-plastic. The package and board assembly were subjected to a temperature increase (ΔT) of 85°C with the assumption that the assembly is stress-free at room temperature. The results obtained from a three-dimensional 1/8th section model are compared with the results from 2-D plane-strain and plane-stress models and with 3-D "strip" models.

NOMENCLATURE

CTE	Coefficient of Thermal Expansion
LCP	Liquid Crystal Polymet
PGA	Pin Grid Array
QFP	Quad Flat Pack
TSOP	Thin Small Outline Package
VSPA	peripheral array semiconductor package
E	Young's Modulus of Elasticity
T_g	Glass Transition Temperature
α	Coefficient of Thermal Expansion
$\Delta\alpha$	CTE Differential
ε_{zz}	Normal strain in the z direction
ε_{yz}	Shear strain in the yz plane
ε_{xz}	Shear strain in the xz plane
σ_{zz}	Normal stress in the z direction
σ_{yz}	Shear stress in the yz plane
σ_{xz}	Shear stress in the xz plane

INTRODUCTION

One of the primary failure modes of electronic packages is thermo-mechanical fatigue of the solder joint connection between the package leads and the substrate. The mechanical stresses that develop from the difference in the Coefficient of Thermal Expansion (CTE) in the package and substrate are usually the driving force of fatigue crack initiation and propagation to failure. Several authors have studied this phenomenon analytically [7, 12] and through numerical methods [5, 6, 9, 11, 13].

This failure mode is of such importance that industry typically employs MIL-spec tests to validate the sturdiness of a package's solder joints. These tests subject a package/substrate assembly to an accelerated series of heating/cooling cycles in order to predict operating environment reliability. Such experimental techniques take several weeks to complete and for every modification of the package design, much time and money is lost in the qualification process. Therefore, it would be advantageous to *simulate* a thermal cycle or thermal shock test and make solder joint fatigue life predictions in hours as opposed to months. This goal is the subject of extensive world-wide research [1, 4, 13] and is one of the main thrusts of the CASPaR Lab at Georgia Tech.

With the increasing need for higher pin counts and smaller sizes, novel electronic packages are continuously developed. One such package currently undergoing qualification is the VSPA peripheral array package, shown in Figure 1. This 25.76 x 25.76 mm square package has 264 butt-type leads in a three-row array. Other sizes and lead counts are also under development. This design is low-cost, reworkable, and uses standard industry fabrication techniques and materials, as well as standard placement machines and board attach processes.

Much research has been done in determining the fatigue life of Quad Flat Pack (QFP) gull-wing, J-type, and leadless chip carrier solder joints [3, 4, 5, 6, 9, 10, 11, 12]. Most of the research on butt-type joints has been done on Pin Grid Array (PGA) solder joints [4, 10, 11]. VSPA represents a new challenge as it is a combination of periphery and array designs.

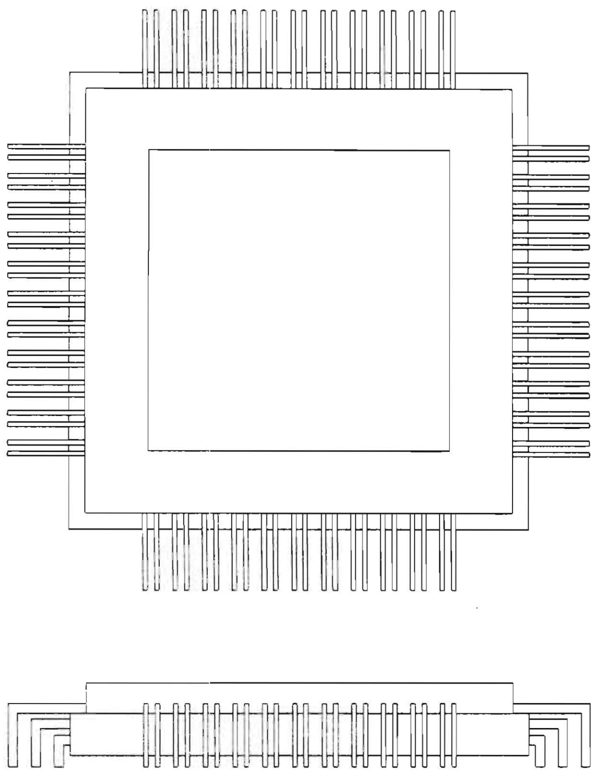

Figure 1: 264 Lead VSPA Package

Also, most finite element modeling of package/solder joint/substrate assemblies have been either two dimensional approximations or simplified three dimensional approximations of the geometry. This is partly because of the high computational expense of full 3-D models These approximations may be satisfactory for first-order analyses of symmetric, simple package geometries [6, 9], but may fail in the face of asymmetric or complicated packagegeometries [7].

The objective of this paper is to develop 2- and 3-D models of the peripheral array package and to compare the results from a 3-D 1/8th section (1 octant) model with the results from plane-strain, plane-stress, and 3-D strip models. These models will eventually be used to estimate the reliability of the butt solder joints.

OVERVIEW OF THE VSPA PACKAGE

A detailed cross section of VSPA is shown in Figure 2. As can be seen, the package consists of a copper heat spreader bordered by a frame of liquid crystal polymer (LCP). The bronze leads, which provide the electrical and mechanical attachment of the package to the FR-4, are inserted into this polymer frame. In typical use, a silicon die would be mounted to the copper plate with a thermally conductive adhesive and electrical connections would be made from the die pads to the bronze leads by wire bonding. The underside would then be encapsulated with an epoxy material, and the package could subsequently be surface mounted on a standard FR-4 printed wiring board producing a "cavity down" type of arrangement.

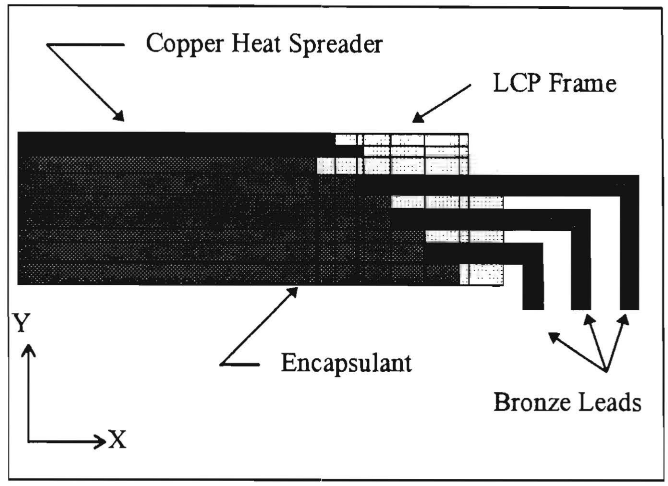

Figure 2: Cross Section of VSPA Package

Dimensions

The exposed copper plate is 13.2 mm square and 0.5 mm thick. The LCP frame surrounding the copper plate is 2.8 mm wide at the top of the package and 0.9 mm wide at the base where it surrounds the encapsulant, with a total height of 3.2 mm. The stair-case interior molding provides seats for the three rows of leads. The 264 leads are gathered in groups along the periphery: two 3-lead planar assemblies on a 0.5 mm pitch with 1.3 mm between groups. Each pin has a cross section of 0.2 mm by 0.4 mm. Including the lead frame, the package is 25.76 mm square in size and 3.67 mm high. The printed circuit board modeled in the study was 100.8 mm (4") square, replicating the experimental test boards, and 1.52 mm (0.06".) thick..

CTE Mismatch

Some of the properties of the various package and FR-4 material are shown in Table 1. The temperature range of interest is 25°C to 110°C.

Table 1. Material Properties of VSPA Package

Component	Material	Young's Modulus (MPa)	CTE (α) (ppm/°C)	Poisson's Ratio (v)
Heat Spreader	Beryllium Copper	117,000	17.6	0.35
Frame	Vectra™	16,600	5	0.30
Leads	Phosphor Bronze	110,000	17.8	0.35
Encapsulant	Hysol™	11,720	18	0.30
Circuit Board	FR-4	22,000	17	0.28
Solder	63Sn/37Pb Eutectic	Temp-Dependent	21	0.40

The coefficients of thermal expansion of the copper plate and bronze leads (17.6 x 10^{-6}/°C and 17.8 x 10^{-6}/°C, respectively) and the encapsulant (18.0 x 10^{-6}/°C) are comparable to the average CTE of FR-4 (17.0 x 10^{-6}/°C). However, the polymer frame of the package has a much lower CTE of 5.0 x 10^{-6}/°C. There was concern that this low CTE frame would constrict the expansion of the package in relation to the board and would induce large stresses and strains in the solder joints due to the CTE mismatch. Because of the stair case geometry and composite design of the VSPA package, the net CTE of the package varies over the height of the package (Y) and, because of the staggered groups of pins (17.8 x 10^{-6}/°C) and LCP (5.0 x 10^{-6}/°C), also varies through the thickness of the package (Z).

This situation differs from the Quad Flat Pack analysis in [6] where a single $\Delta\alpha$ between the package and board could be calculated. VSPA more closely resembles the case of internal thermal bending found in the asymmetric Thin Small Outline Package (TSOP) [7]. Not only will global warpage between the package and board be present, but the package will warp locally as well. This internal package bending will also influence the thermal stresses in the solder joints. Thus, a simple calculation of thermal expansion should not be done; accordingly this study used the finite element model described below to understand the solder joint behavior.

FINITE ELEMENT MODEL

Accuracy in the results of numerical models are largely dependent on how accurately the material behavior can be modeled over the operating temperature range and how effectively the geometric features of the package can be captured without exceeding the computational resources.

Material Modeling

Microelectronic assemblies consist of several components made of dissimilar materials. These materials exhibit temperature-dependent, anisotropic, visco-elastic/visco-plastic behavior over the operating temperature range. Such a behavior greatly complicates the material constitutive equations. Furthermore, not all material parameters are readily available, and efforts are currently underway at Georgia Tech in characterizing the materials used in the package. As a first approximation, material properties were obtained from vendors and the various materials were modeled as discussed below:

- The multi-layer FR-4 substrate is in reality made up of alternating layers of copper and epoxy-glass material. There are two approaches to modeling the FR-4: The first approach is to model the alternate layers using their respective material properties and thus to model the substrate in detail. The second approach is to treat the substrate as homogeneous and to use "orthotropic" properties taken from experimental testing. The former approach is more accurate as it captures all the modes of deformation of the multi-layered structure. The latter approach misses some modes of deformation of the substrate (such as warping) but it requires dramatically fewer finite elements to model the substrate. In this work the latter approach is used.
- The encapsulant material behaves in an isotropic, viscoelastic manner. In the current study, the encapsulant material is modeled as linear isotropic and temperature dependent. In the ongoing research, efforts are underway to model the viscoelastic behavior of the encapsulant. Properties such as $E_{encapsulant}$, and $\alpha_{encapsulant}$ are used as functions of temperature in the current study. The glass transition (T_g) regime is also modeled in this work.
- The Liquid Crystal Polymer (LCP) package material behaves in an isotropic, viscoelastic manner. In the current study, LCP is modeled as linear isotropic and temperature dependent.
- The copper back plate and phosphor bronze leads were modeled as isotropic, bilinear elastic-plastic.
- Eutectic Sn-Pb solder is used to surface mount the VSPA package to the FR-4 substrate. Tin-Lead solders exhibit creep-plasticity interaction and significant strain-rate dependence at the typical operating temperatures of electronic circuits [9, 10, 11, 13]. A coupled creep-plasticity constitutive model is necessary to completely describe solder fatigue, as [13] has suggested that the creep plastic strain is the overriding damage mechanism. Such models are rather complex therefore a reasonable first step is to model solder as a multi-linear isotropic material with temperature dependence as in [5] and [6]. The stress strain curves used for this are shown in Figure 3, obtained from [2].

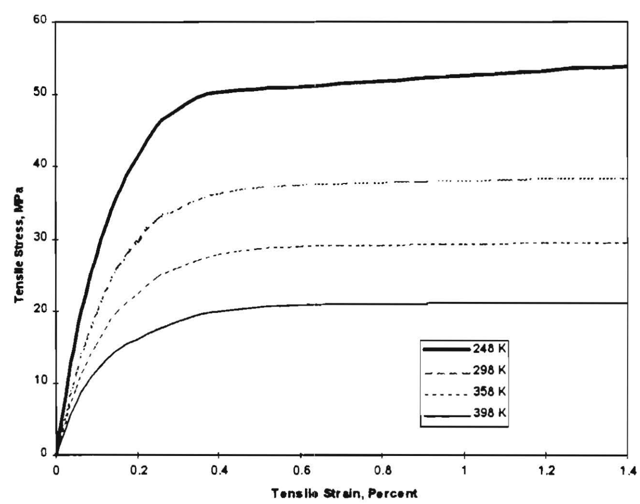

Figure 3. Tensile Stress-Strain Curve 38Pb-62Sn Alloy

Geometric Modeling

The geometry of the package could be modeled in several ways:

- Eighth-Section 3D. A full 3D model was constructed of the package making use of the 1/8th symmetry of the package/board assembly (Figure 4). It is assumed to be the most accurate of the models tested and is used as the benchmark. Approximately 10,000 twenty-node, quadratic brick and tetrahedral elements were used to mesh the model.

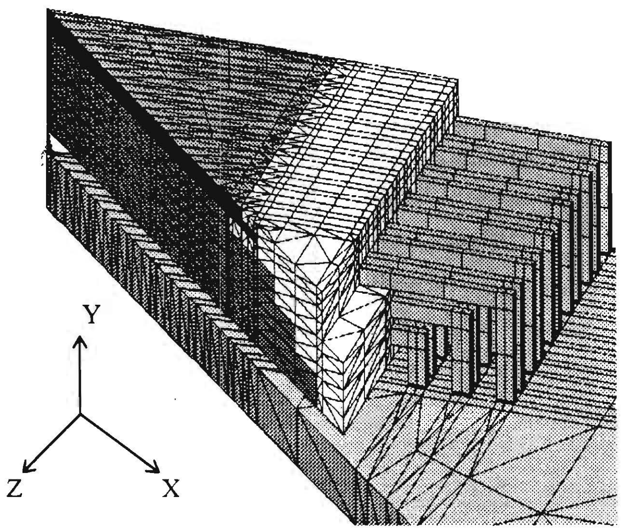

Figure 4. 3D 1/8th Section Finite Element Model

- 2D Plane Strain. The 2D model is essentially a planar slice through the center of the package (Figure 5). The assumption of the plane strain model is that out-of-plane strain is absent ($\varepsilon_{zz} = \varepsilon_{xz} = \varepsilon_{yz} = 0$) which is accurate for bodies seemingly infinite in the Z direction. Symmetry is applied so only half of the package section is modeled. Eight-node quadrilateral elements were used for the 153 element mesh.

- 2D Plane Stress. The 2D plane stress model also represents a slice through the center of the package. The assumption of the plane stress model is that out-of plane stress is minimal and can be neglected ($\sigma_{zz} = \sigma_{xz} = \sigma_{yz} = 0$) and is accurate for thin sheets in which loading is in-plane. The same 153 eight-node quad element mesh was used as in plane strain, with the element type set to plane stress.

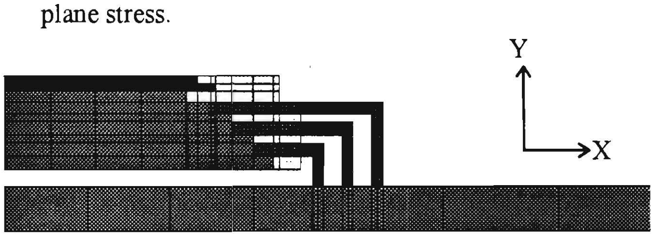

Figure 5. 2D Finite Element Model

- Plane Strain 3D "Strip" Sections. The above 2-D models use a cut-section of the assembly. Such cut sections are not representative of cross-sections in the VSPA package assembly, as the cross-section periodically changes as one traverses along the Z-direction due to the presence of pair grouped pins with LCP between them. Therefore, one needs to model several cut-sections to understand the overall behavior of the assembly. Alternatively, 3D "strip" models can be developed. Three dimensional "strip" models cut a block of the assembly containing several adjacent cross-sections of importance, and plane-strain-like boundary conditions can then be applied on faces normal to the Z axis with Z displacements to be zero. Such models possess the computational simplicity of plane-strain models and at the same time account for geometric complexity of the packaging assembly.

The "thin strip" model (Figure 6) has a cut-section through the center of the package with a thickness equal to the lead thickness. The second "thick strip" model (Figure 7) contains the first strip model and additional strips of LCP, half the pin pitch wide, are added on the positive and negative Z axis. The "thin" and "thick" strips are meshed with 153 and 810, respectively, twenty-node quadratic brick elements.

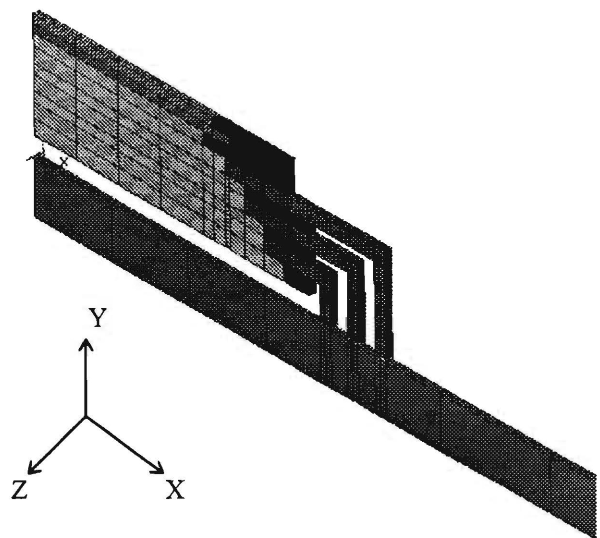

Figure 6: 3D "Thin" Strip Model of VSPA

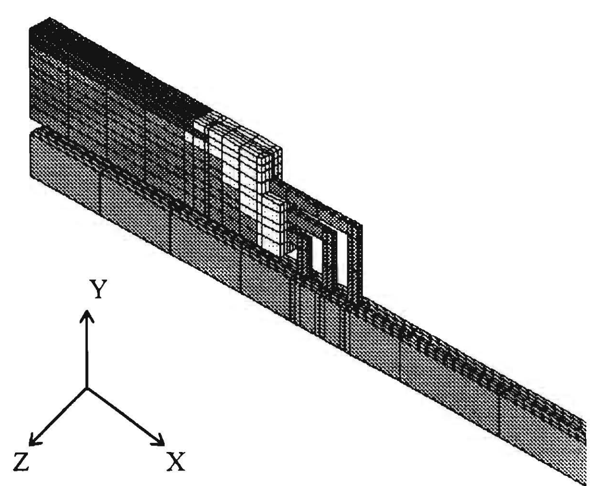

Figure 7: 3D "Thick" Strip Model of VSPA

Boundary Conditions

To simulate a thermal cycle, all of the elements in the body were raised from a stress-free, uniform temperature of 25°C to 110°C (ΔT = 85°C). The 85°C range was chosen to match simulation conditions on a gull wing QFP solder joint in [5] and previous VSPA modeling in [8].

RESULTS AND DISCUSSION

Figures 8, 9, 10, 11, and 12 show the displacements on the Z = 0 plane for the 3D, 2D plane strain, 2D plane stress, 3D "thin" strip, and 3D "thick" strip models respectively.

Three-Dimensional 1/8th Model

The 1/8th 3-D model required several hours to run on a desktop workstation. It can be observed in Figure 8 that the deformed geometry of the 3D model is almost flat. This is largely due to the fact that the net effective CTE of the package is almost the same as the effective CTE of the board. The very small upward warpage under heating is due to the fact that the effective CTE of the board in the X direction is about 1% greater than of the package.

In addition to the board-package assembly, the package itself (Figure 13) shows an upward warpage due to the higher CTE encapsulant on the bottom ($CTE_{net} \approx$ 16.8 ppm/°C) and lower CTE LCP and copper plate at the top ($CTE_{net} \approx$ 13.9 ppm/°C). It should be reiterated that the model assumes that the assembly is stress-free at room temperature. This distortion may vary depending on the residual stresses developed in the package from the encapsulant curing.

Plane-Strain Model

The plane strain model required only 1-2 minutes to solve on a desktop workstation. As seen in Figure 9, the plane-strain model shows the package warping downward while the 3D model (Figure 8) shows the package warping upward. Since the plane-strain model assumes all strains in the direction perpendicular to the plane of paper (Z direction) are zero, the plane-strain model, under heating, introduces compressive stresses in the Z direction which, in turn, exaggerates the strains in the X and Y direction. Rewriting the stress-strain relationship, one can show that the coefficient of ΔT is greater for the plane-strain model than for the 3D model. In other words, the plane-strain model artificially increases the CTE of the package and board, as a function of their modulus and Poisson's ratio, in both the X and Y directions. Based on approximate calculations, one can show that the effective CTE of the package in the X direction is roughly 22 ppm/°C, while that of the board is 19.4 ppm/°C under plane-strain conditions, and thus the assembly will warp downwards under plane-strain conditions.

Plane-Stress Model

The plane stress model also only required 1-2 minutes to solve. As seen in Figure 10, the plane-stress displacements are very close to that of the 3D model, as discovered in [9]. This is to be expected since the out-of-plane stresses, σ_{zz}, σ_{yz}, and σ_{xz}, are low in the 3D model and thus approaches plane-stress conditions. It should be emphasized here that the current combination of materials has serendipitously made $\Delta\alpha$ almost equal to zero. Other substrate or package material CTE values may generate significant out of plane stresses. But, in this particular case, the plane-stress solution is quite similar to the 3-D solution.

3D "Strip" Models

The 3-D strip models required several minutes to solve. The displacement results from the two strip models are presented in Figures 11 and 12. As would be expected, the results from the "thin" strip model (Figure 11) match very well with the plane-strain model, as the "thin" strip 3-D model is essentially the plane-strain model with Z-direction thickness equal to that of the lead thickness. The "thick" strip 3-D model (Figure 12) incorporates the slices of the low-CTE LCP material on each side of a pin group into the cross section and is modeled with the external Z-axis displacements constrained to zero. The X and Y displacements of the "thick strip" move away from the plane-strain values and begin to approach that of the 3-D and plane stress models. In other words, plane strain exaggeration of the net CTE of the package is reduced.

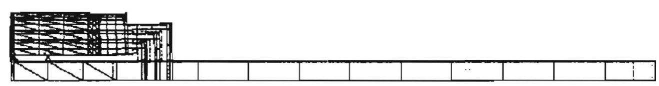

Figure 8. 3D Model Displacement (Z = 0, ΔT = 85°C)

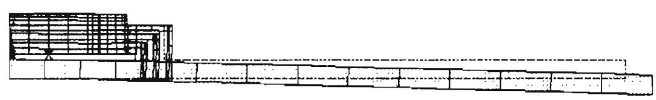

Figure 9. Plane Strain Model Displacement (ΔT = 85°C)

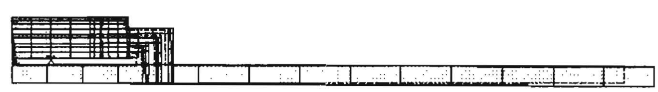

Figure 10. Plane Stress Model Displacement (ΔT = 85°C)

Figure 11. 3D "Thin" Strip Model Displacement (Z = 0, ΔT = 85°C)

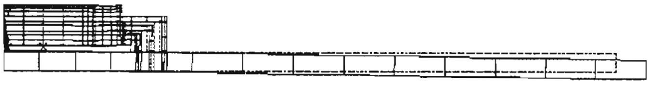

Figure 12. 3D "Thick" Strip Model Displacement
(Z = 0, ΔT = 85°C)

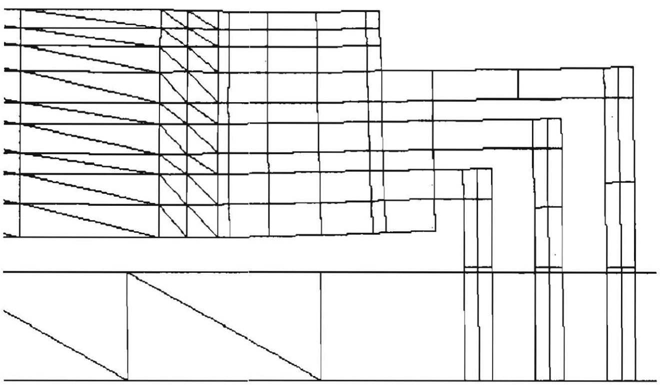

Figure 13. Local Bending in 3D Model (Z = 0, ΔT = 85°C)

CONCLUSIONS AND FUTURE WORK

1. Among the models presented, the results obtained from plane-stress models are closest to the results obtained from 3D models. However, it cannot be generalized that plane-stress models would always provide better results. In the current assembly configuration, plane-stress models approximate the behavior of the 3D geometry due to low $\Delta\alpha$ mismatch.
2. Plane-strain models in general exaggerate strains and thus the displacements in X and Y directions. Such exaggerations would alter the lead boundary conditions which, in turn, will result in inaccurate values for the solder joints.
3. 3D strip models provide computational simplicity while retaining some geometric complexity of the non-homogenous package.
4. As part of future work, the solder material model will be enhanced to account for the creep behavior. Also the temperature range will be expanded from operational range to MIL-spec range to simulate thermal cycle and thermal shock tests. Results from such simulations will be compared against experimental data to validate the modeling methodology.
5. The ultimate focus of this study is to estimate the solder joint reliability of the VSPA package. This will be achieved using a Global-Local method similar to [6] where the global differences in displacement are computed from a coarse model then applied to a refined model of the lead and solder joint region.
6. The corner solder joints are expected to see the largest thermal stresses since they are farthest from the package center and experience both X and Z strain. This has been modeled in [6] and [13]. The 1/8th 3-D model will account for this phenomenon where the 2-D models will not.
7. In this ongoing effort, several parametric studies are scheduled. Effects of the package size, the number of leads, the number of rows, and various lead shapes are of interest.
8. Parallel studies are being conducted to understand the interfacial stresses between the dissimilar encapsulant, LCP, and back plate materials

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