3D Interfacial Delamination Near Solder Bumps in Flip-Chip Package

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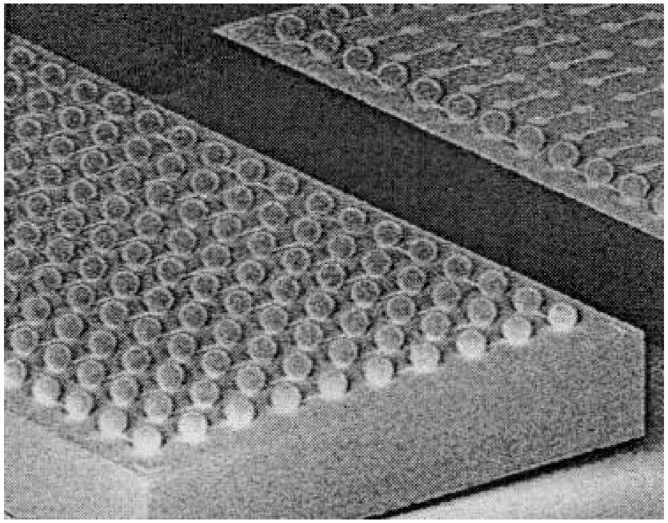
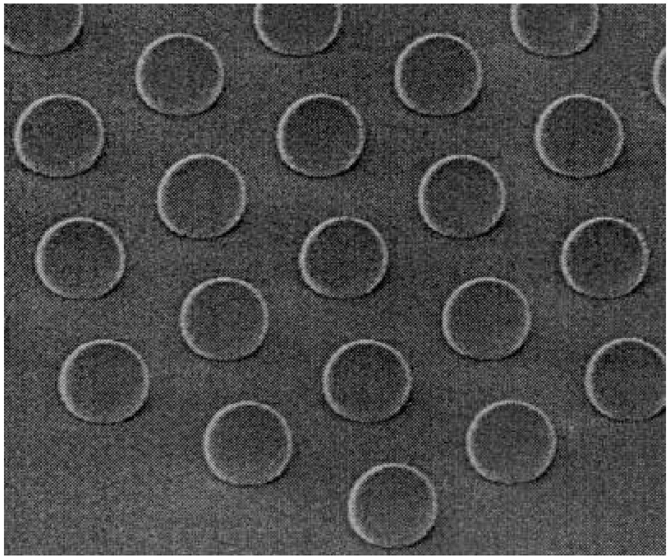
Objectives

- ❑ Utilize global/local modeling to investigate delamination characteristics of flip chips.
- ❑ Quantify the differences between 2D approximation and real 3D structures.
- ❑ Identify potential fracture modes and likely delamination sites near solder bumps.
- ❑ Determine fracture parameters along 3D delamination fronts.
- ❑ Use 3D model to estimate fatigue life of solder bumps in flip chip packages.

Solder Bumps (~100µm dia)





(Microfab Technology. Singapore)

Earlier Works

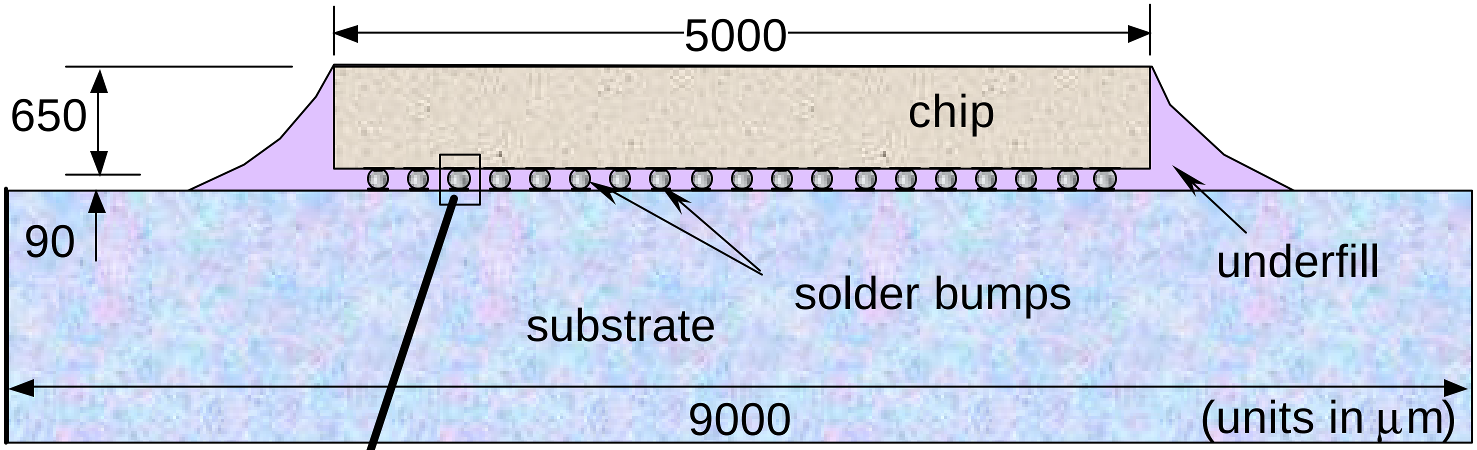
- Understanding roles of underfill materials and interface reliability. *Rzepka et al.*, 1998.
- Optimization of interconnect structure — solder joints. *Wiegele et al.*, 1998.
- Thermal fatigue life estimation in 2D/3D models. *Lau*, 1993; *Paydar et al.*, 1994; *Gektin et al.*, 1997; *Hong, et al.*, 1997.
- Fracture behaviors and effects of process-induced stresses under real loading history with temperature and time-dependent materials. *Gall et al.*, 1996; *Wang et al.*, 1998.
- Global-local analysis. *Buratynnski*, 1992; *Zhu et al.*, 1997; *Madenci et al.*, 1998.

Present Analysis

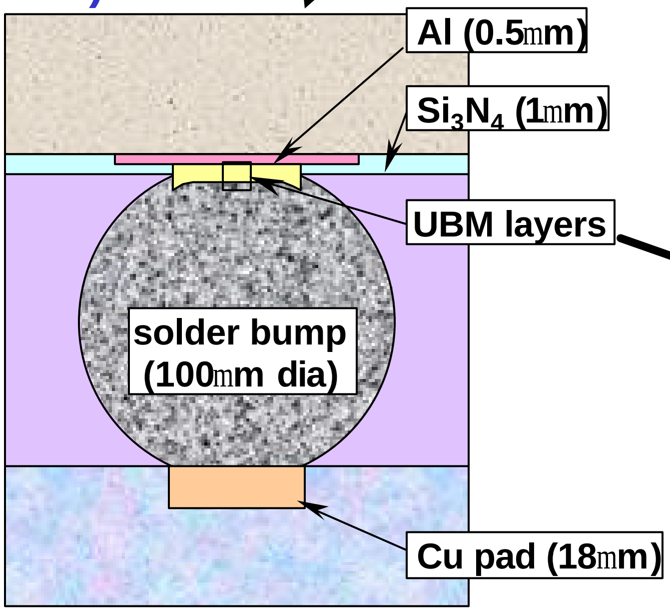
- Multi-scale (global/local) procedure is adopted to model extreme size differences among various components.
- Regions of high stress concentration are identified (e.g., likely failure sites).
- Fracture parameters are determined in complex 3D models.
- Fatigue-life is estimated from cyclic thermal loading.

Multi-Scale FE Analysis (cross-sectional views)

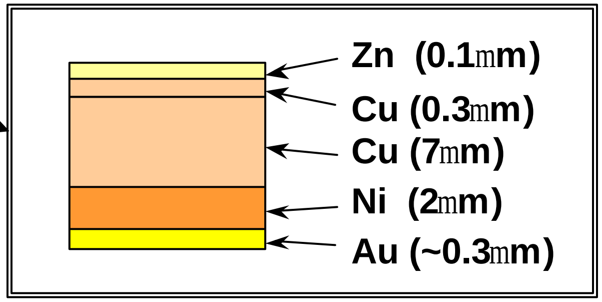
Flip-chip package (*global model*)



Solder bump region (*cell model*)



Under bump metallurgy



Boundary and Load Conditions

- Temperature drop from 155°C to 20°C.
- Global Model: constrain displacements of symmetry and bottom planes in the direction perpendicular to themselves.
- Cell Model: prescribed displacements along the perimeter of cell model — *interpolated from the global analysis.*

Assumption: *1) no initial residual stresses; 2) no transient heat transfer; 3) uniform temperature distribution; 4) gradually applied loads.*

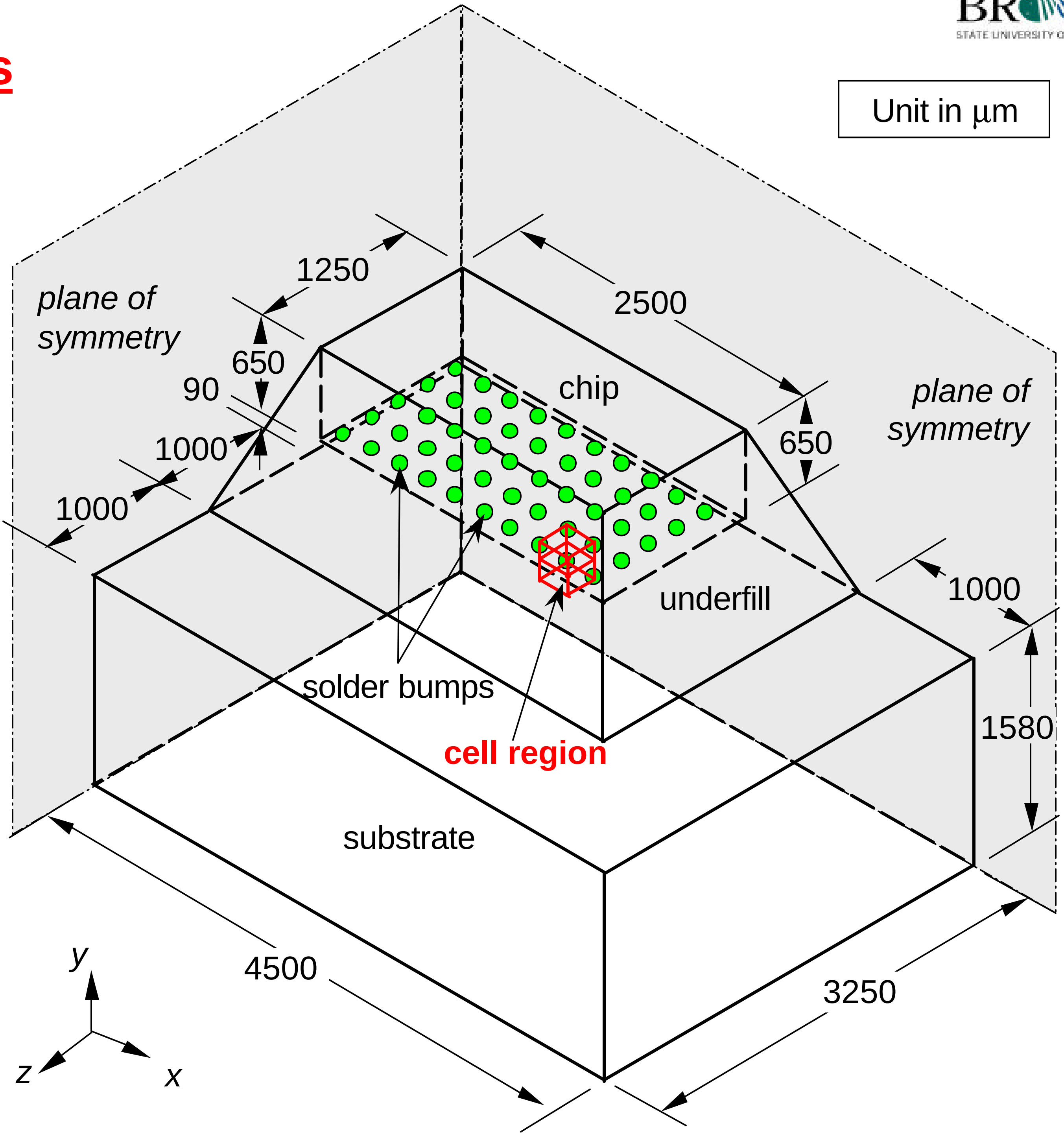
Material Properties

Materials	**CTE** (10^{-6}/ °C)	***E*** (GPa)	n	s_o (MPa)
chip (Si)	2.8	131	0.30	
passivation (Si_3N_4)	2.9	325	0.24	
bond pad (Al)	23.2	70	0.24	
UBM layer 1 (Cu)	16	117	0.30	
UBM layer 2 (Ni)	12.7	200	0.31	
solder bump (63Sn/37Pb)	21	30	0.35	20
underfill	33	8.5	0.28	
substrate	18	22	0.28	

3D Global Analysis

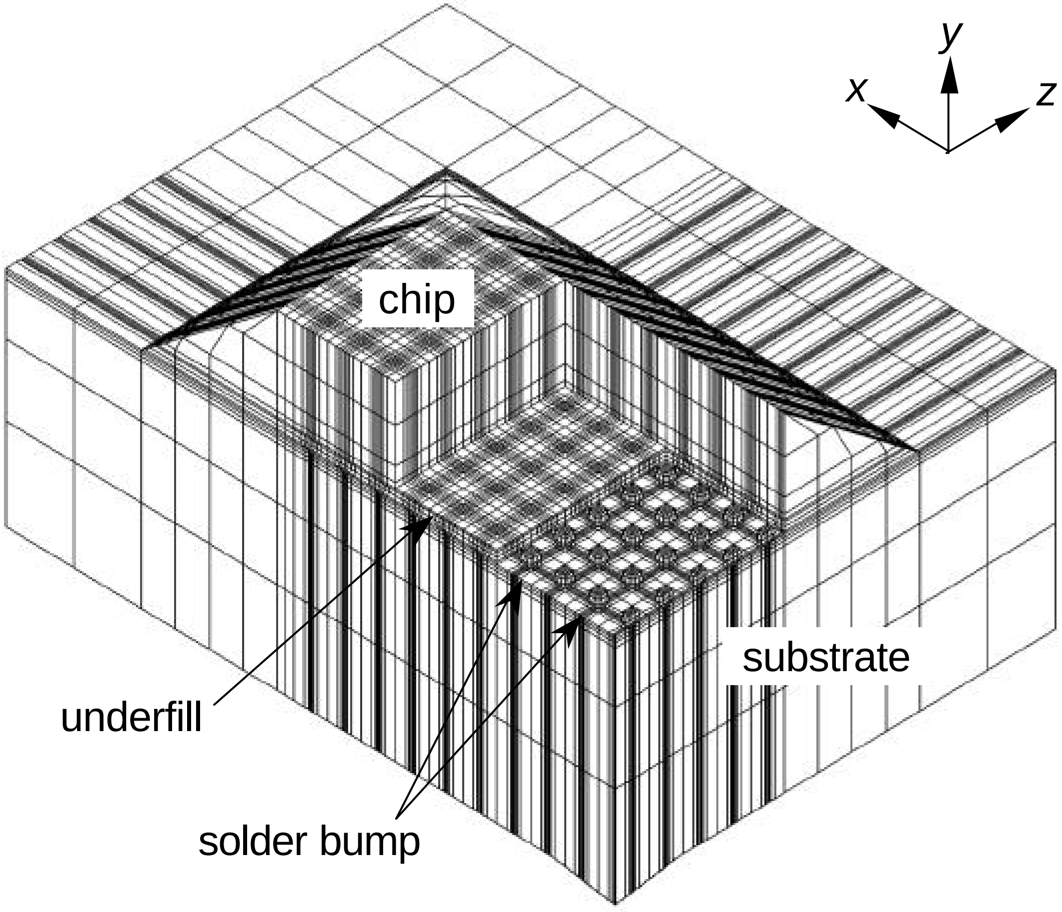
one quarter of the flip-chip package

- *Underfill between chip and substrate for adhesion.*
- *50 solder bumps are individually modeled.*



3D Global Mesh

- *51,675 eight-node isoparametric brick elements.*
- *45 cell regions containing solder bump and Cu pad.*



(b)

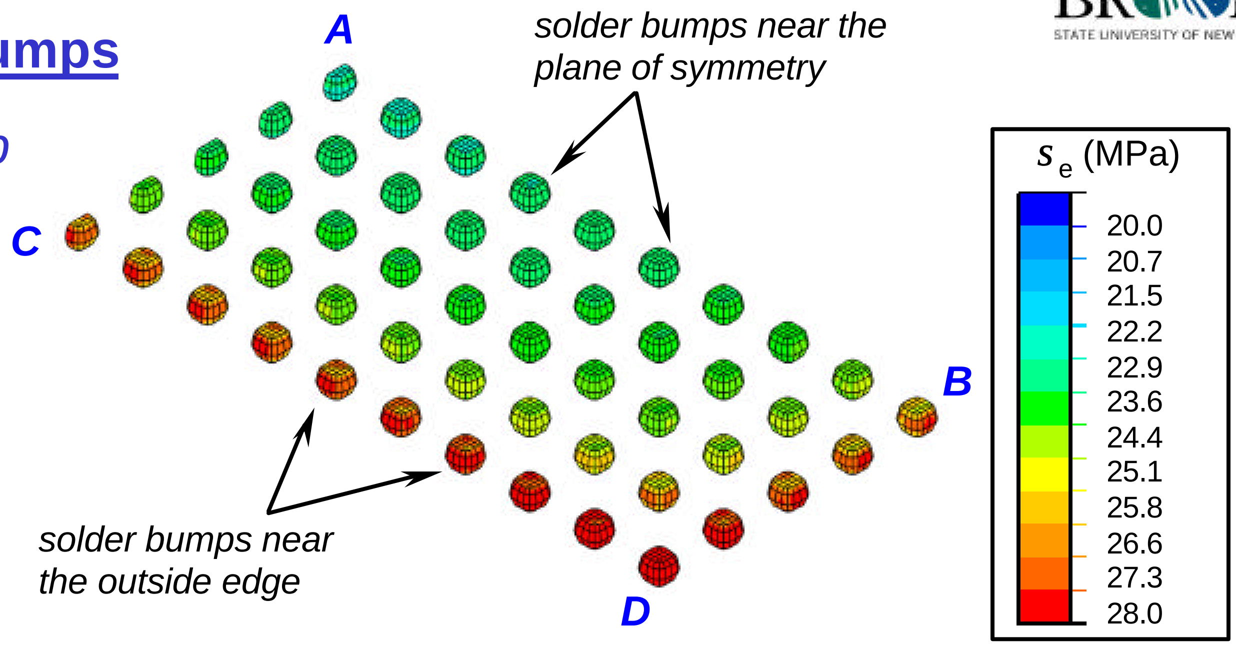
Stresses of Various Solder Bumps

Þ determination of critical bump

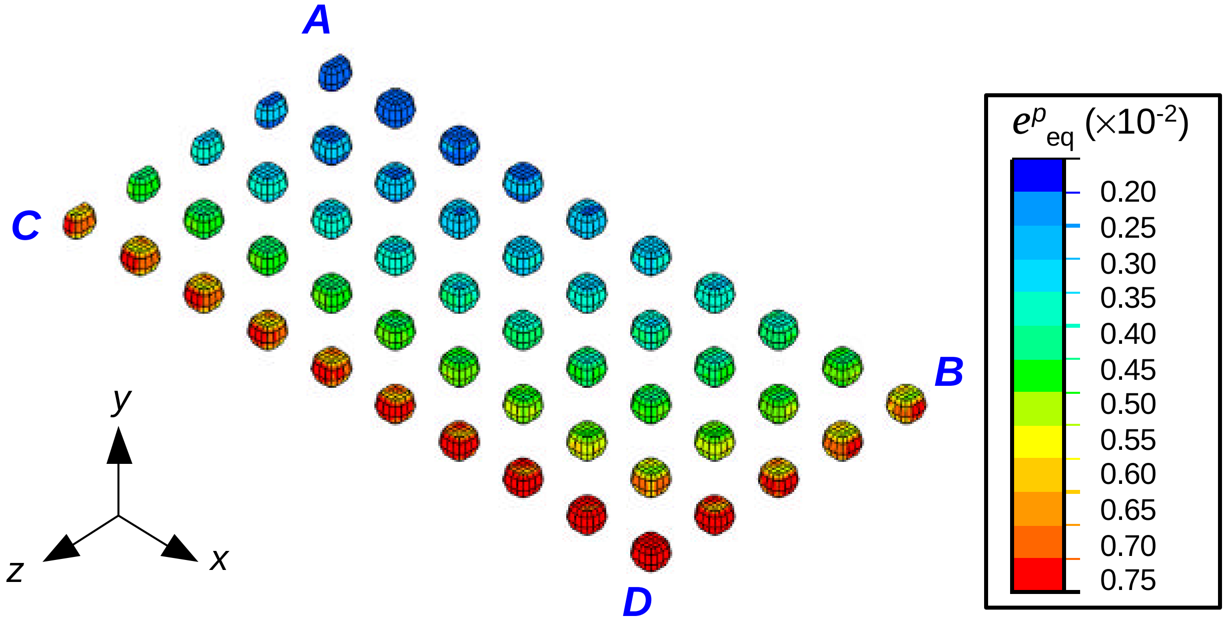
Loading Condition

D*T* = -135ºC

- *Greater stresses are observed for solder bumps further away from the symmetry planes.*
- *Large stress concentration between underfill and chip along edges.*



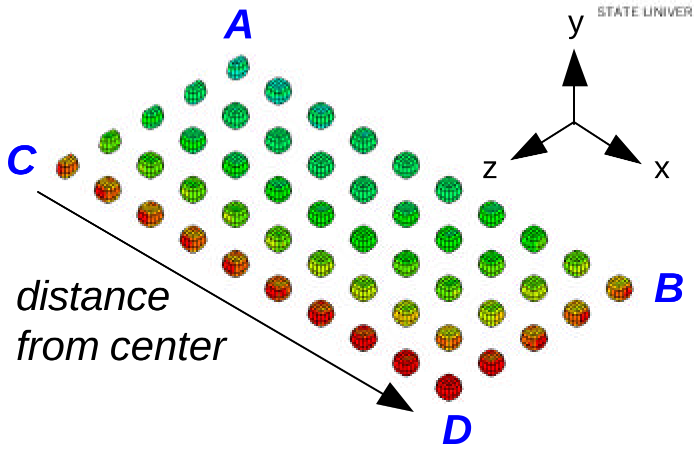
Mises stress of the grid arrayed solder bumps

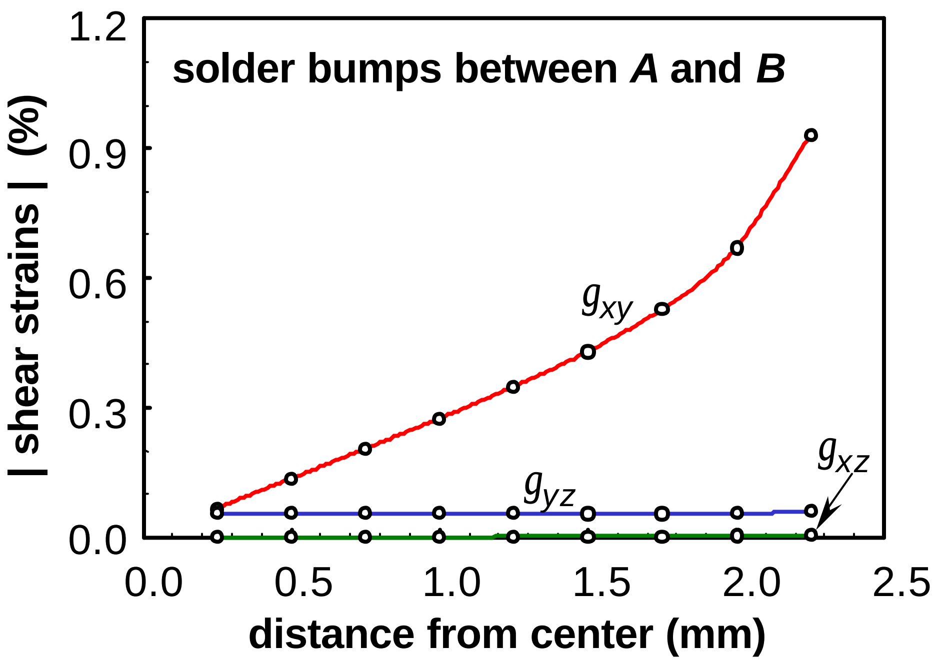


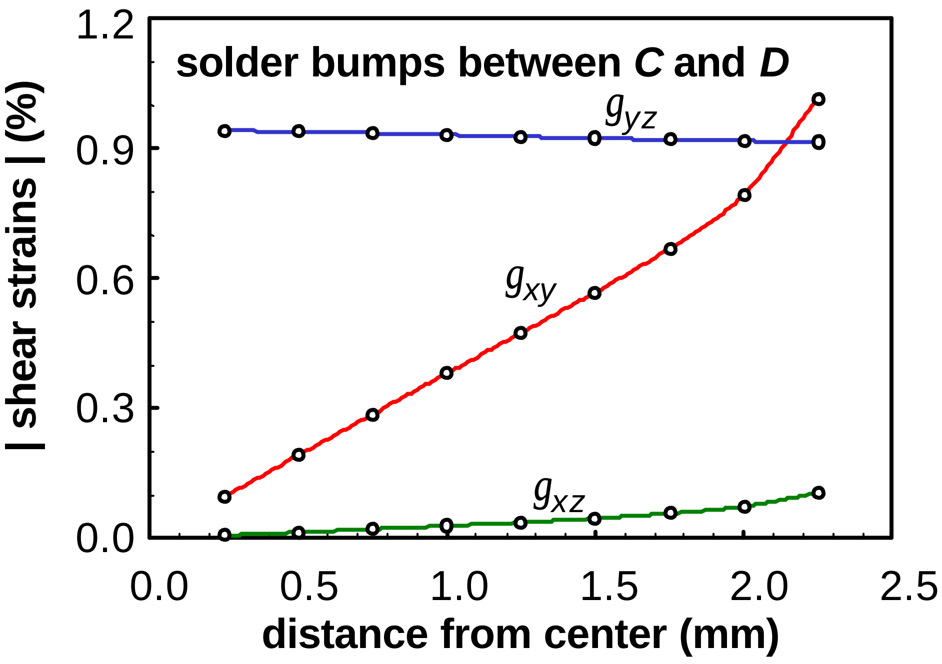
Equivalent plastic strain of the grid arrayed solder bumps

Average Shear Strains in Solder Bumps

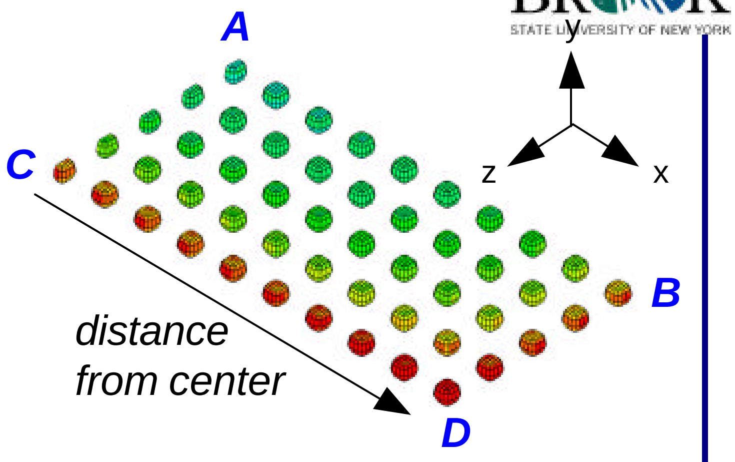
- *Increasing shear strain from center to the edge.*
- *Out-of-plane shear strain is larger near the edge.*





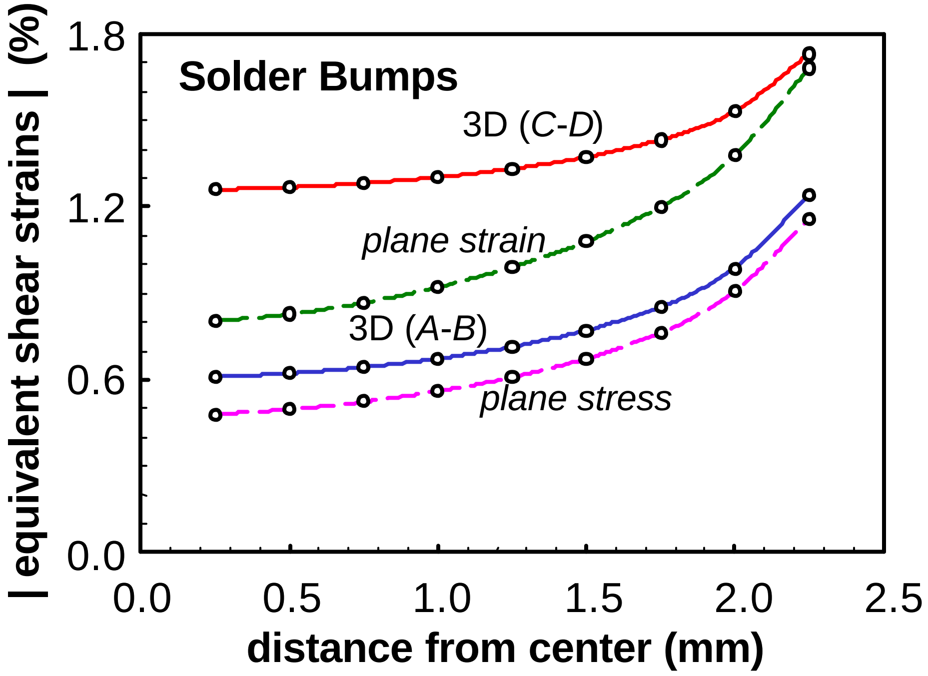


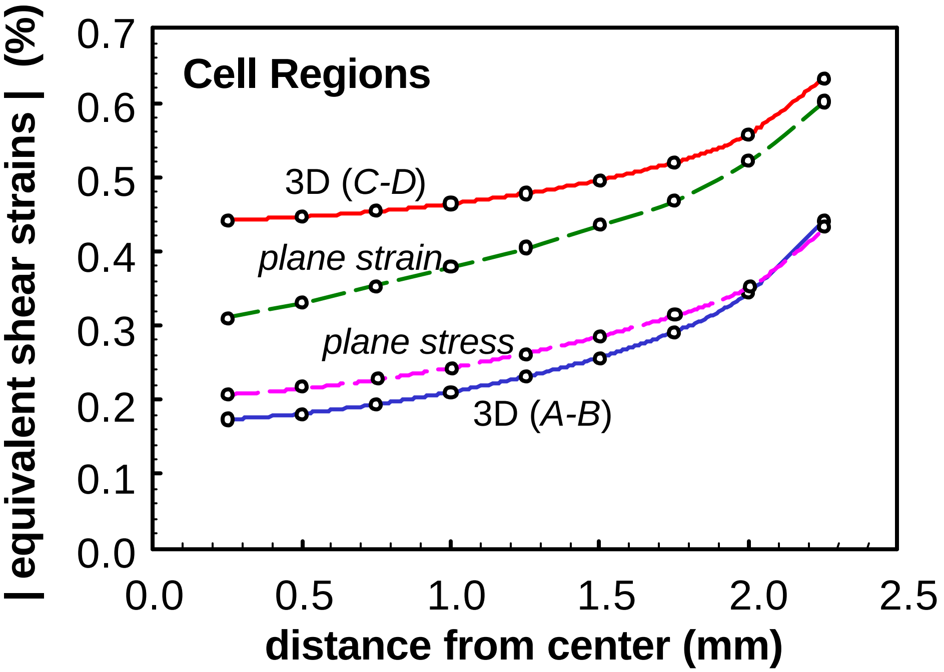
Comparison with 2D Models



Equivalent Shear Strains:

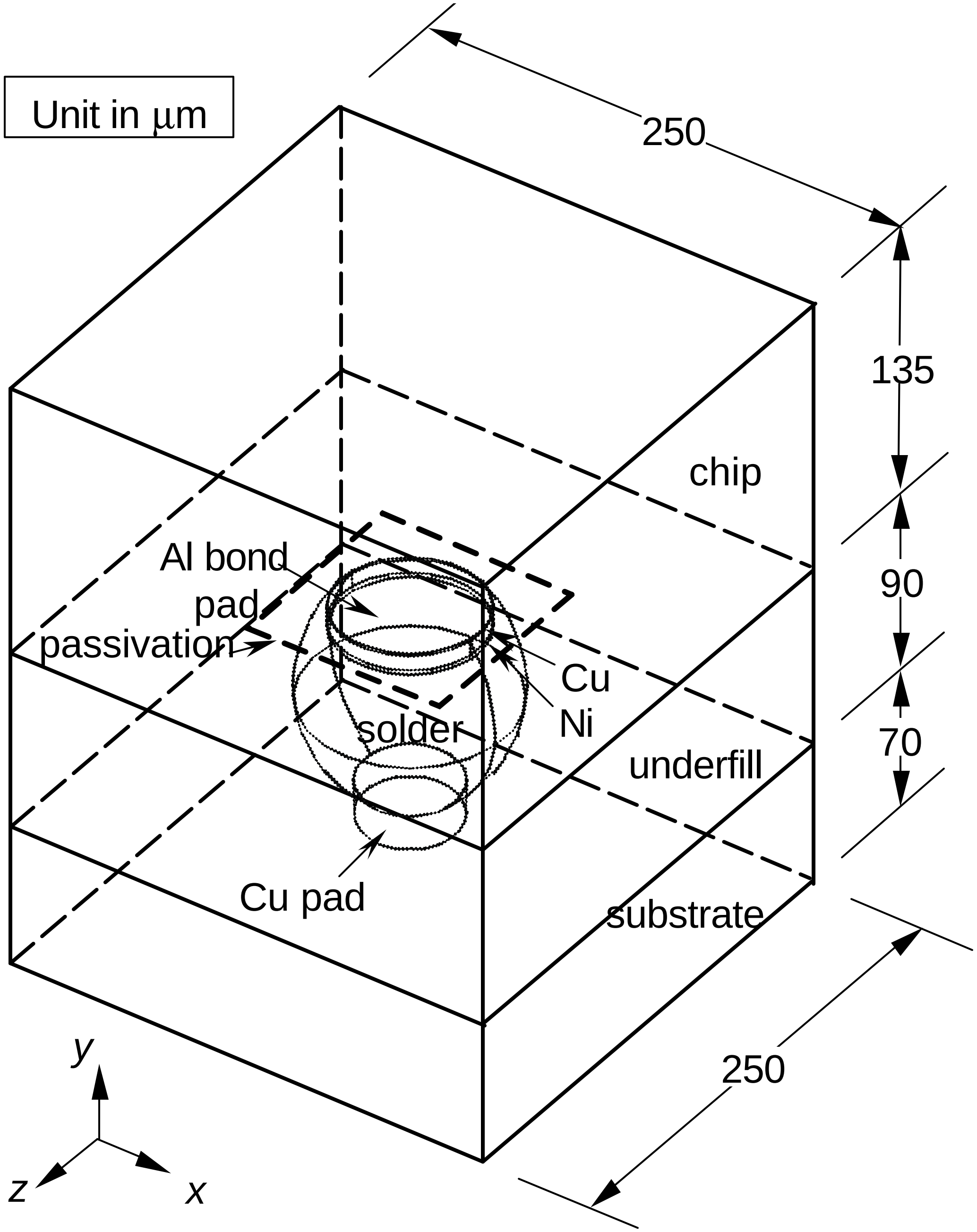
$$g_{eq} = \sqrt{\frac{2}{3}}\left[(e_x - e_y)^2 + (e_y - e_z)^2 + (e_z - e_x)^2 + \frac{3}{2}\left(g_{xy}^2 + g_{xz}^2 + g_{zx}^2\right)\right]^{\frac{1}{2}}$$

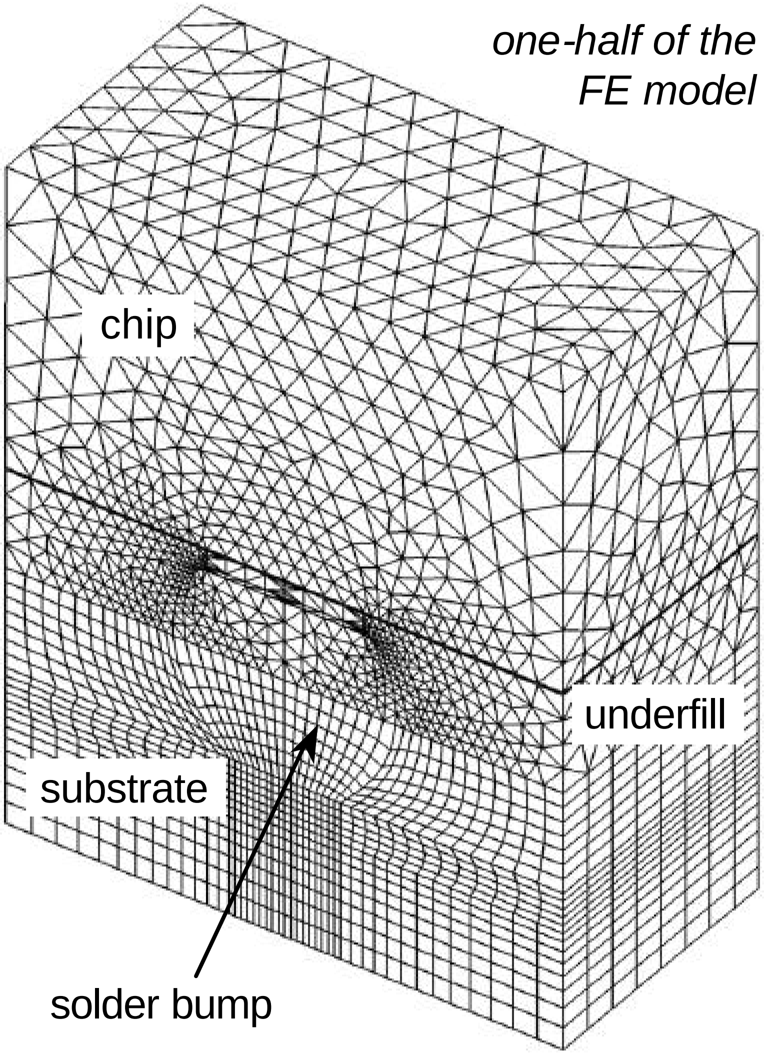




- *3D equivalent shear strain is greater than plane strain and plane stress results.*
- *Out-of-plane shear contributes to higher equivalent shear strains in 3D model.*

3D Cell Analysis

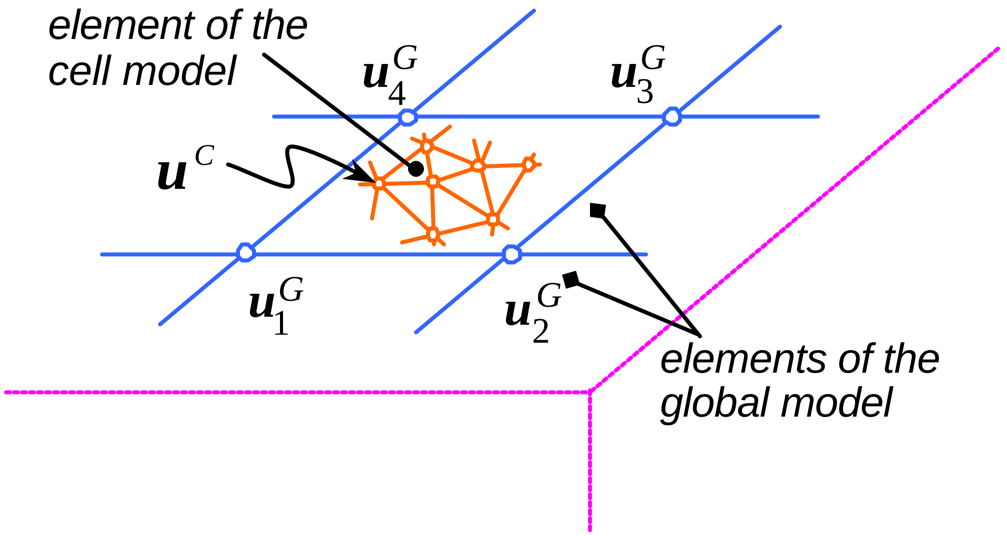



one-half of the FE model

About 70,000 four-node tetrahedron and 20,000 eight-node brick elements

Boundary/Loading Condition for Cell Model

Displacement solutions from global model are prescribed to surface nodes of cell model using interpolation functions.



$$\boxed{\boldsymbol{u}^C = \sum_{a=1}^{4} N_a(\xi,\eta)\,\boldsymbol{u}_a^G}$$

$\boldsymbol{u}^C$: *aimed nodal displacements of the cell model*

$\boldsymbol{u}_a^G$: *known nodal displacements of the global model*

N_a : *shape functions*

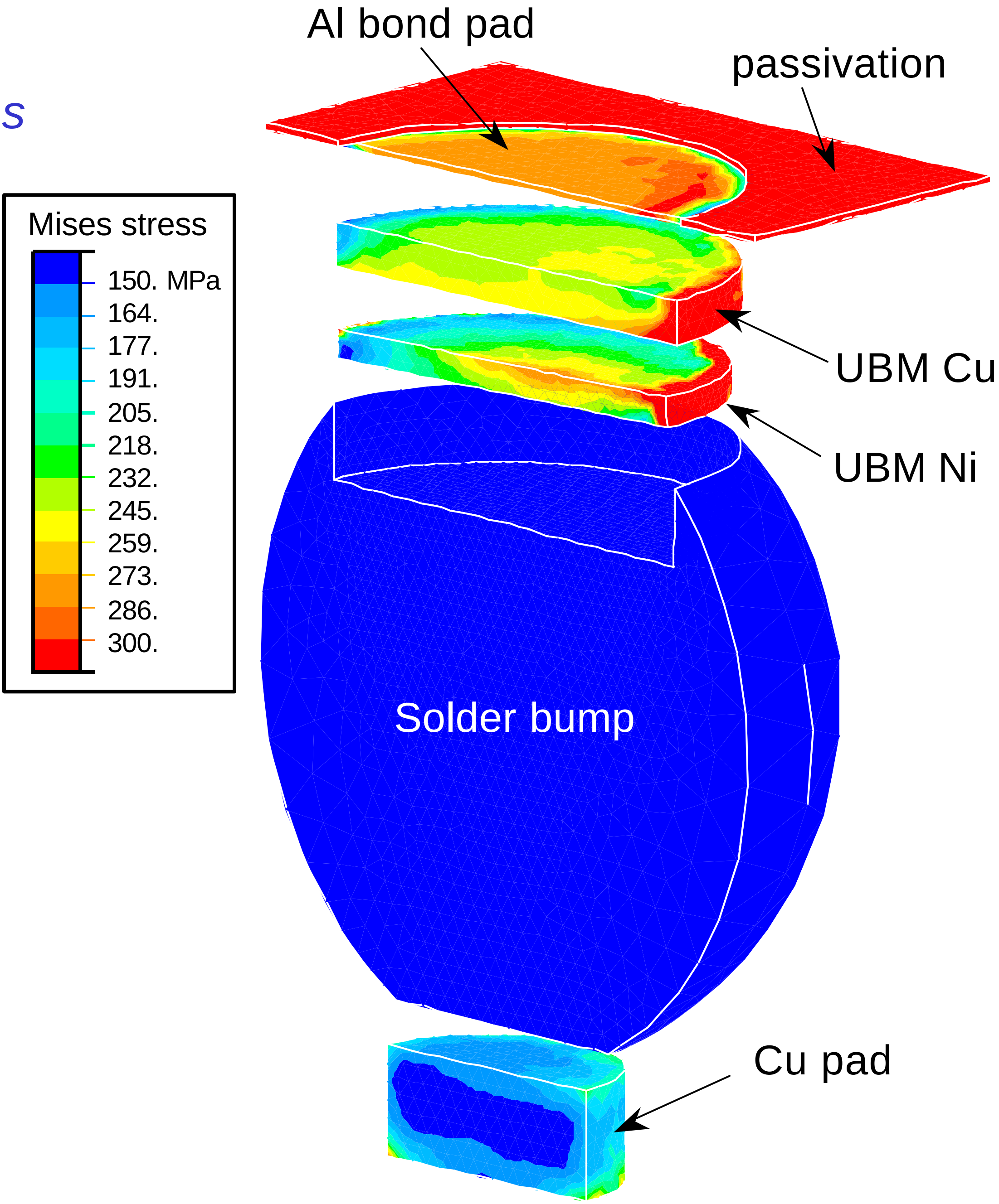
ξ, η : *local coordinates*

Interpolations are carried out for six surfaces of cell models

Stresses near Solder Bump

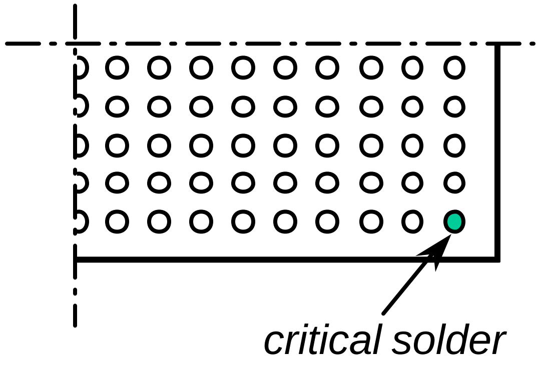
Þ determination of critical interfaces

- *Stress remains low in solder due to plastic flow.*
- *Stress concentration occurs at interfaces of solder bump and UBM (Ni and Cu).*
- *Large stress is also observed near Cu pad.*



3D Fracture Analysis

- *Detailed 3D model to identify fracture behavior.*
- *Comparison with 2D fracture results.*

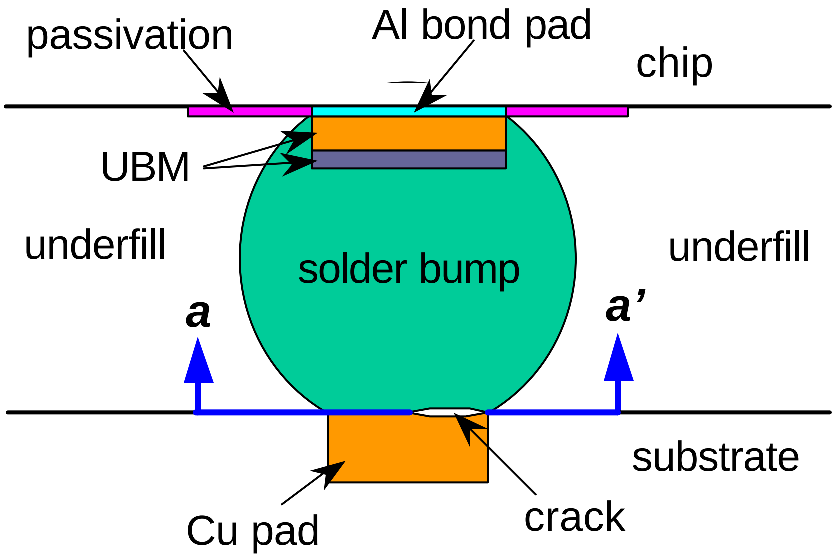


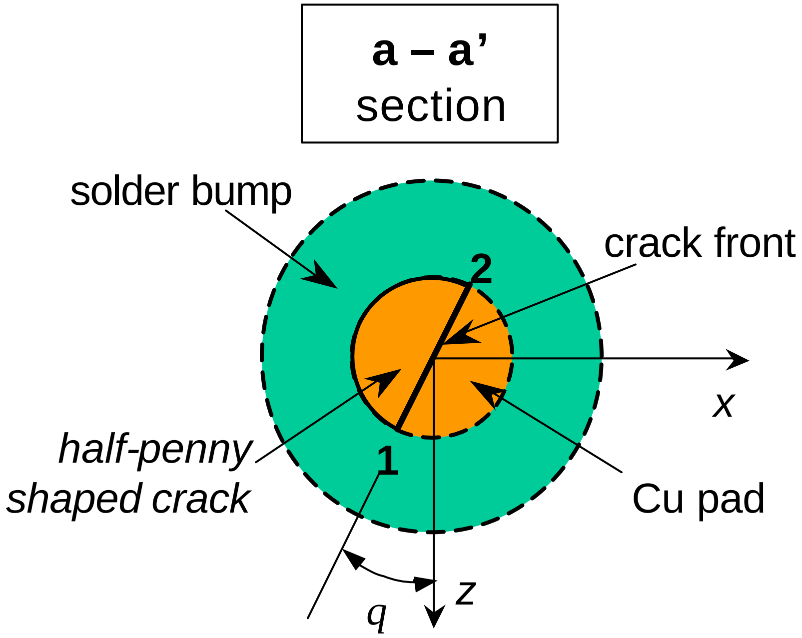
Fracture parameters to be determined

Energy Release Rate — *J*

Phase Angle — $y \approx \tan^{-1}\left(\frac{s_{xy}}{s_{yy}}\right), \quad f \approx \cos^{-1}\left|\frac{s_{yz}}{\sqrt{s_{yy}^{2}+s_{xy}^{2}+s_{yz}^{2}}}\right|$

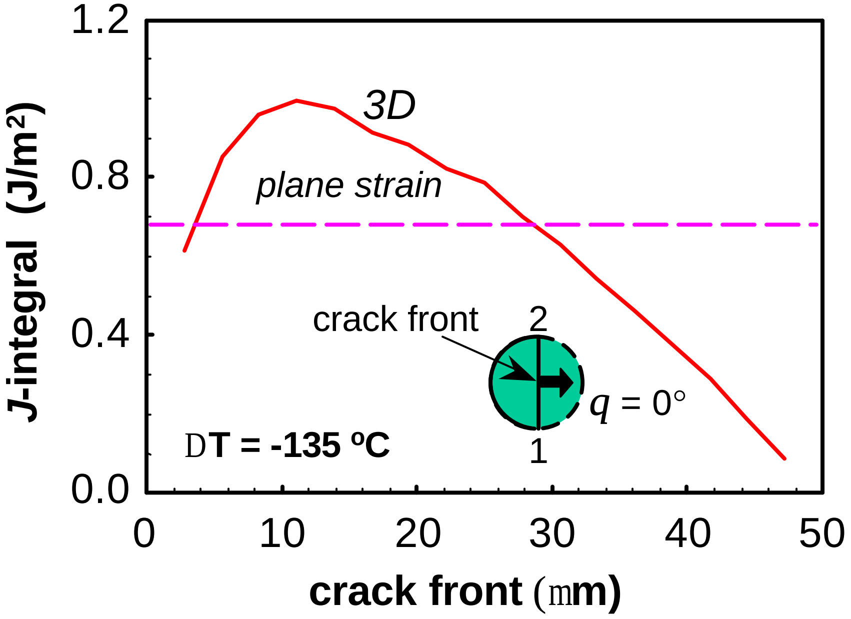
Half penny shaped crack

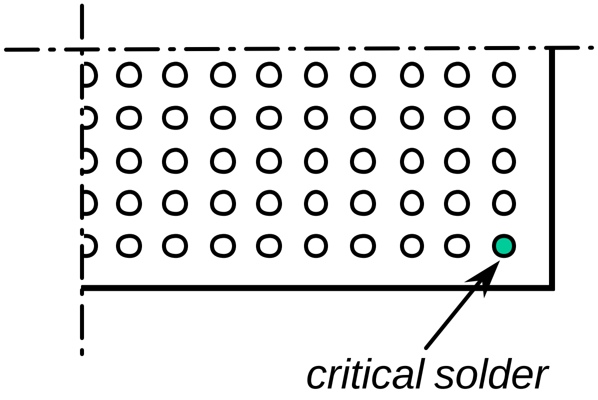




J-integral for 3D interfacial crack front

between solder bump and CU pad

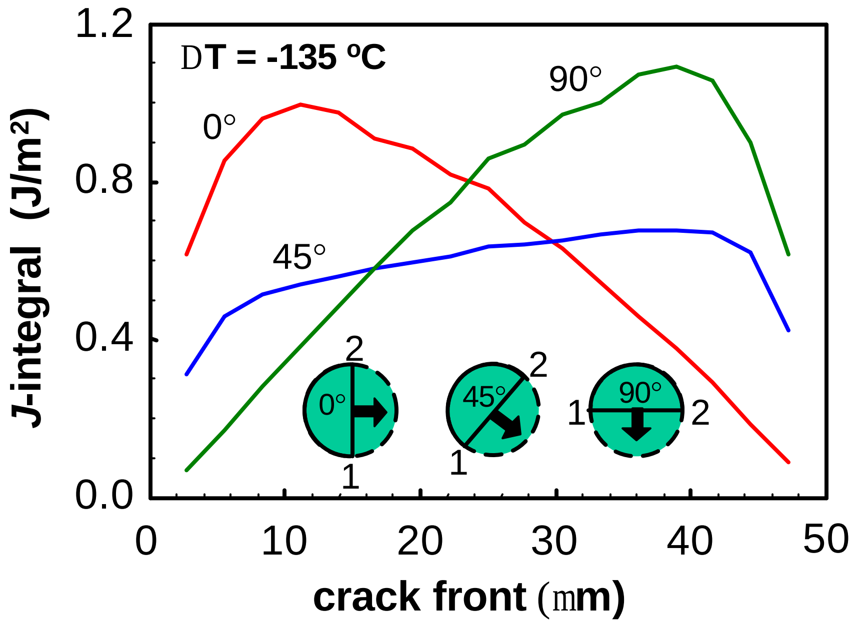


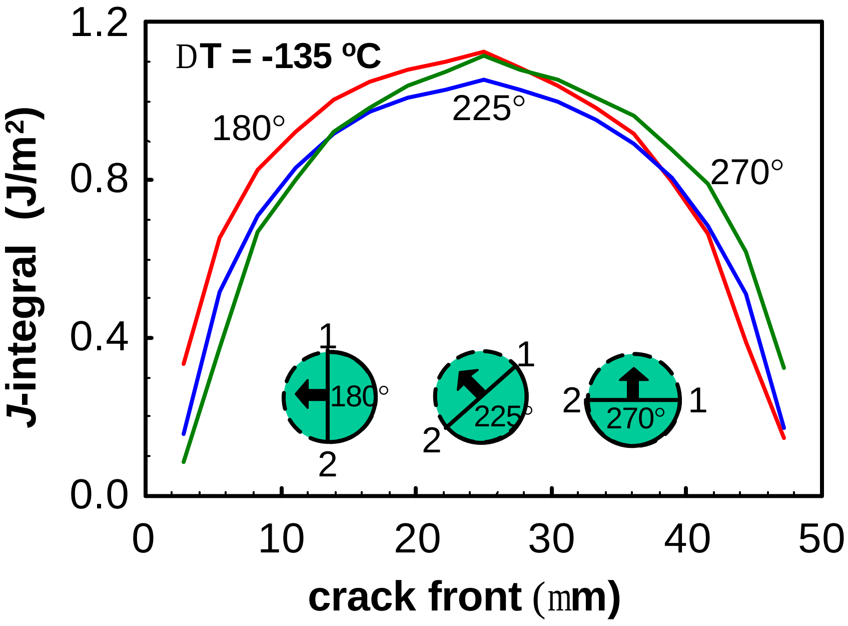


***Phase angle** of the straight crack front*

when q = 0^o is y = 30^o~35^o, f = 65^o~70^o;

For the plane strain case, y ~ 55^o.





Fatigue Life Estimation

Coffin-Manson law

Mean cycle to fail for near eutectic Sn-Pb solder :

$$N_f = \frac{1}{2}\left(\frac{\Delta g}{2e_f}\right)^{\left(1/c\right)}$$

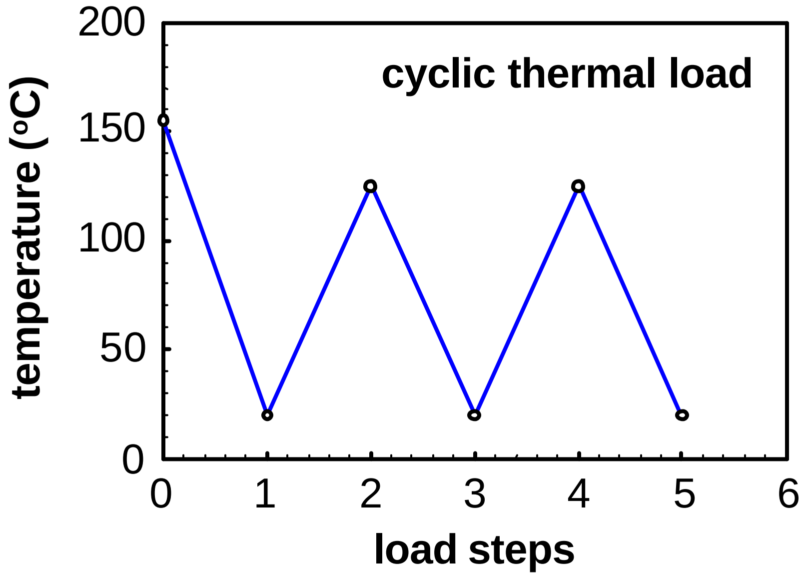
e_f = fatigue ductility coefficient = 0.325

c = fatigue ductility exponent = -0.5

Equivalent shear strain :

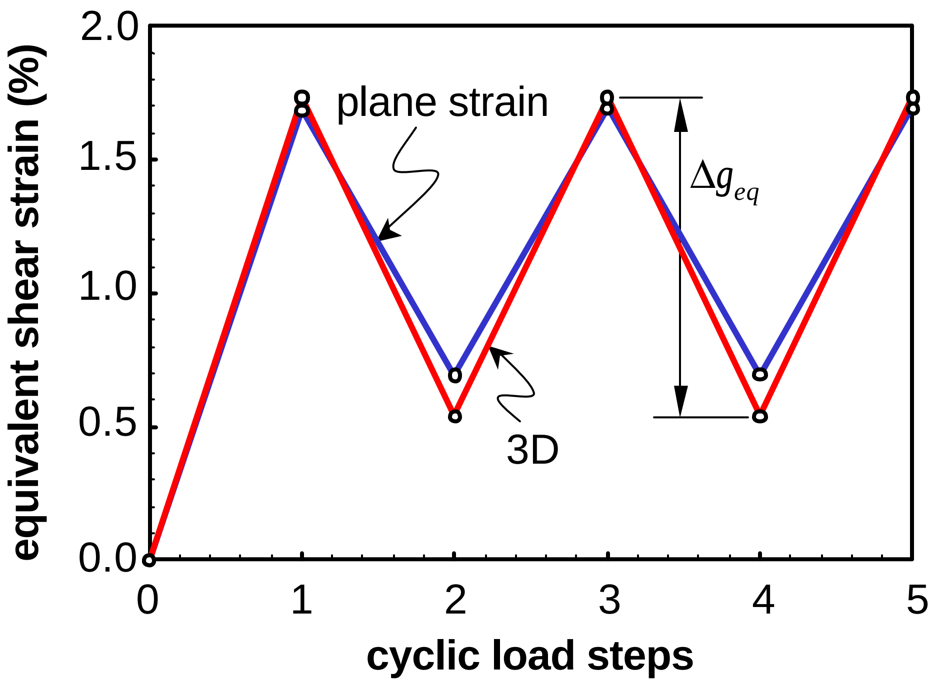
$$g = \sqrt{\frac{2}{3}}\left[\left(e_x - e_y\right)^2 + \left(e_y - e_z\right)^2 + \left(e_z - e_x\right)^2 + \frac{3}{2}\left(g_{xy}^2 + g_{yz}^2 + g_{zx}^2\right)\right]^{\frac{1}{2}}$$

Cyclic thermal load:



Comparison between 2D and 3D Results

Average equivalent shear strains within solder bumps



Thermal fatigue life :

Load steps	Temperature (^oC)	3D		Plane strain	
		Average Δγ (%)	Maximum Δγ (%)	Average Δγ (%)	Maximum Δγ (%)
1	155 → 20	1.73	**2.02**	1.68	1.94
2	20 → 125	1.10	**1.27**	0.82	**1.01**
3	125 → 20	1.10	**1.27**	0.83	**0.98**
4	20 → 125	1.10	**1.27**	0.82	**0.97**
5	125 → 20	1.10	**1.27**	0.82	**0.97**
Fatigue life N_f		2728	**2020**	5058	**3486**

Kinematic Hardening Solder Model

Thermal fatigue life :

Load steps	Temperature (^{o}C)	3D		Plane strain	
		Average $\Delta\gamma$ (%)	Maximum $\Delta\gamma$ (%)	Average $\Delta\gamma$ (%)	Maximum $\Delta\gamma$ (%)
1	155 → 20	1.73	**2.02**	1.68	**1.87**
2	20 → 125	1.19	**1.39**	0.99	**1.13**
3	125 → 20	1.19	**1.38**	1.00	**1.11**
4	20 → 125	1.19	**1.38**	1.00	**1.11**
5	125 → 20	1.19	**1.38**	1.00	**1.11**
Fatigue life N_f		2301	**1691**	3356	**2663**

Kinematic hardening solder : *Lshikawa et al.* (1994); *Basaran & Tang* (2002).

Summary

- Detailed 3D local analysis are carried out based on the global 3D analysis. Results are compared with 2D models.
- Large stress are observed in the flip-chip package for solder bumps and nearby interfaces away from the symmetry planes. Equivalent shear strain is greater than those of plane strain and plane stress cases.
- High stress concentration is observed at interfaces between solder bump and UBM as well as between solder bump and Cu pad.
- 3D fracture analyses show a non-uniform distribution of energy release rate. The magnitude of *J* along some part of crack front is higher than that of plane strain *J*.
- 3D fatigue life estimation suggests a shorter fatigue life than the one assumed from the plane strain analysis.

Flip-Chip Procedure

1. Al metallization — termination pad
2. Passivation coating — insulating/protection
3. Etch/form a hole through passivation and cleaning
4. Deposition of UBM
5. Add solder bump/paste and reflow
6. Flip the chip to the solder pasted substrate
7. Reflow
8. Test and wafer dicing
9. Encapsulation — underfill dispense
10. Curing
11. Final inspection