Design of Connections in Steel Structures
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Module - 1
Lecture - 3
Design of Bearing Type Bolts in Shear: Basic Design Principle

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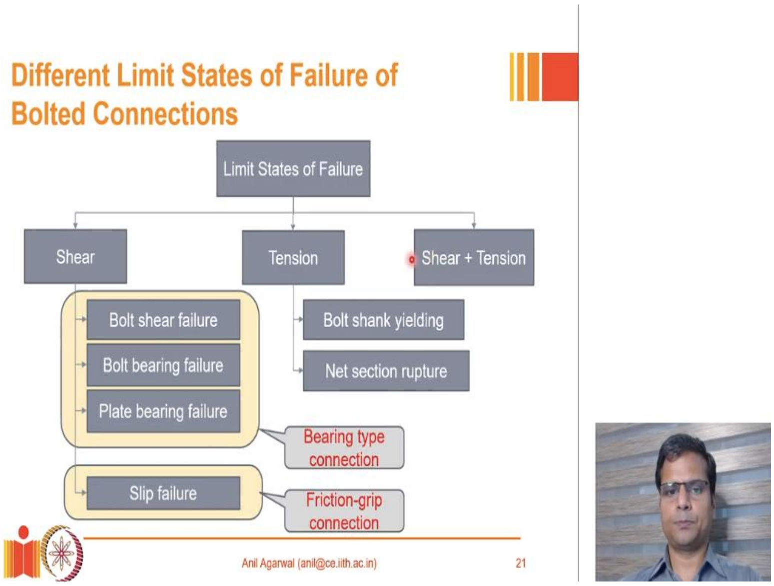

Now, we will talk about the actual design process for a bolted connection. So, first, in this chapter, we will basically study how to design a single bolt. And the bolt group design basically, we will do towards the third section of this course. So, first, before we design a bolt, we have to understand what are the different ways a bolt can fail. So, the ways are also known as limit states of failure.

So, the ways in which a bolt can fail depends on what type of loading is applied on the bolt. If the bolt is subjected to shear, there are certain ways in which it can fail. If it is subjected to tension force, then there are slightly different ways in which it can fail. And also there is a possibility of a combined shear plus tension failure for which there are certain limit states; but the expression is basically more of an empirical nature than actually based on any specific phenomenon.

So, when it comes to bolts which are subjected to shear, depending on whether the bolt belongs to a bearing type connection or a friction grip type connection. So, friction grip type connection you remember, where the bolts are tightened are subjected to large pretension force so that the plates are held together through friction. So, such bolts can fail to slip. So, slip would be the failure criterion for such bolts in shear.

However, if the bolts are bearing type, so that the plates are meant to slip. And then, the bolt shank is expected to come in contact with the bolt hole. Such bolts can fail in one of the 3 ways; either the bolt itself undergoes shear failure; otherwise, the bolt surface, the shank surface undergoes bearing failure; also there is a possibility that the plate hole, the hole of the plate, that can undergo bearing failure.

So, all these will be covered in the subsequent section. When a bolt is subjected to tension, it can have 2 different types of failure. One type of failure would be the yielding of the bolt shank. And alternate type of failure would be rupture of the net section. So, we will talk about that also. So, first we will start with a bolt which is subjected to shear, and the bolt type is a bearing type connection.

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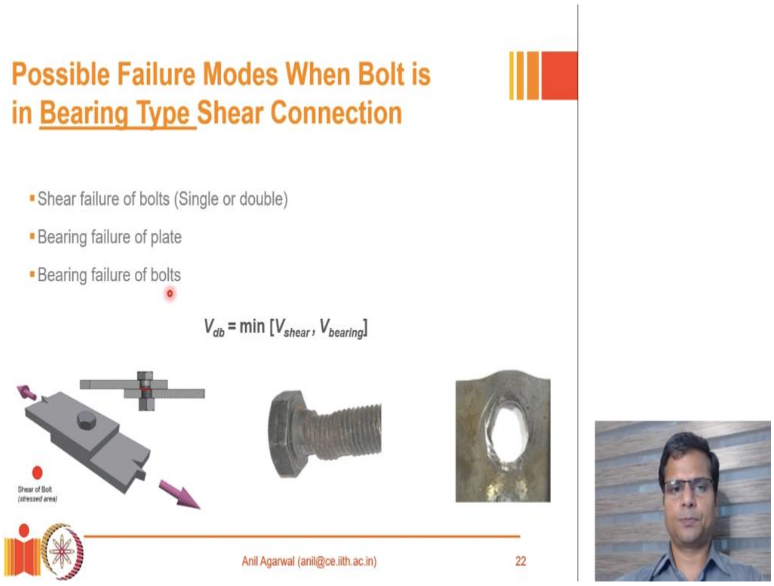

So, if it is a bearing type connection bolt and then it is subjected to shear, there are 2 or 3 distinct ways in which it can fail. So, here is a simple configuration which is shown to you, where these are the 2 plates which are joined together with a bolt like this. And then, these plates are pulled apart as shown here. And there is a possibility that because of this shear force that is applied on the bolt, the net section of the bolt cross-section can fail in shear or rupture in shear.

So, that would be one type of failure. The other type of failure; by the way, this failure surface may pass through a threaded portion of the bolt or the unthreaded, that is shank portion of the bolt; that we need to consider. In addition to this type of failure which is the shearing of the bolt, also there is a possibility of bearing failure of the bolt surface which is marked here.

For example, so, the surface of the bolt deforms locally and undergoes bearing type of failure, or also there is a possibility of bearing of the hole, in which case the hole elongates and then there is a local yielding near the bearing surface of the bolt hole. And all these 3 types of failures are possible. First we will talk about how to calculate the shear strength of a bolt. And the net strength of the bolt will be actually minimum of the shear strength and the bearing strength of the bolt.

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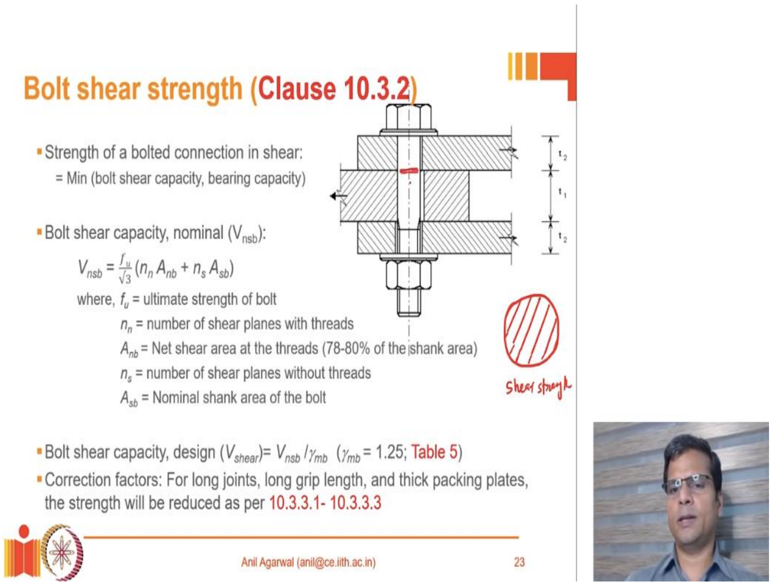

So, when the bolt is subjected to shear force, you can imagine that this is circular surface, a circular round surface which is subjected to shear force demand. And the shear strength of that surface would be actually given by the ultimate stress in shear multiplied by the cross-section area. So, if this is the cross-section area of the bolt, we will take this cross-section area multiplied by the shear strength.

Now, you might realise that the plates or the planes where the shear failure could take place in such a situation are very concentrated, are very well-defined beforehand; they are very well-known beforehand. And in such a situation where the failure is very confined, very restricted in a very small area, we do not use yield stress, but we use ultimate stress.

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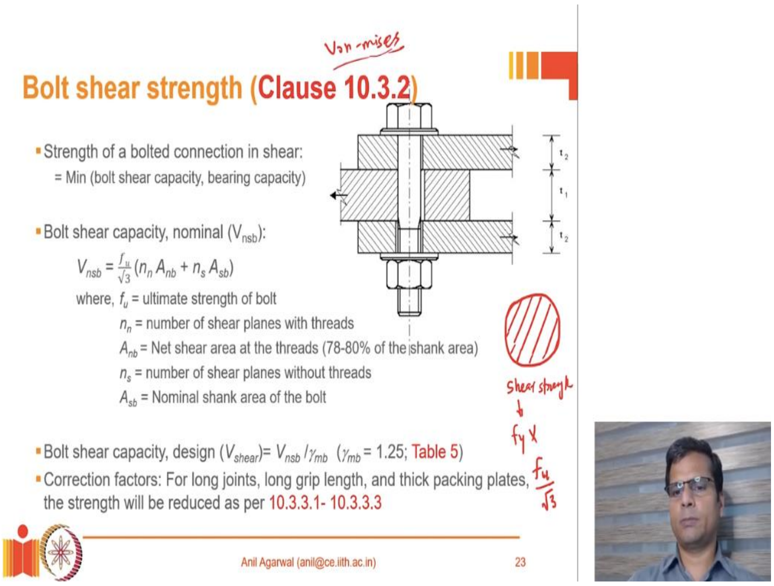

So, instead of using yield stress, we would use ultimate stress, f_u. But f_u is the ultimate stress of steel or the bolt material in pure tension condition. In shear condition, the strength will be given by f_u divided by $\sqrt{3}$. Where is this $\sqrt{3}$ coming from? Do you folks know? What is the reason for a $\sqrt{3}$ factor for shear? The shear strength of ductile materials is very accurately predicted by a criterion called Von Mises criterion.

Von Mises was the scientist who had developed this method which can be used to predict the failure of ductile materials in various triaxial conditions. So, according to that criterion, it was observed that ductile materials such as steel bolt and bolt material 2, they have a yield strength which is approximately $1/\sqrt{3}$ part of the ultimate stress in tension. So, now, you take the case of this bolt. This is a bolt which is holding these 3 plates together.

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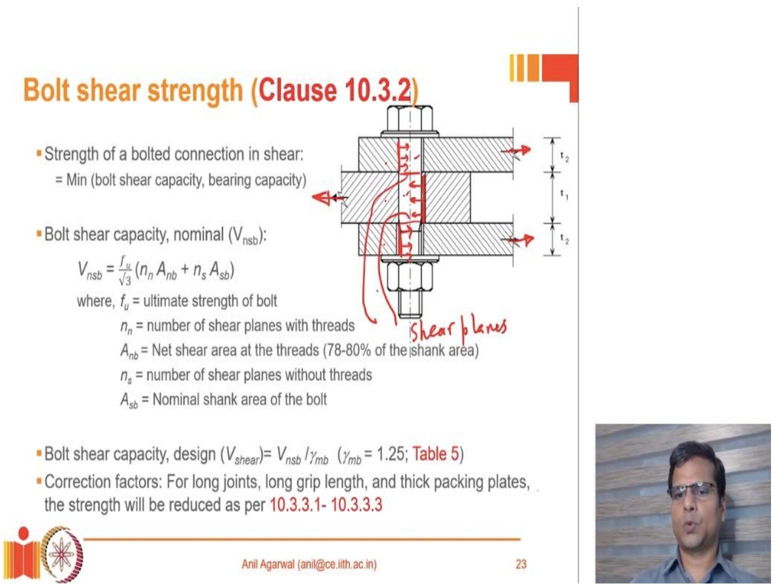

Now, in this particular case, this plate is being pulled in this direction, whereas these two plates are being pulled in this direction. Now, we can very easily identify the shear planes in this bolt. So, if we look at this bolt, here, at this interface, you can see, it is being pulled in this direction. At this interface, it will be pulled in this direction. And at this interface, it will be pulled in this direction. And there will be intermediate cross-sections which would be actually transferring this force from this part to this part. And these planes will be known as shear planes.

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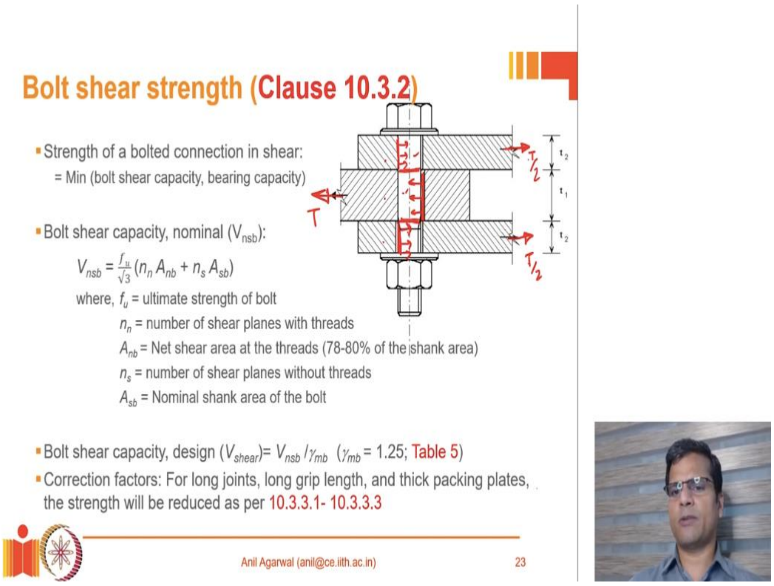

Now, if the total force is T, and let us say this is divided equally between the 2 layers, because these thicknesses are equal. So, this will be T divided by 2; this will be T divided by 2. And if that is the case, the force demand on each shear plane; these are the 2 shear planes I have marked here. The force demand on each of these shear planes will be how much? Take a moment to think about it.

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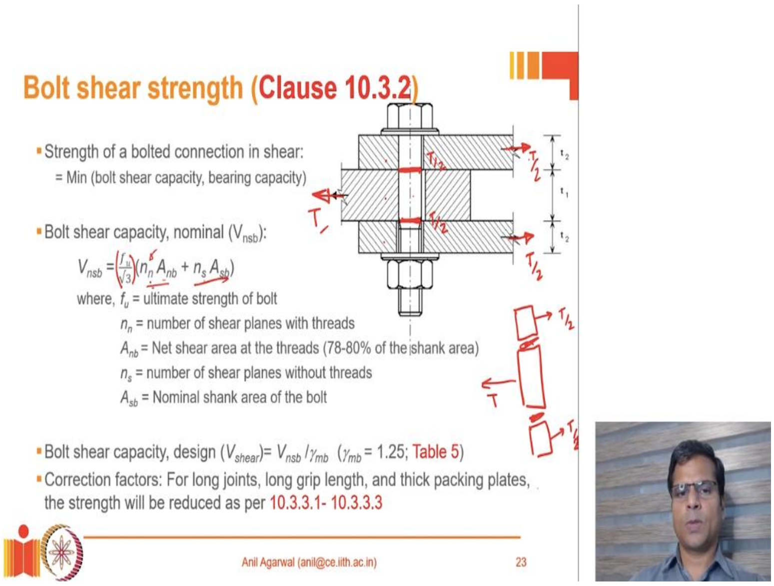

This is the middle portion; I am pulling it by force T. Then this is the other portion which is being pulled by T divided by 2. This is the other portion which is being pulled by T divided by 2. So, how much is the force demand at this shear plane? It will be equal to T divided by 2 at each plane. Each of these two planes will be subjected to a shear force demand of T divided by 2.

In essence, if the total force demand is T, that force demand has to be met by all the interfaces, all the shear planes which are helping resist that force. So, what we can do is, we can calculate the capacity of 1 shear plane, second shear plane, and all of them, and add them together; that should give us the strength of the bolt in shear. That is the capacity or the force that this bolt can resist in shear.

That T force, that is actually the shear capacity of the bolt is written as V_{nsb}, where V stands for the shear capacity; n stands for the nominal shear capacity, because we have not used the factor of safety yet, material factor safety; s stands for shear and b stands for bolt; which is equal to f_u. f_u is the ultimate stress of the bolt divided by $\sqrt{3}$; that is the ultimate shear stress of the bolt, f_u divided by $\sqrt{3}$; multiplied by the number of shear planes multiplied by the area of the shear plane.

Now, there are 2 types of terms here. One is n_n, one is n_s. n_n stands for the net section area and n_s stands for the shank section area. So, if we are careful enough while designing the bolt, we can actually account for 2 different cross-section areas. So, at the shank area, the cross-section area is slightly larger than the cross-section area that is available at the threaded portion. So, we can differentiate between the two and we can actually individually account for those. It is generally a conservative practice to actually assume that.

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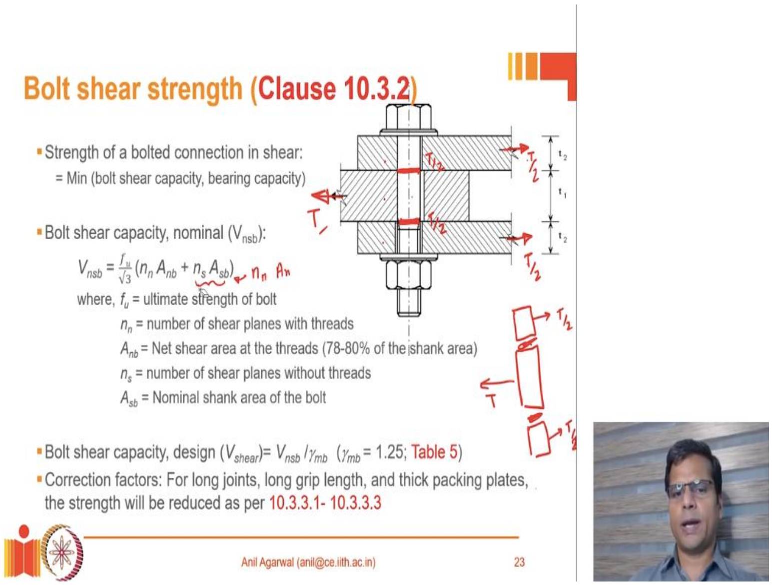

And instead of taking n s multiplied by A_s, we also assume it to be equal to n multiplied by A_n. That is just a simpler approach and a conservative approach as far as design calculation is concerned.

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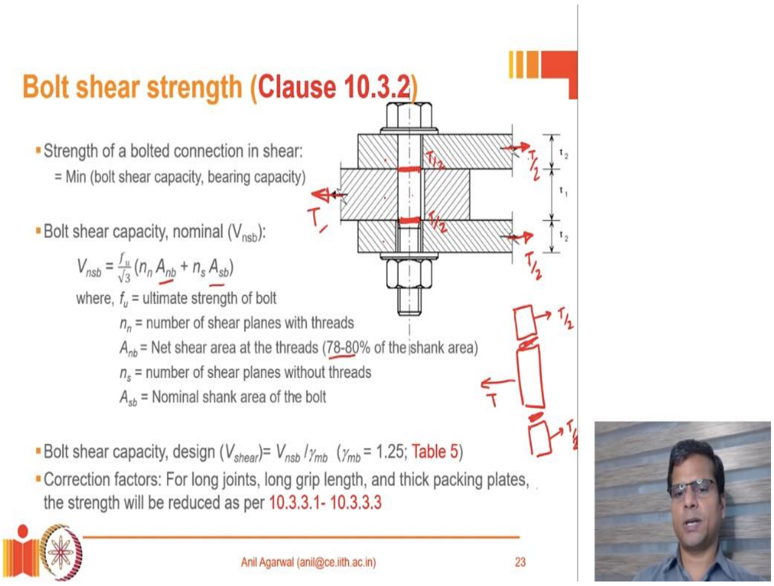

Now, A_s is easy to calculate. If we know the diameter of the bolt, we can calculate the cross-section area of the bolt. That is the cross-section area of the shank. A_n can be calculated as by assuming that the net cross-section area is approximately 78 to 80% of the shank area. So, I hope all the required inputs are available here.

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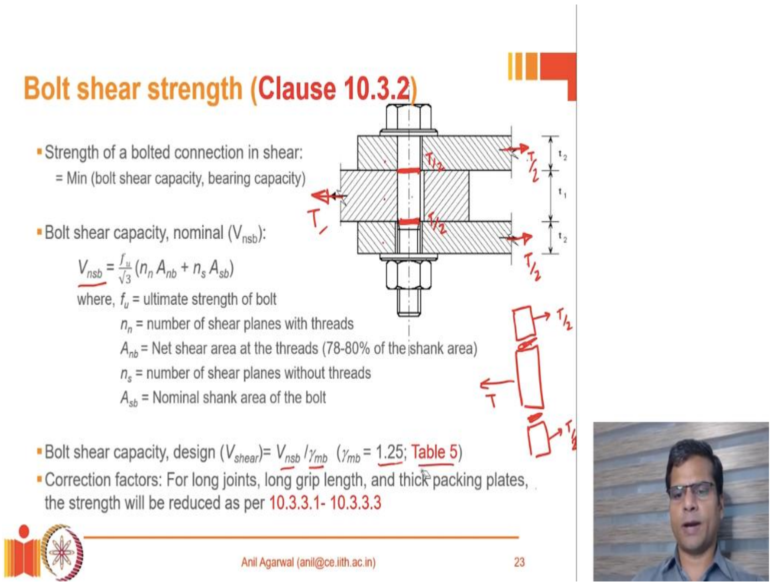

Now, once we know the nominal strength of a bolt in shear, we can divide it with the factor of safety. Now, this factor of safety for a bolted joint in bearing failure or bearing type of a joint is given as 1.25 in Table number 5 of IS 800. So, you go to IS 800, go to Table number 5, you will find the value of γ_{mb}, which is basically the material factor of safety for bolted joints.

You take that factor which is given as 1.25, divide the nominal strength with that factor, and you will get the design strength in shear. Now, one must be mindful that this strength is typically okay for most of the conditions, but there are certain conditions when this strength is not actually accurate.

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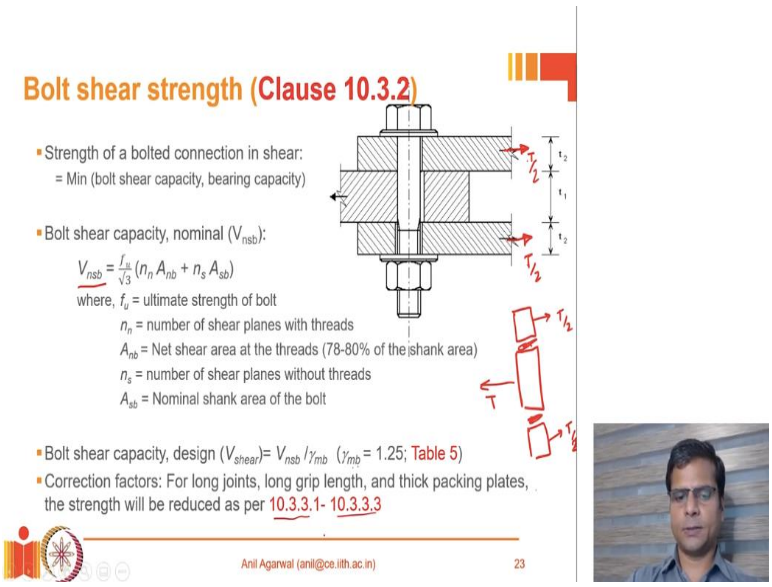

And there are some additional factors which play a role that we will talk about briefly in the next couple of slides.

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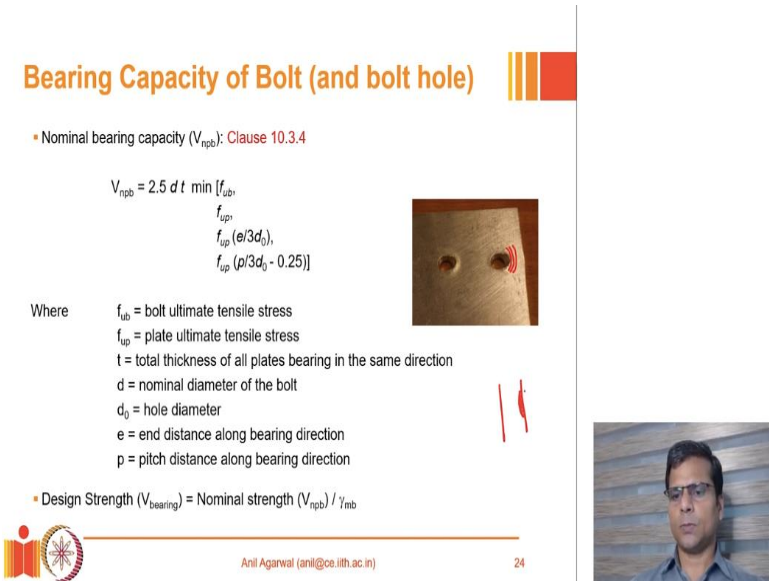

Before we get into the other factors, let us also talk about the bearing type of a failure. So, you might remember, the first limit state was the bolt shear failure and the other two limit states were bolt bearing failure and plate bearing failure. So, as we had seen, if a bolted joint, if a hole is subjected to a shearing stress, it actually translates into the bearing stress concentration at the bolt hole surface.

And then, this portion of the plate or subsequent portion or the corresponding portion of the bolt also can yield locally under that stress. And in such a situation, the strength of the bolt or the bolt hole to resist this load has to be calculated. And that will form the other limit state.

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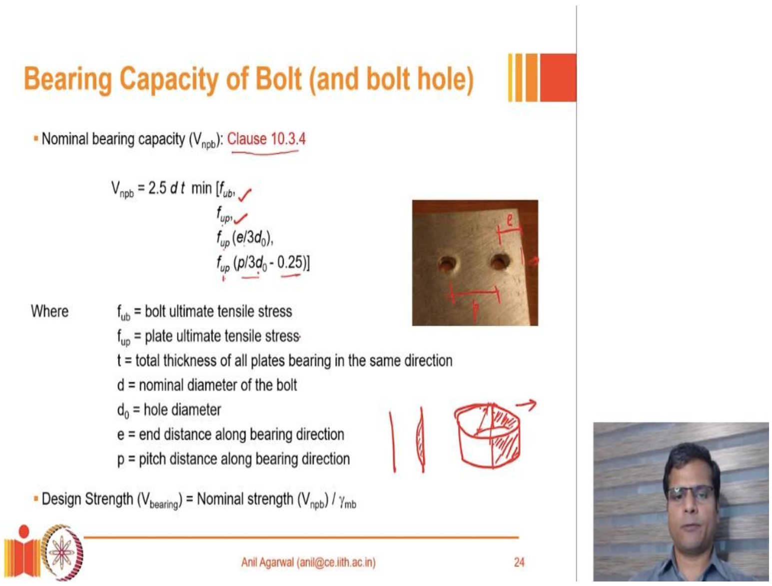

The expression for the bearing strength of a bolt is given in clause number 10.3.4 of IS 800. Now, here, as you might imagine, if I look at a bolt hole and there is a shank inside, there is a bolt inside which is loading this half of the cross-section or this half of the shank surface area in this direction. Now, basically the parameter that should play a role here is the thickness of the plate, the diameter of the bolt.

That is, d is the diameter of the bolt; t is the thickness of the plate; and an empirical factor of 2.5 which basically tells us the effective area which is actually resisting that load, multiplied by some material strength. So, if it is the failure of the plate, we would use f_{up}. If it is the failure of the bolt shank locally, local yielding, then we would use f_{ub}. Also if the hole is very close to the edge or if 2 holes are close together; so, if the hole is very close to the edge, it is bearing strength reduces. So, therefore, instead of using f_{up}, we would use f_{up} multiplied by e divided by $3d_0$, which essentially means is that, if your e value is less than 3 times the hole diameter, then it will start interfering with or reducing the bearings strength of the hole. Similarly, if the 2 holes are close together, then, instead of using f up, we use f up multiplied by the pitch distance; that is the distance of the holes in the direction of the load; divided by 3 d_0; d_0 is the hole diameter; minus 0.25.

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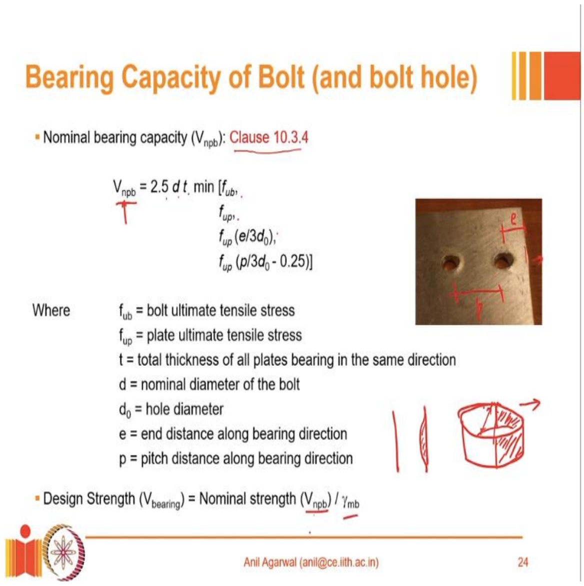

So, and then, basically depending on whichever factor of the 4 of these governs the capacity, which will be the smallest of the 4. The smallest of the 4 will govern the capacity. So, we will calculate all these 4 factors; we will take the smallest of the 4. And that multiplied by t multiplied by d multiplied by 2.5 gives us the bearing strength of the bolt in bearing. And again, the design strength; so, this will be the nominal strength; n stands for nominal strength in bearing. The design strength will be actually equal to nominal strength divided by γ_{mb}; again the material factor of safety for bolted joint.

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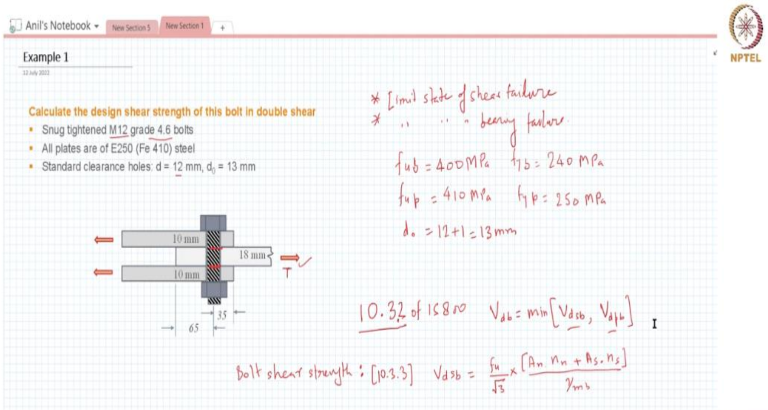

So, we had just gone through the 2 limit states for bolt failure. One limit state was for the bolts which are subjected to shear and are bearing type. There are 2 limit states. One limit state was limit state of shear failure, and the other one was limit state of bearing failure. So, let us do one example here. Here you can read the example. It is required to calculate the design shear strength of this bolt in double shear.

Why am I calling it double shear? Because it is basically 1 plate here which is connected to these 2 plates. This is a lap joint type of a connection. So, this plate is an 18 millimetre thick plate which is subjected to a force in this direction. And then, these two plates which are resisting that force in equal amount, both of them are 10 millimetre thick. And then, a bolt is connecting these 3 plates together.

Now, if we want to calculate the design shear strength of this bolt, we need to follow the following steps. Some details are given that the bolt is 12 millimetre diameter, M12 and the grade of the bolt is 4.6 bolt. 4.6 basically means that f_u of the bolt is equal to 400 MPa; f_y for the bolt is 240 MPa. The plate is given to be E250 or Fe 410 steel, which basically means that f_u for the plate is equal to 410 MPa, and f_y for the plate is equal to 250 MPa.

The bolt is a 12 mm diameter bolt and the hole is a standard clearance hole. So, for a 12 millimetre bolt, we know that the hole diameter would be 12 + 1 which is 13 millimetres. Now, we need to design the bolt. So, we know from section 10.3.2 of IS 800, it says that design shear strength of such a bolt will be equal to minimum of the design shear strength of the bolt and design bearing strength of the bolt.

This is shear strength; this is bearing strength. Now, when we are talking about this particular bolt, we have to first check what is the shearing action that is going on; first we will check for the shear strength. So, as we have discussed before, in this kind of a joint, you might notice that there are 2 shear planes. One shear plane exists here; the other shear plane exists here. And each shear plane will be resisting half of the total force.

So, if the total force is T here, each shear plane will be resisting T divided by 2 force. So, if I want to calculate the total shear strength of the bolt, total shear strength of the bolt will be equal to, we will use section 10.3.3 of IS 800 which says that V_{dsb} is equal to f_u of the bolt divided by $\sqrt{3}$ multiplied by A_n; that is the net cross-section area; multiplied by the number of net sections plus A_s; that is shank area; multiplied by number of shank sections, shear planes, divided by γ_{mb}.

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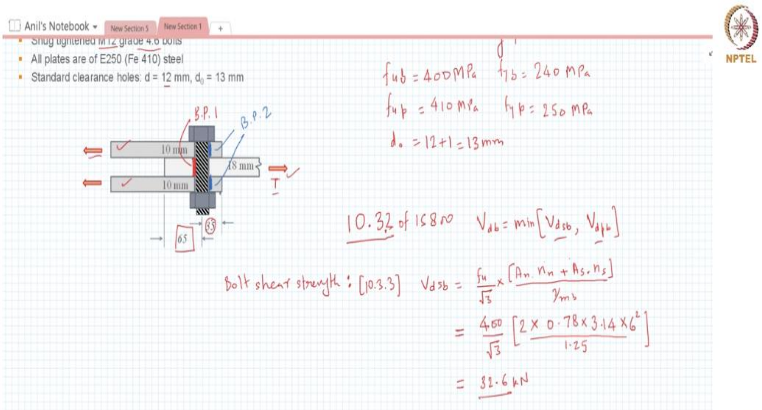

Now, we know that gamma mb is actually equal to; by the way, this is for 1 shear plane. For the 2 shear planes, it will be equal to; since there are 2 shear planes, it will be equal to summation of the 2 strengths. So, first we will look at f_u, that is 400; we know f_u of the bolt is 400 divided by $\sqrt{3}$. Then, we know that there are 2 shear planes. Now, we do not know exactly what is the length of the threaded portion and what is the length of the shank length.

So, it is a conservative way of assuming that both shear planes are passing through the threaded portion. And if that is true, we can simply double the net section area. So, 2; that is, number of net sections are 2; multiplied by the net cross-section area; net cross-section area is approximately 78% of the shank cross-section area. And what is the shank cross-section area? That is Πr^2

The diameter is 12 mm of the bolt, so, radius is 6, squared. So, that is the cross-section area; divided by 1.25. Now, we can calculate this. This turns out to be approximately 32.6 kiloNewton. So, this is the shear strength of this bolt. The bearing strength is slightly more involved. We have to consider 2 possibilities for the bearing strength. If you look at it, if you look at this bolt, here, when this plate is pulling the bolt in this direction, there is a shear plane here.

This shear plane is resisting the entire T force. And also, when these two plates are pulling the bolt in this direction, there are 2 shear planes here; together they are also resisting force T. So, first we need to check whether this shear plane can adequately resist the force. And then we can check what is the capacity of this shear plane. So, let me mark them in different colours for ease. So, bearing plane that is marked in red is called bearing plane 1; and the ones that are marked in blue are called bearing planes 2. So, we need to check for design strength of both of these.

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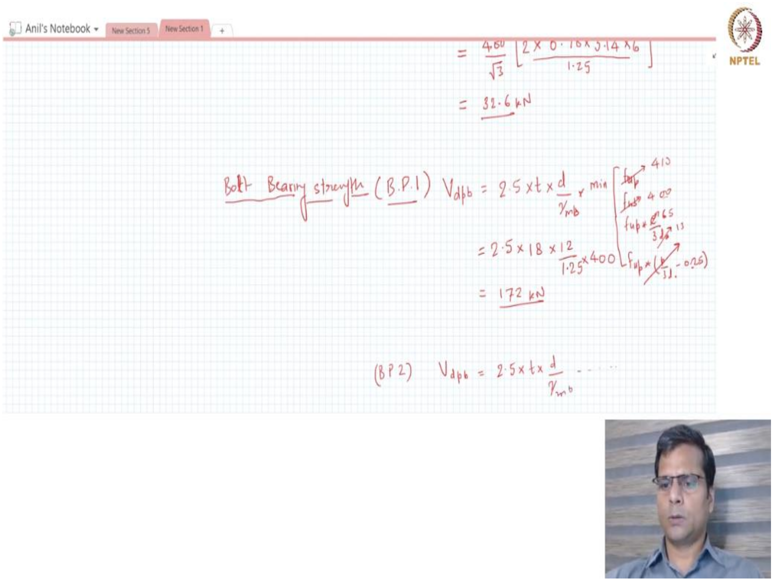

For bearing strength, I will first work with bearing plane 1. For bearing plane 1 or bearing surface 1, the expression for bearing strength is given as 2.5. V_{dpb} is equal to 2.5 times the thickness times the diameter of the bolt divided by γ_{mb} multiplied by minimum of these values, f_u of the plate, f_u of the bolt, f_u of the plate multiplied by e divided by 3 d_0, and f_u of the plate multiplied by p divided by 3 d_0 minus 0.25.

So, now, there is no matter of pitch here, because there is only single bolt, so, there is no pitch. So, this part will be ignored. However, e is the end distance; that we need to be careful about and we need to measure the end distance appropriately based on the force direction. So, for the bearing plane 1, or bearing surface 1, the end distance will be this distance, 65, which is marked 65 here.

So, we will take for bearing plane 1, we will calculate these values, 2.5 times the thickness. So, for bearing plate or bearing plane 1, the thickness of the plate is 18 millimetres, the diameter is 12 millimetres, γ_{mb} is 1.25, multiplied by minimum of f_{up}, f_{ub}. So, f_{up} for the plate is 410; for the bolt it is 400. F_{up} multiplied by e divided by 3 d_0; so, e is equal to 65 divided by 3 d_0. d_0 = 13; this is 65. So, 65 divided by 39, it is more than 1.

So, all these factors are more than 1. The smallest of these is 400. So, we will take 400 here. And as a result, this value turns out to be 172 kN. That is for the bearing plane 1. However, bearing plane 2 has to be considered 2, which basically consists of 2 plates. So, and actually, the minimum of the 2 bearing strengths will be the strength of the bolt. Again the same expression 2.5 times t times d divided by γ_{mb} and so on and so forth.

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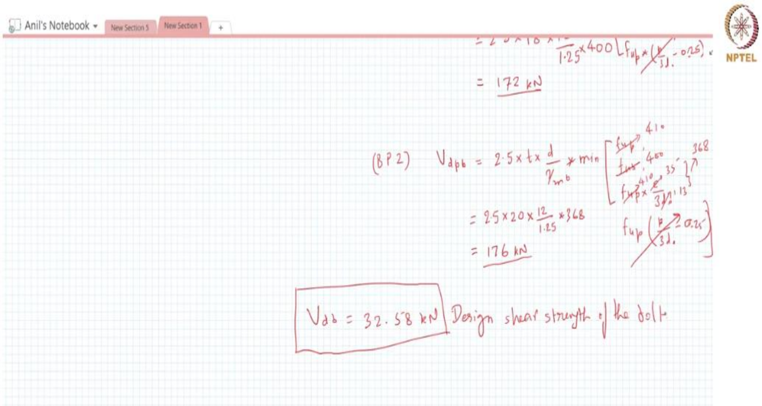

However, let me write it fully; multiplied by minimum of f_{up} first; f_{ub}; f_{up} multiplied by e by 3 d_o; and f_{up} divided by 3 d_0 minus 0.25. So, like the last time, the last term will be not relevant. So, we can ignore it because there is no pitch distance here. f_{up} multiplied by e divided by 3d $_0$, in this case if you see, for the blue surfaces, you might notice that the edge distance or n distance is normally 35 millimetres, which is shown here.

So, the e value is 35 and the d_0 is 13. So, basically, it becomes 35 divided by 39. f_{up} is again 410; f_{ub} is 400; and this is 410. We substitute the values again. 2.5 multiplied by thickness; this time we will take the thickness of the 2 plates. So, each plate is 10 millimetre thick; so, we will take 20 millimetre total thickness. Diameter of the bolt is 12 millimetres divided by 1.25 multiplied by minimum of 410, 400 and 410 multiplied by 35 divided by 39.

Which number turns out to be the smallest of the two? This turns out to be; 368 MPa. So, we will take 368. And this is equal to 176 kilonewton. Now, we have seen there are 2 bearing strengths, bearing strength of the 2 thin plates is 176. Bearing strength of the thick plate is 172 kilonewton, and the shear strength is 32 kilonewton. The actual design strength v_{db} is the minimum of the three. So, V_{db} will be equal to the minimum of the three, which turns out to be 32.58 kilonewton, the design shear strength of this bolt is 32.58kN.