BOARD LEVEL FLEXURAL RELIABILITY TESTING AND FAILURE ANALYSIS OF CUSTOM PRINTED CIRCUIT BOARDS WITH WCSP PACKAGES

by

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Abstract

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Printed circuit boards, widely known as PCBs; are the skeleton behind every technology today. Electronics have integrated with every other engineering domain to improve the outcomes. It is very important that they remain intact in slightly extreme physical conditions. They are used in wide range applications which may lead to mechanical stress-strain in some conditions.

There are various boards with different kinds of packages on them. A 0.7mm thick board with WCSP; Wafer chip scale package is a prime specimen for my work. The research includes designing exact replica of given PCB into ANSYS and its reliability testing. A 3-point and a 4-point bend test are the perfect methods to test flexural response. All tests are carried out by ASTM standards. The reference of this test is an Instron™ machine, which is widely used for 3 and 4 point flexural test.

I replicated the exact model of given PCB in ANSYS-15. Being 0.7mm thickness it has several layers of different materials to it. In order to get accurate

results, layers should be constructed properly. Also, the circuit boards have WCSPs mounted on it. According to standards, different set of loads are used for 3-point and 4-point bend tests.

Test results are then analyzed which predicts the failure points as a part of failure analysis. This gives an idea about mechanical reliability of PCB and its package. Failure modes in solder joints can be cross referenced from previous work to get accurate point of failure.

The results from the analysis are compiled from different tests under different loads. The conclusion from analysis suggests the optimum conditions for the structural stability of given PCBs, in other words performed analysis has successfully proven the reliability of PCB up to a certain limit without failure.

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Chapter 1

INTRODUCTION

As of today, electronic hardware industries are headed towards manufacturing more compact, thin, light and easy-to-use products. Printed circuit boards otherwise known as PCB(s) are skeleton of electronics and its sub applications. Today, electronics is integrated with all other engineering fields, making PCBs the prime component of both study and development. PCBs are the assembly fabricated to mechanically support and electronically connect electric components buy using various interconnections on non-conducting substrate. [2]

1.1 Printed circuit boards and their material properties

PCB is nothing but series of layers stacked in order to obtain an assembly which performs desired function. These layers defer according to the application as well as type of PCB. They are usually of three types. Single layer PCB, dual layer PCB and multi-layer PCB as shown below. [8]

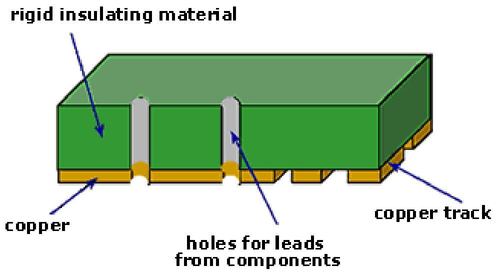


Figure 1.1 Single layer PCB

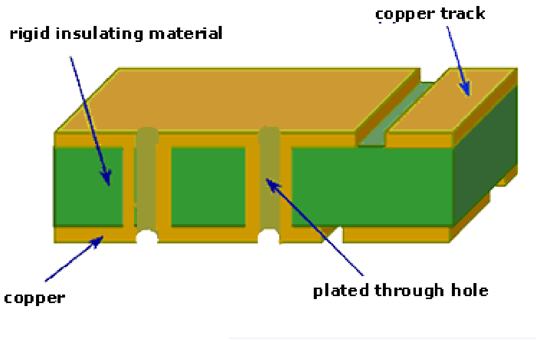


Figure 1.2 Double layer PCB

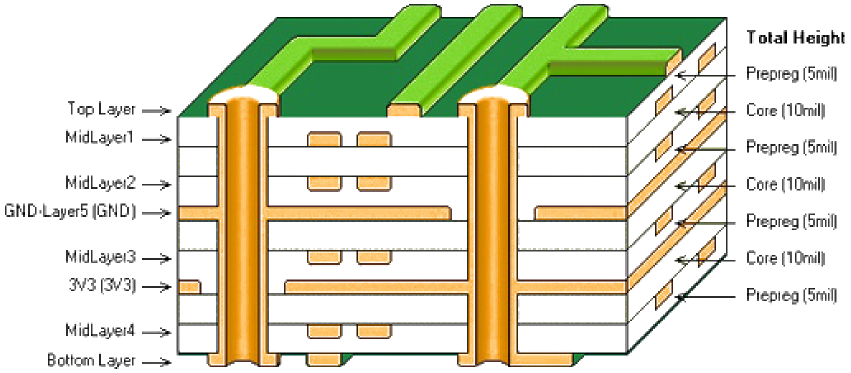


Figure 1.3 Sample multi-layer PCB

Level of application of PCB increases the complexity. As the whole project is focused on multi-layer specimen. Depending upon application layer properties change. Although there are wide range of materials used with respect to PCB's application, few of the materials and their alloys are traditionally used. Few of the most used materials are FR4, Copper and its alloys, Solder mask material, etc. [2]

1.1.1 FR4 and its details

Most commonly used base material for substrate is fiberglass. This continuous filament woven fiberglass is designated as FR4. It is the main component of PCB and referred as the core of PCB. It is contributes to PCB's thickness. Main reason to use FR4 is because of its ability to maintain excellent mechanical, electrical and physical properties.

1.1.2 Copper and its alloys

It mainly works as a conducting material to connect electronic components on PCB. Otherwise designated as "copper interconnects". Depending upon the application, its properties such as density, alloy are chosen. RCC; resin coated copper is usually used to perform this function of interconnects. Copper with high densities have higher material strength but at the same time it can also have some power consumption issues.

1.1.3 Solder mask

Solder mask is an enclosure to all the conductive and interconnect layers which protects the whole assembly without disturbing its function. As per the application and thickness of PCB there is wide range of materials available for solder masks. For thinner PCBs solder masks with high strength are preferred to maintain its functionality in defined set of conditions of reliability

1.2 Manufacturing process

PCBs are manufactured by surface manufacturing technique. Surface manufacturing technique designates layer-by-layer manufacturing. Each layer is fabricated and then machined according to specifications and the glued to next layer. Firstly, inner most layer is fabricated according to its dimensions. The fabrication process is carried out in a cleanroom because added contamination may result in failure of PCB. Secondly, by using series of metal deposition, etching and patterning techniques next layer is fabricated according to its specification. Then, this process is repeated for number of layers till the assembly is complete and then the top most layers are deposited which is non-conducting solder mask. [11]

1.3 Need of reliability testing of PCBs

Every manufactured product is tested for its reliability. Reliability defines the operational conditions for any product. For PCBs reliability testing is an important task which defines its failure modes. Like every other reliability testing we take reference from standard bath tub curve.

There are three main types of failure which can happen to any product. Infant failure, wear out failures and constant failures. It is defined by the standards that infant or early failures decrease and wear out failures increase with increase in operating time where random failures can occur anytime during its life. As shown in figure 1.4, when we trace these failures in a graph, we observe three regions for failure rate. Failures decrease as we make modifications in its early phases then it remains constant for its standard period of operation and after certain period it increases. Reliability analysis enables us to define these regions. Not only that but we can also define optimum set of physical conditions for safe operation of PCB. Rigorous testing of PCB is needed to define such operating and failure modes. PCB is operated under extreme conditions repetitively to achieve the failure modes. They are operated to failure in order to gain full depth knowledge to signify experimental results. [5]

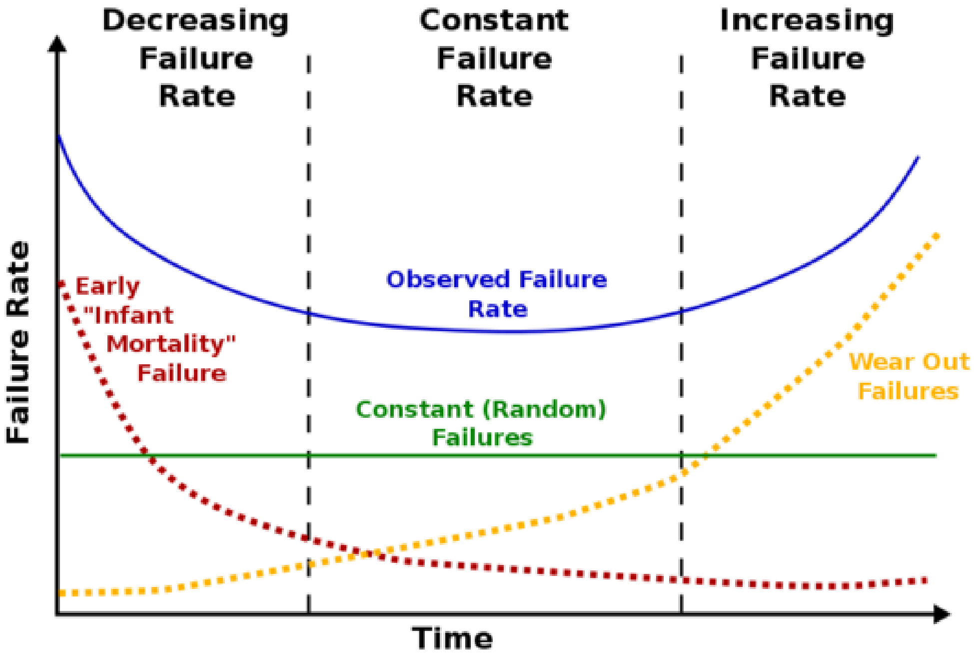


Fig 1.4 Bath tub curve for failure

There are two ways to perform tests; practical and analytical. Where practical testing gives more realistic results, analysis can give in depth overview and accurate results. Softwares of extreme accuracy like ANSYS workbench can help perform and analyze virtual experiments. [7]

Chapter 2

FINITE ELEMENT MODELING FOR RELIABILITY TESTS

There are two ways to perform reliability analysis on any product. One is practical or physical way and other is by virtual analysis. Analysis softwares like ANSYS workbench have so much computational power that we can achieve practical results without a real setup. Practical tests go through a tedious process of pre selection and design. To perform a practical analysis we have to select proper machine, jig and fixtures to make experiment work properly. In most of the cases there is a need to design unique jig and fixtures as almost all products that need critical reliability testing are new invention. Also, they need proper gauges to read and interpret results obtained. The last but not least thing is the mathematics behind all the experiment to support results. [6]

I performed 3 point bending and 4 point bending tests in order to test reliability of PCBs. For our experiment, most used machine is Instron 3000 series fatigue test machine. Any kind of modeling needs few basic things like; specimen dimensions, specimen material properties and test setup standard.

2.1 TI 0.7 mm PCB material properties

Engineering data of materials is the most important thing while performing analysis of any software. ANSYS workbench enables defining material properties directly in engineering data option. In our case given PCB consists of four main materials. Halogen Free Solder mask otherwise known as HF solder mask, FR4-copper alloy, RCC- Resin coated copper, copper layer.

Table 2.1 Thermal properties of PCB materials

	Thermal Properties	
	Coefficient of thermal expansion/°C	Ref Temperature°C
Cu Pad	1.70E-05	25
Fr4	x(1.6e-05)	125
	y(1.6e-05)	
	z(8e-05)	
RCC	3.60E-05	125
Solder mask	Scale 1 offset 0	25

We need mechanical properties for all the materials such as Poisson’s ratio, bulk modulus, shear modulus, tensile strength and ultimate tensile strength. After extensive research on given material properties, team confirmed those properties by mechanical analysis and they are mentioned below.

Table 2.2 Mechanical properties of PCB materials I

	Mechanical Properties			
	Young's Modulus	Poisson's Ratio	Bulk Modulus	Shear Modulus
Cu Pad	1.10E+11	0.34	1.15E+11	4.10E+10
Fr4	2.79E+09	XY 0.11		1.26E+09
	2.79E+09	YZ 0.39		5.90E+09
	1.22E+10	XZ 0.39		5.90E+09
RCC	3.40E+10	0.3	2.83E+10	1.31E+10
Solder mask	4.00E+09	0.4	6.67E+09	1.43E+09

Table 2.3 Mechanical properties of PCB materials II

	Mechanical Properties (Pa)	
	Tensile Strength	Ultimate Tensile strength
Cu Pad	7.00E+03	2.10E+05
Fr4	62000	3.05E+05
RCC	8.40E+04	2.90E+05
Solder mask	3.39E+04	1.05E+05

2.2 TI 0.7mm PCB structure

Given PCB is supplied by Texas Instruments. It has WCSP packages mounted on it. Analysis and given data indicates that the PCB has 17 layers of different materials. Following is the layer dimensions for all the materials. Top view of PCB is modeled in ANSYS workbench with following dimensions.

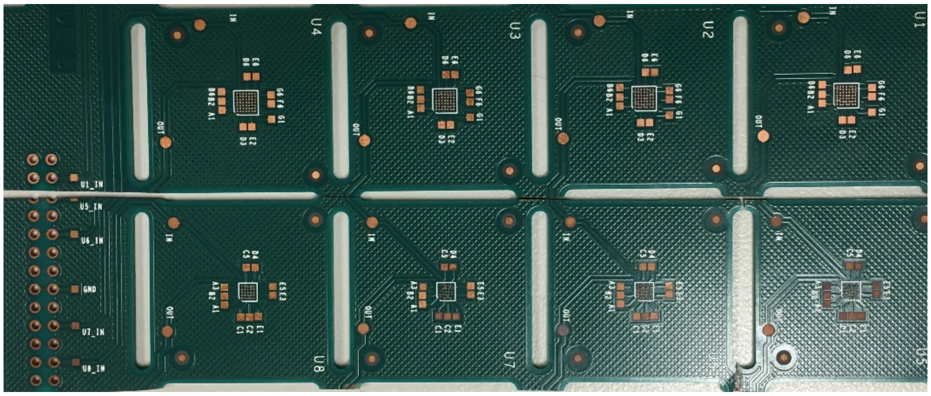


Figure 2.1 Given PCB sample

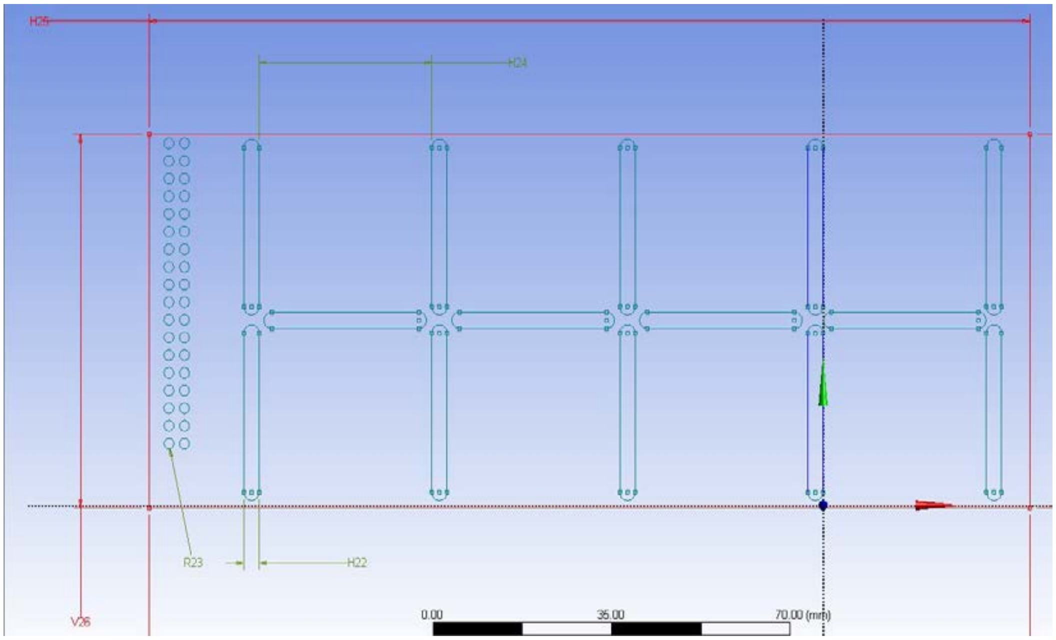
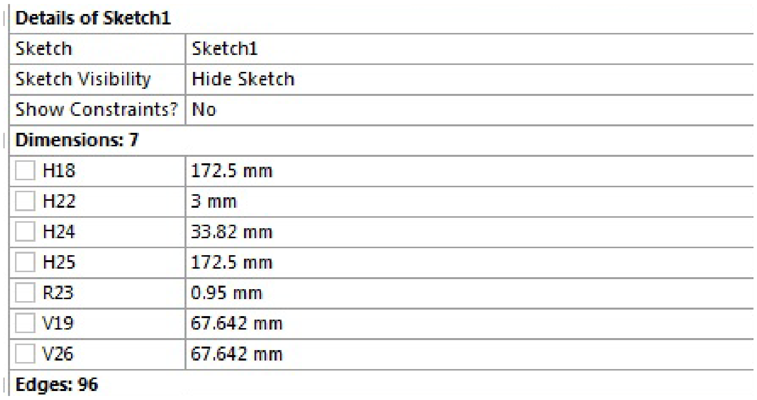


Figure 2.2 Detailed sketch of PCB in ANSYS workbench

Detailed sketch can be seen which replicate the exact dimensions of given PCB.



Details of Sketch1	
Sketch	Sketch1
Sketch Visibility	Hide Sketch
Show Constraints?	No
Dimensions: 7	
☐ H18	172.5 mm
☐ H22	3 mm
☐ H24	33.82 mm
☐ H25	172.5 mm
☐ R23	0.95 mm
☐ V19	67.642 mm
☐ V26	67.642 mm
Edges: 96	

Figure 2.3 Dimensional details

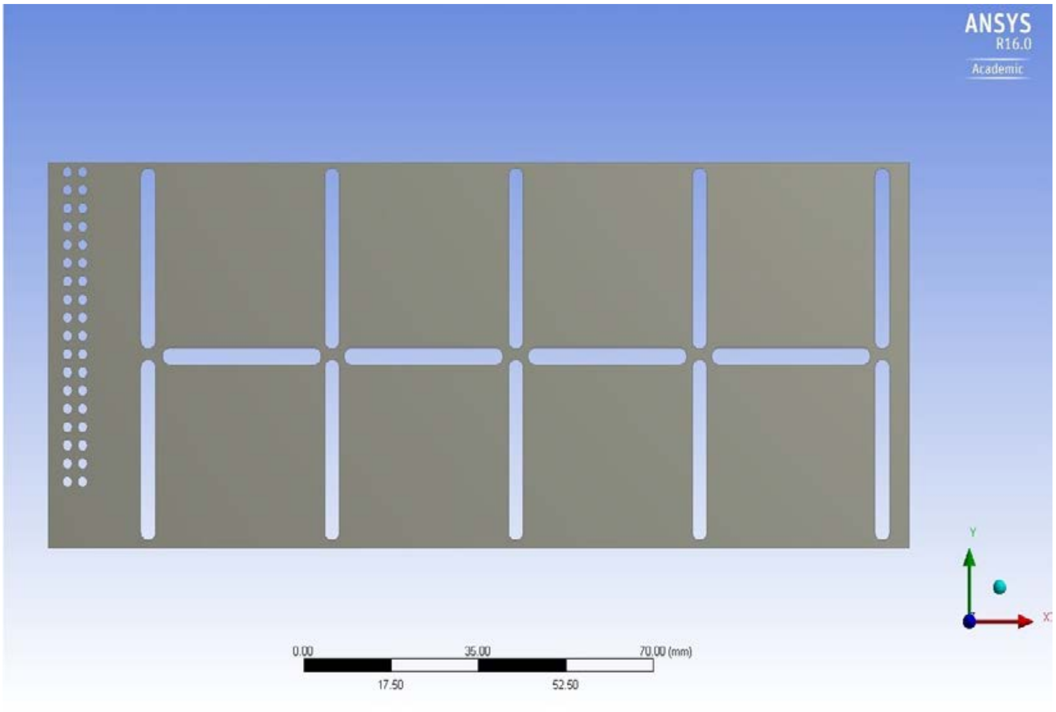


Figure 2.4 Top view of PCB in ANSYS workbench

Overall thickness of given PCB is 0.734 mm. As it is a dual sided PCB it has layer symmetry. FR4 layer 2 is the middle layer with respect to which PCB maintains its symmetry.

Table 2.4 Dimensions of stacked up layers in PCB

Type of Layer	Solder mask	Cu layer 1	RCC1	Cu layer 2	RCC 2	Cu layer 3	FR4 #1	Cu layer 4	FR4 #2
Thickness in Microns	20	25	60	25	60	25	60	17	150
Type of Layer	Cu layer 5	FR4 #3	Cu layer 6	RCC 3	Cu layer 7	RCC 4	Cu layer 8	Solder mask	
Thickness in Microns	17	60	25	60	25	60	25	20	

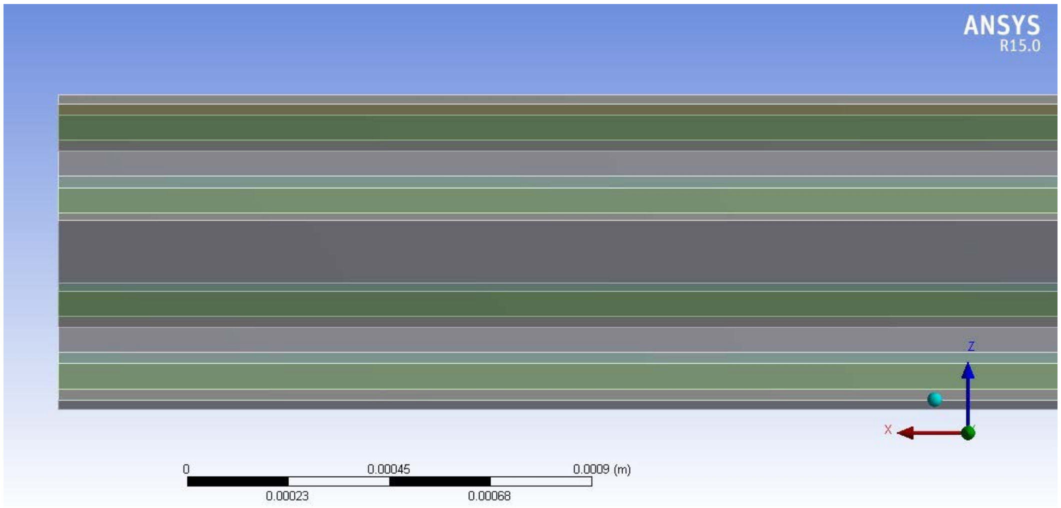


Figure 2.5 Cross-section of stacked PCB containing 17 layers

Chapter 3

SIGNIFICANCE OF FLEXURAL BENDING TESTS ACCORDING TO ASTM STANDARDS

3.1 Introduction

Flexural bending tests are designed to test flexural strength of given specimen. Flexural strength of a product totally depends on its maximum stress and strain. Two kinds of flexural bending tests can be conducted for given PCB. Three point bending test and four point bending test. Both of the tests have their own set of standards defined by American society of testing materials (ASTM). Bending tests are performed till material failure to analyze its failure modes.

3.2 Three point bending test

Three point bending test is one of the two tests used to analyze structural reliability of PCB. Experiment setup is very important to get accurate results. Simple idea behind this is to introduce a line load at exact center of PCB with its supports being situated at the edges at equal distance from center. [3]

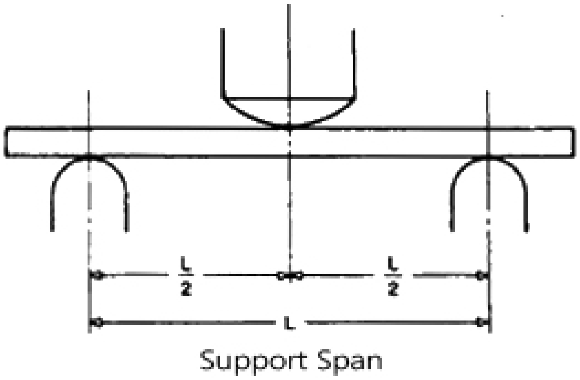


Figure 3.1 General setup for 3 point bend test

3.3 ASTM Standards for 3 point bending test

ASTM has developed set of standards for 3 point bending tests for components with different materials as well as different dimensions. For our PCB the best fit standard is D790-07 standard. Important factor while doing setup for 3 point bending test is span to depth ratio. Span to depth ratio should be between 32:1 to 64:1 if the given standard is to be followed. The idea behind flexural bending test is to test component to its failure. But here we test PCB till either it fails or strain reaches 5% of the value. Following formulae are the mathematics behind experiment. [10]

$$R = Zs^2/6d \qquad\qquad D = rs^2/6d$$

Where,

R= rate of crosshead motion mm.min

Z=rate of straining of fiber mm/mm/min

s= support span mm

d=depth of beam mm

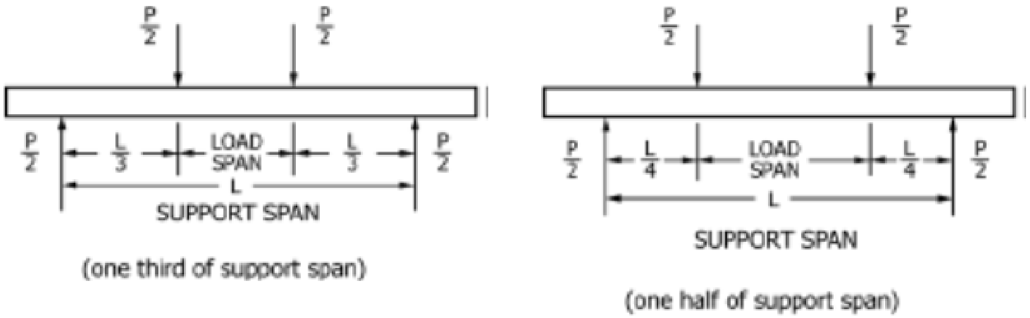
D=midspan deflection mm

r= strain mm/mm

Rate of crosshead motion is important factor if we are to physically perform this experiment. But since we are using ANSYS workbench, this motion can be controlled directly according to application of specific force with respect to time and its progression in PCB.

3.4 Four point bending test

This test is an alteration of previous test with two loads placed equidistant from center of the PCB instead of single load at center.



(one third of support span)

(one half of support span)

Figure 3.2 Types of four point bending test

3.5 ASTM standards for 4 point bending tests

There are two methods to perform four point flexural bending test. One is for large deflections and other is for small deflections. Method for large deflections is mainly used in testing of beams at significantly large scale than a PCB. Here we use the method for small deflections. [4]

As this procedure has two different loads, there are also two different methods to apply loading across PCB’s length. One is by applying loads at equally separated from supports at L/3 length and other at L/4 with keeping load span L/2. A significance behind this test is to generate lifelike loads to challenge reliability of PCB as there are lot of possibilities to how loading will be in real life.

In order to get proper experiment results ASTM standards have derived theoretical formulae for Rate of crosshead motion and midspan deflection. [9]

$$R = 0.185ZL^{2}/_{d} \qquad D = 0.21rL^{2}/_{d}$$

Where,

R= rate of crosshead motion mm.min

Z=rate of straining of fiber mm/mm/min

s= support span mm

d=depth of beam mm

D=midspan deflection mm

r= strain mm/mm

Similarly, the formulae mentioned are to calculate theoretical values to get rate of crosshead motion. These values can be easily derived by inducing gradual increase in force per unit time in ANSYS.

Chapter 4

THREE POINT FLEXURAL BENDING TEST EXPERIMENT

4.1 Analysis setup

ANSYS workbench is the main modeling tool for the experimental setup. The experiment is designed in such a way to replicate exact conditions in real life. Standard three point bend test setup with supports at L/2 = 1.5e-002m distance from center is used. By using split symmetry, single unit of PCB with individual WCSP package on it is tested. Dimensions of single package are X= 3.382e-002 m, Y= 3.382e-002 m, Z= 7.34e-004 m

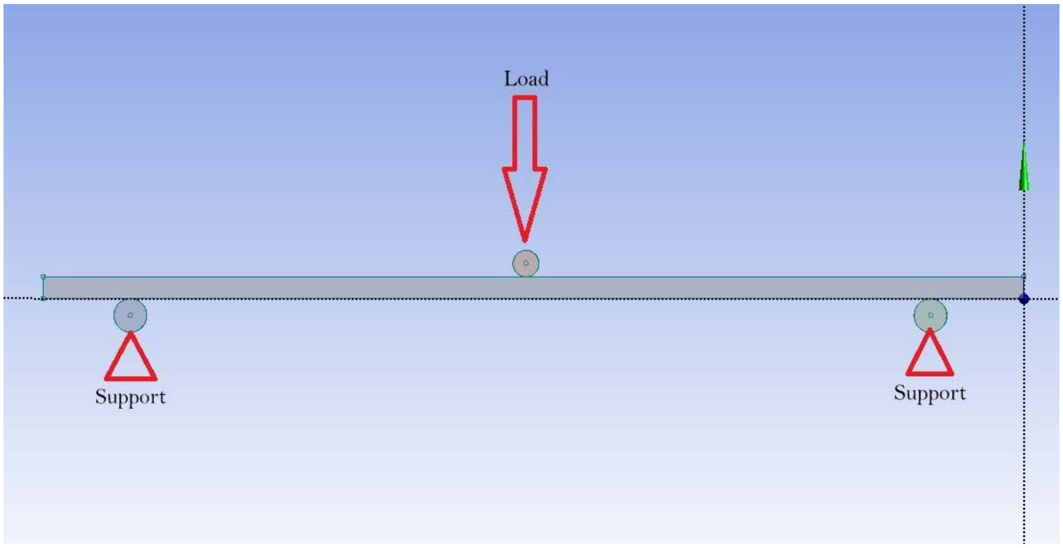


Figure 4.1 Illustration of 3 point bending analysis setup

From given formula defined by ASTM standards it can be derived that rate of crosshead motion is 18mm/min. Hence to achieve that rate we can model different forces.

4.2 Reliability tests and results

Total of 3 tests carried out under 3 point bending test in order to achieve best and accurate results for failure modes. Main advantage of using analysis software is we can analyze any entity given that its inputs are defined. Structural reliability analysis mainly deals with stress and strain developed in PCB. Hence, to analyze our PCB deformation, principal stress and equivalent elastic strain are of prime concern.

Table 4.1 Geometry setup for load and support

Object Name	*Force*	*Fixed Support*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	1 Edge	2 Edges
Definition		
Type	Force	Fixed Support
Define By	Components	
Coordinate System	Global Coordinate System	
X Component	0. N (ramped)	
Y Component	0. N (ramped)	
Z Component	Tabular Data	
Suppressed	No	

4.2.1 Test 1

Test 1 follows the rate of crosshead motion at 18mm/min for span of 10 seconds. To achieve this force of 1000N in negative Z direction; downward direction is applied, gradually increasing over span of 10 seconds.

Table 4.2 Ramped force input for test 1

Steps	Time [s]	X [N]	Y [N]	Z [N]
1	0.	0.	0.	1.
	1.			10.
2	2.	= 0.	= 0.	= -118.11
3	3.			= -246.22
4	4.			= -374.33
5	5.			= -502.44
6	6.			= -630.56
7	7.			= -758.67
8	8.			= -886.78
9	9.			= -1014.9
10	10.			-1143.

Table 4.3 Result table for test 1

Object Name	*Maximum Principal Stress*	*Normal Elastic Strain*	*Maximum Principal Elastic Strain*	*Strain Energy*	*Total Deformation*	*Equivalent Elastic Strain*
State	Solved					
Results						
Minimum	-1.3667e+007 Pa	-5.7181e-003 m/m	8.6835e-006 m/m	1.2883e-008 J	0. m	7.663e-005 m/m
Maximum	4.9157e+008 Pa	4.5244e-003 m/m	4.8826e-002 m/m	3.2733e-004 J	7.7096e-004 m	6.1576e-002 m/m
Minimum Occurs On	Solder mask top	c8	Solder mask top		Solder mask bot	c7
Maximum Occurs On	c1	Solder mask bot			Solder mask top	Solder mask bot
Minimum Value Over Time						
Minimum	-1.3667e+007 Pa	-5.7181e-003 m/m	-4.8111e-006 m/m	5.0155e-012 J	0. m	1.5469e-006 m/m
Maximum	-7.0244e+005 Pa	-9.0701e-005 m/m	8.6835e-006 m/m	1.2883e-008 J	0. m	7.663e-005 m/m
Maximum Value Over Time						
Minimum	1.336e+007 Pa	1.1436e-004 m/m	1.0048e-003 m/m	1.3107e-007 J	1.5444e-005 m	1.2327e-003 m/m
Maximum	4.9157e+008 Pa	4.5244e-003 m/m	4.8826e-002 m/m	3.2733e-004 J	7.7096e-004 m	6.1576e-002 m/m

Simulated results for test 1 show deformation along 10 seconds. PCB deformation shows 0.7mm as maximum deformation at applied load. This deformation value is important as it is used for all the stress and strain calculations in analysis.

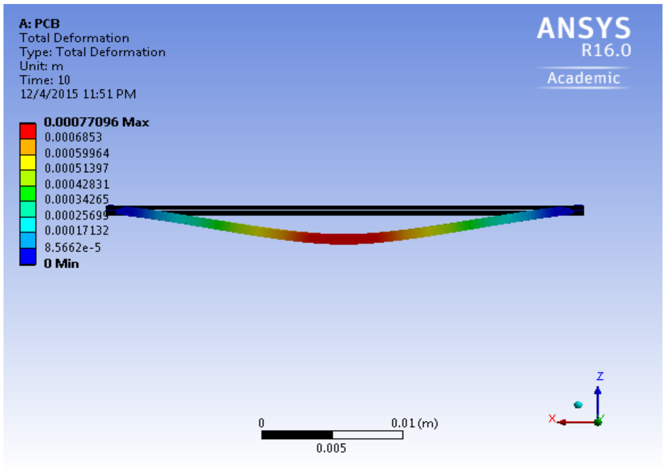


Figure 4.2 Total deformation for test 1

Equivalent elastic strain for test 1 shows lower values than 5% of the maximum elastic strain. Simulated data shows layers with induced maximum strain.

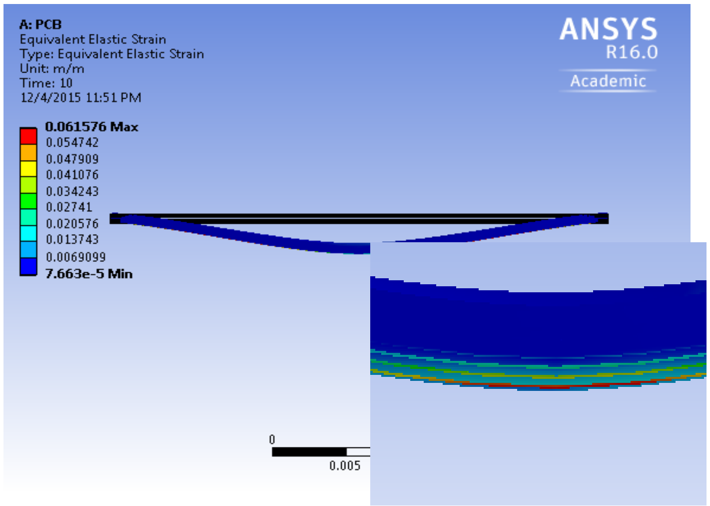


Figure 4.3 Equivalent elastic strain for test 1

4.2.2 Test 2

Test 2 follows the rate of crosshead motion at 27mm/min for span of 10 seconds. To achieve this force of 2000N in negative Z direction; downward direction is applied, gradually increasing over span of 10 seconds.

Table 4.4 Ramped force input for test 2

Steps	Time [s]	X [N]	Y [N]	Z [N]
1	0.	0.	0.	1.
	1.			10.
2	2.	= 0.	= 0.	= -245.11
3	3.			= -500.22
4	4.			= -755.33
5	5.			= -1010.4
6	6.			= -1265.6
7	7.			= -1520.7
8	8.			= -1775.8
9	9.			= -2030.9
10	10.			-2286.

Table 4.5 Results table for test 2

Object Name	*Maximum Principal Stress*	*Normal Elastic Strain*	*Maximum Principal Elastic Strain*	*Strain Energy*	*Total Deformation*
State	Solved				
Results					
Minimum	-7.0407e+007 Pa	-7.7085e-003 m/m	3.6783e-005 m/m	1.5768e-007 J	0. m
Maximum	6.3798e+008 Pa	5.9016e-003 m/m	5.4725e-002 m/m	4.2314e-004 J	8.7457e-004 m
Minimum Occurs On	Solder mask top		c5		Solder mask bot
Maximum Occurs On	c1	Solder mask bot	Solder mask top		f3
Minimum Value Over Time					
Minimum	-7.0407e+007 Pa	-7.7085e-003 m/m	-2.7939e-006 m/m	1.605e-011 J	0. m

Table 4.5 continued

Object Name	Maximum Principal Stress	Normal Elastic Strain	Maximum Principal Elastic Strain	Strain Energy	Total Deformation
Maximum	-4.7386e+005 Pa	-5.9195e-005 m/m	3.6783e-005 m/m	1.5768e-007 J	0. m
Maximum Value Over Time					
Minimum	8.2078e+006 Pa	7.7006e-005 m/m	5.7262e-004 m/m	4.2359e-008 J	8.7626e-006 m
Maximum	6.3798e+008 Pa	5.9016e-003 m/m	5.4725e-002 m/m	4.2314e-004 J	8.7457e-004 m

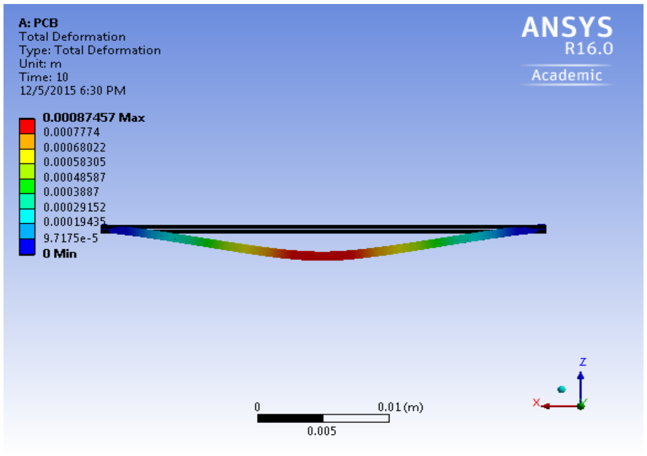


Figure 4.4 Total deformation for test 2

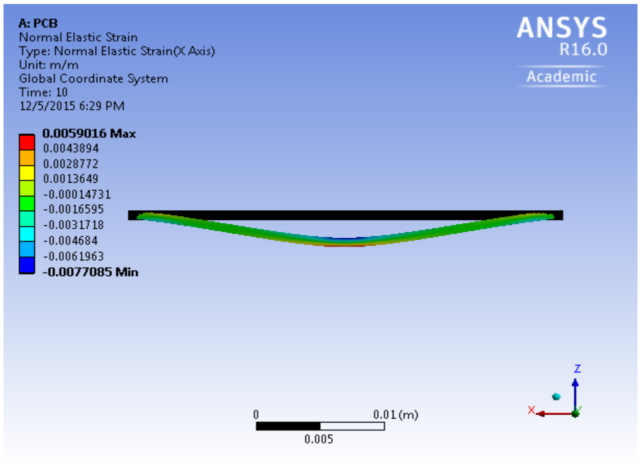


Figure 4.5 Normal elastic strain for test 2

4.2.3 Test 3 – failure mode

Test 1 follows the rate of crosshead motion at 18mm/min for span of 10 seconds. To achieve this force of 3000N in negative Z direction; downward direction is applied, gradually increasing over span of 10 seconds.

Table 4.6 Ramped force input for test 3

Steps	Time [s]	X [N]	Y [N]	Z [N]
1	0.	0.	0.	1.
	1.			10.
2	2.	= 0.	= 0.	= -372.11
3	3.			= -754.22
4	4.			= -1136.3
5	5.			= -1518.4
6	6.			= -1900.6
7	7.			= -2282.7
8	8.			= -2664.8
9	9.			= -3046.9
10	10.			-3429.

Table 4.7 Results table for test 3

Object Name	*Maximum Principal Stress*	*Normal Elastic Strain*	*Maximum Principal Elastic Strain*	*Strain Energy*	*Total Deformation*
State	Solved				
Results					
Minimum	-2.0964e+008 Pa	-2.3105e-002 m/m	9.9207e-005 m/m	1.3704e-006 J	0. m
Maximum	1.8967e+009 Pa	1.7559e-002 m/m	0.15843 m/m	3.7775e-003 J	2.6004e-003 m
Minimum Occurs On	Solder mask top		c5		Solder mask bot
Maximum Occurs On	c1	Solder mask bot	Solder mask top		f3
Minimum Value Over Time					
Minimum	-2.0964e+008 Pa	-2.3105e-002 m/m	-2.7939e-006 m/m	1.605e-011 J	0. m

Table 4.7 continued

Object Name	Maximum Principal Stress	Normal Elastic Strain	Maximum Principal Elastic Strain	Strain Energy	Total Deformation
Maximum	-4.7386e+005 Pa	-5.9195e-005 m/m	9.9207e-005 m/m	1.3704e-006 J	0. m
Maximum Value Over Time					
Minimum	8.2078e+006 Pa	7.7006e-005 m/m	5.7262e-004 m/m	4.2359e-008 J	8.7626e-006 m
Maximum	1.8967e+009 Pa	1.7559e-002 m/m	0.15843 m/m	3.7775e-003 J	2.6004e-003 m

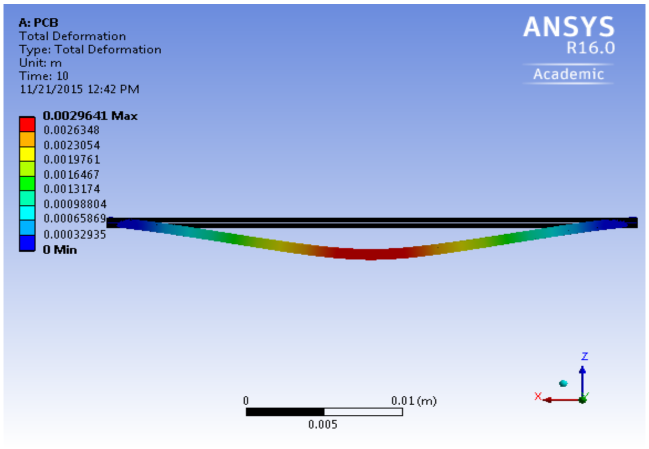


Figure 4.6 Total deformation for test 3

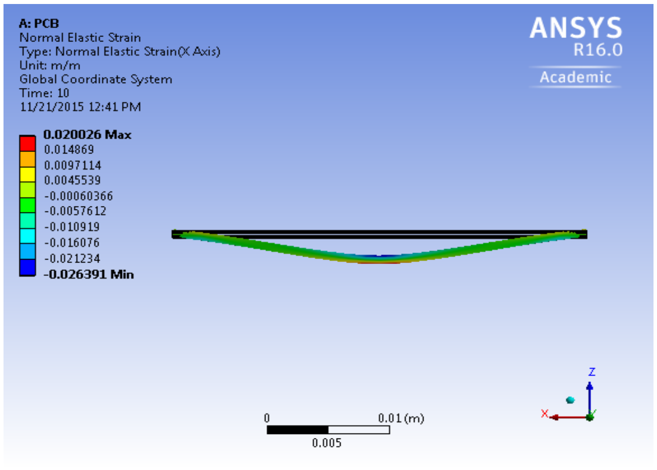


Figure 4.7 Normal elastic strain for test 3

Chapter 5

FOUR POINT BENDING TEST EXPERIMENT

5.1 Analysis setup

Similarly a four point bending setup is generated with two forces having L/3=10mm distance from supports. The individual package remains the same at Dimensions of single package are X= 3.382e-002 m, Y= 3.382e-002 m, Z= 7.34e-004 m. The calculated crosshead motion is 28mm/min. To achieve that force calculations according to 4 point bending analysis give actual force per unit time needed.

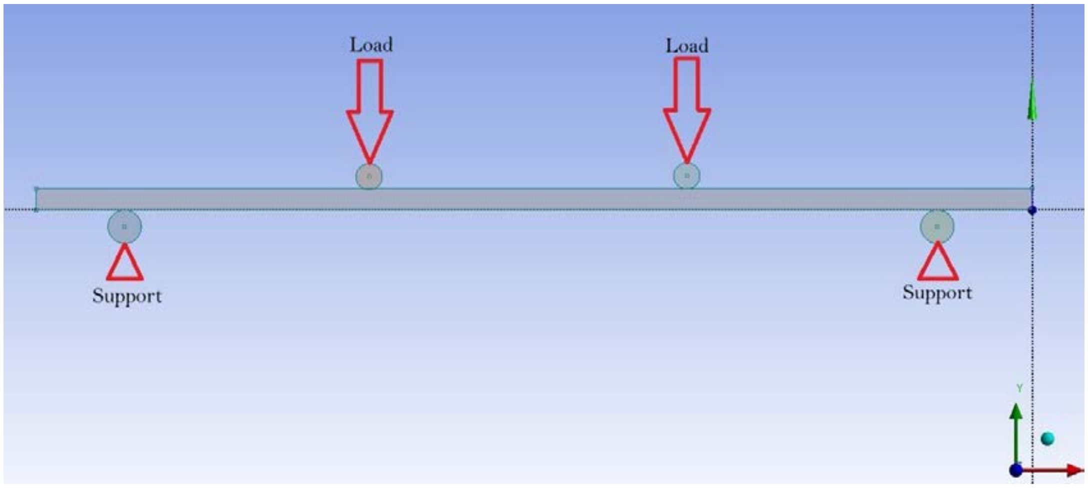


Figure 5.1 Illustration of 4 point bending analysis setup

5.2 Reliability tests and results

Total of 3 tests carried out for 4 point bending test. Structural reliability analysis mainly deals with stress and strain developed in PCB. Total deformation and normal elastic strain still remain the main concern.

Table 5.1 Geometry setup for load and support

Object Name	*Force*	*Fixed Support*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	2 Edges	
Definition		
Type	Force	Fixed Support
Define By	Components	
Coordinate System	Global Coordinate System	
X Component	0. N (ramped)	
Y Component	0. N (ramped)	
Z Component	Tabular Data	
Suppressed	No	

5.2.1 Test 1

Test 1 follows the rate of crosshead motion at 28mm/min for span of 10 seconds. Two loads, 500N each are applied to lines over the span of 10 seconds.

Table 5.2 ramped force input for test 1

Steps	Time [s]	X [N]	Y [N]	Z [N]
1	0.	0.	0.	0.
	1.			10.
2	2.	= 0.	= 0.	= -54.612
3	3.			= -119.22
4	4.			= -183.84
5	5.			= -248.45
6	6.			= -313.06
7	7.			= -377.67
8	8.			= -442.29

Table 5.2 continued

Steps	Time [s]	X [N]	Y [N]	Z [N]
9	9.	0	0	= -506.9
10	10.			-571.51

Table 5.3 Results table for test 1

Object Name	*Maximum Principal Stress*	*Normal Elastic Strain*	*Maximum Principal Elastic Strain*	*Strain Energy*	*Total Deformation*	*Equivalent Elastic Strain*
State	Solved					
Results						
Minimum	-1.0255e+007 Pa	-2.3664e-003 m/m	7.4833e-006 m/m	1.811e-008 J	0. m	3.1197e-005 m/m
Maximum	1.7013e+008 Pa	1.7814e-003 m/m	2.5543e-002 m/m	9.4033e-005 J	3.3315e-004 m	3.1955e-002 m/m
Minimum Occurs On	c8	Solder mask bot	c3		Solder mask bot	c3
Maximum Occurs On	c1	Solder mask top			r1	Solder mask top
Minimum Value Over Time						
Minimum	-1.0255e+007 Pa	-2.3664e-003 m/m	3.718e-008 m/m	6.7697e-012 J	0. m	6.2024e-007 m/m
Maximum	-74493 Pa	-3.5181e-005 m/m	7.4833e-006 m/m	1.811e-008 J	0. m	3.1197e-005 m/m
Maximum Value Over Time						
Minimum	5.3138e+006 Pa	4.718e-005 m/m	5.1996e-004 m/m	3.7645e-008 J	6.6676e-006 m	6.3941e-004 m/m
Maximum	1.7013e+008 Pa	1.7814e-003 m/m	2.5543e-002 m/m	9.4033e-005 J	3.3315e-004 m	3.1955e-002 m/m

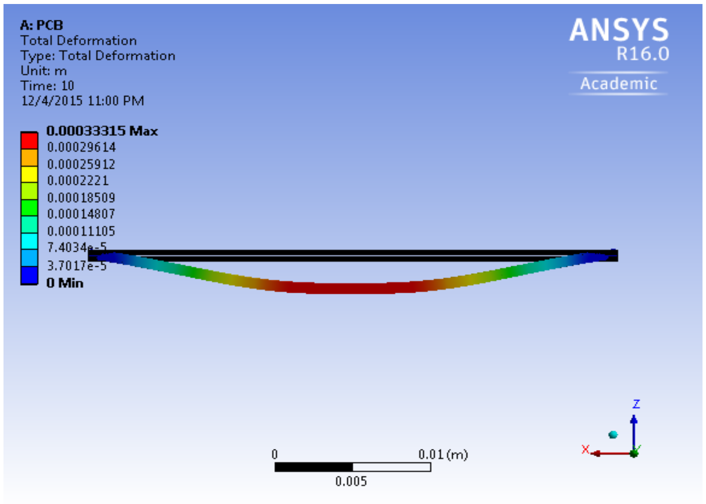


Figure 5.2 Total deformation for test 1

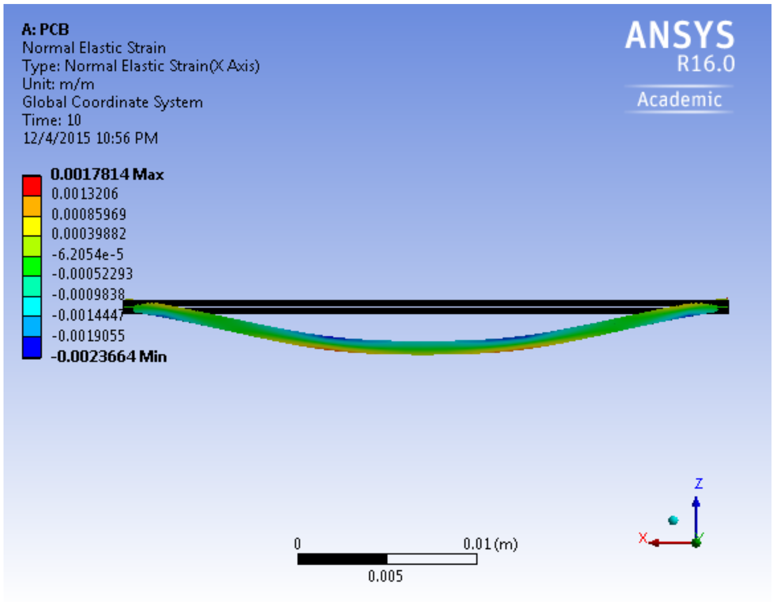


Figure 5.3 Normal elastic strain for test 1

5.2.2 Test 2

Test 2 follows the rate of crosshead motion at 28mm/min for span of 10 seconds. Two loads, 1000N each are applied to lines over the span of 10 seconds.

Table 5.4 Ramped force input for test 2

Steps	Time [s]	X [N]	Y [N]	Z [N]
1	0.	0.	0.	0.
	1.			10.
2	2.	= 0.	= 0.	= -118.13
3	3.			= -246.27
4	4.			= -374.4
5	5.			= -502.53
6	6.			= -630.67
7	7.			= -758.8
8	8.			= -886.93
9	9.			= -1015.1
10	10.			-1143.2

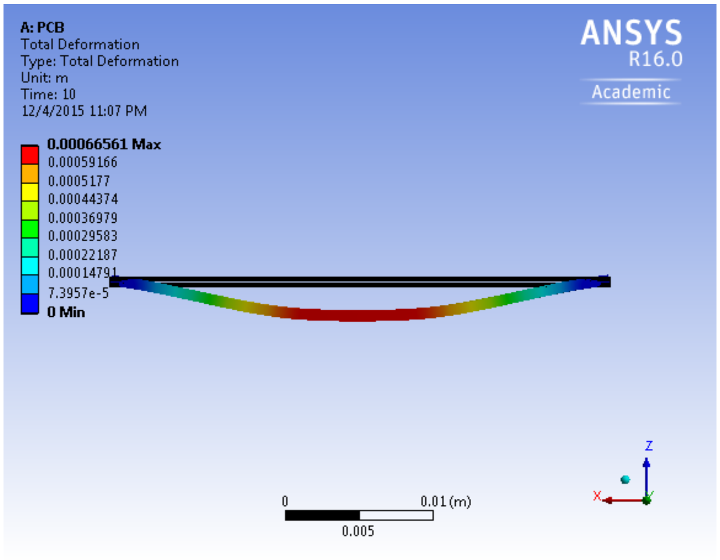


Figure 5.4 Total deformation for test 2

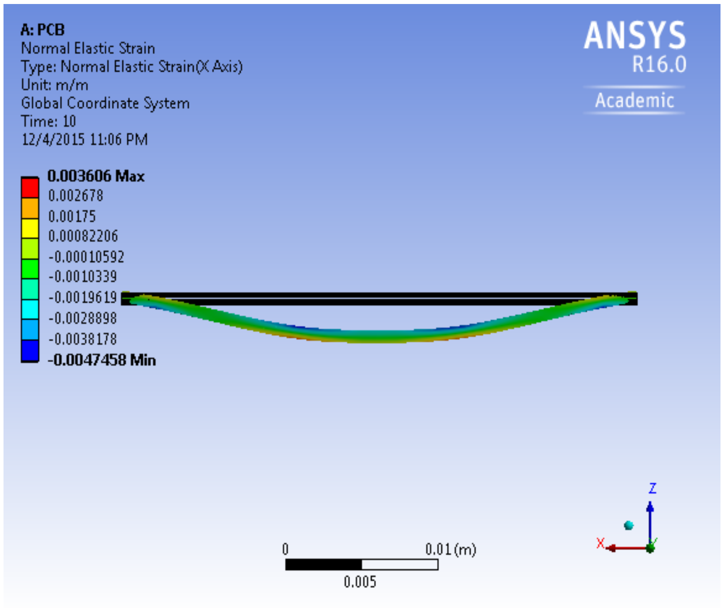


Figure 5.5 Normal elastic strain for test 2

5.2.3 Test 3 – failure mode

Test 3 follows the rate of crosshead motion at 28mm/min for span of 10 seconds. Two loads, 2000N each are applied to lines over the span of 10 seconds.

Table 5.5 ramped force input for test 3

Steps	Time [s]	X [N]	Y [N]	Z [N]
1	0.	0.	0.	0.
	1.			10.
2	2.	= 0.	= 0.	= -245.29
3	3.			= -500.58
4	4.			= -755.87
5	5.			= -1011.2
6	6.			= -1266.4
7	7.			= -1521.7
8	8.			= -1777.
9	9.			= -2032.3
10	10.			-2287.6

Table 5.6 results table for test 3

Object Name	*Maximum Principal Stress*	*Normal Elastic Strain*	*Maximum Principal Elastic Strain*	*Strain Energy*	*Total Deformation*	*Equivalent Elastic Strain*
State	Solved					
Results						
Minimum	-5.197e+007 Pa	-9.5321e-003 m/m	3.8606e-005 m/m	3.4939e-007 J	0. m	1.3006e-004 m/m
Maximum	6.7322e+008 Pa	7.3735e-003 m/m	9.9866e-002 m/m	1.4976e-003 J	1.327e-003 m	0.12736 m/m
Minimum Occurs On	c8	Solder mask bot	r2	c3	Solder mask bot	c3
Maximum Occurs On	c1	Solder mask top			r1	Solder mask top
Minimum Value Over Time						
Minimum	-5.197e+007 Pa	-9.5321e-003 m/m	3.718e-008 m/m	6.7697e-012 J	0. m	6.2024e-007 m/m
Maximum	-74493 Pa	-3.5181e-005 m/m	3.8606e-005 m/m	3.4939e-007 J	0. m	1.3006e-004 m/m
Maximum Value Over Time						
Minimum	5.3138e+006 Pa	4.718e-005 m/m	5.1996e-004 m/m	3.7645e-008 J	6.6676e-006 m	6.3941e-004 m/m
Maximum	6.7322e+008 Pa	7.3735e-003 m/m	9.9866e-002 m/m	1.4976e-003 J	1.327e-003 m	0.12736 m/m

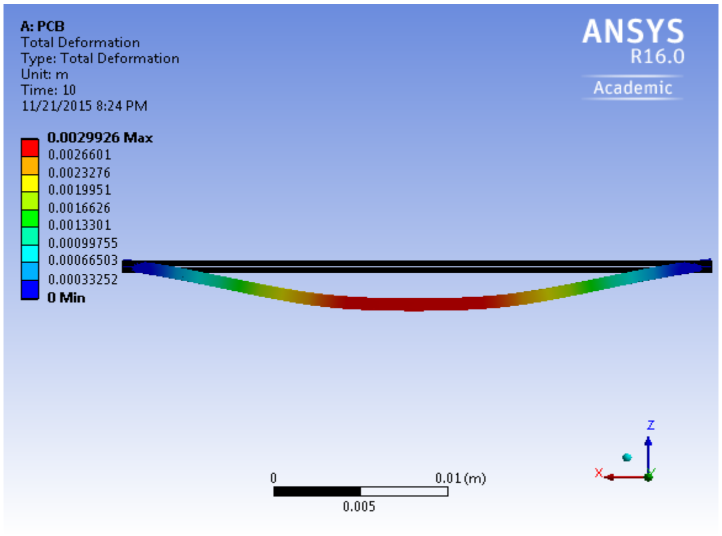


Figure 5.6 total deformation for test 3

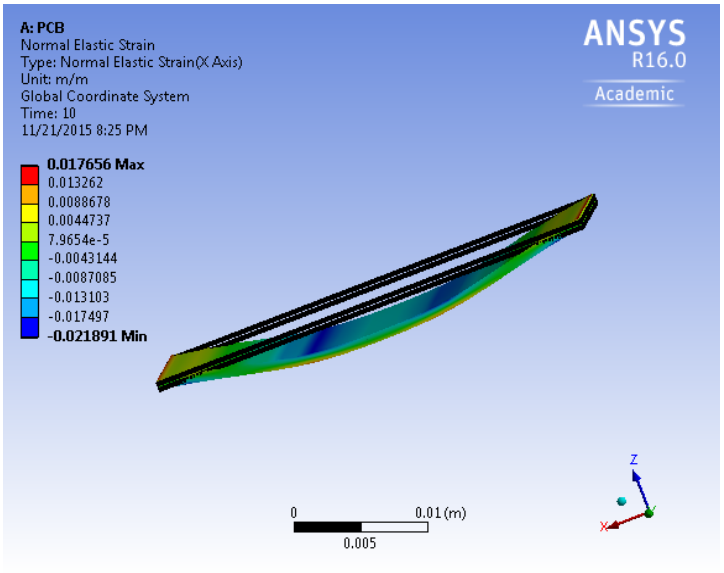


Figure 5.7 normal elastic strain for test 3

Chapter 6

FAILURE MODES ANALYSIS

Calculated results are mainly focused on total deformation, normal elastic strain and principal stress. These mechanical properties will help define failure modes and reliability of PCB. When all the experimental data is analyzed we can tabulate it in two ways for both the flexural bending test. First one is total deformation compared to force applied and the second one being total deformation compared to normal elastic strain. [1]

6.1 Failure analysis of 3 point bend test

Table 6.1 Tabulated forces and deformation for 3 point bend tests

	Deformation in M			Force in N		
Time	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
1	0	0	0	0	0	0
2	1.11E-04	2.22E-04	3.29E-04	-118.2	-245.11	-372.11
3	2.22E-04	4.44E-04	6.59E-04	-246.4	-500.22	-754.22
4	3.33E-04	6.63E-04	9.88E-04	-374.6	-755.33	-1136.3
5	4.44E-04	8.84E-04	1.32E-03	-502.8	-1010.4	-1518.4
6	5.50E-04	1.10E-03	1.65E-03	-631	-1265.6	-1900.6
7	6.66E-04	1.30E-03	1.98E-03	-759.2	-1520.7	-2282.7
8	7.77E-04	1.54E-03	2.31E-03	-887.4	-1775.8	-2664.8
9	8.88E-04	1.77E-03	2.63E-03	-1015.6	-2030.9	-3046.9
10	9.99E-04	1.99E-03	1.30E-03	-1143.8	-2286	-3429

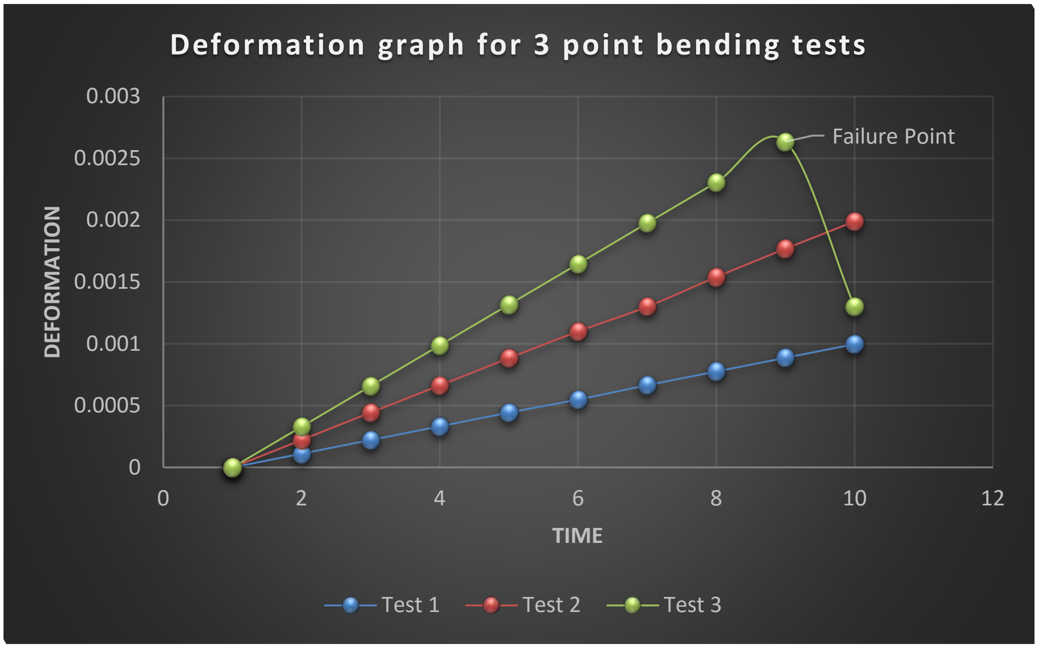


Figure 6.1 Deformation vs time graph for 3 point bending tests

Table 6.2 Tabulated strain and deformation for 3 point bend tests

	Strain M/M		
Deformation in M	Test 1	Test 2	Test 3
0	0.00E+00	0.00E+00	0.00E+00
3.40E-01	1.17E-02	1.36E-02	3.69E-02
6.60E-01	2.43E-02	2.77E-02	7.38E-02
9.80E-01	3.68E-02	4.16E-02	0.10967
1.30E+00	4.92E-02	5.54E-02	0.14432
1.62E+00	6.15E-02	6.91E-02	0.17771
1.94E+00	7.36E-02	8.26E-02	0.2098
2.26E+00	8.56E-02	9.60E-02	0.24056
2.58E+00	9.75E-02	0.10928	0.26999
2.90E+00	0.10925	0.12237	0.2996

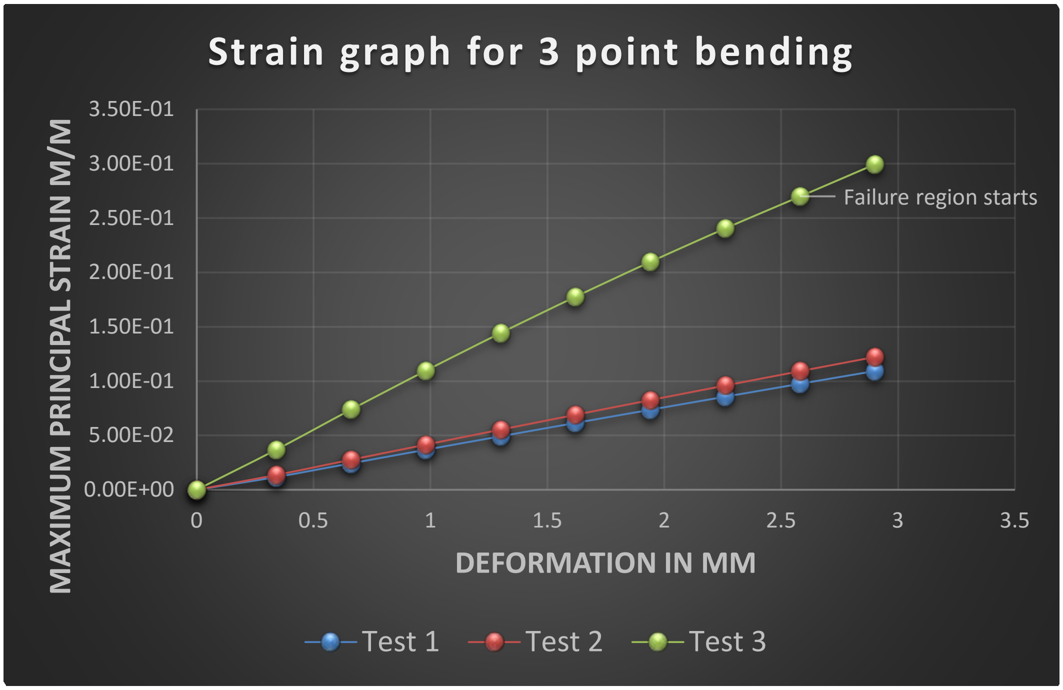
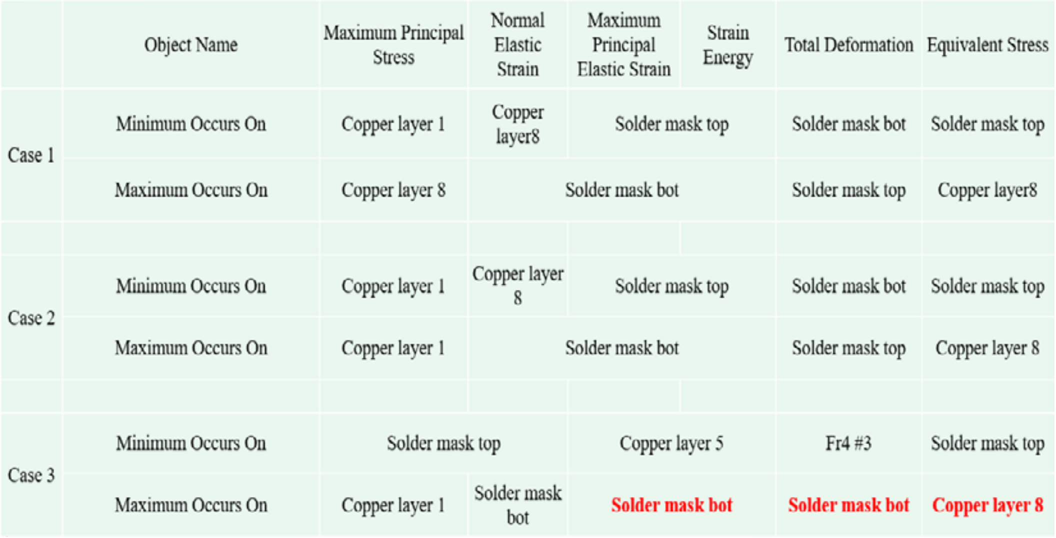


Figure 6.2 Strain vs deformation plot for 3 point bending tests

6.2 Failure analysis overview of 3 point bend test

Table 6.3 Tabulated failure analysis for stacked layers



	Object Name	Maximum Principal Stress	Normal Elastic Strain	Maximum Principal Elastic Strain	Strain Energy	Total Deformation	Equivalent Stress
Case 1	Minimum Occurs On	Copper layer 1	Copper layer8	Solder mask top		Solder mask bot	Solder mask top
	Maximum Occurs On	Copper layer 8	Solder mask bot			Solder mask top	Copper layer8
Case 2	Minimum Occurs On	Copper layer 1	Copper layer 8	Solder mask top		Solder mask bot	Solder mask top
	Maximum Occurs On	Copper layer 1	Solder mask bot			Solder mask top	Copper layer 8
Case 3	Minimum Occurs On	Solder mask top		Copper layer 5		Fr4 #3	Solder mask top
	Maximum Occurs On	Copper layer 1	Solder mask bot	**Solder mask bot**		**Solder mask bot**	**Copper layer 8**

Failure analysis reveals that in 3 point bending test maximum deformation and normal elastic strain is maximum on bottom solder mask which results into failure.

6.3 Failure analysis of 4 point bending tests

Table 6.4 Tabulated forces and deformation for 4 point bend tests

	Deformation in M			Force in N		
Time	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
1	0	0	0	0	0	0
2	8.45E-05	1.68E-04	3.33E-04	-54.656	-118.2	-245.29
3	1.69E-04	3.34E-04	6.65E-04	-119.31	-246.4	-500.58
4	2.53E-04	5.05E-04	9.97E-04	-183.97	-374.6	-755.87
5	3.38E-04	6.74E-04	1.33E-03	-248.62	-502.8	-1011.2
6	4.23E-04	8.42E-04	1.66E-03	-313.28	-631	-1266.4
7	5.07E-04	1.01E-03	1.99E-03	-377.93	-759.2	-1521.7
8	5.92E-04	1.18E-03	2.32E-03	-442.59	-887.4	-1777
9	6.67E-04	1.35E-03	2.66E-03	-507.24	-1015.6	-2032.3
10	7.61E-04	1.51E-03	1.40E-03	-571.9	-1143.8	-2287.6

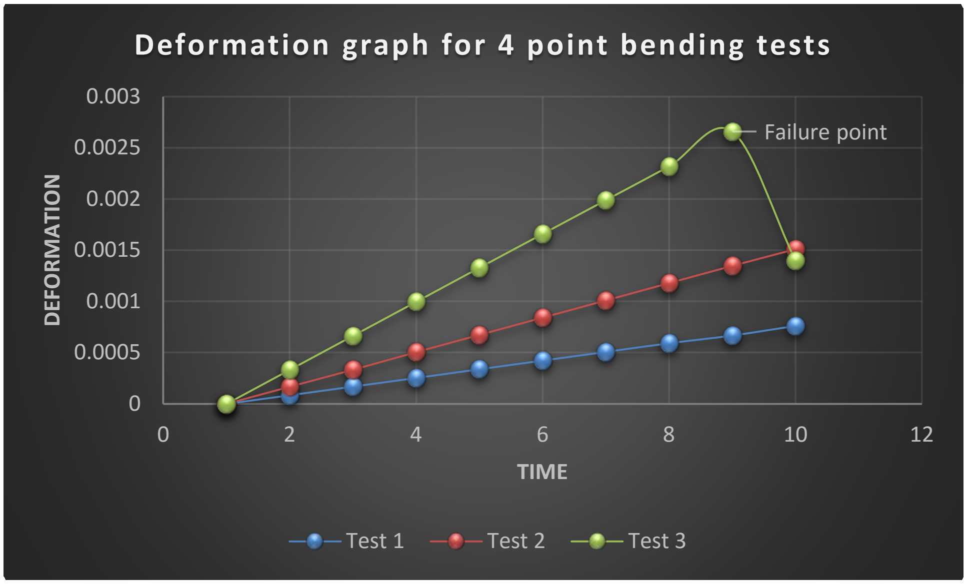


Figure 6.3 Deformation vs time graph for 4 point bending tests

Table 6.5 Tabulated strain and deformation for 4 point bend tests

	Strain M/M		
Deformation in M	Test 1	Test 2	Test 3
0	0.00E+00	0.00E+00	0.00E+00
3.40E-01	5.62E-03	1.22E-02	4.04E-02
6.60E-01	1.23E-02	2.53E-02	8.01E-02
9.80E-01	1.89E-02	3.82E-02	1.13E-01
1.30E+00	2.54E-02	5.11E-02	0.14432
1.62E+00	3.20E-02	6.39E-02	0.17771
1.94E+00	3.85E-02	7.65E-02	0.2098
2.26E+00	4.50E-02	8.90E-02	0.24056
2.58E+00	5.15E-02	0.10143	0.26999
2.90E+00	5.79E-02	0.11369	0.3005

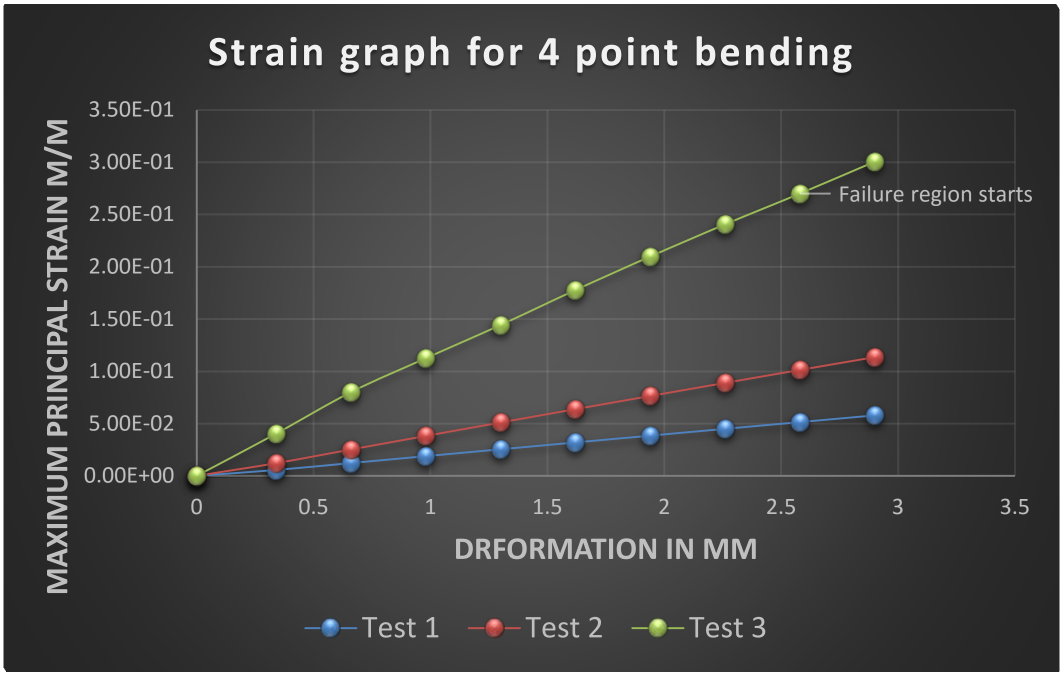
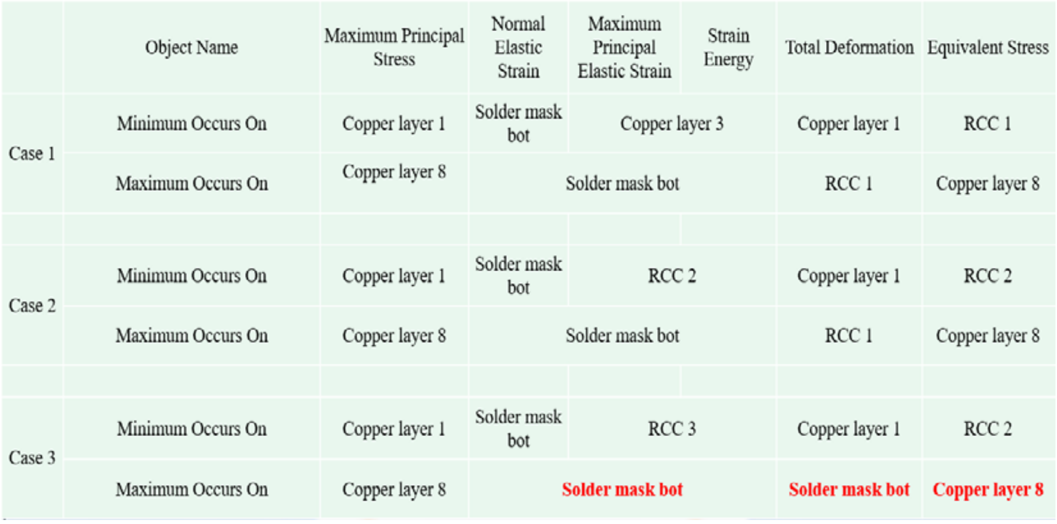


Figure 6.4 Strain vs deformation plot for 4 point bending tests

6.4 Failure analysis overview of 4 point bend test

Table 6.6 Tabulated failure analysis for stacked layers



	Object Name	Maximum Principal Stress	Normal Elastic Strain	Maximum Principal Elastic Strain	Strain Energy	Total Deformation	Equivalent Stress
Case 1	Minimum Occurs On	Copper layer 1	Solder mask bot	Copper layer 3		Copper layer 1	RCC 1
	Maximum Occurs On	Copper layer 8	Solder mask bot			RCC 1	Copper layer 8
Case 2	Minimum Occurs On	Copper layer 1	Solder mask bot	RCC 2		Copper layer 1	RCC 2
	Maximum Occurs On	Copper layer 8	Solder mask bot			RCC 1	Copper layer 8
Case 3	Minimum Occurs On	Copper layer 1	Solder mask bot	RCC 3		Copper layer 1	RCC 2
	Maximum Occurs On	Copper layer 8	**Solder mask bot**			**Solder mask bot**	**Copper layer 8**

Failure analysis reveals that in 4 point bending test maximum deformation and normal elastic strain is maximum on bottom solder mask which results into failure. Deformation data reveals that due of tensile strength variation in the stackup, different concentrations of mechanical properties are observed across stacked layers. In 3 point bend test; top layer has high stress but at point of failure maximum deformation occurs at bottom most layer due to resulting strain. Similarly, 4 point bending test failure initiates through RCC layers and actual failure occurs at bottom most layer. Bottom most copper layers tend to have more stress concentration than any other layers and bottom solder mask shows highest strain resulting in failure

From the analysis results we can now define the safety conditions for given PCB and determine failure modes.

Chapter 7

CONCLUSION

After analysis following conclusions were drawn towards reliability of PCB

- Principal strain is observed maximum at bottom solder mask layer which questions the reliability of PCB at that specific layer.
- From strain analysis of bot 3 point bending and 4 point bending tests it is observed that at the rate more than 4800 micro-strain/sec the PCB fails.
- Both 3 point bend and 4 point bend tests reveal similar results with minor change in strain regions due to position of loading
- Bottom copper layer shows maximum stress before failure exceeding 210MPa
- Detailed analysis also reflects that PCB at board level has proven to be strong in slightly extreme situations. It proves its reliability for moderately extreme mechanical conditions.
- A suggestion would be to use copper alloy with higher tensile strength if there are any applications for extreme applications

Chapter 8

FUTURE WORK AND SCOPE

- Industries follow practical methods for mechanical reliability testing. This analysis part will help correlating the simulation results with practical results to determine which method is more accurate
- For complex circuit boards that has different packages, it is difficult to perform 3 point bending or 4 point bending tests due to their symmetry
- With new era of technology already there are flexible PCBs in market. It is a big challenge to test their mechanical reliability

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His primary research areas include reliability analysis, micro-nano fabrication and MEMS. He has worked at the UTA center of nanotechnology for 1 year. He has also worked on the reliability analysis for various printed circuit boards. The project he has worked on was testing board level reliability of custom printed circuit boards manufactured by Texas Instruments.

He joined the EMNSPC research team under Dr. Dereje Agonafer in February, 2015.