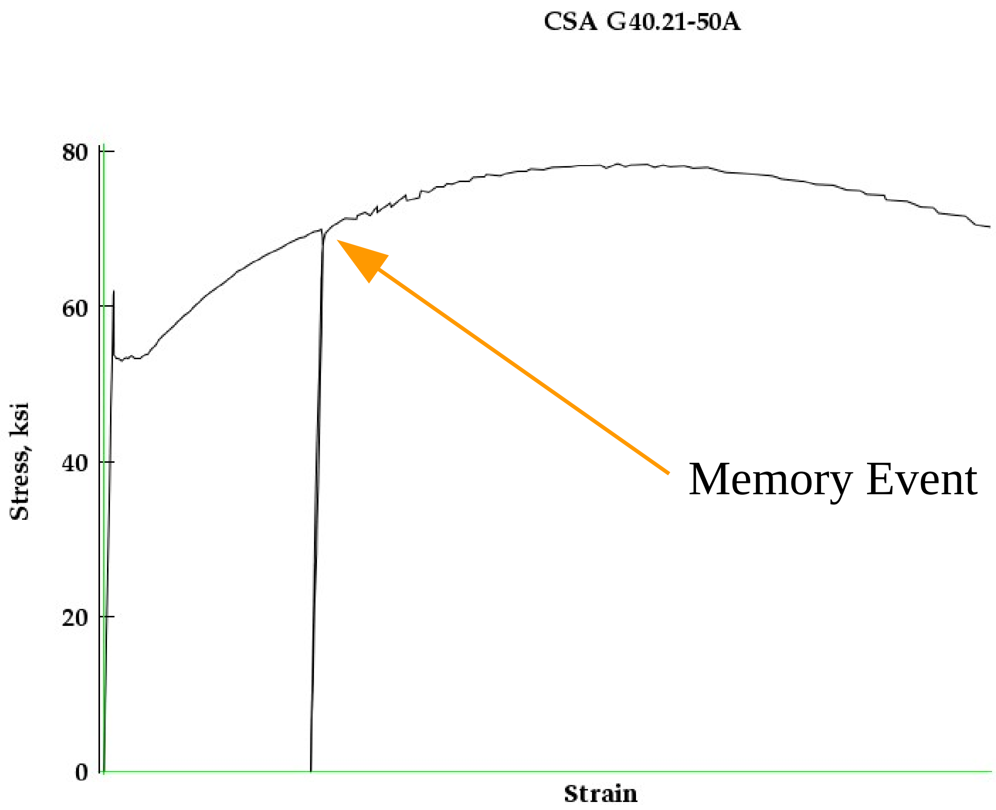
Material Stress-Strain Behavior   Part 3

Material Memory Effects



In the animation of a tensile test that was described in a previous section, we saw an initial stress-strain path that was interrupted by an unloading and a reloading.

https://fde.uwaterloo.ca/FatigueClass/Videos/g40-21TensileData.gif

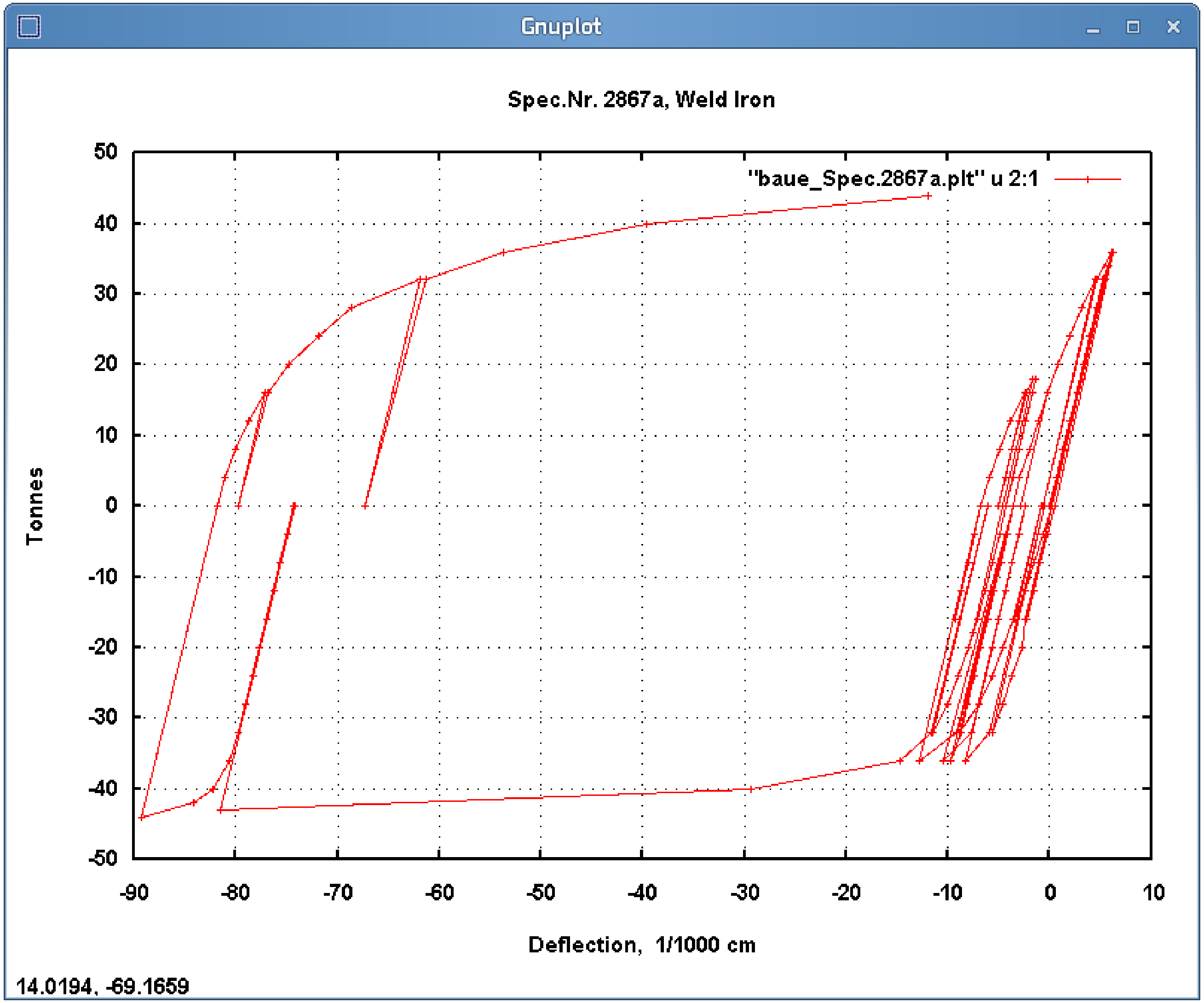
Upon reloading the material remembered its previous unloading point, and returned to the old path.

This behavior is called material memory of prior deformation.

It is important in fatigue assessment because many service histories are not constant amplitude.
There are many path "interruptions"

In 1879 Bauschinger published a paper of data from tests that included loading and unloading sequences on axial specimens. In the plot below one can again see material memory features. The events are more obvious in an animation of the data:

https://fde.uwaterloo.ca/FatigueClass/Videos/spec2867aTotal.gif



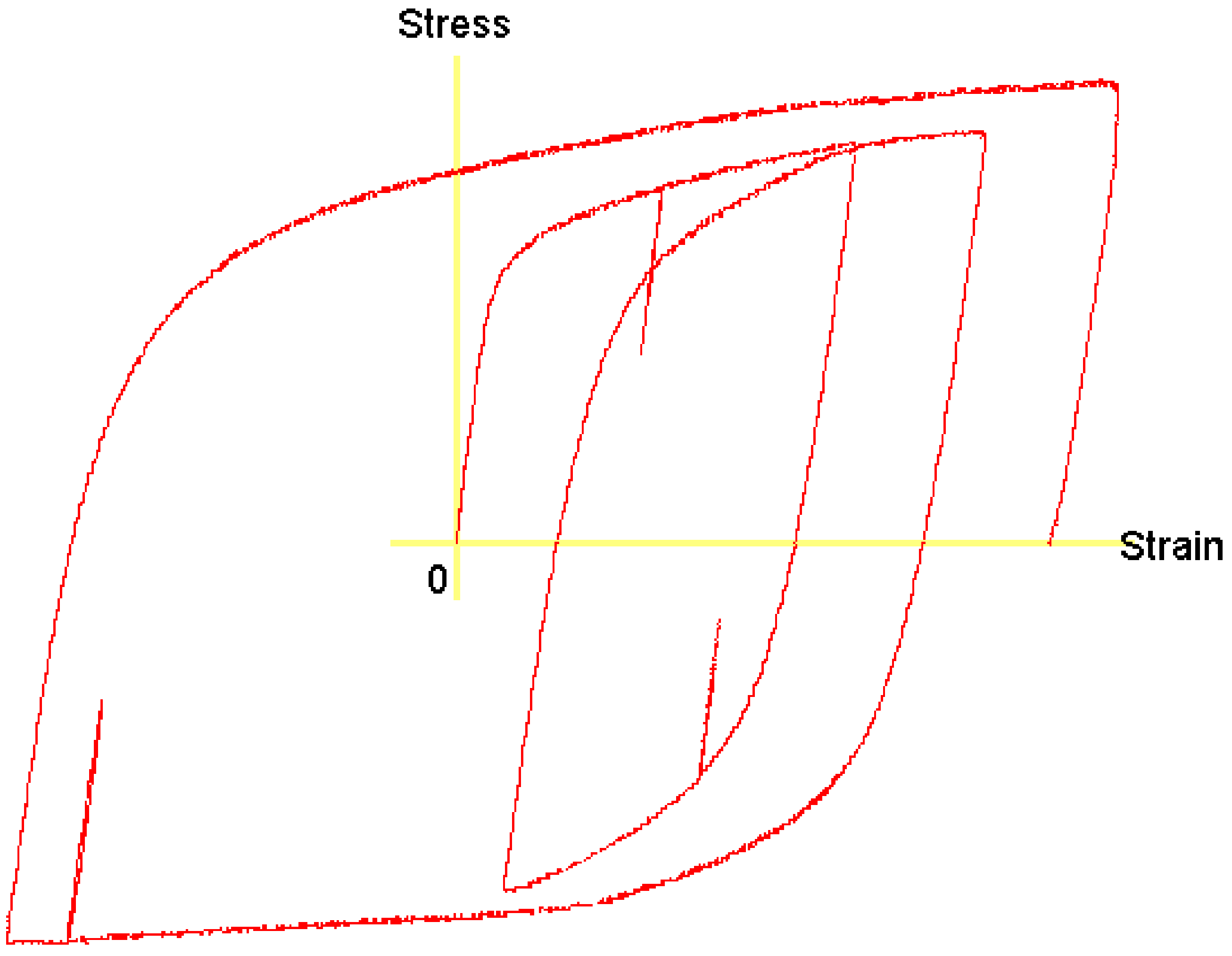
Bauschinger used a lever loading machine and a Martens extensometer, thus the load sequences were recorded in fairly large steps, and once over the yield the material flowed plastically for large strains.

i.e. he was using load control.

The data points can be found on this web page:
https://fde.uwaterloo.ca/Fde/Loads/hindex.html

Ref.: J. Bauschinger, Mittheilungen Mech.-Tech. Lab. von K.Tech. Hochschule Muenchen, Heft 13, No.XV, 1886

With servo-hydraulics and strain control a more modern example of material memory behavior is animated in
https://fde.uwaterloo.ca/FatigueClass/Videos/memoryRun20_0.gif 200Kb



Exercise: Simulate Axial Strain Controlled test

1. Download gnuplot if you have not already done so.
   (We will be using it often in this course)
   https://sourceforge.net/projects/gnuplot/files/gnuplot/

2. Download the pre-recorded F.D.E. Transmission history:
https://fde.uwaterloo.ca/Fde/Loads/Keyhole/transmission.txt
and save it as a text file.

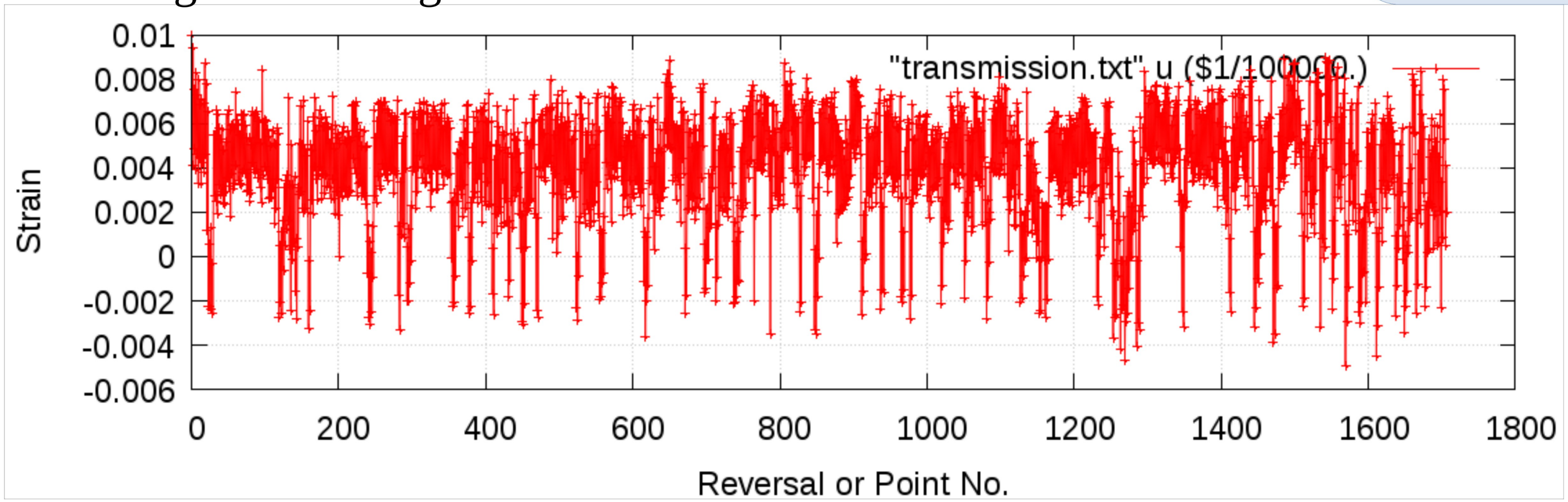
3. Plot the history using gnuplot. The gnuplot commands will be:

```
set grid
set xlabel "Reversal or Point No."
set ylabel "Strain"
plot "transmission.txt" u ($1/100000.) w lp
```

Try the zoom feature
(right click, make box)

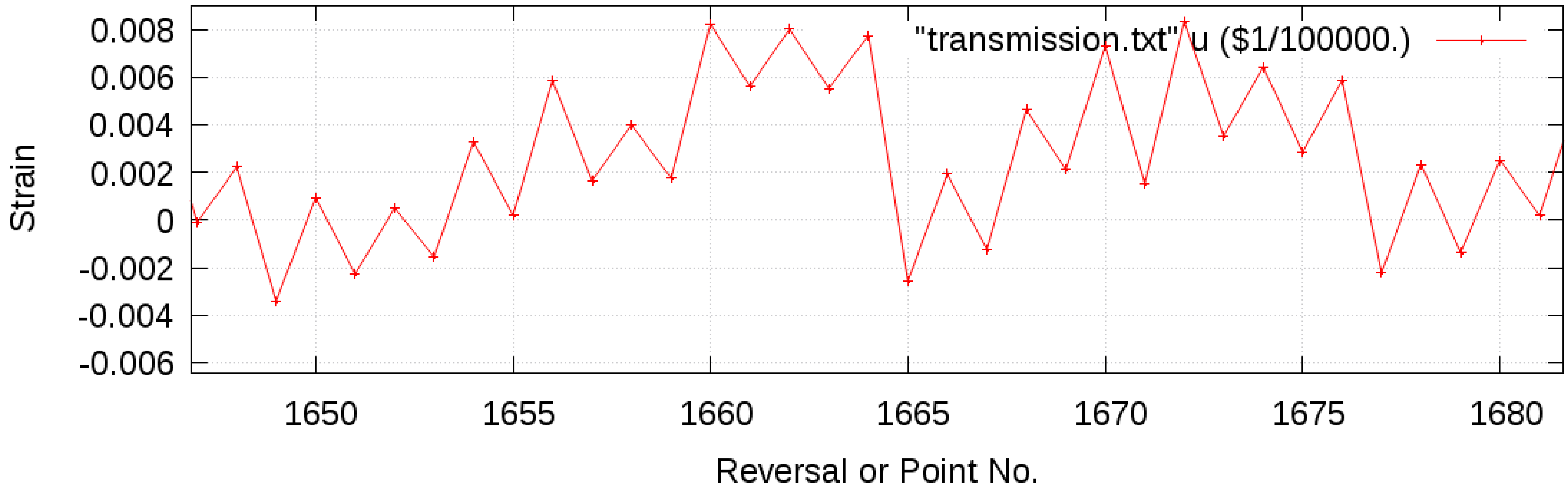
To go back type P
in the plot window

You should get something like this:



points 1647 to 1681
-0.00011
0.00222
-0.00341
0.00094
-0.00227
0.0005
-0.00156
0.00329
0.00019
0.00585
0.00165
0.00398
0.00176
0.00822
0.00561
0.00801
0.00553
0.00776
-0.00258
0.00192
-0.00125
0.00464
0.00211
0.0073
0.00152
0.00834
0.00352
0.00642
0.00285
0.00587
-0.00222
0.00233
-0.00136
0.00251
0.0001

Here is a Zoom of some points near the end of the history:

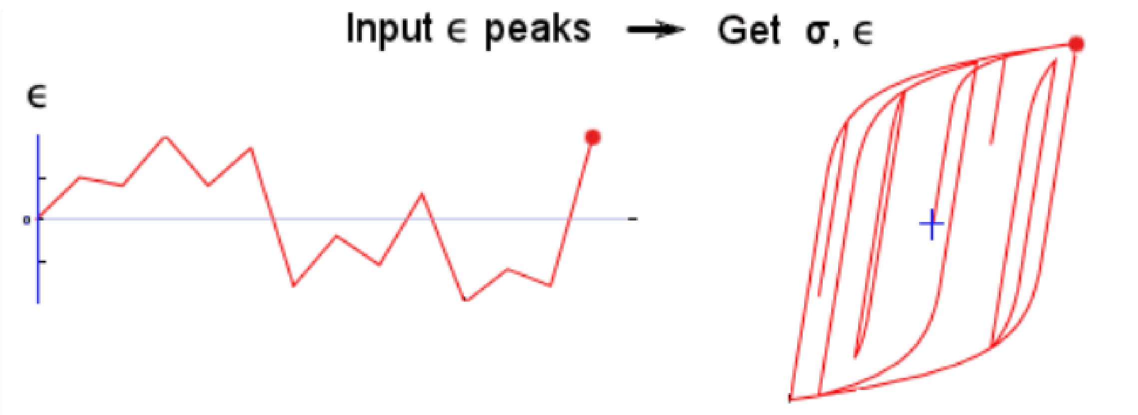


In your web browser activate the page:

https://fde.uwaterloo.ca/Fde/Materials/Steel/Hsla/Merged950X/merged3_SAE950X_sim.html

Pick some points whose stress-strain path you would like to simulate,
or make up a list of your own.

Next page explains simulator



This is just an advertisement gif

In this box you will find a SAE standard “fitted” digital fatigue curve file

#NAME= SAE950X #NAME= Fitted_file_merged_3-sets #

Your material file (its a Digital-Fitted Curve):

```
#SAE_Standard_File=
#
#Copyright (C) 2015  F.D.E. Committee
#This data file is free software - you can redistribute it and/or
#modify it under the terms of the GNU General Public License as
#published by the Free Software Foundation; either version 2 of the
#license, or (at your option) any later version.
#This data file is distributed in the hope that it will be useful,
#but WITHOUT ANY WARRANTY - without even the implied warranty of
#MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
#GNU General PUblic License for more details.
```

Place your strain data points in these boxes, one at a time.

#MagFactor= 1.0 # Enter your Strain Reversal Points:

0.01

Simulate Click here

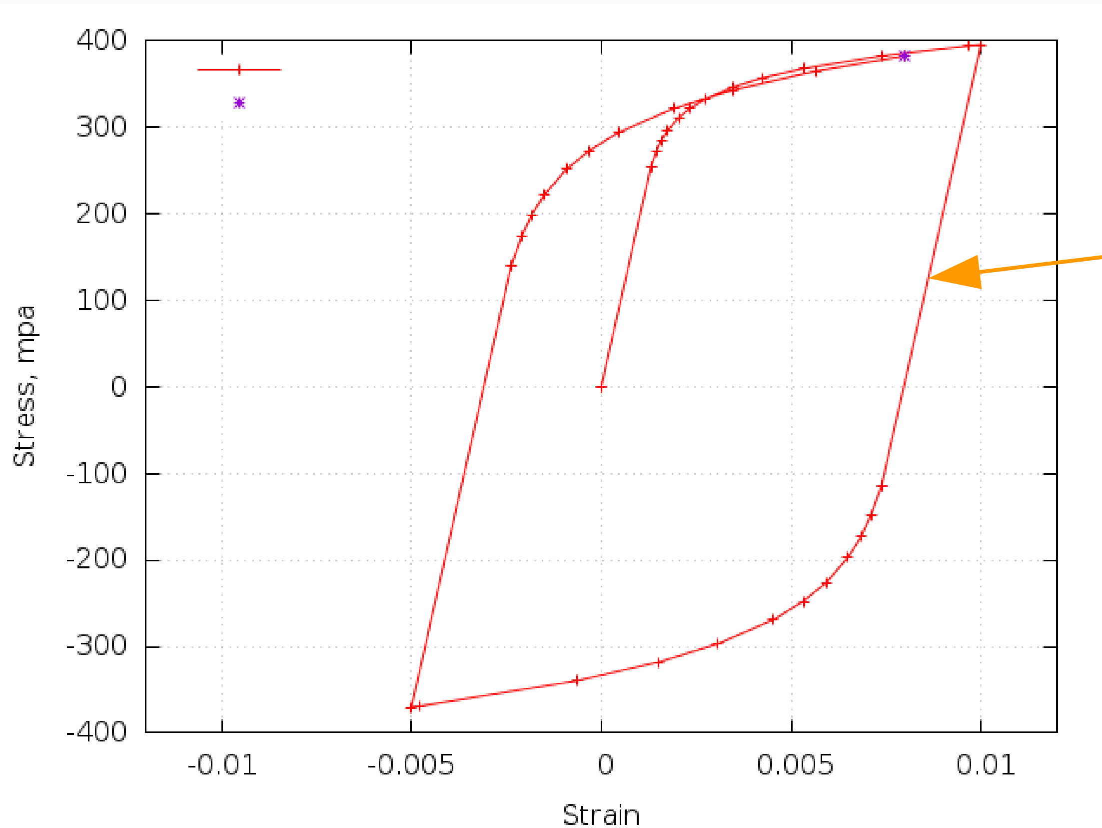
After each input click here

If all goes well the browser should return a page like this one

#MagFactor= 1.0 # Enter your Strain Reversal Points:

0.01 | -0.005 | 0.008

Click here

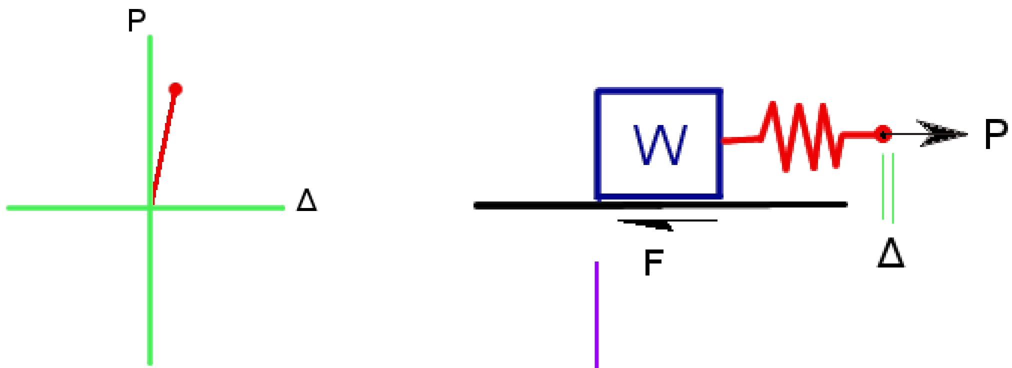


Here are your hysteresis loops

#TOTDAM90= 0.4692731E-03 allowed Repeats= 2131.0 nrev= 3

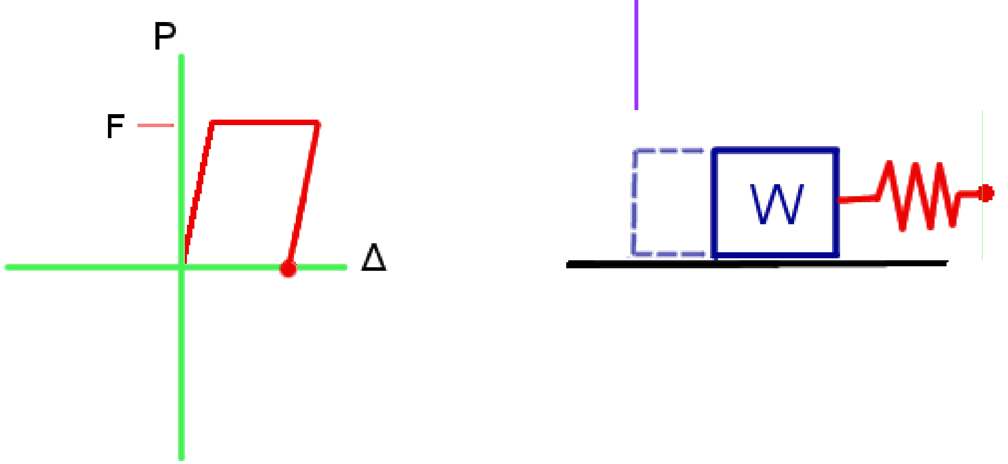
Here is how often the sequence can be repeated to failure

Material memory has been simulated by Rheological models. A simple one is a spring-slider as shown below for elastic-plastic behaviour.



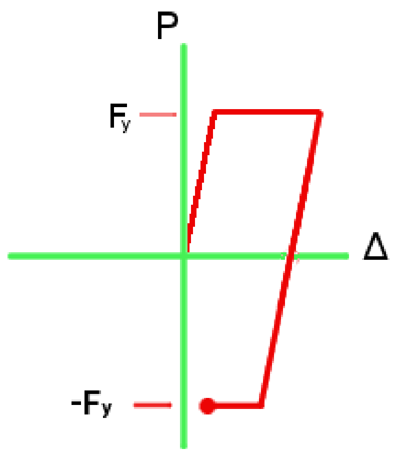
Initially the force P is less than the friction F and only stretches the spring, elastically

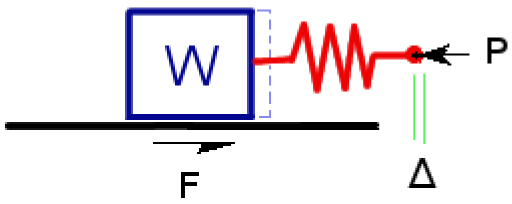
Once P = F the weight W starts to slide with friction.



At some point P can be unloaded. W will remain stationary, while the elastic spring unloads to zero load.

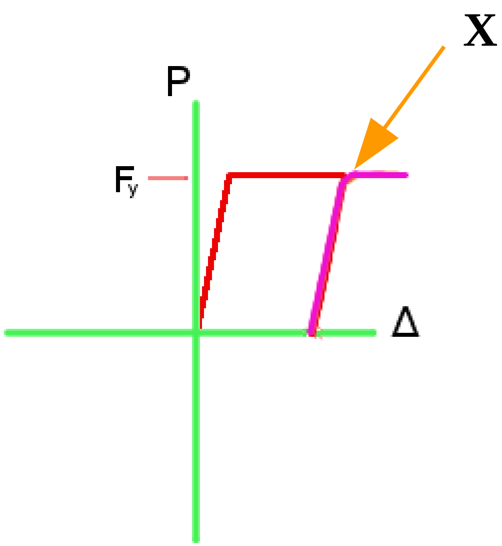
We now have a "permanent set" i.e.: plastic strain - which remains unchanged if we do nothing else.





From zero we have the option of going into compression (-ve force).

When P reaches the friction force F in compression the weight will start to move back towards the origin.

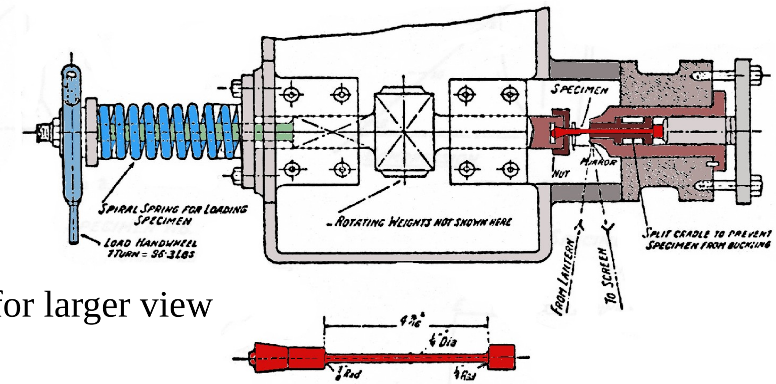


If we decide to go back into tension,
rather than compression,
flow will return to the old path at **X**

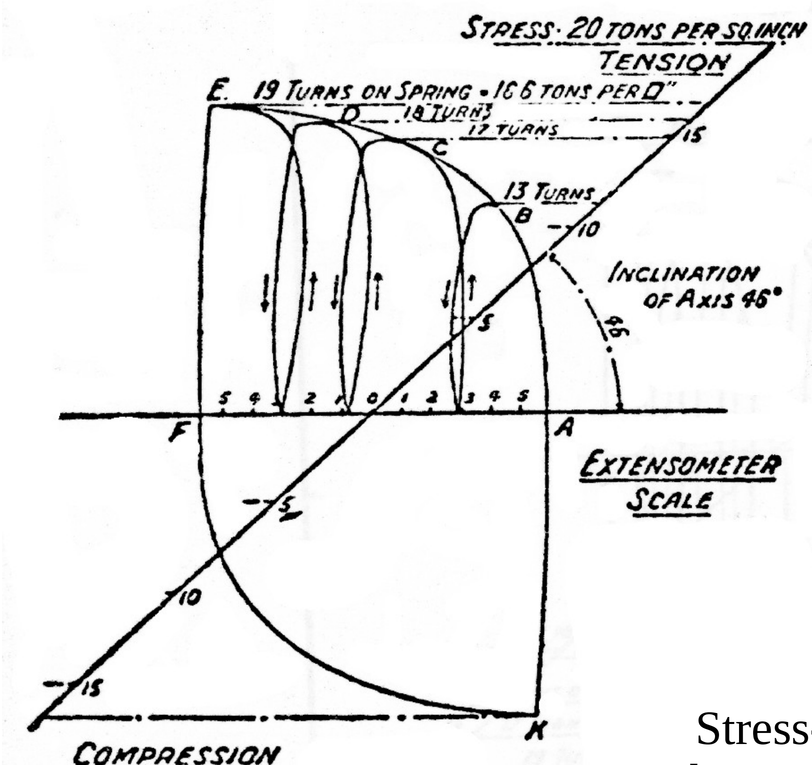
Material memory is attributed to dislocation movements (friction) in the metal’s atomic lattice.

Aside from Bauschinger's work on stress-strain behavior, one of the earliest observations of hysteresis loops and material memory is by Smith and Wedgwood in 1915

[Ref.: J.H.Smith, G.A.Wedgwood, "Stress-Strain Loops for Steel in the Cyclic State," JISI, V91 N1 1915 pp.365-397]



See Chap.2 pg.13 for larger view



Strain scale is reversed

Stress-strain plots show memory events.

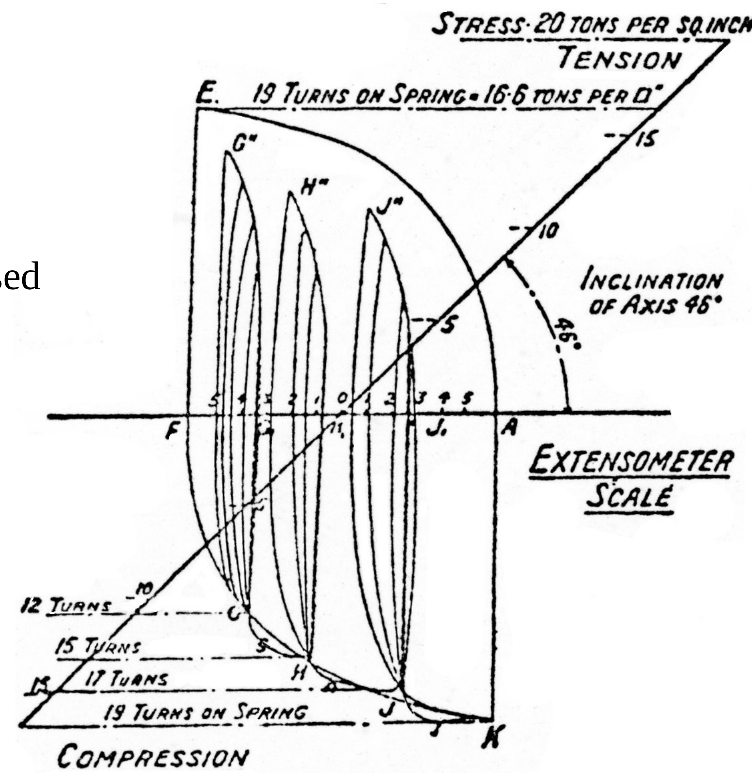


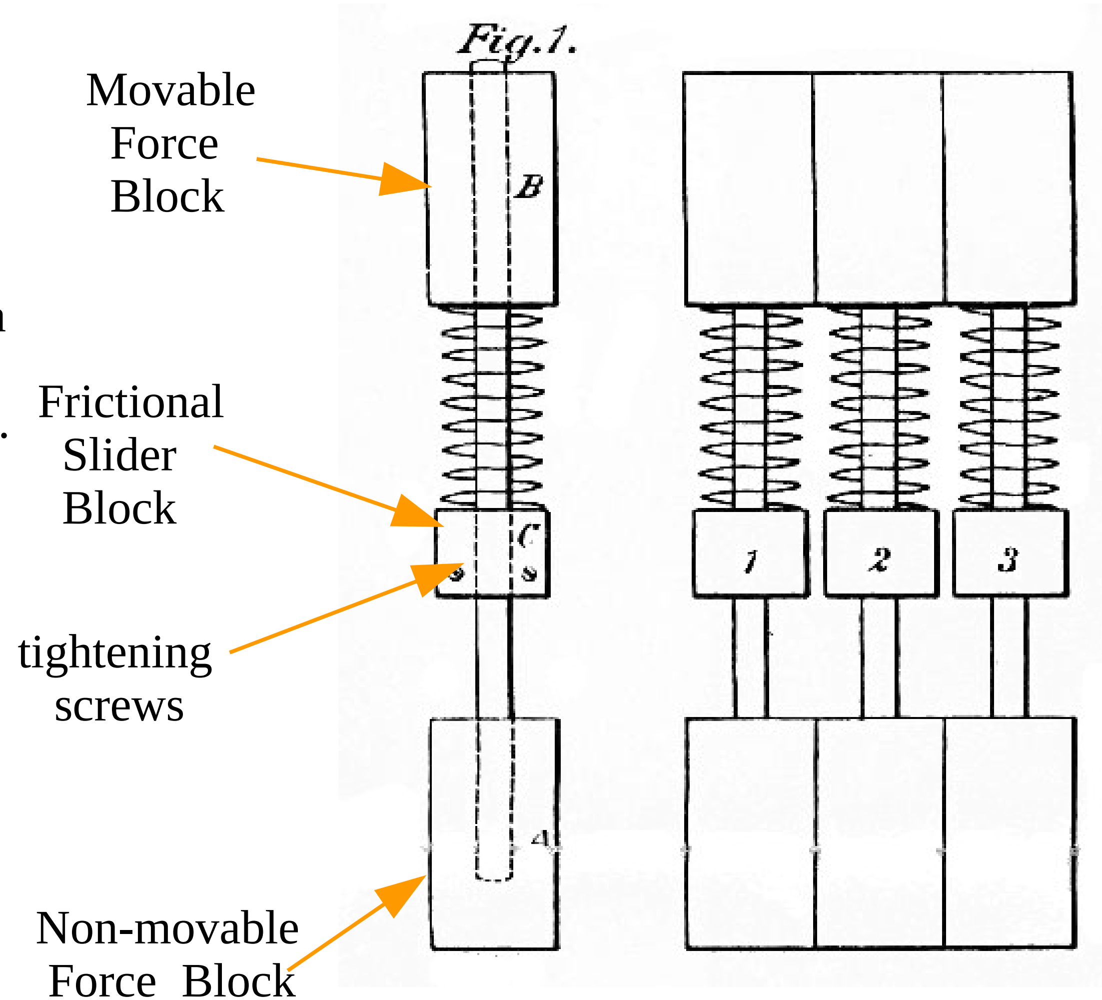
Fig. 12.

In 1922 Prof. C.F. Jenkin presented a physical demonstration model using a set of parallel spring-sliders.

Each of the sliders 1,2, and 3 has a different clamping force.

Thus when the 3 movable blocks have a force applied they move with an elastic constant equal to the sum of the springs.

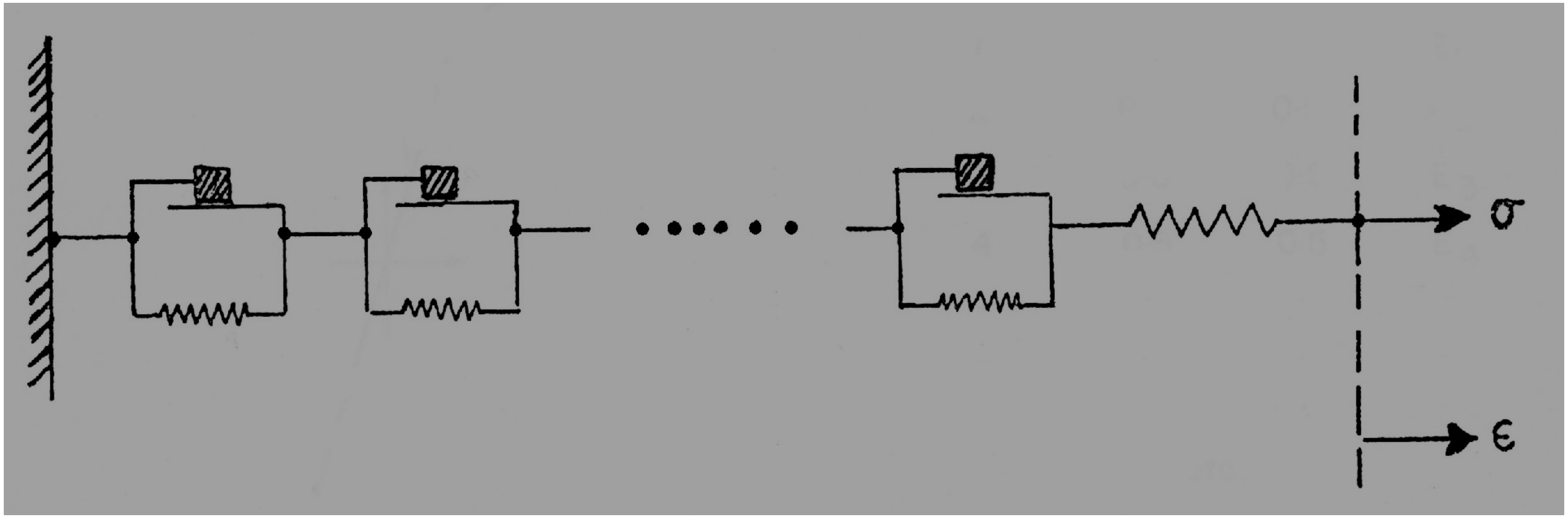
When its force get high enough each slider begins to move and causes the Force vs. Deflection to become curved due to "plasticity"



For full description:
https://fde.uwaterloo.ca/FatigueClass/Notes/jenkin.pdf

Another variation of the spring+slider rheological model was described by Iwan

[Ref.: W.D. Iwan, “On a Class of Models for the Yielding Behavior of Continuous and Composite Systems,” Trans. of ASME J. Appl. Mech., Sept. 1967, pp.612-617.]



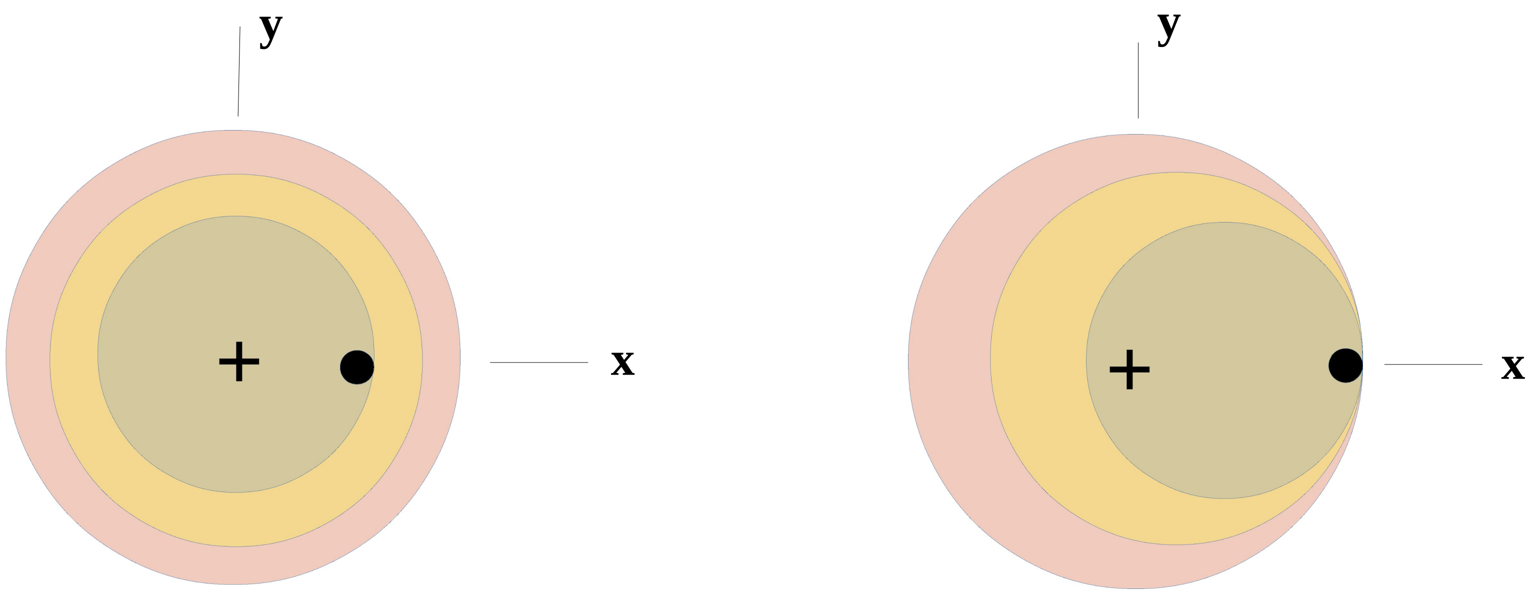
Again the sliders slip at different stresses, and each spring can have its own elastic response modulus.

This model was successfully computerized by J.F.Martin to simulate variable amplitude fatigue loading in 1969.

[Ref.: J.F.Martin, T.H.Topper, G.M.Sinclair, “Computer Based Simulation of Cyclic Stress-Strain Behavior,” T.&A.M. Report 326, U.Illinois Urbana, 1969]

(Hey John, if your reading this can I use some of your figures here? -Al :)

Multiaxial fatigue behavior is beyond the scope of the present course material, but it should be mentioned that the Spring-Slider model mentioned by Iwan was extended to 2D and 3D stress-strain behavior. An analog is a bunch of initially concentric "O" rings of different sizes, that get moved by a "stress" point such as a pin or pencil point.



Each circle defines a slope for the stress-strain response.
The smallest circle is the fully elastic "zone". Bigger circles define lower slopes.

In addition to Iwan, this behavior was suggested for cyclic deformation by Mroz
[Ref.: Z.Mroz, "On the Description of Anisotropic Workhardening,: J.Mech.PhysSolids, Vol.15 1967, pp.163-175]

An excellent summary and extension with experimental verification is given by Chu:
[Ref.: C.-C. Chu, "The Analysis of Multiaxial Cyclic Problems with an Anisotropic Hardening Model," Int. J. Solids Structures, Vol.25 No.1, 1987]

“Why all the emphasis on material memory?”, one could ask.

In my opinion material memory, combined with a cyclic stress-strain curve, is the key element of a fatigue crack initiation or a crack propagation analysis that requires prediction of the stress-strain behavior at a fatigue hot-spot.

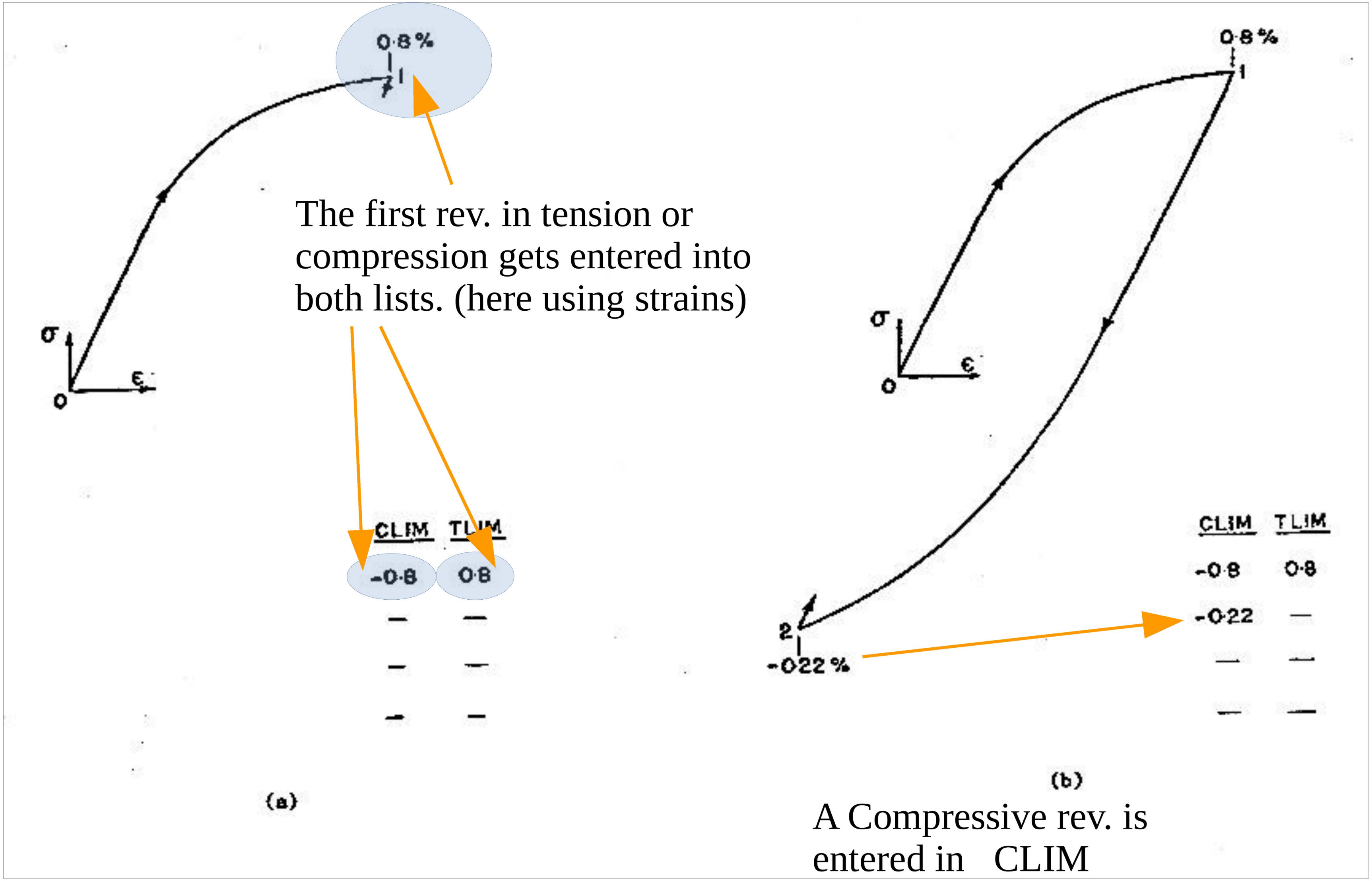
The transient effects of cyclic hardening/softening do not usually dominate the fatigue life. For most of the life the cyclic stress-strain curve is adequate for modeling.
If needed these transients can be simulated but they are not required to predict fatigue life.

The cyclic mean stress relaxation mechanism (ratcheting in load control) is important when “residual stress” is imposed in the fatigue history. Such stresses are can be created by heat treatments, cold work or the service fatigue history itself. Large plastic strain hysteresis loops will quickly change the “residuals” by cyclic relaxation. This is important for fatigue life estimations as fatigue hot-spots with tensile mean stress loops will initiate cracks earlier or propagate existing cracks faster. Compressive mean stresses will delay the onset of the fatigue damage.

In order to evaluate the presence or absence of relaxation one must first have a good idea of the size of the hot-spot stress-strain hysteresis loop and its location in the stress-strain plane. For that one needs a good stress-strain material memory model to follow the variable amplitude component load history.

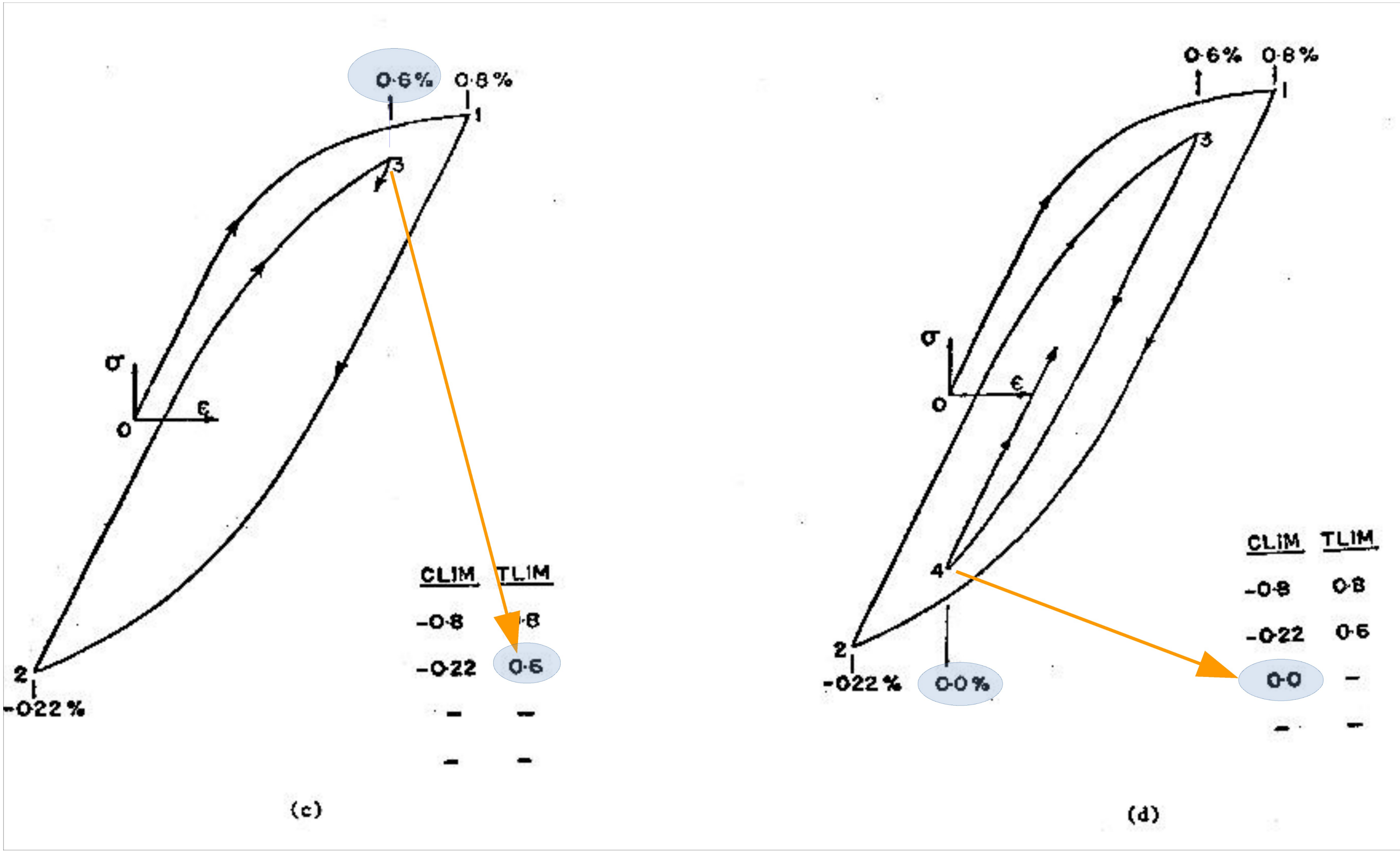
If the component service loading is constant amplitude only, one does not need to use a material memory model. Most service histories, however, have variable amplitude loadings.

One of the ways to track memory events in a simulation is called a LIFO or Push-Down list.
There is a list for Compressive reversal points CLIM and a list for Tensile revs. TLIM

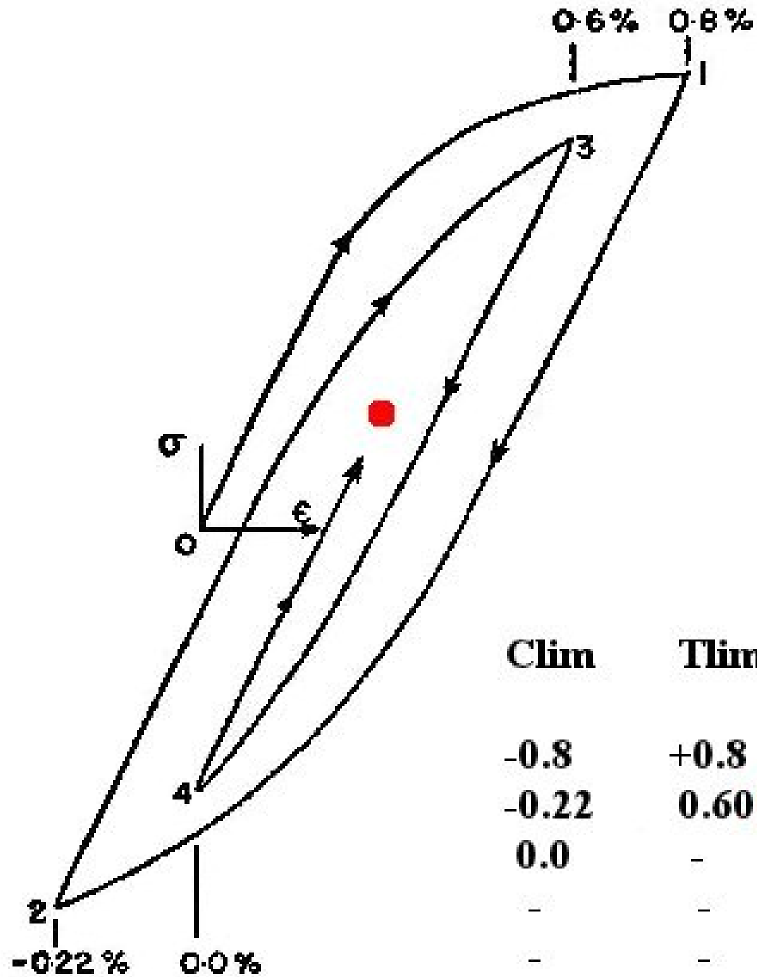


Ref.: F.A.Conle, “A Computer Simulation Assisted Statistical Approach to the Problem of Random Fatigue,” MSc. Thesis, U.Waterloo, March 1974.

If the next tensile rev. does not exceed
any previous tens. revs. it is stacked in TLIM



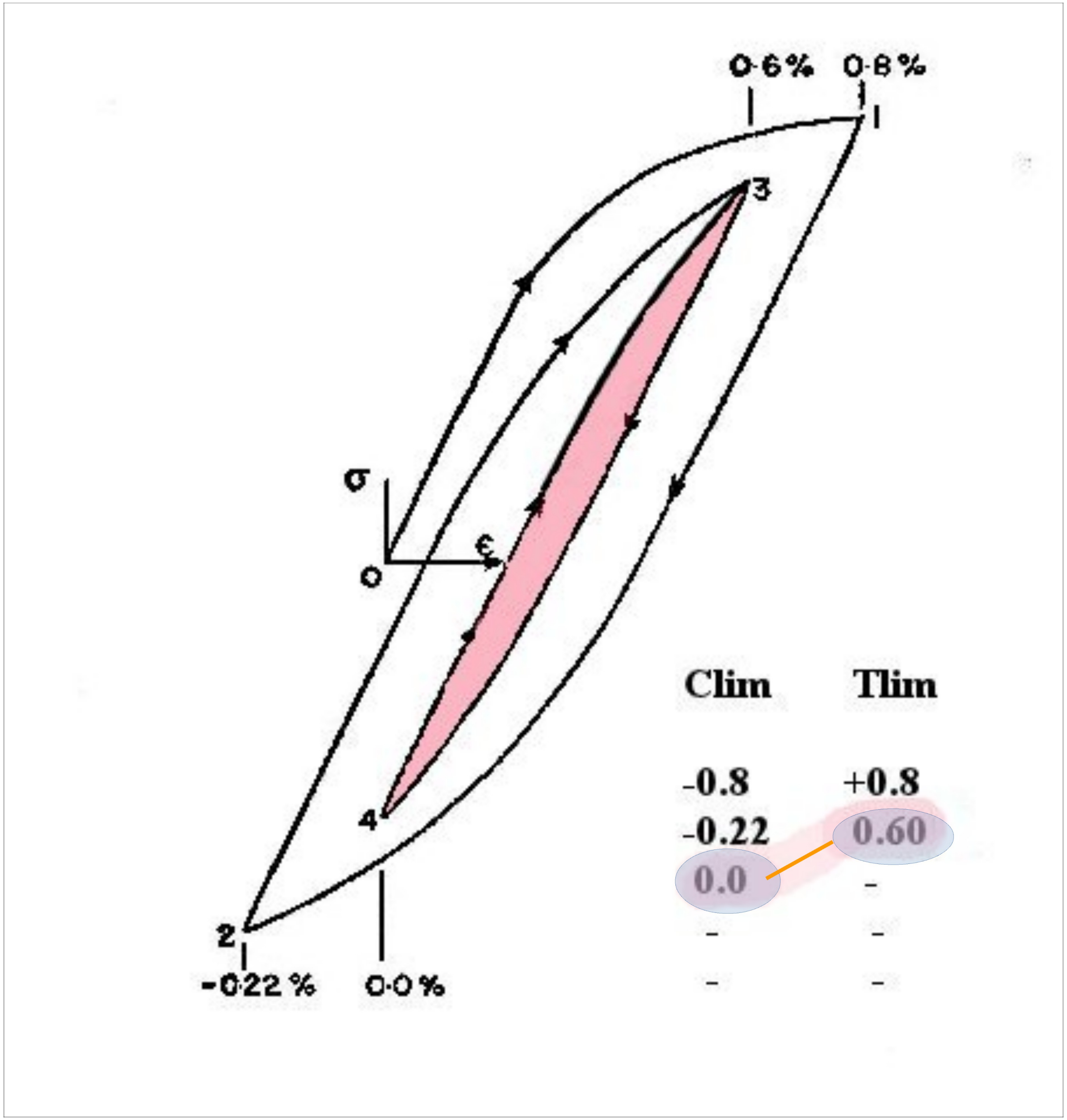
Similarly if the next comp. rev. does not overrun
any previous comp. revs, it is stacked in CLIM



Clim	Tlim
-0.8	+0.8
-0.22	0.60
0.0	-
-	-
-	-

As deformation proceeds one is continually checking for overruns of previous revs.

In this tensile direction half-cycle one must check the last entry in the tensile stack for equal or exceedence.

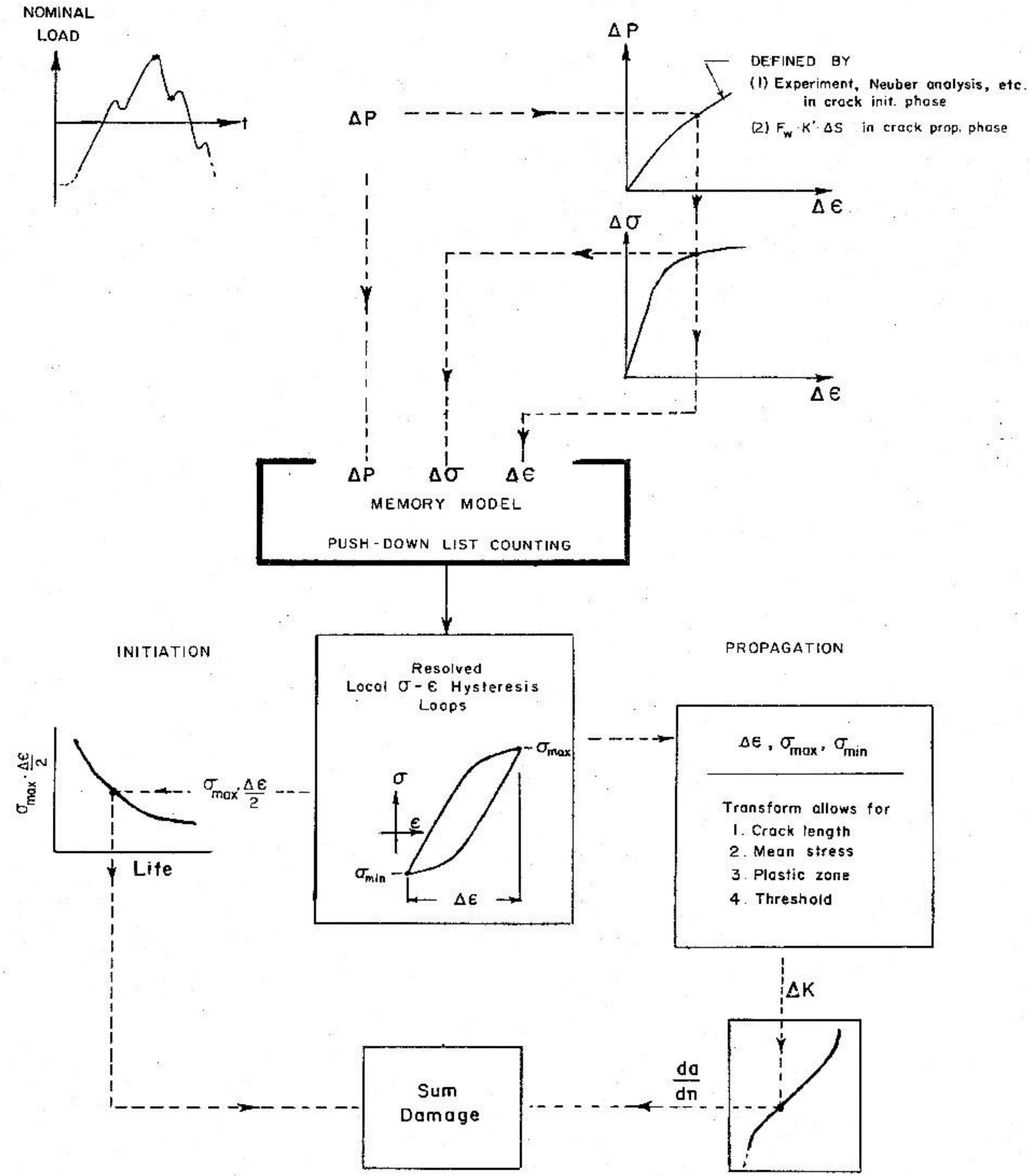


When the path encounters a stack value, a hysteresis loop has closed.

Its size is defined by the last entry in CLIM and TLIM.

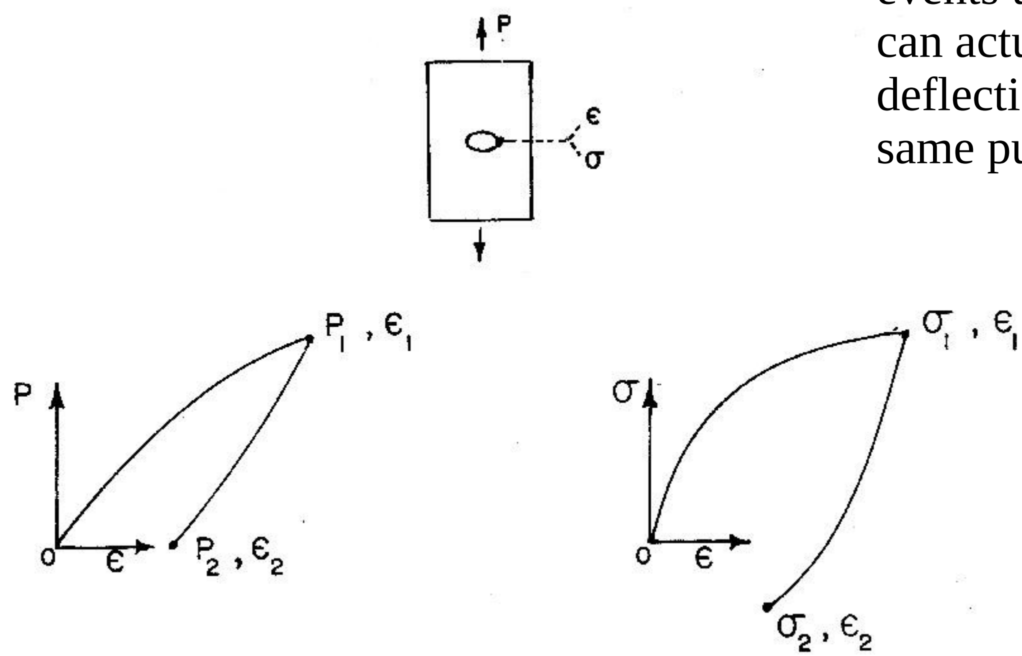
The closed loop is considered to be the **Fatigue Damaging Event** !

Its tips are removed from the stack, the loop is counted for damage, and deformation continues on the old path 2-3.



NOMINAL LOAD
t
ΔP
ΔP
DEFINED BY
(1) Experiment, Neuber analysis, etc. in crack init. phase
(2) $F_w \cdot K' \cdot \Delta S$ in crack prop. phase
Δε
Δσ
Δε
ΔP Δσ Δε
MEMORY MODEL
PUSH-DOWN LIST COUNTING
INITIATION
PROPAGATION
Resolved Local σ - ε Hysteresis Loops
σ_{max}
σ
ε
σ_{min}
Δε
$\sigma_{max} \cdot \frac{\Delta\epsilon}{2}$
$\sigma_{max} \cdot \frac{\Delta\epsilon}{2}$
Life
Δε , σ_{max}, σ_{min}
Transform allows for
1. Crack length
2. Mean stress
3. Plastic zone
4. Threshold
ΔK
$\frac{da}{dn}$
Sum Damage

Although we only "count" memory events using one variable, like strain, we can actually use load, stress, strain, deflection or ΔK (for cracks) for the same purpose.



In most materials when one variable, like load, reverses all the other variables reverse too.

STACKS

COMPRESSION				TENSION			
DAMAGE	STRESS	STRAIN	LOAD	LOAD	STRAIN	STRESS	DAMAGE
D_{01}	$-\sigma_1$	$-\epsilon_1$	$-P_1$	P_1	ϵ_1	σ_1	D_{01}
D_{12}	σ_2	ϵ_2	P_2	–	–	–	–
–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–

Thus we are actually counting lots of variables at the same time.

For those of you already in the fatigue business, this is **"Rainflow Cycle Counting"**