Fatigue and Brittle Fracture

BASICS

Presented by: Ray Delaforce

What is fatigue ?

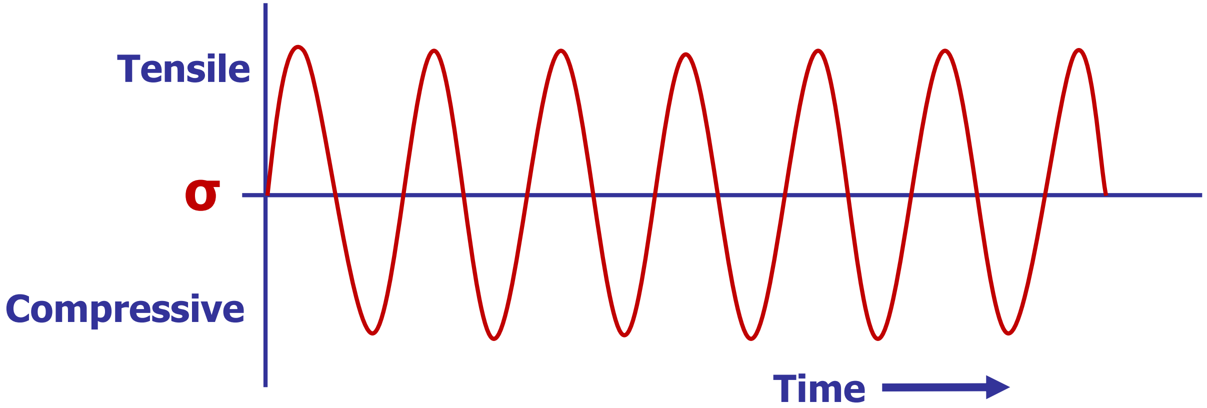
Fatigue has nothing to do with tiredness

Fatigue is:

- **Incremental crack growth over time**
- **Caused be stress reversals**
- **Until failure occurs – the through crack**

What do we mean by stress reversals ?

Consider a bar with a small surface crack subjected to this stress cycle



INTERGRAPH

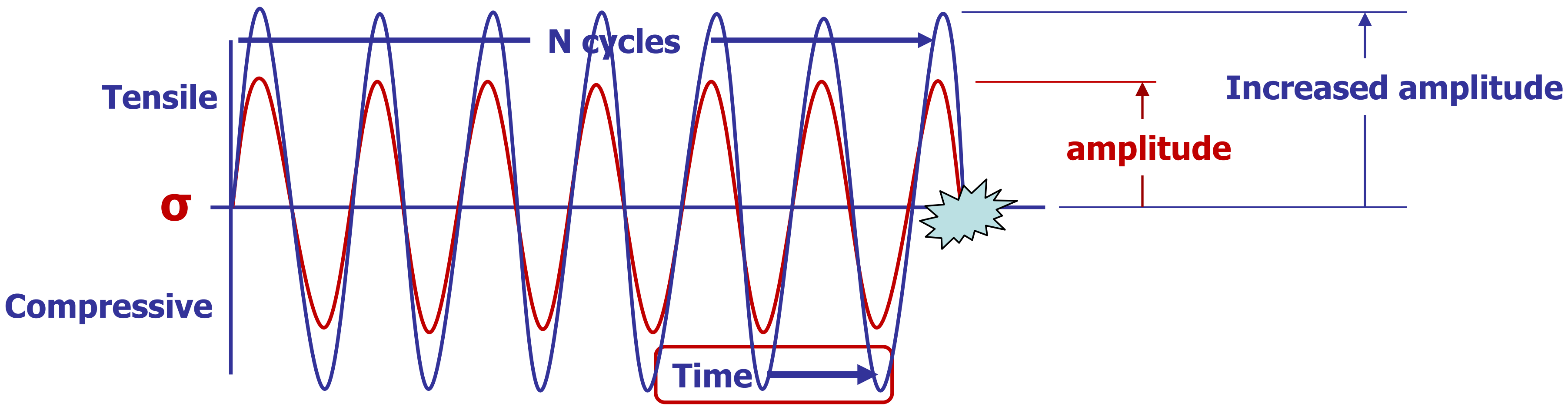
Let us see what we can learn from this cycle history

There are three properties of the graph we can consider

- **The magnitude of the tensile stress – the amplitude**
- **The number of cycles**
- **The time when the component fails**

Logically, failure will be hastened if the amplitude (stress) is increased

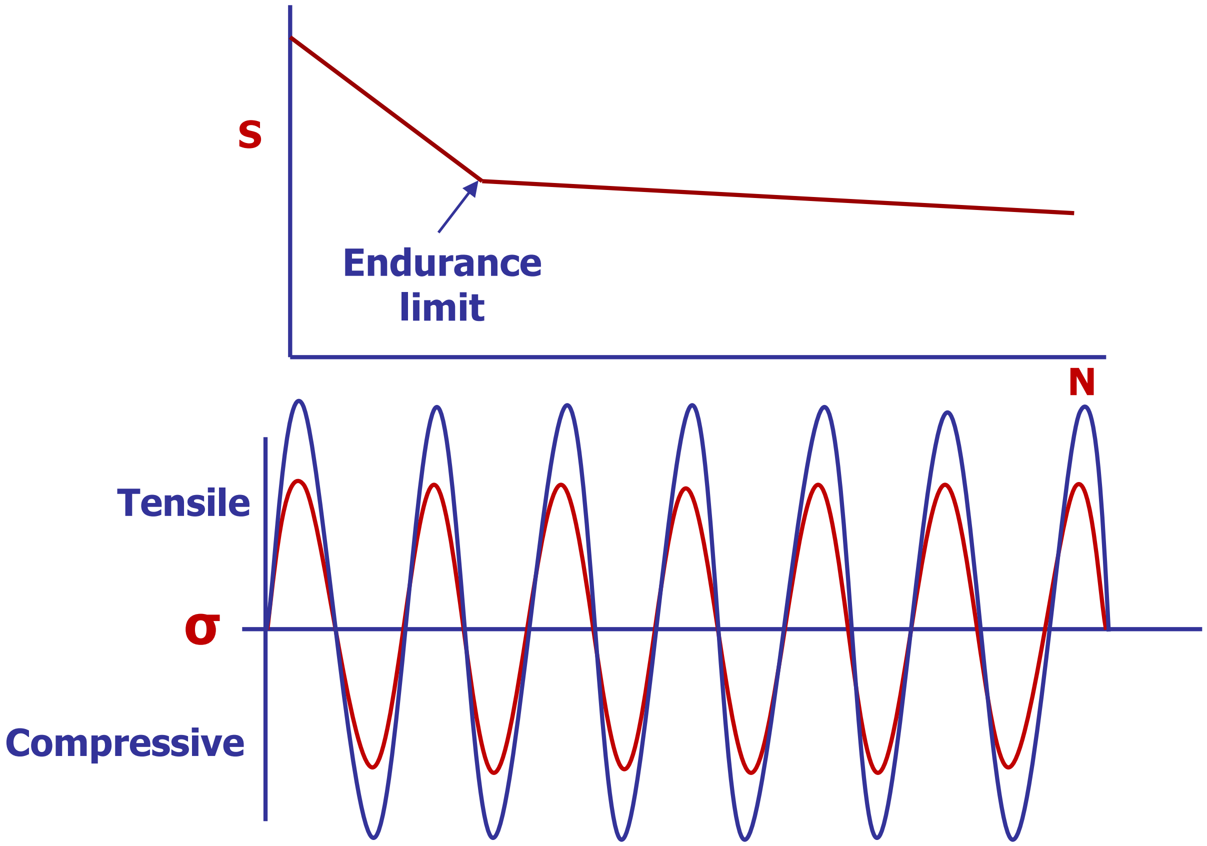
We can deduce N cycles is a function of stress σ



A lot of Empirical work has been done of fatigue

Stress S has been plotted against cycles N to failure

A pattern is revealed when the plot is on Log-Log graph paper



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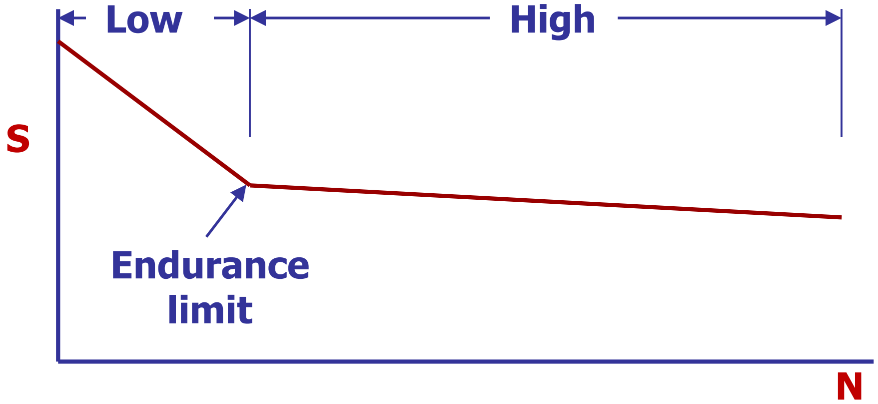


It is divided to two major regions – High and Low Cycle

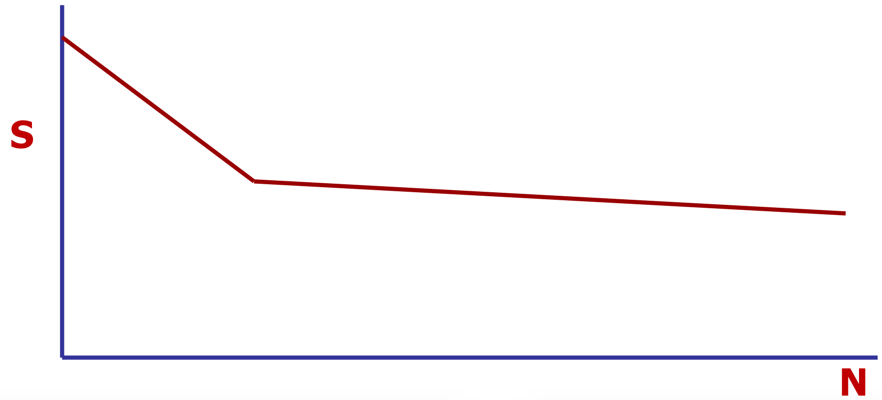
Pressure vessels fall into the Low Cycle region

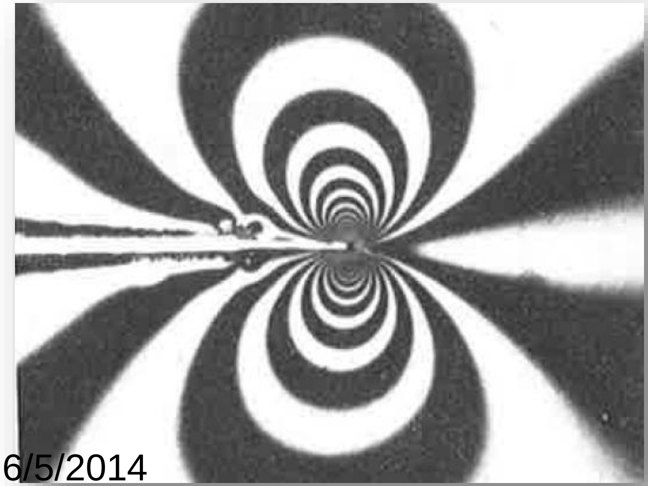
Automobile valve springs fall into the High Cycle region

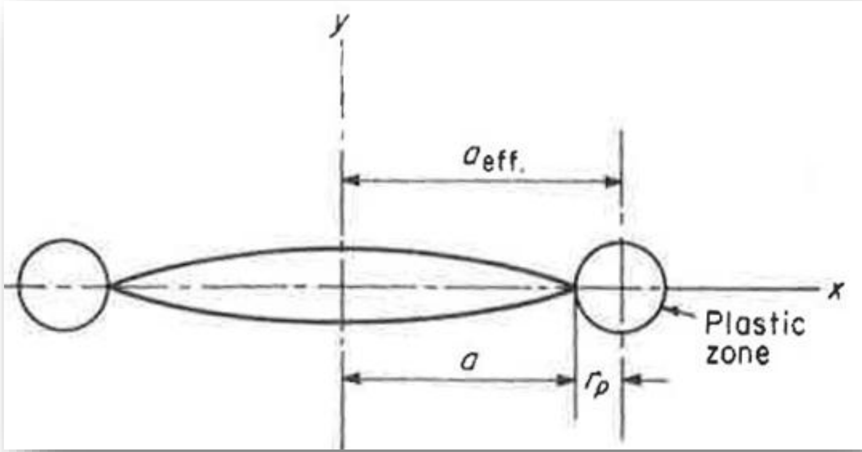
At the tip of the crack, the stresses are high

Stresses are well into the PLASTIC region of the stress-strain curve

The plastic region is suggestive of High Strain







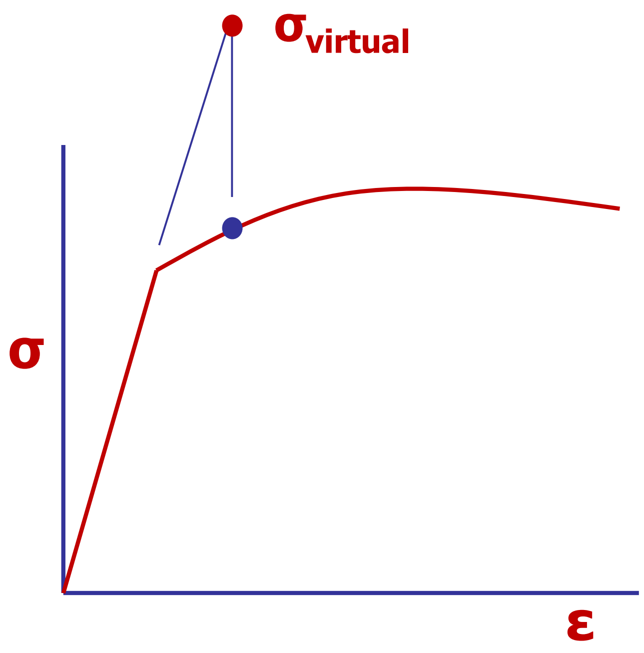
Let us look at HIGH Strain in the stress-strain curve

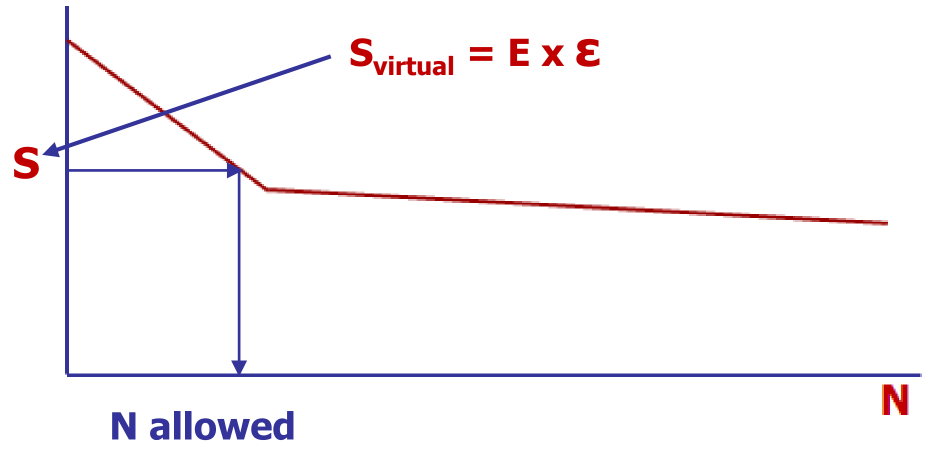
The strain can be well into the plastic region

Construct a virtual stress by extending the elastic line

The stress used in the S-N curve is actually a strain (virtual stress)

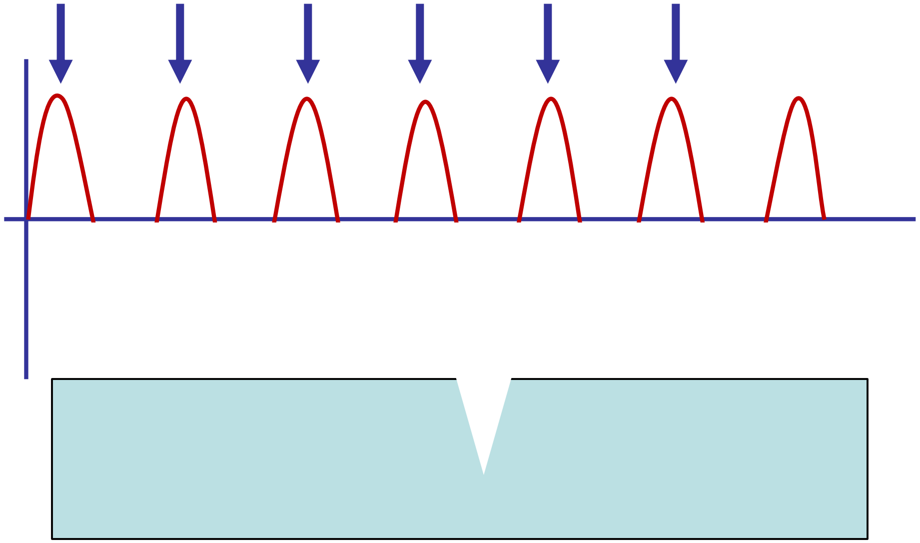
This the 'stress' entered in the S-N curve, which is actually the strain





Each time the cycle goes into tension, the crack increases

Crack grows for each positive cycle



This occurs until failure is reached

Let us look at this from another point of view

Let's see what happens on the Stress-Strain diagram

This is a simplified illustration – the plastic range is flattened

We show both tension and compression

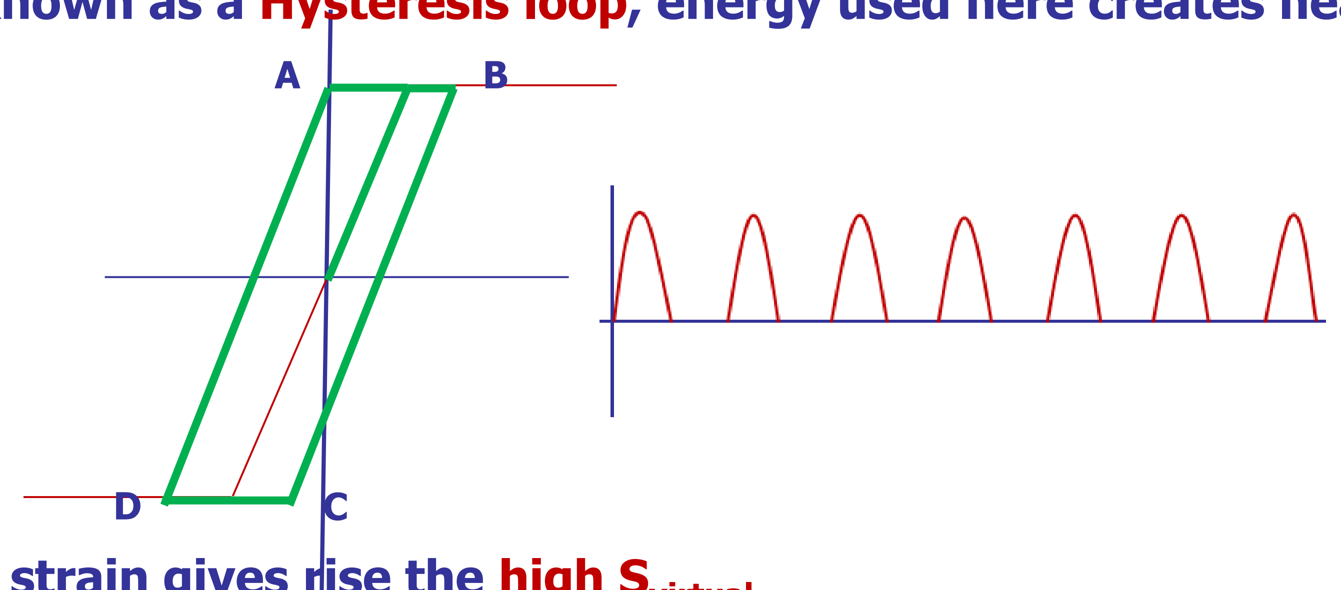
We consider the first cycle, notice – enters plastic region

Now we go into compression

For the second cycle we then go into tension again

Crack propagation occurs when we enter the tension side plastic region

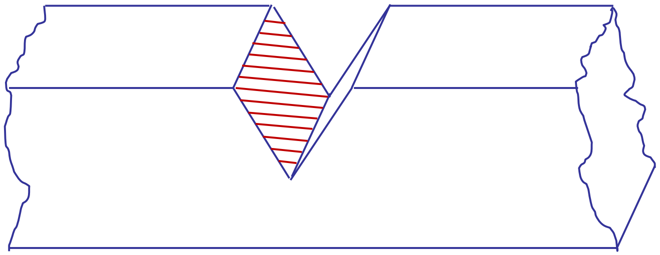
ABCD is known as a Hysteresis loop, energy used here creates heat



The large strain gives rise the high $S_{virtual}$

Consider the crack more closely

As the crack grows, the Free Surfaces grow also



We actually have two free surfaces that are growing area = 2A

The free surface energy of steel is close to G = 1 Joule / m^2

Where does the energy come from to propagate the crack

We get a clue from the Stress-Strain diagram

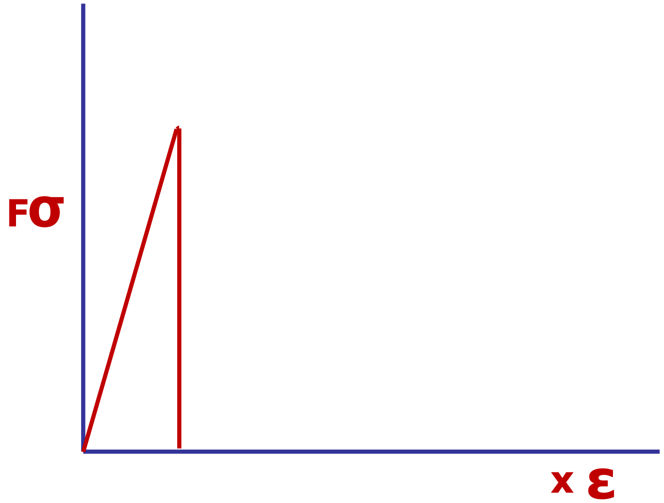
This is the stress-strain diagram

For convenience, we re-label the axes: force F and extension x

For simplicity consider only the elastic line

The area of this triangle is the work done – or Energy Expended

We can easily calculate the energy (work) expended



Computing the energy expended

Energy E:

$$E = F \times x / 2 \quad \text{Area of the triangle}$$

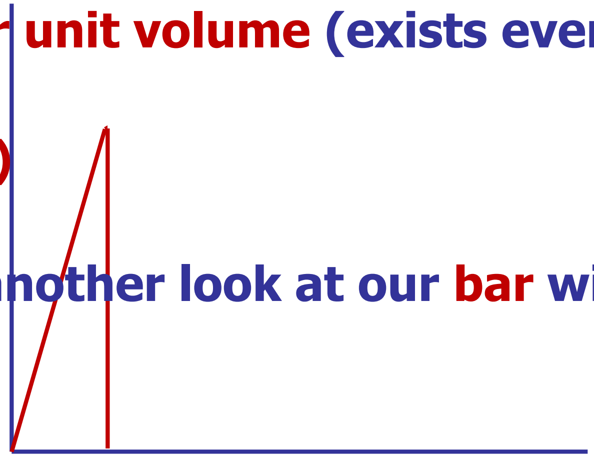
$$= \sigma . A \times \varepsilon . L / 2$$

$$= \sigma . A \times (\sigma / E).L / 2$$

$$= \sigma^2 . A.L/(2.E) \qquad = \sigma^2 . V/(2.E)$$

The energy per unit volume (exists everywhere in the bar)

$$e = \sigma^2 ./(2.E)$$



Now we take another look at our bar with the crack

This is bar from a previous slide

We now consider the energy balance

This volume of metal loses its strain energy e as it relaxes

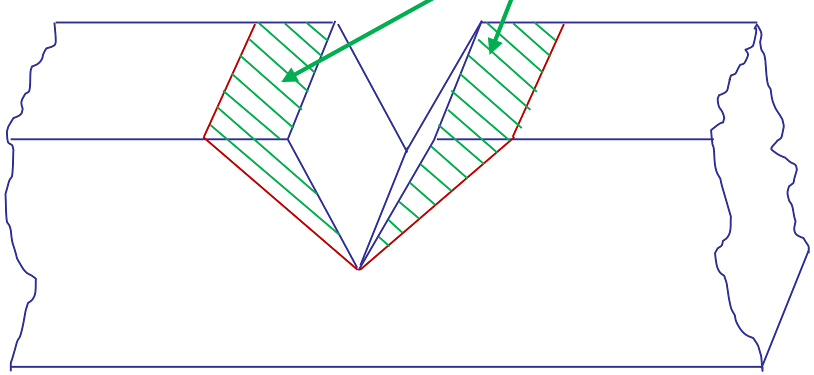
Energy lost creating the free surface = Energy gained by the free surface

Strain energy Lost: $e = \sigma^2 ./(2.E)$

Gained by free surface $e = 2.A.G$

Once the energy is used up, the crack can no longer run

That is the reason why the crack grow incrementally



INTERGRAPH

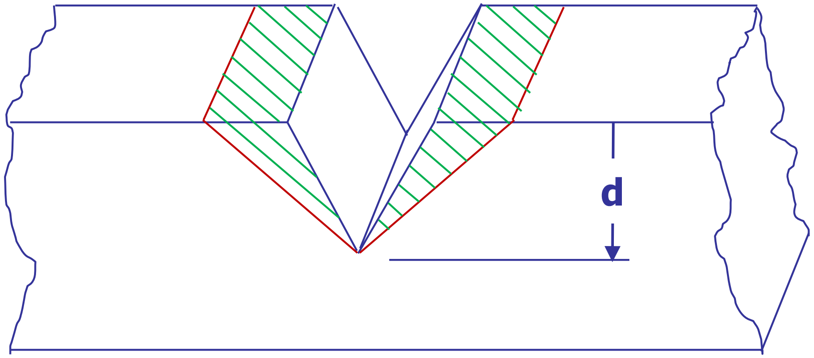
Strain energy Lost: $e = \sigma^2 ./(2.E)$
Gained by free surface $e = 2.A.G$

Look at the depth d of the crack

Area A gained is proportional to the depth d

Energy lost is proportional to the square of the depth d

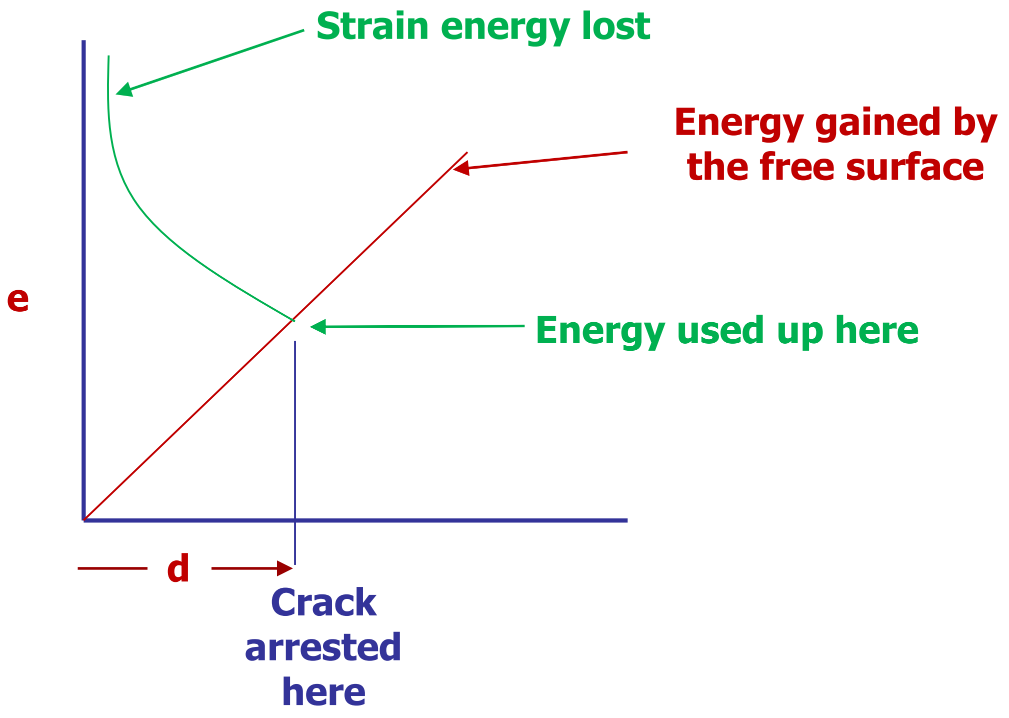
Surface energy based on Area, Energy lost based on Volume



Strain energy Lost: $e = \sigma^2 ./(2.E)$

Gained by free surface $e = 2.A.G$

The energy balance can be drawn on a graph



If we pursue the energy balance, we can learn something

Energy lost can be equated with energy gained by the free surfaces

$$2.A.G = \sigma^2 . A.L/(2.E)$$

By making σ the subject of the equation we get something interesting

$$\sigma = 2\sqrt{\frac{G.E}{L}}$$

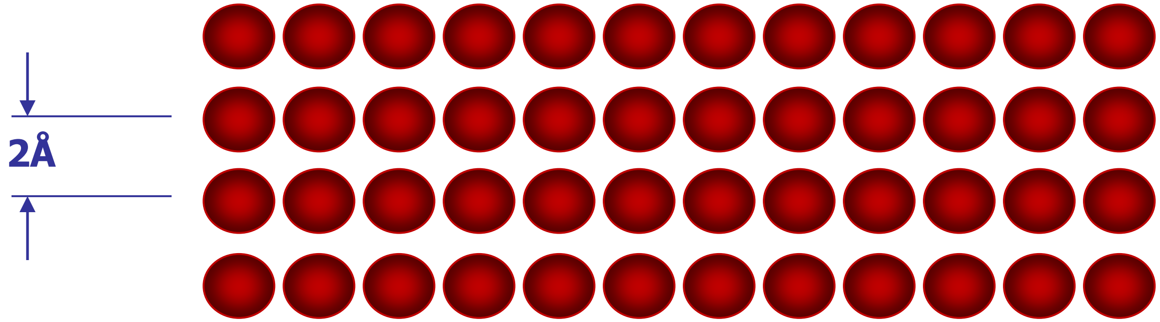
We can compute the Theoretical Strength of steel !

But, what is the distance L in our model, this is interesting

We must look at the atomic structure of the steel

Atoms lie in sheets one above the other like this

The distance between the atoms is about 2 Angstrom units (2Å)



This is the gauge length when the steel fractures, in other words: L

2Å = 2.10^{-10} m (or 0,2 Nanometres)

We are now in a position to compute the theoretical strength

We now have the values to insert into out σ equation

These are the values:

- $G = 1\ \text{Joule/m}^2$ — **Free surface energy**
- $E = 200.10^9\ \text{Pa}\ (\text{N/m}^2)$ — **Elastic Modulus**
- $L = 2.10^{-10}\text{m}$ — **Gauge Length (atomic separation)**

$$\sigma = \sqrt{\frac{G.E}{L}}$$

we drop the 2

$$= \sqrt{\frac{1\ .\ 200.10^9}{2\ .\ 10^{-10}}}$$

$$= 31\ 000\ \text{MPa}\ !$$

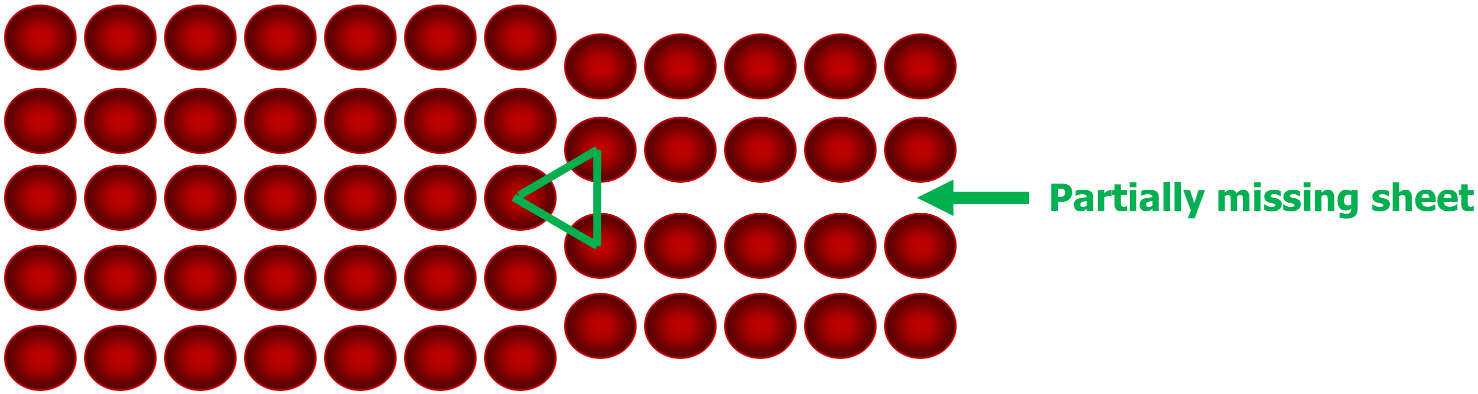
But steel has a tensile strength of about 500 MPa

Why is the actual strength about 60 times weaker that theoretical

Going back to our atomic structure, there are imperfections

A partial sheet of atoms is missing

Can you see that – what appears to be – a crack



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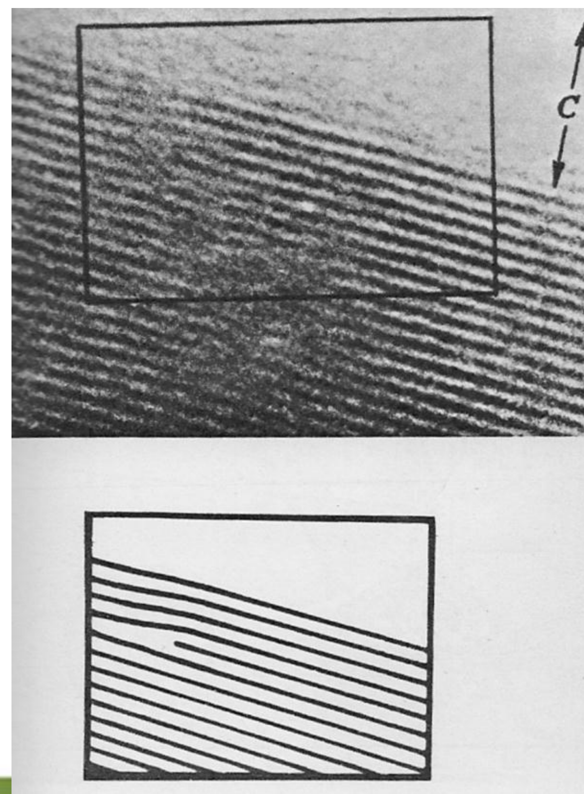
A Cambridge researcher found such a missing sheet of atoms

The crack is the reason why the metal is weaker than theoretical

These ‘starter’ cracks are the reason fatigue failure is experienced



We now consider Brittle Fracture

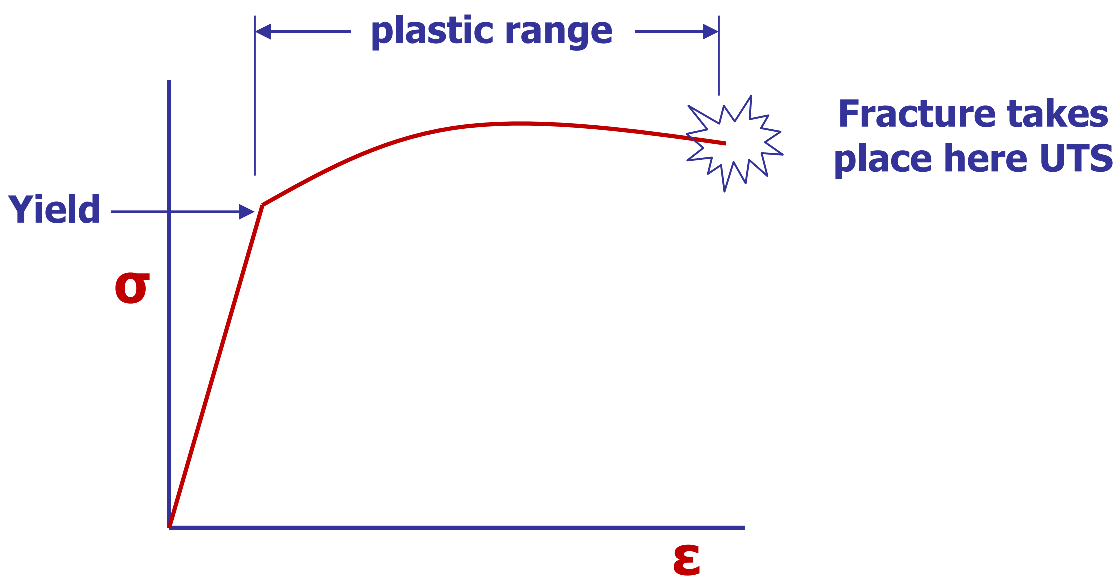
Let us look first at normal fracture that takes place

Look again at the stress strain diagram

This is the ductile range known as the plastic range

Important point: The UTS is above the Yield Point

We are concerned with the geometry of the fracture



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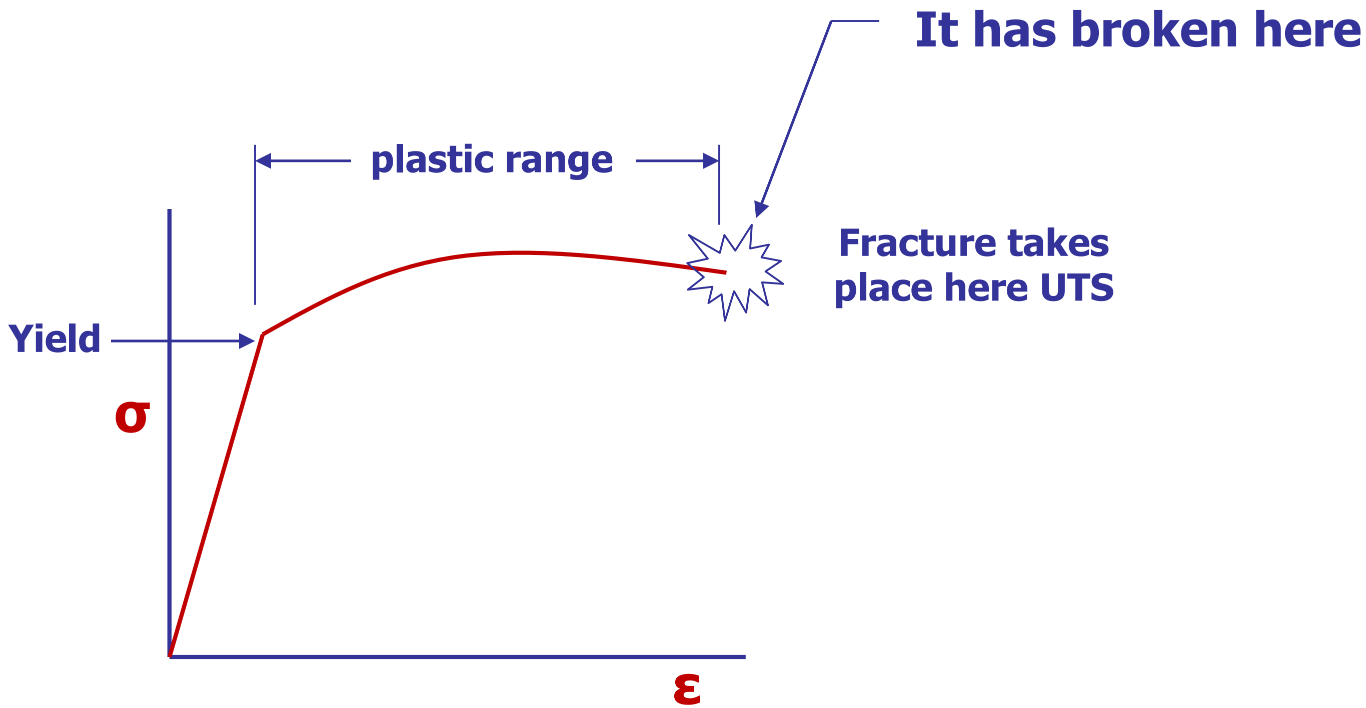
This is what the fracture looks like



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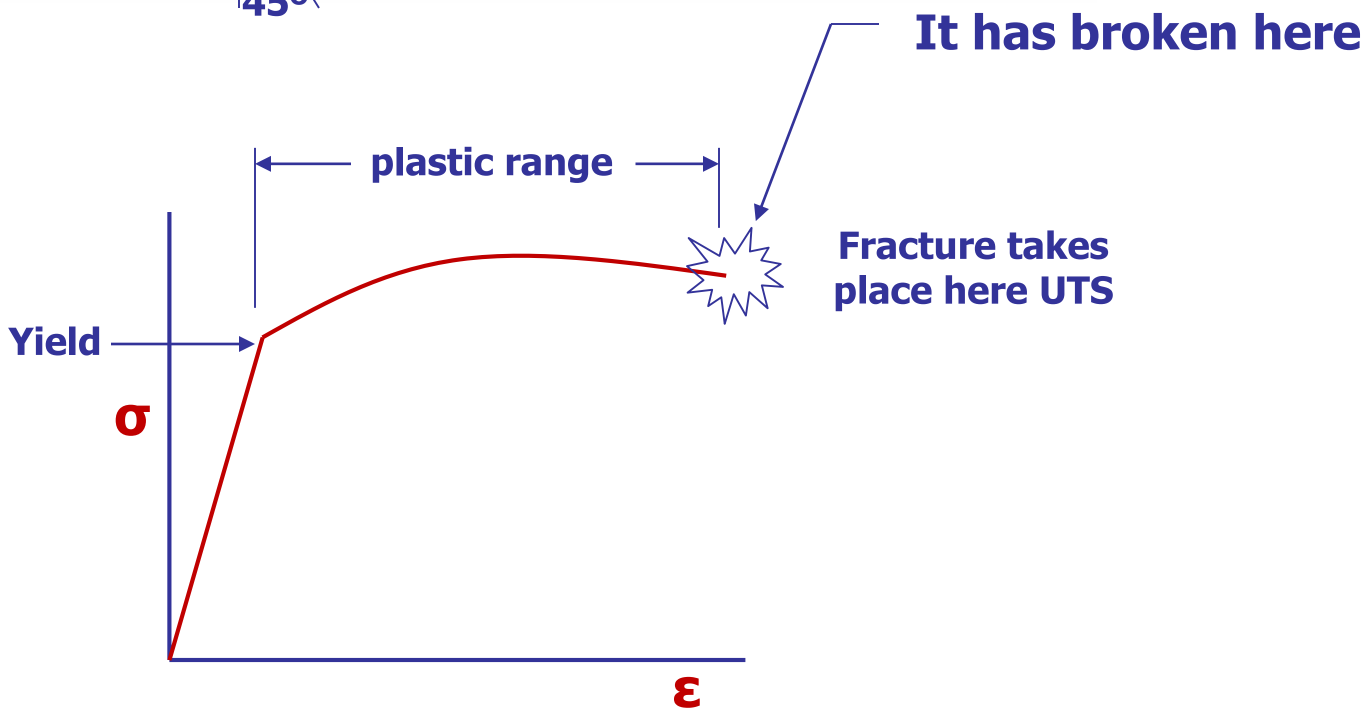
Let us look first at normal fracture that takes place

Notice the angled fracture – about 45^o



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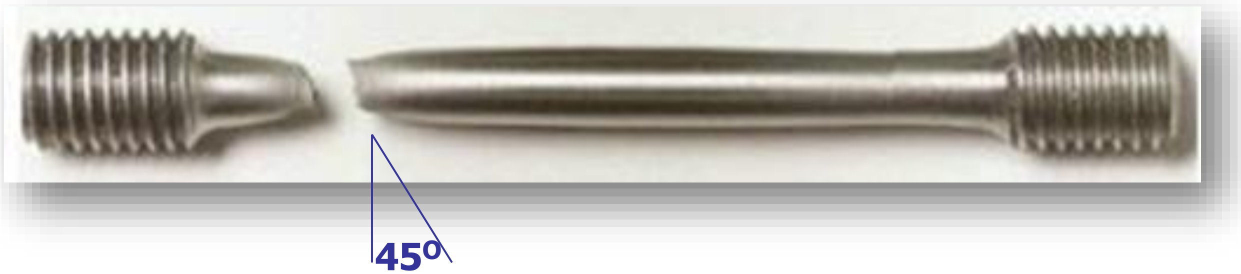
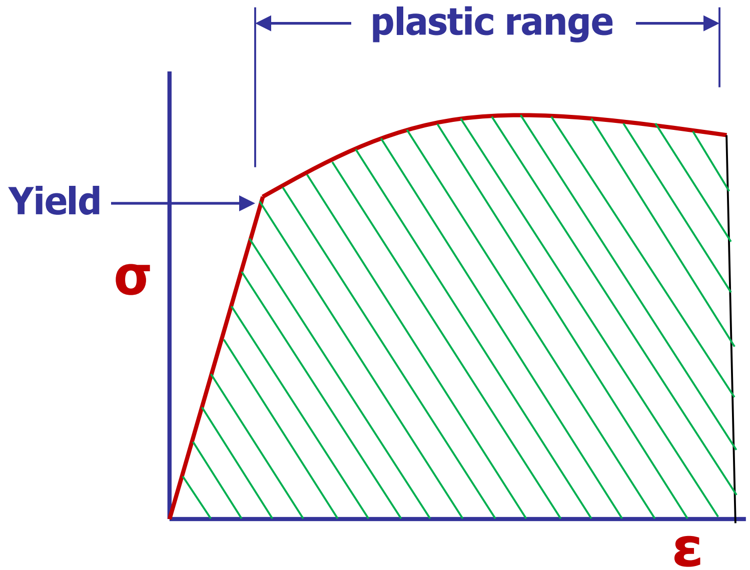


This area represents is the energy to promote the fracture



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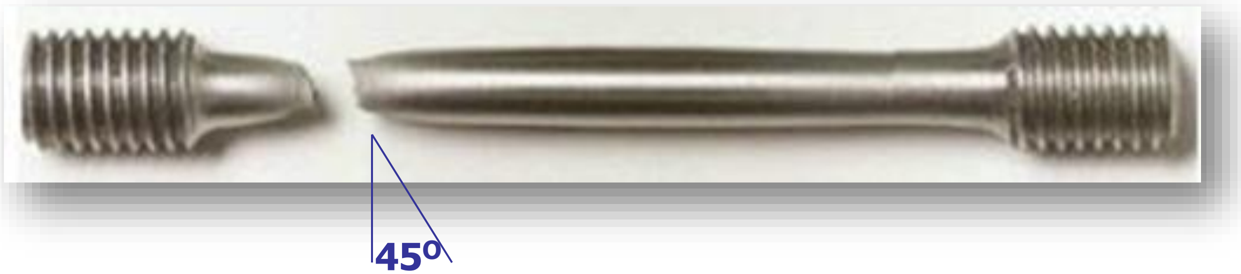

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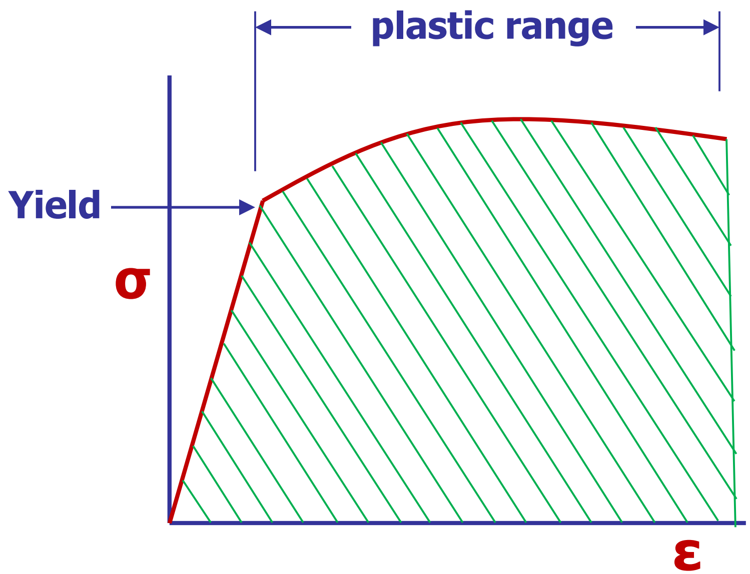
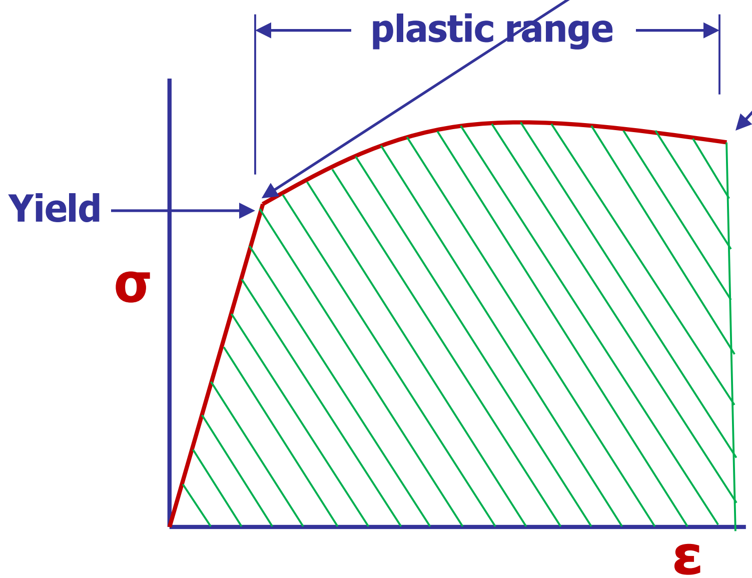


In the case of normal ductile fracture note these points:

- **The amount of energy to promote fracture (above yield)**
- **The facture occurs at 45^{o}**

- **We need to investigate these characteristics**



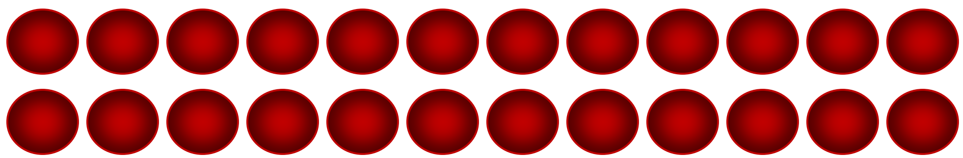
We now consider the 45^{o} fracture face

Look at this block, and how it fails when it fractures

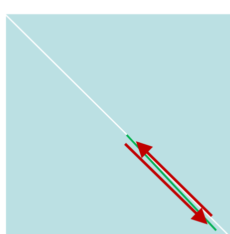
I fails in Shear – this is important, shear stresses must be present

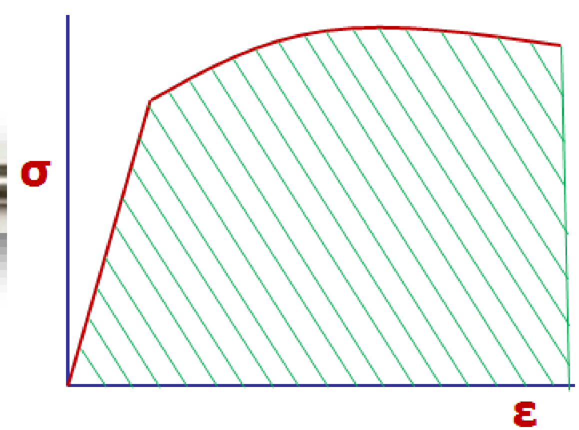
What is happening on the atomic scale ?

At the interface, sliding must take place like this



The amount of energy to promote this, is in the ductile range

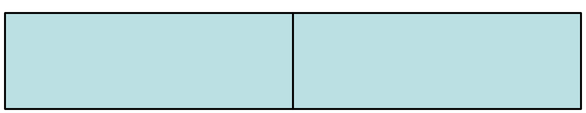




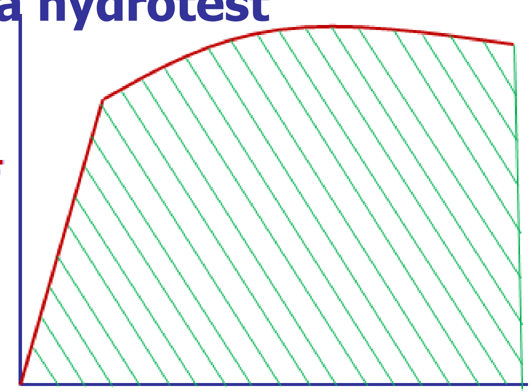
Now consider the situation where brittle fracture takes place

Look carefully at the fracture face:

- It occurs at 90^{o} not 45^{o}
- It occurred **BELOW** yield during a hydrotest



Breaks at 90^{o}

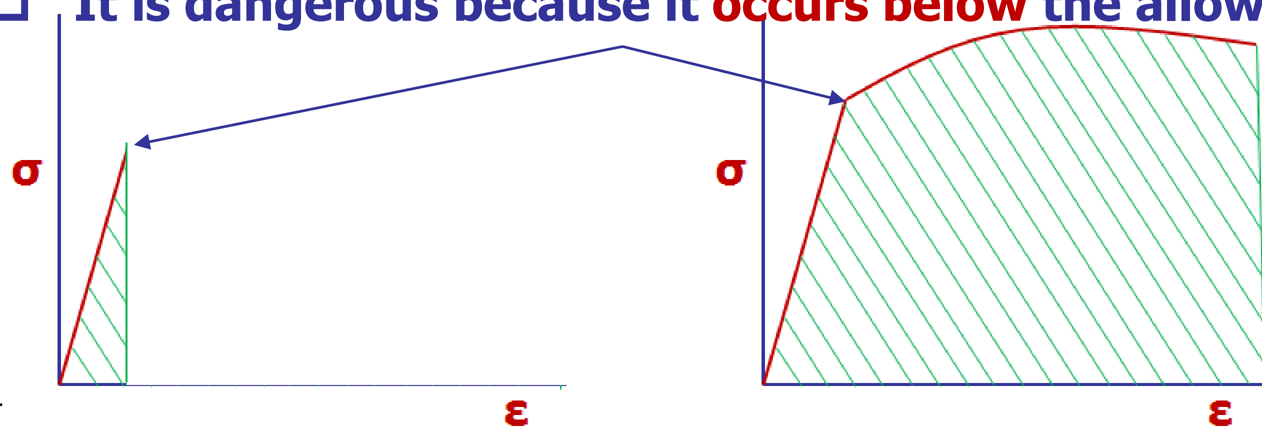


INTERGRAPH

Look at how **little energy** is used to promote brittle fracture

When the metal is brittle:

- When fracture occurs, it **cannot** be predicted
- It is dangerous because it **occurs below** the allowable stress



This occurs in Carbon Steel at **low temperature**

From the foregoing, **ENERGY** (**low energy**) is the **key** to brittle fracture

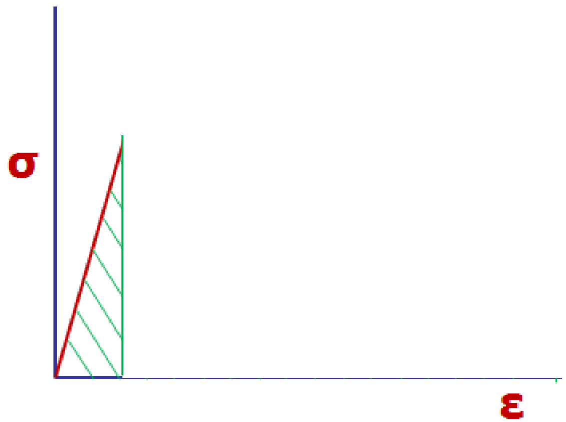
Energy to promote fracture can be determined, consider this specimen

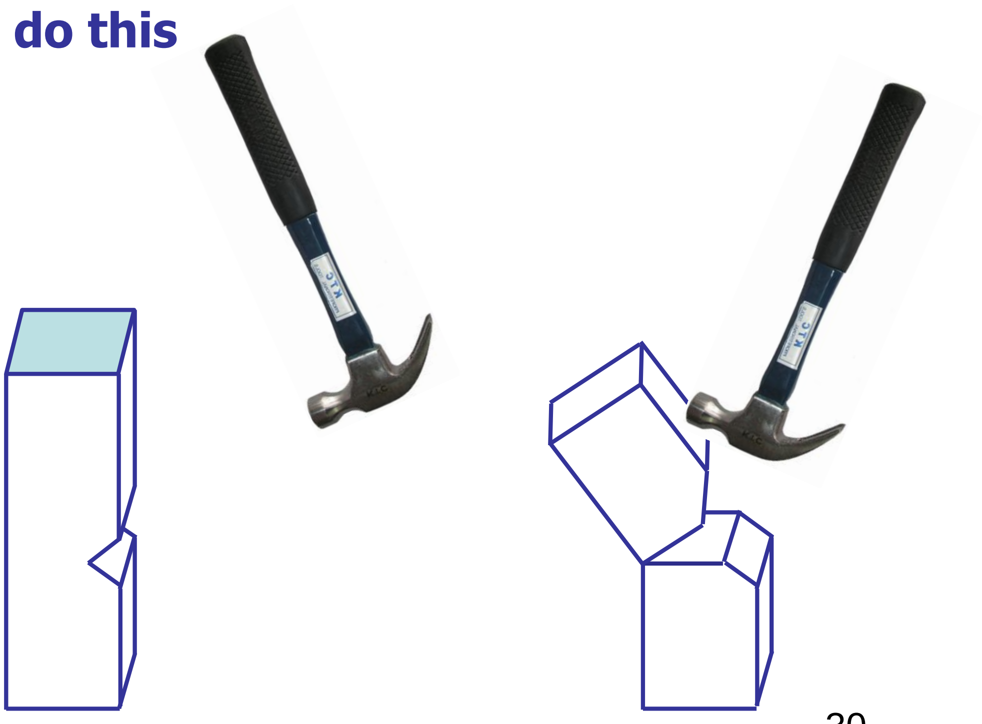
We could find the amount of **energy** to fracture this **charpy** test piece

A hammer striking the face if the test piece could do this

How can find the **amount of energy** consumed to cause fracture ?

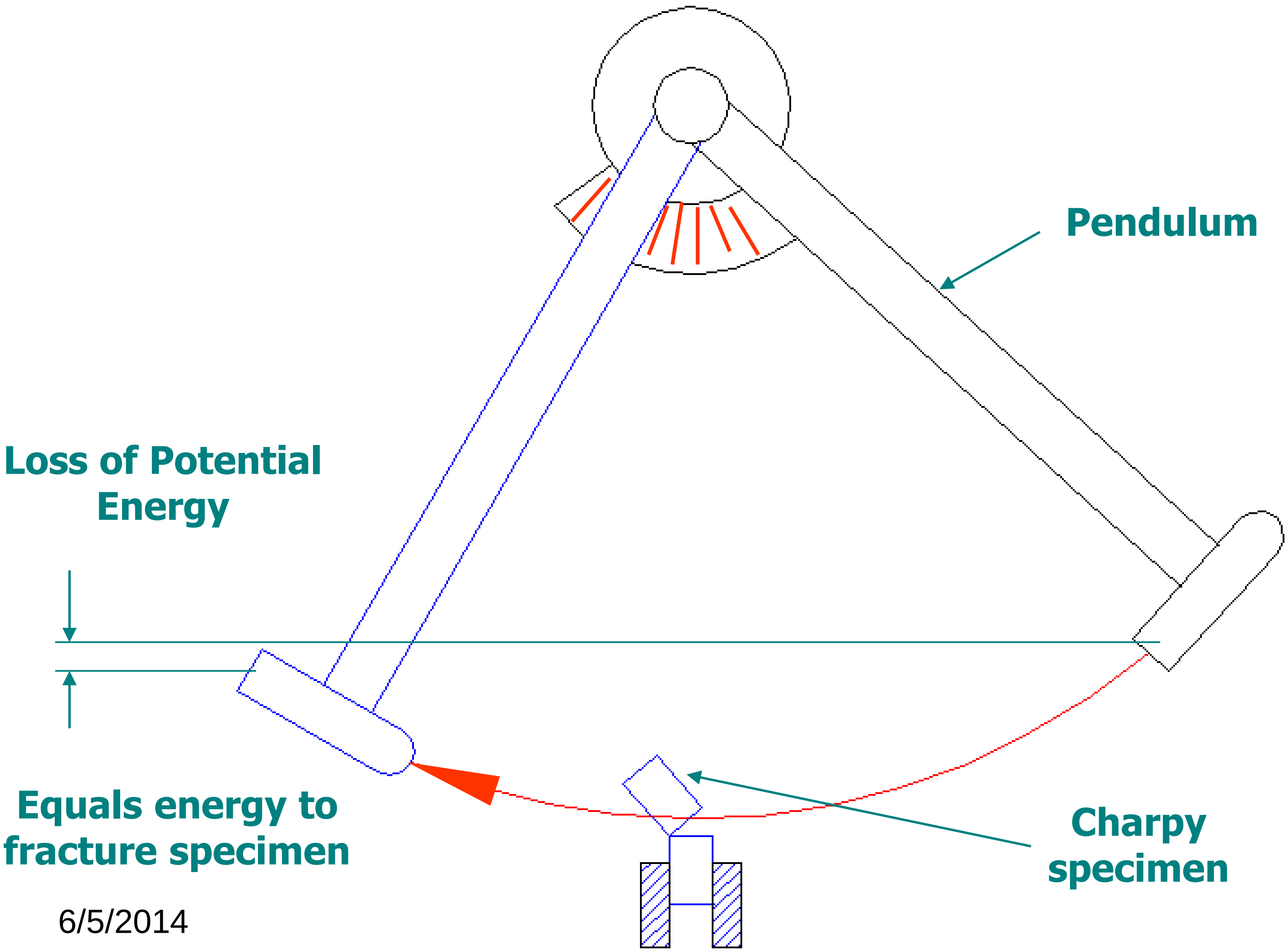
A standard machine is needed to do this



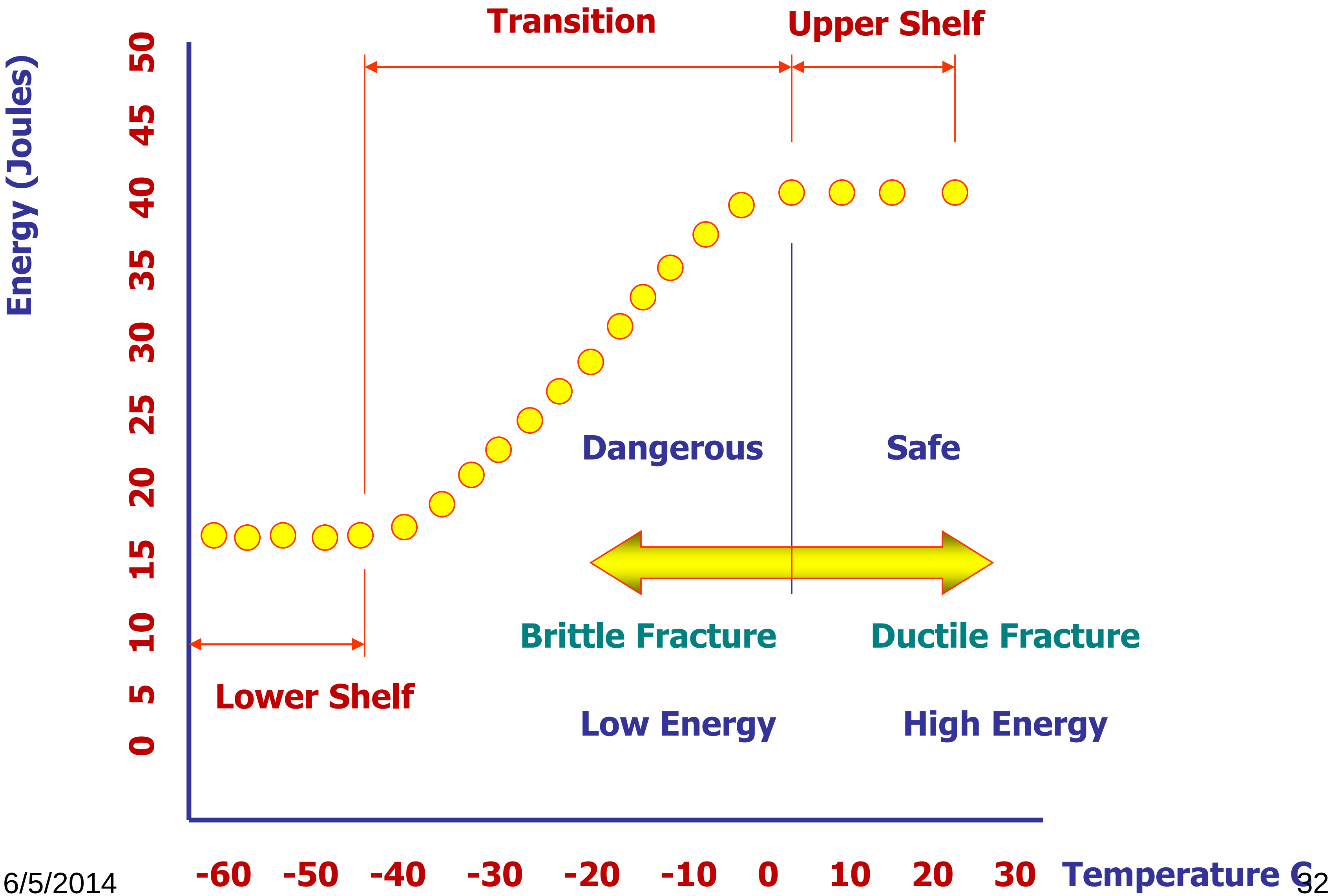


Brittle Fracture – Low temperature failure

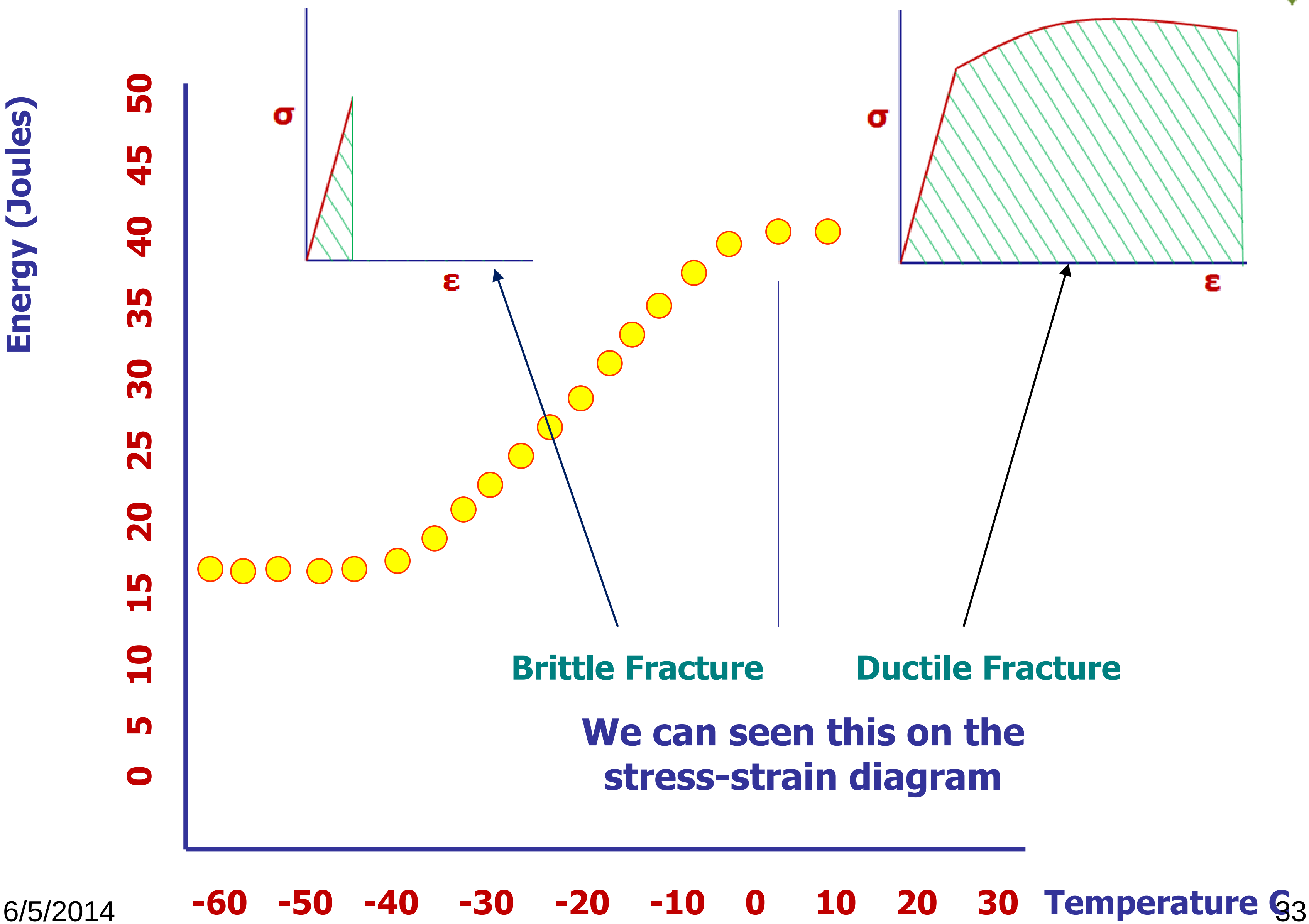
This is done with a pendulum test machine



This is the result of the test



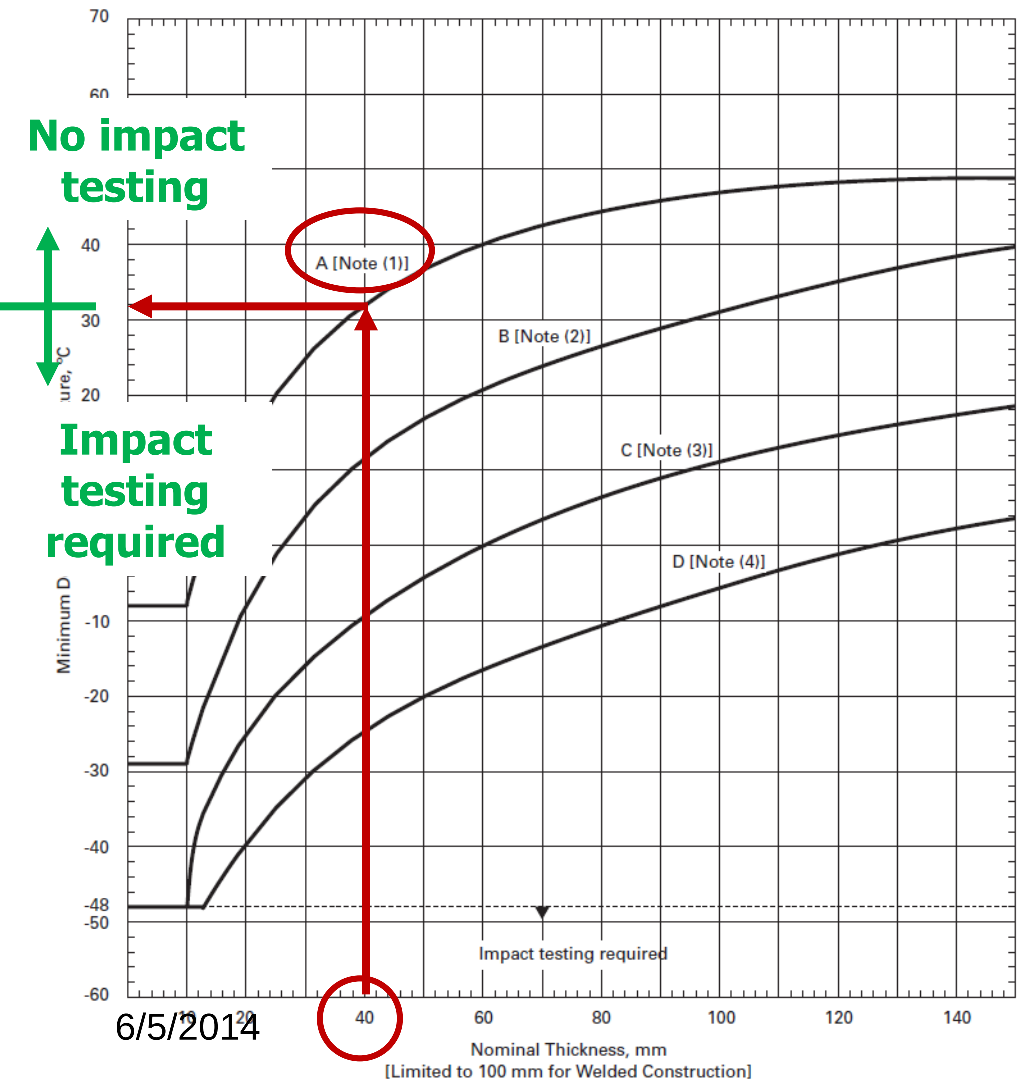
ASME Code uses a slightly different approach to brittle fracture



ASME Code uses a slightly different approach to brittle fracture

What about those groups A, B, C and D ?

FIG. UCS-66M IMPACT TEST EXEMPTION CURVES



Consider a group A material which is 40 mm thick

What is the lowest temperature we can use in service

The Minimum Design Metal Temperature (MDMT) is 32°C

Summary of what we have learned

What about those groups A, B, C and D ?

FIG. UCS-66 IMPACT TEST EXEMPTION CURVES (CONT'D) (10)

NOTES:

NOTES:

(1) Curve A applies to:

(a) all carbon and all low alloy steel plates, structural shapes, and bars not listed in Curves B, C, and D

(b) SA-216 Grades WCB and WCC if normalized and tempered or water-quenched and tempered; SA-2
tempered or water-quenched and tempered.

(2) Curve B applies to:

(a) SA-216 Grade WCA if normalized and tempered or water-quenched and tempered
SA-216 Grades WCB and WCC for thicknesses not exceeding 2 in. (50 mm), if produced to fine grai
tempered
SA-217 Grade WC9 if normalized and tempered
SA-285 Grades A and B
SA-414 Grade A
SA-515 Grade 60
SA-516 Grades 65 and 70 if not normalized
SA-612 if not normalized
SA-662 Grade B if not normalized

(b) all materials listed in 2(a) and 2(c) for Curve B if produced to fine grain practice and normalized, normalized and tempered, or liquid quenched and tempered as permitted in the material specification, and not listed for Curve D below.

(4) Curve D applies to:

There are other criteria, but read them from the code

SA-524 Classes 1 and 2
SA-537 Classes 1, 2, and 3
SA-612 if normalized
SA-662 if normalized
SA-738 Grade A

Summary of what we have learned

With regards to fatigue:

- Fatigue occurs only in the **plastic range**
- The virtual stress is actually based on the strain $\sigma = E.\varepsilon$
- I causes **incremental crack growth** over many cycles
- Failure generally cannot occur during the **first cycle**

With regards to brittle fracture:

- Occurs **below** or (rarely at) the yield value
- It occurs in the first stress cycle – above a threshold pressure
- Fatigue cannot occur with brittle fracture
- It is a **low temperature** phenomenon

Both phenomena depend on the energy to promote fracture