COMPARATIVE STUDY OF VISCOELASTIC MODELING AND LINEAR MODELING FOR WAFER LEVEL CHIP SCALE PACKAGE UNDER DROP IMPACT

by

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Abstract

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Wafer level chip scale packages are one the preferred choice in the electronic industry to meet the need of new miniaturization of the recent devices. It has high efficiency in packaging and has low cost. On the other hand, the drop impact failure is one of the growing risk in day to day use of the portable devices. Therefore, to ensure product quality and to integrate more complicated functionality in these devices comprehensive reliability tests need to be performed before delivering the product. Accelerated thermal cycling, drop testing and power cycling are some accepted test methods used to access board level reliability. The printed circuit boards used for various packages are modeled as orthotropic elastic material. However, PCB substrate materials are macromolecule resins, which are typical viscoelastic in nature. So, assigning viscoelastic properties would me more appropriate for performing the reliability tests. Dynamic Mechanical Analyzer(DMA) is used to characterize the viscoelastic material properties of the PCB's. The frequency and temperature dependent complex moduli are also obtained from DMA are used to model the PCB's as viscoelastic material in ANSYS workbench. Drop test is performed and the results obtained are compared to those obtained from orthotropic elastic modelling of PCB's.

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Chapter 1 INTRODUCTION

1.1 Drop Test

With the increase of miniaturization in Portable electronic devices, the risk of dropping is increasing rapidly. Therefore, it is very important to ensure reliability not only due to thermal stress but also due to mechanical stress. Due to drop impact the shock experienced damages the exterior of the device and imparts stress in the internal parts of the device. Additional stress is caused in the components due to bending of printed circuit board (PCB) during the process. The solder joints used for mounting the parts on the PCB, fail; which causes failure of the assembly of PCB after number of drops. Thus, drop test reliability of the Integrated Circuit assemblies is becoming a matter of concern.

In today's highly demanding market there is a need to establish a fast and cheap method for drop testing. Product level drop test depend on many factors like design, gripping method, etc. making it very complex when compared to board level drop test. Also, it is difficult to manufacture and test the packages experimentally. Friction between gliding rods and the drop table, contact surface, environmental factors, etc. become deciding factors for the accuracy of the test in actual drop set up. for primary study and optimization, the simulation suggested by JEDEC is the well-suited method for the board level experimental setup.

Joint Electronic Device Engineering council (JEDEC) has standardized the board level drop test method in the report JESD22-B111 [1] to evaluate the mechanical behavior by performing the Board Level Drop test reliability on integrated circuit packages. Board consists of 5 columns and 3 rows array of 15 components mounted on the top of the board. The JEDEC standard board is shown in the Figure 1-1 with all the dimensions.

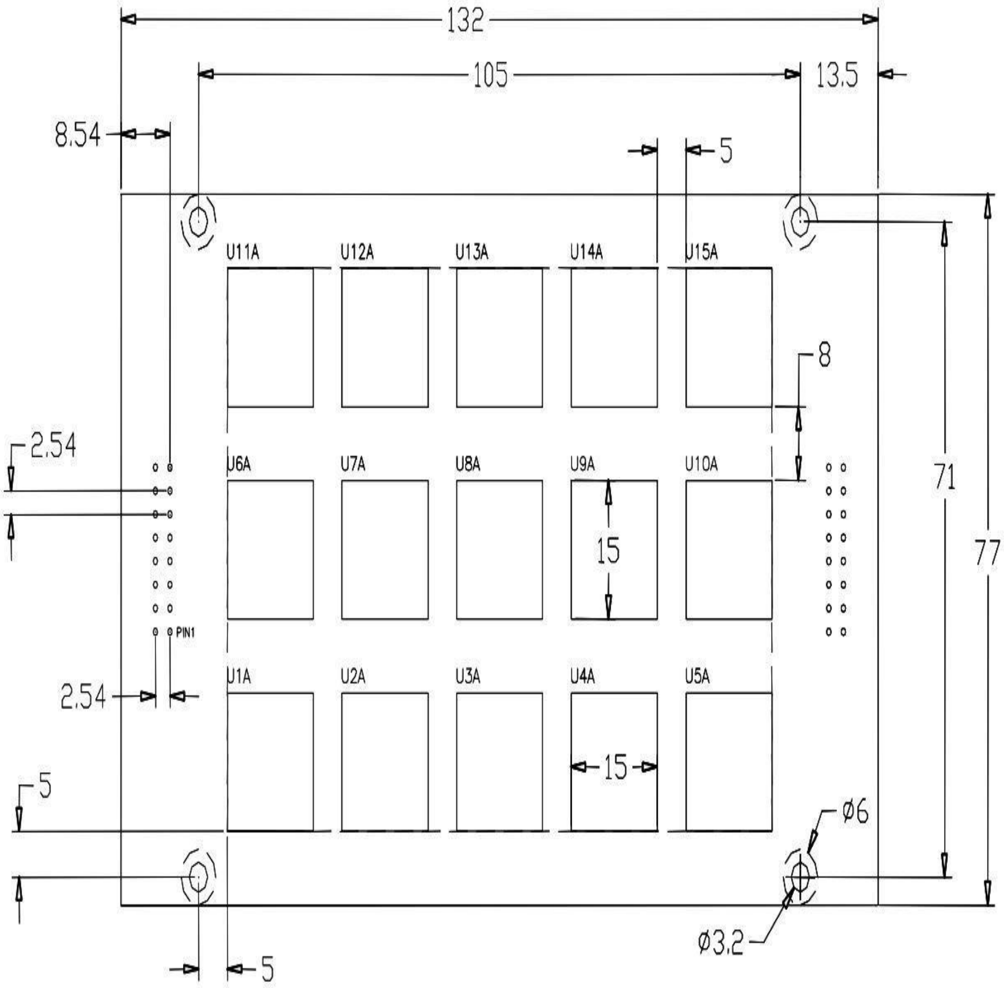


Figure 1-1 JEDEC Drop Board Construction

The JEDEC drop test equipment setup schematic is shown in Figure 1-2

Four screws are used to mount the board on the drop table. The drop table drops down and strikes the rigid base. Between the base plate and the board, this screws acts as standoff which allow the board to bend upon drop impact. To produce the desired load conditions, the base should be of felt material. To produce certain G levels the drop height is adjusted. As per JEDEC, G level is 1500 Gs and the input should be of half-sine wave impulse off 0.5ms as shown in Figure 1-2.

The board should be mounted on the base plate facing downwards and the relative movement between the board and the drop table should be zero.

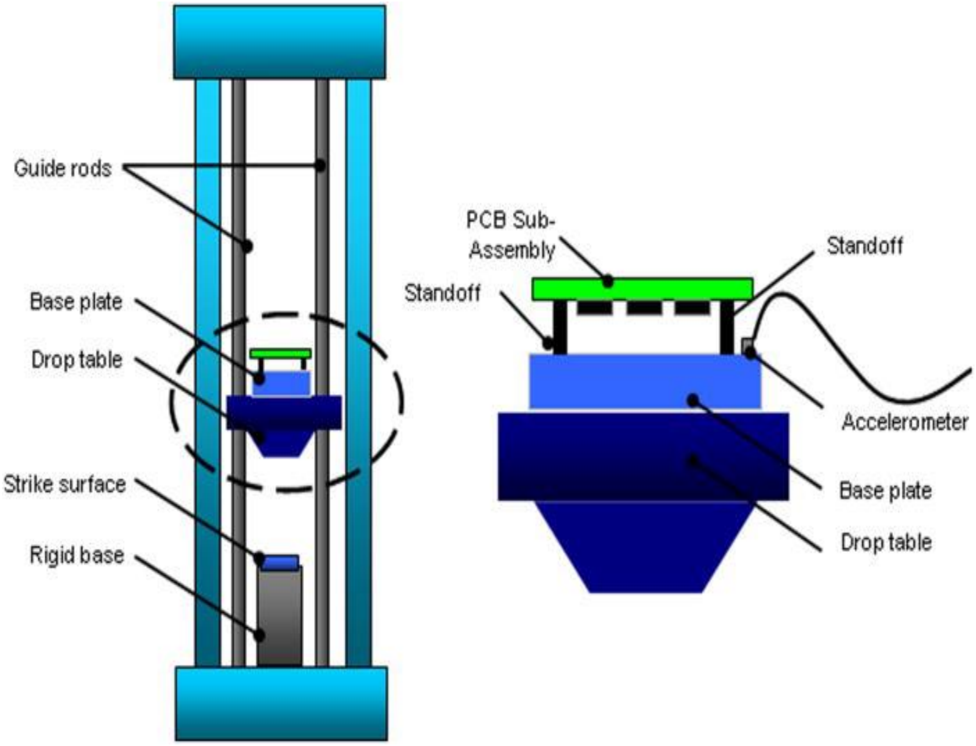


Figure 1-2 Schematic of JEDEC Drop Experimental Setup

1.2 Types of Printed Circuit Board Modeling

Types of Modelling

Finite element tools are widely used for rapid design optimization and also for understanding board level reliability issues

Depending on speed and accuracy desired in thermal and mechanical simulation.

There are three approaches to PCB modeling [2]

1) Lumped board properties approach
    - Orthotropic properties for the in-plane and normal directions are assigned
    - When board performance is not primary focus it is used for system-level
    - Solve time is reduced as mesh count is significantly less and fraction is not computed
2) Explicit geometry approach
    - Geometry of traces, planes and via's are modeled
    - Highly accurate results
    - Very large mesh size leading to very long solution times.
3) ECAD approach
    - From ECAD data, map the metal fraction in each layer.
    - Import of an ECAD file is required.
    - Results of high accuracy and fast.

1.3 Wafer level chip scale package

Wafer level chip scale package are one of the preferred choice in electronic industry to meet the need of high performance and efficiency in electronic devices.

The growing demand of market for faster and cheaper electronic devices gave a mission to develop smaller size packages which resulted in low cost chip scale packages such as Wafer Level Chip Scale Package (WLCSP), Quad Flat No- Lead (QFN) and Thin profile pitch Ball grid Array (TFBGA) [14]. Chip scale package is defined as "A package whose area is generally no greater than 120% of the area of the semiconductor device it contains" [3] to JESD30D.

The important advantage of Wafer level chip scale package is that, it has small form factor because it is basically a chip size package and also packaging cost is very less [4] .

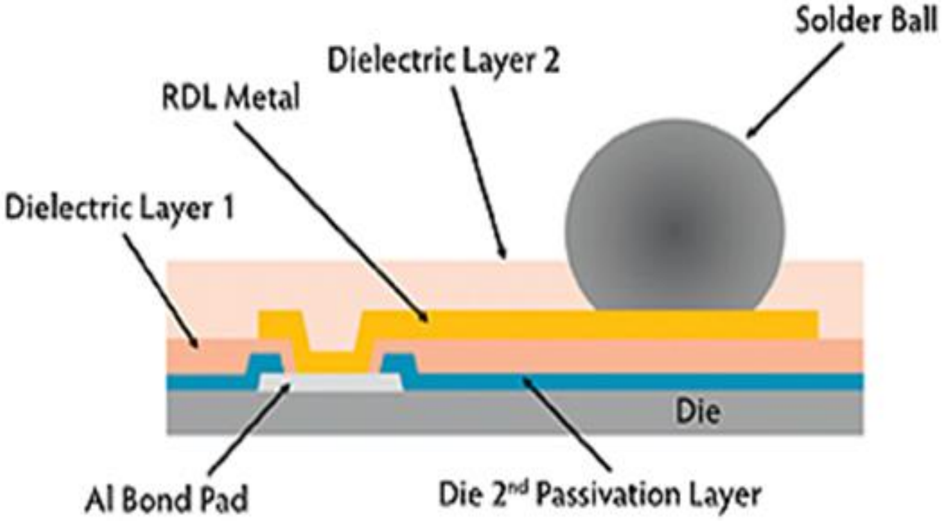


Figure 1-3 Typical WLCSP Construction

For this work, the WLCSP used is Texas instruments (TI) YFF (S-XBGA-N49) as shown in Figure 1-4 [5]. In a single WLCSP as a pattern of 7X7 array there are total 49 solder balls/interconnects. The chip size is 2.8X2.8 mm and pitch is 0.40 mm.

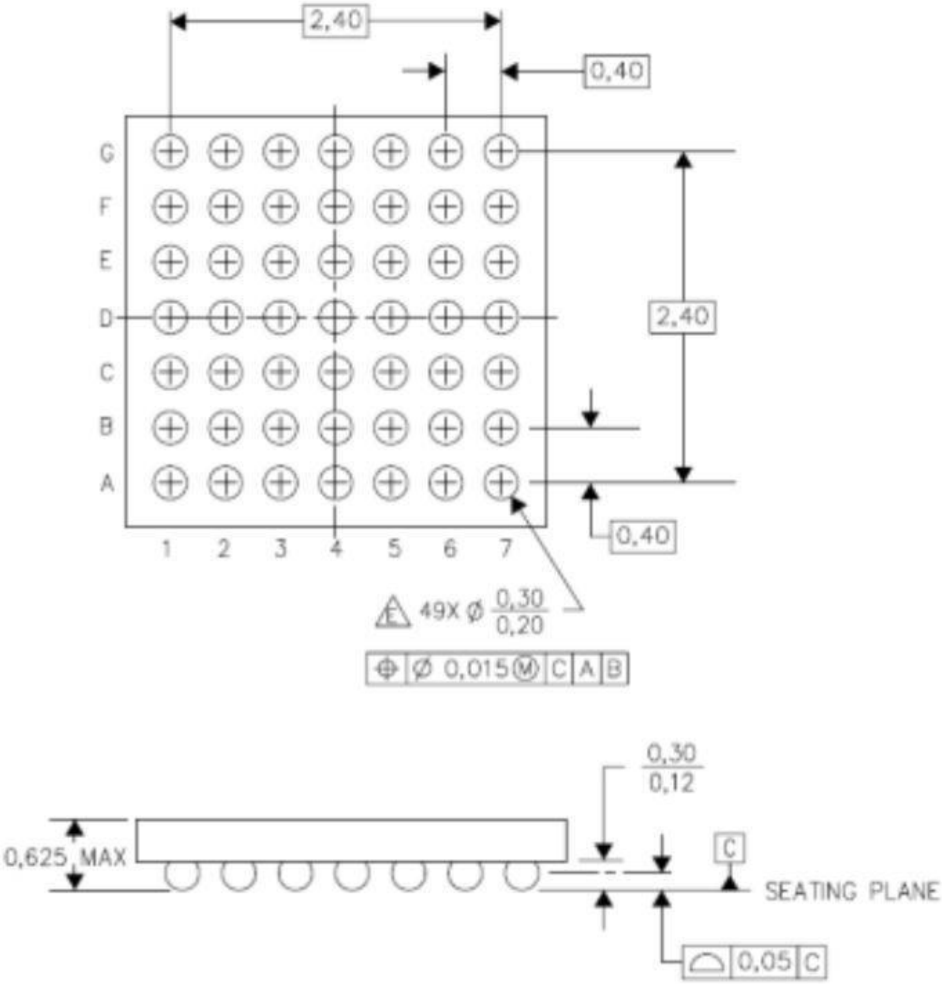


Figure 1-4 TI 49YFF Solder Ball Pattern [5]

1.4 Motivation and Objective

Motivation:

Printed circuit boards are composite materials in which orthotropic elastic material properties are assigned in the lumped board properties approach.

However, PCB substrate materials are macromolecule resins, which are typical viscoelastic in nature.so, assigning viscoelastic properties would me more appropriate. Previous work done by Liu et. al.[6] has analytically shown that the viscoelasticity of the PCB has an influence on the behavior under drop impact.

It has become very important to ensure reliability of the product under thermal stress as well as mechanical stress. To assess board level reliability, Accelerated thermal cycling, power cycling and drop test are few test methods

These tests can be done computationally using finite element simulation software such as ANSYS workbench.

Objective :

- To Perform viscoelastic material characterization of printed circuit boards.
- To investigate the effect of viscoelastic modelling under drop impact
- Comparing the results of viscoelastic modelling and linear orthotropic modelling.

Chapter 2 LITERATURE REVIEW

A comprehensive research has been done on the drop impact reliability in the previous decades. The dynamic behavior of the board due to drop impact have been studied both experimentally and analytically. Procedure to perform drop test is published by JEDEC in the detailed guide JESD22-B111[1] which also list all the failures of drop impact. The product level drop impact behavior has been studied [17]. By conducting drop tests and failure analysis and correlating the drop failure analytically and experimentally Tee, et al [Developed a life prediction model.

J Wu [12] [19] described the drop test computational method by using explicit solver for the drop test simulation at component level and product level. To decrease the computational time and complexity in modelling the solid to Submodel technique for the half symmetry model has been explained by the H Dhiman, et al. [18]. Use of implicit solver to perform simulation of drop test in Input G method which takes less time is shown by Tee et al. [10]. Under the board level drop impact, Liu et al. [6] mentioned that the viscoelasticity of PCB materials affects the dynamic nature of the board. Mottahedi et al [7] mentioned that the unknown proxy coefficients can be determined by conducting relaxation test and they conducted numerical analysis of relaxation test based on Prony series material.

Fernanda et al. [20] have described how viscoelastic parameters can be determined directly from frequency domain experimental data and they also described to characterized the intrinsic evolution of Storage modulus, loss modulus by using DMA with the frequency. Dynamic frequency sweep test can be determined by the dynamic modulus, which contains two parts of the storage modulus and the loss modulus. With the help of dynamic modulus time curves, proxy series coefficients of the generalized Maxwell model can be determined are explained by Yan Hongqing et al.[22]. The results of matrix method from the dynamic modulus E are similar to non-linear fitting tool origin software 8.0.

When the data have significant variance, it is hard to get a direct fitting of a Prony series models to viscoelastic experimental data. S. W. Park and Y. R. Kim [21] have stated an efficient method of fitting Prony-series models to viscoelastic experimental data with power-law presmoothing.

Chapter 3 MATERIAL CHARACTERIZATION

Material characterization is done to precisely anticipate the behavior of material under different loading. Different properties and structure of material are determined by characterizing the material. To analyze the material fully in Finite Element analysis, material properties will be required. Providing more accurate inputs to ANSYS workbench will result in High accurate results.

- Coefficient of Thermal Expansion
- Young's Modulus
- Storage modulus (E')
- Loss modulus (E'')

Material properties mentioned above are determined .

To determine the material properties the below mentioned machines were used

- Thermo Mechanical Analyzer (TMA)
- Dynamic Mechanical Analyzer (DMA)
- Instron Microtester
- Shimadzu Tensile Testing Machine

3.1 Thermo Mechanical Analyzer (TMA)

In plane and out of plane coefficient of thermal expansion (CTE) is detαermined using Thermo mechanical analyzer.

Coefficient of thermal expansion is defined as change in degree of expansion per degree of temperature.

$$\alpha = \varepsilon/\Delta T$$

Where

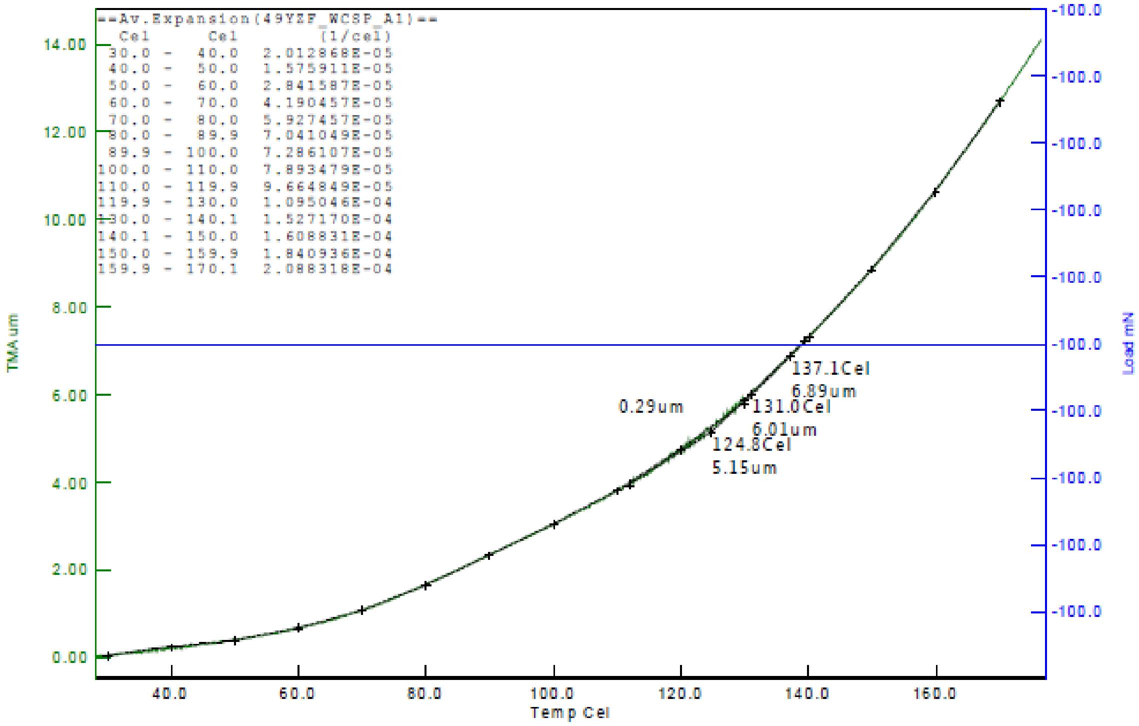
α - Coefficient of Thermal Expansion (CTE) ppm/°C

ε - Strain (mm/mm)

ΔT- Difference in Temperature (°C)

Figure 3-1 Thermo Mechanical Analyzer [15]

For CTE measurement a sample size of 6 mm × 6mm is used. The sample is placed along its length to determine the CTE in XY plane. For CTE measurement along Z direction, the sample is placed on it thickness in quartz cylinder. CTE is measured from 20°C to 180°C and the sample is subjected to constant load of -100mN and ramp of 5° C/min. A plot of CTE values calculated at different temperatures with interval of 10°C is shown below.



```
==Av.Expansion(49YZF_WCSP_A1)==
  Cel       Cel         (1/cel)
 30.0 -   40.0   2.012868E-05
 40.0 -   50.0   1.575911E-05
 50.0 -   60.0   2.841587E-05
 60.0 -   70.0   4.190457E-05
 70.0 -   80.0   5.927457E-05
 80.0 -   89.9   7.041049E-05
 89.9 -  100.0   7.286107E-05
100.0 -  110.0   7.893479E-05
110.0 -  119.9   9.664849E-05
119.9 -  130.0   1.095046E-04
130.0 -  140.1   1.527170E-04
140.1 -  150.0   1.608831E-04
150.0 -  159.9   1.840936E-04
159.9 -  170.1   2.088318E-04
```

Figure 3-2 CTE values at different temperatures

3.2 Instron Microtester

Instron Microtester is used to apply tensile loading to samples in order to determine the young’s modulus.

Young's modulus, is a measure of the stiffness of a solid material and also known as elastic modulus. Young's modulus defines the relationship between stress (force per unit area) and strain (proportional deformation) in a material.

To measure strain during sample extension an Extensometer is positioned on the sample. The Force-displacement graph plotted during the test is given by the software to which extensometer and instron are connected. Stress is determined by dividing the load with the cross-sectional area of the sample and strain is determined using extensometer.

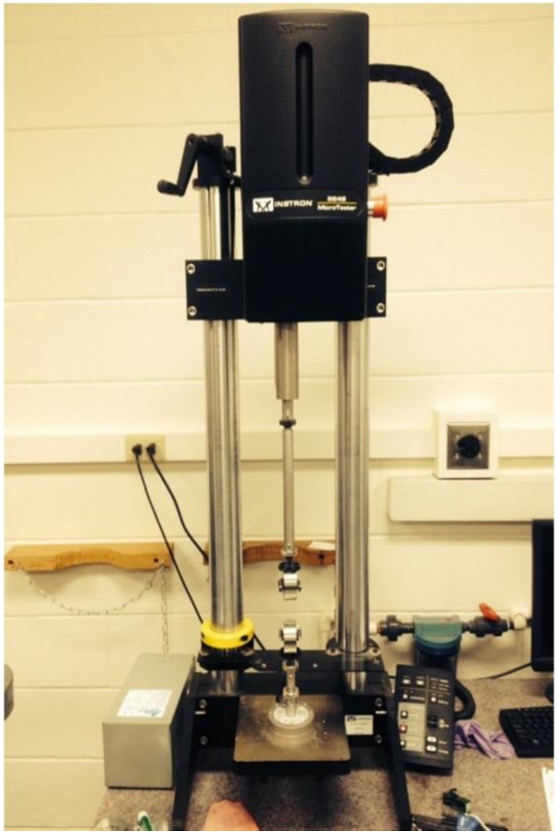


Figure 3-3 Sample Dimensionsron Microtester [15]

As per STM standard Dog bone sample is prepared for testing. There should be good grip space available to hold the sample tightly during the test to get accurate results.

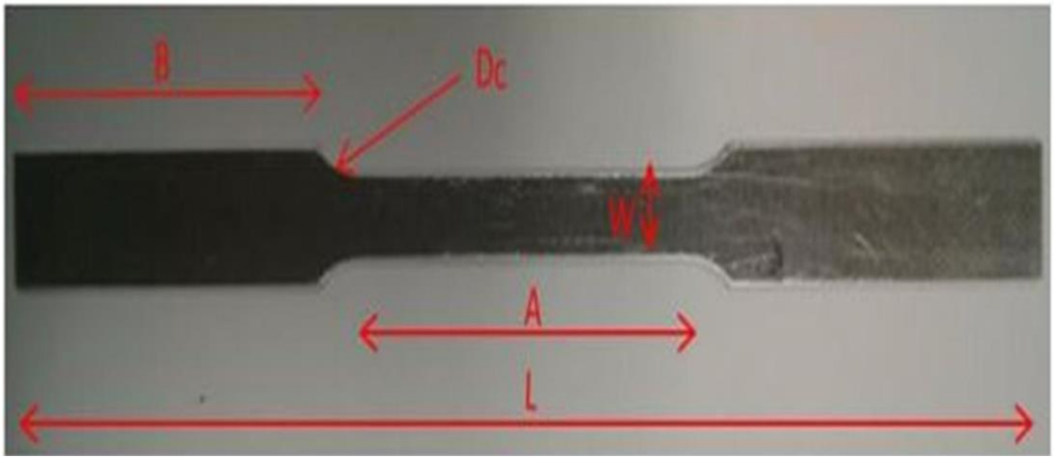


Figure 3-4 Dog bone sample [15]

Table 3-1Sample Dimensions [15]

Dimension	Symbol	Length(mm)
Length	L	100
Width	W	6
Length of Reduced Part	A	32
Length of Grip Section	B	30
Curvature Distance	Dc	4
Radius of Curvature	R	6

Instron Microtester 5848 is used for measuring Young's modulus of PCB Samples with force of maximum load cell of 2kN.Aluminium sample is used to benchmark the test setup and the procedure. The theoretical and experimental results are in complete agreement.

3.3 Shimadzu Tensile Testing Machine

Shimadzu Tensile Testing Machine is an AGS-X series machine. A force of 2N/m is applied on the sample which was placed inside jaws with its length along the direction of loading. Young's modulus is determined using the software trapezium.

Young's modulus obtained at room temperature is as shown below. MS excel is used to linearly fit the data obtained from the tensile testing machine

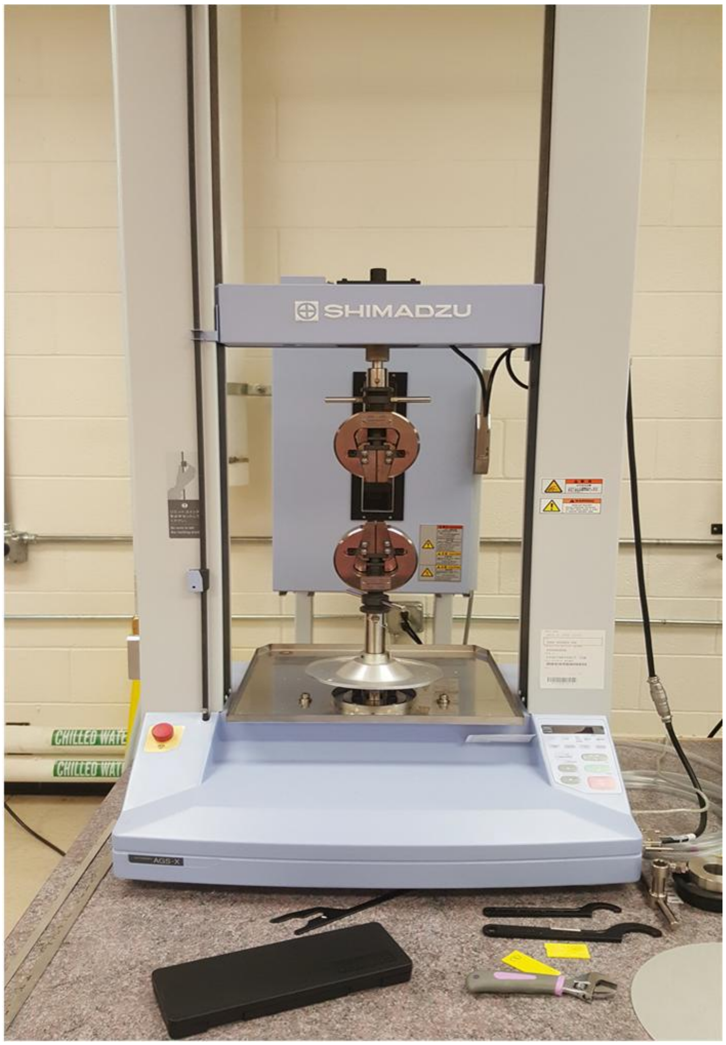


Figure 3-5 Shimadzu Tensile Testing Machine [15]

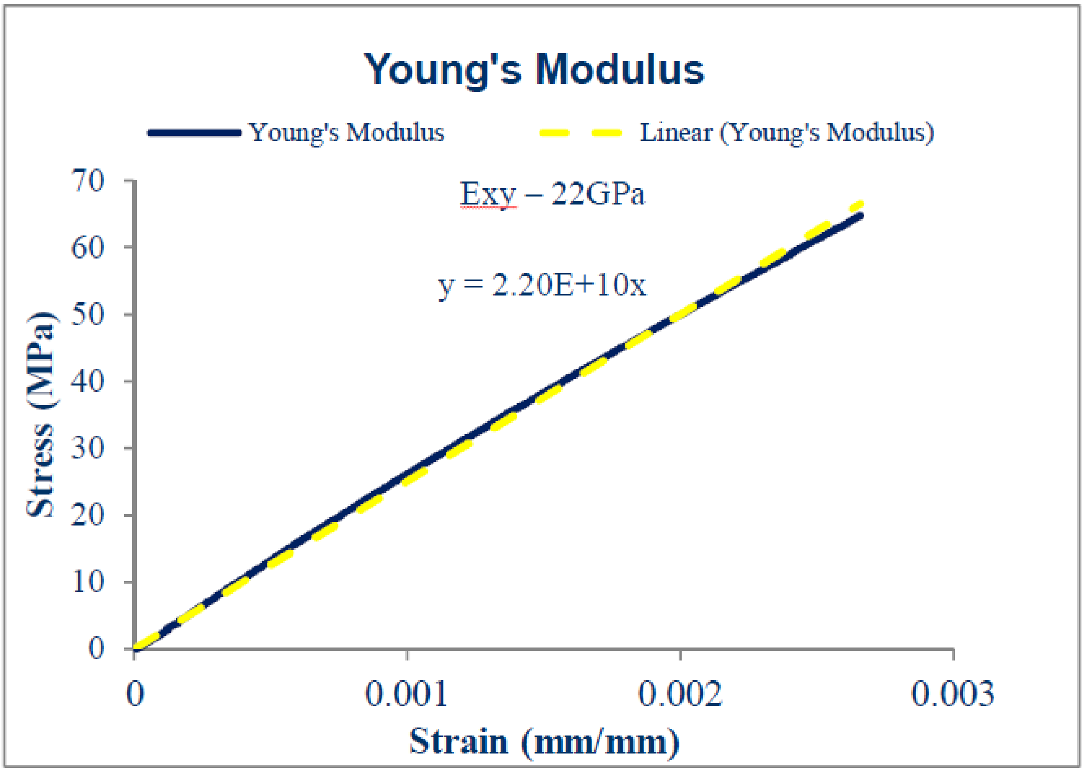


Figure 3-6 Young's Modulus linear fit [15]

3.5 Dynamic Mechanical Analyzer (DMA)

The frequency dependent storage modulus and loss modulus are measured using Dynamic Mechanical Analyzer (DMA). Master Curve is generated using the standard analysis tool on the TA7000 software. The Prony Series constants which are used as inputs in ANSYS are determined using a non-linear fitting tool, Origin Pro.

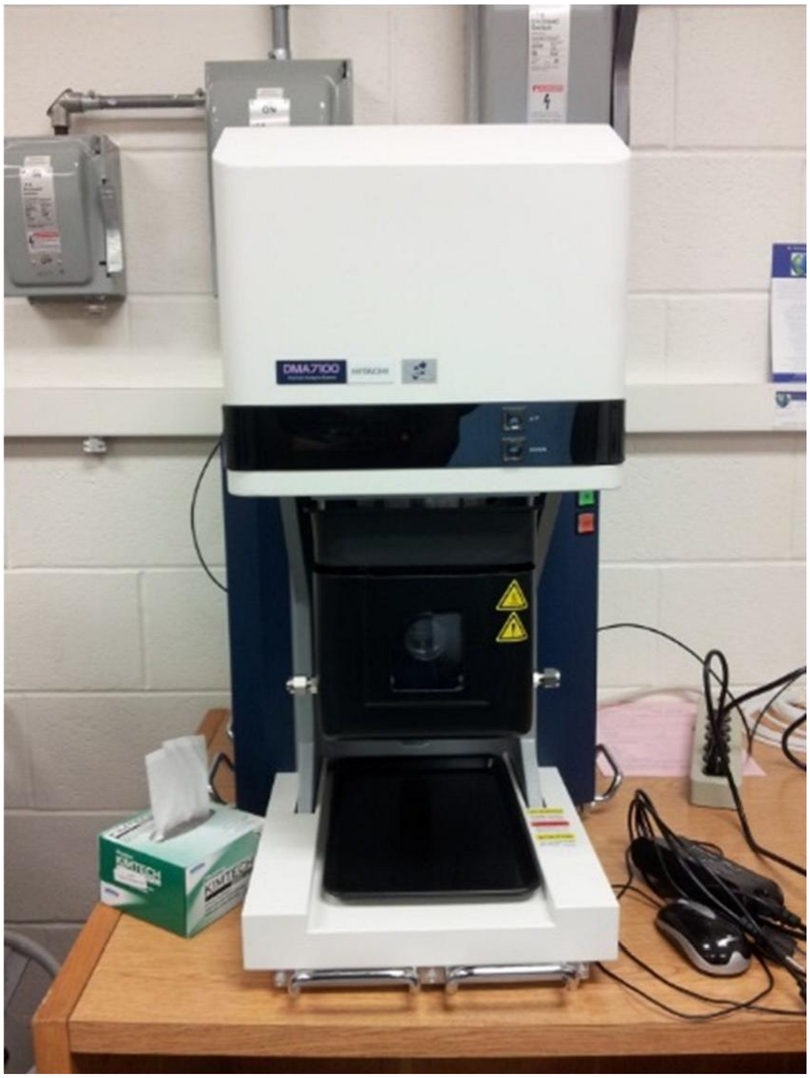


Figure 3-7 Dynamic Mechanical Analyzer [15]

1 mm thick PCB from Texas Instruments as shown below was used to determine viscoelastic properties at different temperatures.

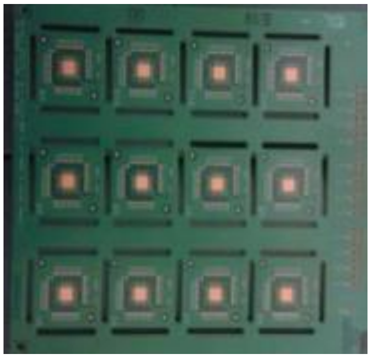


Figure 3-81 mm thick PCB

The experiment is done for the temperature range from 10°C to 190°C to determine the date for Loss modulus (E'') and Storage modulus (E'). Curves are obtained at frequencies 0.1, 1, 2,5, and 10 Hz. For modelling of viscoelastic material, the data obtained for the temperature range from 120°C to 160°C is smooth.

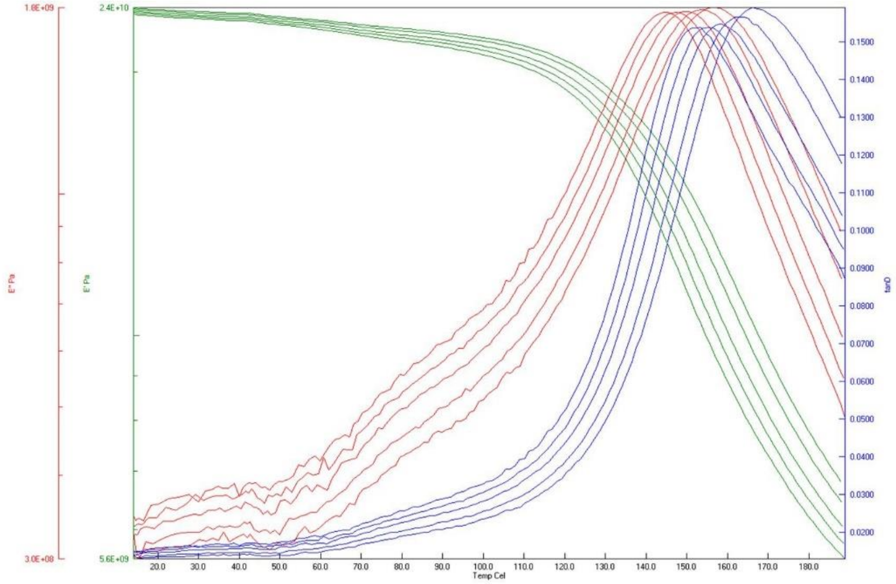


Figure 3-9 Temperature vs. Storage and Loss Modulus and tangent of phase angle [15]

Standard analysis tool on the TA7000 software is used for Master curve analysis. William-Landel-Ferry temperature shift function is used to obtain master curve at different temperatures.

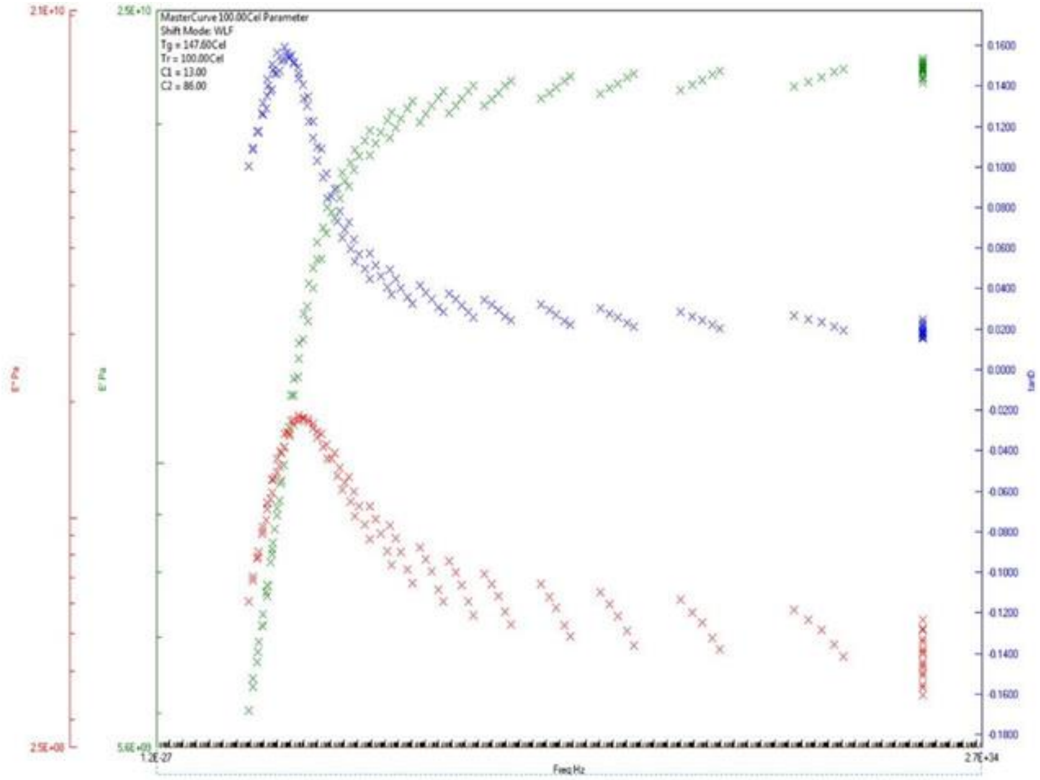


Figure 3-10 Master curve obtained from TA7000 software [15]

TA7000 software is used to export Data from master curve like storage modulus and loss modulus to excel sheet. Least square method of non-linear fitting tool OriginPro is used to fit data. The Prony series constants were extracted after fitting data which is used as input to model viscoelastic material in ANSYS. Curve fitting obtained from OriginPro fits well with the data points and is as shown below. Y-axis represents magnitude of complex modulus (Pa).

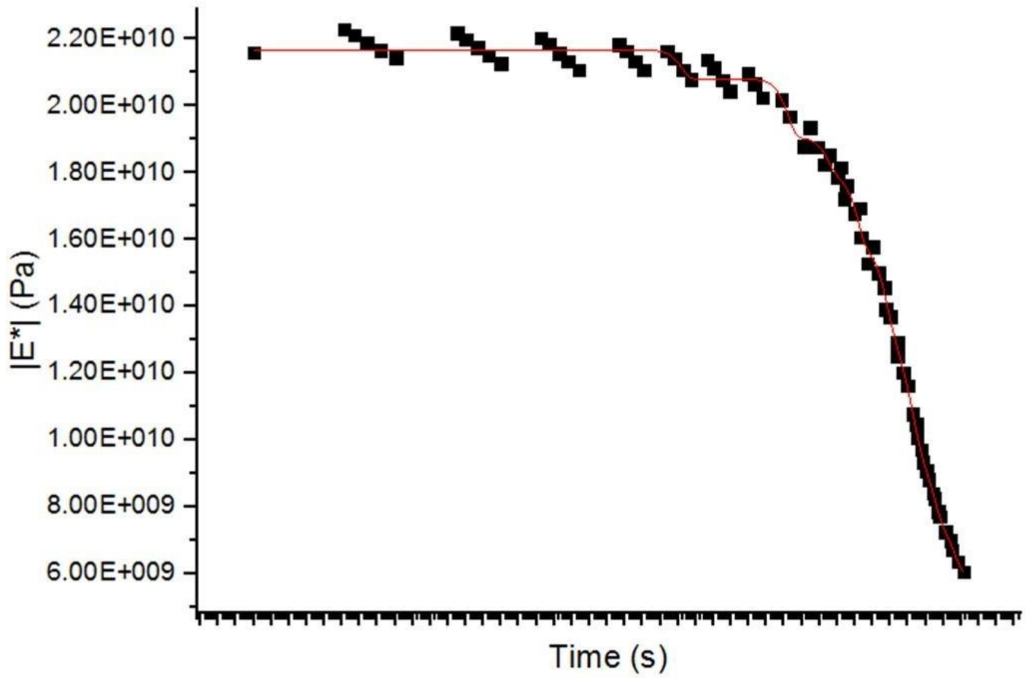


Figure 3-11 Non-linear fit using OriginPro [15]

3.6. Prony Series Representation For Shear Modulus

Maxwell model is used to model viscoelastic material. The model consists of both elastic and viscous property of the material and consists of linear ideally viscous Newtonian damper and linear elastic hook spring in series. The summation of strain in elastic and viscous elements is the total strain. The viscous part needs some time to move to apply instant displacement. However, the spring could move instantaneously [15]. Prony series is one of the best functions for modeling the behavior of the viscoelastic materials [7] .

$$G(t) = G_0\left[\alpha_\infty^G + \sum_{i=1}^{n_G} \alpha_i^G exp\left(-\frac{t}{\tau_i^G}\right)\right]$$

Where,

G_0 =Relaxation moduli at t=0

n_G = Number of Prony terms

α_i^G =Relative moduli

τ_i^G =Relaxation time

Shear modulus over time is represented by Prony Series. Analysis of material properties when constant strain is applied. It would then lead to stress decrease over time. Prony Series constants represent PCB material properties for modeling it as a viscoelastic material in ANSYS.

Chapter 4 MODELLING AND BOUNDARY CONDITIONS

4.1 Material Properties

SAC 396 and PCB materials are modeled as viscoelastic and remaining all other materials are modeled as linear elastic. Anand’s viscoplastic model for SAC 396 was used to model SAC alloy as viscoplastic [8]. PCB is modeled as orthotropic linear elastic and viscoelastic material. The material properties used for different materials are shown in Table 4-1 and 4-2 below

Table 4-1 Material Properties [9]

Material	E (GPa)	CTE (ppm/°C)	V
Die	131	3	0.28
RDL	130	16.8	0.34
Polyamide	1.2	52	0.25
Mold	24	20	0.3
Cu	110	17	0.34
Solder Mask	4	30	0.4

Table 4-2 PCB Material Properties [15]

Material	E(GPa)			CTE (ppm/^{o}C)			N		
	X	Y	Z	X	Y	Z	xy	yz	Xz
PCB (Orthotropic)	22	22	0.1	20	20	60	0.11	0.39	0.39

Table 4-3 Prony Series Constants for 150°C [15]

Relative	Relaxation
0.082023	9.2217
0.075153	1.9581
0.062615	8.4836E-06
0.072695	58.437
0.057023	2952.2
0.090097	0.00737
0.05104	0.00053268
0.05938	393.61
0.066464	1.4171E-10
0.11397	0.20255

The temperature-dependent Young’s modulus is $E=100501-194T$ (MPa).

T- Absolute Temperature (K)

Coefficient of thermal expansion (CTE) of the solder - 23.5 ppm/K.

Table 4-4 Anand's Constants for SAC396 [8]

S. No	Constant	Unit	Value
1	S_0	MPa	3.3
2	Q/R	1/K	9883
3	A	Sec^{-1}	15.7E+06
4	ξ	Dimensionless	1.06
5	m	Dimensionless	0.3686
6	h0	MPa	1077
7	ŝ	MPa	3.15
8	n	Dimensionless	0.0352
9	a	Dimensionless	1.6832

4.2 Finite Element Model

Global Model:

A full Model of the board with dimension 66 mm × 38.5 mm is cut into quarter as for the symmetry. The quarter model from the lower left corner of the full board is designed. The package size is 2.8 mm × 2.8 mm for 1 mm thickness board. Using ANSYS 17.2 a Finite Element Model of JEDEC Board is designed is shown in Figure 4-1. Some very fine details in the solder balls are not included in the global model. The Meshed Quarter symmetry model is shown in Figure 4-2.

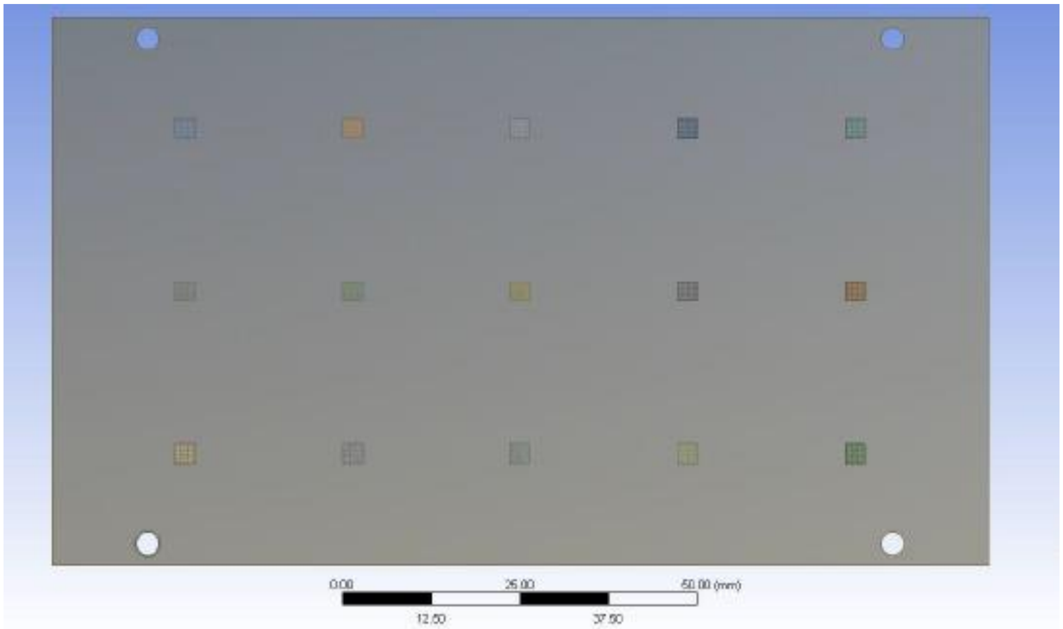


Figure 4-1 Full Global Model [14]

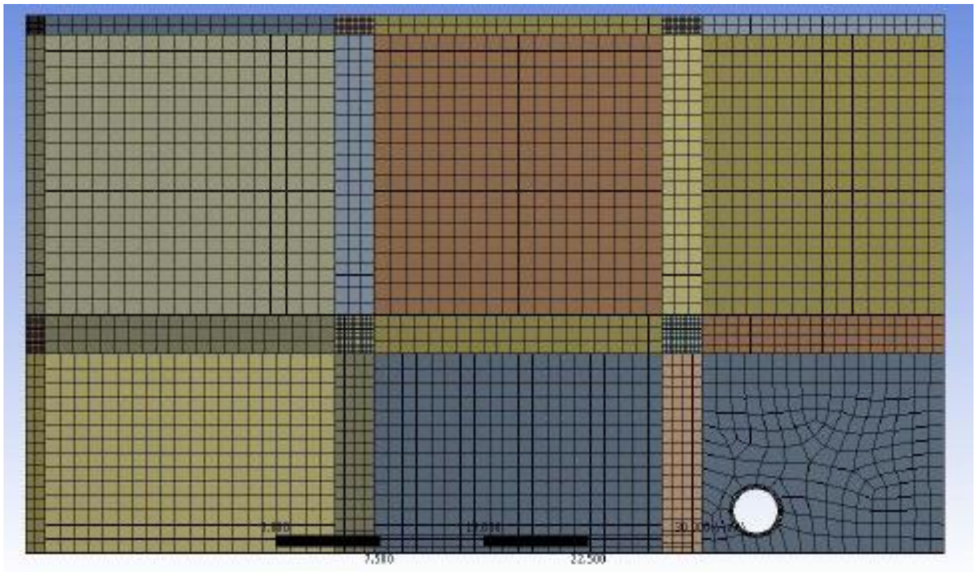


Figure 4-2 Meshed Quarter Symmetry Model [14]

Local Model

The different layers of the package and the fine details of solder interconnections are considered for the analysis in the Local Model. For high accuracy in the results, the solder interconnections are designed as spherical balls instead of square blocks. The cut boundary is taken with the same dimension as the package 2.8 mm × 2.8 mm [14]. The Local Finite Element Model is shown in Figure 4-3.

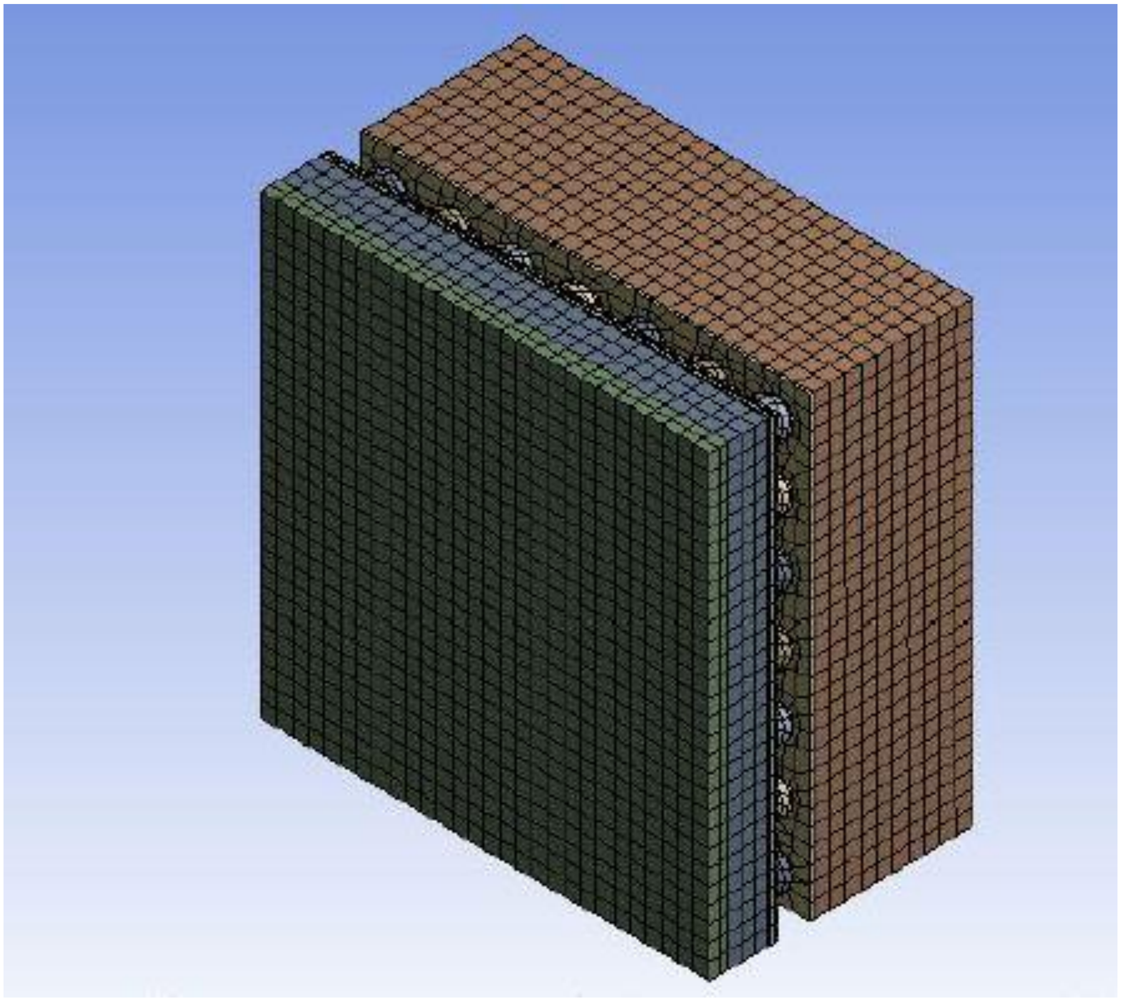


Figure 4-3 Meshed Local Finite Element Model

4.3 Loading Conditions

As per JEDEC standards, in the Finite Element Simulation the input acceleration should be 1500 G which is taken from the Input G Technique [10]. An accelerometer is attached to the board to measure the acceleration impulse.

$$a = \begin{cases} 1500\ g\ sin\dfrac{\pi t}{t_w}, t \leq t_w, t_w = 0.5 \\ 0, \text{t} > t_w \end{cases}$$

a =Acceleration (m/s^2)

g =Acceleration due to gravity (m/s^2)

t =Time (ms)

Acceleration peak value – 1500 G

Impulse Duration- 0.5 ms

In the Input G method assumption, the impulse is directly applied to the board where the board acts as a rigid body. With the modification in applying the loads in the Input G method is called Direct Acceleration Input (DAI) [11]. The Acceleration input is directly applied as a body force in this method [14].

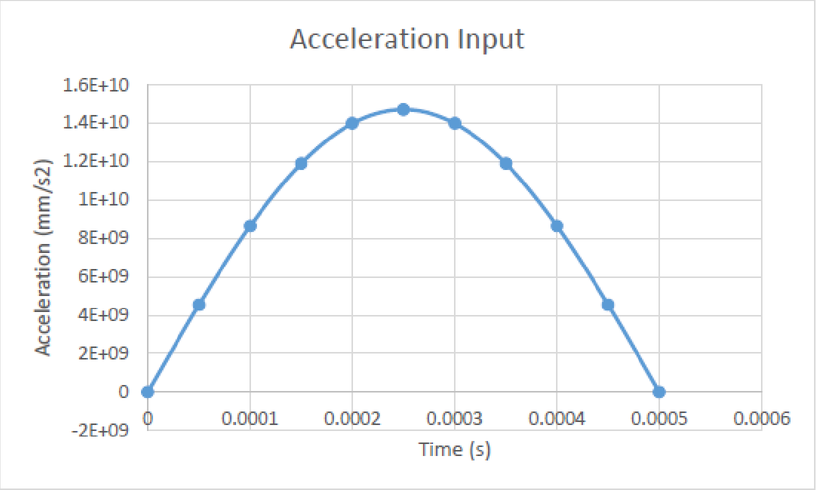


Figure 4-4 Input Acceleration Graph [14]

Table 4-5 Input Acceleration [14]

Time	Acceleration
0	0
0.00005	4.54E+09
0.0001	8.64E+09
0.00015	1.19E+10
0.0002	1.4E+10
0.00025	1.47E+10
0.0003	1.4E+10
0.00035	1.19E+10
0.0004	8.64E+09
0.00045	4.54E+09
0.0005	-4.7E-06

4.4 Submodel Technique

Submodeling technique is based on the Saint- Venant principle in which stress distribution in the area far from the applied boundary conditions remain same when a statically equivalent set of boundary conditions are substituted. This method is also known as Cut Boundary Method. In this method, the global displacements are determined under the application of loads by analyzing the full model. The stress for the area of interest in the original model can be obtained by transferring the global displacements to set the boundary conditions for the local model [14]. Cut boundary displacement method is shown in the below Figure 4-5.

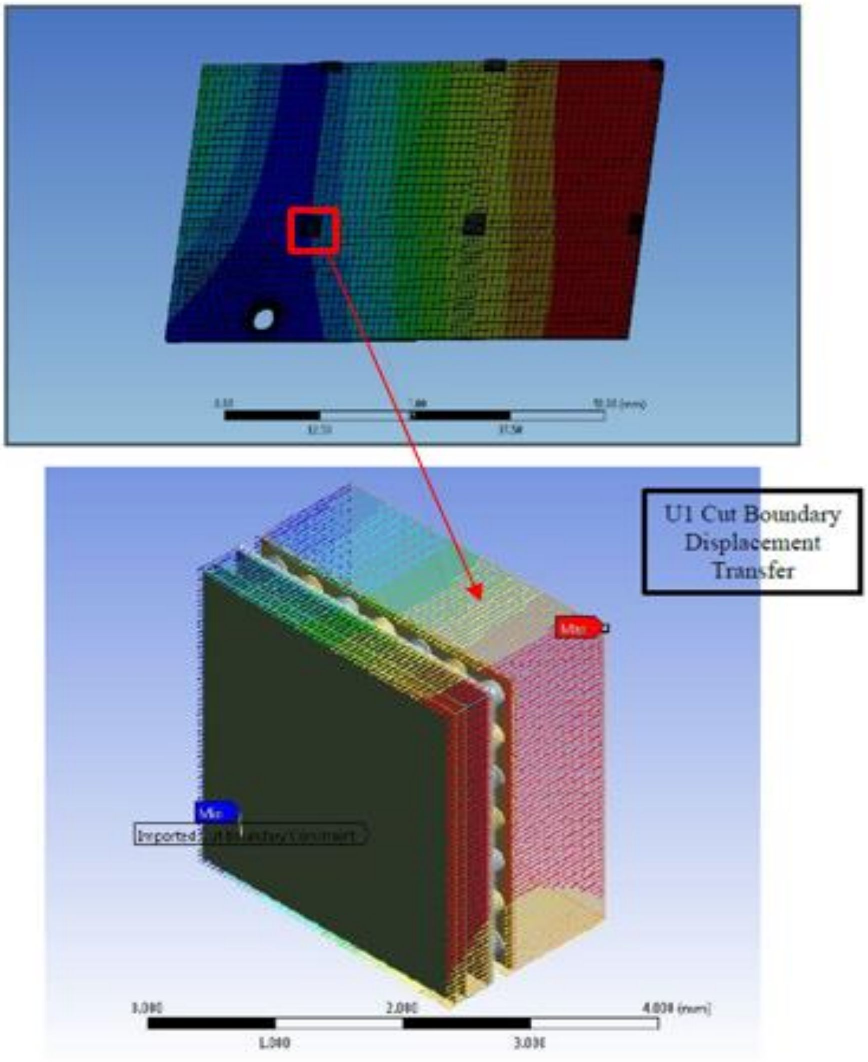


Figure 4-5 Cut Boundary Displacement Transfer from Global to Local Model

Chapter 5 ANALYSIS AND RESULTS

5.1 Modal Analysis

Modal Analysis is the study of dynamic properties of a structure under vibration [12]. Natural Frequencies and modal shapes, which the vibrating system takes, are determined from the characteristic equation || $k-\omega^2 m$ ||.Modal analysis is done to determine the 'initial time step' size required to perform transient analysis and to capture the required mode shapes.[13]. It is performed on the global model.

$$\Delta t = {}^{1}\!/_{20\times f}$$

Δt =Intial time step size

f =frequency of highest mode

The Viscoelastic and Orthotropic linear material have almost same natural frequencies.The frequencies are gradually increasing with consecutive modes for both viscoelastic and orthotropic. The values of frequency for different modes are shown in the Table 5-1 below

Table 5-1 Modal Frequencies for Orthotropic and Viscoelastic Materials

Mode	Frequency of Orthotropic	Frequency of Viscoelastic
First Mode	225.14	232.6
Second Mode	587	605.52
Third Mode	848.84	829.66
Fourth Mode	1255.9	1313.9
Fifth Mode	2055.5	2043.5

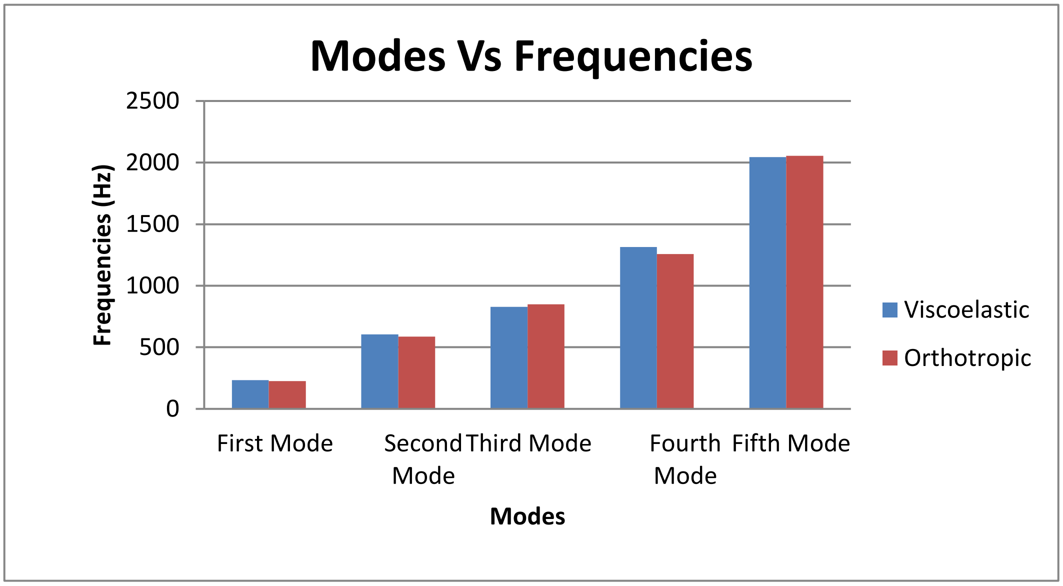


Figure 5-1 Comparison of Frequencies at Different Modes

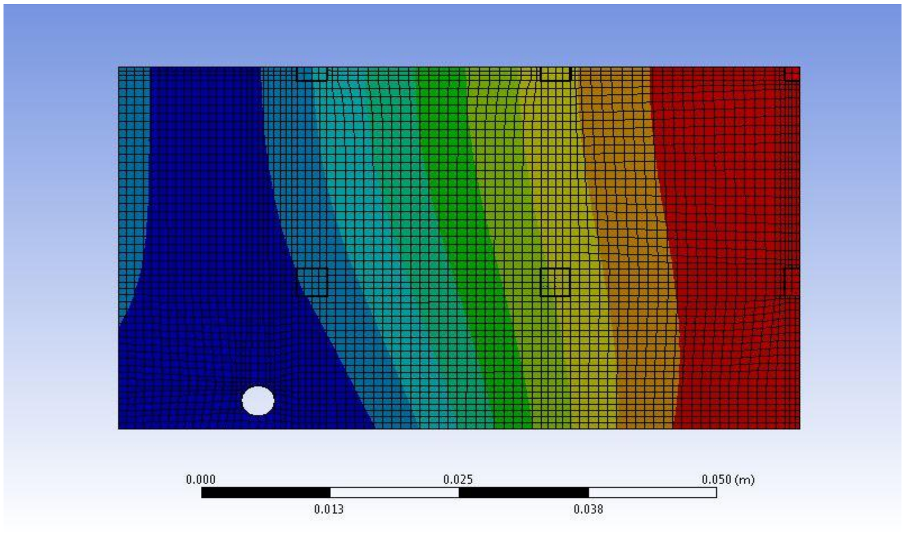


Figure 5-2 First mode of Viscoelastic model

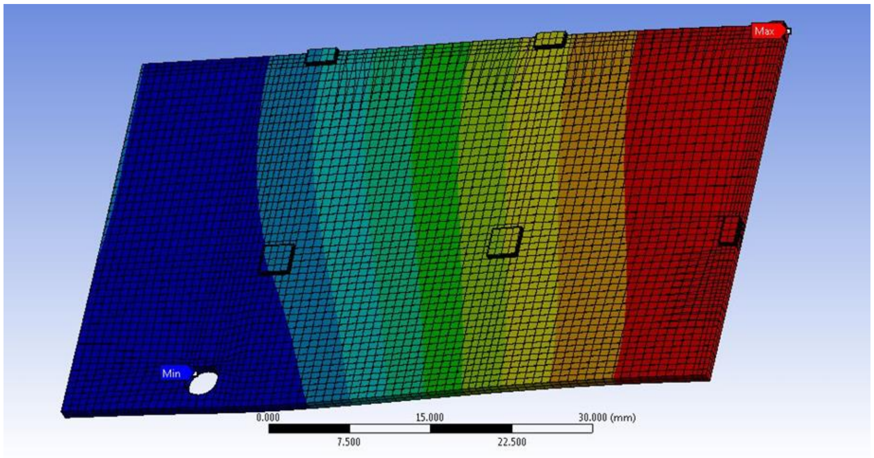


Figure 5-3 First Mode of Orthotropic model

Maximum Deformation:

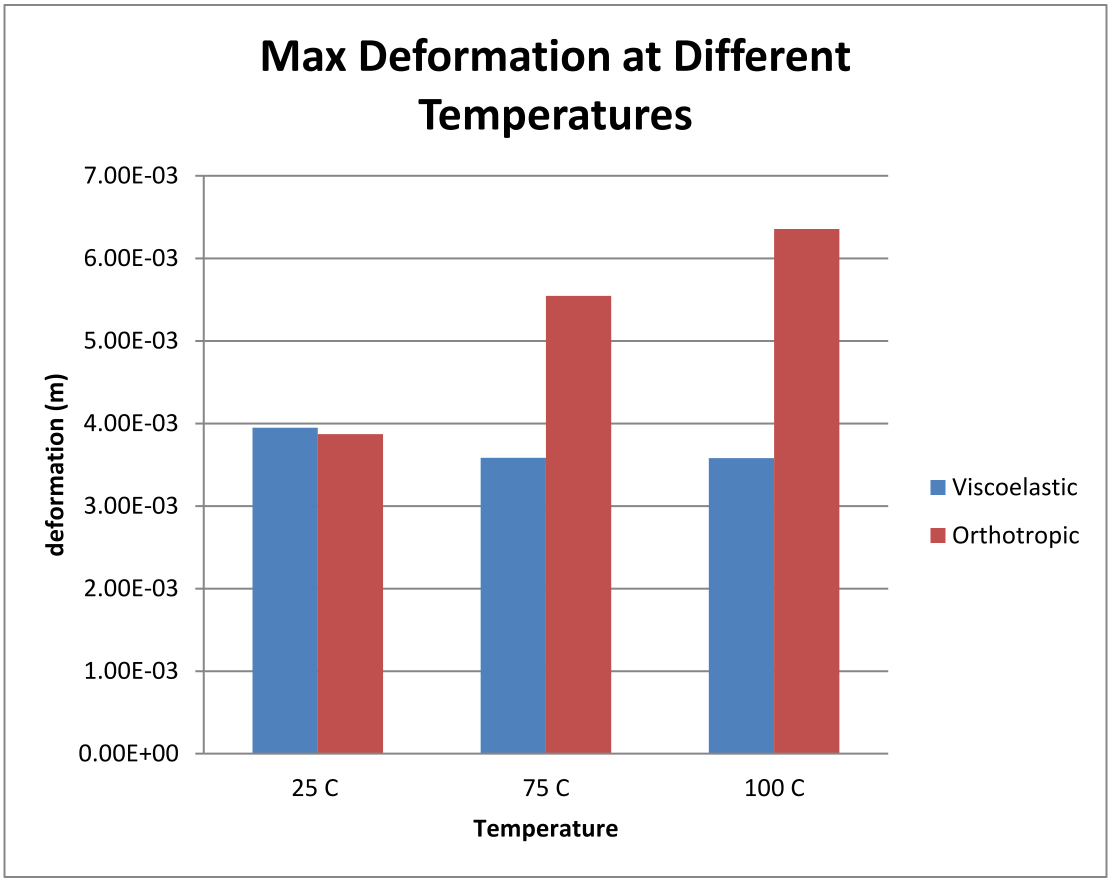


Figure 5-4 Comparison of maximum deformation at different temperatures

- In Viscoelastic, maximum deformation occurs at 25º C, Whereas in orthotropic the maximum deformation is at 100º C .
- For orthotropic linear elastic model deformation is more at higher temperatures.
- As the temperature increases, deformation is decreasing for viscoelastic model.

Total Deformation:

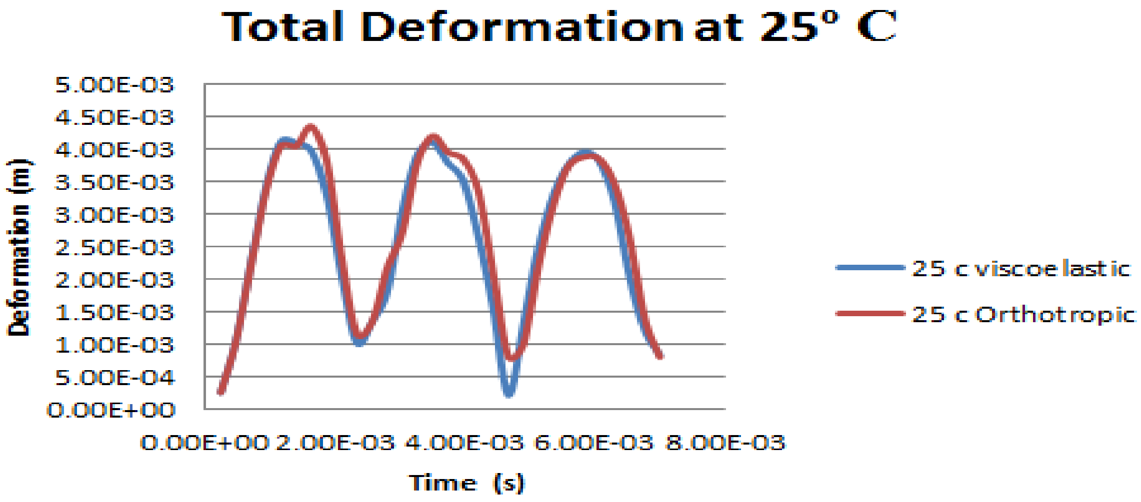


Figure 5-5 Comparison of total deformation at 25 °C

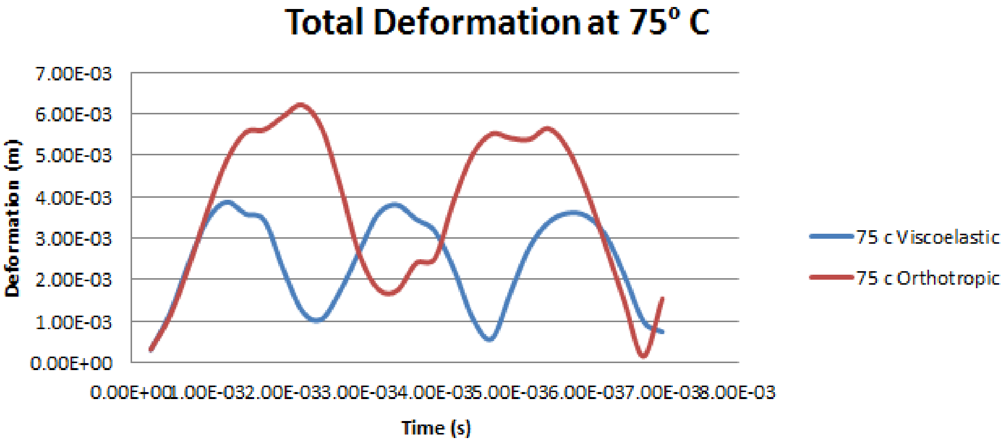


Figure 5-6 Comparison of total deformation at 75 °C

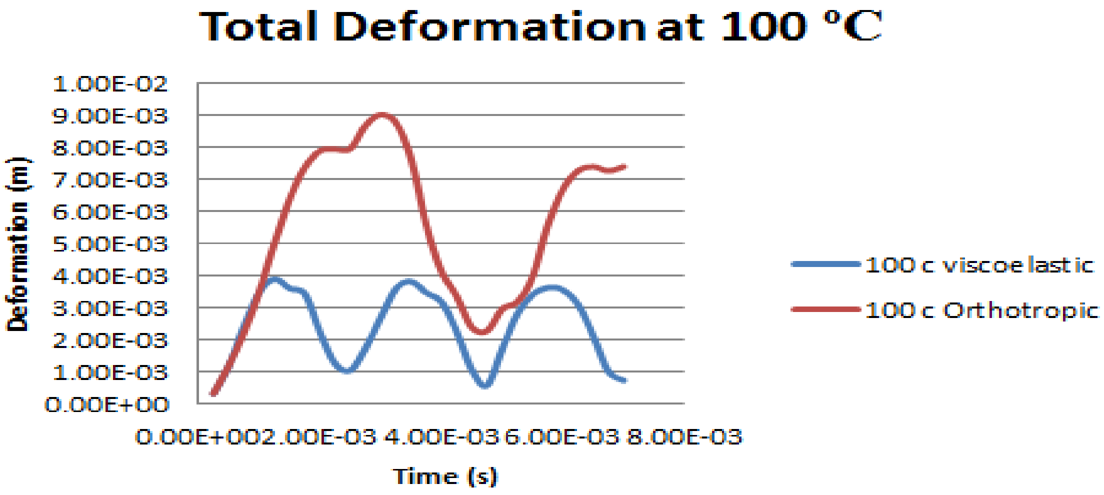


Figure 5-7 Comparison of total deformation at 100 °C

As the temperature increases the difference in deformation between orthotropic and viscoelastic is increasing.

Normal Stress:

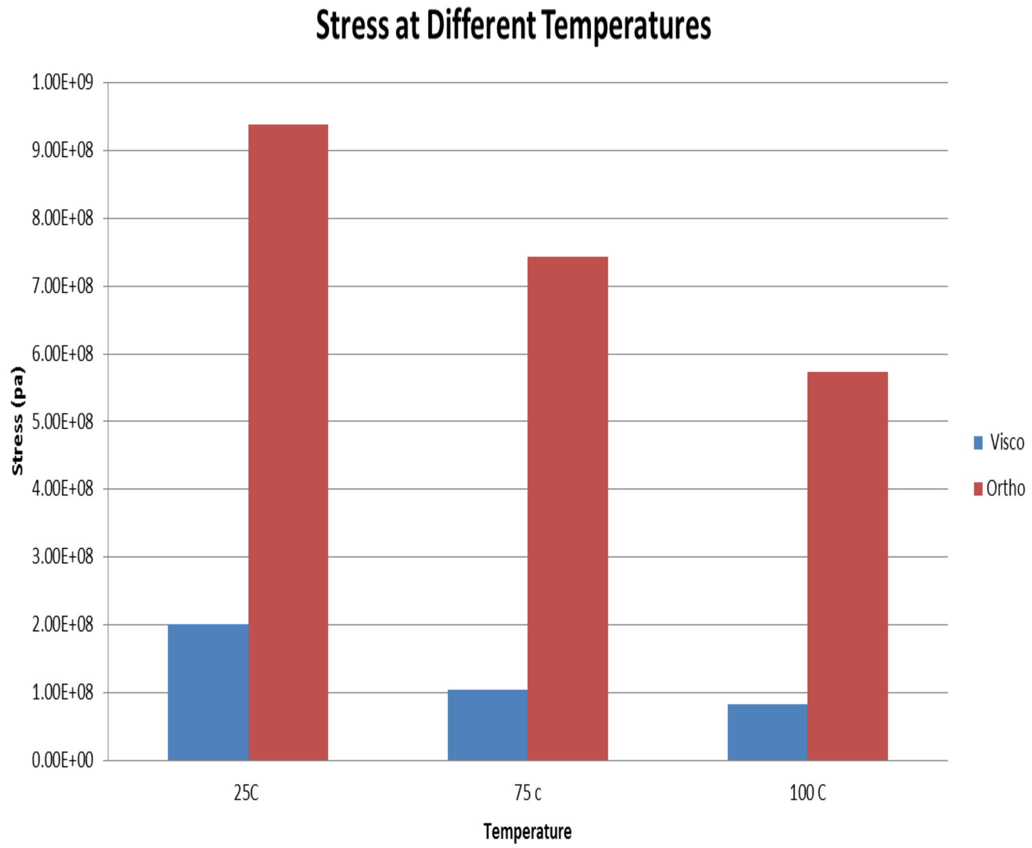


Figure 5-8 Comparison of Normal stress at different temperatures

- Normal stress is very less for viscoelastic when compared to orthotropic at all temperatures.
- Stress is decreasing with the increase of temperature for both viscoelastic and orthotropic linear elastic.

Peeling stress:

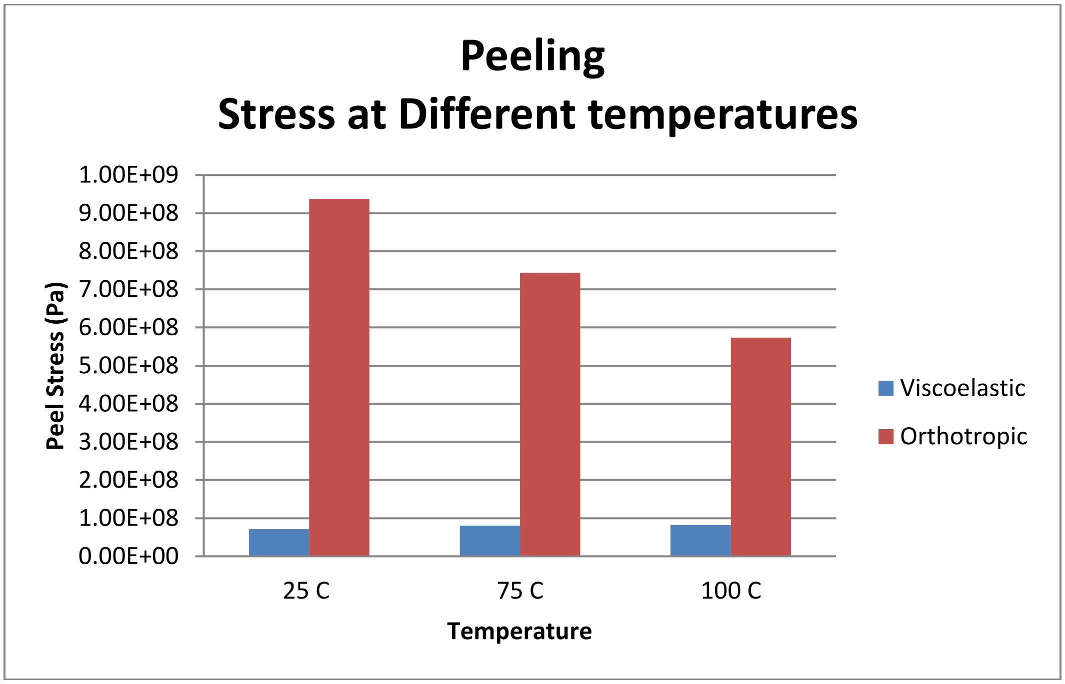


Figure 5-9 Comparison of Peeling Stress at different temperatures

- Orthotropic material have higher peeling stress when compared to viscoelastic model.
- Peeling stress is increasing with the temperature for the viscoelastic, whereas it is decreasing with increase of temperature for Orthotropic model

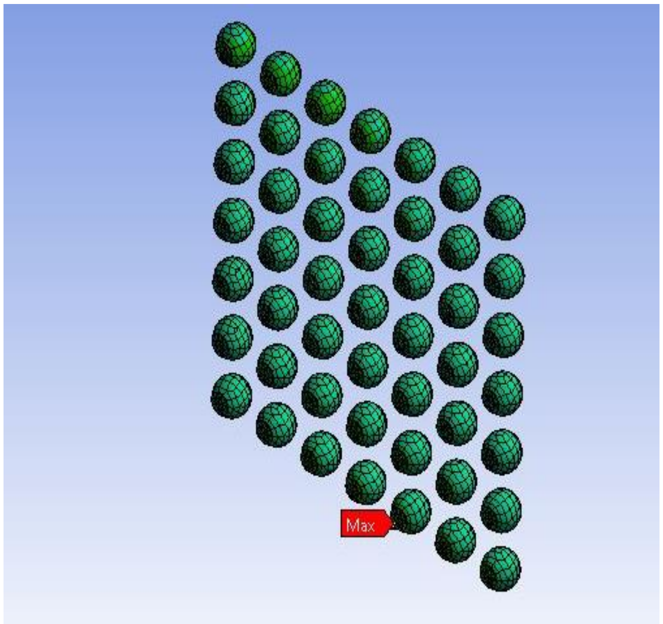


Figure 5-10 Peel Stress Location for the Viscoelastic material at 25°C

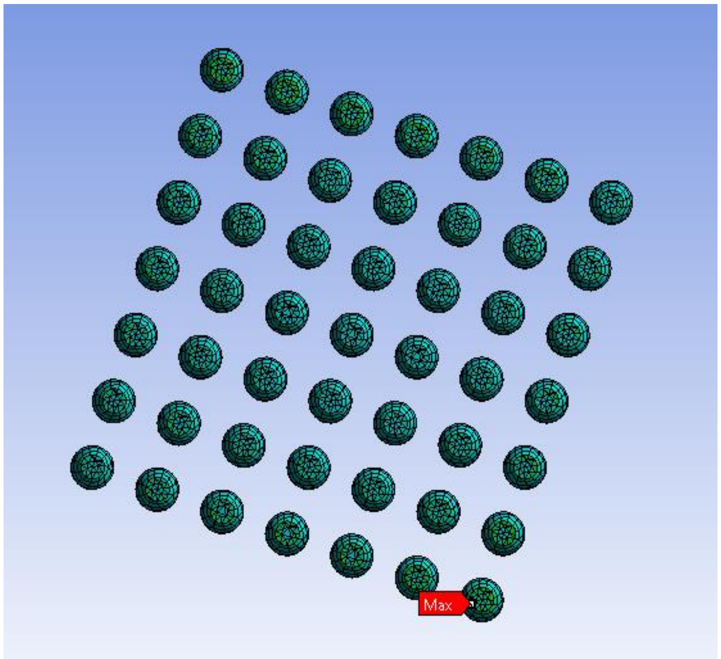


Figure 5-11 Peel Stress Location for the Orthotropic material at 25°C

Chapter 6 CONCLUSION

6.1 Summary and Conclusion

PCB was successfully characterized using DMA to get viscoelastic model which is later used in FEA model. Finite Element Analysis of WCSP was performed to assess board level reliability.

Comparative study was done on the following parameters:

- Modal frequencies- Both viscoelastic and orthotropic linear elastic model have almost same modal frequencies.
- Total deformation- Deformation is Less in Viscoelastic model.
- Normal Stress- Stresses are higher in Orthotropic linear elastic model.
- Peel stress- Peeling stress is significantly higher in Orthotropic linear elastic model

This work has shown that including the viscoelastic properties in the model has a significant influence in the results.

This agrees to the results described by Liu et. al.[6] has shown in their analytical work when compared Orthotropic linear elastic model.

6.2 Future Work

- Present work can be extended to comparing the linear elastic and viscoelastic modeling for PCBs for QFN and other types of packages.
- Drop test can performed experimentally and compare it with the computational results.
- Packages can be analyzed to study effect of viscoelastic modeling of PCB on board level reliability for reflow condition.

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