Twin Cities
ANSYS User Meeting

Solder Joint Simulation

February 11th
3:00 PM

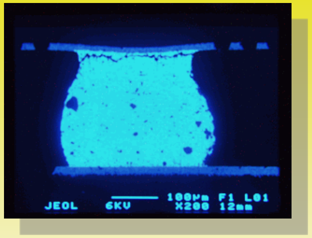
FEA Simulation of Solder in Electronic Packaging

Ball grid arrays, solder pads, with thermal cycling, fatigue, and more.

Join your fellow ANSYS users in the Twin Cities area for an ANSYS user meeting including technical presentation with handouts.

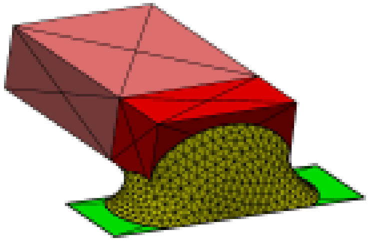
Epsilon FEA's Rod Scholl covers methods of modeling solder in electronic packaging. Subjects include material model selection, creep relaxation, fatigue, and capturing the manufacturing process and solder joint geometry.

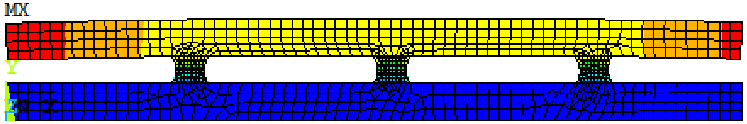
After the presentation, this informal setting encourages users to exchange experiences with ANSYS features, products, and methods new and old (and anecdotes in which no one else has enough interest to listen).



Solder

- Why & When model it?
- Simulating the manufacturing process
- Creating Joint geometry
- When to Submodel
- Material models
- Fatigue Life
- Ratcheting
- Crack propagation



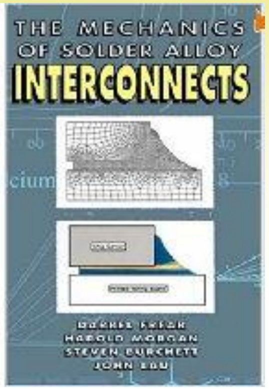


Why & When Model It?

- Solder Joint Failure
  - Mechanical integrity during shock, vib, accel., drop test, etc.
  - Fatigue Failure (most common application)
  - Stresses are usually thermally induced
    - Mismatched CTE’s during assembly or in operation environment
- Component performance
  - Rapid creep relaxation of solder can combine with rapid environmental changes
    - Creep relaxation can be beneficial or detrimental
      - Can affect component life
      - Can affect sensing technology (transducers, micro-measurements, etc.)
    - Requires accurate thermal transient data and material models
- Thermal transients (temperature DOF)
  - Rarely need solder joints modeled explicitly. Usually handled through “equivalent area” joints.

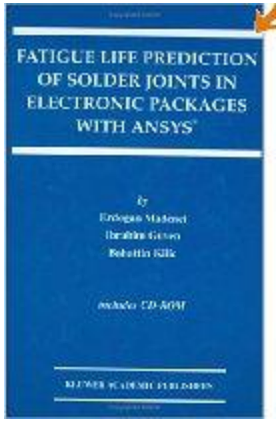
Simulating the Manufacturing Process

- Do a literature search!
  - Tons of papers and books online
  - Buy a vertical application
    - ICEPAK
    - PADT’s ANSPAK
    - Many others



THE MECHANICS OF SOLDER ALLOY INTERCONNECTS

- Often must capture residual strains due to CTE mismatch of soldered components/boards
    - Deflections/Thermal strains can be large
- High temps during manufacturing can fail joints
  - Oven cures may require transient thermals
    - Such as one board cooling more rapidly than another
  - Creation of nearby solder joints
    - If possible, higher melting point solders created first
    - Transient thermals may need consideration

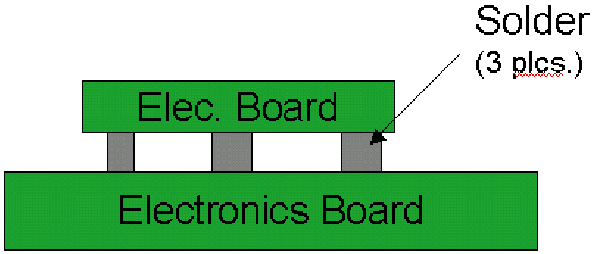


FATIGUE LIFE PREDICTION OF SOLDER JOINTS IN ELECTRONIC PACKAGES WITH ANSYS®

Solder Assembly Warpage

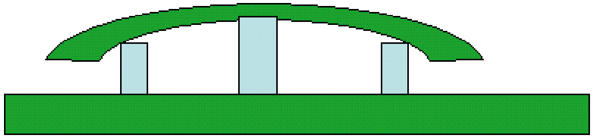
Initial Condition:

260C solder reflow.
Solder joints are liquid
Assume stress free and flat at this temperature.



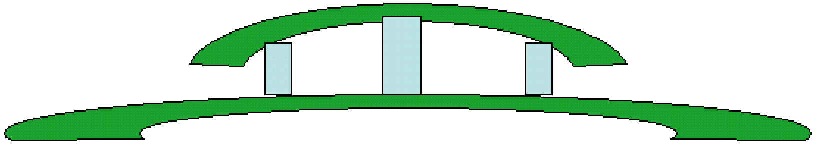
Load step 1: 260C →180C

Lower board still flat
Top board warps (due to multiple materials used)
Solder solidifies at 180C

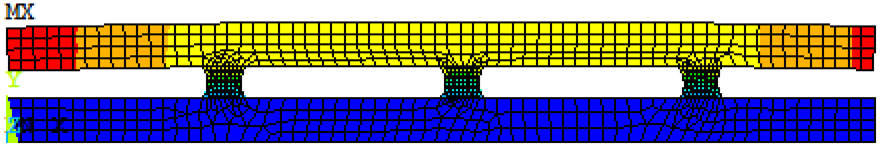


Load step 2: 180C → 25C

Warp of component is locked in due to solidified solder, and the whole assembly is cooled down to room temperature.

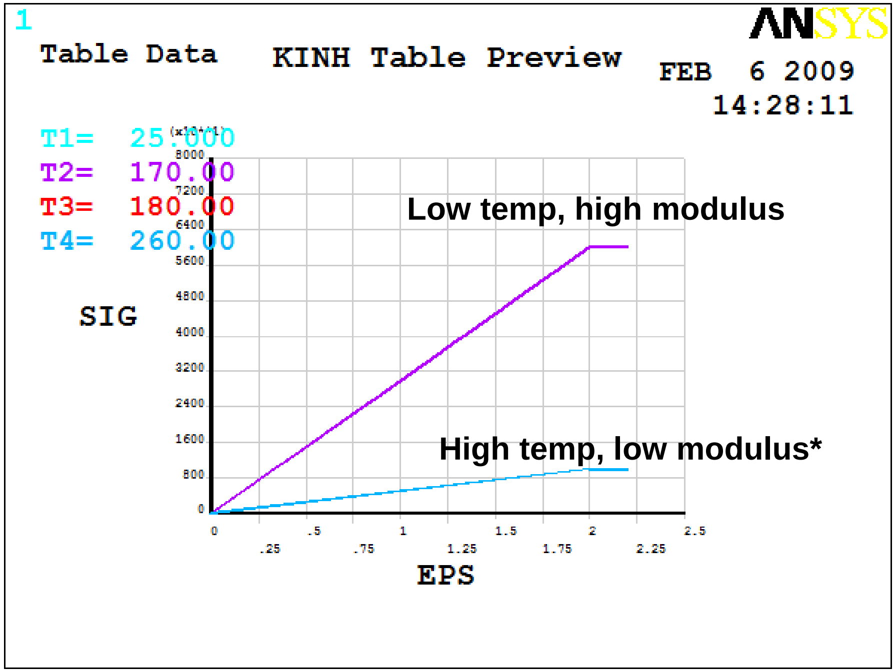


Courtesy of Wei Lin



Simulating the Manufacturing Process

- Step Through Assembly Process
  - Apply actual temperatures!
    - Measured data in ovens, boards, etc.
    - Try to choose worst case combinations when dealing with temperature ranges, and non-uniform environments
  - Use material models that capture melting point phase change!
    - Reduce modulus to trivial value
    - Use plastic material properties (discussed more later)
  - Try to avoid EKILL/EALIVE –
    - hard to get zero strain state after EALIVE'ing between two deformed components.



Low temp, high modulus

High temp, low modulus*

* High temp should be even lower modulus than shown here

Example Script

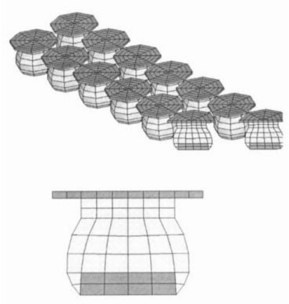
```
!Soldering Process
!Rod Scholl
!Courtesy of PADT

fini
/clear
/prep7

!*** Make Geometry ***
length=10
blc4,0,0,length,.1
blc4,0,.2,length,.05
blc4,0,.25,length,.05
blc4,.45,.1,.1,.1
blc4,.5*length,.1,.1,.1
blc4,length-.45,.1,.1,.1
aglue,all
et,1,42
asel,s,loc,y,.1,.2
esize,.01
amesh,all
esize,.03
asel,inve
amesh,all
asel,s,loc,y,0,.1
esla
emodif,all,mat,2
asel,s,loc,y,.2,.25
esla
emodif,all,mat,3
asel,s,loc,y,.25,.3
esla
emodif,all,mat,4
```

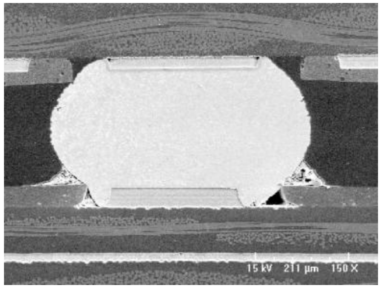
```
/pnum,mat,on
/number,1
alls!*** Mat. Props. ***
MPTEMP,,,,,,,,
MPTEMP,1,25
MPTEMP,2,170
MPTEMP,3,180
MPTEMP,4,260
MPDATA,EX,1,,30e3
MPDATA,EX,1,,30e3
MPDATA,EX,1,,1
MPDATA,EX,1,,1
MPDATA,prxy,1,,.3
MPDATA,prxy,1,,.3
MPDATA,prxy,1,,.3
MPDATA,prxy,1,,.3
TB,kinh,1,4,2,0
TBTEMP,25
TBpt,,1,30000
TBpt,,2,60000
TBTEMP,170
TBpt,,1,30000
TBpt,,2,60000
TBTEMP,180
TBpt,,1e-3,1e-3
TBpt,,2,1
TBTEMP,260
TBpt,,1e-3,1e-3
TBpt,,2,1
```

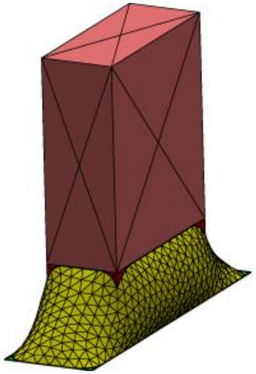
```
mp,alpx,1,20e-6,
mp,ex,2,1e6
mp,ex,3,1e6
mp,ex,4,1e6
mp,alpx,2,1e-7
mp,alpx,3,3e-7
mp,alpx,4,1e-7! ***BC's and Solve
***
/solu
nlgeom,on
d,node(0,0,0),all,0
d,node(length,0,0),uy,0
allsel,all
antype,0 ! static analysis

! 1st load step: from 260C to 180C
solder solidification
tref,260
tunif,180
deltim,.25
solve

! 2nd load step: from 180C to 25C
room temperature
tunif,25
solve

!*** View Results ***
finish
/post1
/dscale,1,50
plns,u,sum
```

Creating Joint Geometry

- Often modeled with very rough guess
  - Literature search can turn up pics/SEM's for your solder/interface type.
  - Depending on model size/detail, you might have a pretty coarse solder joint anyway
  - Some variation due to cooling rates/surface tension, etc.
  - **Note that this source of error is large! So consider how much to rely on results.**
  - Smaller (less solder) is usually conservative
  - If you have unique geometry (and lots of time) use available tools to predict solder shape.

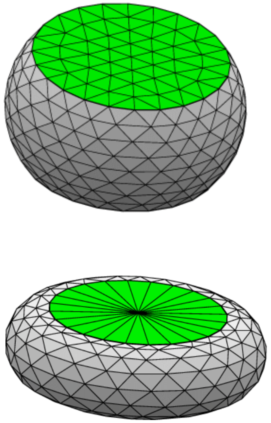


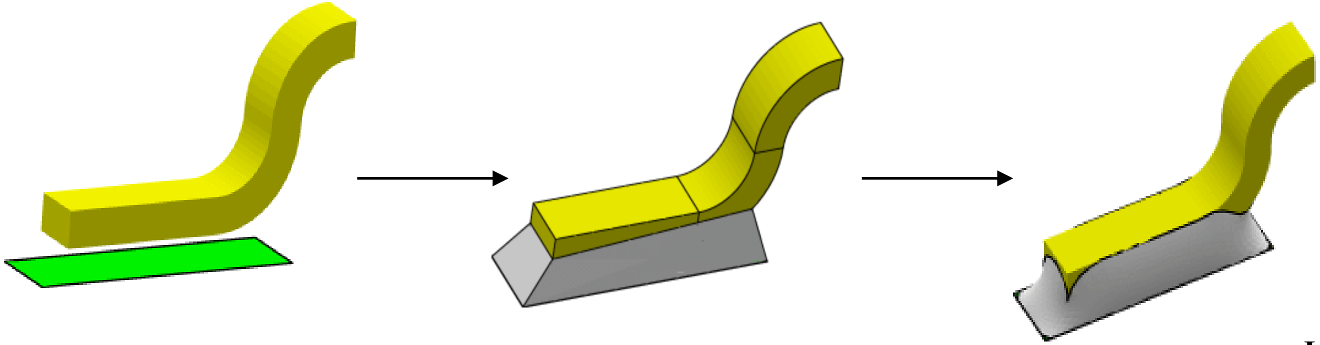




Creating Joint Geometry

- Advanced tools can predict solder joint shapes
- Surface Evolver is free
  - Maintained by Ken Brakke of Susquehanna University
  - Command line driven
    - Takes some time to use (and use correctly)
    - Training classes are available
    - Great/thorough manual
  - Make sure the effort is justified!



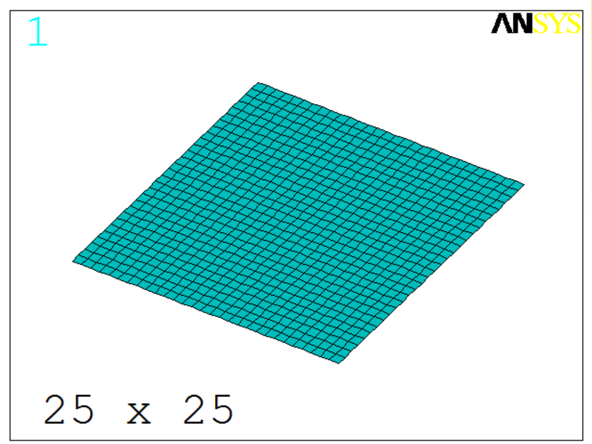


Images courtesy of Ken Brakke / Surface Evolver

When to Submodel

- Submodel vs. large system model
  - Often a difficult question if no historical precedent
  - If *many* joints are present you might have no choice
- Good approach is to use a coarse system model
  - Good estimate of deflections, PWB stresses
  - Good for model debugging, anyway
  - Used to identify critical solder joints
    - Do submodel of these joints/conditions – OR
    - Do mesh refinement only on joint(s) of interest
      - Use APDL/component naming to make life easier
- Inaccuracies due to Submodelling
  - Has linear approximation (system doesn't update with local deflections without doing iterative solution)
  - Can't do ratcheting well, when driven by system deflections only.

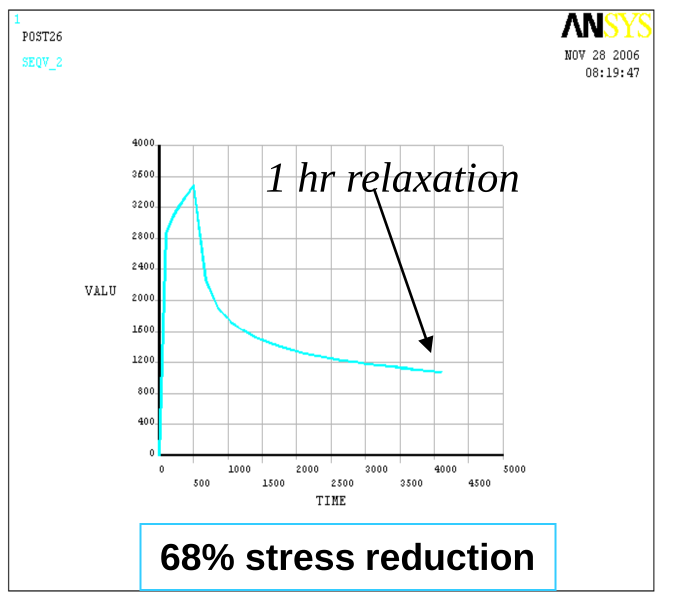
What about Substructuring?



- Great for cutting down model size with many joints
- Takes large amounts of RAM
- Take large amount of time
  - Expect long wait wondering if its crashed
  - Practical up to 2500 MDOF
  - This is a 50x50 mesh of low-order elements.
    - 25x25 mesh of high-order elements
  - After initial superelement creation, processing is quick
- Older technology in ANSYS… no bells or whistles
- Can’t do material non-linearities!
  - The stiffness of the joint, never changes!
  - Highest joint stresses usually are near boundary
  - A coarse joint, with fine submodel is more accurate
    - Submodel approach still has plasticity in coarse model
    - Submodel approach still can use NLGEOM

Material Models

- Solder not like other metals!
  - Very fast creep relaxation
- Three main material technologies
  1. Linear
  2. Plastic (rate independent)
  3. Viscoplastic (rate dependent)



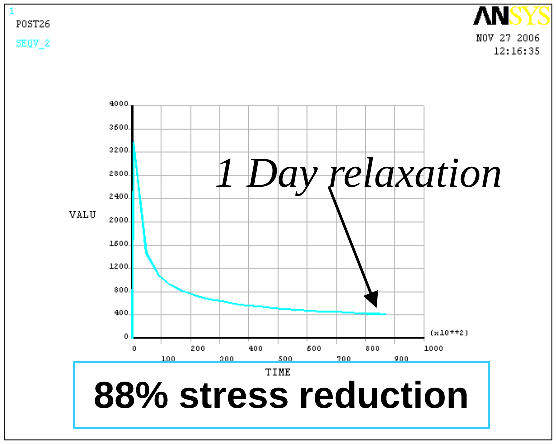
1 hr relaxation

68% stress reduction

Eutectic Solder at 22C and constant strain

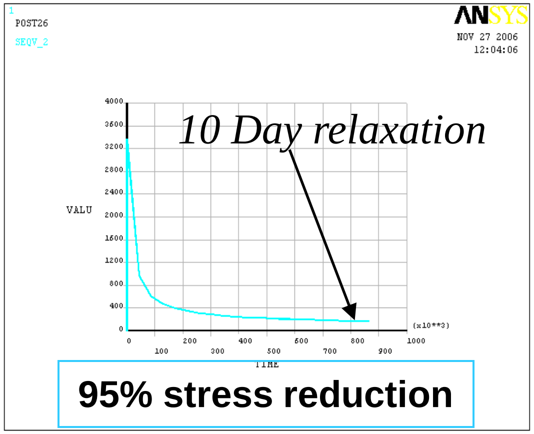
3600 psi initial stress (near material maximum)

Psi vs. seconds



1 Day relaxation

88% stress reduction



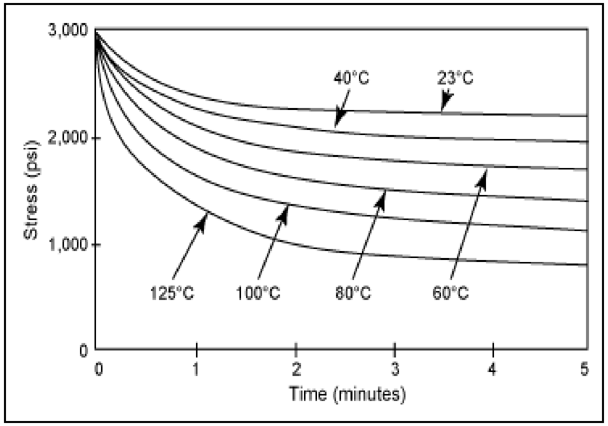
10 Day relaxation

95% stress reduction

Material Models

1. Linear Material Model
   - Fast, easy, & even exotic solder properties in public domain
   - For moderate stresses, temperatures & strain rates

     1 seconds < loading < 5 seconds
   - Steady state not achieved (but usually highest board stresses)
   - Assumes low stress (no appreciable plasticity)
   - Used in various scenarios
     - Some static accelerations (e.g. maneuver loads)
     - Check loading on boards/components
     - Order of magnitude stress check on solder joints
   - Should look at creep data to judge suitability



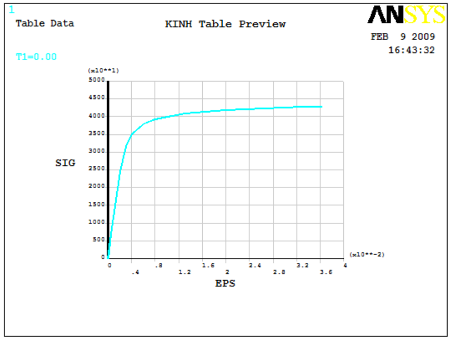
Example data from university of Bolton

Material Models

2. Plastic (rate independent)

- Properties in public domain
- Use Kinematic (not Isotropic) hardening For loading cycles > 1
- Steady state not achieved (ignores creep relaxation)
- Should look at creep data to judge suitability
- For moderate temperatures & strain rates

  0.5 seconds < loading < 5 seconds
- Used in various scenarios
  - Some static accelerations (e.g. manuever load)
  - Check loading on boards/components
    - Usually represents highest stress state (pre-relaxation)
  - If using “rate-dependent curve” and known shock rate, then this is the material model used… a poor man’s “rate-dependent analysis”
  - Often used for fatigue life!
    - Ignores creep relaxation, but still captures extreme stress states
    - If fatigue loads reverses before creep relaxation, it’s a reasonable approximation



Material Models

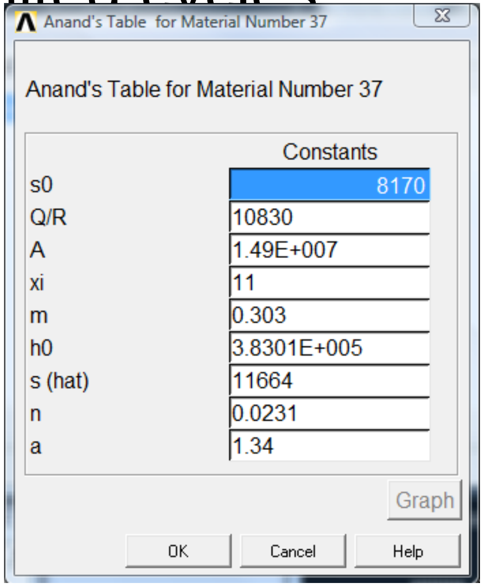
3. Viscoplastic (rate dependent)
   - This is likely a good starting place
   - Once you are nonlinear, might as well go viscoplastic
   - Needs VISCO10X elements
   - Shock data available down to 1.0 msec durations
     - (For comparison Mil-Std-810 is 11 msec, typ.)
     - Data in public domain for several solders
     - Good constintuitive models for large time domains
       - Such as 1 msec through 100 seconds in same model! (X. Nie, 2008)
   - Must capture life cycle time-history
     - Can be a can of worms, with temperature variations, unknown cooling rates, shelf-relaxation differences, field temp variations.
   - Great for fatigue life with long loading periods/reversals!

Material Models

3. Viscoplastic (rate dependent), cont’d.

- Lot’s of data on the web / public domain
  - www.ansys.net even has ANSYS-formatted data listings
  - Lead-free data not as “free” but in papers for purchase
    - (NIST has some?)
- Get help! Choosing between Anands, Chaboche, Hyperbolic Creep, Voce, etc., is not a simple task.
- Anand’s is great for creep relaxation limited cycles
  - Does not handle ractcheting
- Chaboche is good for ratcheting, but more complex to implement/calibrate with test data
  - It’s a nice text book too

    (Mechanics of Solid Materials, Chaboche)



Anand's Table for Material Number 37

	Constants
s0	8170
Q/R	10830
A	1.49E+007
xi	11
m	0.303
h0	3.8301E+005
s (hat)	11664
n	0.0231
a	1.34

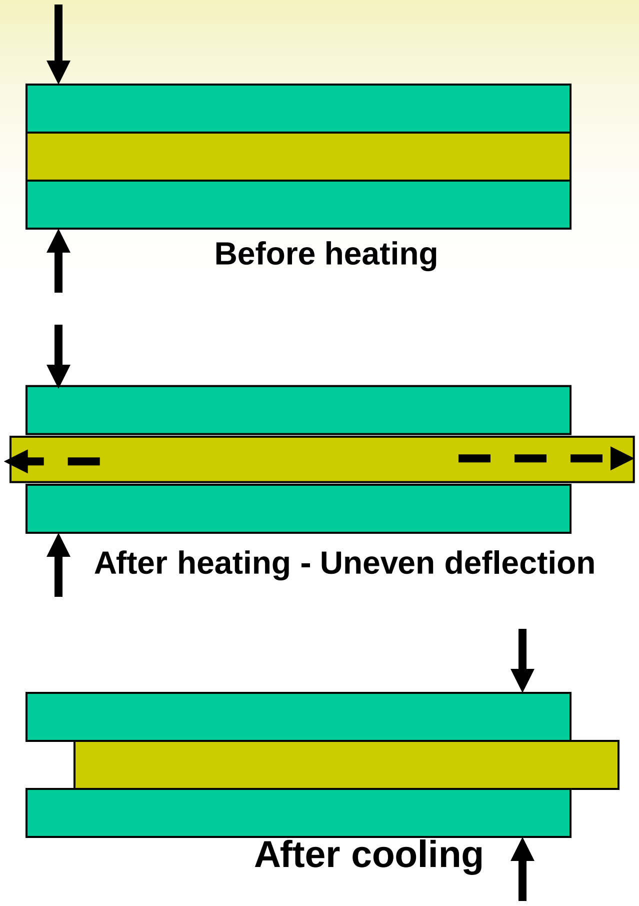
Fatigue Life

- Fatigue Life often is the question motivating inclusion of solder joints in FEA.
- Predicting crack initiation
- Fatigue has two primary sources
  1. Repetitive loading / Ratcheting
     - Temperature induced load variation (mismatched CTE's)
     - Repetitive mechanical loads
  2. Vibratory induced load variation
     - Excited response of known forcing function
     - PSD (Random Vibration) over spectrum

$$\text{Fatigue Life} = \frac{\text{Naps under the desk}}{\text{Hours Worked} * \text{Comp. Crashes}}$$

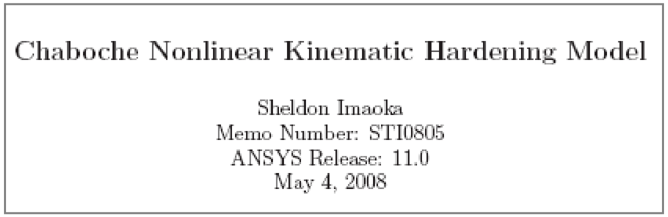
Fatigue - Ratcheting

- What is mechanical ratcheting?
  - Deflection is biased in one direction over repeated cycles.
  - Commonly caused with thermal cycles
- Plastic accumulation can occur in solder joints
  - Because solder's unique stress relaxation in between load reversals, ratcheting can go on (and on, and on…)
  - Difficult to "stiffen" a part sufficiently to avoid phenomena when present. CTE expansion is too forceful.
  - Plastic Strain accumulates to critical max elongation
    - Then a fatigue crack initiates



Fatigue - Ratcheting

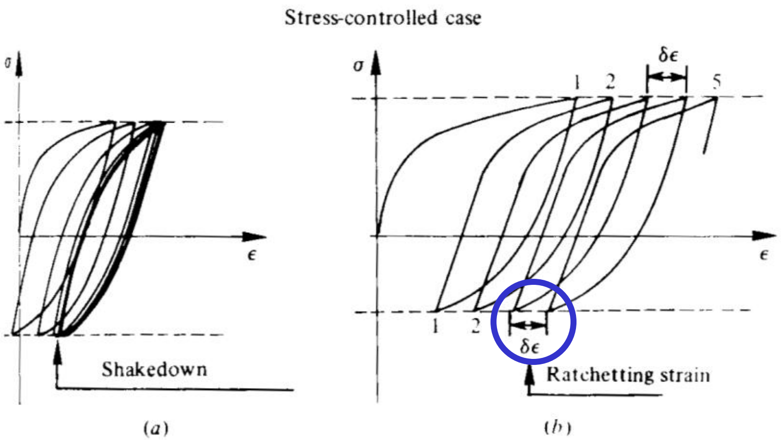
- Solder LCF can be accurately simulated in ANSYS
  - Can be expensive simulation
    - Often desired data is steady state strain / cycle
    - Asymptotically approaches stabilized strain/cycle rate
      - Can quite early if criteria is met
  - Kinematic Hardening per Chaboche is the standard (others have improved on it)
  - If material data is not available:
    - Not *too*-too hard to develop material model from simple tensile tests!
    - Sheldon Imaoka wrote a great paper exemplifying this.



Chaboche Nonlinear Kinematic Hardening Model

Sheldon Imaoka
Memo Number: STI0805
ANSYS Release: 11.0
May 4, 2008

Fig. 3.40. Phenomena of (*a*) shakedown, (*b*) ratchetting, (*c*) non-relaxation and (*d*) relaxation of the mean stress.



(Mechanics of Solid Materials, Chaboche, 1990)

Fatigue Life, Cont’d

- Vibratory Load-Induced Fatigue
  - Vibration testing still the norm
  - Empirical data being developed only over last 10-15 years.
  - Typical FEA Approach
    - Run modal, harmonic/psd analysis at system level
    - Run static equivalent
      - » Refined mesh
      - » Material nonlinearities
  - Use Miner’s combination of damage
    - Multiple freq. sources
    - For PSD use 1σ, 2σ, 3σ buckets
  - **Thermal CTE damage Miner rule combined to low freq. vibration damage overpredicts life!**

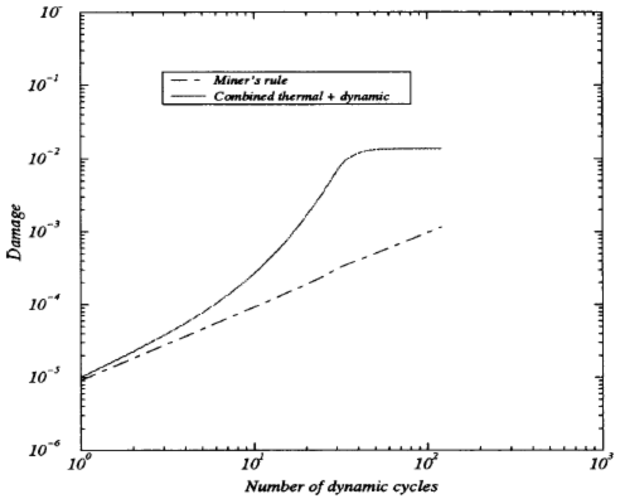
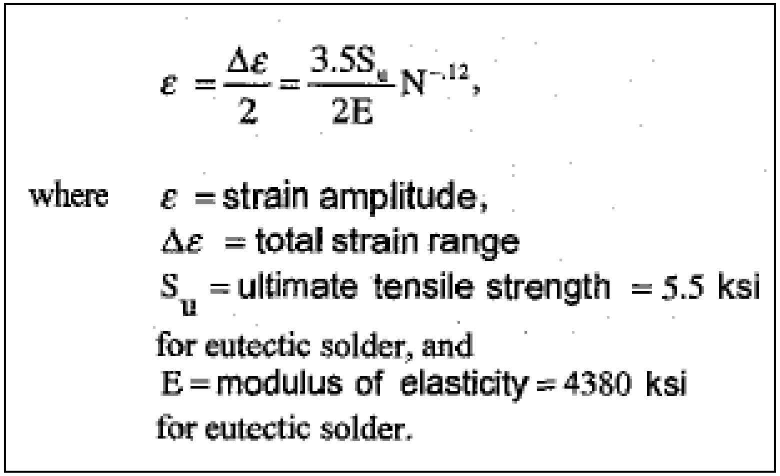


Fig. 12 Damage versus number of dynamic cycles for concurrent thermal and dynamic loading of 5g–10Hz in both X and Y directions

Basaran, Chandaroy 2002

Fatigue Life, Cont’d

- Vibratory Load-Induced Fatigue
  - Empirical data being developed only over last 10-15 years.
  - For low load, high cycles,
    - 15% of life is crack initiation, then its crack propagation!
    - This is one approach! (an endurance-limit-like calc)
      - Empirical data, Manson, 1965
      - Run system modal, then PSD / Harmonic to determine strains
        - » Damping of 0.02 is usu. Conservative
      - Uses average stress at solder x-section
        - » Extreme mesh refinement is then avoided!



$$\varepsilon = \frac{\Delta\varepsilon}{2} = \frac{3.5 S_u}{2E} N^{-.12},$$

where ε = strain amplitude,

$\Delta\varepsilon$ = total strain range

S_u = ultimate tensile strength = 5.5 ksi for eutectic solder, and

E = modulus of elasticity = 4380 ksi for eutectic solder.

Crack Propagation

- Usually a steady state propagation rate is determined
  - Requires selection of energy criteria for crack failure
    - Usually strain energy density
  - Models for common solder exist
    - Input your incremental plastic strain / crack length criteria
    - Correlated to test data
    - Not too expensive… somewhat accurate
    - Doesn’t take into account relaxation due to deflection/strain relief
      - » Conservative approach
  - Actual crack propagation (w/ crack geometry)
    - Really?
    - Will be expensive computationally
    - See papers on FEA models verifying theories
    - J-integral macros exist for ANSYS if full propagation is desired (really?)

/eof

Frear, Jang, Lin, Zhang 2001