Advanced Marine Structure
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Lecture - 16
Plastic design – I

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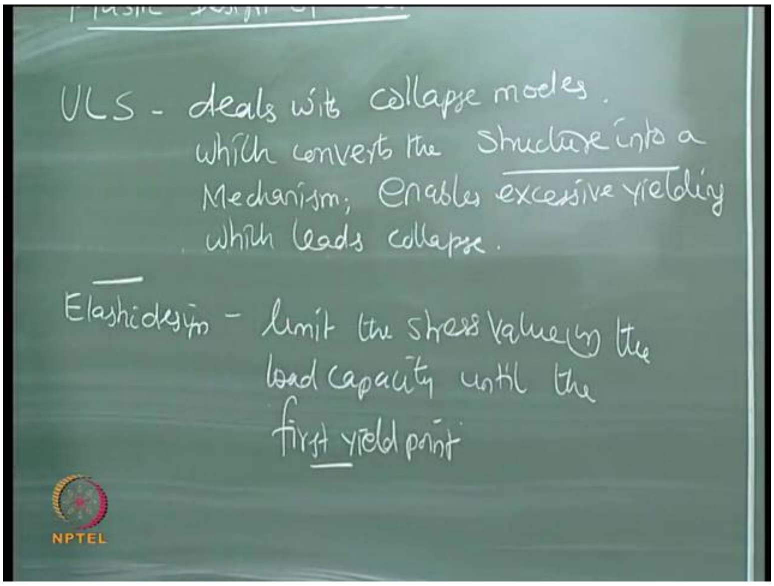

So, in advance marine structures course in first module. We are talking about the ultimate limit state on ultimate load design methodology. If we recollect we already said that ultimate limit state deals with collapse modes which converts the given structural system into what we call as a mechanism that is it enables excessive yielding which leads to collapse and that process is what we call as a mechanism formation. So, it is very clear that ultimate load design deals with or enables excessive yielding. Now, this is the catch where which makes ultimate load design different from elastic design. In elastic design it limits the stress value or the load capacity until the first yield point.

It means the conventional elastic design process does not promote the load carrying capacity of the section beyond the first yield point. Now, let us see what is the difficulty or what is the main lacuna in this design mechanism, and therefore we will parallelly shift our design principles from this to ultimate load design moving on to what we call the concept of excessive yielding or ultimately what the literature refers as plastic design of sections.

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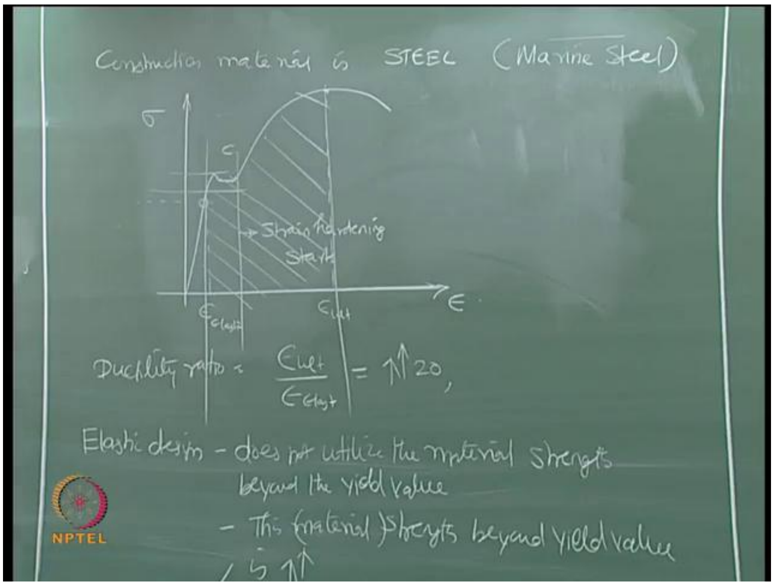

Let us say the common construction material for marine structures is of course, we all known steel, but steel has different grades. To be very specific I should say we should recommend what we call marine steel, the specification, the chemical composition and the structural characteristics of this kind of steel is available in other courses and standard literature. So, we are talking about a special quality or grade of steel which we call as marine steel. We all know the conventional stress strain curve of this kind of steel looks like this. It has got a very distinct yield plateau where we call the lower yield point and the upper yield point and if you say this is the point C, I should say that beyond point C the strain hardening starts.

Elastic design actually limits your stress value somewhere here which is much below the first yield point. So, if I call this as my elastic strain and if I call this as my ultimate strain obviously ductility ratio defines the proposition between ultimate strain to elastic strain. If we look at a typical ductility ratio of a marine steel this value it can be as high as even 20. What does it mean is steel has got very good capacity beyond the first yield which is not utilized in the elastic design mechanism. So, we can simply say conventionally the elastic design principles does not utilize the material strength beyond the yield value.

What is very critical about it? The material strength, this strength beyond yield value is very high. Literature refers this as reserve strength. When you are planning to use this reserve strength in your design, there is an important gain at what you get and there is an important loss at what you also encounter. Let us first look at the positive aspect of this design concept that is a design concept which utilizes or which proposes to utilize the reserve strength of the material which is phenomenally high compared to this area, it is phenomenally high.

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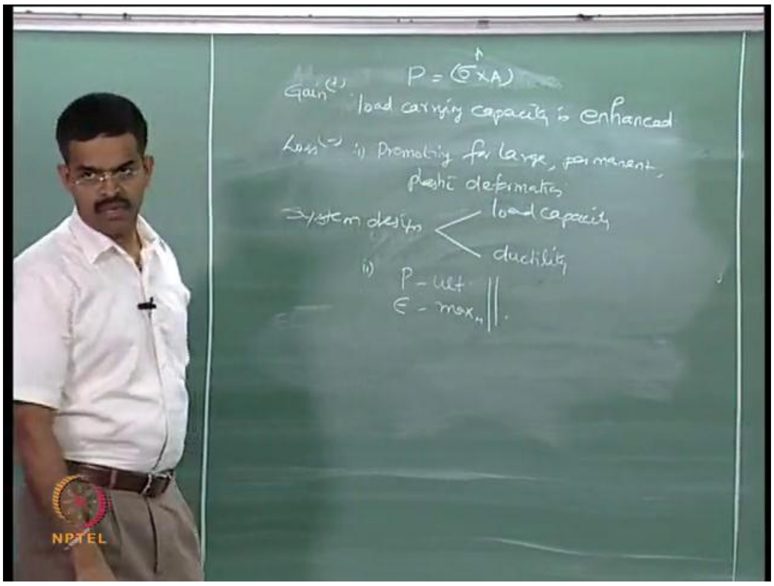

Now the gain what you get is the load carrying capacity as we all know load carrying capacity is simply equal to stress by area if it is an axial loading, if it is bending then it is sigma y into z and all. Of course, it is not as simple as this equation when you go beyond the elastic region, but let us say understand that it is a proportion of the stress and the cross section area or section modulus depending upon what kind of loading you are looking at. So, the gain what you get here is the load carrying capacity is increased from this level to this level, that is the gain what you get. So, the load carrying capacity is I should say enhanced.

What is the loss you get? The most important loss what you will encounter in utilizing the reserve strength of the material beyond first yield point is that you are promoting for large permanent plastic deformation. Beyond this point the deformation set in the material will become permanent, it cannot be regained. It means you are instituting a permanent deformation in the system, it means a system design should not only cater for load capacity, but also should check for the ductility.

Let us say for example, any brittle material which does not have a very good ratio of ductility then obviously this concept of design which you are proposing now to extend beyond a elastic limit or to extend beyond the first yield value cannot be used because it implicitly demand a ductility capacity in the material which is utilized and I will call that as a loss because no structure would like to have a permanent deformation on increment of any load capacity. The most important loss as a structural engineering point of view is that when the load reaches ultimate, the strain reaches maximum. So, the failure will be by both the modes.

One, load is exceeded, material cannot take any more load because that is an ultimate load beyond which cracking starts and failure will start accelerated. And the permanent deformation is maximum, it is maximum beyond which also you can have, but that is instantaneous, it is more or less a cracking mode, not a failure mode. Remember up to this point of strain the material does not fail, is that clear? Beyond this point of strain material is on the failure mode. We do not want any failure anyway, but ultimately when these two values are reached they will reach hypothetically simultaneously.

So, the failure if at all will be initiated it gives a feeling to a designer that the failure will be catastrophic and instantaneous that fail, that feeling is there for a designer who activates a design mechanism which wants to utilize the reserve strength of the material. Now, let us look at the justification why I must not consider the first yield point as my terminal value of load capacity. Let us first argue this. We all convince that the load capacity should not terminate at the first yield point because beyond this point a typical classical marine steel has got very enormous reserve strength.

I want to utilize the strength, but there is a very vital reason why especially in particularly for marine steel I cannot stop my load carrying capacity as an index at the first yield value apart from convincing ourselves that I want to use the strain capacity or the reserve strength. Generally, in marine steel the first yield value occurs not because the stress as reached the sigma y.

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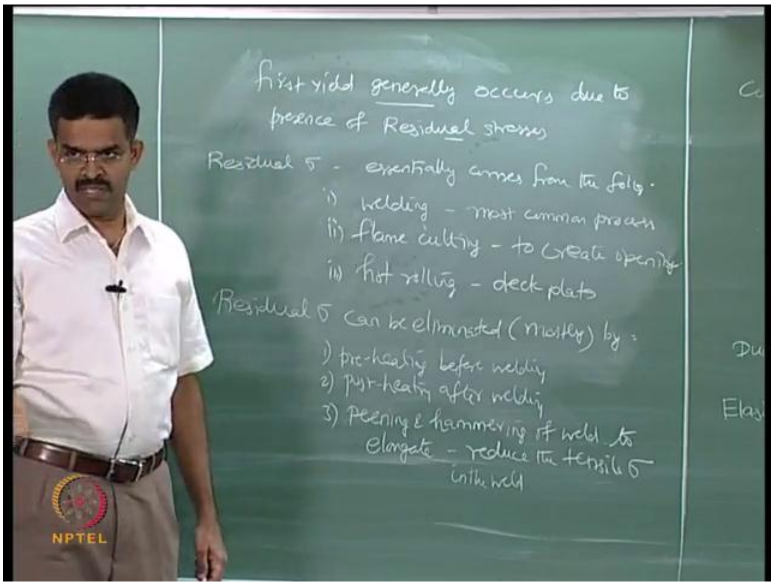

The first yield generally occurs, I make my statement generally occurs due to presence of what we call residual stresses, the presence of residual stresses in marine construction or marine structures triggers off the formation of the first yield point. Now, let us quickly throw light on what is residual stresses, how do they come from? Residual stresses essentially comes from the following. 1 2 and 3, because of the welding process which is a very most common process in marine structures, I mean you cannot construct a marine structure without welding, the moment you do welding it will initiate or it will start accelerating formation of residual stresses.

The second process which is very common in marine structures is flame cutting which is also responsible for formation of residual stresses. Flame cutting is generally done to create openings which you require for provision of piping, for provision of moon pool, provision of location of risers etcetera. So, cutting cannot be avoided. So, flame cutting is generally done because the thickness of the section is so high you cannot do any other formation of cutting, you got to go for mechanical cutting which we call as a flame cutting. The moment this process is done it will initiate residual stresses in the system.

The third could be hot rolling. Generally done for the deck plates, deck plates are of very large in l and b and phenomenally thick as well. We are talking about plates of 30, 50, 75 mm thick, very thick plates. So, they cannot be simply play manufactured without a hot rolling process. This is a manufacturing methodology. This manufacturing methodology will set residual stresses in the material. Once residual stresses are present in the material it will always initiate the first yield point which is not actually because of loading. Now, interestingly sir can we eliminate this? I do not want residual stresses at all because they are giving me a proxy value of an yield which I do not want to have in my material. I am talking about material not the structure.

Residual stresses can be eliminated not completely, but I should say mostly mostly can be eliminated by pre heating before welding. If you pre heat the member before welding you can reduce the residual stresses, post heating after welding, peening and hammering of welds to elongate, you must have seen in construction sites after the welding is done people hit the weld surface to elongate it. This will reduce the tensile stresses. Now, one may ask a question, sir residual stresses are formed in the material because of these construction or manufacturing processes, they can be avoided by following the procedure which can mostly reduce the presence of residual stresses.

Now, ultimately apart from initiating a first yield in the material what damage residual stresses can cause to the material and to the structure is not only because I want to avoid a proxy formation of the first yield I want to get rid of residual stresses. It has got major demerits. Residual stresses result in many unwanted behavior in the structure.

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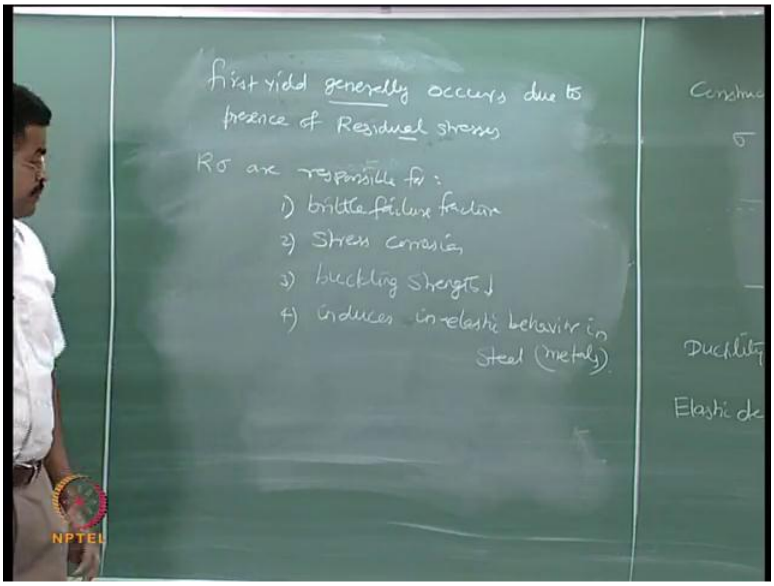

So, residual stresses are responsible for brittle failure fracture, stress corrosion, buckling strength reduction and induces inelastic behavior, please understand this in metals. I am worried about steel, but it is a common phenomenon in all metals. It induces inelastic behavior, what does it mean is this point is very important for us as designers point of view. The moment I have presence of residual stresses in my material because of the reasons what we saw in few minutes back the material does not propagate with an elastic behavior anymore. So, the presence of residual stresses otherwise result in excessive deformation which is a plastic or inelastic deformation.

When the residual stresses cannot be avoided, can only be reduced why not take an advantage of that so called inelastic behavior in a design. It is because of this reason why people have started shifting from elastic design to ultimate limit state design in steel structures for marine structural design. Residual stresses cannot be avoided, they initiate inelastic behavior. Why cannot I use this as an advantage in made design that is what I am looking at a justification from a plastic design because plastic design accounts for the reserve strength which is on inelastic zone. So, people said let me explore the possibility of design beyond so called elastic limit, is that clear? So, let us remove this.

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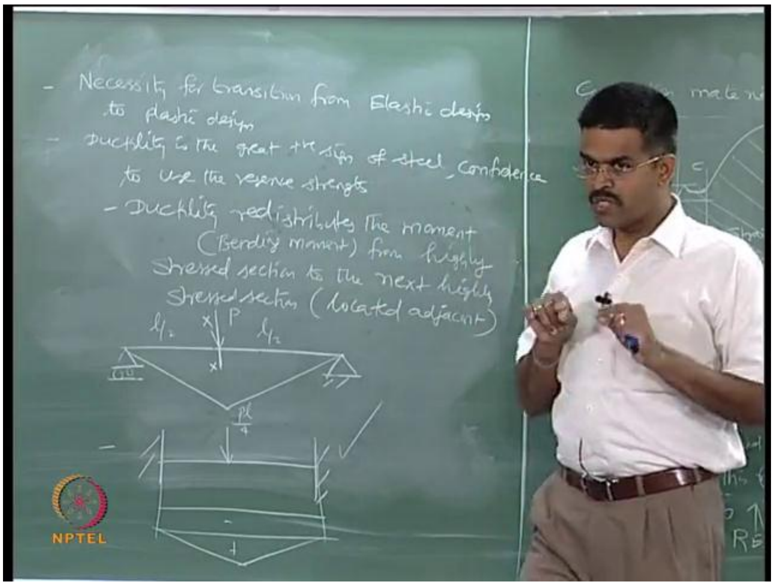

So, when designer started to understanding a transition, the necessity for transition from elastic design to I should say plastic design. Plastic design is nothing but a design related to permanent deformation, I call that permanent deformation single word plastic. Is that clear? It is nothing to do with the name of the material, I am using wooden design, concrete design, plastic design, plastic is not a material it is a phenomenon which causes excessive deformation which we call as a mechanism, later we will introduce this terminology later. So, people have understood the necessity for transition from elastic to plastic design.

Now, what is the great insight designer saw when you transit from elastic to plastic area, the great advantage what designer saw is ductility. Ductility is the great positive sign of steel which gives confidence to use the reserve strength. What does that mean? It means that if I am stretching the material, if I am loading the member beyond the first yield value it is the guarantee that the material will not fail until it reaches a specific strain value which is nothing but a multiplier of elastic strain value that multiplies what you have called as a ductility ratio. That guarantee was seen in the material behavior as far as steel is concerned by the designers that was the positive sign which designer felt yes, I can stress the material beyond elastic limit or beyond my first yield value.

Structurally, what actually this ductility ratio does to the system? Ductility redistributes the moment, if you want to be very specific you can write bending moment also, but I am saying moment from highly stressed section to the next highly stressed section located adjacent. What does it mean? In a given structural system for a given set of loading acting on a system you will generally get the first highly stressed section. For example, let us take a simply supported beam I am giving very simple example where as you can easily follow, subjected to a central concentrated load maybe this value is P and there is l by 2 and l by 2.

The bending moment diagram as we all know is this, the elastic bending moment diagram. So, I should say in a beam this section X X is the maximum stressed section because it is at this section the bending moment is maximum which is P l by 4. Since the section X X the bending moment is maximum in comparison to other adjacent sections this section is highly stressed. If this material is steel which has got a very good ductility ratio then the worst strength in terms of ductility will enable a process of redistributing this moment from the highly stressed section to the next highly stressed section which is located adjacent to it.

Now, interestingly you will trying to find out what would be the next highly stressed section as far as this beam is concerned. There is a very important pre condition that this design process should be applied and can be applied only to structures which are statically indeterminate. This is a determined structure; the degree of indeterminacy for a simply supported beam is nil 0. So, I can look for a statically indeterminate structure which can be a fixed beam subjected to the same central concentrated load.

Now, the elastic bending moment, free bending moment diagram of this could be P l by 4 on the other hand even the supports will also have moments which will have some value which is negative. This is negative and this is positive. Now, I have got sections which are highly stressed, which are lower stressed etcetera. So, when the member of the structure is statically indeterminate then you get successive sections which are on the sequence of getting highly stressed. So, the moment or the bending moment will get redistributed from the highly stressed section to the next successive highly stressed section in the member, but the structure should remain statically indeterminate to use this facility.

We will talk about this slightly later in plastic design in detail. So, here is only a hint. So, it is that capacity of redistribution of moments which enables the designer to think of using the plastic design principle for a structural system which has a material with large reserve strength and for sure the material will not fail until the strain reaches the ultimate value. This has been seen from the material property, you stretch the material keep on loading the material, the material does not seem to fail until P reaches P ultimate or the corresponding strain of epsilon ultimate beyond which of course, the material will fail.

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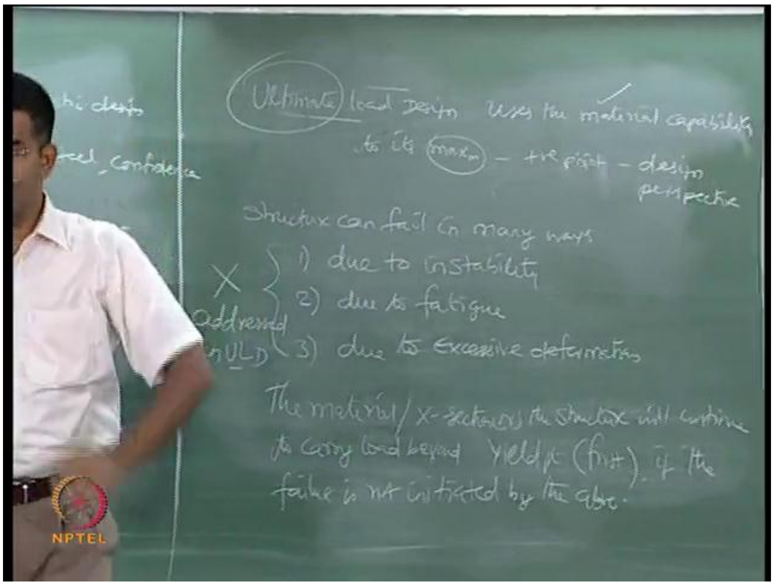

Having said this we can make a very important comment saying that ultimate load design uses the material capability to its maximum. It is because of this adjective in mind designers gave this name as ultimate. We are using the load carrying capacity to its maximum it means ultimate. So, ultimate is an adjective which also tells me that beyond this the load carrying capacity cannot be increased, it is the maximum, ultimate that is why the name ultimate comes. So, this design mechanism uses the material strength or material capability to its maximum whereas elastic design does not. So, that is seen as one of the positive point in design perspective.

Once we understand that we are enabling a failure, that design enables a failure, is it not? Whereas we are taking the load to that level beyond which the material or the section or the structure will fail. It means we are instigating the structure to fail, is it clear? Now, the structure can fail in many ways. Let us see what is that failure we are addressing in ULD? We must be very clear in this. The structure can fail in many ways. It can fail due to instability, it can fail due to fatigue, it can fail due to excessive deformations. Dear friends, these modes of failure are not addressed in ULD.

It means ultimate load design will be employed to only that structure which does not fail by any one of this, then the structure does not fail either by instability either by fatigue either by elastic deformation, excessive deformation then the material or the cross section or the structure as a whole will continue to carry load beyond yield point, to be very clear let me write this as first yield point. The material or the cross section or the structure will continue to carry load beyond the yield point.

If the failure is not initiated by the above, what is by the above? These three, if the failure is not initiated by the any one of the above then the material or the member or the structure will continue to carry load beyond the yield value. Then the question comes how do you define the failure? Because the failure is not been initiated by any one of them, the material is keep on carrying load beyond yield value, we have got to stop somewhere and say that the material is failed or the structure is failed.

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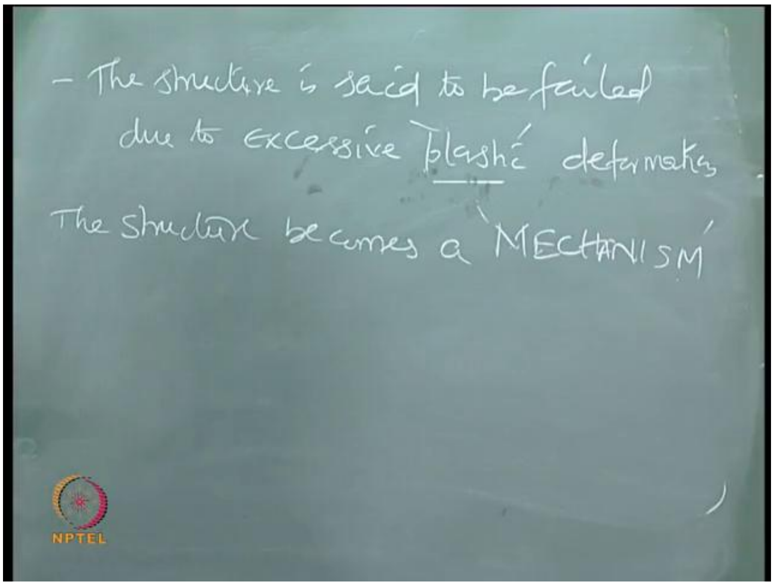

The structure is said to be failed due to excessive plastic deformation. So, when the structure has attained or enjoyed excessive plastic deformation, why I said excessive because in the stressed end curve beyond the elastic deformation all are semi plastic and plastic only. So, there is a cutoff which we call as an excessive plastic deformation. There is a special name given to the structure once this deformation level is reached the structure becomes mechanism, it is no more a structure it becomes a mechanism.

A special name given to the structural system where or in which this deformation is set in, it is because of this adjective the design method is also called as plastic design. Why we call this plastic design is because we are enabling plastic deformation in the system. Is it clear? Now, we will take a very simple example to illustrate what to do the plus and minus of a plastic design compared to inelastic design in a statically indeterminate system? Very simple example, we will try to show you how this can be done by an example.

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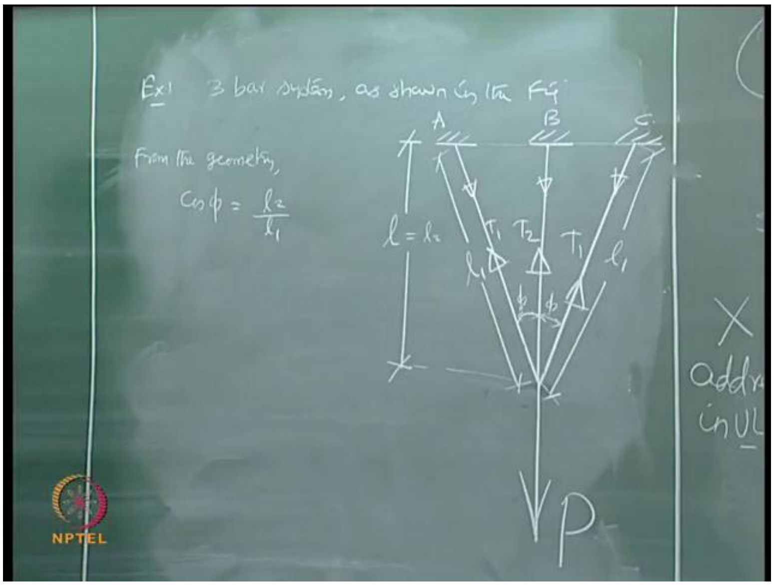

So, we say a very classical mechanics example which we have studied already, but I want to just use very little time on this to explain you how this can be seen in a different perspective, a different story. So, let us say I consider 3 bar system as shown in the figure. The 3 bar system what you see here is what I am drawing. This angle of inclination is let us say phi. So, from the geometry cos phi can be said as l 2 by l 1, when I apply a load P at this point where the three members are connected the load will now distributed to all the three members, I call that load distribution which will be a tensile load as T 1, T 2 and T 1.

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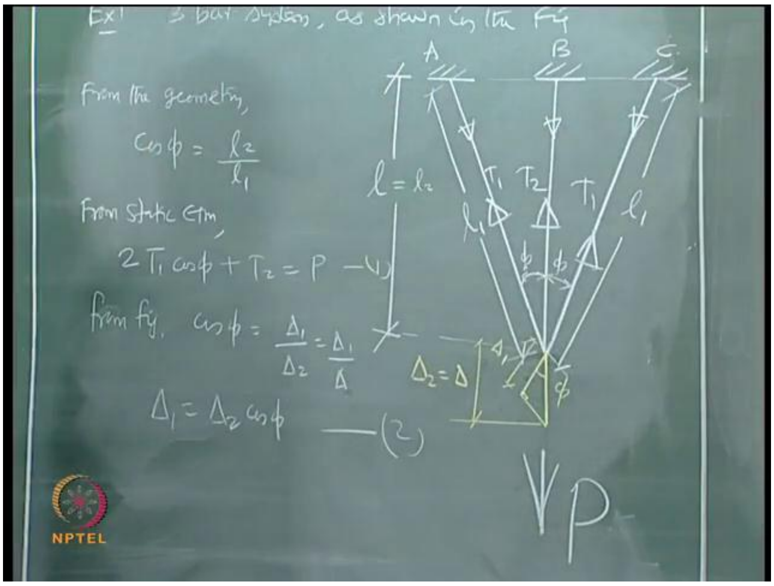

From static equilibrium we can say 2 T 1 cos phi plus t 2 will be equal to P; I call this equation number 1. Once, I start applying this force these members will start elongating, let me draw those elongations. I call this elongation as delta 2 which is simply delta that is the second bar, I call this elongation as delta 1 which elongation of the first bar same as this you can do it the other way also.

Of course, this is 90 degree and of course, this remains phi. So, from this figure of elongation I can say, from figure I can say cos phi is again equal to delta 1 by delta 2 or you can say even delta 1 by delta. We can say delta 1 is delta 2 of cos phi; equation number 2. We keep on applying this load P so the elongation will remain first elastic then go to plastic state.

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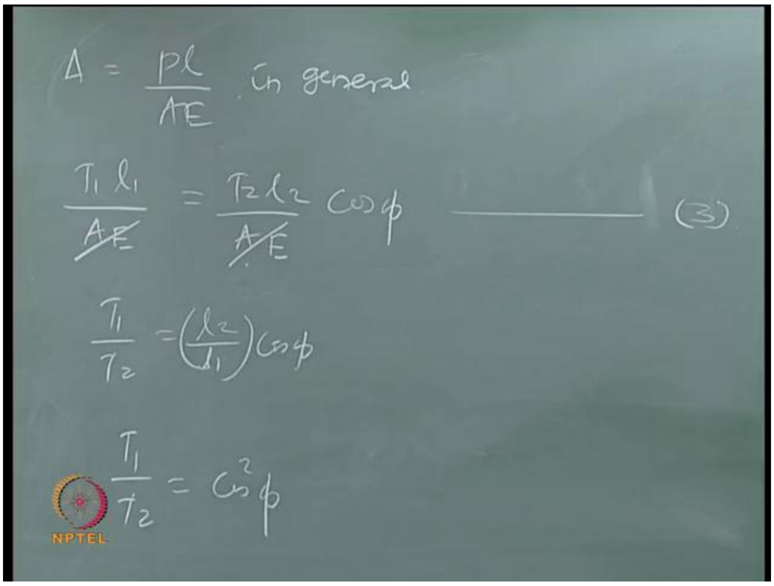

So, as long the elongation you have the delta extension elastic then we can say this delta can be given by simple expression of P l by A E in general, is it not? To be very specific I can say T 1 that is the load on the first rod, l 1 is the length. I want to maintain the area of cross section of all the 3 bars same and hence forth the material remains same. That is nothing but delta 1 equal to T 2 l 2 by A R and I already know delta 1 is delta 2 times of cos phi, I multiply cos phi here, equation 3. A E goes away. Now, I have a ratio between T 1 and T 2 which is l 2 by l 1 of cos phi. l 2 by l 1 is already cos phi therefore, I can say T 1 by T 2 is cos square. I will remove this.

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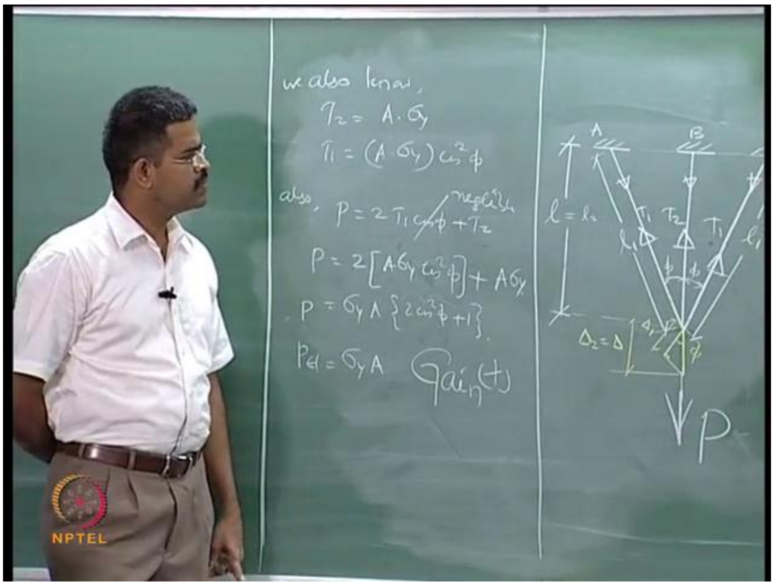

We also know T 2 is A times of sigma y. In that case T 1 will be A times of sigma y of cos square phi from this equation and we also know P is 2 T 1 cos phi plus T 2. We already said this from the static equation of equilibrium and we can also appreciate that there are two unknowns here T 1 and T 2 there is only one equation. So, this structure is statically indeterminate. So, I can apply plastic analysis concept to this system, is that clear? Indeterminate by 1 degree because there is one equation, but I have got two unknowns, is it not. So, it is indeterminate by 1 order, 1 degree.

For very small values of phi practically let us say the 3 bars are vertical for very small values of phi, I think I think this value can be negligible because it will be almost unity. So, let me substitute T 1 and T 2 from here in this equation T will become A sigma y cos square phi plus A sigma y, I can say sigma y A 2 cos square phi plus 1 is P. We already know P elastic is sigma y of A, we already know this. However, this equation is not P elastic because this equation has got one value added to this, is it not.

For a very small value of phi we can practically see that this P or the load carrying capacity will be three times of elastic, is it not? That is the gain. The load carrying capacity of this arrangement is enhanced beyond its elastic limit because there is an multiplier to this, agreed? So, this P is much beyond than P elastic, agreed? Let us look at the last or I would not call this as the last, I would call this as a caution.

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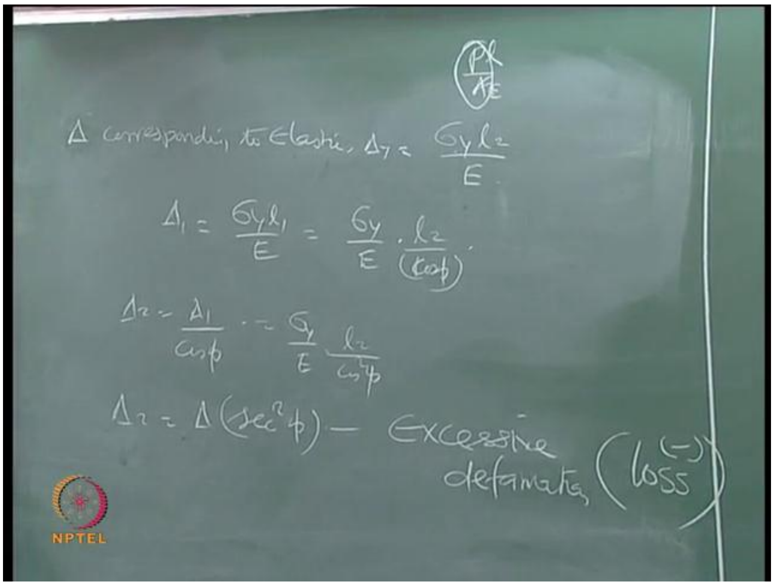

We already know the delta or the deformation corresponding to elastic which I call as delta y is nothing but sigma y l 2 by E, is it okay? Nothing but P l by A E, P by A is stress and l 2 by E there is delta in the figure, you can see here. Let me use this delta delta. If we want to really know the delta 1 part of it we have an equation connecting delta 1 and delta 2. What is that equation? Delta 1 is nothing but so this is going to be sigma y l 1 by E.

I can also say this as sigma y by E, instead of l 1 I can say l 2 by cos phi, can I say that? Is it not? So, delta 2 is delta 1 by cos phi, which is nothing but sigma y by E l 2 by, now cos square of phi or I should say delta 2 is delta times of secant square. Delta is the value corresponding to elastic deformation, delta 2 is at a plastic stage because P is beyond elastic value. There is a multiplier here by a very small value of phi this value will be very large. So, you have landed in so that is the loss, landed in excessive deformation that is the loss. The gain is load carrying capacity is enhanced the loss is the elongation or the deformation is much more than the elastic value.

So, this example illustrates very clearly the plus and minus of applying the plastic analysis concept to a statically indeterminate system of 3 bars system as you see here. We will take some complicated problems later to explain in beams and frames, but this is very simple illustrative example to make us to understand how I transit from an elastic behavior to a plastic behavior using this simple problem. I have taken this example because this is very common problem everybody understands. So, this problem has been used in a different vision to explain the positive and the negative points of our discussion which we wanted to focus, is that clear?

So, it is very clear from this lecture that a transition from elastic to plastic is mandatory because I want to use the excessive reserve strength available from the first yield point. Marine structures are made out of steel and steel has the first yield point not because of the load phenomenon, but because of residual stresses set in the material by some other manufacturing and construction process which are initiated in the marine structural system design. So, they can be eliminated, completely is not possible, but partially you can reduce it. So, the presence will be the significantly causing what we calling inelastic behavior, the system apart from making the failure brittle.

So, designer start I can use that inelastic behavior as an advantage to me in my design, this is possible only when two things are available. One, enough ductility is present in a material. Two, the structure should remain statically indeterminate because this ductility is seen as a mechanism to redistribute the moments from highly stressed cross section to the successive highly stressed cross section. The structure is determinate, this distribution is not possible. That is what you have seen, we have taken example, explain how the gains and losses can be forcing, we will continue in next lecture.

Thanks.