Advanced Design of Steel Structures
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Lecture - 17
Plastic design- 1

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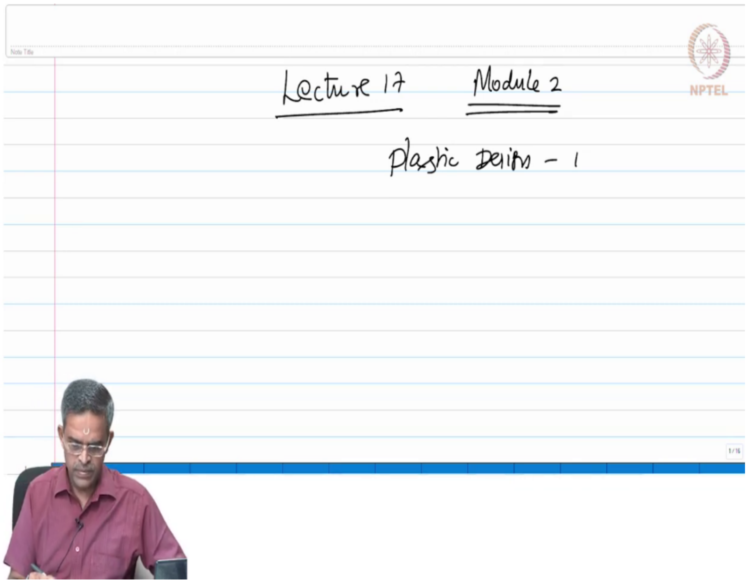

Lecture 17 Module 2

Plastic Design - 1

Welcome to Lecture 17, where we are going to talk about Plastic Design. This is actually a part of 2nd Module of Advanced Steel Design course which is under NPTEL IIT, Madras. Before we enter into discussing the plastic design fundamentals and its applications and theories related to the conceptual development of plastic design, let us try to ask a question, what will be the general design considerations in designing a steel structure? Let us ask this question.

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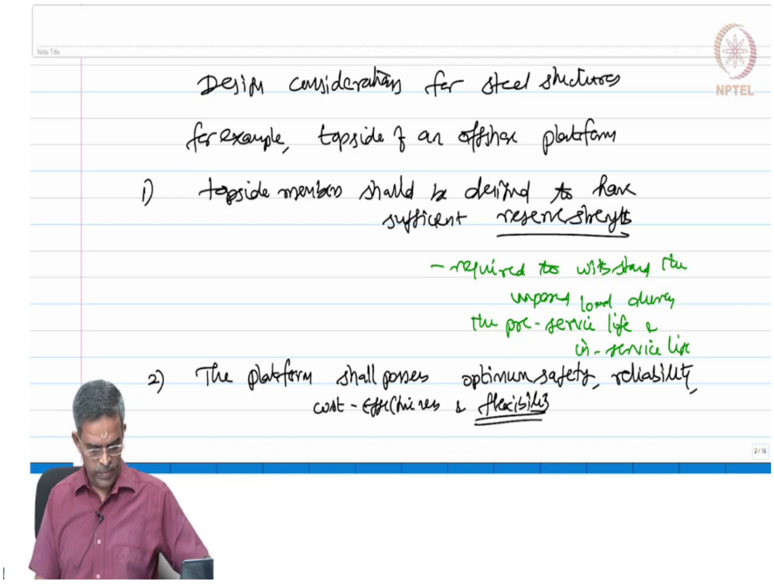

Design considerations for steel structures

for example, topside of an offshore platform

1) topside members shall be designed to have sufficient reserve strength

- required to withstand the imposed load during the pre-service life & in-service life

2) The platform shall posses optimum safety, reliability, cost-effectiveness & flexibility

So, let us talk about design considerations for steel structures, when I say steel structures, I am not talking about conventional structures I am talking about strategic and special form of structures where the structures resist majority of the load by the geometric form. I am talking I am keeping this in mind because we are always talking about advanced steel design procedures. So, the conventional design of steel structures is not discussed under the purview of this course at all.

So, for example, for our convenience let us take the design of topside of an offshore platform. Offshore platform is a strategic structure, if it happens to be a compliance structure it will have a form dominance. Let us talk about the design consideration which you have for topside structures. So, the first condition should be that the top side members should be designed to have sufficient reserve strength.

Why it is required? The reserve strength is required to withstand the imposed load during the pre-service life and in service life. So, that becomes a first requirement. The second requirement could be, the platform or the structure shall posses, optimum safety, reliability, cost effectiveness and flexibility that is very important we are talking about form dominance.

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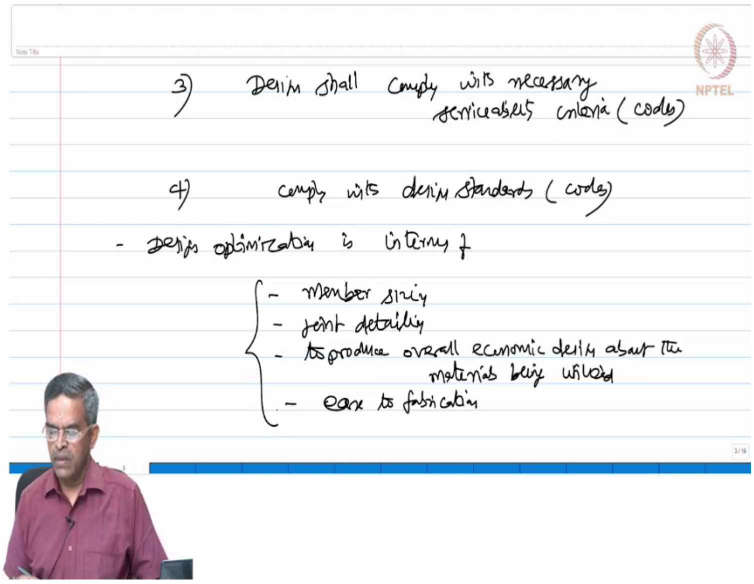

3) Design shall comply with necessary serviceability criteria (codes)

4) comply with design standards (codes)

- Design optimization is in terms of
  - member sizing
  - joint detailing
  - to produce overall economic design about the materials being utilized
  - ease to fabrication

The third condition could be the design shall comply with necessary serviceability criteria that is very important as stipulated by the design codes. The fourth could be it should comply anyway with the design standards as imposed by the codes. So, therefore, the design optimization is in terms of member sizing, joint detailing and to produce overall economic design about the materials being used and ease to fabrication.

So, these are the factors based on which a structural design of an offshore platform is generally optimized. Now let us talk about what would be the general design criteria or design acceptance criteria.

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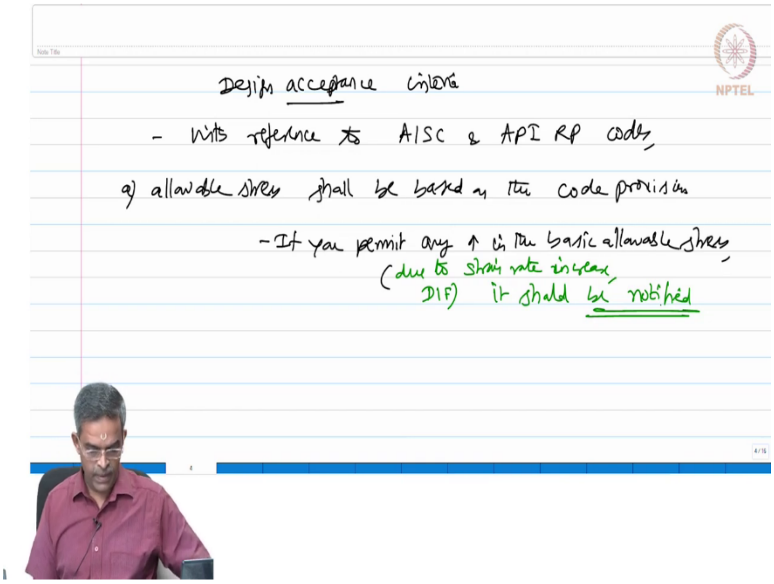

Design acceptance criteria

- With reference to AISC & API RP codes,

a) allowable stress shall be based on the code provision

- If you permit any ↑ in the basic allowable stress, (due to strain rate increase, DIF) it should be notified

Let us talk about the design acceptance criteria. Now when you talk about design acceptance criteria, we have to refer to the codes of practice, let us say with reference to AISC and API RP codes. There are some basic criteria stipulated by these codes. Let us say the allowable stress shall be based on the code provisions. If you permit any increase in the basic allowable stress, it may be due to many reasons. It can be due to strain rate increase, it can be due to dynamic increase factor, etcetera.

If you permit that in the design it should be notified that is very important you must have to specify this very clearly in the design. That is one of the requirements of the design.

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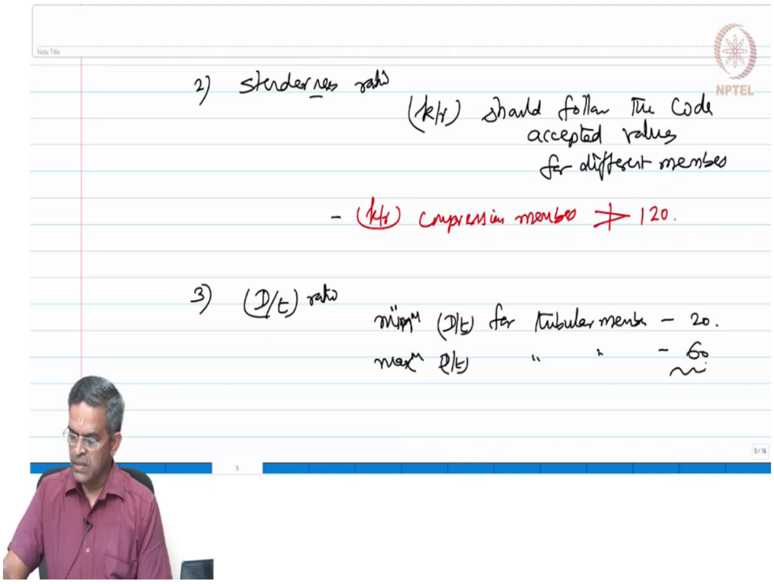

2) slenderness ratio

(k/r) should follow the code accepted values for different members

- (k/r) compression members $\ngtr 120$.

3) (D/t) ratio

min^m (D/t) for tubular members – 20.

max^m (D/t) " " – 60

Furthermore, the second condition of course, comes is the slenderness ratio. The slenderness ratio $\frac{k}{r}$ should follow the code accepted values for different members. We all know this is the standard procedure we are not discussing that here; however, you must note that the slenderness ratio for compression members in form dominant designs, cannot be more than 120 is a limit.

The third conditions come from the sizing, which is diameter to thickness ratio. The minimum diameter to thickness ratio for tubular members is 20 the maximum $\frac{D}{t}$ ratio for tubular members is 60; however, under exceptional circumstances we can increase this.

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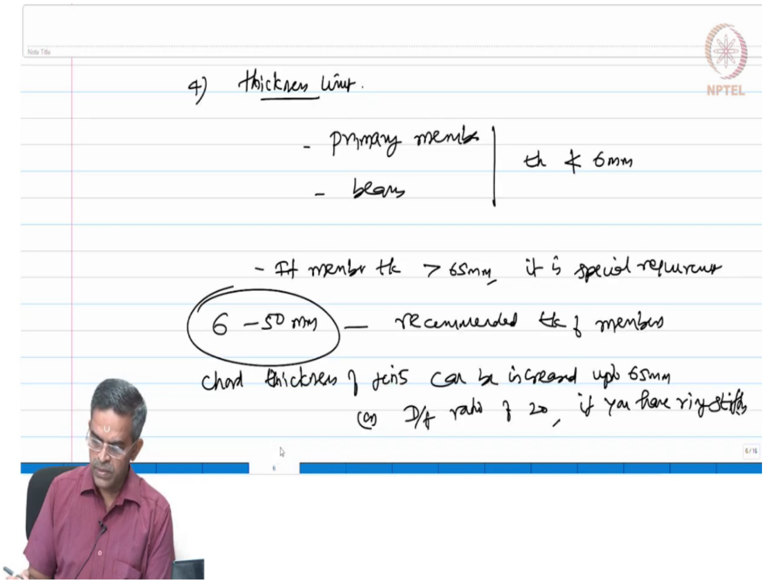

4) thickness limit.

- primary members
- beams

th $\not<$ 6mm

- If member tk > 65mm it is special requirement

6 – 50 mm — recommended tk of members

chord thickness of joints can be increased upto 65mm

(or) D/t ratio of 20, if you have ring stiffe

The next condition the design acceptance criteria is thickness limit of the member. There is a limit imposed on the thickness of the member. The primary members the beams that is flexural members cannot have a thickness lesser than 6 mm. If members if the member thickness exceeds 65 mm, then its a special requirement.

So, its upper limit we have. So, anywhere from 6 to 50 mm is the recommended thickness of the members. Furthermore, the chord thickness of the joints because we are talking about tubular members the chord thickness of the joints can be increased up to 65 millimeters or here $\frac{D}{t}$ ratio of 20 if you have ring stiffness.

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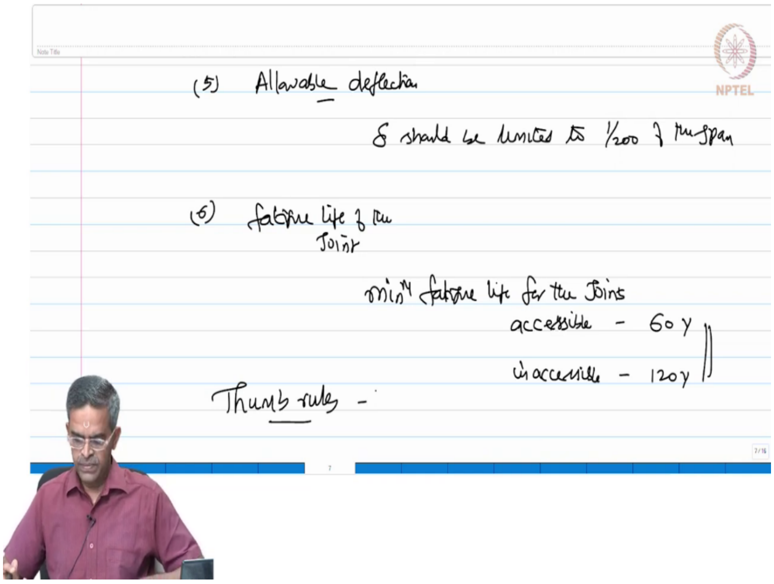

(5) Allowable deflection

δ should be limited to $1/200$ of the span

(6) fatigue life of the joint

min^m fatigue life for the Joints

accessible - 60 y

inaccessible - 120 y

Thumb rules -

Then next condition comes as allowable deflection. Is one of the important serviceability criteria. The deflection should be limited to 1 by 200 or to be very specific of the span. The next condition is the fatigue life of the joint. The minimum fatigue life for the joints both accessible, inaccessible or different. For accessible joints the minimum fatigue life is 60 years for inaccessible joints the minimum fatigue life should be 120 years.

See these are some thumb rules, these are some basic guidelines, design governance which international codes commonly follow when we talk about large displacement structures in marine environment where the environment influences the material degradation. And of course, it also causes special kinds of loads on structural systems where steel is considered to be one of the most promising material for such kind of construction.

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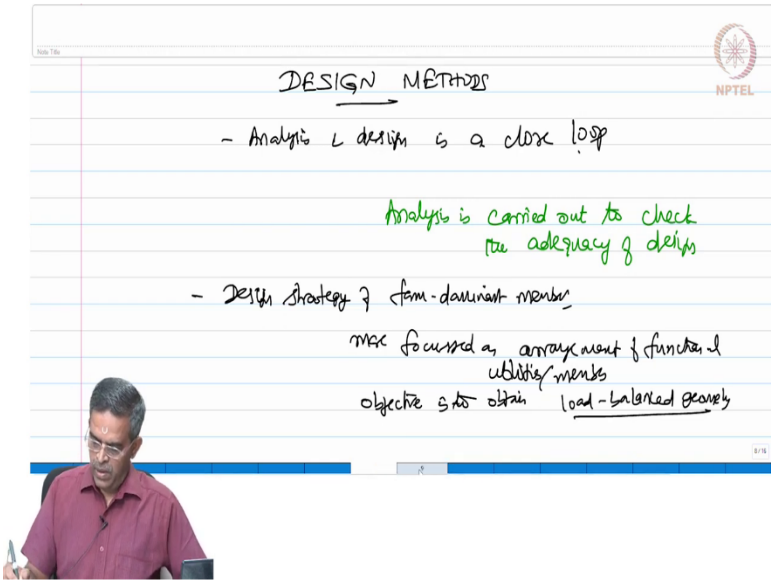

DESIGN METHODS

- Analysis & design is a close loop

Analysis is carried out to check the adequacy of design

- Design strategy of form-dominant members

more focussed on arrangement of functional utilities/members

objective is to obtain load-balanced geometry

Having said this, let us now get into the design methods, before we enter into plastic design. We all know that analysis and design is a closed loop. The structural design generally is carried out to control the response of the structure under the combination of various loads. Analysis reflects the response behavior of a designed structure. Therefore, friends it is a common understanding the analysis is carried out to check the adequacy of design.

Structural design is more based on experience or understanding of the structural behavior under combination of various loads. But analysis is a sophisticated process, which is computer aided to solve high end mathematical equations with the help of various numerical tools. The results of analysis; however, need to be checked with the designer to correlate this with the actual behavior of the structure.

When we talk about strategic structures structural design is more focused on arrangement of functional utilities to obtain a load balance geometry. If you talk about design strategy of form dominant members, then we can say it is more focused on arrangement of functional utilities and the members. So, the objective is to obtain load balanced geometry, that is the objective. So, the design should not be seen as sizing of the structural members.

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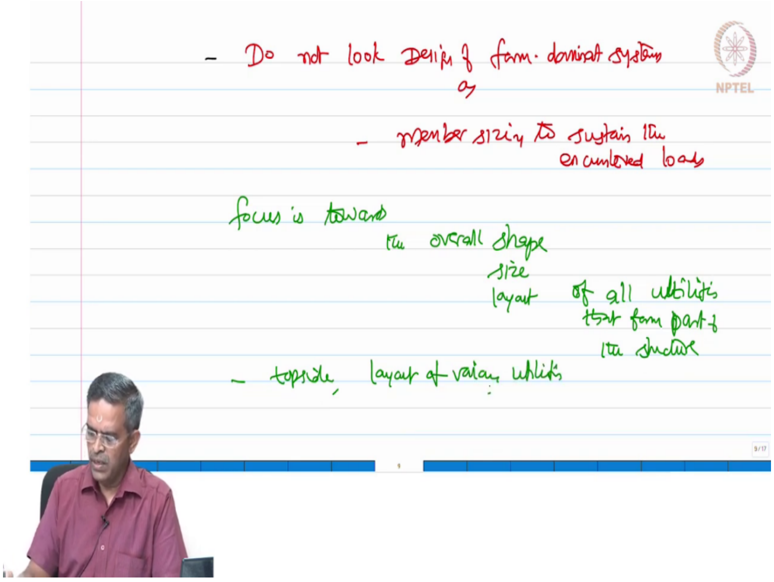

- Do not look Design of form-dominant systems
  as
  - member sizing to sustain the encountered loads

focus is towards
the overall shape
size
layout of all utilities that form part of the structure

- topside, layout of various utilities

So, let us not do not look design of form dominant systems, as member sizing to encounter or to sustain the encountered loads. It is not simply the member sizing, its a large picture in reality. The focus should be more towards the overall shape and size and geometric layout of the structure. So, the focus is towards the overall shape, size, layout of all utilities that locate or that form the part of the structure. So, if you talk about the top side of an offshore platform.

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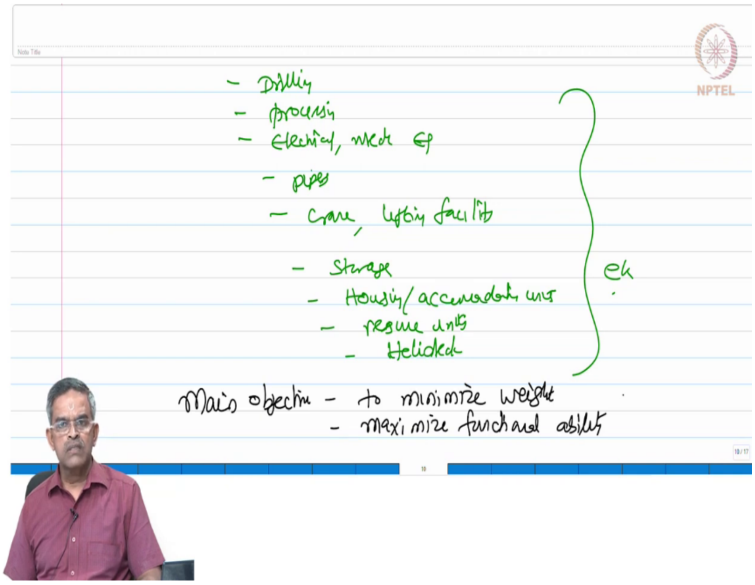

- Drilling
- processing
- Electrical, mech eq
- pipes
- Crane, lifting facility
- Storage
- Housing/accomodation units
- rescue units
- Helideck

etc.

Main objective - to minimize weight
- maximize functional ability

Then it is layout of various utilities, let us quickly see what are various utilities of an top shore platform drilling, processing, electrical, mechanical equipment, pipes, cranes and other lifting facilities, storage, housing or what we called as accommodation units, rescue units, helipad or helideck, etcetera.

So, various utilities are first arranged based on that a load balance geometries obtain that is actually the design it is not member sizing friends. So, we are looking design as much larger perspective. So, the main objective of the design therefore, is to minimize weight and maximize its functional ability. Therefore, friends the functional design of a top side or any strategic structure preludes the structural design.

So, ideal design philosophy maintains the equilibrium between the applied load and resistance that can offer by the structural system. Unlike in conventional design practices where resistance is accounted only from the strength of the material for strategic structures or form dominant designs.

The resistance is also offered equally from the geometric form. So, even the geometric form arrangement of members, their sizing, placement of heavy equipment's both vertical and horizontal zoning, spacing of critical operations such as lifting loading, unloading, drilling plays a very important role in balancing the load acting on the structure. That is very important.

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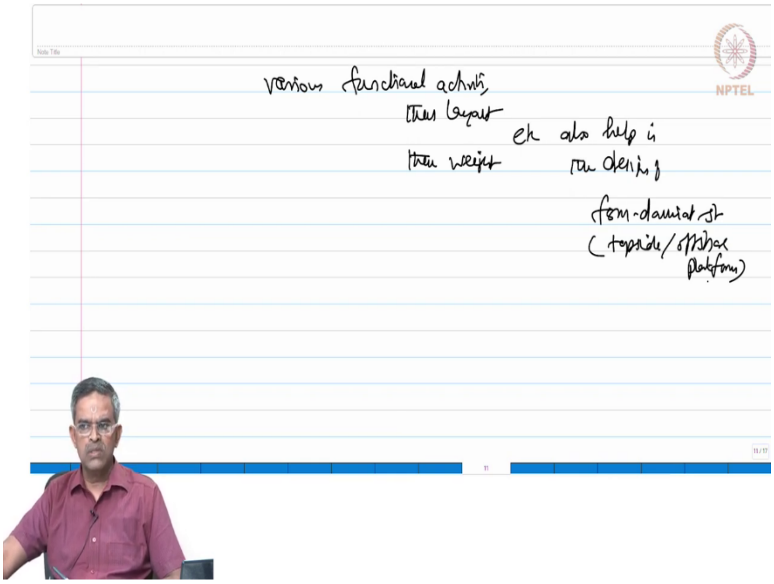

various functional activi,
their layout
etc also help in
their weight
the design

form-dominant st
(topside/offshore
platform)

So, various functional activities their layout and their weight, etcetera also help in the design of form dominant structures. Example top side of an offshore platform. The very examples we have seen in different kinds. Therefore, friends a safe design is termed as resistance exceeding the load capacity. Resistance exceeds the load demand.

As a resistance can also arise from geometric form, form dominance is carefully exploited to maintain the dynamic equilibrium between the resistance and the loop. Therefore, it is important to ensure that the large displacement structures like, form dominant systems maintain geometric stability while they are under activation of loads.

Because they undergo large deformation these large deformation can get into a plastic deformation of the material. So, there should be one to one correspondence and support from the material to the structure and vice versa so, that the encountered loads are counteracted by the capacity of the form and of the material string together.

So, please note that the deformations being discussed here are not at the material level we are also including them at the structural level. So, now, there are different design methods which we all know. Like working a stress design, ultimate load design, limit state design, etcetera. Let us quickly look at an overall view of this before we get into the plastic design. So, in working stress design method.

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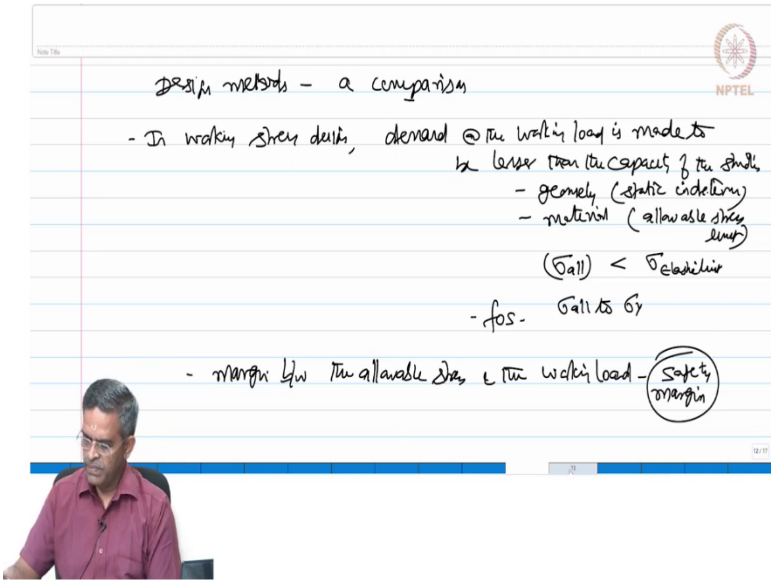

Design methods – a comparison

- In working stress design, demand @ the working load is made to be lesser than the capacity of the structure
  - geometry (static indeterminacy)
  - material (allowable stress limit)

$(\sigma_{all}) < \sigma_{elastic\ limit}$

- fos - σ_{all} to σ_y

- margin b/w the allowable stress & the working load – Safety margin

So, let us say design methods a comparison. This is only just to review what we already know most of you know this, but still for the completion sake. Let us review this quickly without spending much time and get into the plastic design. In working stress design, the demand at the working load is made to be lesser than the capacity of the material or capacity of the structure, let us put it like this.

Now, the capacity of the structure comes from two, one comes from the geometry which is static indeterminacy redundancy we call, the other comes from the material. The one which comes from the material is stated as allowable stress limit. Usually, this value is kept within the elastic limit of the material.

So, we say $\sigma_{allowable}$ usually is lesser than the elastic limit or stress at elastic limit of the material. That is the usual practice what we do in working stress design. Therefore, friends the ratio of capacity the material which is taken at the σ_{yield} to the $\sigma_{allowable}$ is called as a factor of safety. So, this has got something called factor of safety which is a ratio of $FOS = \frac{\sigma_{allowable}}{\sigma_{yield}}$.

We do not take it till yield, we will limit it below yield and that is the factor of safety. So, the margin between the allowable stress and the working load is actually termed as a safety margin, right. So, there is an explicit safety margin in the design like this. Hence in this design method there are 2 tire safety margins.

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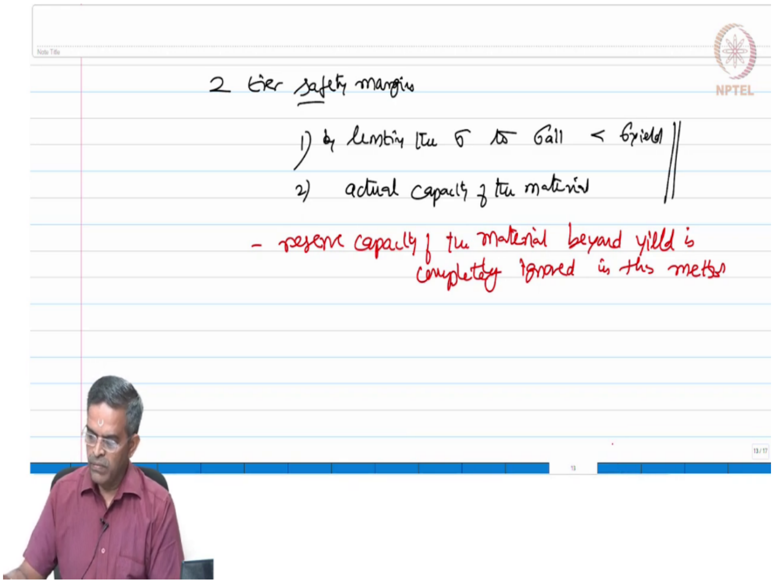

2 tier safety margin

1) by limiting the σ to $\sigma_{all} < \sigma_{yield}$

2) actual capacity of the material

- reserve capacity of the material beyond yield is completely ignored in this method

So, there are 2 tire safety margin. What are they? The first one is limiting by limiting the stress to stress allowable which is lesser than yield. So, there is a reserve capacity in terms of the material. The other one is the actual capacity of material. Now the material also has reserve energy. So, these two together has to safety margin.

So, one should carefully note, that still the reserve capacity of the material is beyond its yield which is completely ignored in the design procedure. Let us put this mark here. The reserve capacity of the material beyond yield is completely ignored in this design position correct. The second one, which is very common is ultimate load design.

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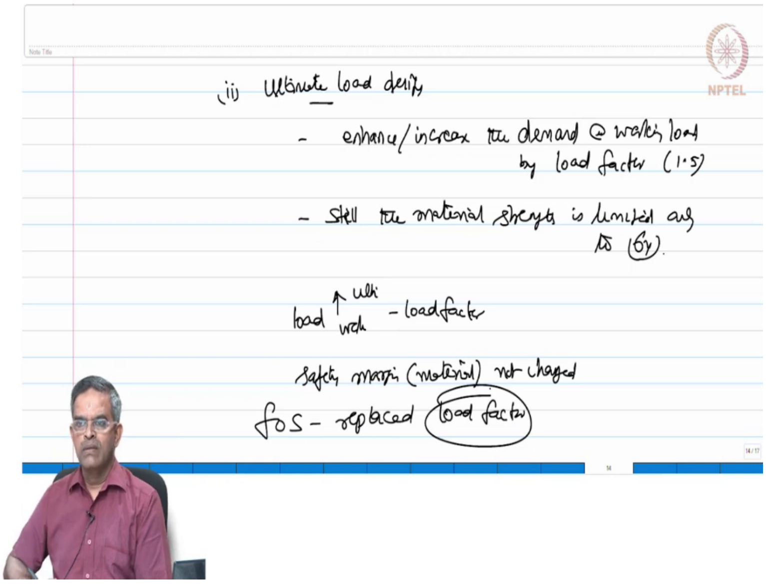

(ii) Ultimate load design

- enhance/increase the demand @ working load by load factor (1.5)
- Still the material strength is limited only to (σ_y).

load $\uparrow^{\text{ulti}}_{\text{work}}$ - load factor

safety margin (material) not changed

fos - replaced load factor

In ultimate load design case, the ultimate load is computed by enhancing the demand at working load by a load factor. So, in this case what we do we enhance or increase the demand at working load by a load factor we all know for example, the load factor of 1.5 is being recommended. But still the material strength is limited only to its yield value.

Hence the safety margin which was present in the workings stress method remains unchanged, is it not? The safety margin present in the earlier design method remains unchanged, but the load has been increased from working load to ultimate load, right. So, what we did is we have increased the load from working to ultimate using a load factor, but the safety margin of the material is not changed. Therefore, the factor of safety is now replaced by load factor, is it not?

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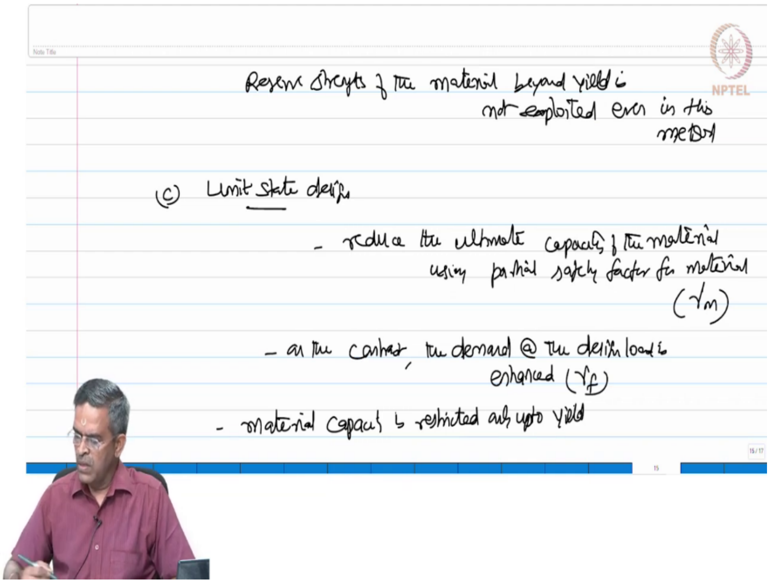

Reserve strength of the material beyond yield is not exploited even in this method

(c) Limit state design

- reduce the ultimate capacity of the material using partial safety factor for material (γ_m)
- on the contrast, the demand @ the design load is enhanced (γ_f)
- material capacity is restricted only upto yield

However, you must understand that the reserve capacity of the material beyond yield is still unexploited even in this method, correct. In limit state design procedure, the ultimate capacity of the material is also reduced by a partial safety factor. So, what we do is we reduce the ultimate capacity of the material using a partial safety factor for materials, which is generally indicated as γ_m. On the contrast; on the contrast the demand at the design load is enhanced.

We call this as γ_f. Using a partial safety factor for loads which we discussed in detail. So, the material capacity is restricted only up to yield. As in other methods therefore, let us quickly see this as a good graphical comparison on the screen.

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We will say that, let us say its may 0 level and we say this is my working stress method. So, what we do from here is, this is working stress value, working stress value. So, let us say we try to increase or in working stress design.

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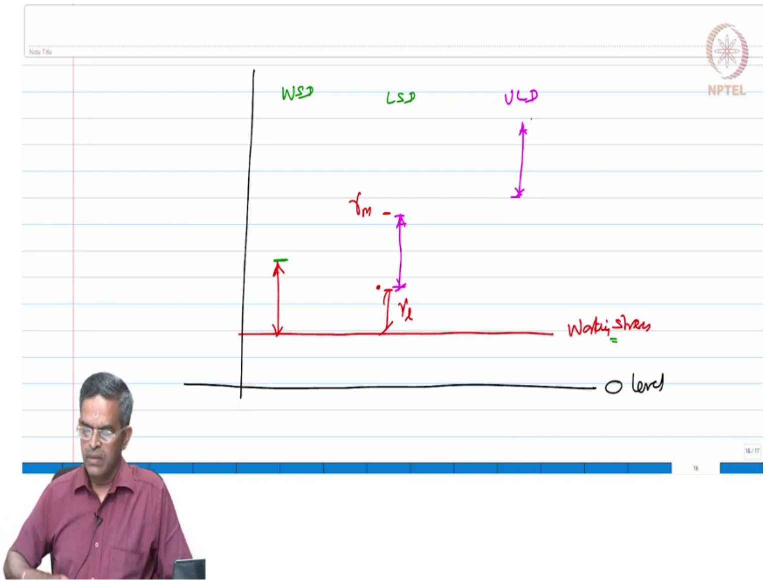

This becomes my load criteria or the strength criteria. Whereas, in limit state design the load at working load is enhanced, is enhanced by γ_l. But the material is applied with γ_m. So, this becomes my parameter for working stress design and this becomes my parameter for limit state design. If we talk about ultimate load design what I do is I enhance the material characteristic further and take it till the top.

So, in all the three cases we can very well see the safety factor is inherited in the material level itself. However, the reserve energy possessed by steel is relatively higher.

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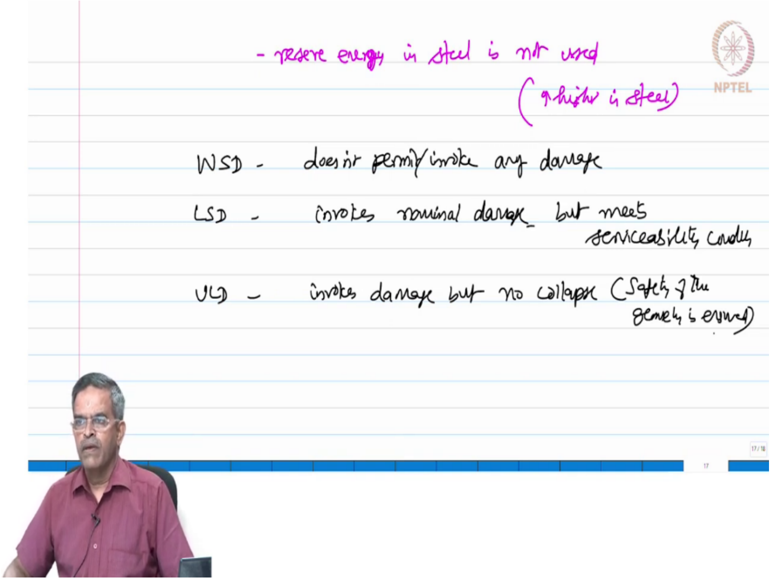

- reserve energy in steel is not used
(is higher in steel)

WSD - does not permit/invoke any damage

LSD - invokes nominal damage but meets serviceability condn

ULD - invokes damage but no collapse (Safety of the geometry is ensured)

And that is not used is not used, is it not? And it is relatively higher in steel and that should be accounted in the design, is it no? So, if you look at the reserve energy before, we do let us make a comparison the working stress design does not permit or does not invoke even any damage.

So, 0 damage condition. The limit state design invokes nominal damage, but meets serviceability requirements. The ultimate load design invokes damage, but no collapse. So, safety of the geometry is ensured. So, if you look at the reserve energy possessed by structural steel its very amazing. Let us see this let us try to plot the stress strain curve of structural steel.

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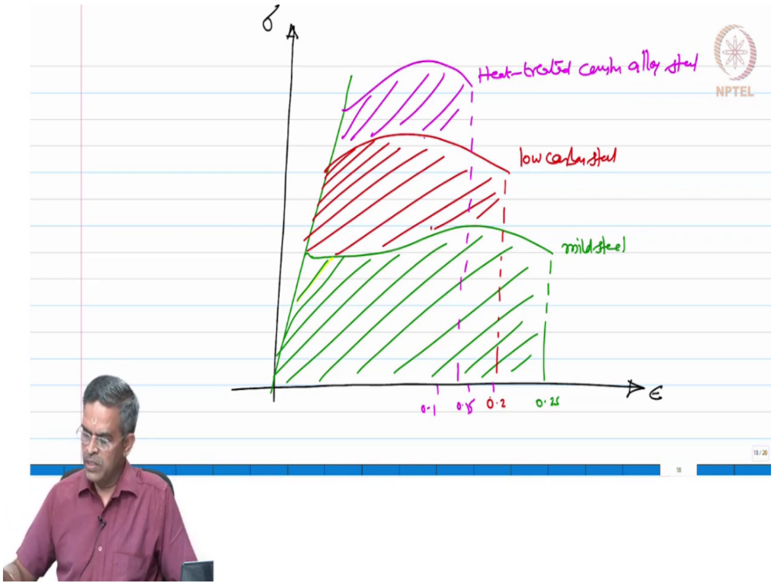

So, the initial slope let it be same for all the types of reserve energies. So, initially this is for mild steel. I am just drawing qualitatively. Now I will say this is going up to 0.25. If you look at the high strength steel. This is the mild steel, this is the energy. We have, when you look at high strength steel this is low carbon steel.

And the limitation stops at about 0.2 and this becomes there is the energy. When we talk about special grade of steel which is heat treated this is furthermore, but stops at about this is point this is 0.15 this is 0.2 this is 0.1. So, this is heat treated construction alloy steel which is quenched and tempered alloy steel, this reserve energy is still high.

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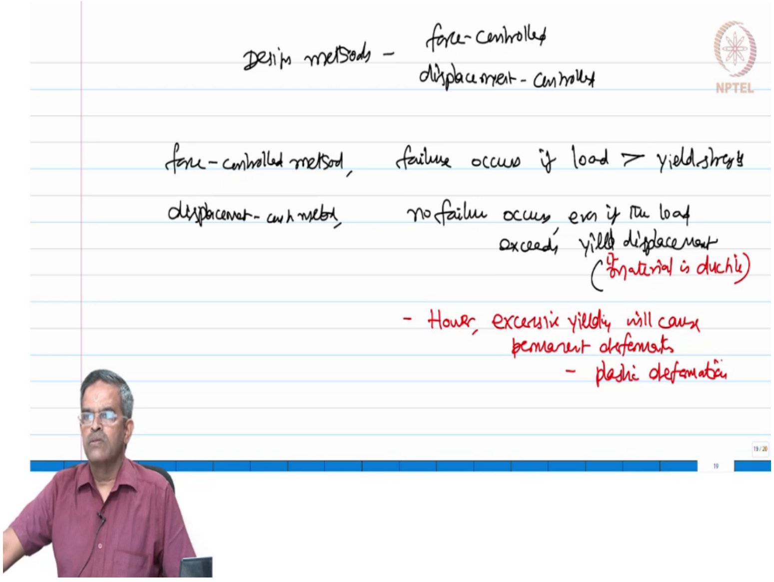

Design methods – force-controlled
displacement-controlled

force-controlled method, failure occurs if load > yield strength

displacement-contr method, no failure occurs even if the load exceeds yield displacement (if material is ductile)

- Howev, excessive yielding will cause permanent deformation
  - plastic deformation

So, friends one can very well see the design methods can be now divided into 2 major domains can be divided into 2 major domains; one is force controlled other is displacement controlled. In force-controlled design method failure occurs if the imposed load exceeds yield strength. So, in force-controlled method failure occurs if the load exceeds yield strength, but in displacement control method no failure occurs even if the load exceeds yield displacement.

Please carefully understand this. Provided the material is ductile; however, damage occurs in excessive yielding and will cause permanent deformation this is termed as plastic deformation. So, let us say what would be the concept of plastic design now based on this.

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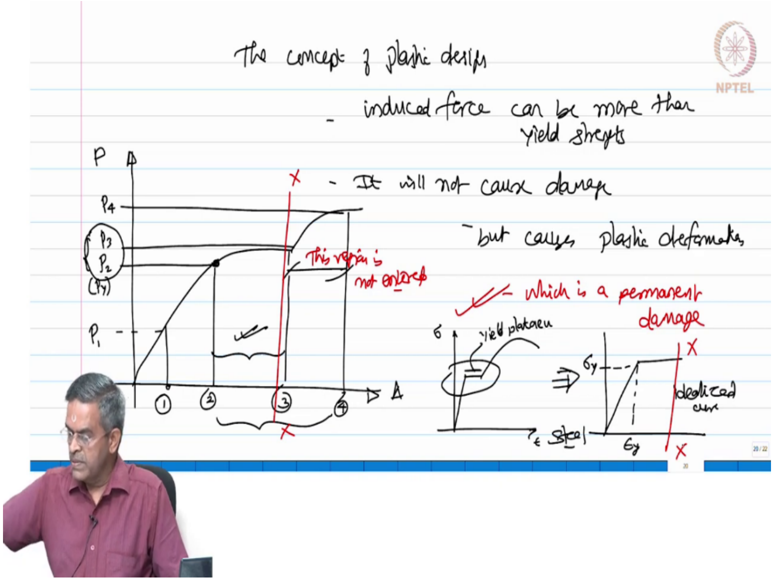

The concept of plastic design

- induced force can be more than yield strength
- It will not cause damage
- but causes plastic deformation which is a permanent damage

This region is not enlarged

So, the concept of plastic design is induced force can be more than yield strength it will not cause damage but causes plastic deformation which is a permanent damage, please understand that. So, in plastic design you are enabling you are permitting a permanent damage, but; however, the force level will be much more than the yield strength of the material. Therefore, friends material to be used in plastic design should possess high post elastic deformability, steel has this property. So, let us look into this graphically. If we plot this as deformation and load curve.

So, we can have a nice curve and like this. Let us say at 1 we can have a load level which is load level 1 I call this P_1 where no permanent deformation is caused. It is at this point which level; I will call this as level 1 level 2 which has reached yield the load can be still more than that, see here the load can be still more than that. But during this increase in load, you also encounter large permanent damage.

And of course, it collapse, it will undergo a permanent damage or a failure. Now if you look at the elastoplastic deformation of steel, I will draw it here itself is easy. Elastoplastic deformation of steel, steel has got ideally a good yield plateau and then it goes. So, this is the yield plateau. The strain and stress of course. So, this is now going to be idealized in my plastic design as a bilinear curve where I am going to stop this at σ_y, I am going to and this is my ε_y.

So, this is going to be my idealized curve which I am going to use for plastic design this is for steel. So, steel has got good ductility, elastoplastic idealization which can be applicable to steel. And still shows a very good yield plateau which suffices the design requirement of increase from P_2 to P_3 with permission of permanent damage as envisaged here.

Of course, we are not entering into the region at all. This region is not entered. We are limiting till here. So, if I say this is my XX line the XX line is here. I am limiting till here, friends.

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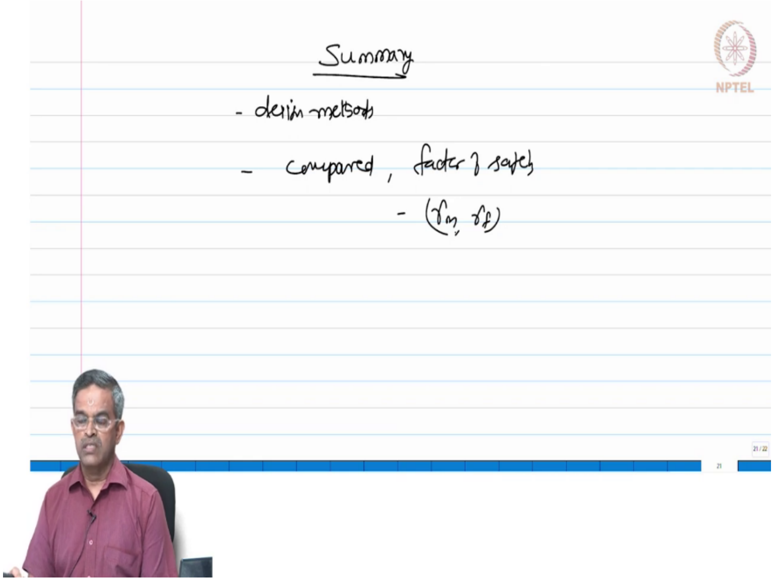

Summary

- design methods
- compared, factor of safety
  - (γ_m, γ_f)

In this lecture, let us look at the summary what we learned. We learnt various design methods quickly, we compared them and we understood something called factor of safety, γ_m and γ_f for load and material. And we realize that how the methods of design exploits the steel capacity reserve energy up to a level. Then we moved on to the plastic design we states that the design process controls the stress at yield, but allows increase in imposed load at a cost of plastic deformation which is a permanent damage in the member.

So, if you want to allow this design to be incorporated you have to have the material capability of ductility induced in the material plus when the structures are undergoing large displacements because of the form dominance, it should be supported equally and parallelly by the material therefore, the material should be also remaining elastic or elastoplastic conditions should be available in the material with enact ductility.

So, that the one-to-one relationship between the demand from the structure, expectation from the material matches each other to contract the load acting on the structure without any failure. In all the time remember friends, the geometric stability of the structure even under accidental worst scenario should be guaranteed.

There is no design procedure which is acceptable by any course of practice in the world which says that the geometric stability can be over toppled at the cost of increase in load carrying capacity of the member or the material usage effectiveness, friends. So, we will close it here for this lecture, we will continue in the next lecture.

Thank you, have a good day, bye.