Equipment Design: Mechanical Aspects
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Lecture 20
Vessel under very high pressure

Welcome to the fifth lecture of week 4 where we will discuss vessel under very high pressure. So let us start the discussion. So if you remember the design of pressure vessel, there we have considered one standard and that is IS2825 code 1969 okay. Now what are the limitations of this code. The first limitation is that it does not give design for pressure exceeding 200 kg force per cm square, that is greater than 20 meganewton per meter square or approximately greater than 200 bar.

And second limitation is when D O/D I should be less than or equal to 1.5. So when I am having the condition where pressure exceeds 20 meganewton per meter square because there are so many processes in which very high pressure is dealt or that processes are operated at very high pressure. So that cannot be designed while following the rules available in IS:2825-1962 code.

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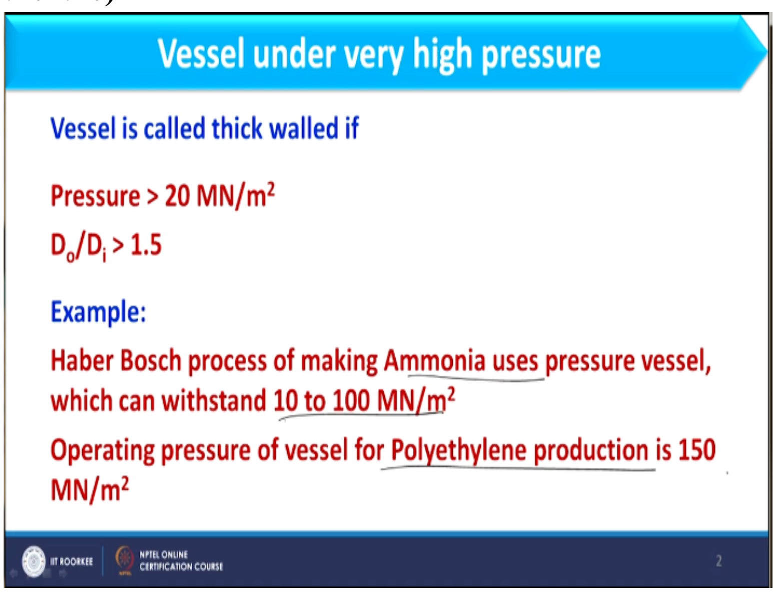

So for that condition we have a few examples that in which particular case pressure exceeds 20 meganewton per meter square and very well known example is the Haber process. I hope you are getting that. So Haber Bosch process for making ammonia uses pressure vessel which can withstand 10 to 100 meganewton per meter square pressure, and similarly operating pressure of vessel for polythene production is 150 meganewton per meter square.

So here we have few examples where pressure exceeds beyond 20 meganewton per meter square. So what should be the design procedure for such cases. Now design of such vessels require failure theories. We will discuss here four failure theories and based on that we will design the pressure under very high pressure.

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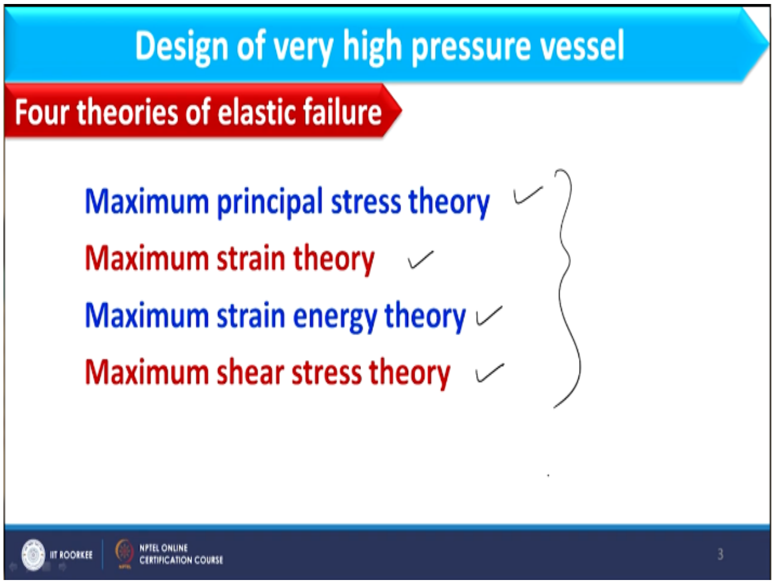

So first theory we have is maximum principal stress theory. Next we have is maximum strain theory and then maximum strain energy theory, and we have maximum shear stress theory okay. So these theories are there to design the vessel under very high pressure and the funny part about these theories is that while seeing the name of the theory you can find or you can identify what should be the failure condition.

For example, if I am considering maximum principal stress theory it says that my material fails when principal stresses generated or induced in the system or induced in the material is equal to principal stresses generated or induced in a simple tension test okay. So what is simple tension test. For example, if I am having this wire okay and from both sides I am pulling it through tensile force okay. So the behavior or deformation occurring in this wire will be studied and then we can decide different properties of the material.

For example, proportional limit, elastic limit, its yield points, etcetera. So that is nothing but the simple tension test. So all these theories fail occur when these particular parameter fail in simple tension test theory okay. So let us start with the first theory that is the maximum principal stress theory.

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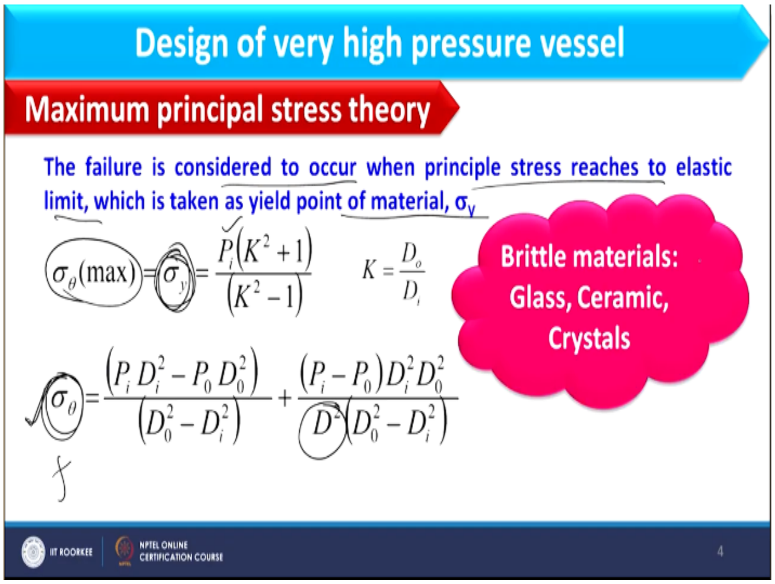

So according to this theory failure is considered to occur when principal stress reaches to elastic limit, which is taken as yield point of the material, so that we can obtain through simple tension test for that particular material. And here this is the expression for maximum principal stress if you remember this is nothing but the hoop stress and that would be maximum at inner diameter or inner radius of the vessel and that would be equal to sigma y because that we are considering as yield point of the material.

It is equal to P i (K 2 + 1)/(K 2 – 1) okay. And this we have derived from this expression. If you remember this expression we have already discussed in lame's analysis, but there this hoop stress is replaced with allowable stress when D is considered to D I. There we have derived in terms of radius and here it is shown in terms of diameter. And further K would be equal to D O/D I okay.

So here I am having sigma y that is nothing but the yield point where permanent failure will occur so this will be considered with some of the safety margin. So considering this expression we will design the vessel. Now what we will design over here. If you consider the expression there K is designed as D O/D I. So sigma y is what yield point, yield point we will consider with some safety factor and usually safety factor exceeds 1.

So sigma y will be divided by that factor of safety and considering this equation we will compute value of K okay. And then either D O or D I will be known to me. So next diameter I will calculate and then difference of this diameter divided by 2 will give me the thickness of that particular vessel. Experience says that this theory is more suitable for brittle material. Brittle material means such as glass, such as ceramic and crystal etcetera okay. So application of this theory is better for these materials. Next move to other theories.

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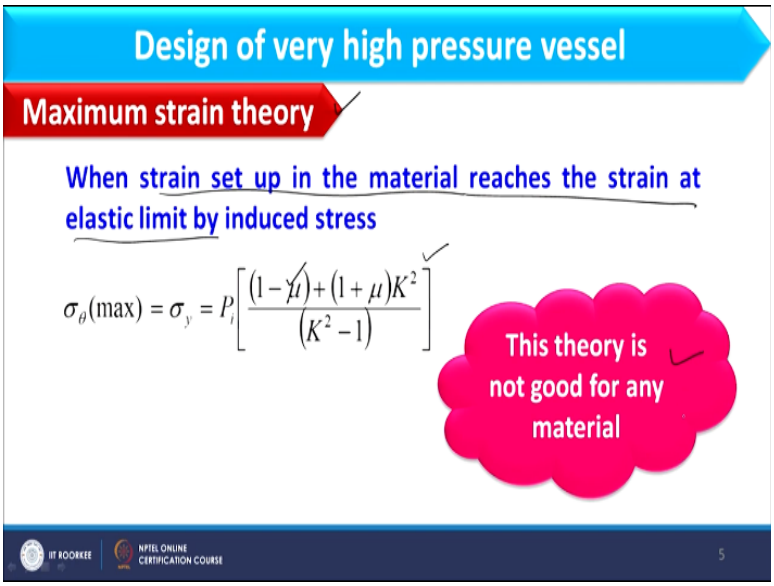

Second theory I am having is the maximum strain theory and according to this when strain set up in the material reaches the strain at the elastic limit by induced stresses then the failure will occur and that would be the condition for design. So considering that we can have the expression this, where (1 – mue) + (1 + mue) K 2 / (K 2 – 1) into P will be considered as sigma y okay. That mue is nothing but the Poisson's ratio. And usually this theory is not good for any material. If we design the vessel using this theory it will not give the proper results.

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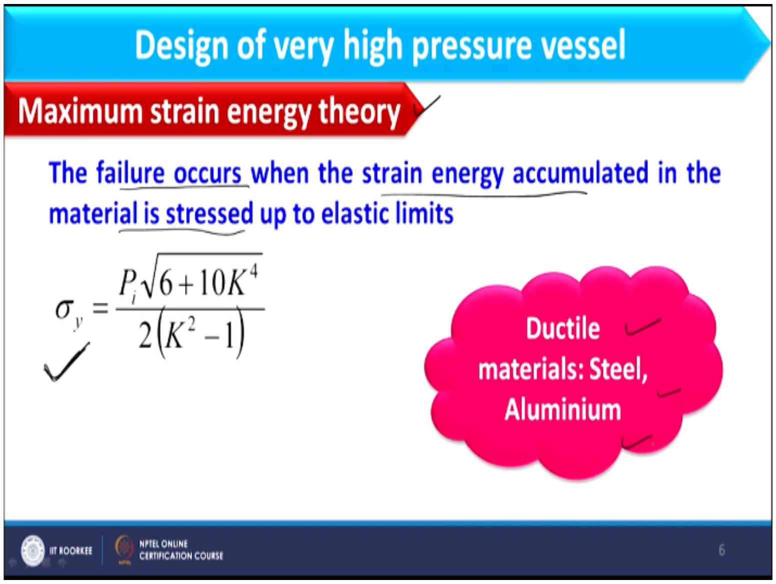

And next theory I am having is the maximum strain energy theory okay. So what is strain energy. Strain energy we can define when I am putting a load on this bar okay. So when I am putting tensile load on this bar to this direction what will happen, elongation will take place in this bar okay. And that elongation is basically the strain which is occurring over here. So once elongation takes place it means it absorbs some of the energy okay. And that energy is basically the strain energy.

So what is strain energy. It is the work done by this load, which I am pulling in this way. It is the work done by this load on this bar in the case when energy is not going out or coming into this bar in the form of heat. So that work we can call as strain energy. And the theory says that failure occurs when strain energy accumulated in the material is stressed up to the elastic limit. And this is the expression to design the high pressure vessel using this particular theory or to compute value of K.

And this theory is most suitable for ductile materials such as steel and aluminium okay. So this is basically the application of this theory, and now we will focus on fourth theory and which is on maximum shear stress theory.

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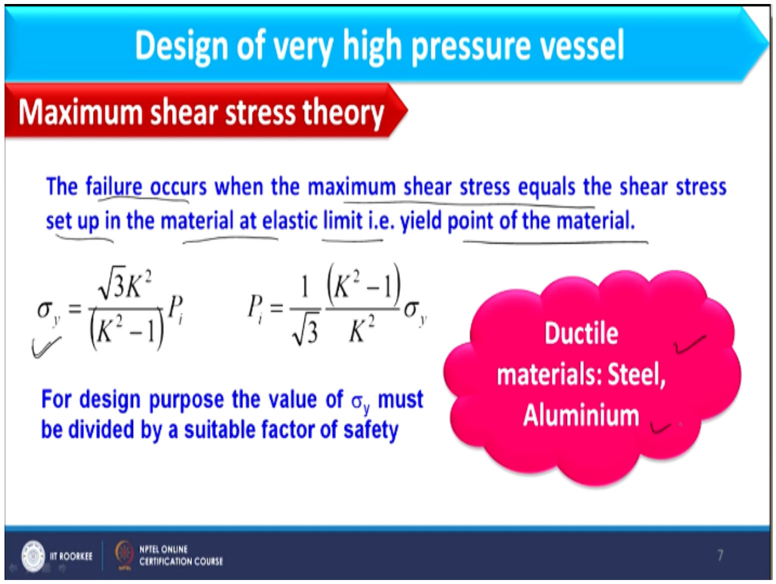

According to this theory failure occurs when the maximum shear stress equals the shear stress set up in the material at elastic limit that is the yield point of the material. Considering this theory, we can have the design equation and which is sigma y = square root 3 K 2 / (K 2 – 1) into P i, and then we can calculate P i from this expression also. And this theory is also suitable for ductile material steel as well as aluminium okay. So as you have seen that for ductile material, we use two theories, the maximum strain energy theory and maximum shear stress theory.

So if ductile material I am using I use both theory to calculate the thickness and then I will choose the higher one. And further I would like to repeat that sigma y is the extreme point where failure will occur. So we will consider slightly lesser value in design and that would be sigma y / factor of safety.

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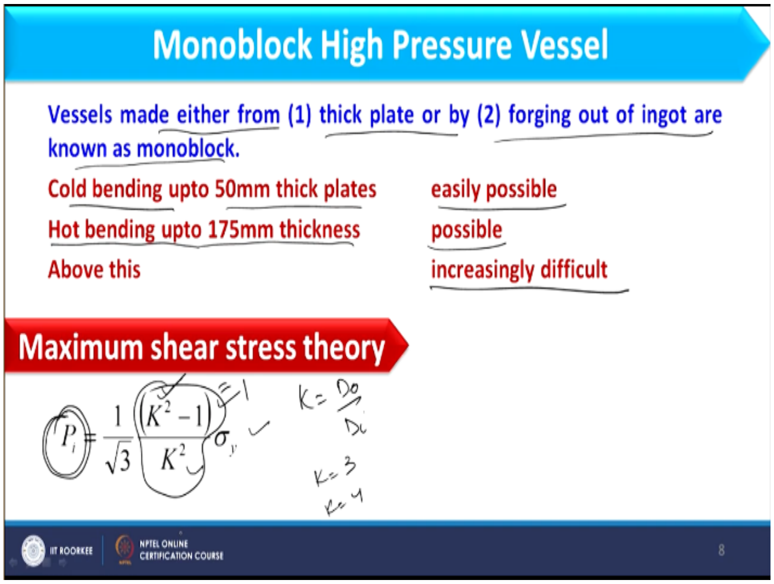

So let us move further. Here we are discussing some of the high pressure vessel. The very common high pressure vessel is called as monoblock okay. So monoblock as you can understand it is prepared with single sheet okay. So vessels made either from thick plate, if I am using thick plate or by forging out of ingots are known as monoblock. So you can understand that monoblock is basically prepared with single sheet. In that case I can consider thick plate or that plate I can prepare by forging out ingots.

So what is ingot, ingot means the metal bar okay. And what is forging, I guess you understand the forging, forging means continuous tapering or continuous hammering the hot metal. You must have seen the person who makes the instrument through iron. So what he does, he basically heats up the iron and then when it is heated up he continuously hammer it to give a particular shape. So that process is basically called as forging.

So when I am having ingot or very thick bar of metal, after continuous hammering it we can prepare a metal sheet from this and then that can be used for monoblock. So monoblock will be prepared by cold bending up to 50 mm thick plate, so that can be easily possible. Now how this cold bending occur. When we have the very thick metal sheet, we first roll it okay and when we roll it, it is done by cylinders okay. There are three cylinders, one is here, second is here and third is here. All these cylinders roll okay.

This will roll in this direction, this will roll in this direction. So according to the adjustment of these cylinders we can roll the sheet okay. So that is done by cold bending. It means at whatever temperature sheet is available that is at room temperature, it is simply rolled when the thickness is up to 50 mm.

Further we consider hot bending up to 175 mm thickness and that is possible. It means up to 175 we can roll the metal sheet, but for that purpose if metal sheet is slightly heated up or it is at higher temperature it is easy to roll, so that is again the possible process. And above this it is increasingly difficult. It means after certain thickness rolling of metal sheet is very complicated, so we avoid that process. Now what are the possibility for that. To discuss that possibility, first of all we will discuss the limitation of monoblock.

And to illustrate that limitation of monoblock we will consider maximum shear stress theory for example. So if you consider this theory, it says that P i = 1/root over 3, (K 2 – 1)/K 2 into sigma y. Now if you focus on this equation what this term gives or what should be the maximum value of this term. The maximum value of this term would be equal to 1 okay. Now K is basically D O/D I. It means K will speak about the thickness of vessel. So if I am considering K = 3, this will give 0.88 value and if I am considering K = 4 it gives 0.93 value.

So what is the point, I cannot exceed the pressure after certain limit even if I increase the K value manifolds okay. What is the meaning of this. If I keep on increasing the thickness, then also it will not able to sustain more pressure than the limited value and that limited value can be decided by keeping this factor as 1 okay. So pressure will not increase after certain value okay. It means monoblock can be used up to certain pressure values and beyond that it cannot be used. I hope I am clear.

So how I can accommodate more pressure in monoblock because it has the limitation. So if change sigma y, I can sustain some of the pressure okay because (K 2 – 1)/K 2 it has the maximum value 1, it cannot go beyond this okay. So sigma y value if I change I can change certain pressure okay. So that sigma y can be changed by making alloying in the material, fine.
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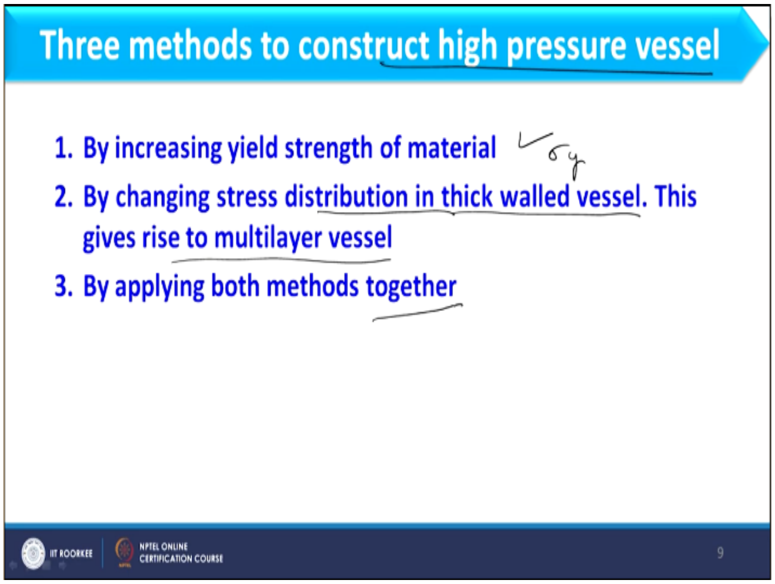

So in this way let us discuss three different methods to construct high pressure vessel. First is by increasing yield strength of the material that is sigma y as I have already discussed. Second is by changing stress distribution in thick walled vessel and this gives rise to multilayer vessel, this is the second way. And third way is by applying both methods together. So in these three ways we can make the vessel which can be operated at higher pressure than that was limited in monoblock okay.

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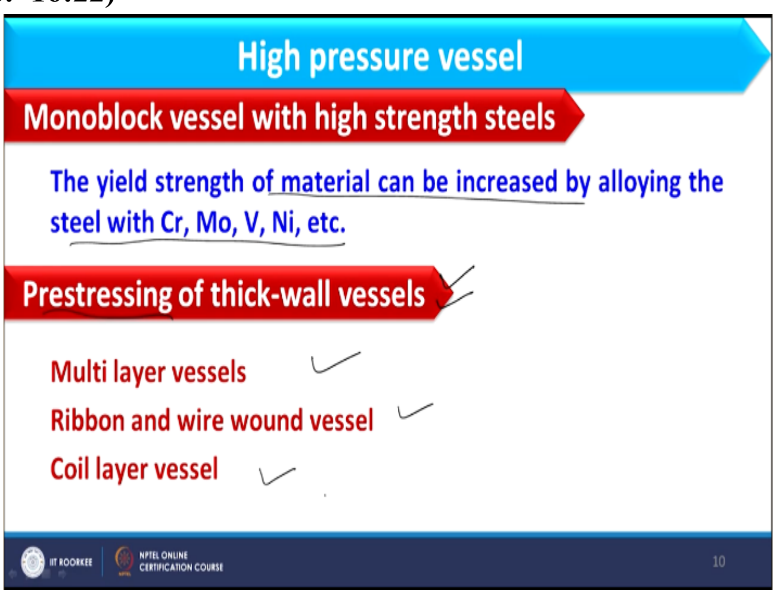

So let us discuss what would be the first point that how I can increase the yield strength of the material. Yield strength of the material can be increased by alloying the steel with chromium, molybdenum, vanadium, nickel, etcetera. So by doing this we can increase the yield strength of the material.

And second method is pre-stressing of thick walled vessel. As we have discussed that we should re-distribute or we should distribute the stress properly and that can be done through pre-stressing of thick walled vessel. And this pre-stressing gives multilayer vessel, ribbon or wire wound vessel and coil layer vessel. So these three type of vessel we can prepare using pre-stressing. In pre-stressing we basically distribute the stresses in such a way so that more pressure can be sustained in given thickness.

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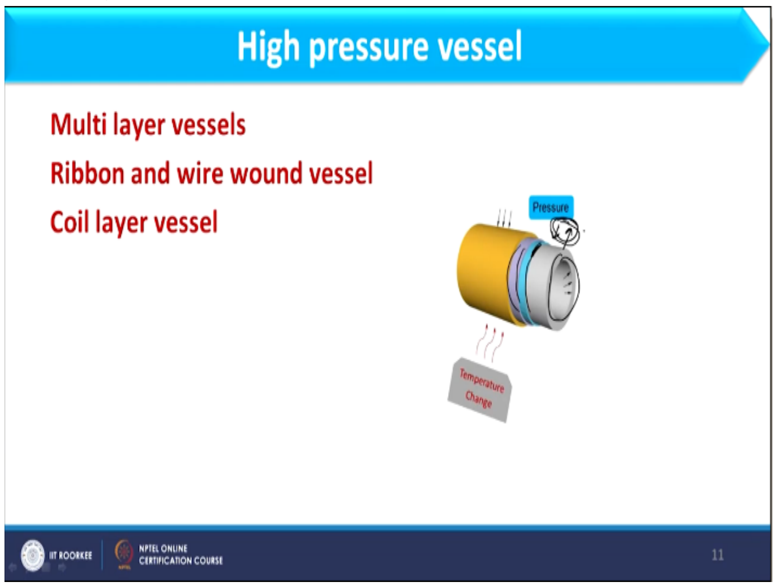

So what is multilayer, that can be explained through this figure. If you see here I am having this inner vessel, then outer vessel, then outer vessel and then outermost vessel. So in this way we are preparing the vessel with layers. So what happens in the layer. When I am considering innermost layer, it means the pressure will work in this direction okay. However, when I am considering this layer, its pressure the pressure at inner side of this vessel will act in this way.

It means these two pressures will act opposite to each other and then it distributes the pressure properly, okay. So in this way we prepare the multilayer vessel. Now how these multilayer vessels are prepared. For example, if I am having this one vessel and second layer is this okay, I hope you are getting it. So what I need to do that this vessel I will heat up and this vessel which is falling above to this, this will be chilled or quenched.

So what happens when these two layers were falling to each other, to equalize the temperature it will expand because it has the heated property okay, so it will expand. And this basically quench so it will squeeze okay. So therefore both layers will sit one over another in this way. However, a small gap will be there and therefore pressure will be distributed in that layer, but sufficient gap will not be formed because of this process of multi-layering. So this is the concept of multilayer vessels.

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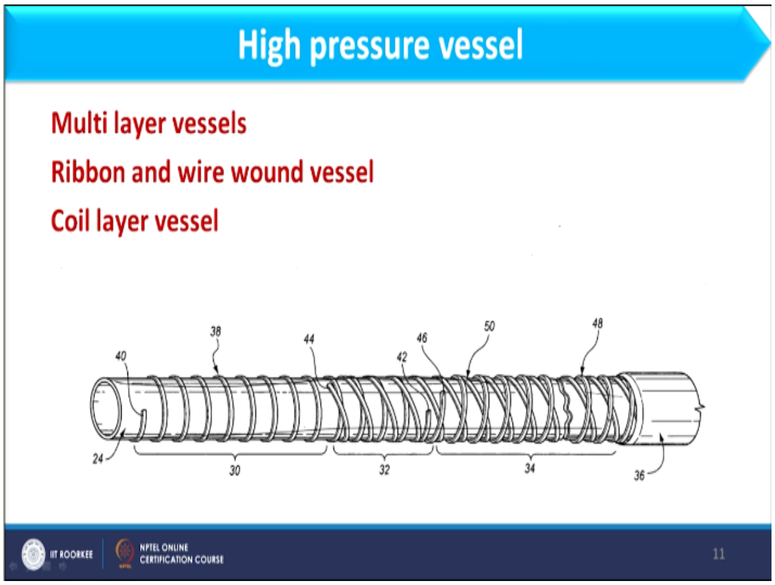

Next I am having ribbon and wire wound. So you can consider this is the vessel okay, where this metal strip is wired or metal strip is rolled over this periphery, which gives strength to this vessel to sustain more pressures.

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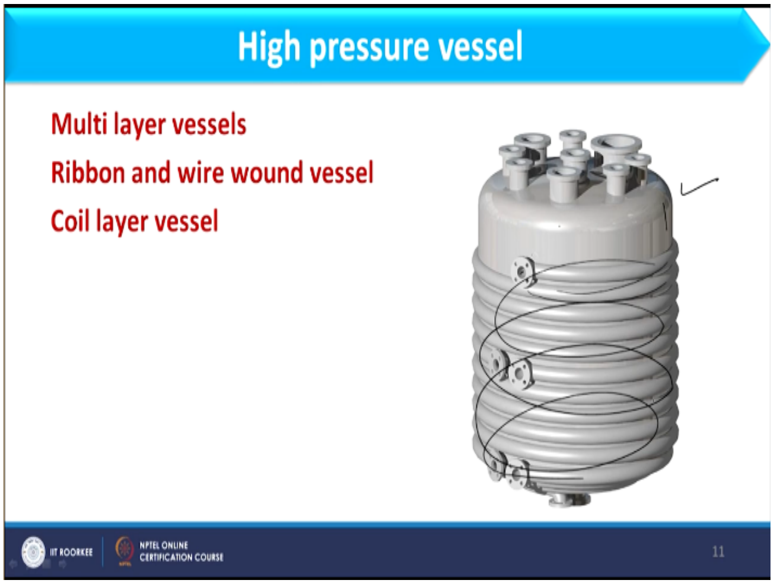

And the third we have the coil layer vessel, in which if you see this image, this is basically the vessel and around this we have the coiling okay. And this coiling is nothing but half pipe okay. If we cut the pipe along the length and then we revolve that section around this, in this way the coil layer vessel will be formed okay.

And the advantage of this coil layering is when I need to supply any heating or cooling media in the vessel for process purpose, these pipes will solve that purpose also okay. So basically this coil layer gives stiffening to the system and along with that it can be used as a media for heating or cooling. So in this way we pre-stressing the vessel and therefore it can withstand high pressure than that is limited in monoblock.

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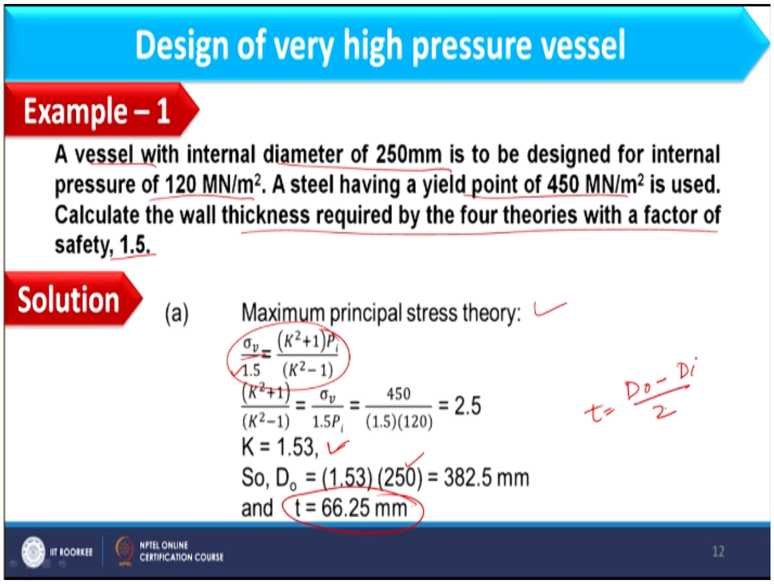

And now we will discuss few examples to illustrate design of high pressure vessel. So here I am having example 1, a vessel with internal diameter of 250 mm is to be designed for internal pressure of 120 meganewton per meter square, steel having a yield point of 450 is used. What I need to find is calculate the wall thickness required by four theories with a factor of safety as 1.5 okay. So let us start with the solution.

First theory I am having is the maximum principal stress theory and this is the expression where this sigma y will be divided by this 1.5, that is FOS or factor of safety. Considering these parameters we can solve this equation and find out that K would be equal to 1.53. As I know the internal diameter, I can find out outer diameter which is 382.5 mm and therefore thickness of vessel comes as 66.25 mm, and thickness I think you can calculate easily that is D O - D I/2. It is simple.

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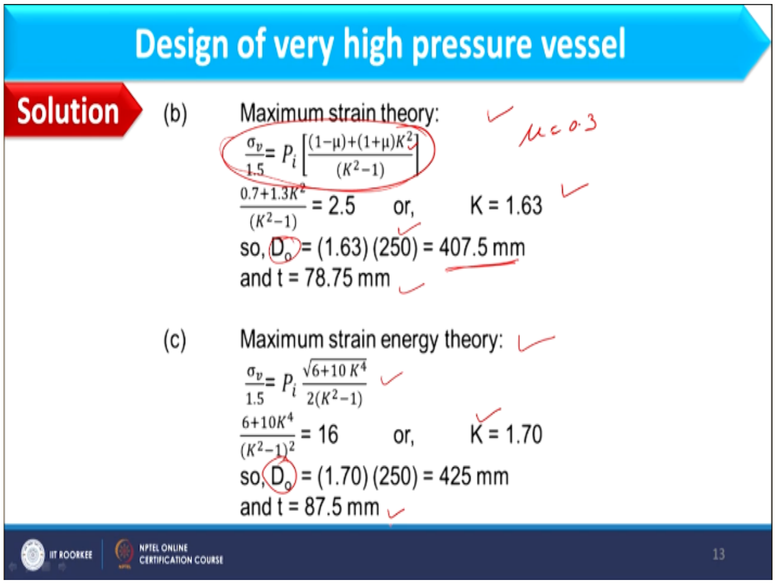

And next theory I am having is maximum strain theory and that is given by this expression, where mue is the Poisson's ratio and mue you can consider as 0.3. So that sigma y/1.5 = P i ((1-mue) + (1+mue) K 2 / (K 2 – 1)). So putting all values over here I need to extract x and that comes out as 1.63 okay. I know the internal diameter, I can find out D O, which comes out as 407.5 and then the thickness becomes 78.75 mm.

Third theory I am having is maximum strain energy theory. This is the expression, you can find out K by putting all values given over here and K comes as 1.7 and then D O I can find as 425 mm and corresponding thickness is 87.5 mm.

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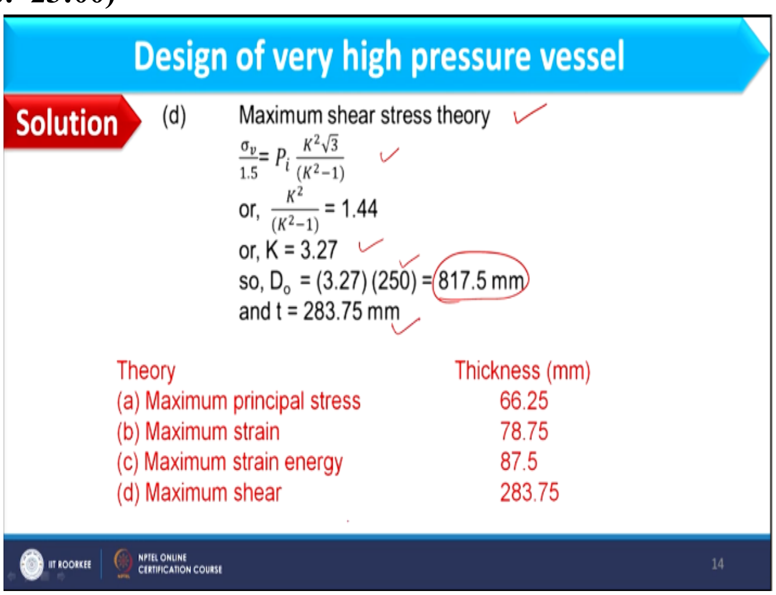

And here I am having the final theory that is maximum shear stress theory, expression you know already, and after solving this we can have K as 3.27 and considering internal diameter and K value I can find outer diameter which is 817.5 mm and then the thickness is this. So here I have summarized the thickness, which I have computed through all four theories and as steel is the ductile material maximum strain energy theory and maximum shear stress theory are more applicable.

And as steel is the ductile material which we have considered in this example, the thickness found through maximum strain energy theory and maximum shear stress theory are more applicable in such cases. So that is for example 1, now I will focus on example 2.

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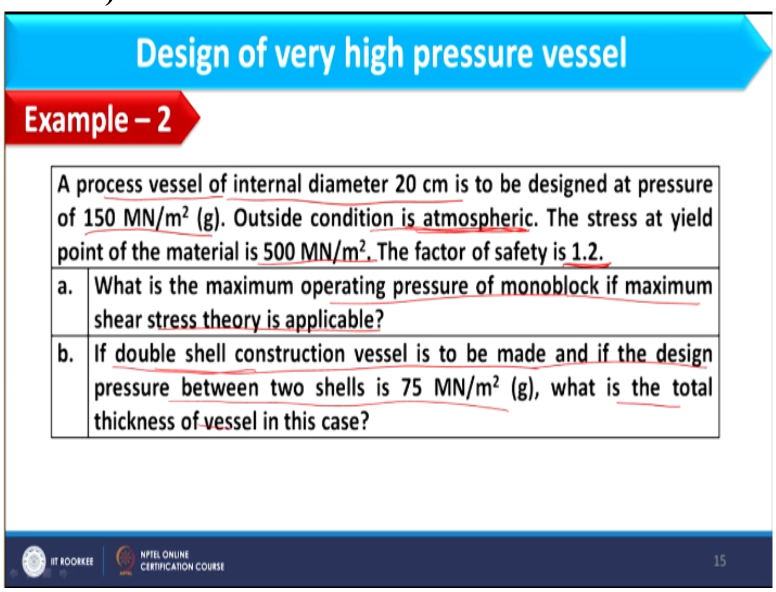

In this example, a process vessel with internal diameter of 20 cm is to be designed at pressure of 150 meganewton per meter square in gauge. Outside condition is atmospheric. The stress at yield point of the material is 500 meganewton per meter square and factor of safety is 1.2. In Part A I have to find that what is the maximum operating pressure of monoblock if maximum shear stress theory is applicable. So here basically I have to find out what is the limited pressure in monoblock okay.

In Part B if double shell construction vessel is to be made and if the design pressure between two shells is 75 meganewton per meter square, what is the total thickness of vessel in this case. So in

Part B it is double layer, so we have to find out thickness of two layers separately and then we will speak on total thickness of the vessel. So let us start the solution.

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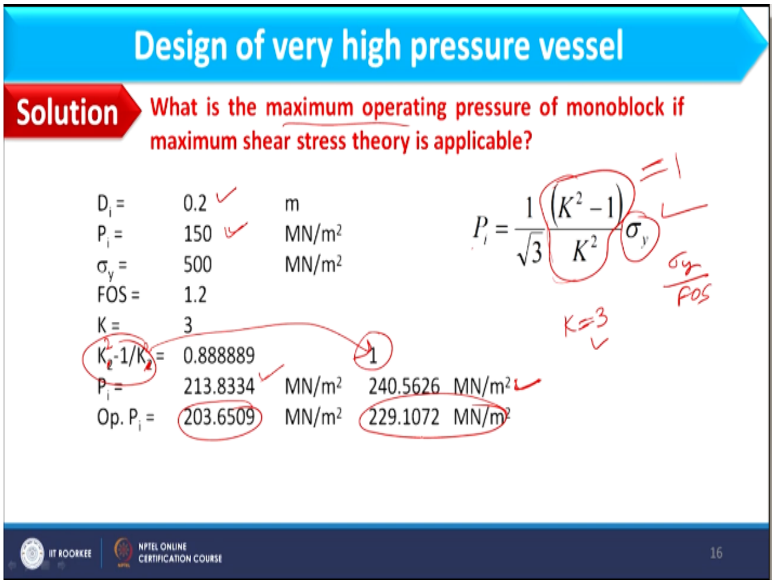

Now Part A says that what is the maximum operating pressure of monoblock if maximum shear stress theory is applicable. So this is the expression of maximum shear stress theory. Now what happens here I am having sigma y which is 500, so this sigma y would be divided by factor of safety that is FOS as 1.2.

And if I am considering monoblock, it means the maximum value of this expression should be equal to 1. And further we can also consider that if K = 3 or more than that it means this factor value will not change significantly and therefore we can calculate the limitation of P. So in this particular example I am computing P i value for K = 3 and when the whole expression becomes 1.

So here I am having this internal pressure 20 cm, P i as 150, P i I need to calculate so I do not consider this P i, sigma y 500 is given, so that would be divided by 1.2, and K I am considering as 3. So once I am considering K 3, this expression becomes 0.889 okay. And maximum value of this expression can be 1. So once I am having this K 2 - 1/K 2 = 0.889, P i will be equal to 213.8. And when I am considering one value for this expression, P i value becomes 240.56 meganewton per meter square.

So these values of P i are basically the design pressure. Operating pressure would be 5% lesser than this, so operating pressure for both condition we can find over here and for K = 3 it comes as 203.65 and for the expression equal to 1, we have 229.107. So in this way we calculate the maximum operating pressure in a monoblock. In this particular problem, we are given 150, so that can be operated in monoblock.

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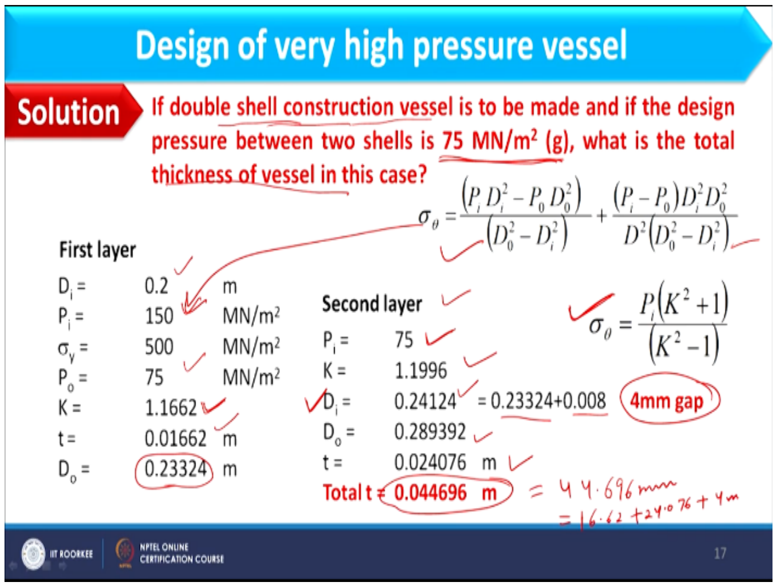

So let us move towards Part B of this example. And here as we discussed earlier Part B includes double shell construction vessel, where design pressure between two layers are 75 meganewton per meter square and I need to find out total thickness of the vessel. So here I am having this sigma y and here I am applying principal stress theory. So you see (P i D i 2 – P o D o 2)/ (D o 2 – D i 2) plus this expression okay.

Now what happens in first layer internal pressure would be 150 meganewton per meter square; however, pressure between two layers is given as 75 meganewton per meter square, so for inner layer both pressure will act, 150 as inner and 75 as outer. So we will consider the expression where both pressure will be acting, it means this equation. And here we have P i as 150 and P o 75 as I have already discussed.

Considering this equation we can find out K, which comes out as 1.1662 and then inner diameter is given as 0.2, I can calculate outer diameter as 0.23324 and therefore the thickness becomes

16.62 mm. Now here I am having value of D O, which will work as a reference point to determine the inner diameter of second layer okay. So let us start the calculation of second layer.

In second layer I am having pressure 75 meganewton per meter square, so what happens in second layer, second layer inner side pressure is 75 meganewton per meter square, however, outer side pressure is atmospheric only okay. So in gauge that would be equal to 0. So I will use this particular equation to determine thickness of second layer.

Considering this expression and P i = 75 I can find out K as 1.1996. Now what is D i for second layer, D i I am considering as 0.24124; however, D o for the first layer was 0.23324 okay. So 0.23324 + 0.008 I am considering because I am assuming 4 mm gap between two layers. So considering these values D i comes as 0.24124. So taking D i value as this, I can find out D o because I know the K value and then I can find out the thickness which comes out as 24.076 mm okay.

So in this way we have calculated thickness of layer 1 and layer 2, but how I will calculate the thickness of whole vessel because inner thickness is there, outer thickness is there, but 4 mm gap is also there, so total thickness of the vessel becomes t1 + t2 + gap okay. So that will come as 0.044696 meter or 45.696 mm. And that is equal to 16.62 mm plus 24.076 mm plus 4 mm. So in this way you can find the thickness of multilayer system okay. So here we have solved two examples to illustrate how to design the vessel under very high pressure.

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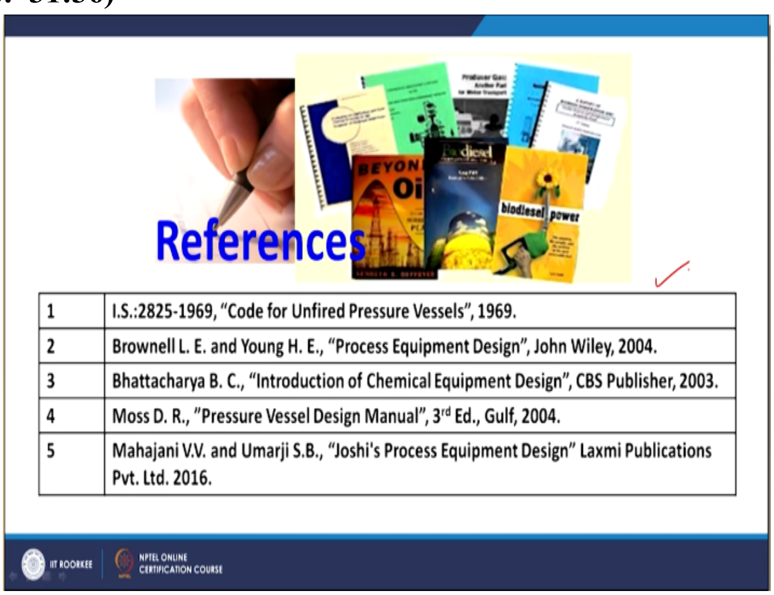

And here I am having some of the books, which you can refer.

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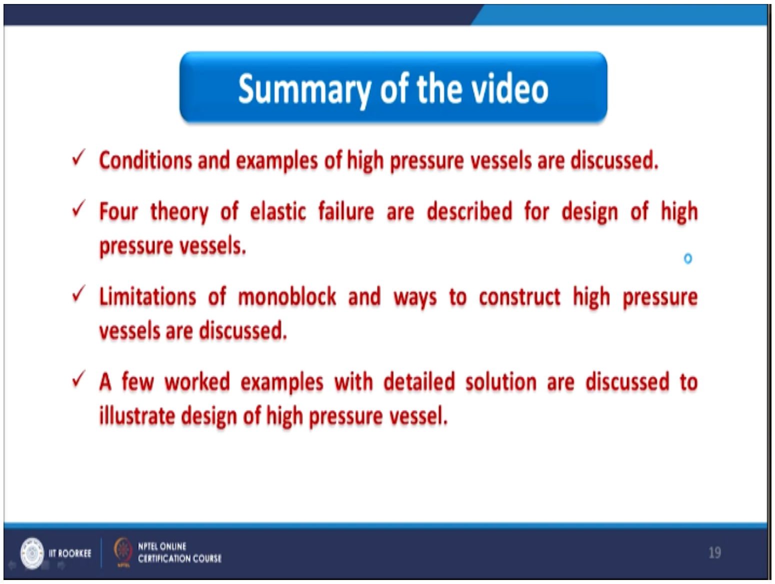

And now I will summarize this lecture and it goes as, conditions and examples of high pressure vessels are discussed, four theory of elastic failure are described for design of high pressure vessel, limitations of monoblock and ways to construct high pressure vessels are discussed and a few worked examples with detailed solution are discussed to illustrate design of high pressure vessel. And here I am stopping lecture 5 of week 4. And it was the last lecture of this course. I hope you are benefited by the content of this course and I wish you all the best for the upcoming exam of this course. That is all for now, thank you.