Design of Connections in Steel Structures

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Module - 2
Lecture - 12
Design of Fillet Welds - 1

Hello. So far in the previous 2 classes, we have discussed the various aspects of welding for designing and developing structural connections in structural steel members or structures. Also, so, in that process, we discussed the various materials that we use, various considerations for weld design, what kind of loading conditions they can be used for, what are the different configurations, some details of the manufacturing processes and some dimensional restraints, constraints that we have to follow while we provide a welded joint.

Also, towards the end of the previous lecture, we discussed how to design a simple groove weld connection. So, we did 2 examples using groove weld connections. One example was with the groove weld where the weld was subjected to pure tension. And in the other case, a groove weld was provided where it was subjected to an in-plane bending moment requirement.

And we learnt how to design the 2 connections for the given loads using the Indian Standard Code. Moving forward, we will now focus today's lecture and some more part of it on the design of fillet welds.

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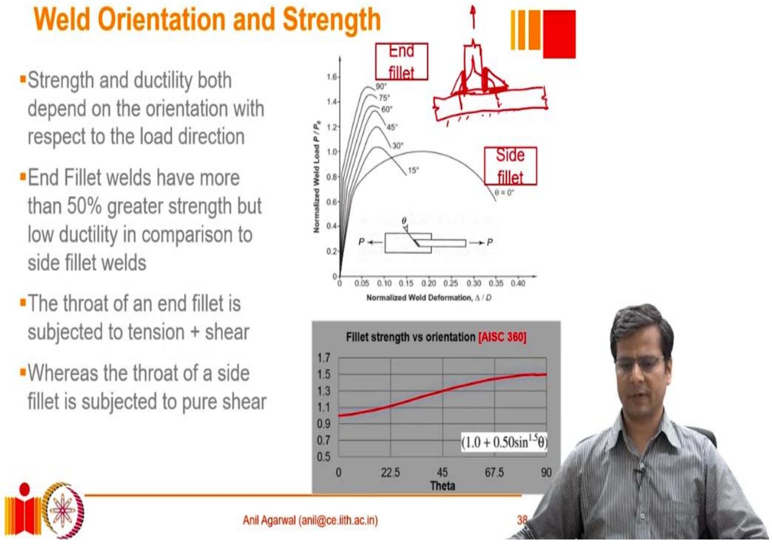

So, actually, the behavior of fillet welds is relatively very different or much more complex in comparison to the behavior of groove welds. The reason for that, as we have discussed in the past also is that the load path for a fillet weld is significantly different from that for a groove weld. So, for example, a fillet weld typically can be approximated to a triangle, a structure of triangular shape.

This is one plate to which it is welded, and let us say this is another plate to which it is welded. I am creating some gaps in between so that we can appreciate the difference. Now, let us say this plate, the bottom plate is restrained at this location, and the top plate is being pulled. If that is the situation, imagine how the force would get transferred from this plate to this plate.

And for sake of symmetry, let us put another weld on the other side so that there are no questions about the possibility of opening the root. Let us say this is the system. Now, the load is applied to the vertical plate, and that force has to get transferred to the bottom plate. The load path, as you may imagine, would be somewhat like this, and then it will go to the support and so on.

So, at this interface, if we see the weld to the vertical plate interface, these 2 interfaces; here the force gets transferred through proper shear; and at this interface, the force gets transferred through tension; and also there may be some local stress effects which I am not getting into.

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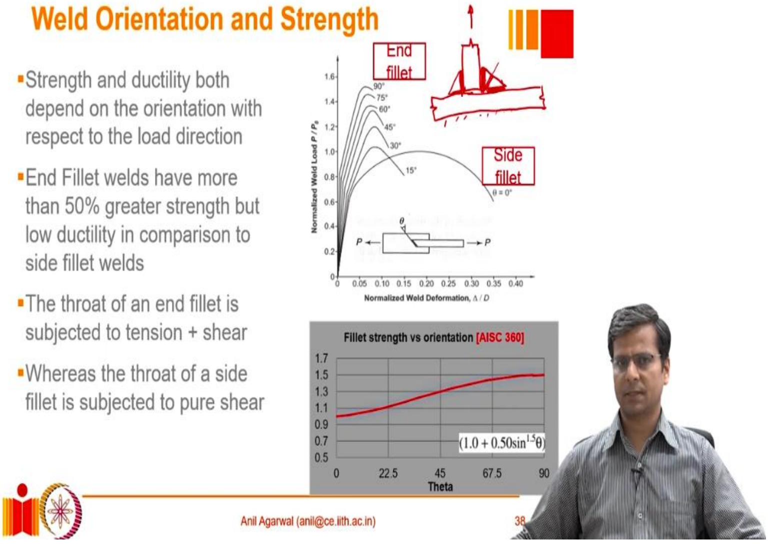

In addition to these, typically what we have seen in the past is that the throat, which is the smallest cross-section of a weld exists or lies somewhere at this location. So, if it is an equal-legged fillet, the throat will be right in the middle of this triangle. And if that is the case, most probably that creates the, that forms the weakest section in the fillet or in that load path.

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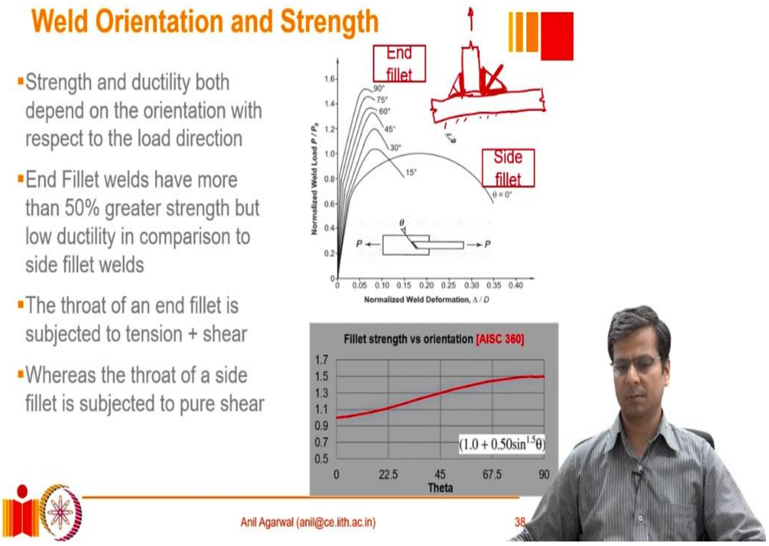

And that is where the; this is the section that would govern the strength of this fillet; same thing here. Now, what is the stress state at this situation at this location? Understanding this is quite complex. Actually, there is a part as we saw, at this edge, it was primarily shear, but at this edge, it was primarily tension. And at this interface, it will be somewhere in between shear and tension.

So, basically, shear force and normal force, both exist at that interface. And their interplay controls the strength of this material. Several people conducted a lot of experiments to understand the behavior of fillet welds under various types of configurations.

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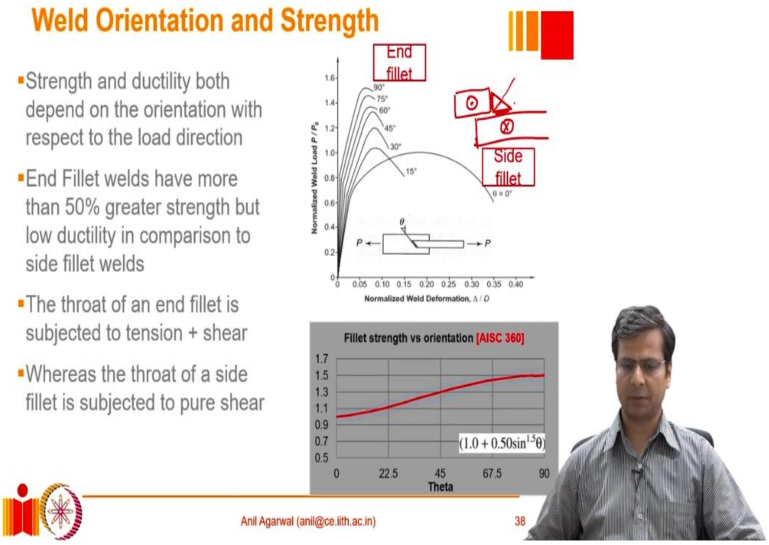

So, let us say I give you a scenario where there is a plate, and there is another plate right under it. The 2 plates are welded together using a fillet weld. And imagine that everything is symmetric and so on, so that there is no moment introduced. Now, what we do is, pull this plate outward, while we push this plate into the screen, into the board. Now, what do you expect the stress state in that fillet would be? In this situation, the stress state is relatively simpler.

There is a shear at this interface, and also there is a shear at this interface. So, this situation is very different from what I had just discussed before. In such a scenario, we have got shear and shear on both sides. And we can understand that of course, wherever there is the smallest interface, the weakest point, that is where the failure would take place, and we can just check the shear force demand there, which will again be dominated by shear stresses. And if we know how to design this fillet for pure shear condition, we would be able to accurately predict the shear capacity of this weld under this situation.

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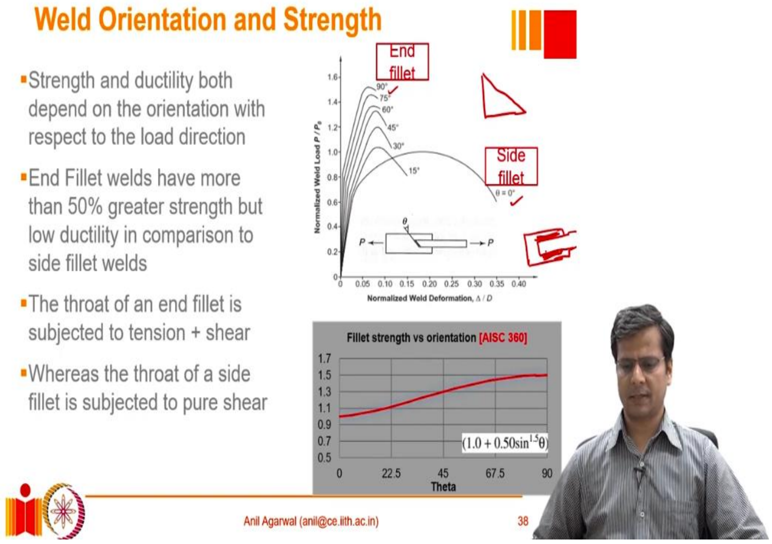

But the other situation that we saw where there was a possibility of tension, a combined tension plus shear, is where it becomes slightly more complex. So, what does it depend on? So, here is a schematic of that experiment that several people have done. They have taken 1 plate and another bar or a plate. They are lap joined together with the help of a fillet at the end.

So, this is an end fillet primarily, but the angle of this end edge was varied. It varied from 0 degrees to 90 degrees. So, when this value becomes when this angle becomes 0 degrees; what we are talking about is basically a side fillet. So, ultimately, when the angle θ becomes 0, the joint actually looks like this; only at the sides, it was welded. And when this θ became 90, at that time, the fillet was provided only at this edge, perpendicular edge.

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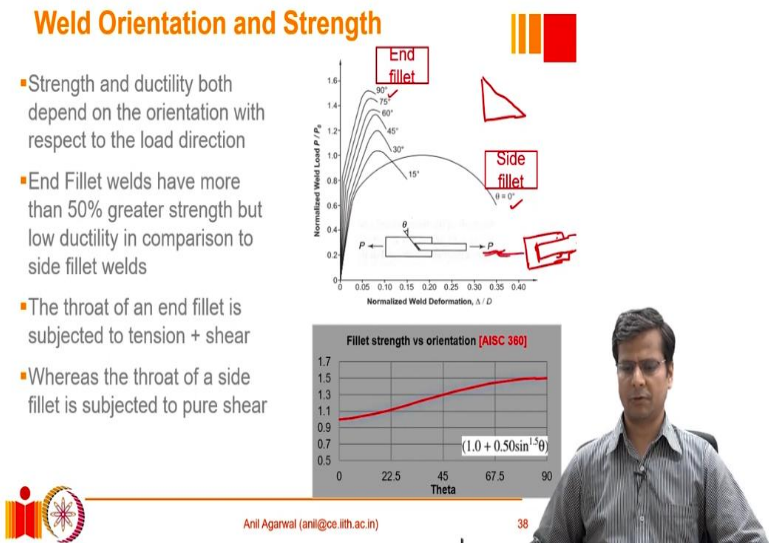

And this angle theta is measured with respect to the direction of loading. So, the direction is in the longitudinal direction. So, basically, this theta represents the angle between the loading and the longitudinal axis of the weld. Then they plotted the deformation on the weld against the load resistance of the weld. And what they observed was quite significant here, which controls the behavior of a fillet weld.

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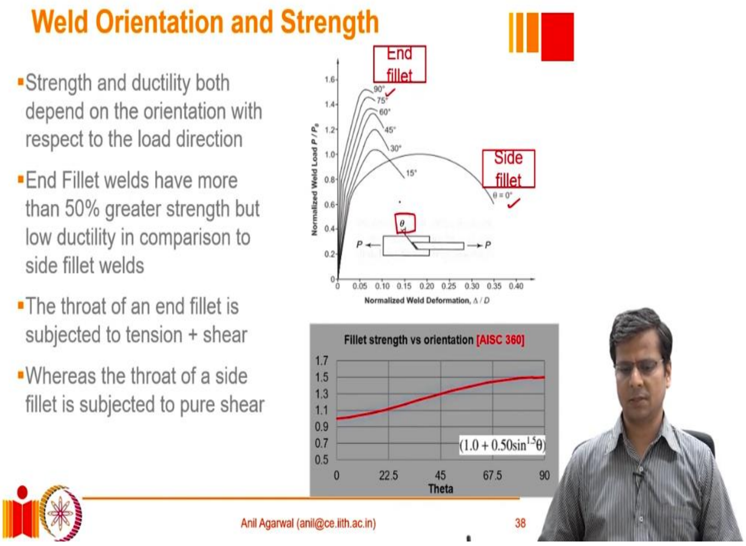

They observed that when we are talking about side fillets where, that is when the angle θ is 0, at that time, the strength is very small.

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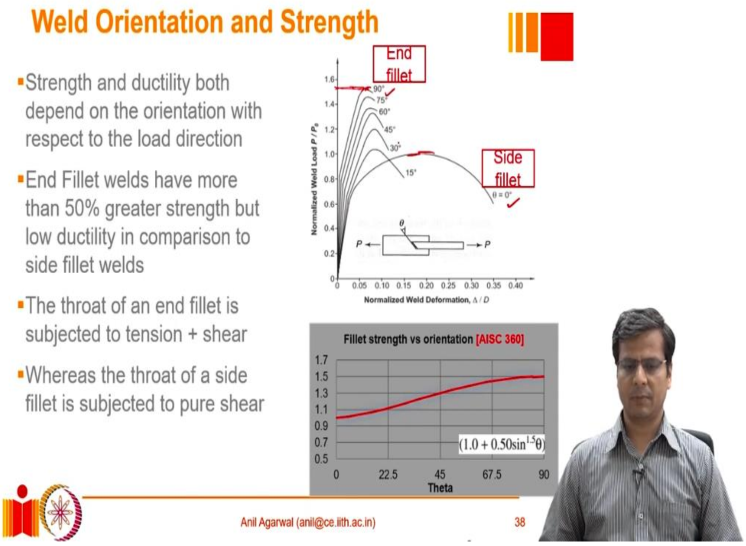

But when the angle changes to 90 degree, that is when we talk about the end fillet, at that time, the strength of that fillet weld is much higher than in the earlier case. That is approximately 50% or higher than the original strength in comparison to the side fillet. Also, the weld is much more ductile in a side fillet configuration in comparison to the end fillet configuration. And as we have discussed, the stress state within the fillet itself changes from side fillet to end fillet. In a side fillet, it is primarily governed by shear, and the end fillet is primarily governed by shear plus some normal stresses. And that has an effect on the ultimate failure strength also.

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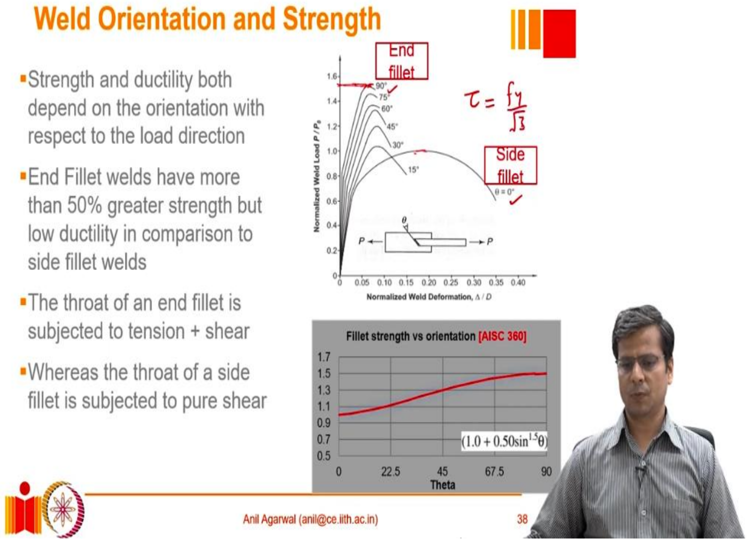

So, when we look at this member, we understand that the behaviour of most of the ductile materials can be predicted by using von Mises failure criterion. If we use von Mises failure criterion, it says that the shear strength is equal to yield strength divided by √3. That is what the von Mises criteria says.

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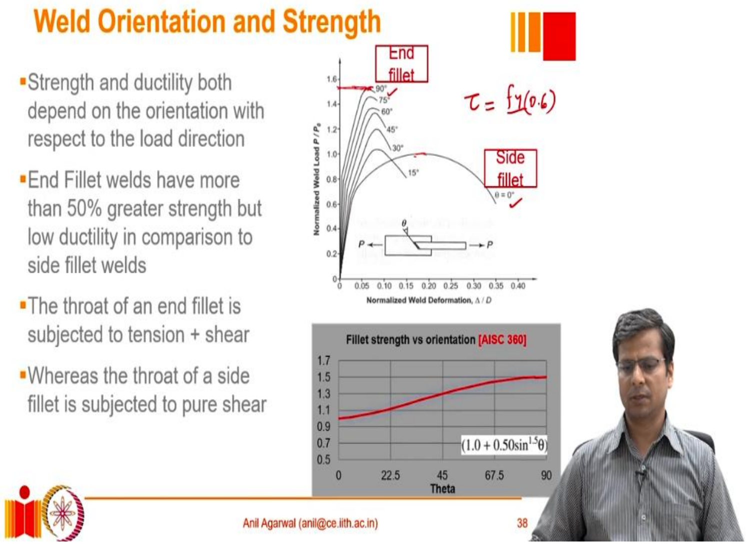

So, basically, which turns out to be approximately 0.6 times the yield strength.

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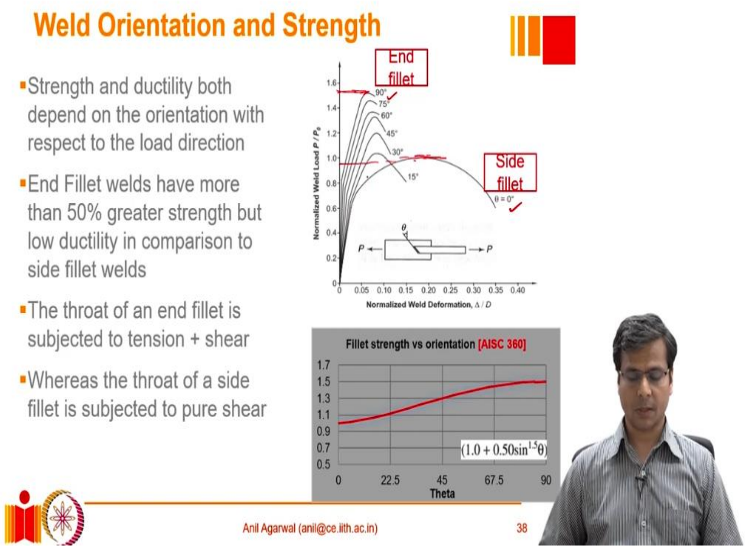

So, we can anticipate that since this is primarily shear behaviour and this is some shear and a significant amount of normal stresses are involved, we can expect that von Mises criteria would also suggest that the shear strength should be smaller than the yield strength or ultimate strength under tension. So, that is understandable. Also the ductility is quite a significant part here.

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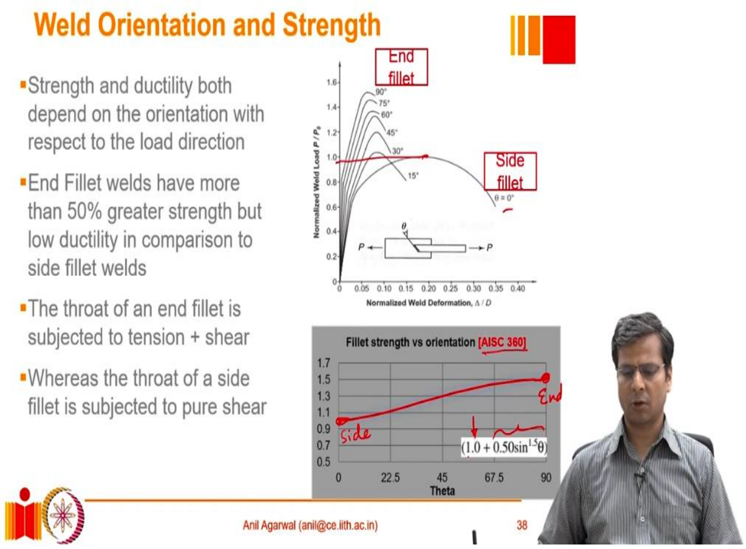

The welds which are side welds which have a 0 smaller angle, they act in a much more ductile manner than the welds that are at the ends. There are various researchers who have also tried to quantify the difference here. The American steel design code AISC 360 actually provides an equation which gives you a relative variation as you change from angle 0 to 90 degree angle.

So, basically, at this end we have the side fillet and at this end we have the end fillet. So, as we move from the side fillet to end fillet, what it recommends is that you can change the strength from 1.0, but that is whatever strength you have calculated for this value, that is governed by shear alone, you change that by about 50%. Therefore, the end fillet will be about 50% stronger than the side fillet.

So, this one corresponds to the side fillet. This additional strength is because of the change in angle. When theta becomes 90, this sine θ becomes 1. So, its power 1.5 also remains 1. So, we are talking about about 1.5 strength in comparison to the side fillet strength.

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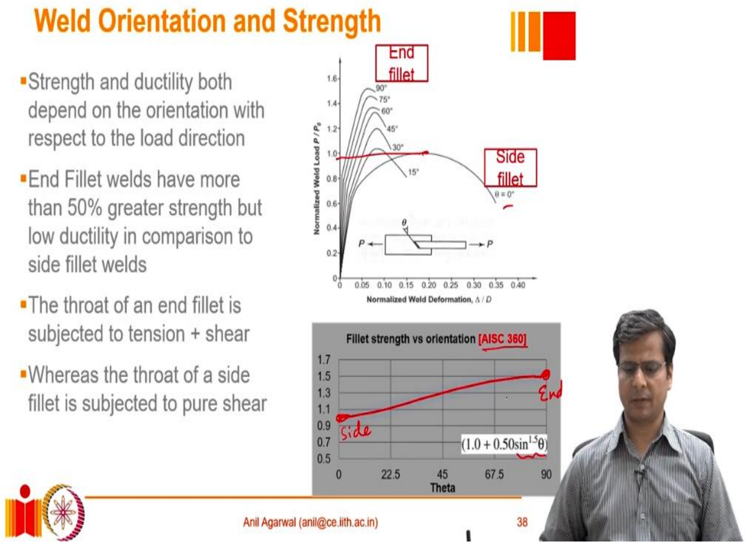

And in between it has this function, sin to the power 1.5 theta that controls the interpolation function.

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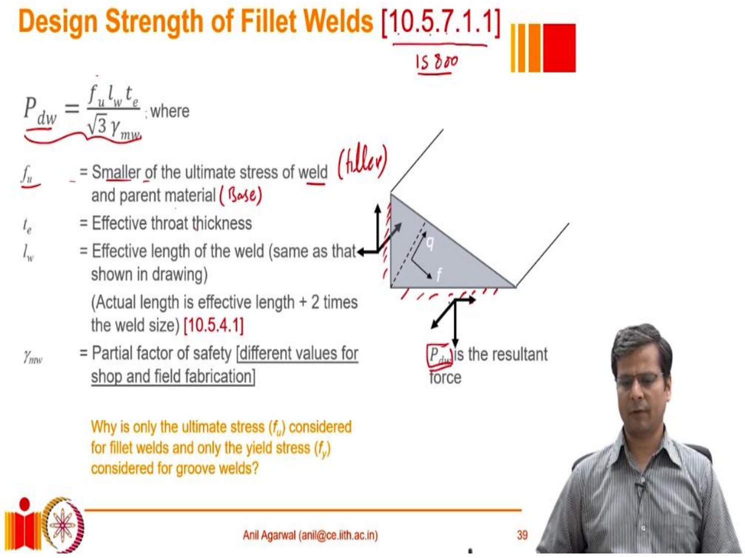

How does the Indian code IS 800 recommend we should design a fillet weld? So, if you go to clause number 10.5.7.1.1, it talks about design strength of fillet welds. And basically, the expression that it gives is P_dw is equal to (f_u x l_w x t_e)/(√3 x γ_{mw}). There are various terms; let me explain them. f_u is given by the smaller of the ultimate stress of weld and the parent material.

The weld material is the filler material, which is coming from the electrode being deposited at the welding location. And parent material is the base metal; so, that is where that is being welded. So, it asks us to take the smallest or smaller of the two f_u values. So, the first question is, why it is using the f_u value and not f_y value? And the second question is, why the smaller of the two? We will discuss that.

In the meanwhile, while I am talking about other parameters, you try to think about why think about the answer to these 2 questions. Then comes the effective throat thickness. So, basically, what this equation is telling us is that failure can be expected to happen at this throat. This is the actual critical section in a fillet weld. So, you can imagine that there is certain force, net force acting at this interface of the weld, and equal and opposite force will be acting at this interface.

And if we assume that the weld is small enough, then the moment, because of unevenness in these forces, may not be very significant, when we can ignore it. So, P_dw, what we can say is that this is the resultant of all the 3 forces. Or in other words, if there is a P_dw force, it can have 3 components.

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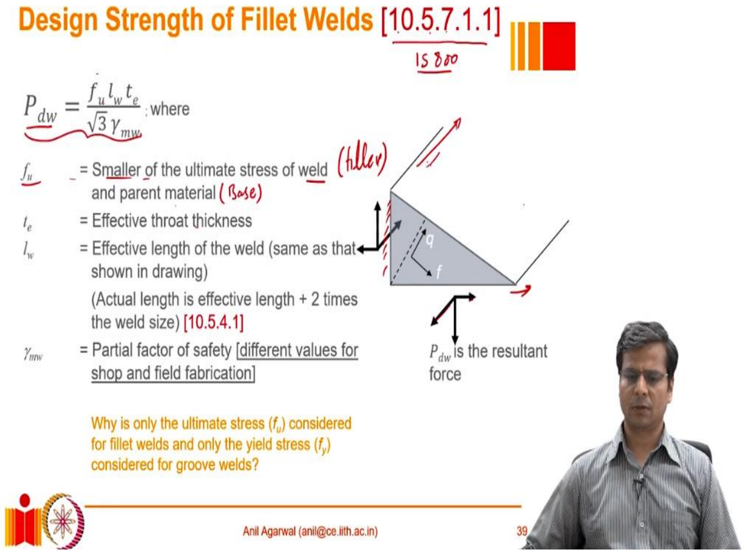

The first component could be in the horizontal direction. The other component could be on the vertical direction. And the third component could be in the longitudinal direction of the weld. So, this is the longitudinal direction of the weld. The third component of that force would be in that direction. And the other boundary of this weld will be resisting all these forces by equal and opposite forces.

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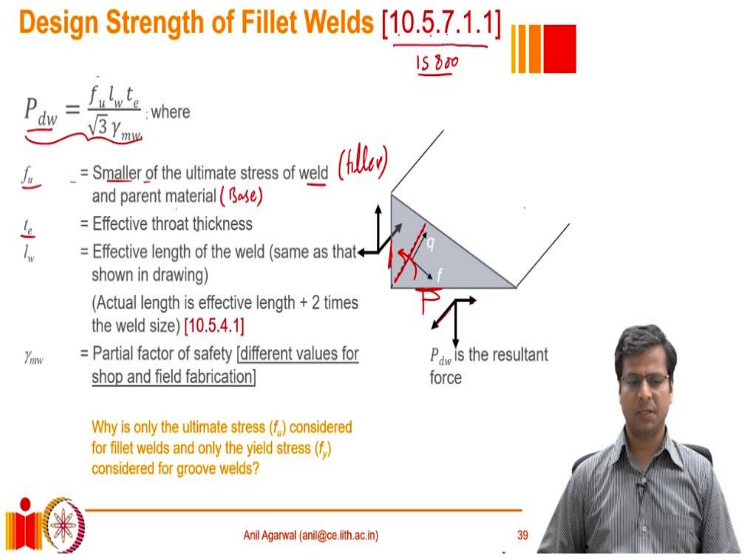

So, of course, that force has to be transferred from here to here, from this edge to this edge, and that has to pass through this interface. And that is why this interface dimension t_e is adopted. We have already discussed how to calculate t_e for different types of fillet welds.

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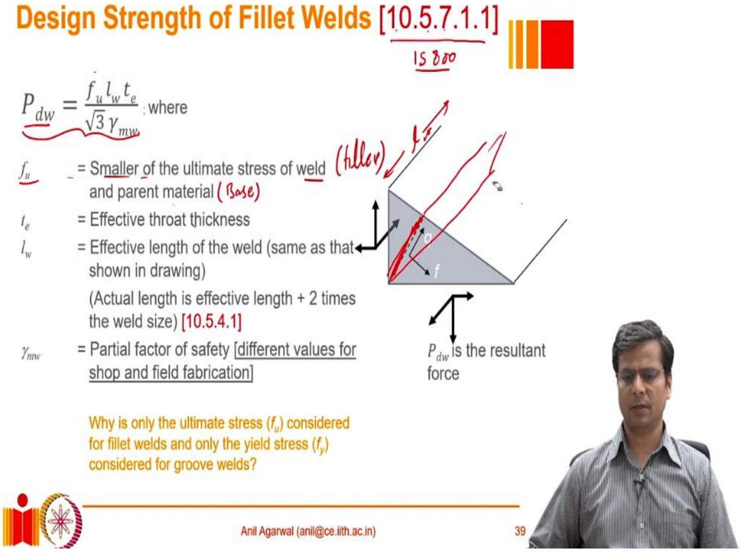

l_w is the length of the weld in this longitudinal direction. So, that is an obvious thing, because we can expect that, as this is the width of the critical section, there will also be a length component, and together they will form the critical cross-section area.

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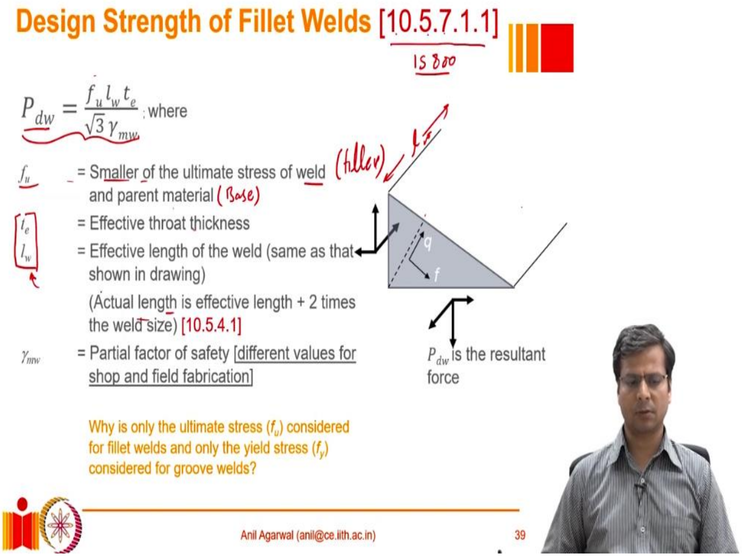

So, we are basically, when we multiply t_e and l_w, we are calculating the critical cross-section area. The actual value of the length will be slightly higher than the l_w value. But as an engineer, we need not worry about the actual length. Whatever we calculate in our design calculations, that is what we will specify in the drawings also.

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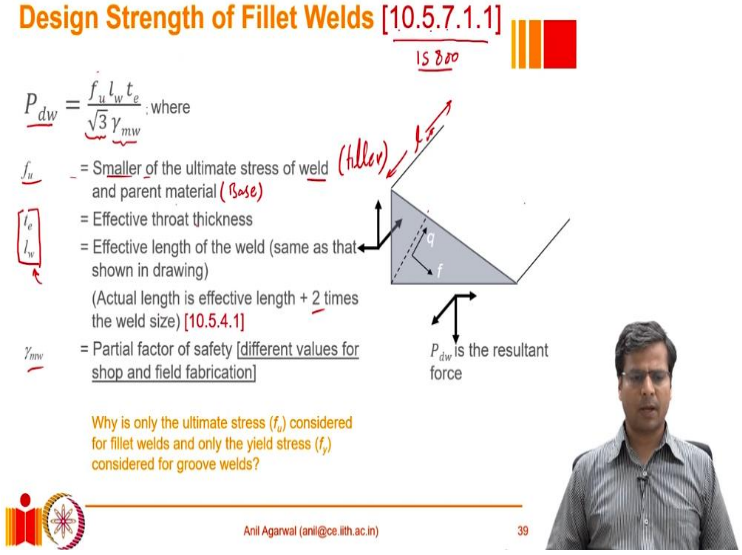

And the welders themselves will increase the length. So, we need not worry about it. But when we do a real site inspection, at that time, we should be mindful that the actual length, whatever we are seeing, the effective length will be 2 times the weld size length less than the original length, the actual length. Then divided by, this expression has a term at the root, at the base, in the denominator, $\sqrt{3} x\ \gamma_{mw}$. √3, whenever we see √3, we automatically understand that this is coming from the von Mises criterion. So, basically, we are using von Mises criterion here.

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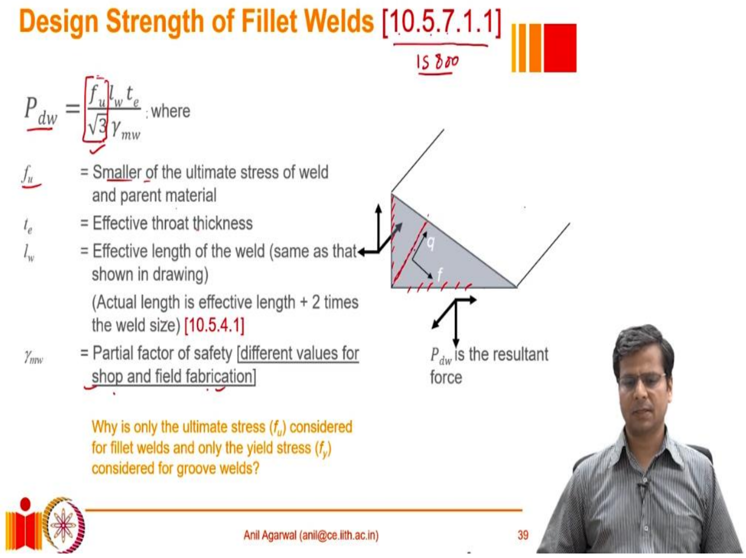

Von Mises criterion basically suggests that if the material has a strength of f_u in pure tension, it would have a strength of f_u divided by √3 in pure shear. So, this indicates, this √3 here indicates that we are talking about shear dominated behaviour or failure under shear.

Then there is a term of γ_{mw} it is the partial safety factor, which is different, as we have seen for groove welds also, there are 2 different values.

There is one value for a shop welded fillet, and there is another value for the field fabricated fillet. So, 1.25 is for the shop welded and 1.5 is for the field welded; that we have discussed before. So, all the terms here make sense. And essentially, what it means is, what we are saying is that, let there be any types of forces acting here, and they will be resisted by the other boundary.

All those forces have to pass through this interface. And let us design this interface as if it is acting under shear. So, and let us calculate how much strength it has in shear and let us say that, that strength it has in for whatever forces you are applying.

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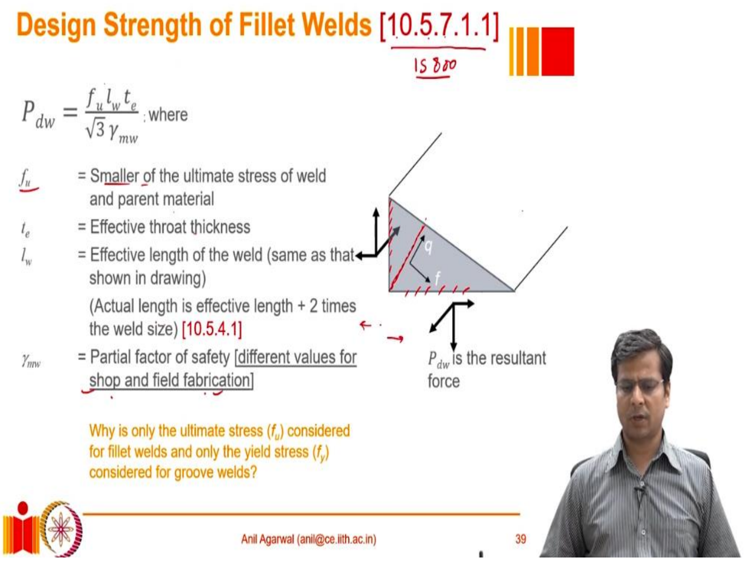

And that makes quite a bit of conservative sense, because a material, a ductile material as we know has the lowest strength in pure shear. Whenever we have a ductile material, if we calculate using von Mises criterion, if we calculate its strength under pure tension or a combination of tension and shear or pure shear, we will see that we will always have the lowest strength under pure shear.

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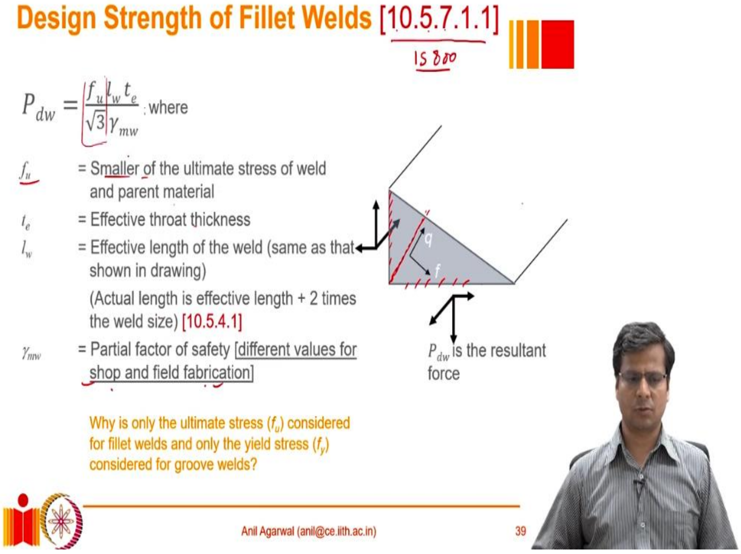

Therefore, what it is saying is that, you take its strength under shear and say that, that is its actual strength, no matter what the loading is. So, this is basically, conservative way to estimate the strength, but this is very frequently used. Now, coming back to the original question. I had asked why are we using f_u.

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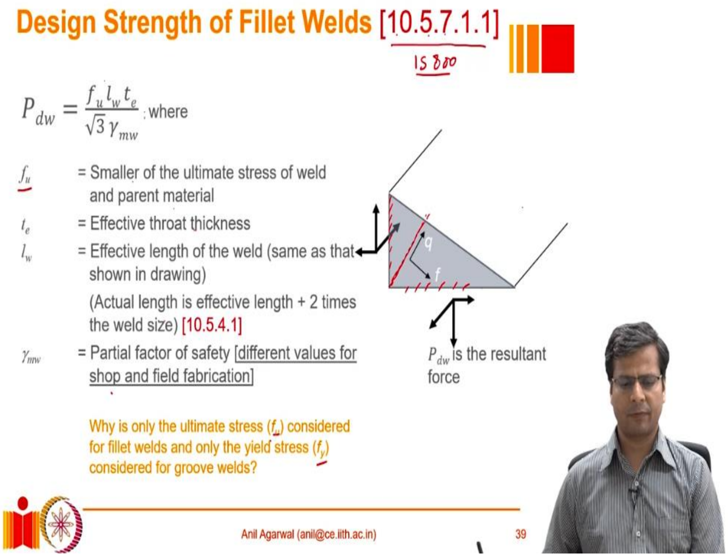

If you remember, for groove welds, we had used the value f_y and not f_u. So, the question was, why are we using f_u here and not f_y? f_y is the yield stress and f_u is the ultimate stress. And then, we are taking the f_u value which is smaller of the two materials. So, there is a base plate or the base material, and there is the filler material. So, we take the f_u, the smaller f_u of the two. So, the answer to this question is that, whenever the failure is not guaranteed or we do not know the exact location of the failure;

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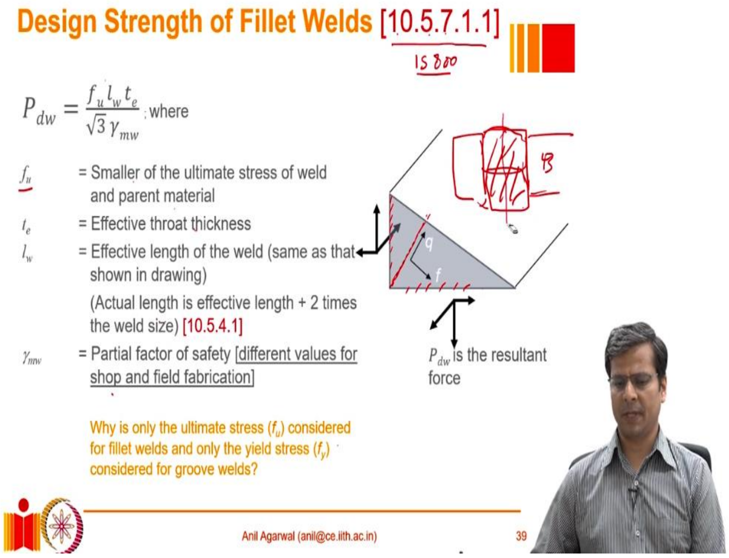

So, for example, in case of a groove weld, when we were talking about a groove weld, we had these 2 plates let us say. And we wanted to weld these 2 plates together using a groove weld. So, when we provide a groove weld, we completely fill this area. And then, the groove weld actually behaves exactly like the plate, the base metal. When it does that, the failure location is not already restricted to a particular plane; it can be anywhere.

When that is the possibility, then the yielding becomes the critical parameter for us, because we have to also worry about the flexibility of this structure; because, once it yields, it yields over a very large area, and then the strength, the stiffness drops so much that even the strength cannot be utilised. However, when we have a critical plane already, which we do in case of a fillet weld; so, in case of a fillet weld, we have a very restricted critical plane, which has the smallest cross-section.

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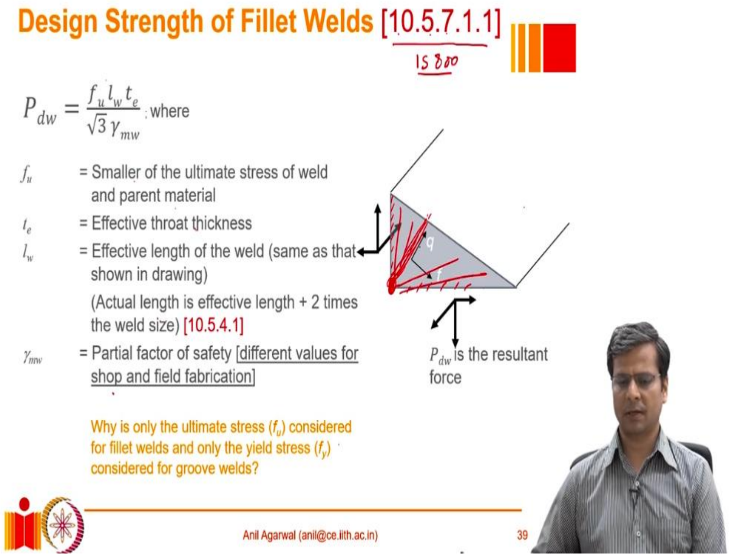

Any other planes, the root is here, the crack if it has to happen, has to start here. So, any other plane is larger than the critical plane or the throat thickness. So, when we talk about the throat thickness, we have already known where the failure is going to happen, which is basically a very narrow band of area where the failure can happen. Therefore, the yielding will be confined into a very small area and it will happen in the very early stages. So, we cannot start worrying about the yielding, but we want to prevent the fracture; that is why we go for f_u divided by √3 rather than f_y divided by √3.

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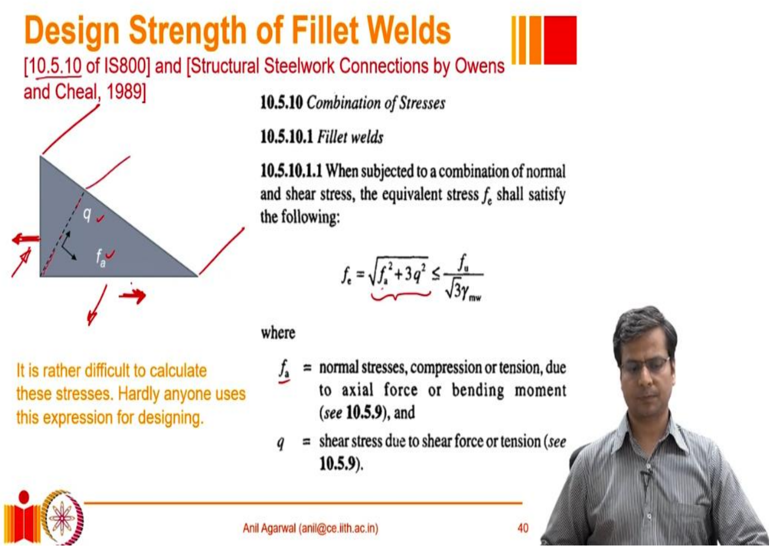

So, we have just seen that for fillet welds, the Indian code recommends using of f_u divided by √3 as the design stress value or the nominal stress value. And that is what you will use for designing of fillet welds under any type of loading condition. There is also another clause 10.5.10 in IS 800 which also gives a slightly different requirement or equation for designing of fillet welds, especially for the situations where there is a combination of stresses are acting simultaneously.

For example, the case that I had shown before. If those all 3 stresses were acting simultaneously on the fillet as we have discussed before; this is the longitudinal direction, so, there will be force acting here, and the equal and opposite force will be acting at the other boundary. And let us say there is a force acting in this direction. And this will be registered in the form of a; so, what was shear stress here at the bottom edge turns into a normal stress at the vertical edge.

At that interface, it is somewhere in between; it is partly shear, partly tension. Now, the code recommends that you can also, instead of using that equation that we just saw before in clause number 10.5.7, you can also use clause 10.5.10 in such a situation. And what this clause gives us is basically some kind of an interaction equation. It accounts for the normal stresses at the interface at the critical cross-section.

And so, f_a here is the normal stress, which is basically the stress perpendicular to that plane. And q here is the shear stress at that plane. So, it recommends that you can use, calculate the f_a and q values at the throat interface or the net cross-section. And then, use this interaction equation to calculate the effective stress.

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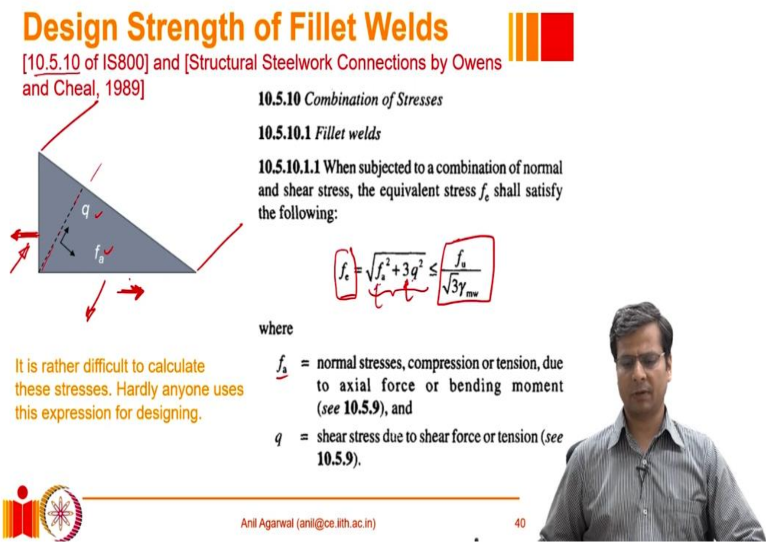

And then, make sure that effective stress, that f_e that we get remains less than f_u divided by √3 divided by γ_{mw}. So, it is basically trying to say is that you calculate the effective stress here, which is again dominated by shear because it is using a factor of 3 for accounting for shear; whereas, only a factor of 1 to account for the normal stress values. But in any case, you calculate the effective stress and then you compare and make sure that this stress remains less than or equal to f_u divided by √3 divided by γ_{mw}.

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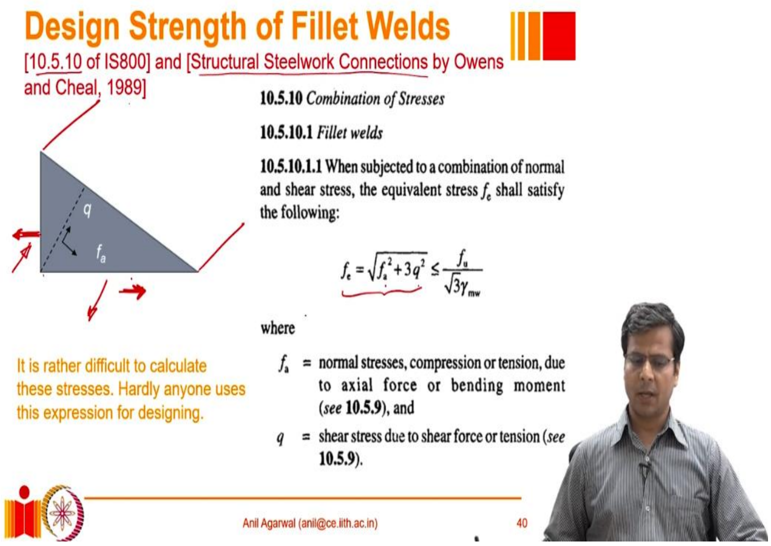

So, this is a method that has been discussed in quite a bit of detail. Various international codes have adopted this similar method. And this method is discussed, a lot of discussion is available on this method in the book that I have mentioned here, Structural Steelwork Connections by Owens and Cheal, 1989. The challenge however is that calculation of f_a and q at that interface is more complex than what it may appear as of now.

These forces we knew are at this interface, but these forces are not really uniform necessarily through this interface; the forces vary quite a bit. Also there are lot of local edge effects. So, even if we discount for all of them, still there is quite a bit of variability in the geometry of the weld. And therefore, calculating this stress accurately becomes very challenging and inaccurate. And as a result, it may not, it has been not found to be worthy to go through this calculation.

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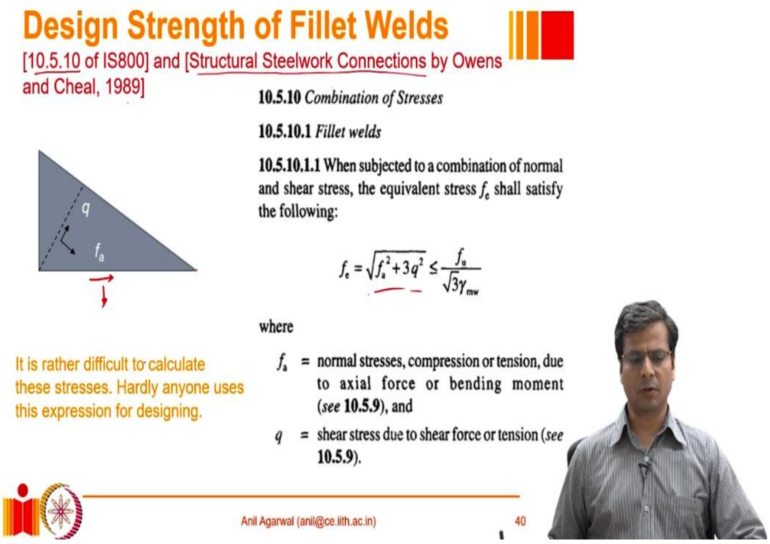

Some of the other international codes have simplified this process and they have given you some easier ways to calculate; so, to basically estimate their strength again by using the forces which are known to us at the boundaries, rather than the actual stresses inside the fillet. However, this provision is available in the Indian code if somebody wants to use it. But as we know, it is relatively difficult to use, and hardly anybody actually uses this provision. They usually use the provisions given in the clause number 10.5.7.

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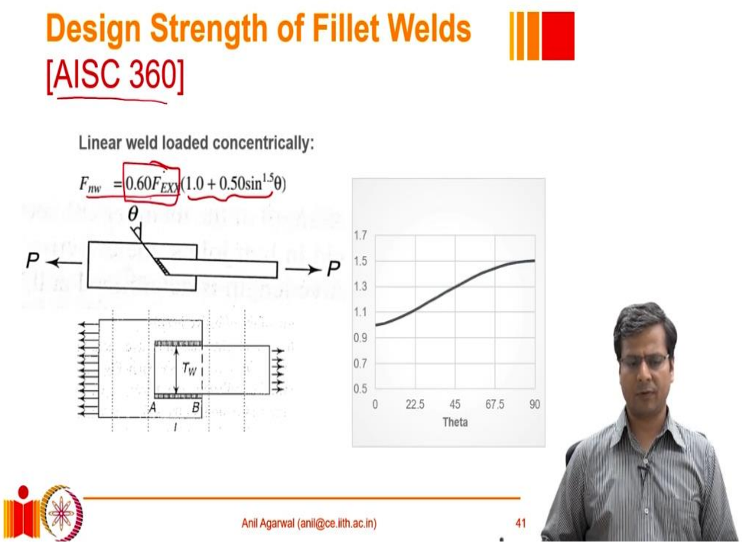

What does the international practice involve? So, internationally, as I had mentioned before, for example, if we take the example of America, in the U.S., the prevalent design code for steel structures is AISC 360. And as we have seen this equation; this equation I believe you have seen already, the second part of this equation. So, what it says is that, this material would have the strength of 0.6 times f u.

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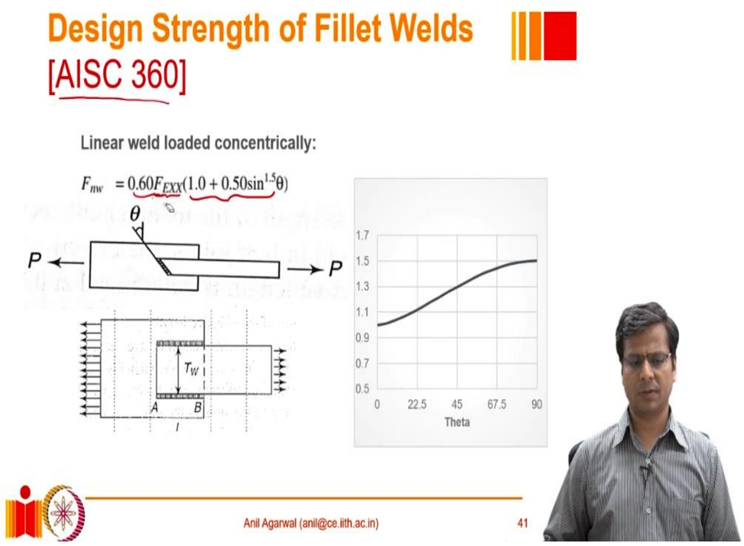

This F EXX actually represent the f_u, ultimate stress. So, it already has a shear strength of 0.6 times f_u. Now, if you want to increase it to account for a θ value which is not 0;

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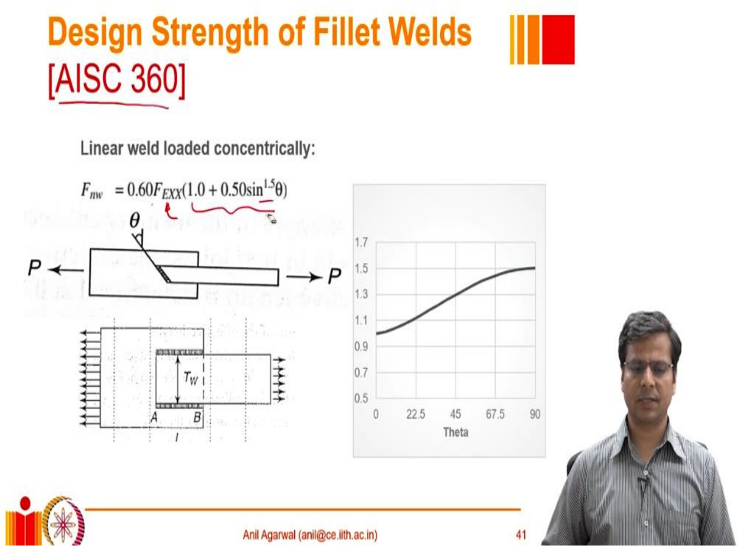

So, if the θ was 0, we would be talking about side fillet; but if θ is not 0, we are talking about a different level of inclination all the way up to when it becomes an end fillet. If you are talking about any of those possibilities, you use this expression to increase their strength beyond the pure yield strength.

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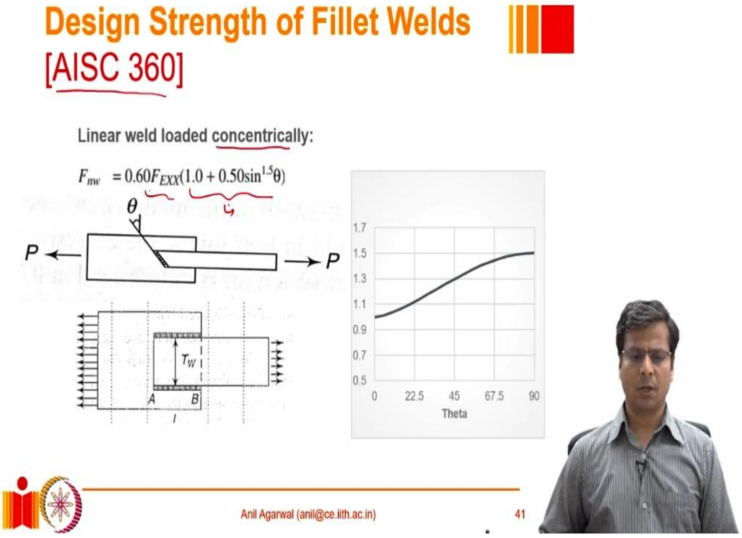

And this is the plot of that second function. Such a situation could be applied to design connections such as these. So, for example, if I have a connection like this, where the load is applied concentrically. That is an important parameter; that is an important condition. Only in these conditions, this equation can be applied.

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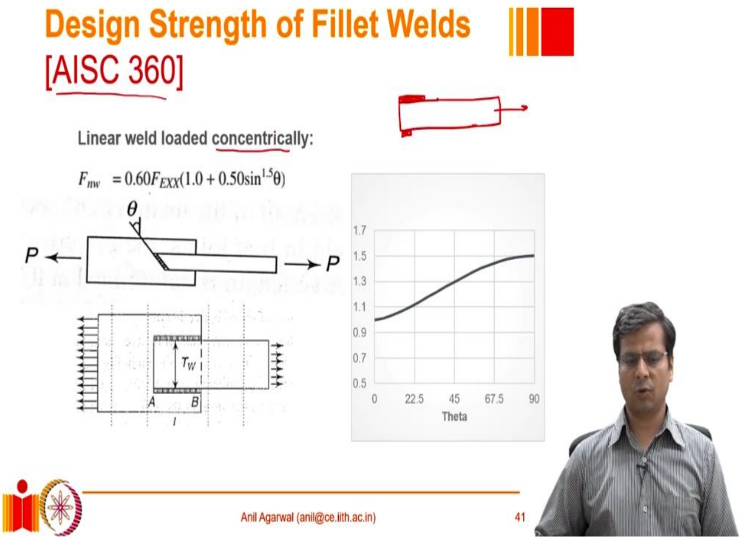

For example, it cannot be applied to a condition where this weld is bigger than this weld, and it is being pulled in the middle.

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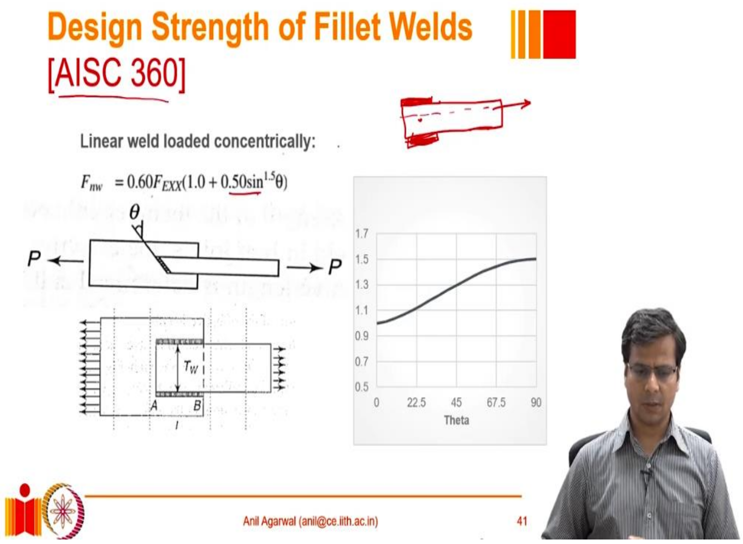

If load is not applied concentrically; or in other words, if the welds are symmetric but the load is not concentric. So, let us say the 2 welds are of equal size, the top and the bottom one, but the load is not actually concentric; it is acting at an eccentricity. So, the centre of gravity of the two welds is here, but the load is acting away from there. And in such a situation, this type of an equation cannot be applied. As long as that condition is satisfied, we can apply this equation.

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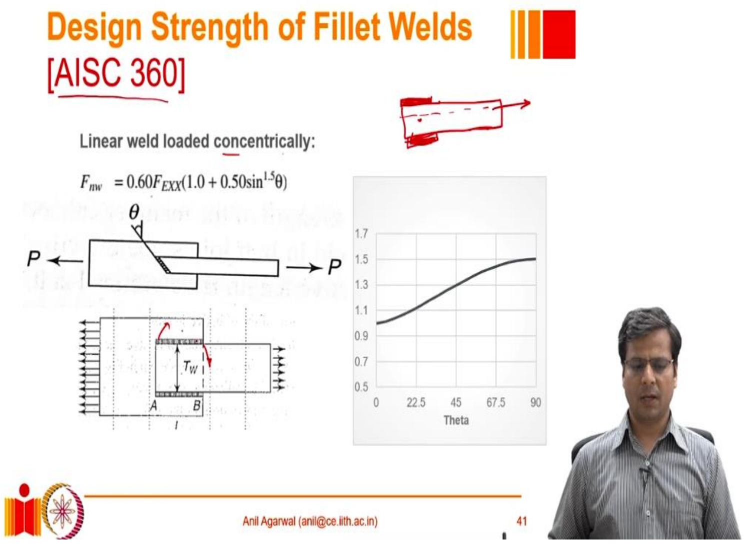

Like the case shown here, the loads are concentric, the welds are symmetric; therefore, the entire force will be going equally to this. And there will not be any moments at the ends which will be acting, which may affect the stress levels. So, if that is true, then we can apply this equation.

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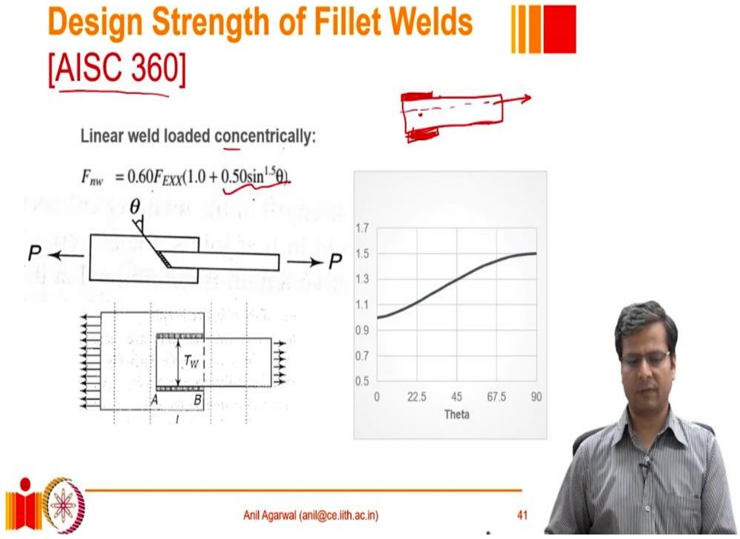

And we can utilise the additional strength which is available at a given angle. However, there could be another situation where we do not only have; unlike the previous case, these welds are placed symmetrically, but both of them were longitudinal welds.

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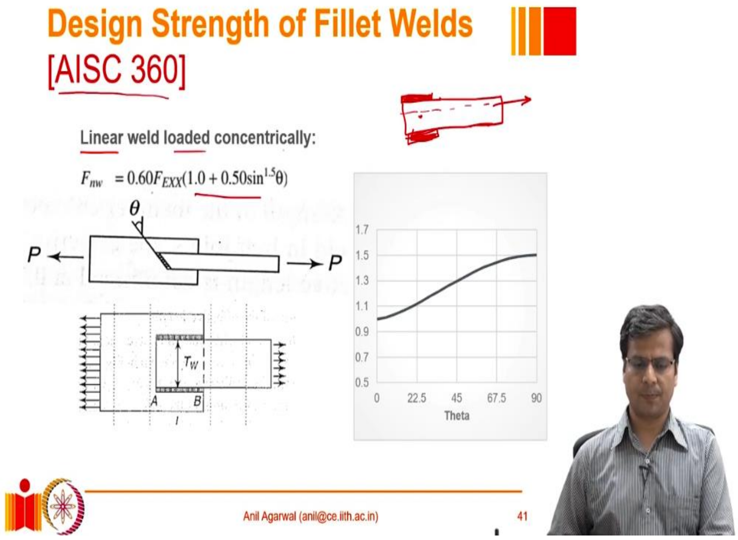

So, they were linear welds loaded concentrically, but it was not a combination of longitudinal and transverse. If we have such a situation, then we cannot use this equation.

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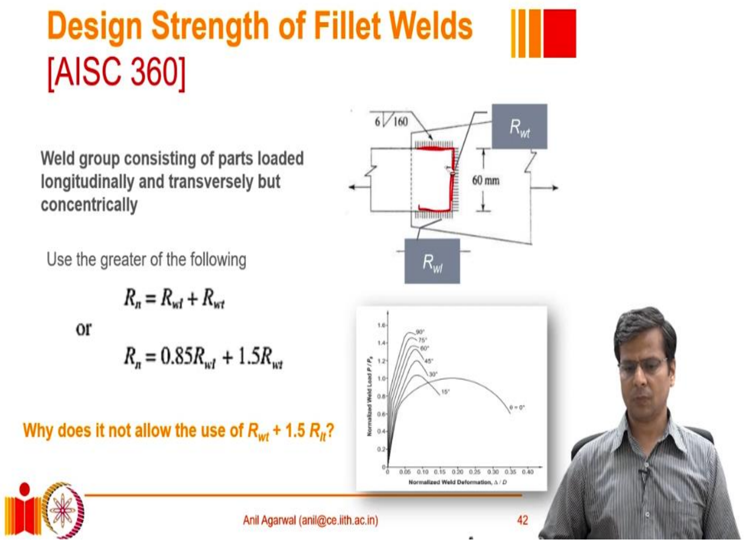

In such a situation, when a portion of the weld is longitudinal and a portion of the weld is transverse in comparison to the direction of loading, which is the case here. So, you have got 2 plates, lap joint, and this is the total weld length. Out of the total length, one portion of it is transverse and the 2 equal and opposite portions are resisting the load longitudinal action. And it is a symmetric weld, the load is concentric in everything.

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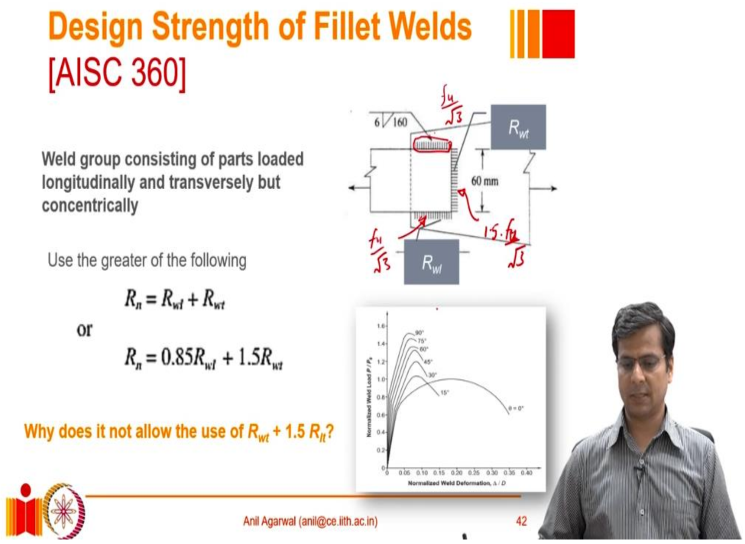

Now, in such a situation, we cannot simply say that we will take the full strength of this weld, which is basically purely in shear; a longitudinal weld is purely in shear. So, we will take f_u divided by √3 strength here. And for this weld, we will take 1.5 times f_u divided by √3. And for this again, we could take f_u divided by √3. Can we do that? That is the question. What the code says is that you cannot do it. We cannot take their respective full strengths to calculate the total strength of the complete weld. What can we do, however?

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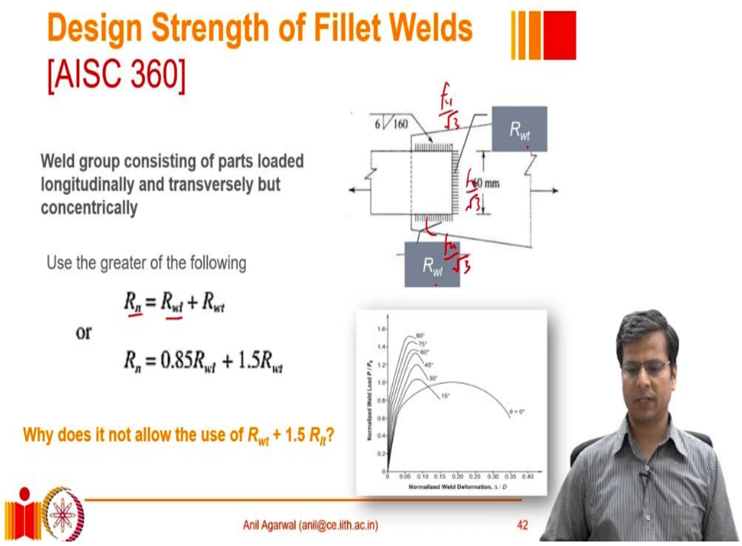

It says that R_n is the total capacity which can be taken as a summation of R_wl and R_wt, which is basically saying, you take f_u divided by √3 here and you take f_u divided by √3 here and f_u divided by √3 here. You take the shear strengths, whichever are available and you design them as of that. That is what the Indian code also says. So, either you take this one;

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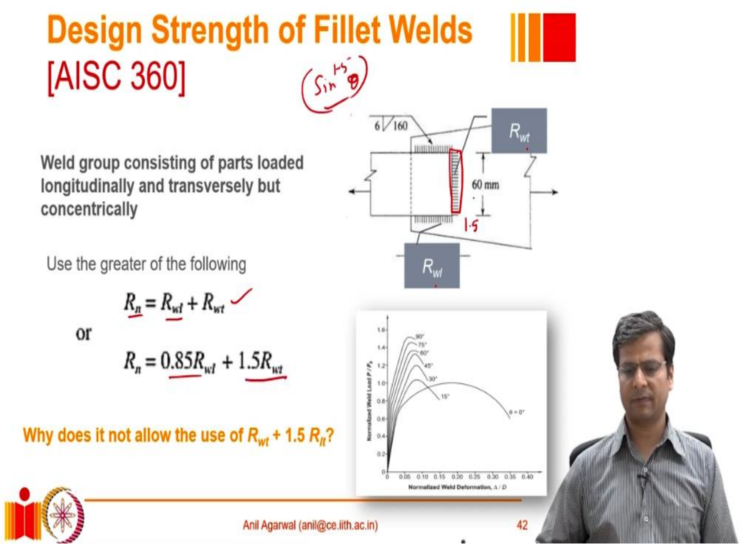

Or what you may do is, you can take, you can increase the strength of this weld by 50%, which is as per that equation which had this function of sine to the power 1.5 theta. Do you remember? So, as per this equation, we were having an amplification of 50%. So, it says you amplify this weld strength by a factor of 50%.

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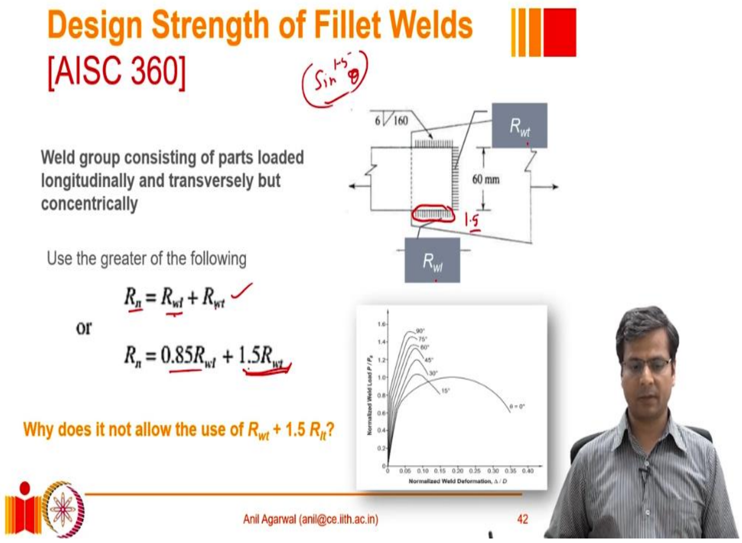

But if you want to do that, you cannot amplify this one also, or you cannot use the full strength of this weld. In fact, you have to reduce the strength of this part by 15% and use only 85% of the strength. So, either you can use both of their full shear strength or for this one, for the end one, you use the full tensile strength, which is after amplifying for the factor, but then you have to reduce the strength which is available at the other weld. The question is, why does it do that?

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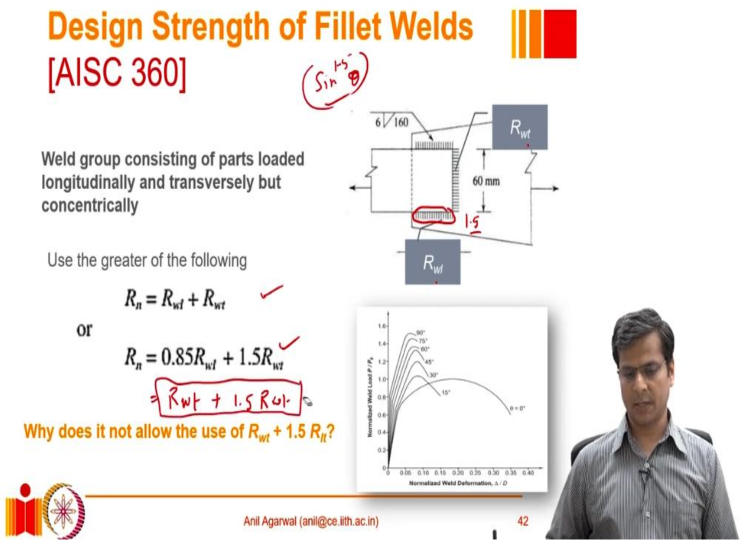

Why does it not allow us to do R_wt plus 1.5 R_wt. It says you can do either this or this, whichever one is giving you higher value, you can take that. We know that obviously this formula given a higher value, but we cannot do this, why? The answer to this question actually lies in the entire plot.

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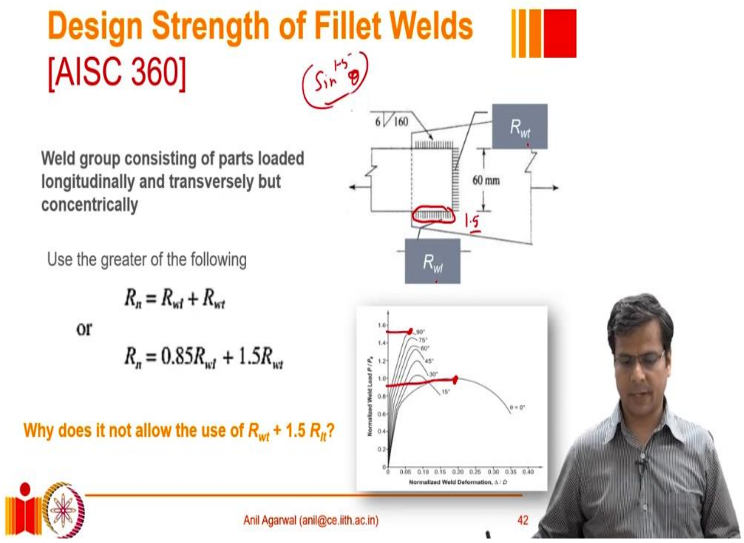

So, we cannot only look at the peak values of these; let us say we are talking about 0 and 90 only. So, we cannot purely look at only the peak values and say that this much of strength is available for an end fillet and this much of strength is available for the side fillet, so, let me use these strengths directly. It does not work that way. The reason for that is, these 2 fillets have different stiffnesses or they achieve their full strength at different displacements.

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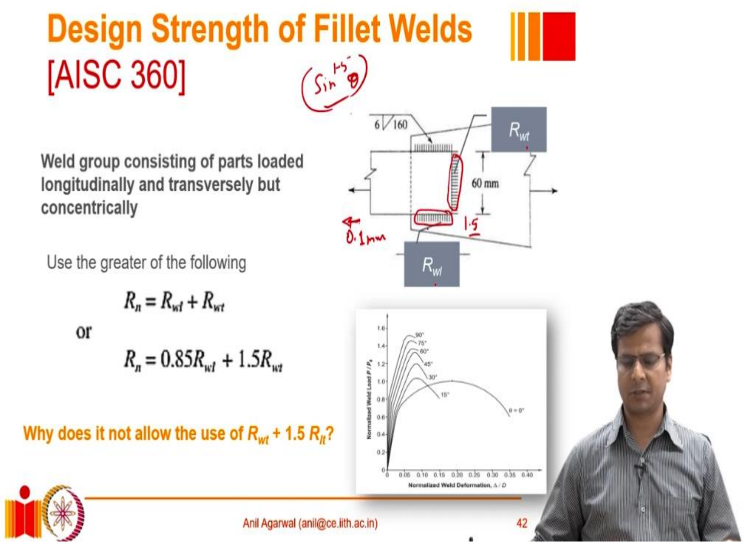

So, if this plate is moved, let us say by a particular displacement, let us say 0.1 millimetre. So, at 0.1 millimetre, maybe the end fillet would have already, would have reached its ultimate strength, but at that time, the side fillet would not have reached its ultimate strength, it might still be at a much lower strength. And if that is the case, we may not be able to utilise the full strength. We can understand that by these plots.

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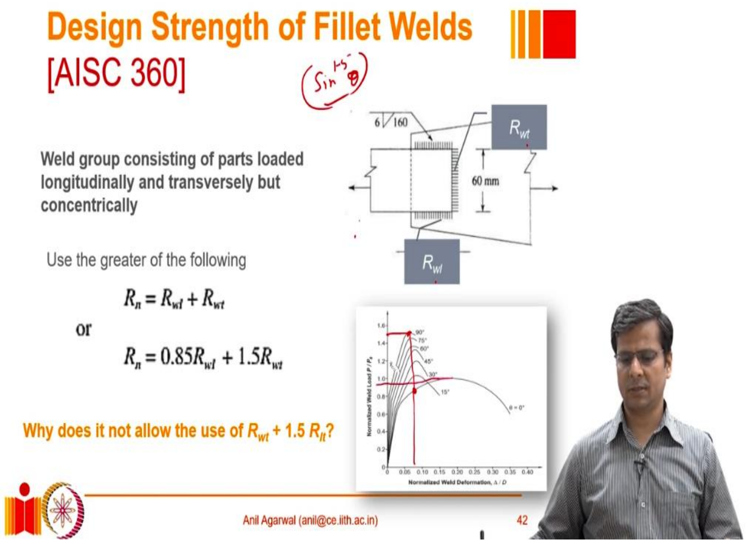

So, the displacement, when the end fillet reaches its full strength, the side fillet only reaches this much of strength which is not really equal to its ultimate strength.

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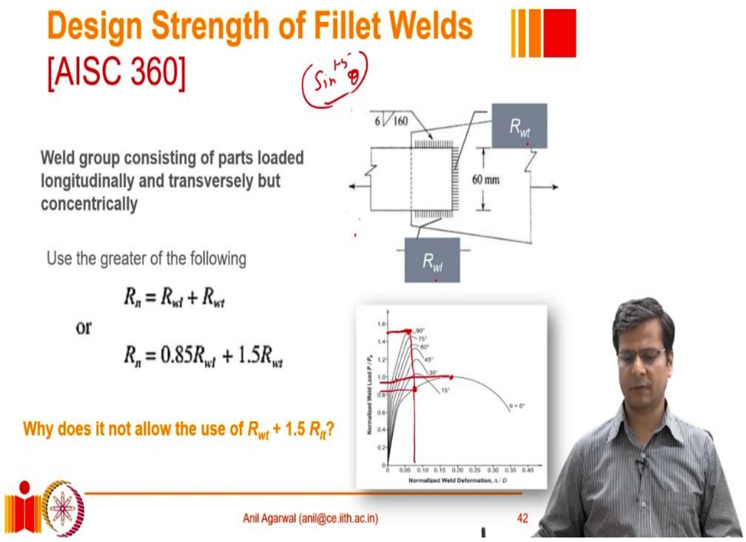

So, when we are taking the ultimate strength of the end fillet, we cannot take the full strength of the side fillet; we have to only take about 85% of the side fillet. However, the other option is to take the full strength of the side fillet.

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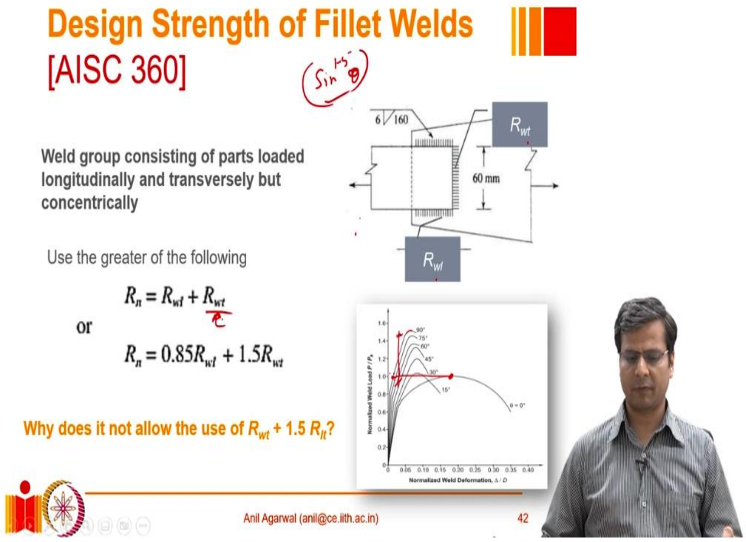

And at the same displacement, what is the force available in the end fillet? And at that time, the end fillet could only have a much smaller strength; it will not have the full strength; it will be only the strength which may be approximately 50% less than the full strength. And therefore, we take only the shear part of it, we do not take the combined amplified part of it.

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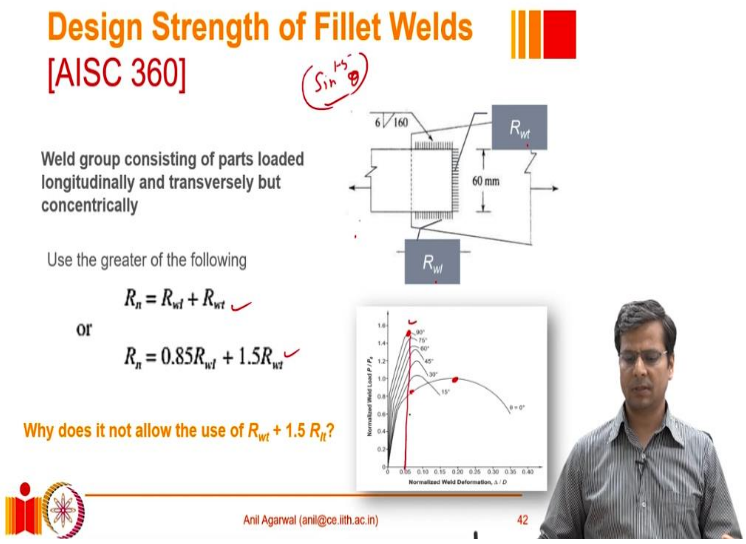

That is the reason either we can use this or we can use this. In fact, we can use greater of the two, because, for the weld to fail, it has to pass both of those peaks, one peak here or one peak here. So, we will consider this peak and we will consider the equivalent force here which lies somewhere here.

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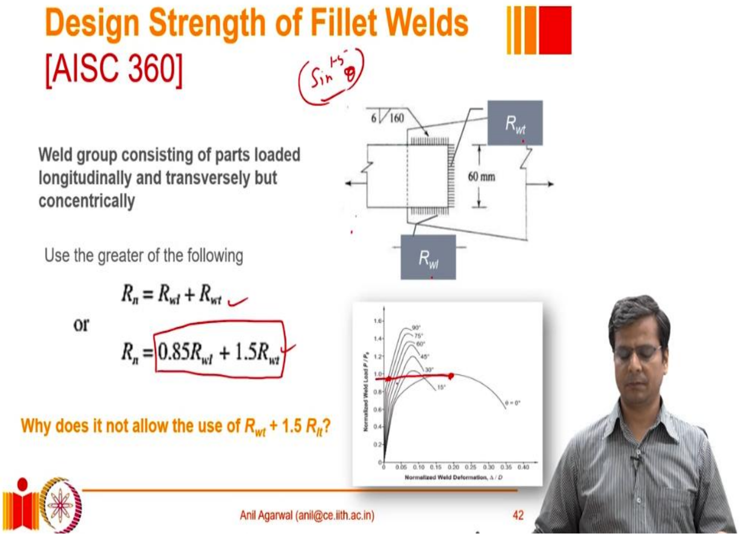

That is, this configuration. Or we will consider this peak. And for that peak, we will see at the time, how much was the stress developed here. And then we will say, this is the strength that we are going to use.