Maintenance and Repair of Concrete Structures
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Lecture – 04
Corrosion of Embedded Metal; Types of Reinforcement – Bare Steels

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Today, we are going to talk about corrosion of embedded metal. In the previous lectures we looked at the significance of corrosion and fundamentals of corrosion. Basically, we looked at the corrosion circuit and then in the second lecture, we looked at the carbonation induced corrosion and the chloride induced corrosion mechanisms in concrete structures. And now today, we are going to talk about bare steel, what are the different type of steel reinforcement available and we will have one lecture on bare steel which we will cover today and in the next lecture, we will talk about coated steel and non-metallic rebars.

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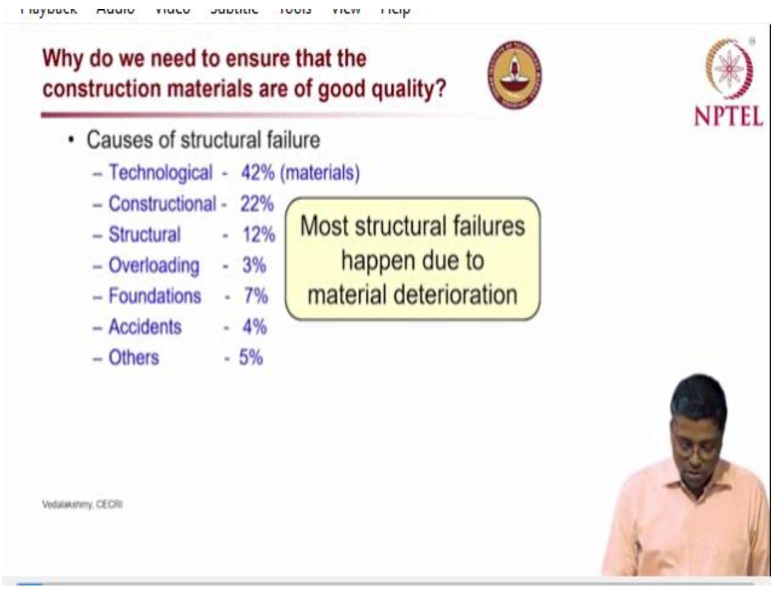

Let us look at the bare steel, before getting into the different steel reinforcement types, first of all let us look at why do we need to ensure that these construction materials or for example, steel is of good quality in steel and concrete. The main reason is most of the structural failure happens due to material deterioration, if you are talking about long term deterioration process.

Based on the case studies, we found about 40% failures are mainly due to the materials, I mean not being able to meet the adequate properties.

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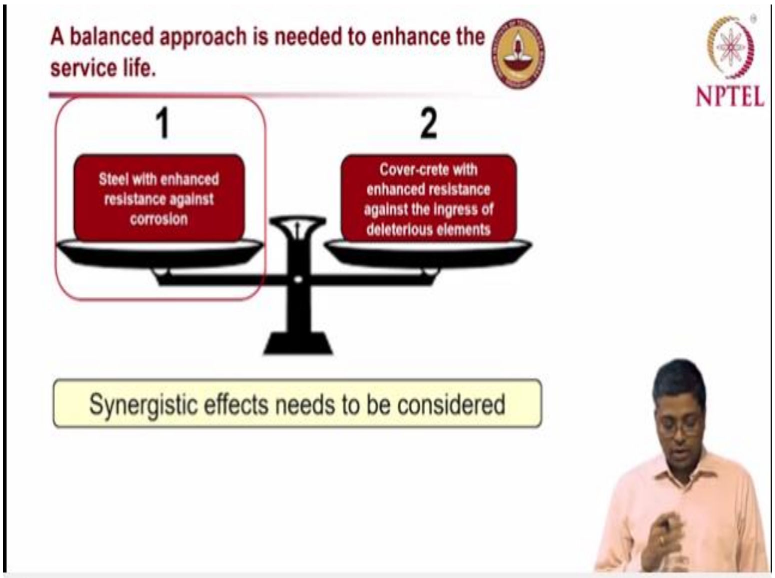

So, if we want to enhance the service life or avoid such failures, we have to make sure that both the steel and the concrete, if you are talking about deterioration which is basically, the chemical attack or long-term degradation process. So, we have to make sure that the steel which we use is of good quality and at the same time, the concrete not just the concrete but mainly, the cover concrete, which is actually protecting the steel reinforcement that also have to be very highly resistant against the deleterious elements.

So, both these have to be looked at and there should be a balanced approach, in this module we are going to focus mainly on the steel reinforcement.

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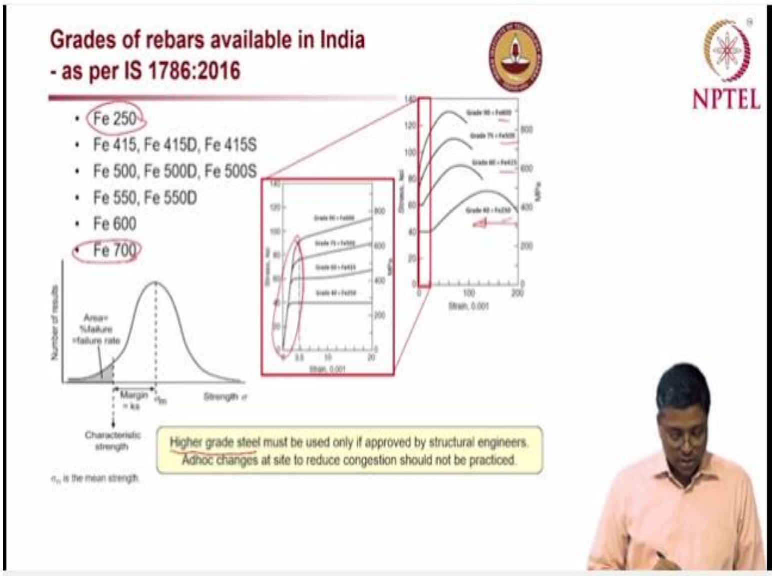

Now, let us look at different type of grades of steel rebars available in the country. Earlier we used to use Fe 250, but then there was a demand for higher yield strength, so we went on increasing. Even today people are thinking about Fe 700 type or grade steel, so, the different grades are Fe 600, Fe 500, Fe 415 and Fe 250. Generally, you can see (graphs on the right side) that as the yield strength is decreasing, the ductility or the end of the graph actually is moving towards the left or in other words, the ductility of the rebar is actually reducing as we go for higher and higher strength. If you look at the modulus of elasticity, you see that pretty much all the steels have similar modulus of elasticity, so that is maintained.

But definitely, ductility is a problem. Especially, when we talk about the earthquake resistant structures, ductility is very, very important. So, the structural system when we talk about steel concrete system should be still ductile enough so, the structural engineers have to take care of that part and why I was mentioning here is this higher grade, when we go for higher grade steel, we should not make ad hoc changes at the site like reducing the number of steel rebars and increasing the grade of the steel. We should leave it to the structural engineers or designers to approve then only, we should go for higher grade steels otherwise, it might affect the ductility of the structural system.

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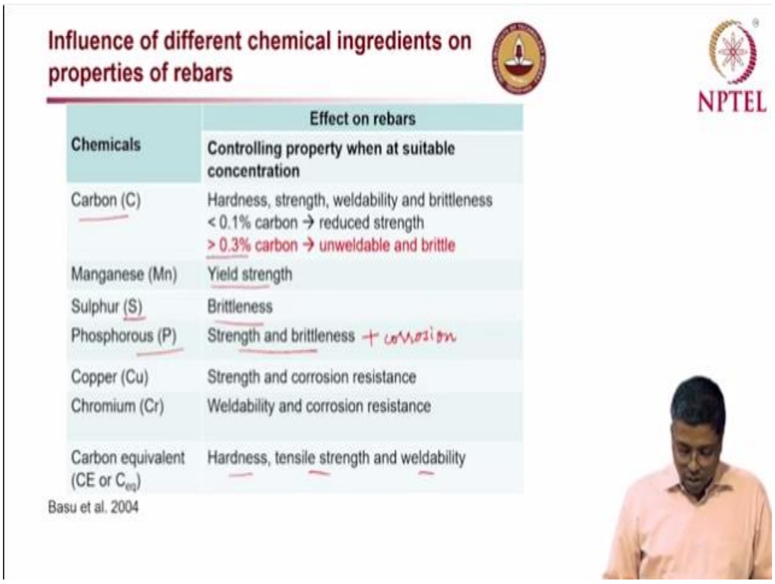

Now, let's look at the influence of different chemical ingredients or what is the chemical composition of the steel and how they are actually influencing the various properties. Let's say very briefly we will go through. Carbon; it influences the hardness, strength and weldability, brittleness all these properties will get influenced if you change the carbon content. For example, here you can see if the carbon content is more than 0.3%, then the steel might become unweldable or it might become very brittle in nature.

Manganese; it influences the yield strength. Sulphur; it influences the brittleness. Phosphorus; it influences the strength and brittleness. Phosphorus influences the corrosion properties also.

Then the copper also it influences the strength and corrosion resistance, chromium influences the weldability and corrosion resistance, then carbon equivalents affects the hardness, tensile strength and weldability. So, all these properties are very much important for the good performance of the structural system. Even though, some of these elements are in very, very small quantity in the steel, they are still very important to be considered. Otherwise, you will see that the steel which we used is having very different properties than expected.

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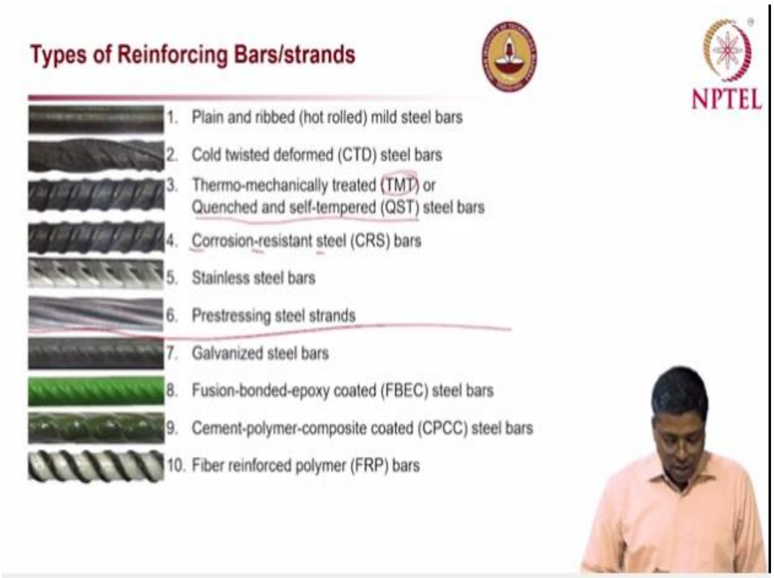

Now, let’s look at different type of rebars, which we are going to cover in this module. First one is plain and ribbed (hot rolled) mild steel rebars and next one is cold twisted rebar, then we now we use Thermo Mechanically Treated, scientifically speaking, it is Quenched and Self-Tempered steel, it is QST steel rebars but in India we call this as TMT.

And then we also have CRS rebars which is Corrosion Resistant Steel and then we have stainless steel rebars and prestressing steel strands, so until Prestressing steel strands we will cover today in this lecture, and then we will move on to coated reinforcing systems.

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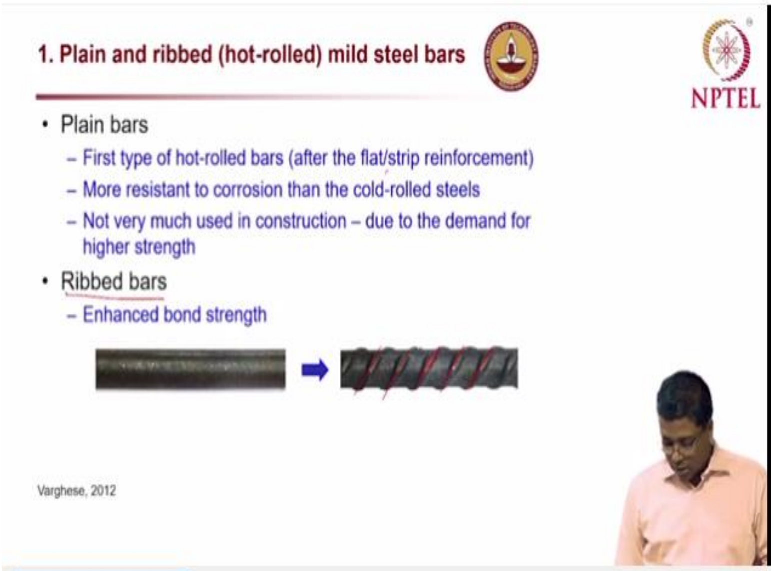

Now, let’s look at plain and ribbed, hot rolled mild steel rebars, so these are the first type of hot rolled bars which were in use in the industry. Mainly, after the flat or strip reinforcement, which were used in the first-generation concrete structures. then there was a need for more resistant steel and higher strength. So, let’s look at the plain and ribbed mild steel rebars mainly, hot rolled steel.

So, in the plain rebars these are the first type of hot rolled rebars, initially, the flat or strip type reinforcement were used and then industry started using this round shaped rebars, and these are actually, more resistant to corrosion than the cold rolled steels because the energy level is less of this type steel. These are not very much used in today's construction.

Mainly, today we are talking about high strength elements and the demand for high strength materials are there, So, we are not using plane ribbed or mild steel rebars much. Let us look at the first type of rebar discussed in the previous slide which is plain and ribbed mild steel bars, these are mainly hot rolled steel, and these were used in the very beginning just after the flat or strip reinforcement came into the market.

And then, this type of rebars are more resistant to corrosion than the cold rolled steel because when the process is hot roll, the energy level of the final product is little less than the cold rolled steels and then you have also, there was a demand for higher strength steel so now we do not use this type of plain bars much and also there was a requirement for better bond between the steel and the concrete.

So, people started using the ribbed bars, which is you can see that because of these ribs over here (2^{nd} picture), it enhances the friction between the steel and concrete. You will see that it is the deformed bars are used in the market especially, for the primary reinforcement. In the shear stirrups you might still see in some places where the plain bars are used.

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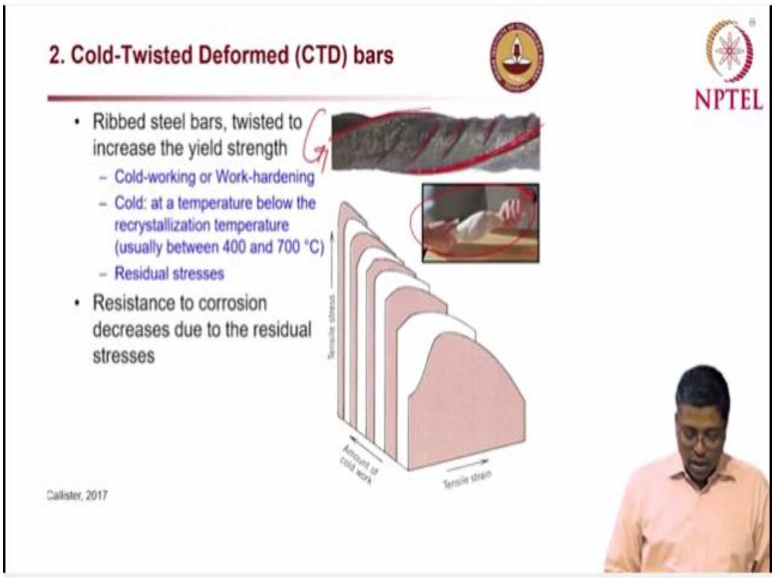

The other type of rebars which were in the market earlier is cold twisted deform bars because there was a demand for a higher strength. Without really changing the chemical composition industry went on with cold working the steel. These are basically, cold worked steel or work hardened steel, this cold here does not mean the cold which we feel. But it is a temperature below the recrystallization temperature, they twist the rebar as you can see in the image here just like an after taking bath, we twist the cloth or the towel, so just like that these rebars are twisted rebars, you can see the ribs are different from today's steel, which is available in today's market.

So, these are the ribs and these are this long (picture in the top right corner), I call it seam, like in a cricket ball you can see this portion here. And it is twisted bar, you can very clearly see how the bar is twisted but this twisting process leads to some residual stress on the surface of the steel because of which there it is more vulnerable to corrosion because of this residual stress, this surface has higher energy level, and that will lead to more vulnerable steel surface.

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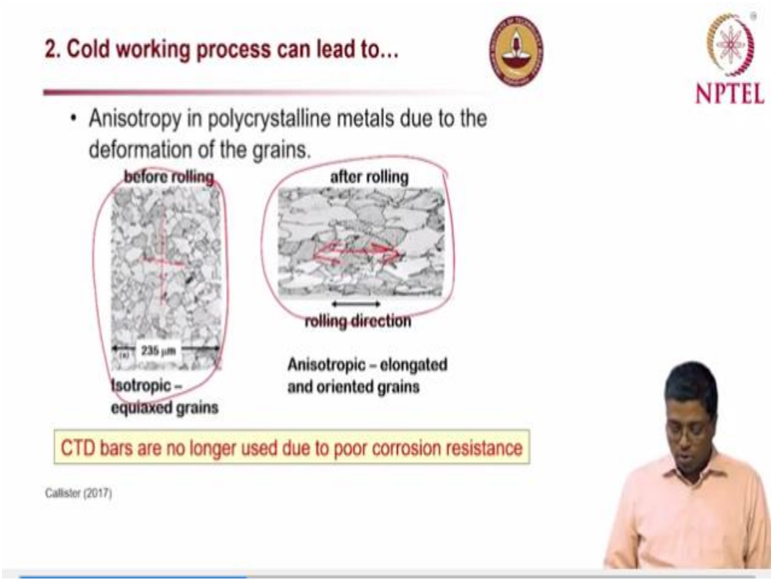

If you look at the microstructure how this cold working process, and what it does to the micro structure. Before the rolling, you can see here in this picture, all these grains have similar size in both the x and y direction or the horizontal and vertical direction in this picture whereas, in the second image here after rolling, the rolling direction is in this way.

In the second image, we can see that these grains are elongated in the direction parallel to the rolling direction, this leads to a higher energy level and the bars will tend to corrode faster, because of this it is not really used in today's construction.

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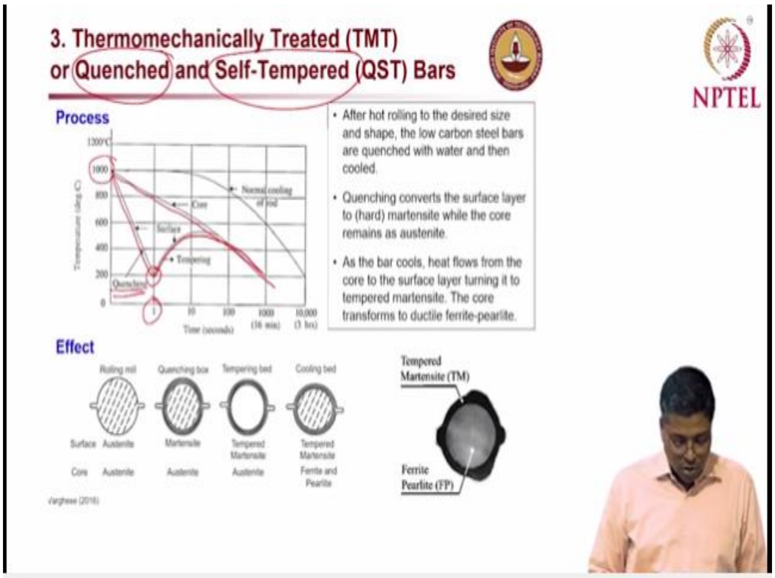

And the industry went on to another solution which is thermo mechanically treated steel, where again the chemical composition is not much changed but the manufacturing process is changed a little bit, and what you can see is you look at this graph here in the manufacturing process of this type of steel, Initially, the temperature is around 1000 degree Celsius and within 1 second, the horizontal axis is in log scale here in about 1 second.

Because of the quenching process, the steel surface temperature reaches about 200 degrees, that is about 800-degree reduction in about 1 second. 1 to 2 second you can say, and then at that moment, the core of the steel is still really hot, so the core temperature is this curve here is indicate the core temperature and this curve here indicate the surface temperature, so the core; the heat from the core is radiating outward.

And, it tempers the surface which is quenched, so that is why we are calling this quenched and self-tempered steel, so in other words we are tempering it because of the heat which is radiating outward from the core of the steel, so this is the correct term for this TMT rebars but in Indian jargon, we call it TMT steel.

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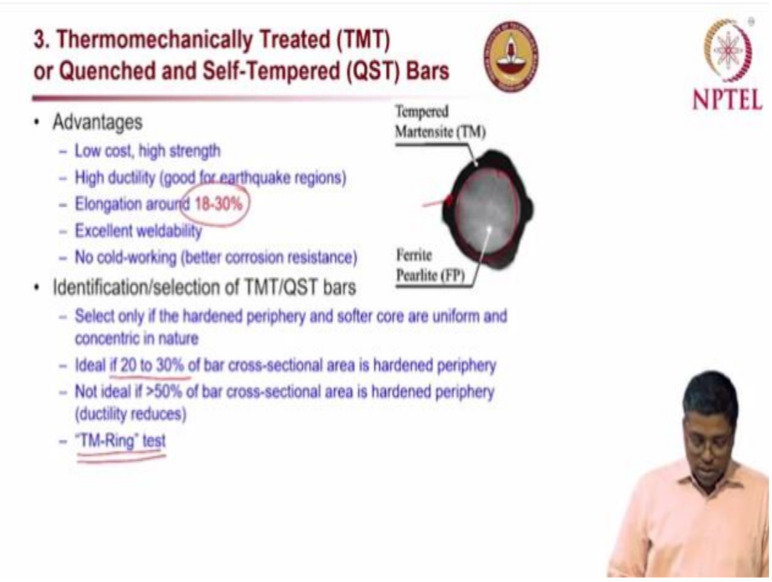

What are the advantages of this TMT steel? Main advantage is it is very ductile in nature mainly, because this centre portion here or the core of the steel is ductile in nature whereas, the peripheral region which is tempered martensite, it contributes to the strength and hardness or the surface hardness.

Because of this large area covered by ferrite pearlite which is more ductile you get really, it is possible to get about 18 to 30% elongation, which is very much necessary for building earthquake resistant structures. Now, most of the time we have seen that in some type of rebars available in the market, this composite nature or the cross section of the rebars are not as it is as shown on the picture here.

You have to have this core, which is ferrite pearlite, this region ferrite pearlite and you also have to have a peripheral tempered martensite region, then only you will get highly ductile with good surface hardness and sufficiently strong steel. Ideally, 20 to 30% of the cross-section area should be having this tempered martensite phase but we have seen that there is a huge variation in these things which leads to variation in the mechanical properties of the steel.

Also, we recently observed that there is a need to test the rebars at the site and make sure that rebars are actually having this kind of cross section. We had developed a test which we are calling TM ring test. TM stands for Tempered Martensite ring test. I will go through that test a little bit later.

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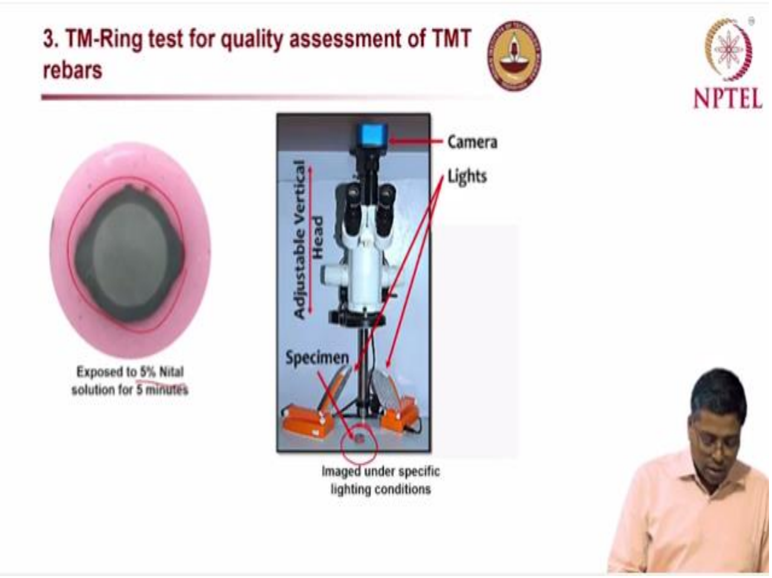

So, this is how that test setup looks like. On the right side what you see is the test setup where at the bottom, you see a small test specimen. On the left side you see the test specimen that is kept here on the bottom of set up. You have a camera and a proper lighting and you can cut the steel cross section and then etch the steel surface using a 5% Nital solution.

It is a very simple test. It hardly takes about 5 minutes to get the test results. You cut the steel surface (I will show a video later to cut the steel surface) and then etch it by using 5% Nital solution and then you will see that the steel will start reacting with the acid and then it will form this 2 different colours on the surface.

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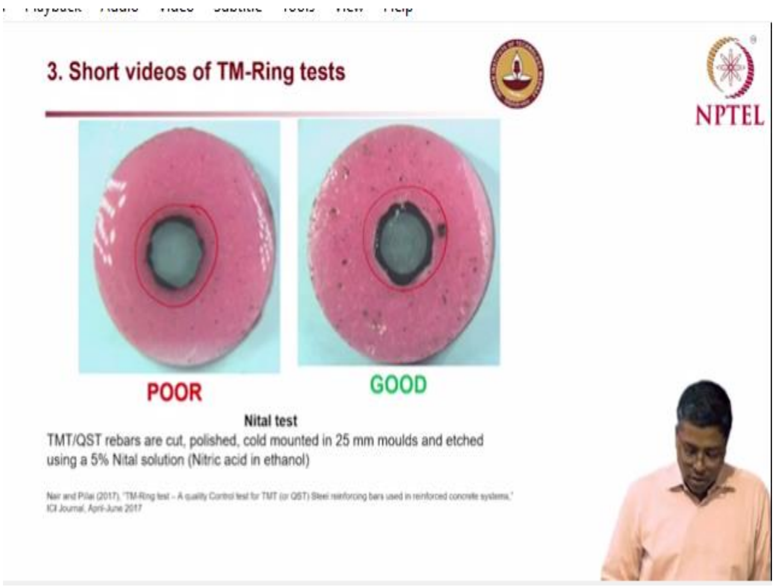

You can see this video here, on the left side is a poor-quality rebar specimen. On the right side it is a good quality rebar specimen. You can see now we have placed this Nital solution which is basically nitric acid in ethanol, not in water, in ethanol 5% Nital solution, you can see on the left side, there are proper ring is not being formed whereas, on the right side you have a very good ring formed.

So, very clear, that the right-side rebar is actually better manufactured, or the quenching process and the self-tempering process that is better controlled in the steel on the right side. So, this is what you see on the right side is what we really need to have but there are many products in the market where you see only inadequate ring.

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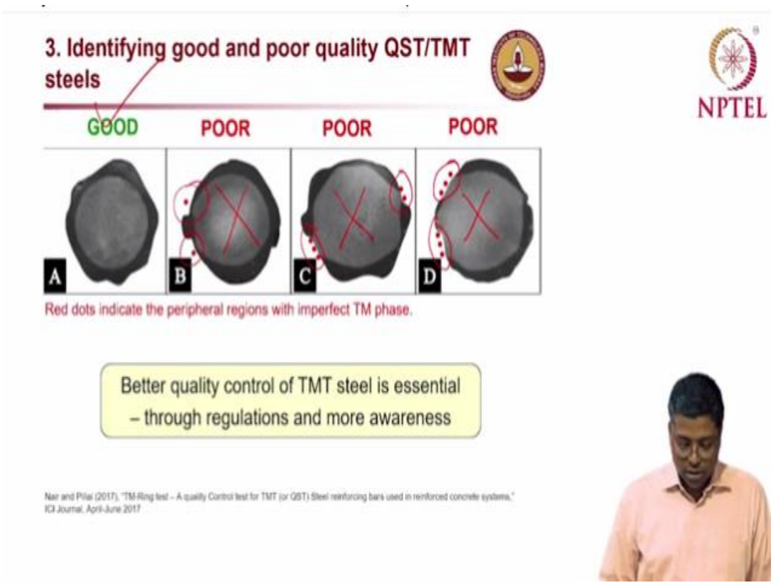

This is an example, case A is a good rebar, it is very good. Whereas case B, C and D are not good because you can see where these red dots are placed, this region you have very little tempered martensitic phase, here also there is a disconnectivity, this leads to earlier corrosion or it can lead to corrosion at a lower chloride concentration.

So, we definitely have to prevent the use of such type of steel, so I request, we must actually, do this test and ensure that the TMT steel is having this composite nature like what is on this first picture (case A) a proper ring is necessary.

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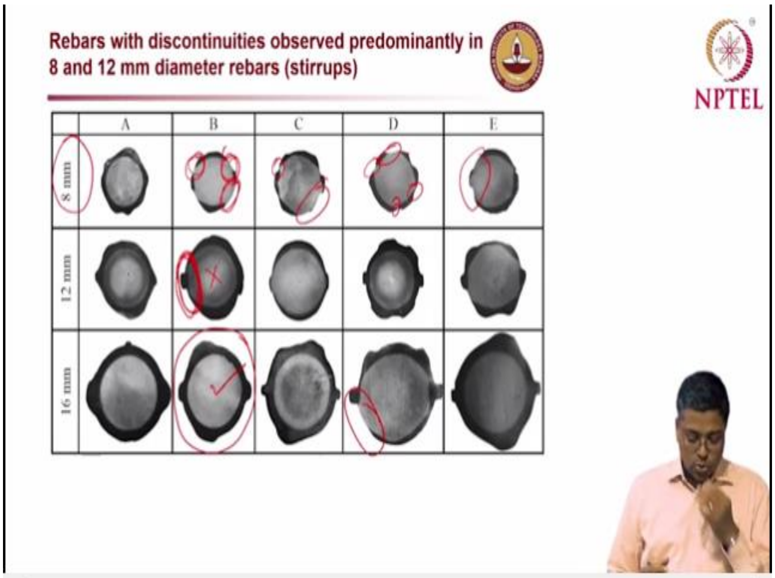

This is a market survey; results from a market survey, where we did some testing. These A, B, C, D, E are the different products which we found. As the diameter is smaller, you can see that this kind of problems are much more in the smaller diameter rebars. So, all these are not really good type rebars.

Whereas, in the larger diameter bars, only one case over here (case D of 16 mm dia) we found some problem now, we can you know if we do this test why I show this slide is to make sure that the test is done on all the diameters or the rebars, all the different diameters because you cannot just grade or the rate the product based on a TM ring test on a larger diameter rebar because in this case B, you can see the 16 mm diameter bar is okay, but the 12 mm diameter bar it is not okay because, you have a very thin tempered martensite over here. Like this you can see very thin tempered martensite region, so it is not good, as you go reduce the diameter to 8, it is really bad steel. So, what is the impact of this, why I am saying this is not good?

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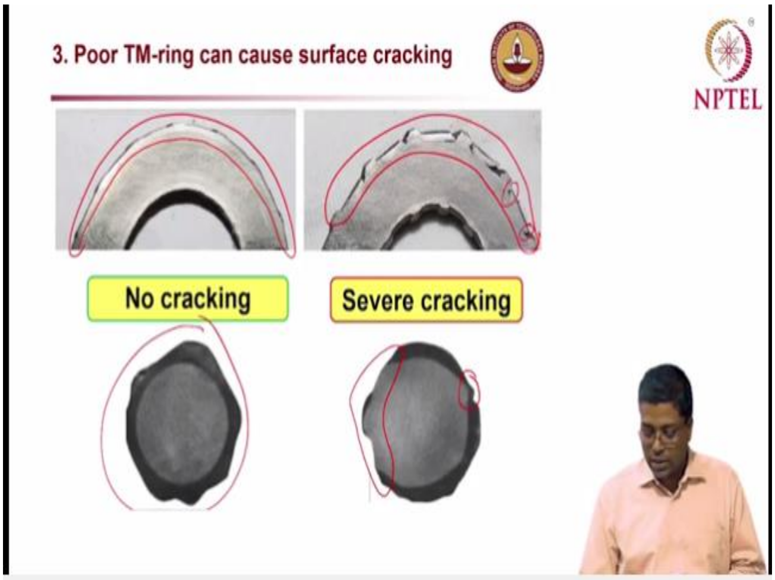

The impact is this; on the left side is an image you can see at the bottom of the screen, on bottom left you can see a cross-section, it is very good steel. when you bend that there is no crack in this region, it is perfectly alright, there is no crack induced due to the bending. But on the right-side image, you can see here this is the how the cross section is, here also very little, it is not uniform.

And when you bend this, it leads to significant cracking, you can see all this region with several cracks here, so this is the problem when you talk about or when you use this kind of rebars with inadequate tempered martensitic phase or inadequate cross section.

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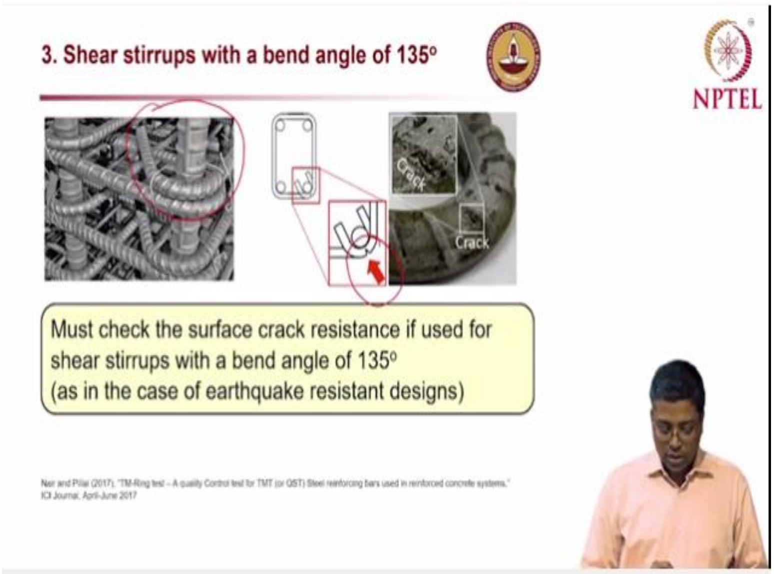

Now, why again, I am saying what is the issue with this crack or where you can see this crack? First of all, we are using these TMT steel mainly because you want ductility and you want earthquake resistance. So, when you talk about earthquake resistant design, you have to have a requirement most of the time, the stirrups we bend it by 135 degrees not just 90-degree bend, like shown in this picture here.

You can see in the picture; this is bend by 135 degree as it is shown in the sketch or here the diagram. Now, when these bars are gone to cracking, it will crack right where the bending is happening or at the bend region and outside surface of the bend it will crack. If you have a crack like this, this will tend to corrode even with very, very low quantity of for low concentration of chlorides.

Because the mechanism is slightly different, we can call it as a crevice type of corrosion. So, if I go back to the previous slide here, what will happen is; if I have a crack like these, so chlorides can enter through this, go into this crack and then stay there and then it will start corroding deeper and deeper right here (under the crack). That is the danger and one more thing to mention here is when we talk about the shear stirrups, shear stirrups will have smaller cover than primary reinforcement.

Now, if the shear stirrups are cracked and you will see that they will corrode before the primary reinforcement. So, if you look at any structure which is corroded, you might most often see that these shear stirrups are corroding and that too at the bend portion of the bar.

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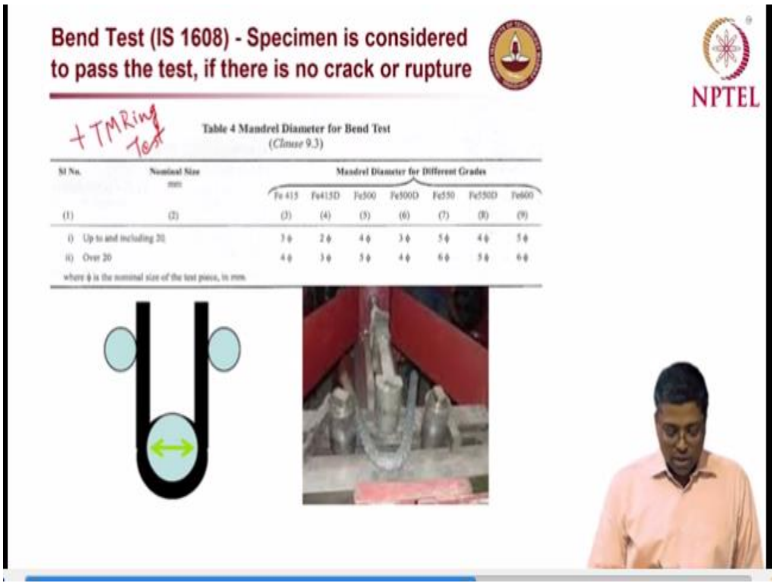

So, then it will compromise the structural capacity, so point here is we must do bend test on the TMT steel and also do this TM ring test, so bend test plus TM ring test. So, these 2 things we must do in addition to all the tensile strength test. Otherwise, we might be actually compromising the corrosion resistance of the steel.

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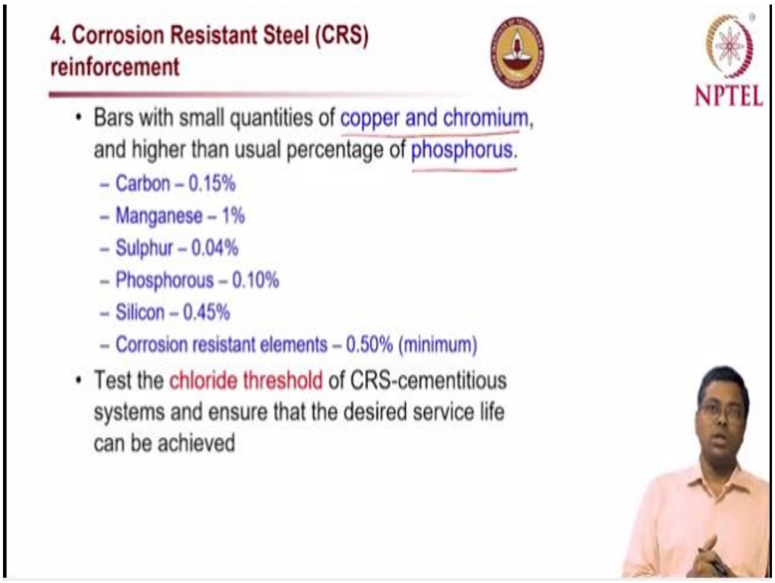

Now, we also have this corrosion resistant steel or CRS rebars in the market. Mainly, these are the rebars with difference in the chemical composition. They have a small quantity of copper and chromium is present and also, slightly higher quantity of phosphorus, this is the main difference in the CRS steel when compared to other type of steel. Now, people say that the CRS steel is highly corrosion resistant.

I mean the name itself claims so. But when you talk about the service life, it is not the corrosion rate which is the key factor, it is an important parameter, but additionally, we must ensure that the chloride threshold or the amount of chlorides required to initiate the corrosion, because when you talk about the service life, the initiation phase is the one which really governs the life of the structure.

So, what we should have is a steel which has a higher chloride threshold than a steel which has a lower corrosion rate. If you really look at these 2 and look at the impact of them on the service life, we must test the chloride threshold of CRS steel in addition to the corrosion rate. I am not saying not to test the corrosion rate but the decision should be mainly based on the chloride threshold and its impact on the service life, which is not usually done.

We generally test only the corrosion rate and make decisions, so we must test chloride threshold that is a key thing, which is the amount of chloride required to initiate the corrosion.

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So, now let us look at the stainless steel. What is stainless steel? Steel with more than 11% chromium plus nickel plus molybdenum. This enhances the resistance of this type of steel. Mainly, by having a passive film, which is rich in chromium oxide passive film and the picture here very clearly says the advantage; depicts the advantage of stainless steel.

On the left side, what you see is these pillars, which were built about 30 years after building this structure which is made of stainless steel. So, this bridge on the right side is still standing without any corrosion issues, stainless steel cost about 6 to 7 times more than the regular conventional reinforcement, but still there is an advantage of using this.

The point is if you have enough money, budget constraints are not there and you want long life with minimal repair, then definitely stainless steel is a very good option to go for provided financial constraints are not there.

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This is a couple of other examples of bridges with stainless steel rebars, one in new jersey and other in Toronto Canada. So, it's not that people do not practice this, they practice this because they may know very clearly that if they go for the other type of rebar, there will be huge repair activities or the need for very frequent repair, so in such cases we really may have to go for highly corrosion resistant steel, one of them is stainless steel.

Now, in India, there is a trend to use combinations of stainless steel and other steel rebar, in some structural elements, because stainless steel is very costly. If I use stainless steel in some portion of the structure and the other type of rebar in another portion of the structure, the project cost is still not varied, it does not increase significantly.

But when we practice this, the mix of two type of steels, we must check the possibility of galvanic corrosion between the conventional steel rebar and the stainless steel rebar. If the impact of this galvanic corrosion on the desired service life, not just the immediate future but if something is designed for 100 years, this galvanic corrosion should not lead to any significant problem and for that time period.

So that must be checked, so the galvanic current should be so low that even after 100 years there is no significant problem that must be checked before recommending such combinations.

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Prestressing steel strands is another type of steel which we are using very much in different type of structures today. Railway sleepers or railroad ties, this concrete sleepers and then very tall electric poles or mast you can see here (1st picture in the 2nd row), when you go for very tall then the lateral loads are so high and then you really need to go for pre-stressed concrete, otherwise the structure will be very bulky.

And for long span bridges, mostly they come in as a coil because you are talking about using these steel in very long spans, small rebars of 10 meter long is not enough, so it comes in coil and also nowadays, we use these type of strands in high-rise buildings also, there uncoated strands are also used but also there are products with a sheathed strands.

These sheathed strands comes in single units, when you talk about these in high rise buildings, in post-tensioned slabs they use this kind of mono strands very much because you do not want to bunch a lot of strands which will lead to significant bursting stress or they distribute the positioning of this strands, so for which mono strands are used.

And now, in some new project we even started using fusion bonded epoxy coated strand. I would say we should be very careful, when we use the epoxy coated strand. More details I will cover in the next lecture but there should not be any scratch on this epoxy coating and they should not be exposed to ultraviolet radiation or sunlight for that matter otherwise, you might see that this coating will degrade.

And if there are scratches, it will not serve the purpose for which they are designed for, so when you use coated rebars, you have to be very careful in handling them very delicately, so that mechanical damage and UV induced degradation is avoided.

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So, where we use this high strength steel material? In metro rails, elevated highways and flyovers, long span bridges, power plant any large structure when you talk even high rise buildings, we use heavily all these different type of steel rebars and strands and cables.

So, different types of cables are used, so go from single solid rebar or wire depending on the diameter and then multi strand, multi wire strands and then you have multi-layered cables and so, these are different type of steel reinforcement when you talk about very high strength requirements.

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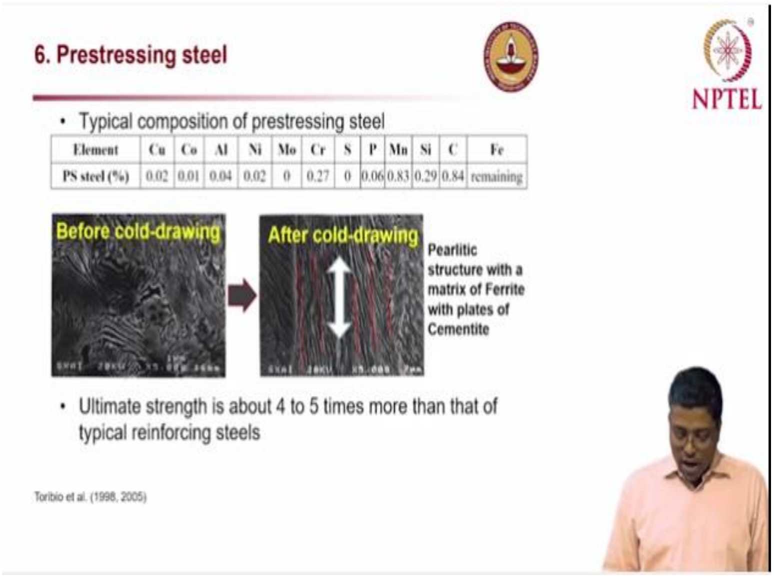

Now, the prestressing steel, it's a cold drawn steel, not like the mild steel which is hot rolled. What is happening in this cold drawing is you see the picture on the left, which shows the microstructure before the cold drawing process and on the right side, you can very clearly see all these phases are aligned in the direction of drawing or rolling direction you can see these are kind of vertically aligned over here.

And that actually, induces some factor of corrosion in the steel also, so you can see a pearlitic structure with a matrix of ferrite with plates of cementite, so parallel laminar structure you can see in this after cold drawing, so there is a rearrangement of the phases. Now, ultimate strength of this type of prestressing steel is about 4 to 5 times more than that of typical reinforcing steel and also the yield strength is at similarly 4 to 5 times yield strength is also expected depending on what your base steel is.

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I will cover separately one full lecture on what are the different type of corrosion mechanism in pre-stressed concrete. But very briefly, let us look at this on the first picture, the top bar is a deformed bar or the typical conventional reinforcement, the bottom bar is the steel strand. Second picture is prestressing strand and third picture is conventional steel rebar.

And in the close up image shown here (2nd picture), where you can see that there is a severe pitting happening locally, not everywhere but very local, as in the case of the conventional reinforcement (3rd picture) you can see that the number of locations of pit is much more or spread is more along the surface of the steel when as compared to what is happening on the prestressing steel. So, this localized corrosion is very, very dangerous.

Because the prestressing steel is under stress all the time and because of the stress, there may be some micro cracking and which is leading to this localized corrosion.

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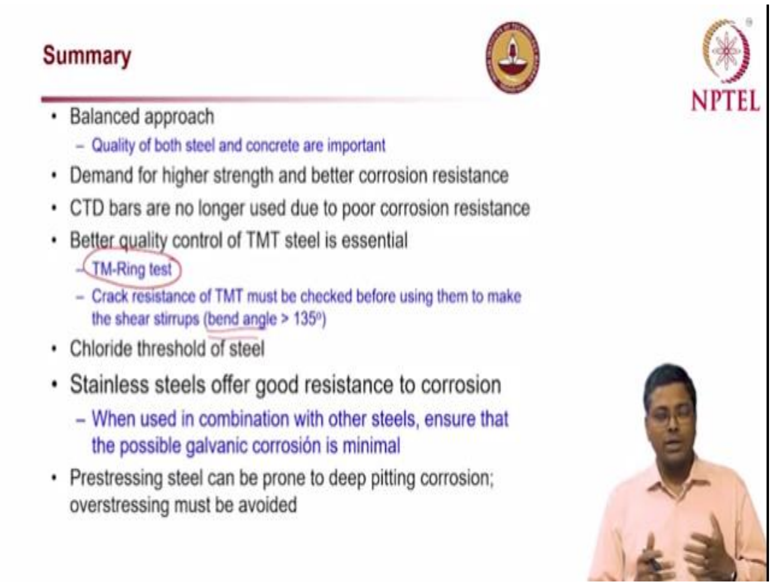

Now, to summarize, we looked at the balanced approach necessary to enhance the quality of the steel concrete system. We have to work on the quality of both steel and concrete. Demand for higher strength and better corrosion resistant let to different type of steel rebars which are now available in the market from mild steel, we went to CTD and then we went to TMT steel, now we are talking about stainless steel, prestressing steel.

So, different types of steel's are available to cater to different requirements of various structural elements, CTD bars are no longer in use because of its relatively poor corrosion resistance. Better quality control of TMT steel is essential, lot of products are available in the market.

But when we really look at the cross section or the composite structure of the TMT steel, we find that there are many products are not meeting the requirement of having a very good TM or tempered martensite ring. Recommending the TM ring test to do in addition to the tensile strength test or test on mechanical characteristics and also, we must do bending test when you talk about TMT steel.

In bending test we look at whether steel is really cracking or not, if it is cracking we should not use that because that will lead to corrosion at much lower chloride content mainly because of crevice corrosion phenomenon and also chloride threshold is a very important parameter especially, when you talk about CRS or any steel for that matter.

Chloride threshold should be looked at in addition to the corrosion rate because chloride threshold and the diffusion coefficient of the concrete really governs the service life of the structure and stainless steel offers good resistance. But of course, the combination of stainless steel and other steel is in practice today to reduce the expenses.

But that must be allowed only if the galvanic corrosion is minimal for the desired service life. Prestressing steel can be prone to deep pitting corrosion or localized corrosion because of the high stress they are experiencing as compared to conventional steel. All this must be looked at when we talk about steel.

In the next lecture, we will talk about what are the different type of coated reinforcement which we have in the market, both metallic and non-metallic coating we will look at.

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And these are the list of references, if you want to read more about this, you can please go through these references. Thank you.