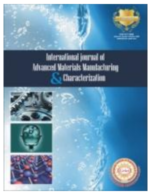

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Closed Form Bi-Layered Interfacial Thermal Stress Model in Electronic Packaging

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A B S T R A C T

Closed form solution of thermal mismatch stresses in perfectly bonded electronic packaging subjected to uniform temperature change was presented in this paper. The bi-material shearing stress model was developed by solving a simple second order differential equation instead of a relatively complicated integro-differential equation of earlier solution. The interfacial stresses were further investigated with the consideration of continuous and partial bonding layer to evaluate their relative influence in electronic packaging. The FEM simulation of an electronic packaging example was compared to the analytical solutions. The comparison between the present model and the finite element solution showed reasonably good agreement. It was concluded that the bi-layered electronic packaging in partial bond can be ignored and assumed as continuous bond if the center distance between the two bonded locations in partial bonded assembly is very small.

Introduction

Thermal mismatch stress is the major contributor that causes the layered structure failure between two or more connected devices during manufacturing or operating stages in composite materials and electronic packages. Thermal mismatch stresses inevitably arise due to the mismatch of coefficients thermal expansion (CTE) between constituent materials under thermal loading. According to Wang [1], high stresses always occur around the free edge or the junction of the packaging structures due to the presence of thermal mismatch, usually lead to interfacial delamination failure where electronic signals may subsequently become incorrectly transferred. Moreover, in the reality, the location and size of a crack in electronic packages are irregular and bring the structure to a functional failure. Therefore, an understanding of the nature of thermal mismatch interfacial stresses in packages or composite materials is a critical issue in achieving trustworthy structures subjected to thermal loading. As a consequence, thermal interfacial stresses developed in bonded layers is of interest in the modeling of reliability in packaging structure. The results can be a useful reference in other related scenarios, for instance, in wall painting or adhesive layers. Timoshenko [2] first proposed a classical thermal mismatch model by using the popular bi-layered thermostats using the beam theory. However, he assumed that the stresses in the beam remain unchanged along the strips and only predicts interfacial shearing stress, but no peeling stress. Chen and Nelson [3] considered thermal mismatch stress distribution at the interface by using force and moment equilibrium in bonded materials. Suhir [4] developed a theory on interfacial stresses of bonded structure by introducing interface compliance and extensively predicted the shearing and peeling stress at the interfacial of two dissimilar materials based on Timoshenko's [2] bi-layered thermostat theory. Notably, it is the first model to calculate the interfacial peeling stress of a thermostat structure. Suhir's [4, 5] analytical solution is considered as the benchmark development in the electronic packaging literature. Due to remarkable simplicity of Suhir's model, it had received wide attention in various microelectronics application and many more researchers have been dealing with interfacial package structure on diversity finding based on Suhir's model. Wong [6], Eischen [7, 8], Liew [9], Tsai [10], Wang [1], Luo [11], Sujan [12] to name but a few.

Flip Chip Ball Grid Array (FCBGA), a new development in bonded layers, is widely used in electronic packaging in recent years. It is a special type of a BGA package where the die is flipped in order to provide the shortest interconnection distance between the chip and package [13]. Thus, it improves the electrical performance as it minimizes impedance, resistance and

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inductance [14]. However, the interfacial stresses are induced due to CTE mismatch occurs during manufacturing and operating stages which causes the overall bending of the flip chip assembly [15].

The bi-layered interfacial stress model presented in this paper is developed with perfect bonding condition, which means bonding with negligible bond layer thickness. The model is developed by solving a 2nd order differential equation which is much simpler compared to Suhir's [4] integro-differential equation method.The perfectly bonded model is then upgraded with the consideration of continuous bond layer. Subsequently the bi-layered model is upgraded to partial bonded layered assembly to match with the bonding structure of a FCBGA package. An electronic packaging example was simulated using FEM and compared with the analytical solutions.

Symbols and their meanings throughout

i= Material layer no. as subscript =1 and 2;
E = Young's modulus: h_i = Thickness of the layers;
α_i = Coefficient of thermal Expansion;
ν_i = poison's ratio; R = Radius of curvature;

Shear modulus, $G_i = \frac{E_i}{2(1+\nu_i)}$;

Flexural rigidity, $D_i = \frac{E_i h_i^3}{12(1-\nu_i^2)}$ where $D = D_1 + D_2$;

Axial compliance, $\lambda_i = \frac{(1-\nu_i^2)}{E_i h_i}$;

Coefficient of interfacial compliance, $K_i = \frac{h_i}{3G_i}$

BI-LAYERED MODEL

Uniform temperature shearing stress Bi-layered perfectly bonded model.

The uniform temperature shearing stress model is presented here by solving a simple 2nd order differential equation instead of a relatively complicated integro-differential equation of Suhir [4, 5]. Fig. 1(a) represents the full length of the 2-*D* uniform temperature model where AA showing the line of symmetry. The 2-*D* model is considered to be of unit width in a direction perpendicular to the paper and all forces and moments

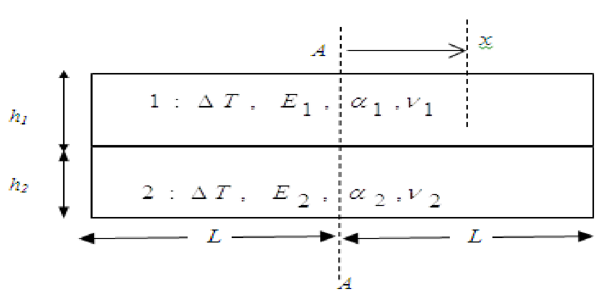

Fig. 1(a): Geometric and material parameters of the bi-layered model

are defined with respect to the unit width. Fig. 1(b) shows the free body diagram of the model.

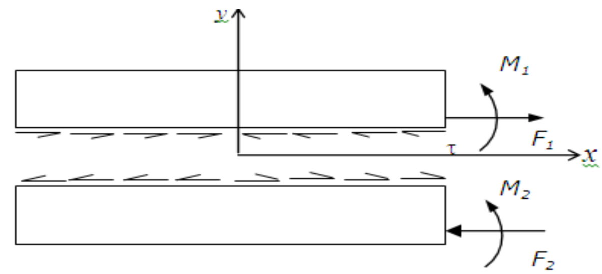

Fig 1(b): Free-body diagram of the bi-layered model

In order to develop the analytical bi-layered model under uniform temperature, the entire electronic packaging was simplified into a unit width strip cut parallel to the plane. The bi-layered shear stress model formulation is based on the assumptions below:

i. There is no external force acting among them
ii. Two layers are assumed perfectly bonded (zero bond layer thickness)
iii. Axial force varies along the assembly length contributing shear stress at the interface
iv. Entire assembly is subjected to uniform change in temperature

In the earlier approach [11], the compatibility at the interface was expressed as: $U_{x(1)} - U_{x(2)} = 0$, (1)

where U_i, i=1, 2 are the axial displacements for the layers.

In the present approach, the above condition is expressed in its following simpler form:

$$\epsilon_{x(1)} = \epsilon_{x(2)} \tag{2}$$

where $\epsilon_{x(i)}$, i = 1, 2 are the axial strains given by $\epsilon_{x(i)} = \frac{\partial U_i}{\partial x}$

The conditions (1) and (2) are mathematically equivalent. Suhir [4] used eq. (1) as the compatibility condition which required solving a complicated integro-differential equation.

The axial strains at the interface take the form as,

$$\left.\begin{aligned} \epsilon_{x(1)} &= \alpha_1 \Delta T + \lambda_1 F_1 + \frac{h_1}{2R} - K_1 \frac{\partial \tau}{\partial x} \\ \epsilon_{x(2)} &= \alpha_2 \Delta T - \lambda_2 F_2 - \frac{h_2}{2R} + K_2 \frac{\partial \tau}{\partial x} \end{aligned}\right\}, \tag{3}$$

where $\alpha_i \Delta T$ $\alpha_i \Delta T_i$, $\lambda_i F_i$, $\frac{h_i}{2R}$, and $K_i \frac{\partial \tau}{\partial x}$ are the strain components due to temperature changes, thermal mismatch axial forces F_i, bending, and shearing force respectively.

The compatibility of axial strains at the interface in eq. (2) demands the following condition(s),

$$(\alpha_1 \Delta T - \alpha_2 \Delta T) + \lambda F - K \frac{\partial \tau}{\partial x} = 0 \quad (4)$$

where $\lambda = \lambda_1 + \lambda_2 + \frac{h^2}{4D}$, $K = K_1 + K_2$, $F_1 = -F_2 = F$,

and $\frac{1}{R} = \frac{(h_1 + h_2)}{2(D_1 + D_2)} F = \frac{hF}{2D}$

Differentiating eq. (4), one gets a 2nd order differential equation in τ as $\frac{\partial^2 \tau}{\partial x^2} - \kappa^2 \tau = 0$, (5)

where $\kappa^2 = \frac{\lambda}{K}$

Based on [16], the solution of this equation takes the form,

$$\tau = C_1 \sinh \kappa x + C_2 \cosh \kappa x \quad (6)$$

Applying boundary conditions and using eq. (6), the differential equation (5) has a solution for shearing stress $\tau(x)$ as follows,

$$\tau = \frac{\Delta T(\alpha_1 - \alpha_2)}{K \kappa \cosh \kappa L} \sinh \kappa x \quad (7)$$

Case study: Bi-layered perfectly bonded assembly

A case study of the bi-layered assembly under uniform temperature was conducted. The properties and other parameters of the materials of the assembly are shown in Table I.

Table 1. Bi-layered assembly material properties and parameters

Properties/ parameters	**Symbol**	**Layer 1**	**Layer 2**
Young Modulus (GPa)	**E**	188 GPa	49.7 GPa
Poisson's ratio	***v***	0.3	0.29
Coefficient of thermal expansion (1/°C)	**α**	$3.0\text{x}10^{-6}$ 1/°C	$2.5\text{x}10^{-5}$ 1/°C
Thickness (m)	**h**	$3.5\text{x}10^{-4}$ m	$1.5\text{x}10^{-4}$ m
Length (m)	**L**	0.0025m	
Temperature	**ΔT**	60°C	

Fig. 2 shows comparison between analytical and FEM simulation for shearing stress at the interface of the two layers. Results are presented from x/L = 0.7 to 1 only since the stresses values are considered insignificant beyond this point. It can be observed that FEM result shows good agreement with analytical results almost entire length of the interface except near the free end for the region around 0.95 < x/L < 1. The FEM results come into a huge variation and singularities take place for the region around 0.95 < x/L < 1. According to [17], it is well known that stress singularities occur at interfacial edges. Different meshed configurations of the FEM result in stress of different extreme magnitudes at the interfacial edges. Therefore, the mesh size of the FEM model could affect the results obtained. However, the overall results were acceptable. Hence both analytical and FEM method would be applied in the subsequent models of continuous and partial bonded model analysis.

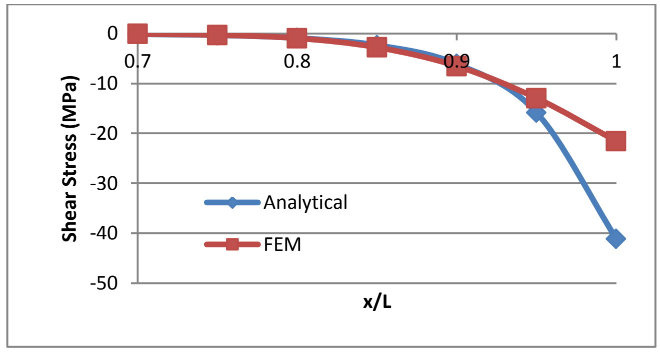

Figure 2: Comparison of shearing stress between analytical and FEM solution

Bi-Layered Model with continuous bond

Bi-layered assembly with continous bond under uniform temperature change formulation

Fig. 3 shows the free body diagram of the continuous bonded bi-material model analyzed.Here h_0 represents the thickness of the bond layer.

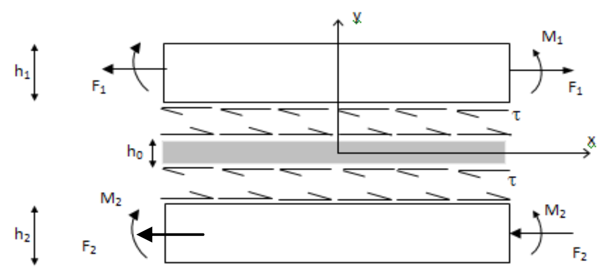

Figure 3: Free body diagram of bi-layered assembly with continuous bond

The perfectly bonded (zero bond layer thickness) bi-layered model (eq. 7) can be utilized to develop shearing stress model with continuous bond as given in eq. (7). Including the solder bond layer thickness, the strain compatibility condition at the interface can be expressed as

$$\epsilon_{x(1)} - \epsilon_{x(2)} = K_0 \frac{\partial \tau}{\partial x} \quad (8)$$

where$K_0$is the interfacial compliance coefficient of the bond layer.

Replacing the strain components of $\epsilon_{x(1)}$ and $\epsilon_{x(2)}$, eq. (8) takes the form as,

$$(\alpha_1 \Delta T_1 - \alpha_2 \Delta T_2) + \lambda F - (K_1 + K_2) \frac{\partial \tau}{\partial x} = K_0 \frac{\partial \tau}{\partial x} \quad (9)$$

The above eq. (9) is similar to eq. (4), the compatibility condition for the case of perfectly bonded layers except the right hand side shearing force component contributed by the bond layer. Differentiating eq. (9) and following the similar steps for the case of perfectly bonded assembly, it has a solution for shearing stress *τ(x)* as follows

$$\tau(x) = \frac{(\alpha_1 - \alpha_2)\Delta T}{K\kappa\ \cosh(\kappa\ L)}\sinh(\kappa\ x) \qquad (10)$$

It is observed that eq. (7) and (10) are of same expressions as equations for the case of bi-material assembly with perfect bonding condition. The major differences are $h = h_1 + h_2 + 2h_0$, $\lambda = \lambda_1 + \lambda_2 + \frac{h(h_1 + h_2)}{4D}$, and $K = K_1 + K_2 + K_0$ that the quantities h, λ, and K are all redefined. The quantity κ, although given by the same expression in terms of K and λ, is also redefined.

Case study: Bi-layered assembly with continous bond

A case study of the bi-layered assembly with bond layer under uniform temperature was conducted. The properties and other parameters of the materials of the assembly are shown in Table II.

Table 1: Bi-layered assembly with continuous bond material properties and parameters

Properties/ parameters	Symbol	Layer 1	Layer 2	Layer 0
Young Modulus (GPa)	**E**	188	49.7	70.5
Poisson's ratio	***v***	0.3	0.29	0.41
Coefficient of thermal expansion (1/°C)	**α**	3.0×10^{-6}	2.5×10^{-5}	1.68×10^{-5}
Thickness (m)	**h**	3.5×10^{-4}	1.5×10^{-4}	1.0×10^{-5}
Length (m)	**L**	0.0025		
Temperature	**ΔT**	60°C		

Fig. 4 showed the shear stress distribution of 2*D* FEM model of the continuous bonded bi-layered assembly. The magnitude of shear stress was represented by the scaled colour intensity as shown in Fig. 4. Based on the colour change near the free end in the FEM model, it can be noticed that the higher shear stress distribution was observed between layer 1 (top layer) and the bond layer (red colour) compared to the layer 2 (bottom layer) and bond layer (green colour). This might have caused due to the fact that the coefficient of thermal expansion (CTE) difference (mismatch) between layer 1 and bond layer was greater compared to the CTE difference between layer 2 and bond layer. Therefore, the thermal mismatch stress induced between layer 1 and bond layer were much higher.

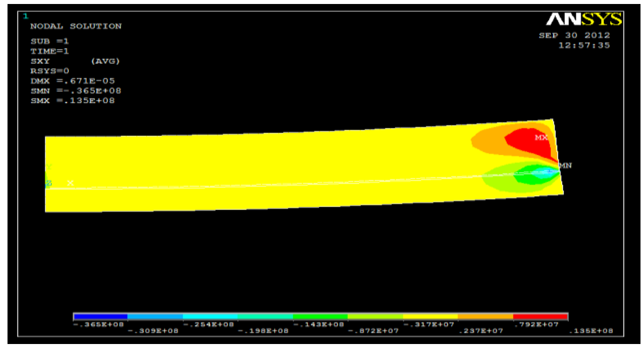

Figure 4: Shear stress distribution in FEM model for bi-layered assembly with continuous bond

Graphical comparison was made between FEM and analytical results and presented in Fig. 5. The shearing stress results were presented in this case only from x/L = 0.7 to 1 since stress magnitudes beyond this point were insignificant. It can be seen that the FEM results were in good agreement with the analytical results except for the region around the interfacial edges where 0.95 = x/L = 1. According to [18], those singularities are indicating as boundary layer edge effect. It explained that this is merely due to elasticity clarification of FEM models which predicts that stresses approach infinity at free edge and cause FEM results inaccurate at the free edge. However, the FEM solutions are still applicable in the further analysis since the overall results did not deviate to a great extent.

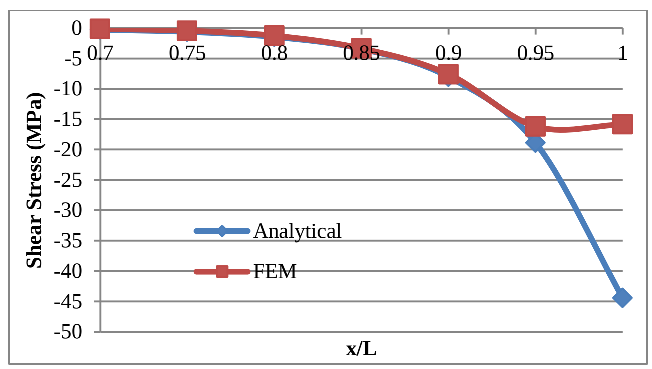

Figure 5: Comparison of shear stress between analytical and FEM solution for bi-layered assembly with continuous bond

Bi-Layered Assembly Model with Partial bond

Bi-layered assembly with partial bond under uniform temperature change formulation

A flip chip ball grid array (FCBGA) is an electronic package formed by attaching the integrated circuit to the substrate as shown in Fig. 6a[19]. Fig. 6b represents a simplified model of a unit section of a partial bonded bi-layered assembly of FCBGA where silicon die is attached to the substrate by solder interconnects. Here 'C' is the center distance between two solder interconnects. Fig. 7 shows the free body diagram of half of the model of Fig. 6 with force and moment notations.

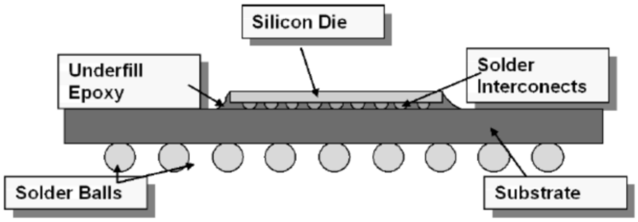

Figure 6(a): Flip Chip Ball Grid Array [19]

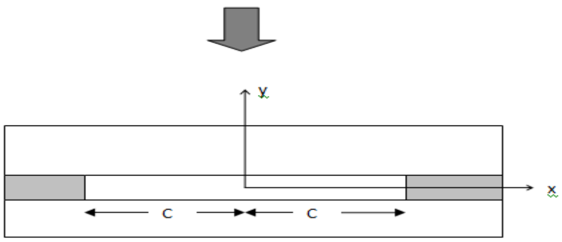

Figure 6(b): simplified schematic diagram of FCBGA assembly with partial bond [16]

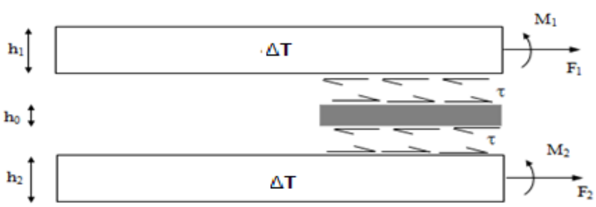

Figure 7: Free body diagram of bi-layered assembly with partial bond

The strain compatibility condition in this case is same as eq. (8), which is for the case of continuous bonded layer.

The equation for the shearing stress τ can be expressed as

$$\tau = C_1 \sinh \kappa(x - C) + C_2 \cosh \kappa(x - C) \qquad (11)$$

The governing equation can be expressed using the same continuous bond bi-layered assembly equation (9), which is,

$$(\alpha_1 \Delta T - \alpha_2 \Delta T) + \lambda F = K \frac{\partial \tau}{\partial x} \qquad (12)$$

Based on [16], differentiating equation (11) and applying boundary condition at x=C can obtain,

$$C_2 = C_1 \kappa C \qquad (13)$$

$$C_1 = \frac{(\alpha_1 \Delta T - \alpha_2 \Delta T)}{K\kappa\left[\kappa\, C \sinh\kappa(L - C) + \cosh\kappa(L - C)\right]} \qquad (14)$$

Replacing the expressions for C_1 and C_2 from equations (13) and (14) into (11), results in the expression for shearing stress for partial bond can be expressed into:

$$\tau = \frac{\Delta T(\alpha_1 - \alpha_2)\left[\sinh \kappa(x - C) + \kappa C \cosh\kappa(x - C)\right]}{K\kappa\left[\kappa C \sinh \kappa(L - C) + \cosh \kappa(L - C)\right]} \qquad (15)$$

Case study: Partial bonded bi-layered assembly with different centre distances (C)

A case study of the bi-layered assembly with partial bond was conducted. The same properties and parameters of the materials of the assembly as shown in table II. In this case study, the center distance, C was varied in order to observe and compare the shearing stress induced in different length of partial bond sections. The center distance, C = 0.0015m, 0.00175m and 0.0020m are considered. This case study was analyzed by using both analytical and FEM approach and the solutions were compared.

Fig. 8 showed the graphical plot of analytical results for continuous and partial bond with different 'C'. The results was presented only for the region near the free end of the assembly since it was the area where the partial bond was located and the shearing stress generated significantly at this region. Based on the Fig. 8, it can be clearly observed that the analytical results of continuous bond with C = 0.0015 and 0.0175m had good agreement with the analytical result of partial bond. The analytical results for C = 0.0020m had some difference at the region x/L = 0.7 to 0.8. The difference for C = 0.0020m might be resulted due to the bond location for C = 0.0020m at x/L = 0.8. However, for all the C cases, shearing stress values were equal or lower than the case of continuous bond.

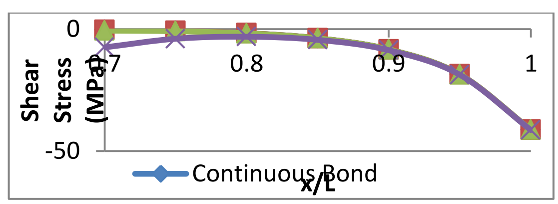

Figure 8: Shearing stress distribution of analytical results for bi-layered assembly with continuous and partial bond.

Fig. 9 showed the graphical comparison of FEM results for continuous bond and partial bond with different C values. From the trend, it can be clearly seen that all the FEM results had good agreement at the free end region, x/L from 0.85 to 1. However, the results for C = 0.00175m and 0.0020 m at the region x/L = 0.7 to 0.85 were not in good match with other results. As mentioned previously, this might be due to the partial bond location.

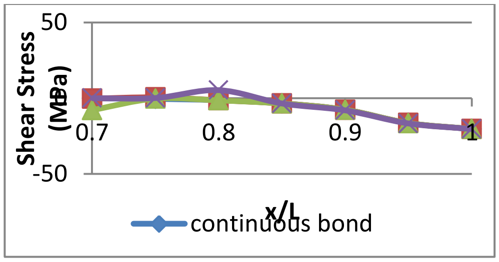

Figure 9: Shearing stress distribution of FEM results for bi-layered assembly with continuous and partial bond

From the analysis based on Fig. 8 and Fig. 9, it can be concluded that the interfacial shearing stresses are identical for continuous and partial bonded layers near the edges where the stress values are higher. However, stress values vary to some extend towards the inner location (towards the center) for continuous and partial bond consideration. Since the inner stress values are significantly smaller compared to the edges, one can ignore their relative effect. Thus, it can be concluded that the bi-layered electronic packaging in partial bond can be ignored and assumed as continuous bond if the center distance between the two bonded locations in partial bonded assembly is very small.

Conclusion

The shearing stress thermal mismatch bi-layered model was developed with the condition of perfect bonding (zero bond layer thickness) condition. The model was developed by solving a simple second order differential equation compared to earlier integro-differential equation method. The perfectly bonded shearing stress model was verified using FEM simulation of an electronic packaging example. The FEM results were found in reasonably good agreement with the analytical solution. The perfectly bonded model was subsequently upgraded with the consideration of continuous bond layer with small thickness. The bi-layered model with continuous bond was further upgraded to partial bonded layered model to match with the bonding structure of FCBGA package which is widely used in electronic packaging in recent years.The analytical and FEM results for continuous and partial bond with small center distance were found in reasonably good agreement. Based on the analysis, it can be concluded that the partial bond layer with small center distances can be assumed as continuous bond layer for bi-layered shearing stress model analysis. The research work presented in this paper is expected to be used as useful reference to address thermo-mechanical stress in electronic packaging to minimize mechanical and functional failures.

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