Design of Connections in Steel Structures
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Module - 1
Lecture - 5
Design of Friction Grip Bolts in Shear and Design of Bolts in Tension

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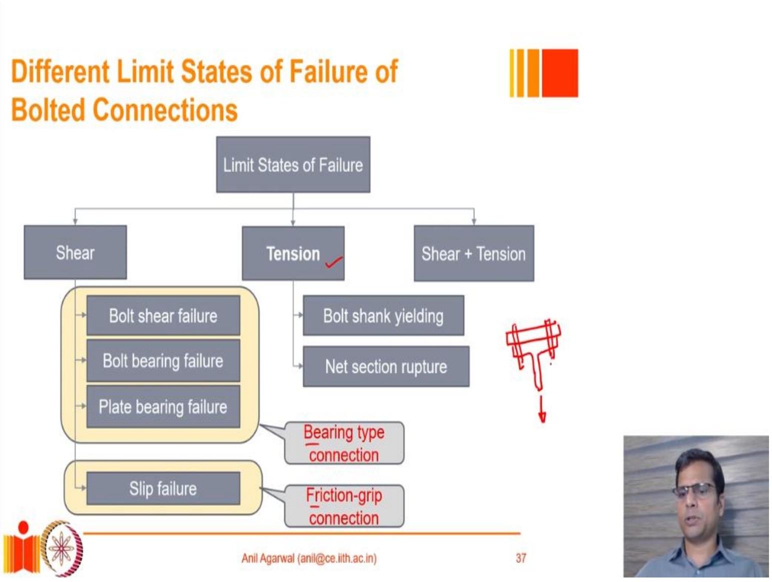

So far we have seen how to design or how to calculate the strength of a bolt if it is subjected to shear force and if it is of bearing in nature. So, these are the 3 cases where bearing type connections or a bolt which is a bearing type bolt, when it is subjected to shear force how to calculate its strength. And we have considered the shear strength, bearing strength and including the correction factors which correspond to extra-long bolt or extra-long joint or the case where there is a packing plate, extra-thick packing plate.

Now, we will talk about the bolts which are not bearing type connections but they are a part of friction grip type connection, where the plates are held in place through friction. And such plates have to be designed to resist slip between the plates or such connections are designed to resist the slip. And the limit state, corresponding limit state is the slip failure. So, we will talk about how to design under such conditions.

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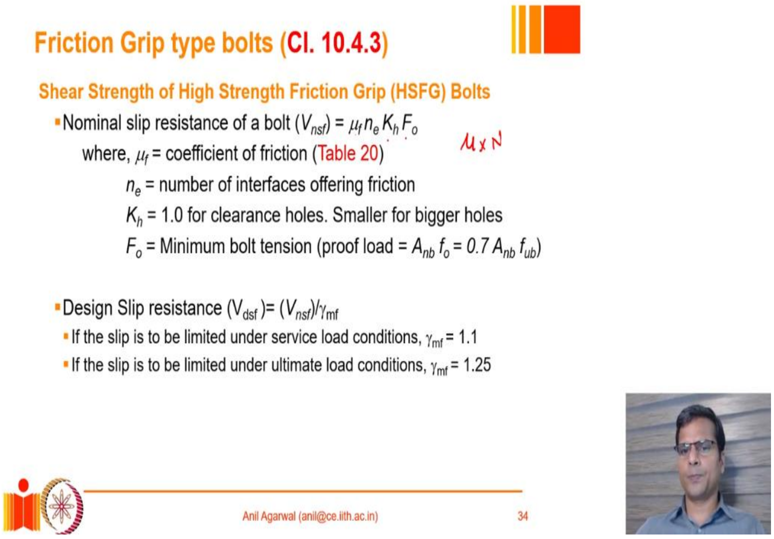

So, since we know that the plates are held in place through friction, the strength of that connection would be basically a function of the friction force. So, the slip resistance of the bolt will basically control the strength of the connection. So, a single bolt would have a strength which is basically equal to the slip resistance of the bolt that again can be calculated as the friction coefficient between the plates multiplied by n e.

n e here corresponds to the number of interfaces which are offering the friction. K_h is a coefficient which represents the situation when the holes are slightly larger than clearance holes. So, if the hole size is greater than the clearance hole size, then the K_h is reduced; otherwise, for standard clearance holes, K_h remains 1. And f_0 here corresponds to the amount of tension that is present in the bolt, because the amount of tension that is present in the bolt that is proof stress level load, that would be same as the compressive force between the plates which are trying to slip.

So, essentially if you see this formula, this formula is nothing but friction coefficient multiplied by the normal force. So, f_0 corresponds to the normal force and friction coefficient is the friction coefficient which will be the slip force or sliding force.

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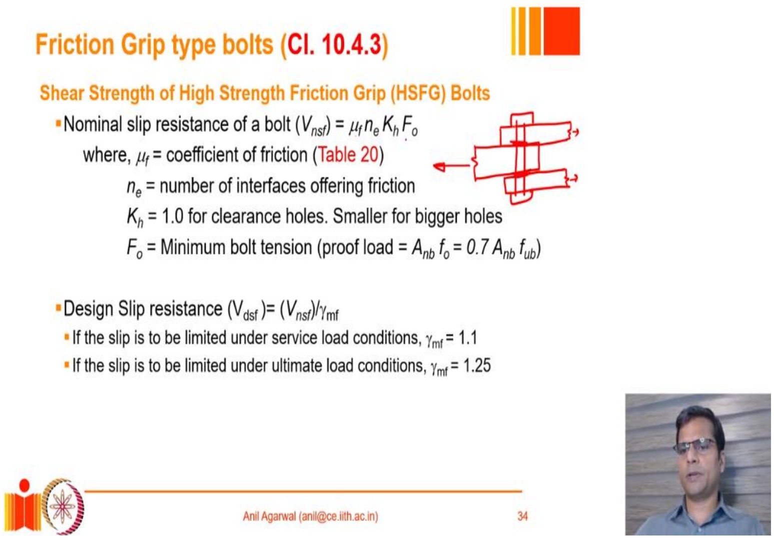

For example, if I have this lab joint that we have seen before as well, and there is a bolt which is connecting these 3 plates together and it is pretensioned, then for this plate, the middle plate to be able to slip out, we need to overcome friction at these 2 interfaces, at these 2 planes. So, there are 2 such planes where the friction is acting.

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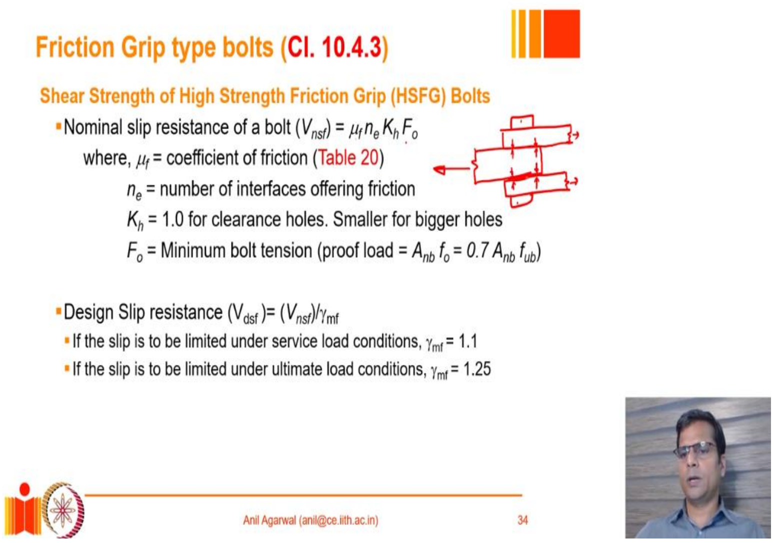

And why is that friction present there? The friction is present because of the tension in the bolt, there is a compression between these 2 plates. So, between this plate and this plate, there is a compressive force which is holding the bolt in place. Likewise, there is a compression between this plate and this plate. And because of the presence of this compression that normal stress, there will be a shear slip resistance that will be present.

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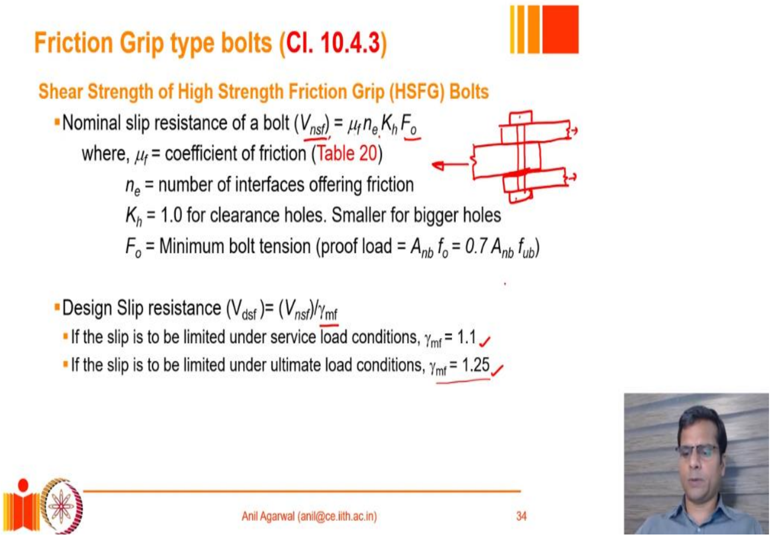

So, in this particular case for example, we would have n e equals to 2. Now, that V_{nsf} which is given here is basically the nominal strength, there is no factor of safety applied yet. After applying the material factor of safety, we would use Υ_{mf} value which is the material factor of safety, which is either 1.1 or 1.25 depending on the following condition. If this joint is supposed to behave like a slip critical joint under ultimate conditions also, that is under ultimate loads also, then the factor of safety is to be taken as 1.25.

But there are situations when many a times these connections are designed to be slip critical under service loads, that is under serviceability conditions, but they are designed to be bearing type connections under ultimate load conditions. So, basically, we do not have to apply enough tension force, so that it can resist through friction, the entire maximum load. Through friction it has to only resist the service loads, so that from day to day requirement there is no slip.

But however, whenever there is an ultimate load, the maximum possible load that comes to the structure, at that time it allows for the slip and then the connection changes its behaviour into a bearing type behaviour. So, if that is the design philosophy, then for service load conditions, that is for slip resistance, we will take a factor of only 1.1.

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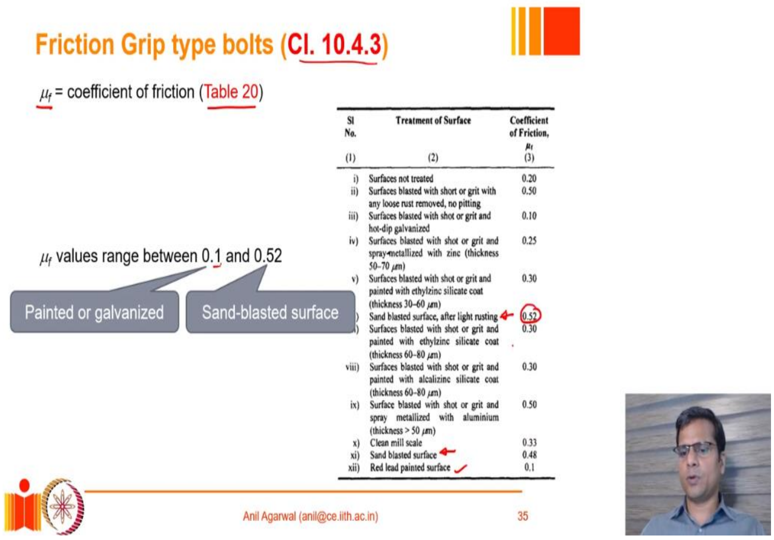

The friction coefficient that we just saw, we can get the values of friction coefficient from table 20; this is again clause 10.4.3 of IS 800. The values of friction coefficient between the 2 steel plates can vary between 0.1 and 0.52. So, this is a wide range and of course it depends on the surface treatment that is provided between the 2 plates. So, if the 2 plates are treated with a smooth finish; what could be an example of a smooth finish?

If it is a red lead paint surface or if it is a galvanised surface, then the friction coefficient will be very small and we can take a friction coefficient of only up to 0.1. However, if the surface is sandblasted and followed by some rusting, in such situations, we can see that friction coefficients of up to 0.52 can be taken which is basically a very rough surface and that will increase the slip resistance. So, these coefficients can be taken from this table.

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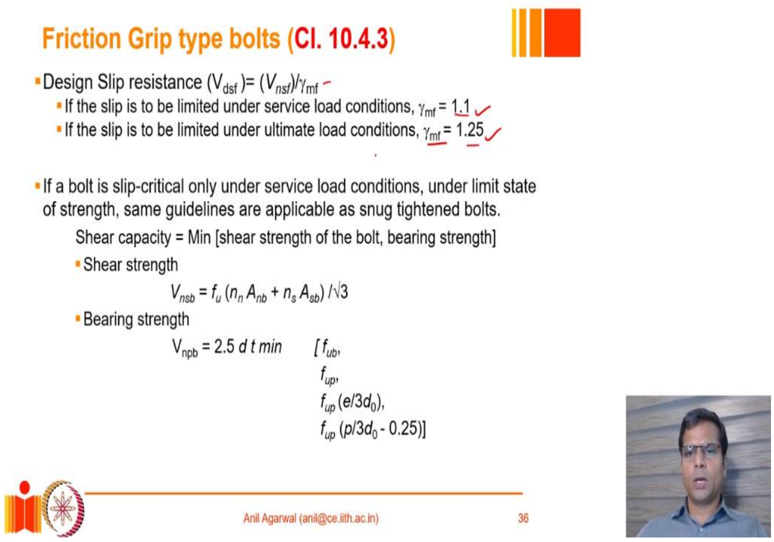

Now, just to reiterate, the 2 different factors of safety, material factors of safety, for service load conditions, if it is slip critical, we will be taking 1.1, but for ultimate conditions, that is strength limit state, if we want the connection to behave as a slip critical connection, then the factor of safety will be taken as 1.25. Now, in such a situation where the connection is assumed to be slip critical only for service conditions.

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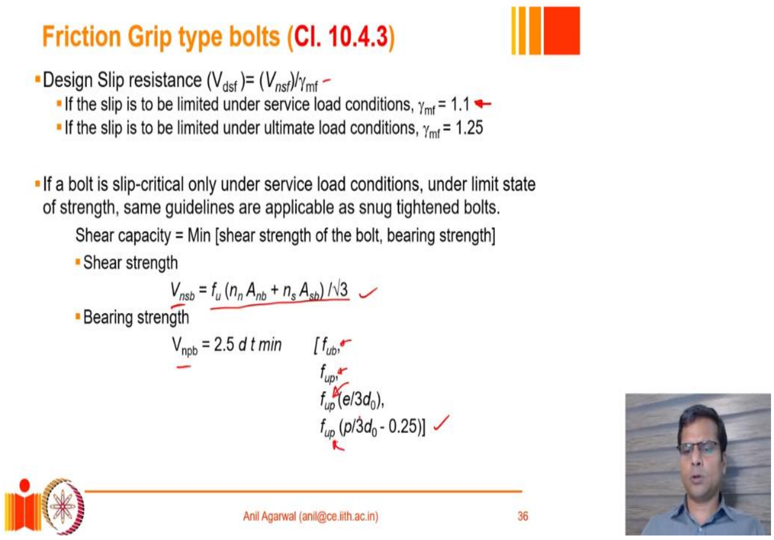

For ultimate loads, we would design the connection just like we did design the bearing type connection. So, the shear strength in that case will be similar to this, and a factor of safety of 1.25 will be applied. And the bearing strength will be again given by the same expression that we have seen before. This corresponds to bearing failure of the bolt, bearing failure of the plate, bearing failure of the plate if the hole is very close to the edge, and bearing failure of the plate if the holes are too close together in the direction of the load.

So, the same limit states that we have seen before for bearing strength, the same limit states would apply, only thing is, just like before, the material factor of safety will be taken as 1.25 in this case too. So, now, so far we have discussed all the possibilities when the bolted joint is subjected to shear. The bolted joint could be of bearing type or it could be a friction grip type. Now we will talk about the situations when a bolted joint is subjected to tension.

What could be such a situation? A common situation could be, when I have a plate and to this plate I attach a T section, and this T section is basically supporting some load, and this T section is bolted to the other plate using these 2 bolts; so, these 2 bolts in this situation would be under tension. So, what could be the design strength of such bolts when they are subjected to tension, we will discuss that. Then at the end, we will discuss the situation when the bolts are subjected to a combination of shear and tension.

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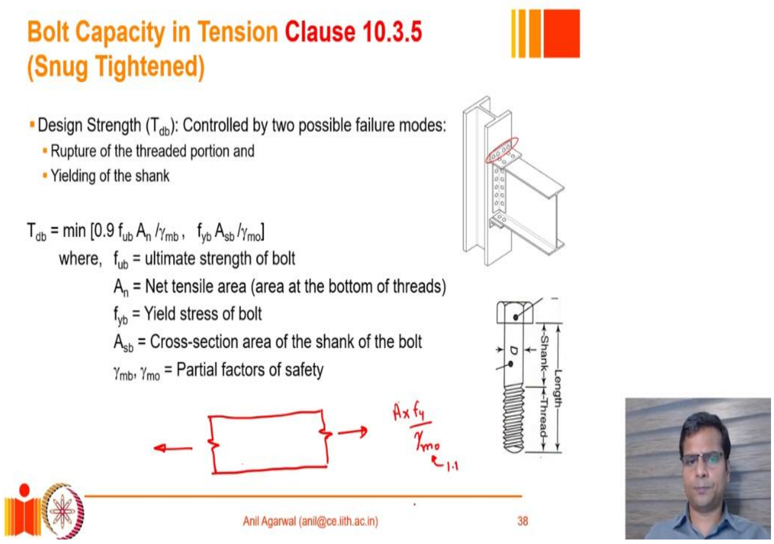

So, now, before I go into the details of how these bolts are to be designed in tension, let me try to recall some basic concepts that you might have learnt while learning the design of members, steel members in tension. So, you might recall that when we have a steel plate that is subjected to tension, if it has a uniform cross-section like the one that is shown here, the strength of this plate in tension is given by cross-section area multiplied by f_y divided by Υ_{m0}. So, area was the cross-sectional area; f y was the yield stress of the plate; and Υ_{m0} was the factor of safety for yielding, which had a value of 1.1.

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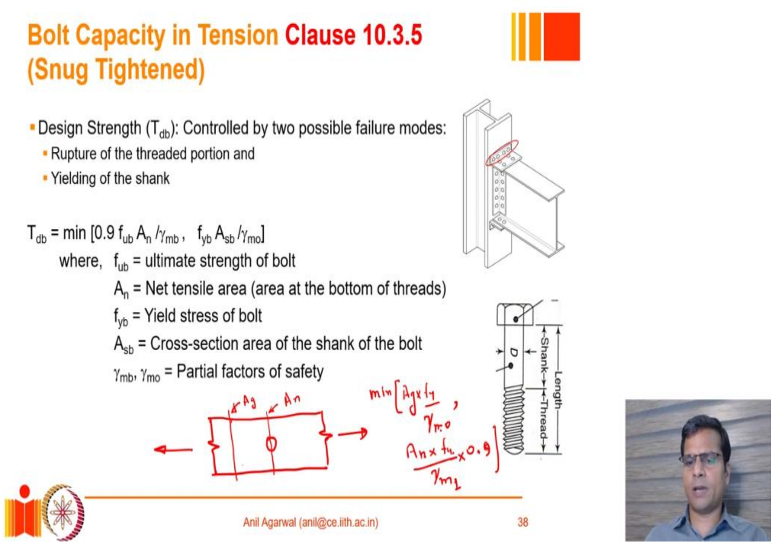

However, when this plate had a non-uniform cross-section, let us say there was a hole in the plate somewhere. And then, the cross-section area here is different from the cross-section area here. In such a case, the tensile strength of this plate was actually equal to, was governed by whichever section had lower strength. So, the gross cross-section; this cross-section was called gross cross-section and this cross-section was called a net cross-section.

Net cross-section is susceptible to rupture. We did not worry about net cross-section yielding, because, when we confine the failure, the governing limits, it becomes the rupture limit state, and then we take the net cross-section area. So, the strength was basically equal to minimum of A_g, gross cross-section area multiplied by f_y divided by Υ_{m0}; that was one. And the other value that was A_n, net cross-section multiplied by f_u divided by gamma m 1.

And then there was an additional factor of 0.9 that was applied to account for the significant consequences of a rupture type of a failure. You might recall that. So, here there are fundamental differences. One was that A_n was taken instead of A_g; f_u ultimate stress was taken instead of f_y. Because, when we talk about net cross-section, we talk about rupture failure.

We do not mind if in net cross-section, that is in localised cross-section, if it has some localised yielding. That is not a problem; that we tolerate, but we do not worry about it yielding there. We say only when a localised cross-section starts to rupture, that is when the strength limit state is reached. gamma m 1 is basically provided as an additional factor of safety which has a higher value than gamma m0. Generally, it was taken as 1.25; and then an additional factor of safety of 0.9 was used. Exactly the same concept can be utilised while designing a bolt in tension.

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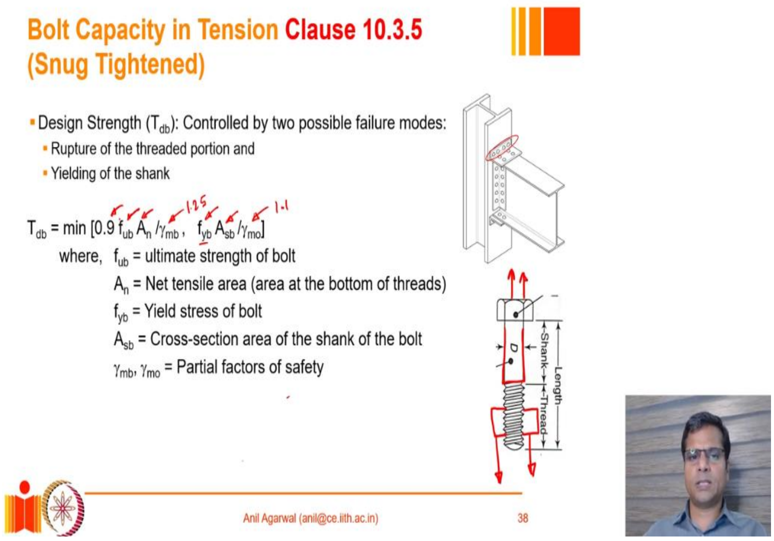

So, when we see a bolt that is subjected to tension, you can imagine that this is a bolt and then there is a nut here which is basically pulling the bolt to this side at this end, and it is being pulled to this side at this end. As a result, this portion of the bolt is subjected to pure tension. Now, this much part of the bolt is having a uniform cross-section which is larger than the portion that is here.

So, this portion has a net cross-section which we call A net. And the strength or the failure in the net cross-section area will be a rupture type of a failure and we will use the limit state of f u, that is ultimate stress multiplied by the net cross-section divided by gamma mb which has a slightly higher value than gamma m0, and an additional factor of 0.9 because we want to avoid rupture. And we prefer to have a failure governed by yielding.

The other limit state is f yb which is yield stress multiplied by A sb which is the entire cross-section area, gross cross-section of the shank and divided by gamma m0 which has a smaller value, that means the factor of safety is smaller, 1.1, whereas this value is 1.25. So, the concept wise, the bolt in tension has very similar limit states as a plate in tension.

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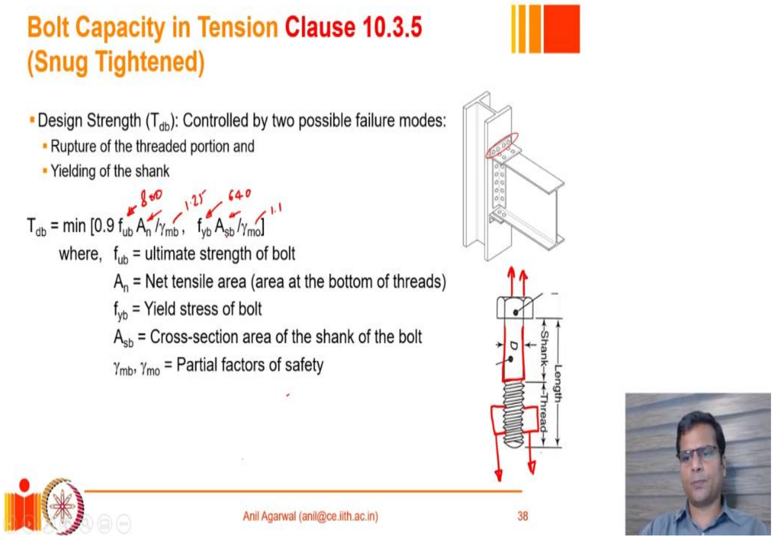

Now, as we already know, f_u value; for example, if I have a bolt of grade 8.8, then f_u value will be 800 and f_y value for this bolt will be approximately 640 MPa. Similarly, A_n and As the relationship between A_n and A_s is, A_n is approximately 78% of A_s shank area. So, these 2 relationships we already know. We know the values of Υ_{mb} and Υ_{m0}. By using these values, we can calculate the tensile strength of a bolt.

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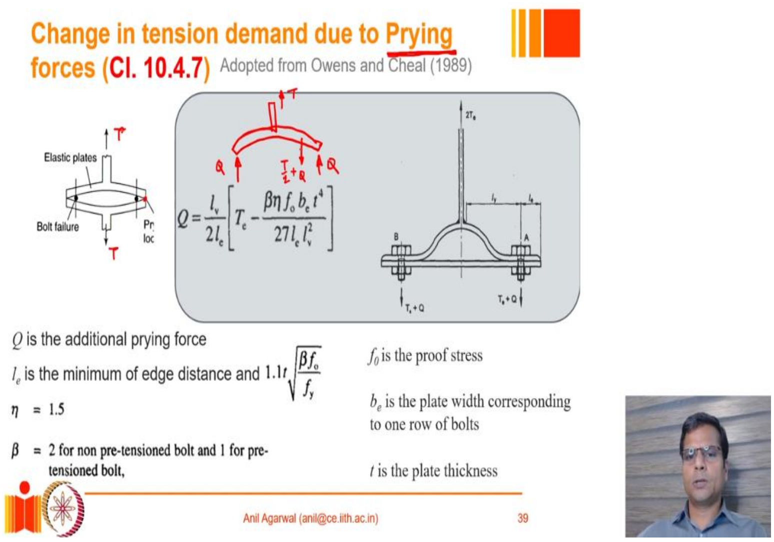

Whenever the bolts are subjected to tension, there is a phenomenon which is known as prying action, you might notice it here. That is a very interesting phenomenon and let us talk about that for a minute. This happens only when the bolts are subjected to tension, it does not happen when the bolts are subjected to shear type of force. So, let us take a situation. Let us say these are the two T sections.

One T section is this one and the other T section is this one. These are straight in the beginning, and then they are being pulled in 2 different directions as shown here. And they are held together with the help of 2 bolts; both of them are marked here, bolt 1, bolt 2. Now, you might appreciate that the bolt cannot be placed at the very edge, it has to be slightly inside.

And if the plates themselves are not perfectly rigid, they are slightly flexible which they are most of the times. So, if this plate is flexible and the bolt itself is also slightly flexible, when these plates pull apart, they undergo a curvature and as a result, the farthest end of these plates or these flanges start to bear against each other. And that additional bearing, if you draw the free-body diagram of this plate, you would see that, that additional bearing is actually an additional force that is acting on this plate which has to be resisted by the bolt.

So, if there was no prying action, we would assume that if T force is applied here, so, each bolt would resist a force of T divided by 2 if it is a symmetric system. However, because of the prying action; let me draw the free-body diagram of this, one of the T sections. If this force is T and there is a prying action, let us say that force is Q; then, similarly there is a Q force here; at both ends you have a prying force of Q, which is basically coming through the bearing with the other plate.

Now, as a result, the only way this T section can be in equilibrium is if the bolt resists a force of T divided by 2 plus Q. So, now you can see that in comparison to the situation where there was no prying action, now, we have got an additional force of Q in the bolt. That is an unintuitive, non-intuitive kind of situation which has to be accounted for when we are designing a bolt in tension.

There are lot of researchers who have looked into this behaviour of plate sections or plates which are subjected to this kind of a tension. And the bolts, how the force increases for the bolt; there are several equations which have been proposed in the literature.

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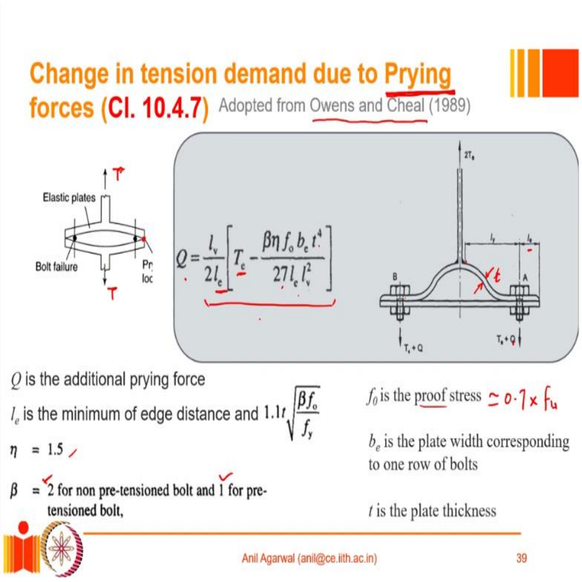

The Indian code accepts, has adopted the equation which was proposed by Owens and Cheal in 1989. The equation for this Q force; Q is the additional tension force in the bolt; is given by this expression. This is primarily an empirical equation wherein some of the factors that are listed here; you can see. l v is the distance from two of the weld to the centre of the bolt. So, that is basically kind of a lever arm on this side.

This is the l_e value; l_e the lever arm on the other side. T_e was the original tension force which was acting on a single bolt, that T. **β** is a factor which depends on whether the bolts are pretensioned or not. If the bolts are non-pretensioned, beta can be taken as 2; if the bolt is pretensioned, beta will be taken as 1. Another factor **η**, it has a constant value of 1.5. f_0 is the proof stress, the level of proof stress in the bolt.

So, we know the proof stress is typically taken as 70% of f_u value; that is what f_0 will be. b e is the depth or width of this plate in the perpendicular direction; that is the width that is corresponding to the one row of bolt. So, this is one row of bolt; so, how much of the width of this section is supported by 1 bolt, that is the width v. t is the thickness of this plate, because, how much prying action will develop also depends on the plate thickness.

If the plate is very thick, it does not deform at all and as a result, there will not be much of a prying action. So, t has an important role to play there. Divided by 27 l_e l_v which we have seen already, which factors these are. So, we can use this expression to calculate the additional tension force demand in the bolt.

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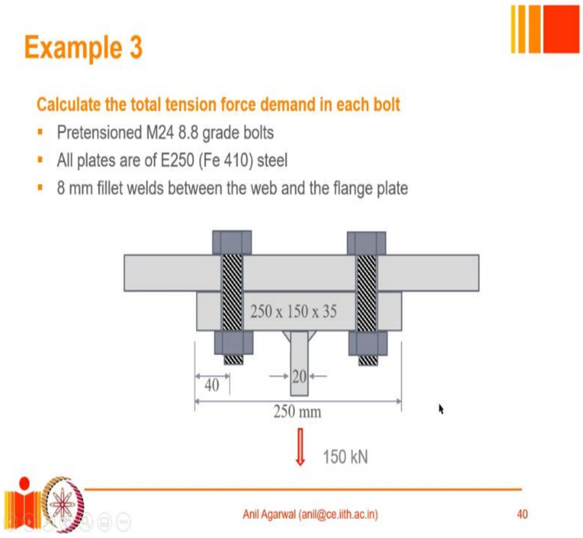

So, now, let us do an example.

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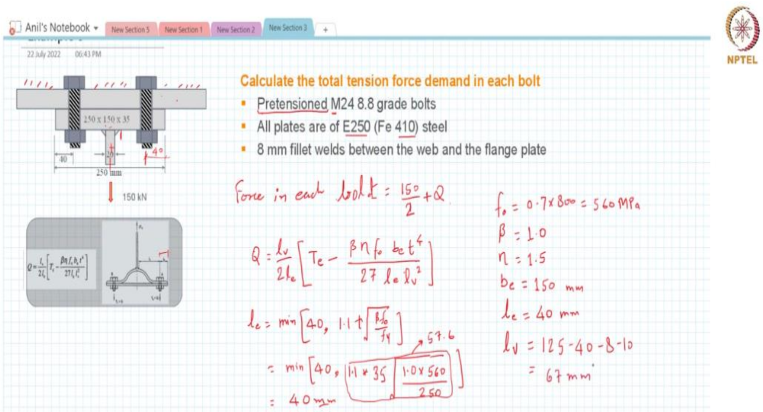

So, let us try to solve this example. This plate is held in place. The thickness of this plate and properties of this plate do not really matter. This particular plate is tied to the first plate using these 2 bolts. The bolt properties are given. The diameter is 24 millimetre and material is 8.8 grade bolt. This plate, the second plate, its dimensions are 250 millimetre width in this direction, the depth is 150 millimetres.

So, that 150 millimetre depth is supported by these 2 bolts, and thickness is 35 millimetres. The plate is made of E250 steel. It has a yield stress of 250 MPa and ultimate stress of 410 MPa. Also, this web is welded to the plate, to the flange using two 8 millimetre fillet welds as shown here. The other dimensions, for example, the edge distance here is marked as 14 millimetres. So, the bolt is given as a pretension bolt.

So, some of the factors in that equation will be affected by that. Now, we remember that we copy paste that formula for the capacity for the prying force. Now, in this expression, you might see, Q is the additional force. So, each bolt is likely to have; will be equal to 150 kilonewton divided by 2 plus the Q force. So, we need to calculate what is the Q value. Q value will be given by l_v divided by 2 l_e T_e; T_e is actually the force in each bolt without accounting for the prying action; minus **β** , **η** f $_o$ b_e t to the power 4 divided by 27 l e l v squared.

Let us try to calculate the values of each of these factors. f_0 here is the proof stress level which is generally taken as 70% of the ultimate stress. The ultimate stress of the bolt is 800, therefore, we will take it as 560 MPa. **β** , since this is a pretension bolt, **β** will be taken as 1.0. If it were not a pretension bolt, **β** would have been 2.0. **η** is a constant with a value of 1.5. b e is the depth in this other direction; that depth is equal to 150 millimetre.

l e, we need to calculate. So, l e is actually given as minimum of the edge distance, that is distance from the centre of the bolt to the edge, which in our case is 40. And there is another small expression which was mentioned there in the previous slide, 1.1 times t multiplied by square root of beta f 0 divided by f_y. So, this f_y is f_y of the plate by the way. So, let us try to calculate it.

1.1 multiplied by thickness of the plate; the plate has a thickness of 35 millimetre; square root of, beta is again 1.0; f o is 560; and the yield stress of the plate is 250. This value turns out to be 40 millimetres, because the value on the right-hand side is actually equal to 57.6 millimetre. So, the minimum of the two will be 40 millimetres. So, l e is 40. l v is relatively straightforward in comparison to l e.

L_v is the distance from the edge of the filllet to the centre of the bolt, so, which is easy to calculate. We know the distance from the centre of this plate to the centre of the bolt. The total distance was 250; half of that is 125; this distance is 40; that means, this distance is also 40. So, l_v will be equal to 125 - 40. So, this part is gone; minus 8 minus the half of this thickness, 10, which will be equal to 67 millimetres.

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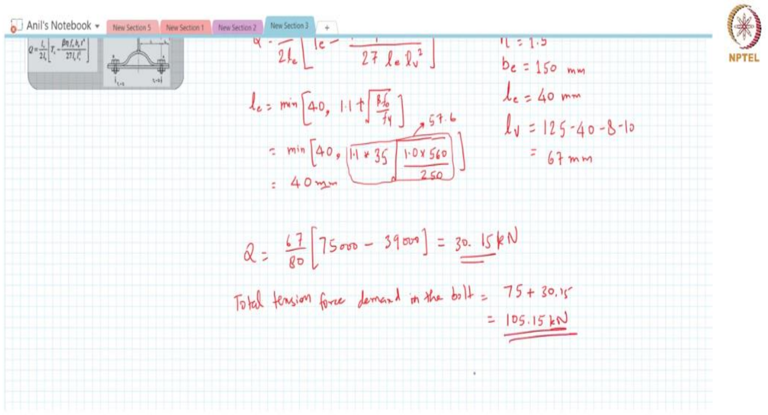

Now, we know all the components of Q. So, Q value can be calculated as, we can substitute all these values here in this expression actually. I am not going to substitute them again; which basically turns out to be, we have to be mindful because t e we have to put in newton's. So, the t_e value that is given to us is 75 kilonewtons, so, we will put 75,000. And basically this turns out to be 67 divided by 80, 75,000 minus, I believe 39,000.

And this turns out to be 30.15 kilonewton. So, you might realise, original force without the prying action was 75 kilonewton. Now, that force has increased by 30.15 kilonewton. As a result, total tension force demand on the bolt 75 + 30.15 which turns out to be 105.15 kilonewton. This is the total force demand on the bolt.

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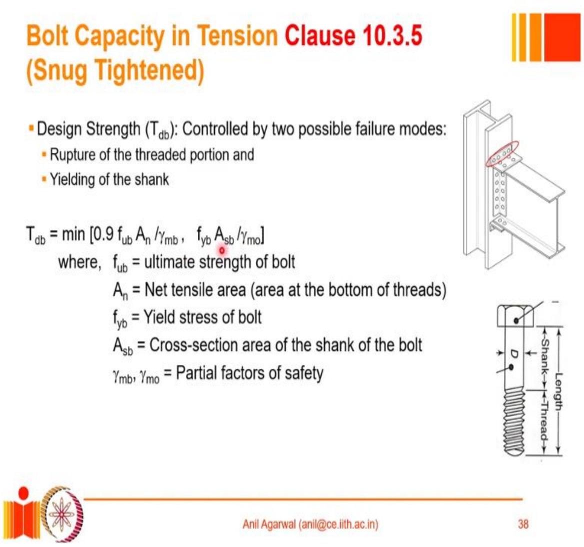

So, we have seen that when the bolts are subjected to tension, they have a strength which is governed by the yield of the shank cross-section or the rupture of the net cross-section. So, this was the expression. Now, it is worth it to notice that this expression remains the same even for the bolts which are pretensioned. So, other than the prying action effect which depends on whether the bolt is in pretension or not, the tensile strength of a bolt does not really depend on whether the bolt is subjected to a pretension or not.

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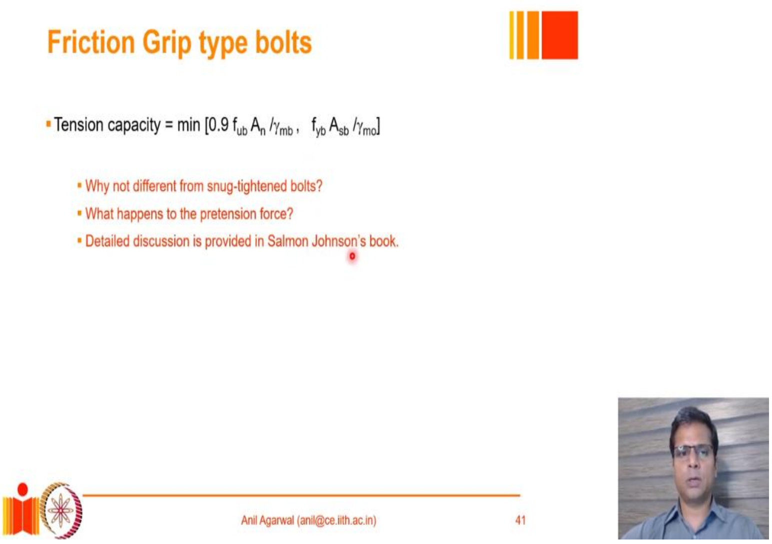

So, the tension capacity of a friction grip type bolt which is in pretension, it remains the same, it is given by the same expression. And this is a rather counterintuitive proposition. As you might understand that when the bolt is subjected to an external tension force demand, even before that, a pretension bolt is already at a very high level of tensile stress, which is usually approximately 70% of its total strength.

So, a bolt which is under that high tensile stress already, when we apply an external stress to it, how can it still resist the entire bolt strength which was available if the bolt were not in pretension? The same strength or same amount of external force, it can resist still. How is that possible? That is a very counterintuitive kind of phenomenon. And it is explained very nicely in the book that is one of the reference books that I mentioned in the beginning of this course, by Salomon Johnson's book.

So, I strongly recommend you to read that part. I am not going to be able to explain that in this course, but it is recommended that you read through that material and develop an understanding of why is that the case. So far we have discussed the shear behaviour, tensile behaviour for both a bearing type of bolts and friction grip type of bolts. Now, we will go into the behaviour of bolts which are subjected to a combination of shear and tension.

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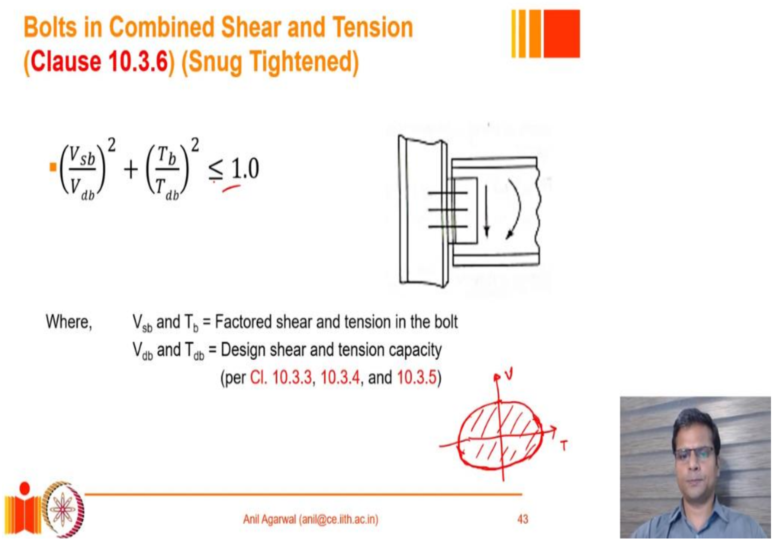

So, as you might see in this diagram, these bolts are likely to be subjected to a combination of shear force because of this force. Direct effect of this force will be a shear force demand on these bolts. And as a result of this moment, there will be tension force demand in the top bolt and there will be some kind of a reduced tension force demand in the bottom bolt most probably if there is a contact between the bottom flange and the column.

If there is no contact, there may even be some bearing resistance coming from here. Anyway, for such type of bolts which are subjected to a combination of shear and tension force demand, there is an interaction curve. This interaction curve basically has an elliptical shape, which is given by this equation. So, essentially, this expression tells us that we will calculate the shear force demand which is given by V_{sb}; this is factor shear force demand; and shear capacity which is given by V_{db}.

Likewise, we calculate the tension force demand and tension capacity individually. So, this tension capacity is calculated as if there is no shear force acting on the bolt and the shear capacity is calculated as if there is no tension acting on the bolt. And by the way, these capacities already include the material factors of safety. So, that is why these are design strengths.

Then, in this interaction equation, we take the division and then we square it both the terms, and that final value should be, the summation of the two should be less than or equal to 1. This is an interaction equation. If I plot it on a plane which represents tension force in the horizontal axis and shear force demand in the vertical axis, and let us say this is the shear demand capacity or shear capacity and this is the tension capacity of a bolt, then the interaction curve will be looking like this.

Everything under or inside this ellipse will be safe. At the boundary, the limit state of strength under a combined tension and shear condition is reached. So, that is this equation. This equation can be used to calculate the combined tension and shear capacity of a bolt.