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The Fatigue Life Prediction Analysis of Solder Joint in BGA Packages Under Mechanical Cyclic Bending Loading and Their Probability of Failure Using FORM and SORM Methods

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Abstract: Nowadays electronics play a crucial role in several applications: medicine, embedded systems of transportation and telecommunication. While achieving electrical functions, electronic systems must be safe, reliable, have low thermal resistance (To dissipate the heat properly) and must be durable and insensitive to the exterior environment variations (Humidity, thermal and mechanical shock ...) In this study a three-dimensional finite element simulation using ANSYS 15.0.7 APDL on solder joint in a Ball Grid Array (BGA) under Mechanical cycling bending test was executed to predict the fatigue life of solder joint. To predict the latter, we divide our simulation analysis into e three parts as follows: First: three-dimensional finite element analysis for calculating the stiffness assembly and imposed strain values. Second: one dimensional conjoint creep and time independent plastic deformation analysis under mechanical cyclic bending loading for calculating the inelastic strain energy. And finally, the life prediction analysis. Even when the solder joint under mechanical cyclic bending loading reaches the steady-state response, the three-dimensional non-linear finite element analysis simulation calculation is impractical; to make it practical, we have to determine the most critical solder joint based on the equivalent stress values within the solder joints according to Darveaux and Syed (2000). In this paper we also used a probabilistic approach to predict fatigue life of the most critical solder joint under Mechanical bending cycle; to use only a determinist approach is not enough because it neglects the variability of input parameters and this has an impact on the output result. The failure probability of the most critical solder joint of BGA packaging is defined using two methods of numerical study of probabilistic methods which are: The First and second Order Reliability Methods (FORM) and (SORM).

Key words: Fatigue Life Prediction · Solder Joints · Mechanical Bending Damages · BGA Packaging · Failure Probability · FORM · SORM

INTRODUCTION

In most used microelectronic devices, a solder joint of BGA package electronic plays a crucial role because it provides mechanical and electrical connections [1-7].

In this study we are going to focus on the reliability concerns of a solder joint of BGA package since BGA package is widely used in the electronic industry.

The goal of this paper is to determine a combined determinist and probabilistic simulation model to predict the fatigue failure of solder joints under a mechanical cyclic bending loading environment [8-10].

In our study the failure of solder joints in BGA package is mainly caused by the stress generated by the mechanical cyclic bending loading, besides the package variables such as the package, the substrate, the die sizes, the number of solder joints, the DNP, the pitch and the material proprieties. However, it is not simple to consider

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all these issues. To overcome all these problems, a combined determinist and probabilistic model was developed and applied to calculate the number of cycles of failure of solder joints in BGA package of an electronic device. The combined model is composed of a finite element modeling and two probabilistic methods such as First and Second Order Reliability Methods (FORM) and (SORM).

MATERIALS AND METHODS

Package Dimensions: The Our BGA package model is composed of 196 solder balls with 8 balls in each direction (X and Z) as shown in (Fig. 1). The pitch is 0.8 mm, die and substrate sizes are given as (7*7*0.3 mm^3) and (12*12*0.075 mm3) and the PCB size is (30*30*0.692 mm^3) as shown in (Table 1).

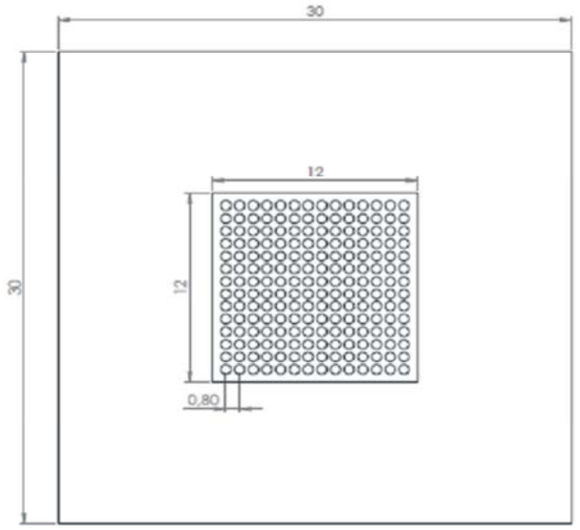


Fig. 1: The dimension and schematic of BGA Package

Table 1: Shows the package parameter for each component

Parameter	Dimensions (mm)
Substrate	12*12*0.075 mm3
Solder Joint standoff heights	0.3231 mm
Solder Joint Pitch	0.8 mm
PCB	30*30*0.692 mm3
FR4 PCB	30*30*0.592 mm3
Polymide PCB	30*30*0.05 mm3
Die	7*7*0.3 mm3
Die attach	7*7*0.07 mm3
Molding compound	12*12*0.730 mm3
Solder mask	12*12*0.0317 mm3
Adhesive	12*12*0.012 mm3
Copper pad diameter	0.235 mm
Copper pad thickness	0.021 mm

Package Materials and Properties: This is a 3D dimensional model of a rectangular shape consisting of the following materials: Solder joint, substrate, PCB, Die, Die attach, copper pad, solder mask, adhesive and molding compound. Their properties are detailed in (Fig. 2) and (Table 2).

FEA Modeling: In this paper, we used the Finite Element Methods (FEM) to predict the numerical value of the mechanical solder joint's degradation caused by the repeated mechanical bending cycling, leading to the cracking of the solder joint.

The following steps are created in ANSYS 15.0.7 to describe the steps for generating a non global model:

Step 1: global model:

The goal of global modeling is to identify the most critical solder joints and to provide a deriving boundary condition for the analysis. We consider only one half of the package due to the presence of symmetry in loading and support conditions as shown in (Fig. 3).

The symmetrical boundary conditions are applied along the center line of the PCB and node of diagonal bottom center of PCB is constrained with boundary condition Ux=Uy=Uz=0 to prevent free body translation.

The most critical solder joint:

To identify the most solder joints of BGA packages at the end of the last Mechanical cycle, the maximum value of the equivalent stress occurs; as shown in (Fig. 4)

Mechanical Cyclic Bending Loading: The package is subjected to cyclic loading at its center. The loading and loading range vary between 0 and 30 N over a period of 1 second with the maximum load. The latter is applied uniformly distributed over a 1 mm radius area.

Fatigue Life Model: In general, electronic devices experience failure due to solder joint fatigue provoked by mechanical damage during the component operation life. To predict the fatigue life of these solder joints, we used combined finite element simulations and the one-dimensional combined creep and time-independent plasticity model. This model will help us find the number of cycles a component could resist before its fatigue life.

There are several fatigue life models proposed by various investigators such as: Darveaux, Farooq, Perkins, Park, Engelmaier … the model we will be using in this study is one-dimensional combined creep and time-independent plasticity model defined by Darveaux.

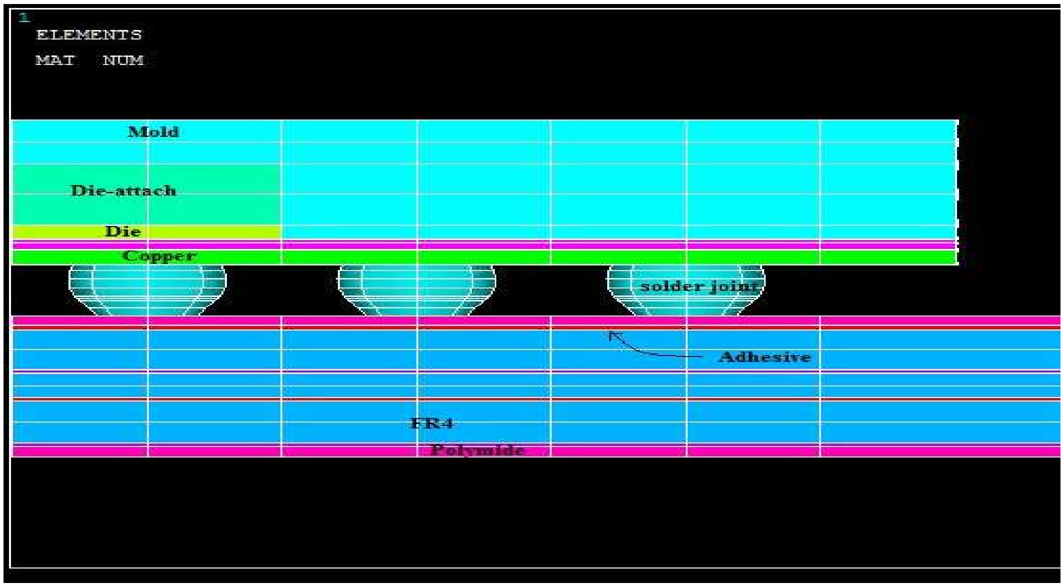


Fig. 2: Side view of BGA package model

Table 2: Material properties

Material	Young's Modulus (MPa)	CTE (ppm/°C)	Poisson's Ratio
Substrate	5170	160	0.33
Solder (SnPb)	30636	24.5	0.35
Copper	128930	16.066	0.344
Die (Si)	162700	2.52	0.278
FR4	20000	18	0.38
Polyimide	5170	160	0.33
Adhesive	4800	100	0.3
Solder Mask	4900	95	0.3
Die-attach	265	160	0.33
Mold	13800	17	0.22

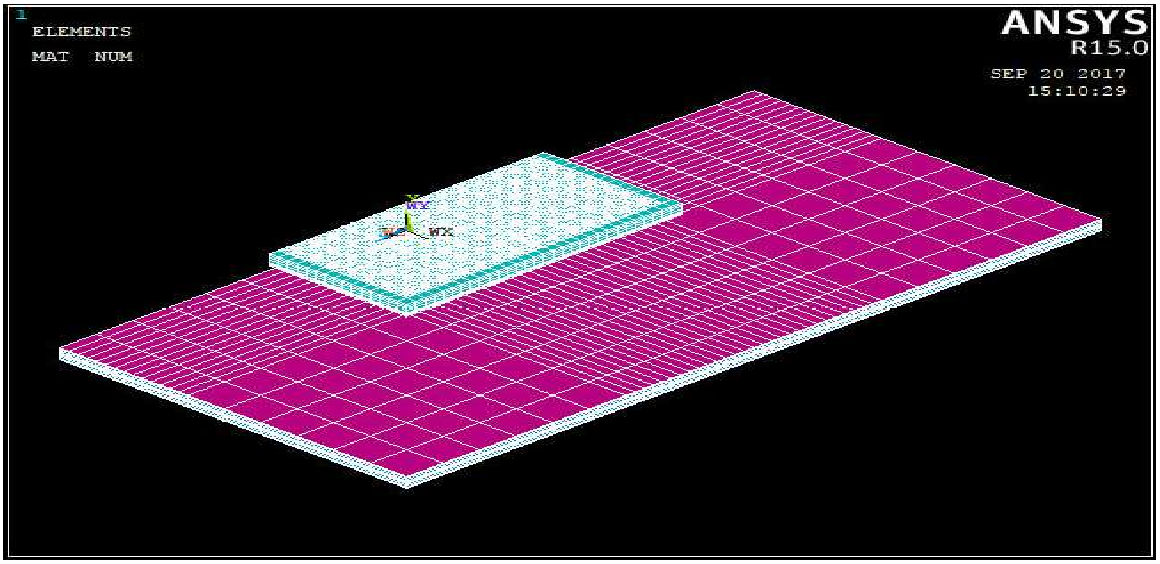


Fig. 3: Global Finite Element Model of BGA package

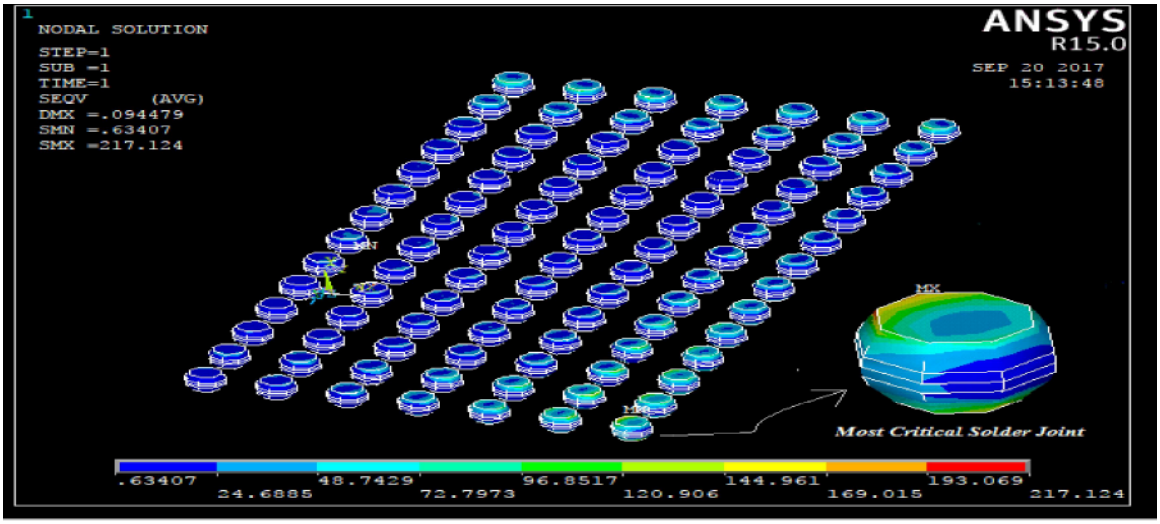


Fig. 4: The most critical solder joint

We can define one dimensional nonlinear deformation for a specified assembly stiffness, imposed strain and period of cycles loading of the solder by solving the coupled nonlinear ordinary differential equations given below Eq. (1-4):

$$\frac{d\varepsilon_c}{dt} = \frac{d\varepsilon_{ss}}{dt}\left(1+\varepsilon_T + B_T e^{-B_T \dot{\varepsilon}_{ss} t}\right) \tag{1}$$

$$\frac{d\varepsilon_{ss}}{dt} = C_{5t}\left[\sinh\left(\alpha_{1t}\sigma\right)\right]^n e^{-}Q_a / kT \tag{2}$$

$$\varepsilon_p = C_{6t}\left(\frac{\sigma}{G}\right) \tag{3}$$

$$\varepsilon_p = \overline{\varepsilon_p} + \frac{C_{6t}}{G^m} 2^{1-m}\left(\sigma - \overline{\sigma}\right)^m \tag{4}$$

where:
ε_p: plastic strain
ε_c: creep strain
σ: effective stress
$\overline{\varepsilon_p}$: strain value at the end of each load cycle

$\overline{\sigma}$: stress value at the end of each load cycle

The numerical values of the constants, C6t and m and the shear modulus, G, are given by Darveaux *et al.,* (1995) [19] as:

C6t=3.35*1011; m=5.53; G=1.697*106 psi; T=298 K.

Table 3: Material constants

Parameter	Value
C_{5t}	8.03x10^4 (1/sec)
α_{1t}	4.62 x 10^{-4} (1/psi)
n	3.3
Q_a	0.7 eV
k	1.38 x 10^{-23}
T	Absolute temperature (DK)
ε_T	0.023
B_t	263

After a numerical integration, the result of plastic strain, creep strain, effective stress, inelastic and total strain energies are calculated at every time step for a specified number of cycles. A sufficient number of cycles must be used in the simulation in order to achieve the steady state response.

Inelastic and total strain energies can be used to determine life prediction of package by the equation given below Eq. (5-7). With the empirical constants provided by Darveaux and Syed (2000) [20].

$$N_a = N_0 + \frac{a}{da/dN} \tag{5}$$

With:

$$N_0 = K_1 \Delta\overline{W_i}^{K_2} \tag{6}$$

$$\frac{da}{dN} = K_3 \Delta\overline{W_i}^{K_4} \tag{7}$$

where:
Na: characteristic life cycles
N0: number of cycles to crack initiation
a: the crack length
ΔW_i: strain energy per cycle

Table 4: Numerical values of empirical constants used in mechanical fatigue life prediction

K1	71000 cycles/psiK2
K2	-1.62
K3	2.76xlO-7 in./cycle/psi^{K4}
K4	1.05

With:

K1, K2, K3 and K4 are the empirical constants of Darveaux are presented in (Table 4).

Probabilistic Methods: In The aim of probabilistic methods is to deal with the uncertainties emerging from the random changes in geometry dimension of packaging assembly and material properties. These approaches are used to increase the design's robustness and to estimate the impact of parameter uncertainties in the system response. Furthermore, the combination between the probabilistic methods and the finite element simulation not only does not allow the establishment of the scope and the boundaries of the usual deterministic approach but it also gives it an improvement by providing more information and increasing the effectiveness of the use of the empirical data.

The probabilistic structural methods lie in the determination failure probability of a given structural system. This approach represents the next step of the deterministic analysis inputs for random variables. The First and Second Order Reliability Methods (FORM-SORM) are widely used to outline the random response and the probability density function (PDF) of the response.

To proceed with this method, we firstly have to define the design variables Xi (i=1, 2, …., n) having an important level of fluctuation. Secondly, we have to define the number of potential failure scenarios, each of them needs a performance function G(xi), which splits the space into two regions of the variables: safety domain G(xi) > 0 and failure domain G(xi) ≤ 0. The limit between these two domains is defined by G(x) = 0, which is called the limit state function. The failure probability is given by Eq. (8):

$$P_f = \Pr ob\left[G(X) \le 0\right] = \int_{G(X)\le 0} f(X)dX \tag{8}$$

fX1, …, Xn (x1, … , xn) is the joint density of probability of the variables Xi. The evaluation of this integral is very costly in time of calculation because it comes to be a very small quantity and because all the required information on the joint density of probability is not available. And it is very rare that this integral can be studied analytically. Traditionally, we distinguish two main methods: the methods based on simulations such as Monte Carlo simulation and those using approximate methods such as First Order Reliability Methods (FORM). This approximation method is based on the determination of the reliability index β, which allows access to an approximate value of probability of failure Pf and they are illustrated in Figure (6) around the design point [11-13].

First Order Reliability Method (FORM): The FORM method (First Order Reliability Method) is being used for the approximation of the probability of failure; in this method, we firstly restate the problem according to its normal standard space using the isoprobabilistic transformations. For this, we transform a physical variable X into a random variable reduced centered and independent U; then, we determine the basic vectors of the normal space and this is how the space becomes perfect for a simple line calculation as shown in (Fig. 5).

However, the difficulty stands when the identification domain of the physical variable is avoided due to the infinite support of the Gaussian Density.

Recently, this method has been used by several researchers; it is useful in the determination of the reliability index and the failure probability. The FORM is based on the first order Taylor series approximation for a limit state function, which is stated as follows:

$$Z = R\text{-}S \tag{9}$$

The Where, R is the capacity (Or resistance) normal variable and S is the demand (load) normal variable. And that is supposing the resistance and the load variables are statistically independent; hence, the variables are also obtained through normal (Or Gaussian) distribution. Therefore, when the resistance is larger than the load variable, the failure (Or fracture) occurs.

(R<S or Z<0)

In general, the relationship between the failure probability and reliability using the cumulative distribution function of a variable in the standard coordinates of the system which rests on the probability density function of the normal distribution, which is obtained as follows:

$$P_f = 1 - R = P\left[Z < 0\right] = \int_{-\infty}^{0} \frac{1}{\sigma_Z \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Z-\mu_Z}{\sigma_Z}\right)^2\right] dZ$$

$$= \int_{-\infty}^{-\beta} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{U^2}{2}\right] dU = \Phi(-\beta) \tag{10}$$

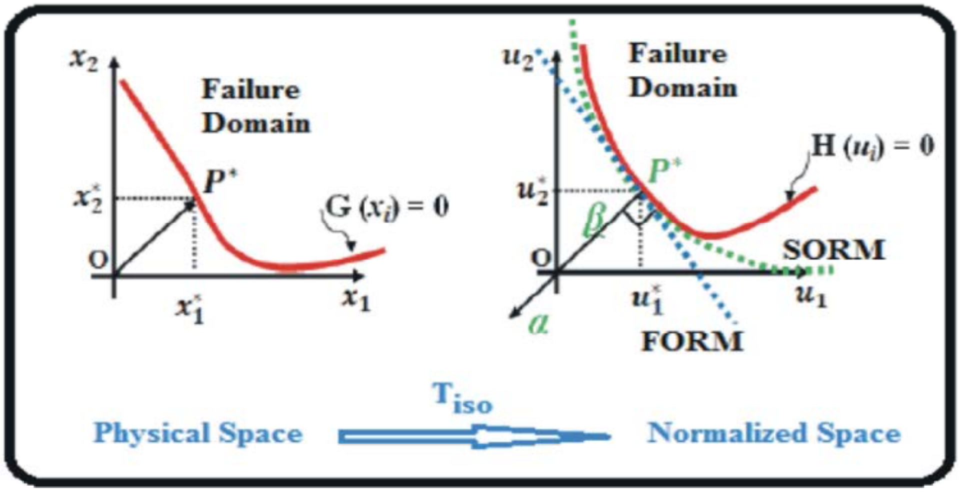


Fig. 5: Physical and normalize spaces

Table 5: Statistical properties of random variables

Description	Mean	Standard Deviation	Type of Distribution
Young Modulus of solder joint (MPa)	30636	0.05	Normal
Young Modulus of substrate (MPa)	5170	0.05	Normal
Young Modulus of FR4 (MPa)	20000	0.05	Normal
Young Modulus of Polyimide (MPa)	5170	0.05	Normal
Thickness of solder joint (mm)	0.3231	0.05	Normal
Thickness of substrate (mm)	0.075	0.05	Normal
Thickness of FR4 (mm)	0.692	0.05	Normal
Thickness of Polyimide (mm)	0.592	0.05	Normal
Thickness of Die (mm)	0.3	0.05	Normal
Thickness of Die attach (mm)	0.07	0.05	Normal
Thickness of Molding compound (mm)	0.730	0.05	Normal
Thickness of Solder mask (mm)	0.0317	0.05	Normal
Thickness of Copper pad thickness (mm)	0.021	0.05	Normal

where Φ is the cumulative distribution function for a standard normal variable, β is the safety index or reliability index [8, 15-18].

Second Order Reliability Method (SORM): The method of reliability of the second order SORM (Second Order Reliability Method) is based on a more accurate approximation of the limit surface state since the latter is approximated by a quadratic surface having the same radius of curvature as the real surface at the point Design. It is necessary to find an approximation of the limit state function by developing Taylor series of the second order around the design point. The state boundary surface is written as follows:

$$G_U(U) = 0 \approx \nabla gu(u^*)^T (u - u^*) + \frac{1}{2}(u - u^*)^T D(u^*)(u - u^*) \tag{11}$$

D is the symmetric Hessian matrix of the function GU, which is the partial derivative matrix of the second order in the design point:

$$D_{ij}(u^*) = \frac{\partial^2 g_u(u^*)}{\partial u_i \partial u_j} \tag{12}$$

With such an approximation, the probability of failure can be approximated by several approaches. The probability of failure is:

$$P_f = \Phi(-\beta)\prod_{j=1}^{n-1}(1 - \beta k_i)^{-\frac{1}{2}} \tag{13}$$

It is clear from (11) that SORM approximation of the probability of failure is obtained by a correction from the one calculated by the approximation FORM expressed in Eq. (6).

Case Study: The varying boundary conditions affect the failure probability of the solder joint and the LSF (Limit State Function), including varying boundary conditions. We can define LSF to estimate the impact of boundary conditions to the failure probability.

The limit state function is defined by Eq. (14):

$$G(X) = S_{yield} - S_{vmis} \quad (14)$$

Syield and Svmis are respectively the yield stress and the equivalent maximum Von Misses stress.

To estimate the failure probability of the solder joint, we've utilized the random variables presented in (Table 5).

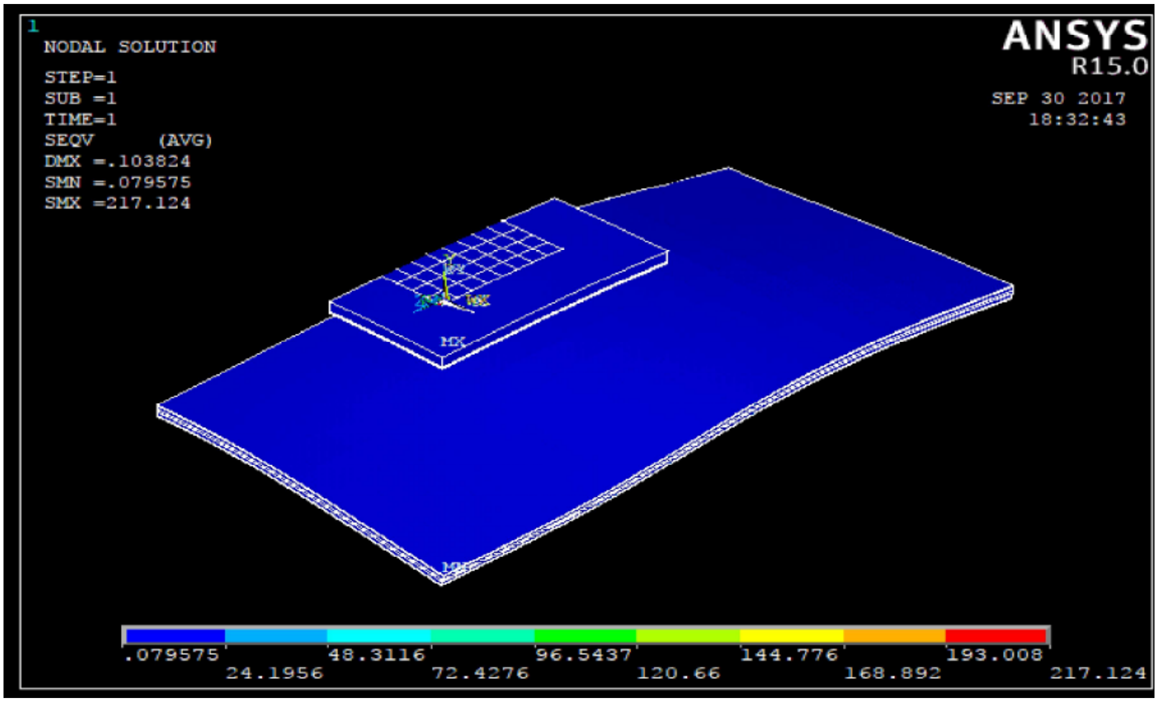
RESULTS AND DISCUSSION

Deterministic Results: The (Fig. 6 and 7) shows the results of the deterministic analysis of a BGA Package under the mechanical cyclic bending loading.

By using finite element simulation, we've been able to determine the major parameter in the failure mechanism, which is the local maximum of the equivalent stress values within the solder joints that leads to the crack initiation at any given region of the joint.

After having determined the most critical solder joint in the BGA Package (As shown in (Fig. 8)), we find out the deterministic analysis results (As shown in (Table 4)).

The following figures shows the time dependent behaviors of the stress, the creep strain, plastic strain and inelastic strain for the both board side (Bottom) and component side (Top).



```
1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV       (AVG)
DMX =.103824
SMN =.079575
SMX =217.124
```

Fig. 6: The overall deformation for BGA Package

Table 6: Statistical properties of random variables

Parameter	Value for the component side (Top)	Value for the board side (Bottom)
Total strain energy of solder, Δw_{tote} (Mpa)	31.033814	22.0467515
Cycles to crack initiation, N_0 (cycles)	425.157684	739.783629
fatigue life predicted N_f, α(cycles)	2370.45664	3681.91988

Table 7: Statistical properties of random variables

Methods	Probability of failure P_f	Reliability index β
FORM	0.04627	1.6811
SORM	0.04512	1.6941

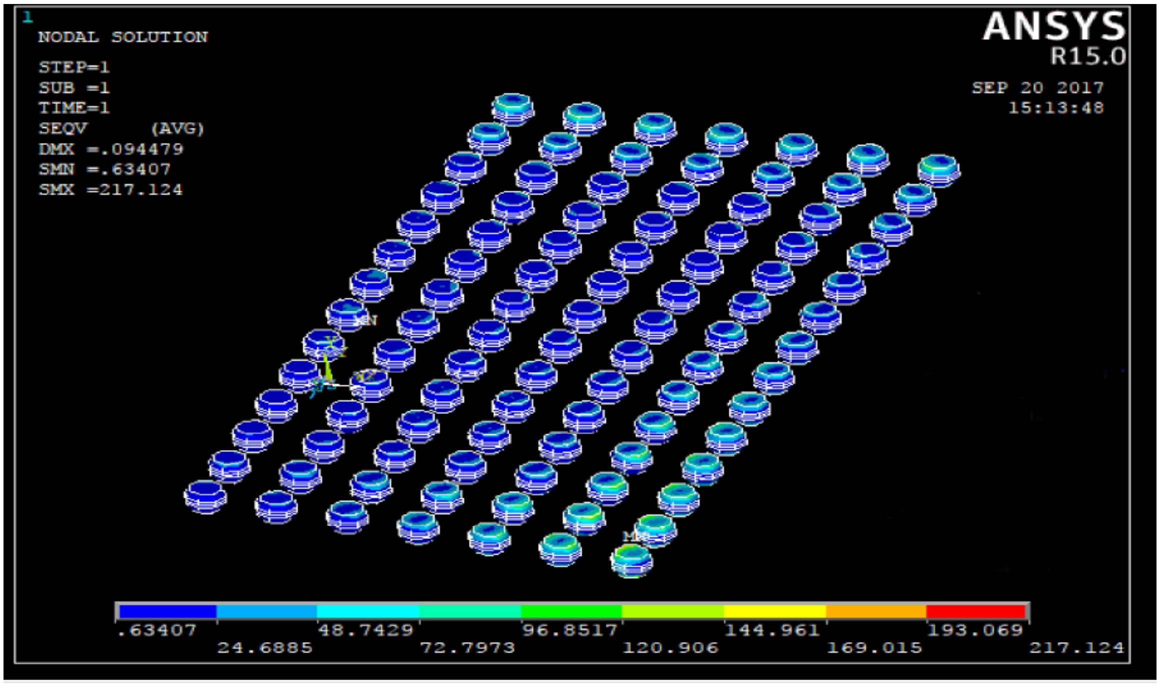


Fig. 7: The equivalent stress values within the solder joints

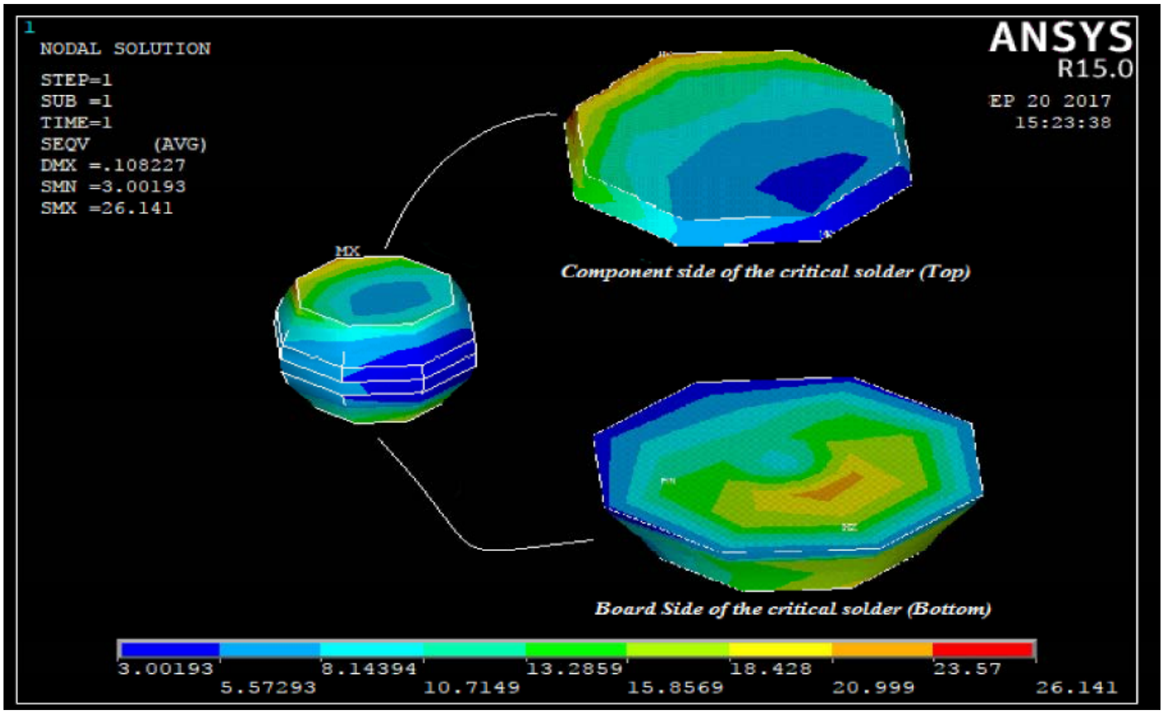


Fig. 8: The most critical solder joint

The (Fig. 11 and 12) shows the variation the stress as a function of the total strain and the inelastic strain for the both board side (Bottom) and component side (Top).

Probabilistic Results: Table 7 shows the results of the failure probabilities obtained by using FORM and SORM.

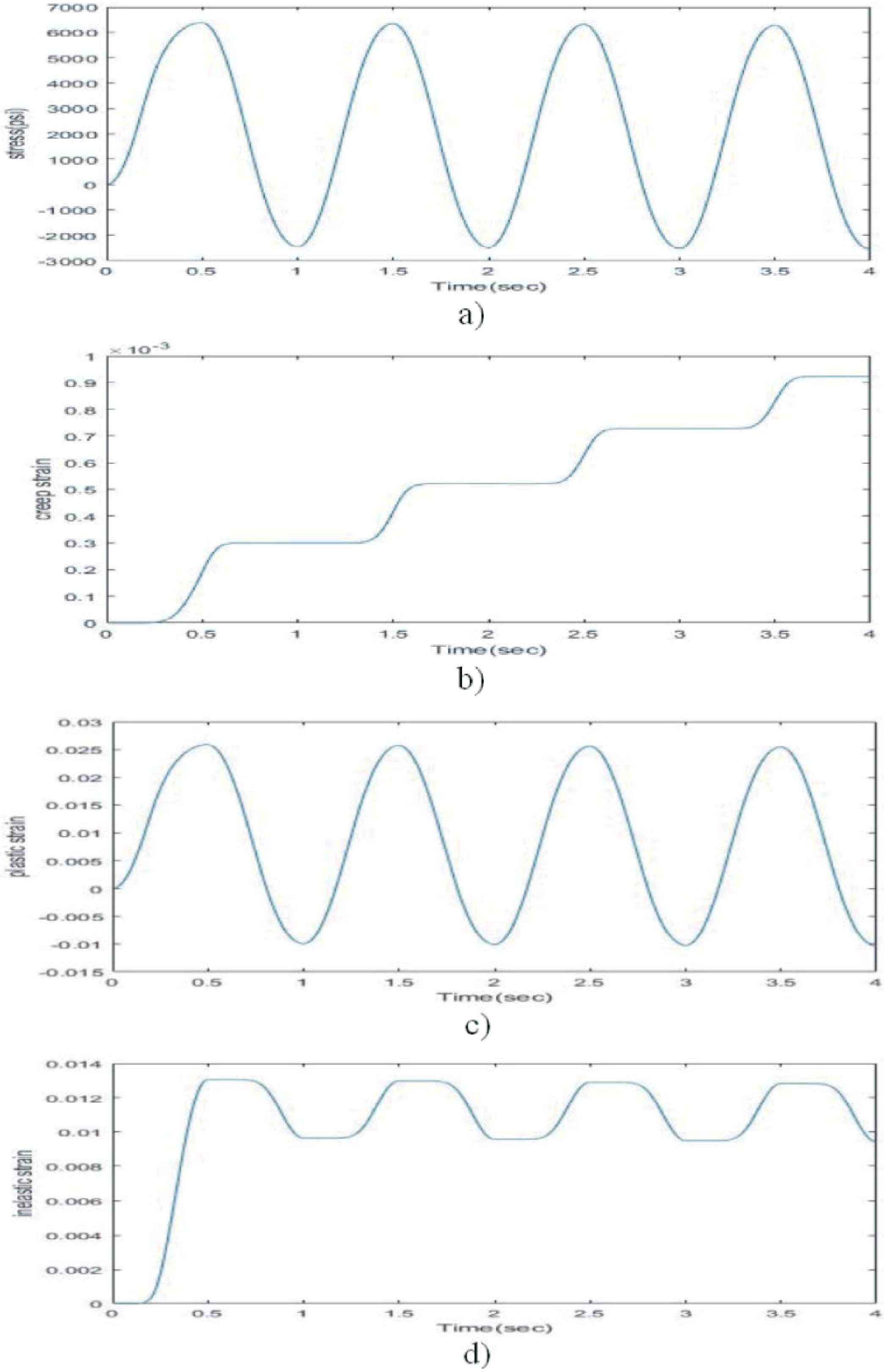


Fig. 9: a) stress, b) creep strain, c) plastic strain and d) inelastic strain for board side

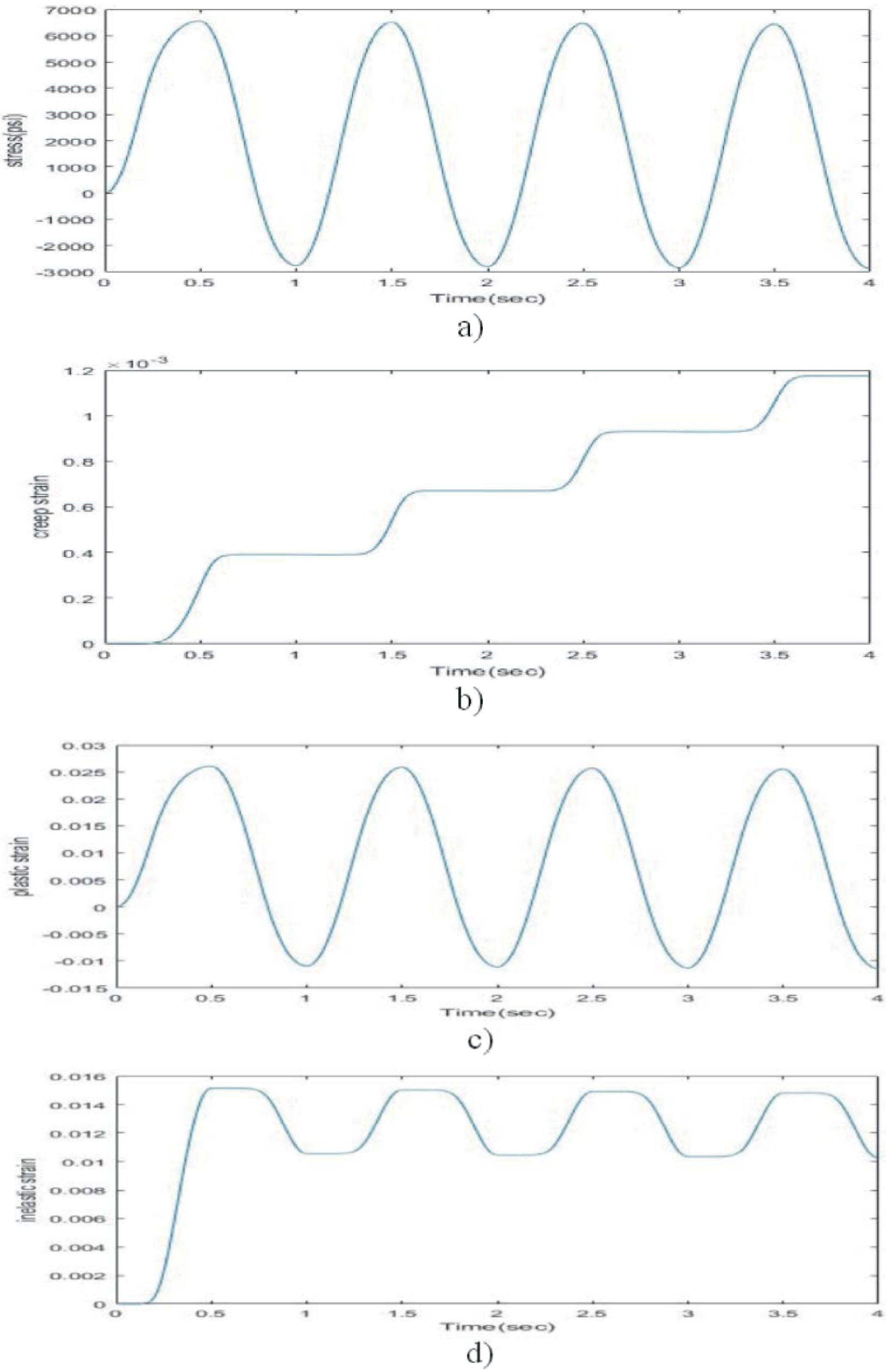


Fig. 10: a) stress, b) creep strain, c) plastic strain and d) inelastic strain for component side

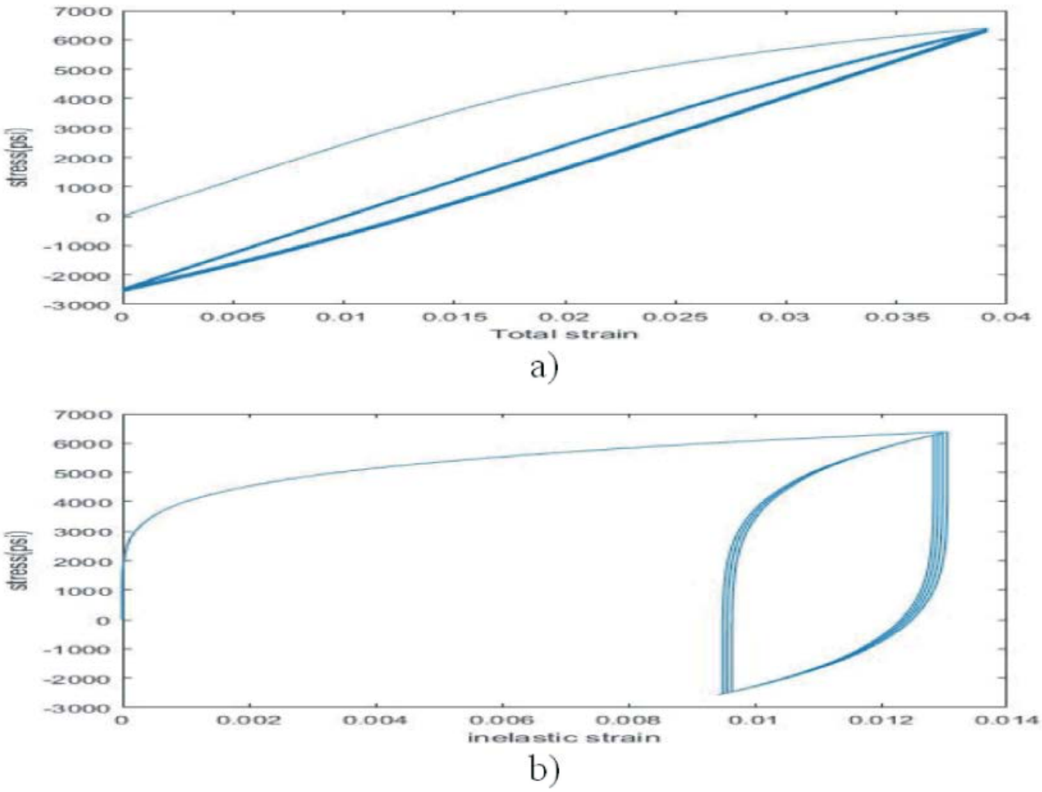


Fig. 11: a) variation of stress with total strain, b) variation of stress with inelastic strain for board side

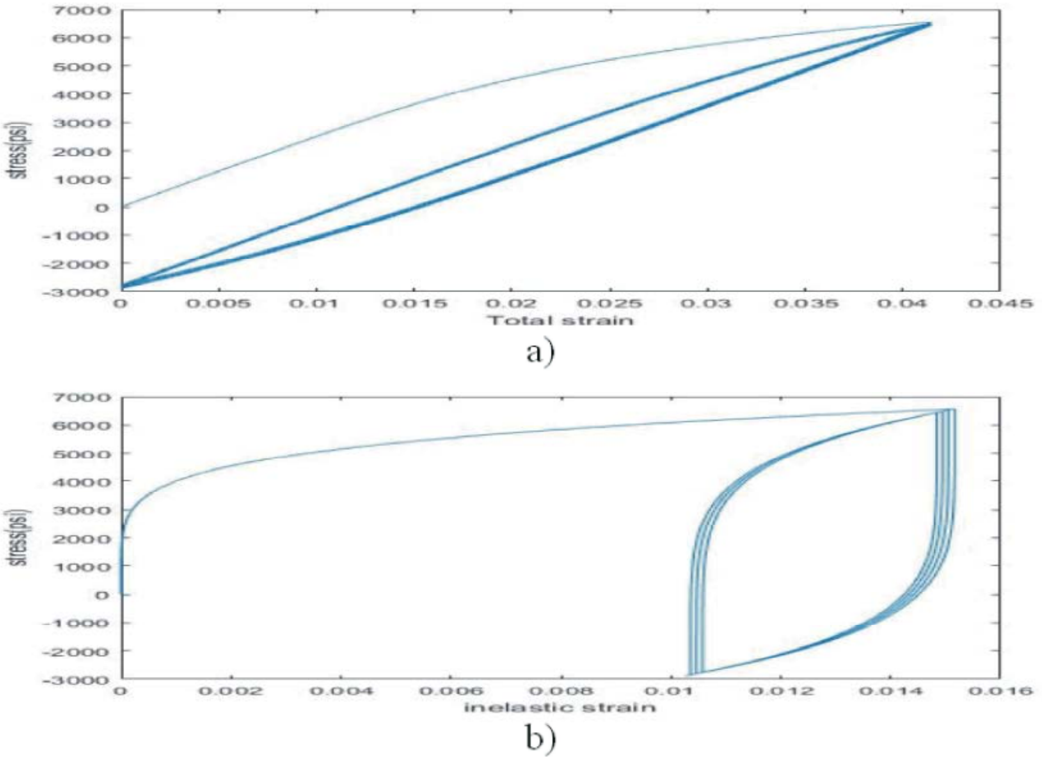


Fig. 11: a) variation of stress with total strain, b) variation of stress with inelastic strain for component side

CONCLUSION

A mechanical cyclic bending finite element simulation combined with a probabilistic approach was executed in our paper. The purpose is to predict fatigue life of solder joint of BGA packaging using The First and second Order Reliability Methods (FORM) and (SORM). According to the results reached, the critical solder joints are exposed to damage and crack initiation for both sides: board side (Bottom) and component side (Top); but the latter is more exposed to damage according to the results displayed in table (4).The results obtained by FORM and SORM methods are almost the same. The FORM and SORM methods are considered efficient methods to estimates the probability of failure of solder joints.

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