Modern Construction Material
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Module - 3
Lecture - 7
Response of Material to Stress

This is the third part of the lecture seven of modern construction materials we've been looking at response of materials to stress until, now be looked at how the material behavior when subjected to stress goes through stages of elastic plastic. And failure behavior we discussed in the last part brittle fracture which occurs in a sudden manner and without significant deformation, that is why we concerned about brittle failure now in this lecture we look at other cases which can cause brittle failure, which are time-dependent such as fatigue creep and the very fast loading rates in in the lead slides of this lecture, I have included some pictures of the ruins of the city of a Vijayanagara near hampi where we can see stone, that is with stroud almost five hundred years plus of loading for which it was designed for probably and the effect of environmental conditions over these centuries and it as which stood well the trouble inflected by time and loading incidentally vijayanagara was supposedly one of the largest cities in his time in the world I is t s located near the present hampi in karnataka which is in the south of India.

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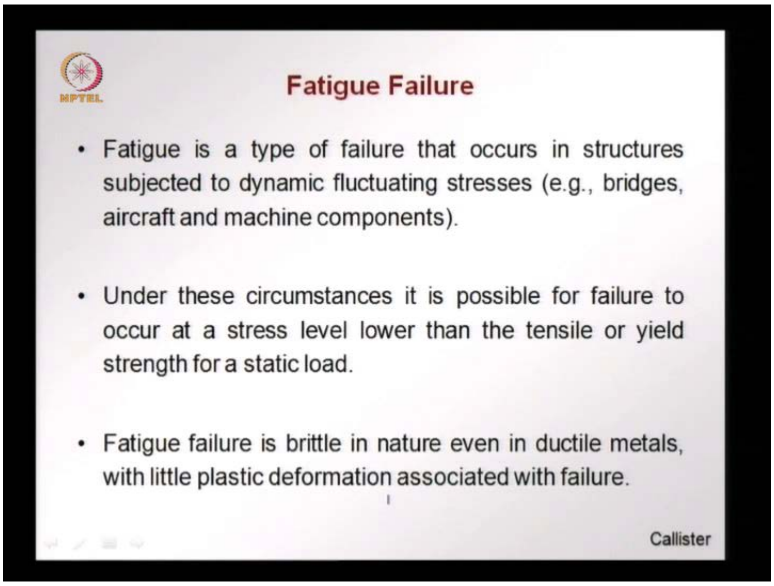

So, let us get back to the response of the materials that we are considering. First let us look at fatigue failure fatigue is a type of failure that occurs in structures and elements which are subjected to dynamic fluctuating stresses that is the stress, that is the stress is going up and down as a function of time this happens in many structures such as in bridges aircraft machine compounds were we have stresses going up, and down during the service life, why it is of concerned to us is that under these circumstances of cycling of stresses the failure in the material occurs at the stress level lower than the strength lower than the tensile or yield strength for a static loads static load meaning that the stress monotonically increase over a short period of time, that is what we used to characterized the tensile or the yield strength of a material what we find.

Now under fatigue loading were we have cycling of stresses over a long period of time failure can occur at stress level that all lower than the strength that we get from static or monotonic loading further of concern is that fatigue failure is brittle in nature even in a ductile material such as in a elemental. We can have fatigue failure occurring with almost no plastic deformation very little plastic deformation before failures occurs which means that fatigue failure is generally brittle.

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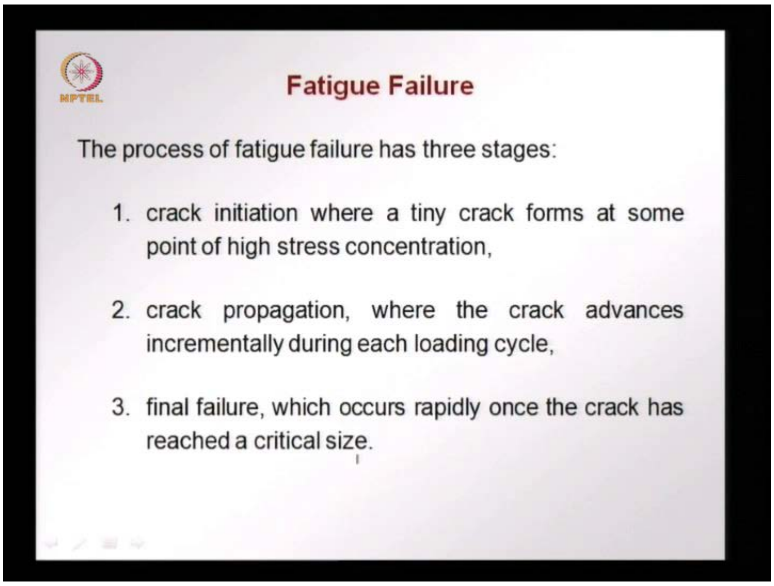

The process of fatigue failure the mechanisms are in three stages the first the crack initiates at a defect a tiny crack at some point of high stress concentration, there are defects in materials they can be tiny cracks forming due to the high stress concentration at these defects the crack initiates there in the first stage as the material now undergo cycling stresses is subjected to cycling stresses this tiny cracks start propagating failure does not occur right then the crack is just propagating in a stable manner with each loading cycle the crack is propagating a little bit more finally, w hen the crack now as the reached a large enough size a critical size the stress is high enough to cause sudden brittle failure.

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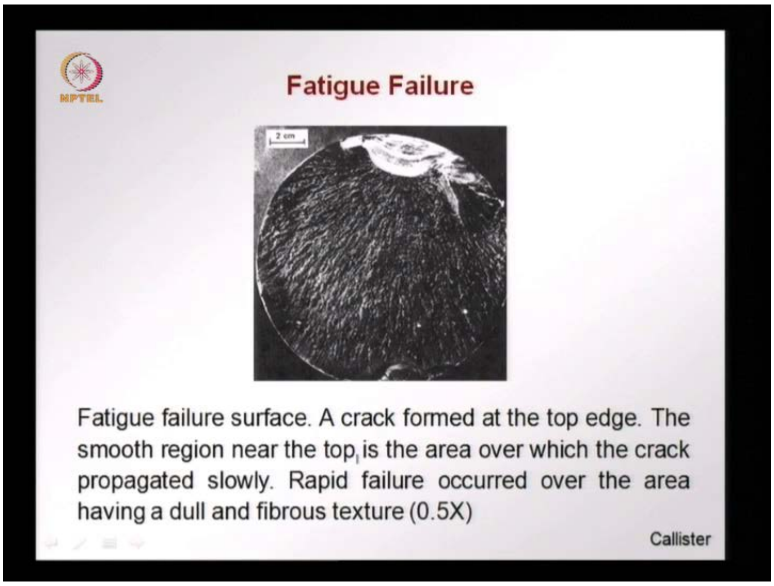

That is the final failure stage. So, crack initiation occurs first followed by the stable propagation and finally, sudden dramatic failures occurs we see that reflected in this photo taken from calister where we have a fatigue failure surface of a bar subjected to fatigue loading. And we find at the top here at the top is where the crack would have initiated the crack would have initiated here probably there was tiny surface defect which cause the highest the stress concentration, and over a period of time the crack propagated in a stable manner giving the shiny surface this light-colored surface at the top then the critical size of the crack was reached, and under probably in the final cycle sudden failure occurs shown by this dull fibrous structure in indicating sudden failure in the metal we had the crack propagating through the section causing sudden failure.

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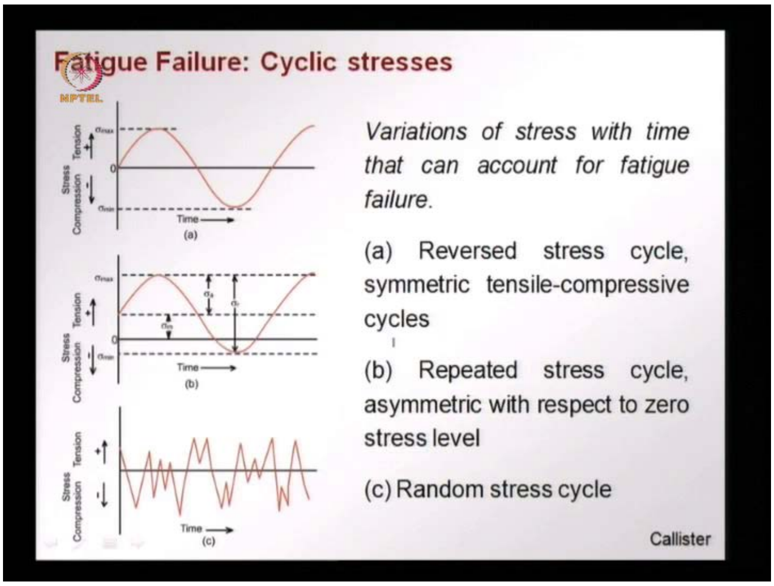

Fatigue failure can occur through a wide range of cycling stresses the stress could be going from compression to tension in a symmetric manner or it could be have more of compression or more of tension as in this diagram we have more of tension little bit of compression and back to tension this cyclically occurring over a period of time or we can have ransoms stress cycles, they need not be as periodic and of the same shape as in the curves a and b, but we could have random cycles of any form occurring through some natural phenomena or some other mechanically induced phenomena.

So, in any type of cycling stress can lead to fatigue failure over a long period of time and you should remember. That when we talk about fatigue failure we are talking about failure occurring at stresses that are lower than this strength and also in the brittle manner. So, this stress under fatigue loading we can be significantly less than the strength that we obtained from a monotonic or a static test.

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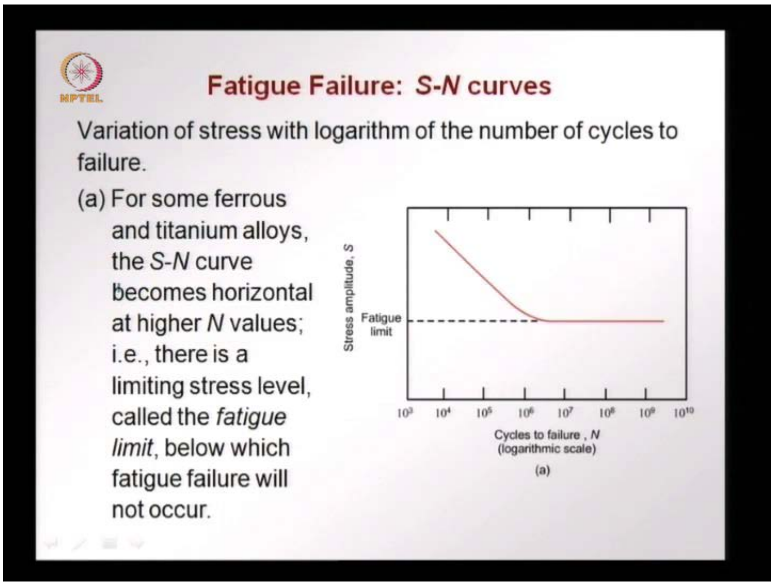

So, how do we take care of this in design what do we do to understand the material and how it will behave under fatigue loading what we do is go to what is called the s n curve a curve showing stress amplitude on the y axis that is the stress over which the cycling is done and on the x scale, we have the logarithmic cycles to failure the log of cycles to failure on the loc scale and we find that we will have a curve such as this this is the curve for cases such as ferrous and titanium alloys, where we have. Now the s n curve dropping that is as the number of cycles increase the stress amplitude that can be endured under fatigue loading drops and becomes flat this flat part corresponds to a stress amplitude called the fatigue limit below this fatigue limit cycling loading does not cause failure in these materials. So, one way of using this in design is to ensure that the stress amplitude in service and the cyclic loading never exceeds the fatigue limit. So, you will have the element enduring many many cycles without failure.

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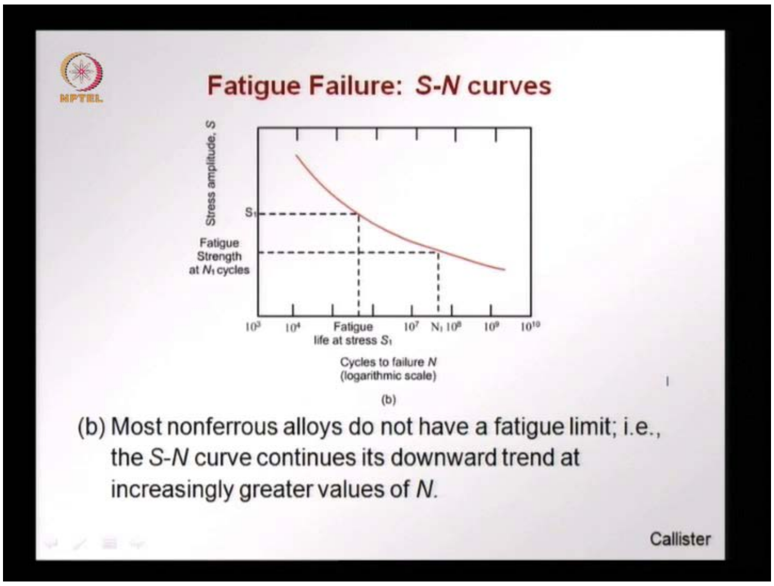

It could happen that in some cases we cannot use a stress that is that load is stress as to be above the fatigue limit or we can have a case were the material does not have a well-defined fatigue limit that the curve does not becomes flat like in the case of non ferrous alloys like we see here in this curve we have the stress amplitude always dropping as a function of the life that it as to endure or the number of cycles to failure. So, in this case what we see is the stress amplitude that can be endeared as a function of the different number of cycles always keeps decreasing.

So, how is this used in design in two ways first if we know the number of cycles that the structure or element as to endure during itself service life its useful life we can go from those number of cycles to this curve back to the y axis and find out what is the stresses corresponding to that number of cycles as long as the stress applied in service is less than this value then the failure life failure during its life is ensure again if I know the number of cycles that I will subject the material two in its life I go from those number of cycles to the s n curve of that particular material go back to the y axis and find out what is the stress amplitude that corresponds to these number of cycles.

So, as long as the stress applied is less than this fatigue strength a t n one cycles there will not be any failure due to fatigue in this situation on the other hand if I know what is stress that will be applied and that cannot be changed in design I can also find out what would be the fatigue life or the number of cycles that the material can endure. So, here I start of with the stress amplitudes one I go to this curve drop-down and then it will tell me what would be the maximum number of cycles that can be endure under this stress amplitude or what is the fatigue life at this stress one.

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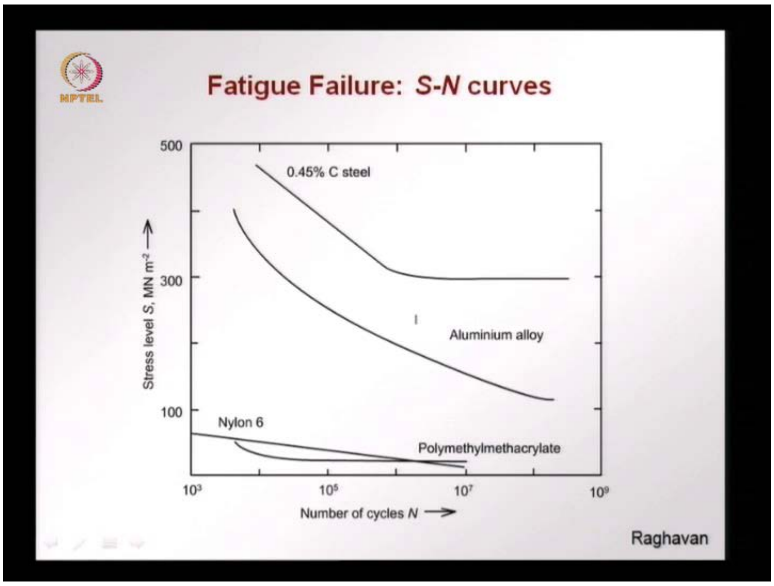

So, these are two ways that we s n curve can be induced in design or prediction of the life under fatigue w e see here in this plot the s n curves for different materials at the top we have point four five percent carbon steel with the s n curve having a flat part that is this is the fatigue life this is the fatigue stress or the fatigue limit this is the fatigue limit as long as we are below this stress level this point four five percents carbon steel will not fail under fatigue whereas, in the case of aluminum alloy we find that a curve the curve has the shape which is always going down the curve is always down.

So; that means, we have to define for each number of cycles that we design for we have to find out what is the stress level and ensure that that stress level is not exceeded. So, that failure does not occur within those number of cycles we also find that polymers such as nylon and polymethylmethacrylate can be characterized by s n curves in the case of nylon this is a particular nylon six we have an s n curve that is almost linearly dropping in the case of polymethylmethacrylate we have a curve with fatigue limit like what we saw in the point four five percent carbon steel.

So, different materials can be characterized in terms of s n curves and these can be used in design to limit the stress that is applied on the material or alternatively can be used to determine the fatigue life or the number of cycles that term arterial can be endured under a certain fluctuating stress level.

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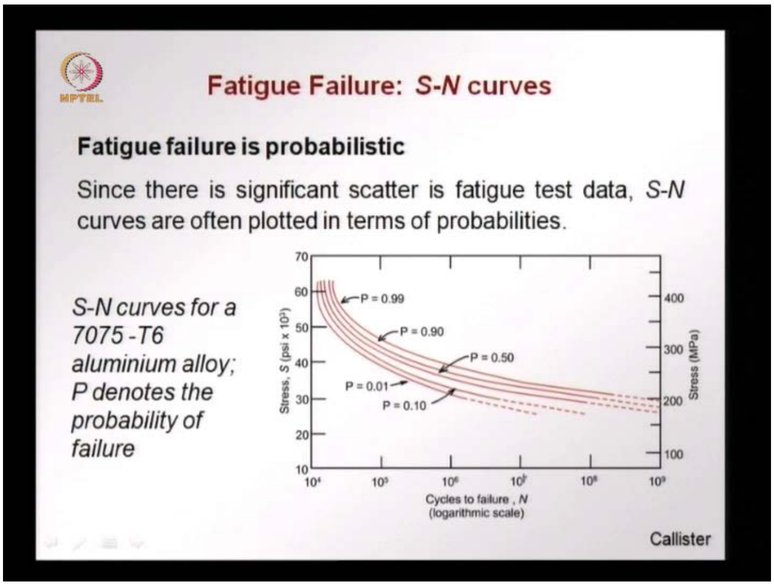

Another important aspect is that fatigue failure is probabilistic we saw that fatigue failure is initiated by defects and these defects need not always occur in the same place and of the same dimensional in an element the probability that a defect is large is not zero no hundred there is a certain probability. So, this probability determines how the failure will occur when we look at fatigue test data we have a lot of scatter and this is because the defects that originate fatigue failure vary in location and been size therefore, s n curves are offered plotted in terms of probabilities like we see here from calister the s n curves for a seventy seventy five e six aluminum alloy and the p value along given along with each curve is the probability of failure. So, if you want to ensure that the probability is very low say ten percent at a number of cycle then you would take this curve the curve second from the bottom this corresponds to a probability of failure 0.1 or ten percent.

So, in this case this s n curve will give you probability that only ten percent can exide this value when we use it in design point nine nine will be the upper limit of the s n curve what we find is the as the probability becomes smaller the lower probability that we can assume in design means that we have to go for an s n curve, that is lower that is the stress can applied is over when the probability of failure that we can accept is lower.

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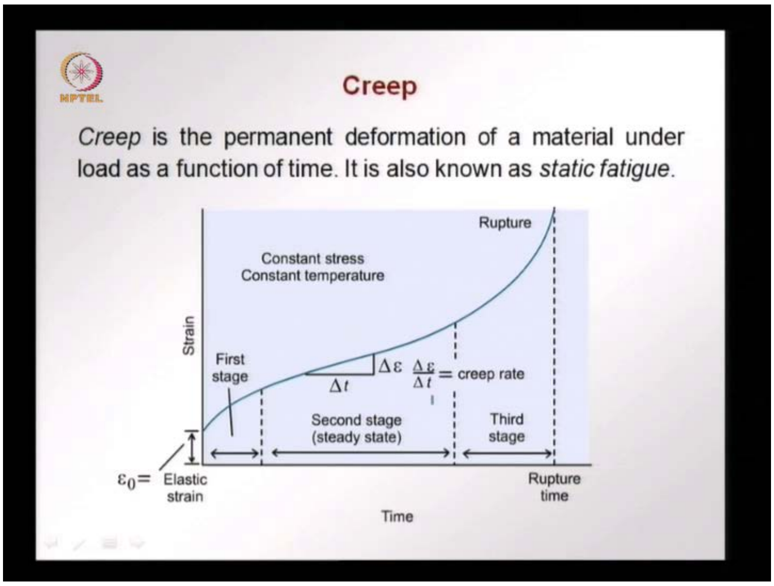

Now, we move on to another time dependence failure that is that can because by creep in fatigue failure what we saw is that the stress is cycle over a period of time in creep we do not have a cycling of stress, but the stresses constant over a long period of time that is the reason why this is also called static fatigue whereas, the previous case that we discussed until now is called cycling physic creep is the permanent deformation of a material under load as a function of time that is sustain the load and we see that the strain will continue to increase beyond just the elastic or the instantaneous part the curve below gives the different stages of creep this is under a constant stress and a constant temperature will see later on that creep can be driven by temperature also the most curves for defining the creep behavior have to be given under a certain temperature.

So, when we look at the strain change as a function of time under a constant applied stress and constant temperature we find that initially we will have elastic path has announced the load is applied as a function of the stiffness there will be an elastic strain then though we are maintaining the stress the strain continues to increase with time here in the first stage we will have slow increased of strain here the increases almost with a constant slope and then we have very sudden large increase of strain leading to finally, ruptures or failure this is called the first stage where there is a gradually increase this is the second stage where you have a steady-state increasing the scope is almost constant then we have a third stage whether the slope is increasing very, very rapidly to rupture in the third stage.

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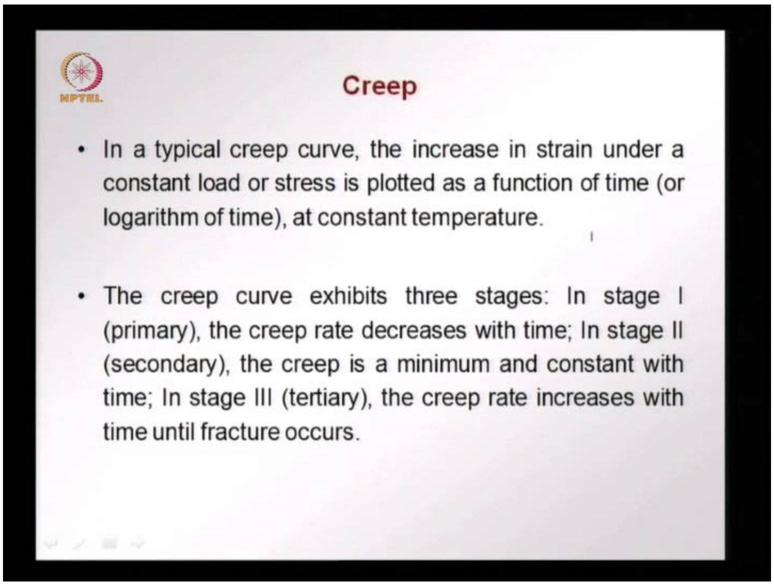

So, what we saw is that in a typical creep curve the increase in strain under a constant load or stress is plotted as the function of time or logger them of time at constant temperature we saw three stages that can be identified in the first stage for the primary stage the creep rate decreases with time the slope decreases with time in stage ii which is a secondary stage which is the longest stage creep is minimum and constantly increases with time the slope is almost constant, and in the third stage called the tertiary stage which is the final stage of creep the creep rate increases the slope increases rapidly with time and until we have sudden failure or fractured occur.

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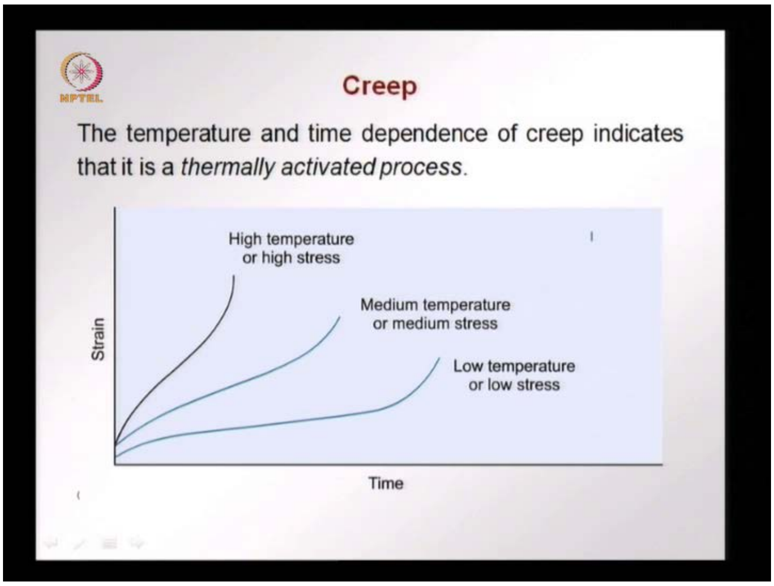

We said a few minutes back that temperature drives creep and we see here the difference restrained stress tine curves for different temperatures the lower curve corresponds to lower stress or a lower temperature the next one if it is the same stress could be at a higher temperature same medium temperature and the third one if the stresses the same could be a higher temperature. So, under the same stress what we find is the strain will increase more rapidly when the temperature increases failure will also now occur in a shorter period of time under creep by the temperature is high. So, we can say that temperature somehow accelerates creep and therefore, we say that creep is a thermally activated process it is driven by temperature high year the temperature more will be the creep has if more load is being applied or more stresses being applied.

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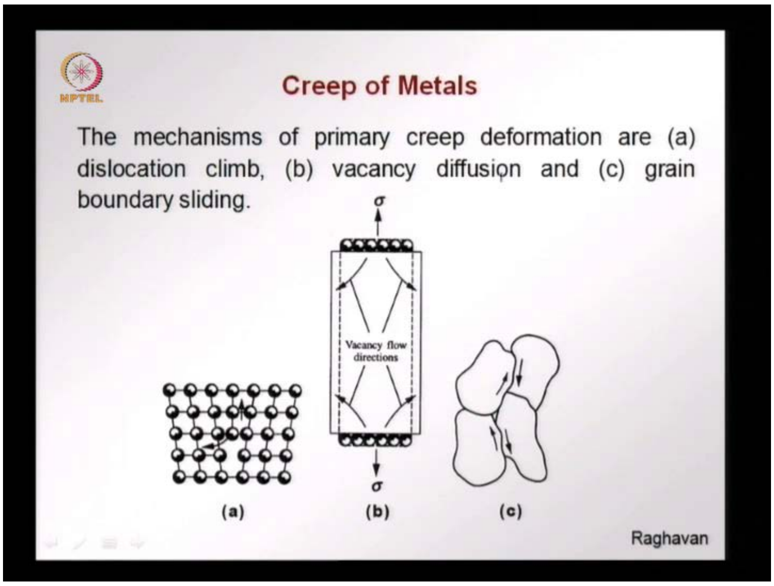

We can identify some mechanisms of creep say metals there are three mechanisms of primary creep one is dislocation climb. So, we have here the dislocation that we have discussed in line defects and later instead of dislocation moving this way along the street plain when we are applying tension see we are applying tension this way will find that the dislocation climbs the dislocation moves up vertically that causes a decrease in the section and elongation this is one of the mechanisms of creeping in metal the other mechanism is that the vacancies which are inside that is again, we are talking about defects in this case there are line defects then vaccines are point effects we have mixing atoms or particles within the material has no stresses is applied and kept constant these vacancies start moving outward the wreckage start flowing outward again decreasing the section the vacancy or the gap now is on the outside and again we have creeping other the third mechanism means that the grain boundaries start sliding against each other remember again that we looked at grain boundaries been areas of defects is called a surface defects. So, the bonding between the atoms is not very strong in the grain boundaries. So, when we have a large sustain stress kept for long time these grain starts sliding against each other are aligning themselves and these give rise to an increased in elongation along.

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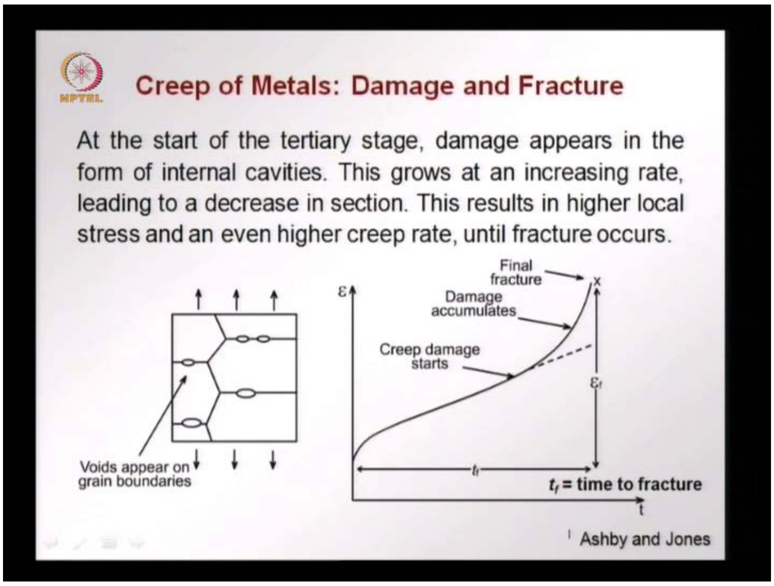

This direction giving rise to creep strain in the tertiary stage what happens in matters is that cavities or wides start forming along grain boundaries we saw in the previous stage that the grain boundary start to slip and this give rise to some strain and in the treasury we start having wides or cavities forming along the grain boundaries this is form of damage that is occurring due to creep and you'll see that as the grain boundary now has a wide more stress has to be taken by the rest of the grain boundary to transfer the stress coming on to the this highest stress increases creep and increases the possibility that the material can fail more easily the cavitation is also increases at an increasing rate and this further decreases the set the local stresses increase and the creep rate become even higher.

So, what we have is now deviations from the secondary stage instead of secondary stage is continuing for a longer period of time here now damages started to occur on that grain boundaries there is accumulation of damage finally, the damage or the wides are…

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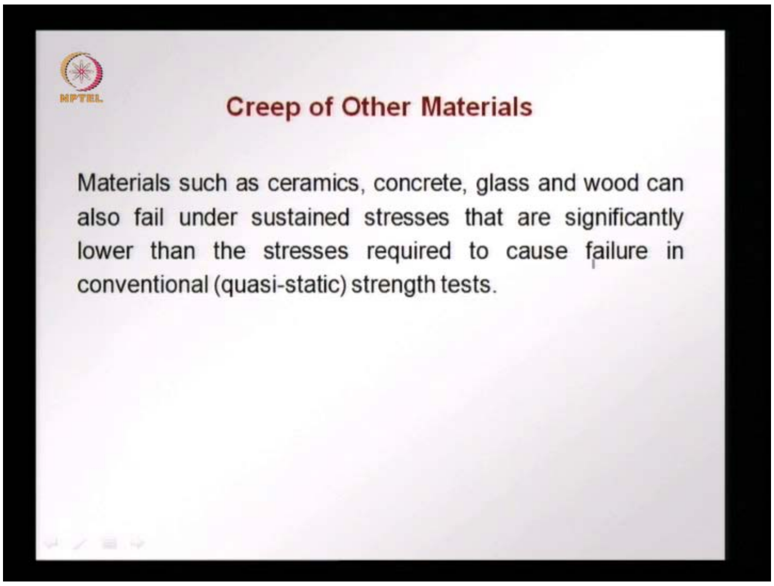

So, high that failure occurs and this give rise to the treasury phase or the final stage of creep response, materials other than metals also can undergo creep materials such as ceramics concrete glass wood can also fail under sustain stress at value significantly lower than that required to cause failure in conventional static quasi static strength test quasi static means is not very very slow, but in the range of test are done in the laboratory.

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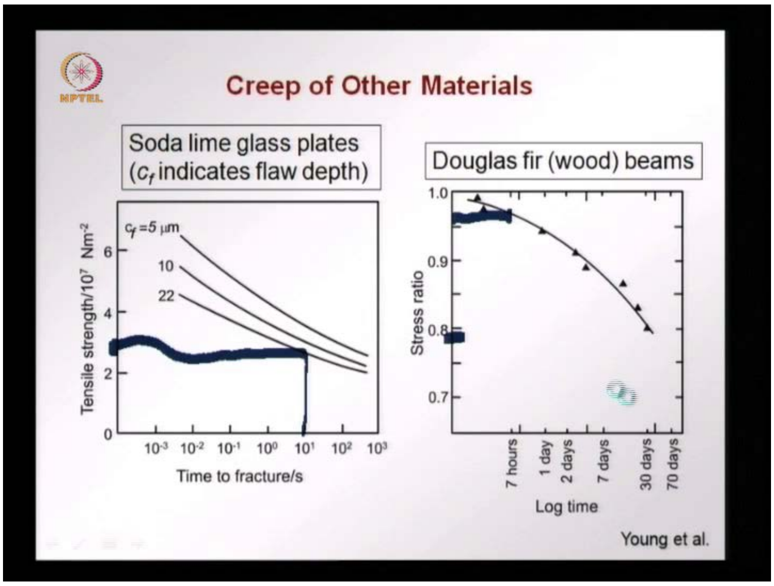

We look at a couple of examples here on the left we have soda lime glass plates that are subjected to tension these glass plates have different types of c f in the plot denotes the plot depth ranging from five microns about twenty microns and the for each of this flow depth we have a curve relating the stress at failure to the time it took to cause failure the stress at failure is given as in absolute terms as a tensile strength. So, how we look at this graph is that if we wanted the glass plate to survive for a certain amount of time the stress applied should not increase should not be more than this. So, if you go from here and go back we find that this would be the stress that, we should not be exceeded and this is now is the functional of the flaw depth what we see is larger the depth lower is the stress that the material can take for a longer period of time.

So, creep is also dependent on the surface defects in the case of a brittle failure here for forward we have a similar graph, but instead of the absolute value of stress we have a stress ratio one been the strength at static monotonic loading and the stress at failure is now given normalized to that value has a stress ratio. So, again we have the case that wood now this this is douglas fir wood means failing at different times when the stress that is kept sustain varies. So, at seven hours we have the material failing at a stress of say point nine five that of the strength, but if we want the to know the stress ratio at failure when the load is to be maintained at least for thirty days we find that it is not more than about point eight in practice we want we would want this stress to be even lower.

So, that the life of the beam is much larger we want the life of a structures to the much more than a few days. So, what we do is we would extrapolate this curve and find out what the stress value should be for many many years probably less than point seven or point six. So, as long as the stresses is kept less than that we will not have failure due to creep.

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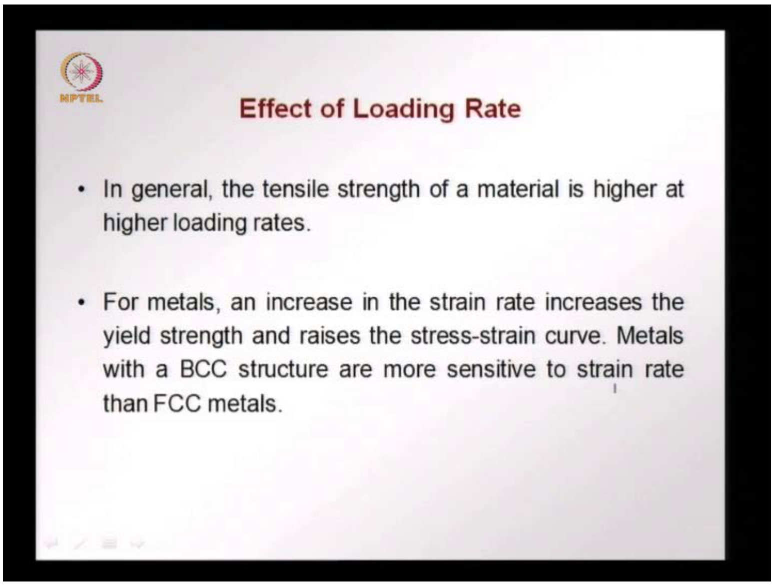

Thirdly we look at how failure is affected by the loading rate first we looked in this lecture at fatigue loading were we recycle the load next we looked that a sustained load for creep now what happens when the loading rate changes we find in general that the tensile strength of a material is higher at a higher loading rate that is when we load very fast the tensile strength actually goes upfor metals this is reflected as an increase in the yield strength with an increase in the strain rate and it also raises the stress strain curve it pushes the stress strain curve up this is also is related to the microstructure we find that metals with the b c c structure are more sensitive to strain rate then f c c metals that is a material a metal with b c c structure will change is tensile strength more has the strain rate is changed.

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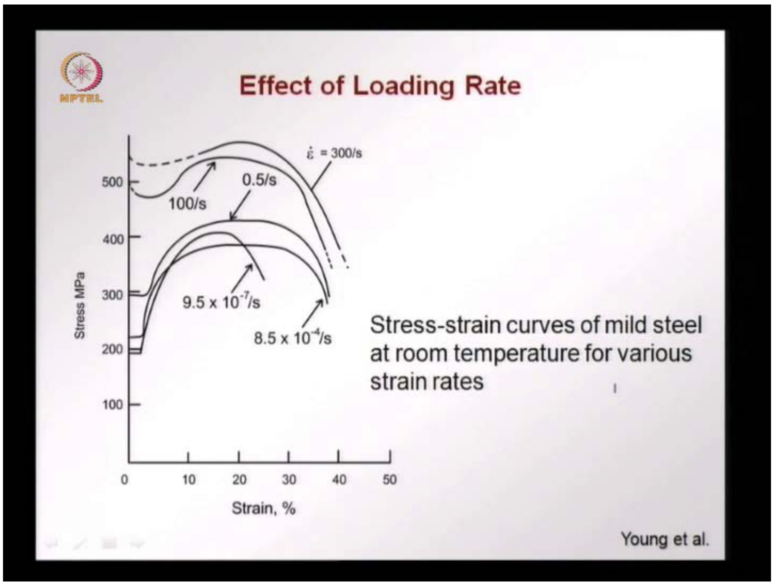

These occurs from young at all for mild steel at room temperature and difference stable rates the values that you see here are the strain rates going from three hundred per second down to eight point five if time ten to minus four seconds and be find that has the strain rate increases. So, strain rate is increasing that is we are loading faster and faster and we find that the stress strain curve is now pushed up the yield strength and the week strength are pushed up. So, there is an effect of time in many waves on failure going from failure at lower stresses compared to monotonic value in the case of fatigue and possibly creep and in the case of loading rates we changing we saw that when the strain rate is fast we have and increase in the tensile strength

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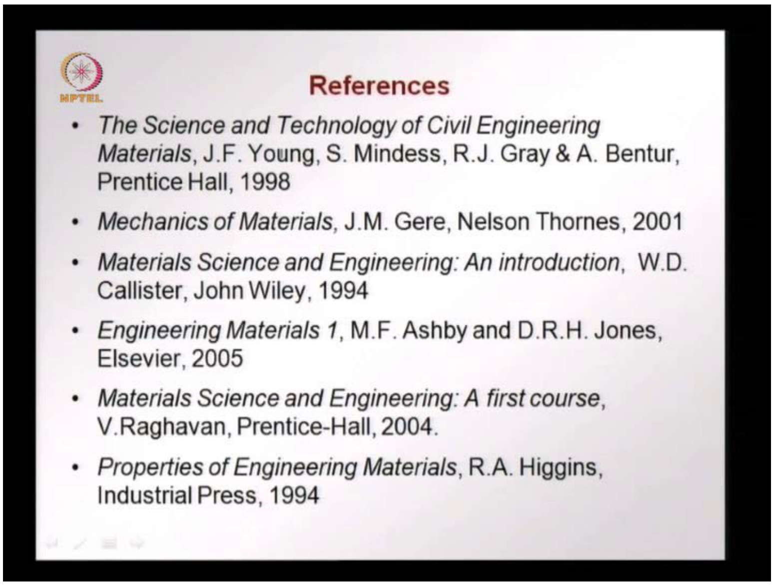

So, these are the references as in different lectures there is a lot of literatures on mechanical properties of civil engineering materials and in all the libraries I am sure there are enough materials materials that you can refer to you have to look to understand the fundamental nature you have to look at textbooks that cover material science aspects and material engineering aspects such as what I have listed here the bottom three books are basically looking at the material science aspects calister looks more at the fundamental nature, and then we have the book of young at all looking more in this at civil engineering materials.

I finish this lecture on a lighter note this is cartoon that I coupler days back this is a carton of tiger asking why rubber bands that he has with them do not stretch, but break and his friend says that they have lost their elasticity. So, poor tiger is now emptying the box and trying to find their elasticity to put it back andhe does not seem to find it and they are perplexed. So, they do not know what as happening to the elasticity, but I hope that you have gotten some idea of what happens in the microstructure by material stop being elastic and gone to plastic ductile failure and can even have a brittle failure sometimes.

So, that is the end of this relatively long lecture on how materials responded to stress we looked at transition from elastic through ductile yielding shearing type failure to final rupture and brittle failure we also looked at cases where failure occurs at stress slower or higher than the normal strength value is that we obtained in a lab fatigue and creep can cause failure at stresses lower than the strength and we also saw that of loading rates which are very fast can increase the tensile strength the material can endure higher strength than in the monotonic test in the next lecture we look at failure theories how we can anticipate failure as a function of this stress state in a material, and use that appropriately.

Thank you very much.