Fracture, Fatigue and Failure of Materials
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Lecture 56
Failure Analysis- Case study- Point Pleasant Bridge

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Hello everyone, we are at the 56th lecture of this course Fracture, Fatigue and Failure of Materials and in this lecture once again we will be discussing another case study, which is the collapse of the Point Pleasant Bridge.

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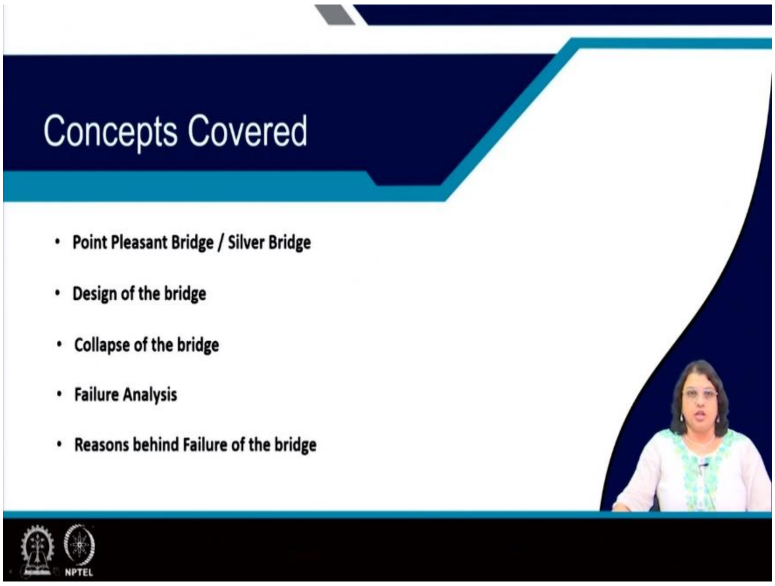

And once again we will look into what metallurgical factors have actually led to the collapse of a bridge. So, the following points will be covered in this lecture. First of all, a little bit information will be given on the Point Pleasant Bridge and the actual time frame for this incident that has happened. The design of the bridge and of course, the incident for the collapse of the bridge will be thoroughly discussed. And this will be followed by the subsequent failure analysis and what we have understood from there, how we can implement the corrective measures to achieve improved performances for bridge.

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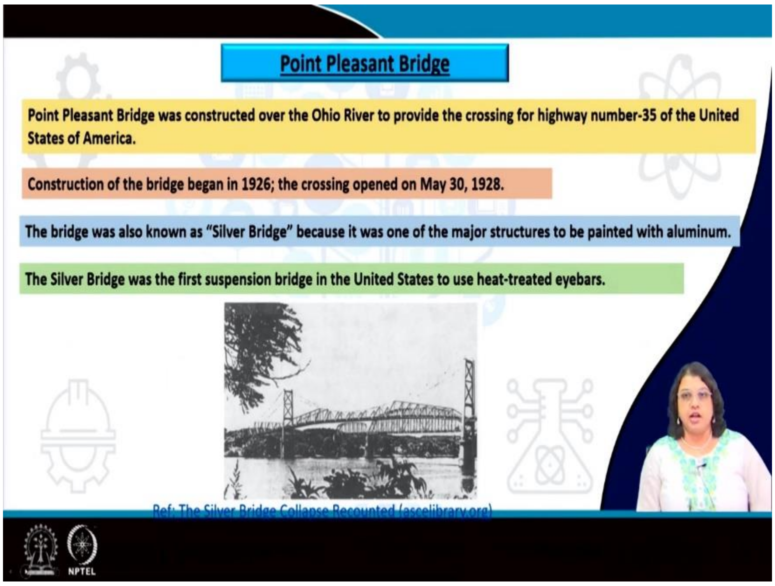

So, let's talk about a Point Pleasant Bridge. This was constructed over the Ohio River to provide the crossing for highway number 35 of the United States of America. So, this actually the bridge construction was had begun in 1926. And finally, after 2 years, it was open for public usage on actually today's date so, May 30 1928. The bridge was most popularly known as Silver Bridge, like we have seen how Golden Gate Bridge in USA is popular name. So, similarly, this one is known as the Silver Bridge. And the reason for naming this silver is because it was one of the major structures that is painted with aluminum. So, this aluminum paint gives a shiny, lustrous silver color and that is why it is known as a Silver Bridge.

So, this bridge structure is very much an aesthetically pleasing structure, it was actually serving for almost 40 years prior to this incident. This one is also very much important to note that this bridge is the first suspension bridge in the United States that used heat treated eyebars. We will go through the details of what an eyebars means and how does this eyebars work on the bridges. But before that, let us get some more statistics.

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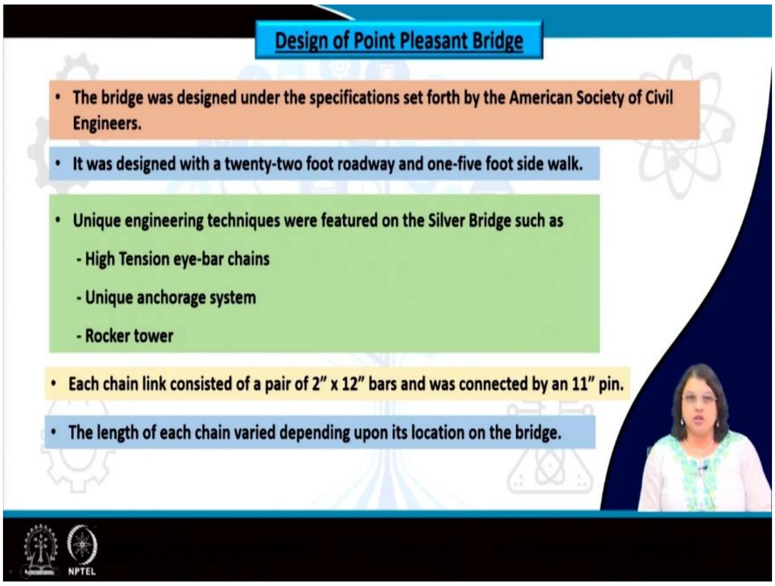

And the bridge was designed under the specification set forth by the American Society of Civil Engineers. So, it was designed with a 22 feet roadway and a 15 feet sidewalk. And the unique engineering technique were featured on the Silver Ridge such as it has very high tension eyebar chains that were used and unique anchorage system, rocker tower et cetera. All those things were once again considered as engineering favorable structures and are used in this bridge.

Now, each chain link consisted of a pair of 2 inch into 12-inch bars and was connected by an 11-inch pin. So, that constructed one eyebar. And the length of each chain varied depending upon its location on the bridge. So different lengths have been used for the different parts of the bridge. It was quite a long bridge and of course, that needed shorter or longer chains.

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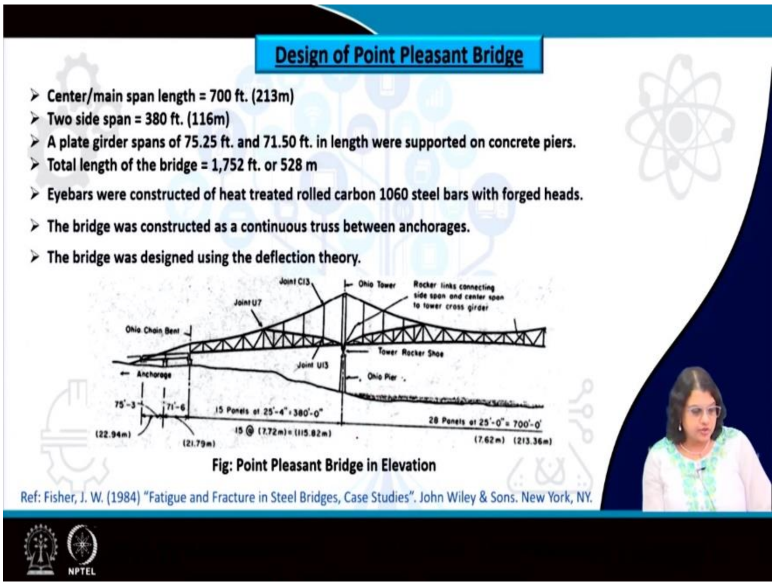

The center or main span length is of 700 feet which is like 213 meters, which is quite long. 2 sides span has 116-meter length and a plate girder spans of 75 feet and 71 feet respectively, were supported on concrete piers. So, the total length of the bridge is around 528 meters. So, that was quite a lengthy structure and need typically consists of 2 such spans. So, eyebars were constructed of heat treated rolled carbon 1060 type steel bars, which has the forged heads. The bridge was constructed as a continuous truss between anchorages.

So, they were encouraged to protect the bridge from falling down it provides a strength as well the bridge was designed using the deflection theory. You can see the specifications for the different parts of the bridge and how the design has been used.

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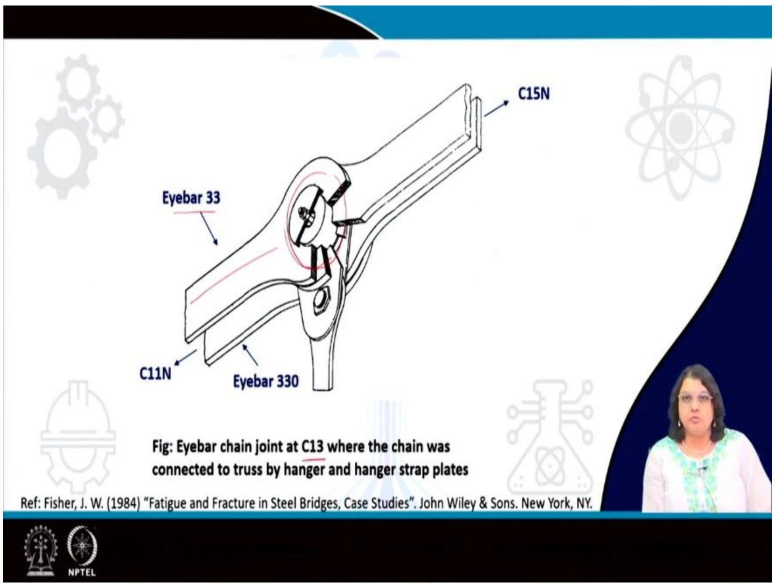

And this is what is known as an eyebar. So, you can see that there is one. So, this is one eyebar part of one eyebar which has a circular section followed by a certain length and then there is another eyebar which is connected to it through this pin. So, this is one particular section showing C13. So, all these eyebars are numbered and there are several hundreds of such eyebars in the entire bridge structure.

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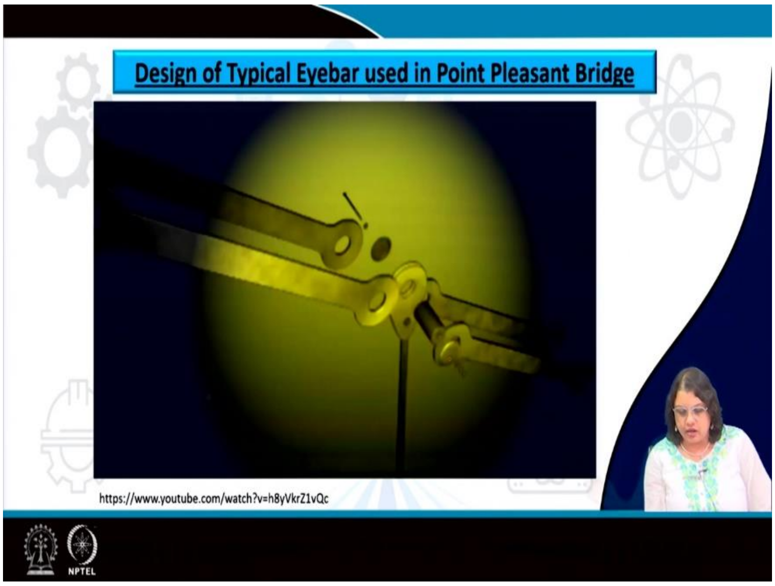
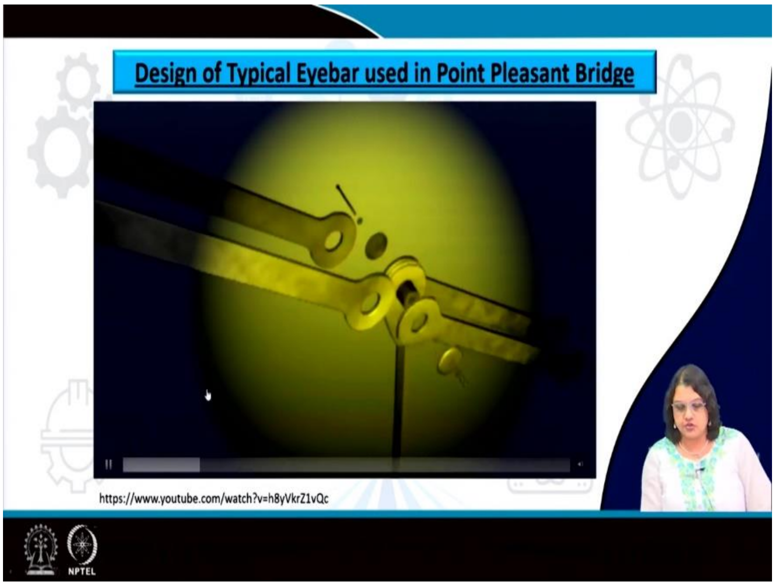
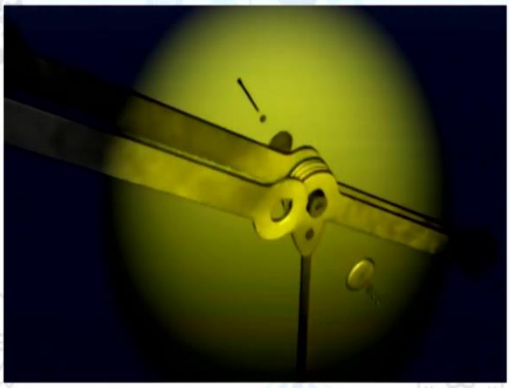




Design of Typical Eyebar used in Point Pleasant Bridge



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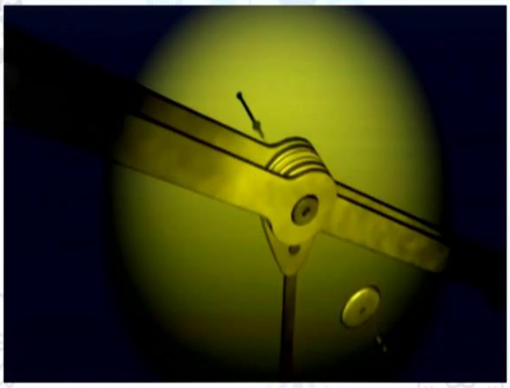

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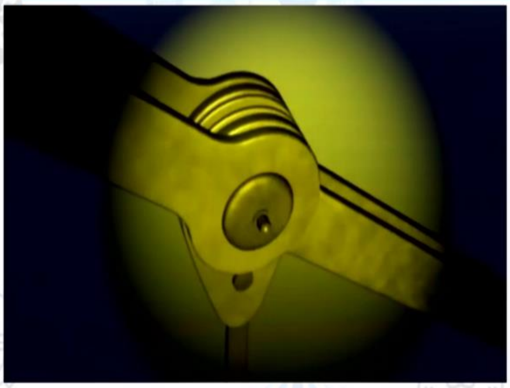
Design of Typical Eyebar used in Point Pleasant Bridge



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So, this one here shows the structure of the eyebars, you can see the eyebars very well this the circular section here with a hole followed by a length. And so, this is how the structure is fitted. So, one eyebar and the other is fitted with the help of this bolt and the pins and this makes the structure robust and at the same time it gives it some allowance so that it can move and till the structure is maintained its integrity.

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So, similar kind of bridge was also previously designed and constructed using the heat treated eyebars in a chain suspension and that bridge was completed in 1924-25 around that period in Florianopolis, Brazil. So, that was not in the United States, but similar design was also familiar at that time. So, this is like almost a century back not exactly 100 years, but almost 100 years 90 something years back, and at that time, this kind of bridge design was quite commonly used, as has been seen for the case of the Brazil.

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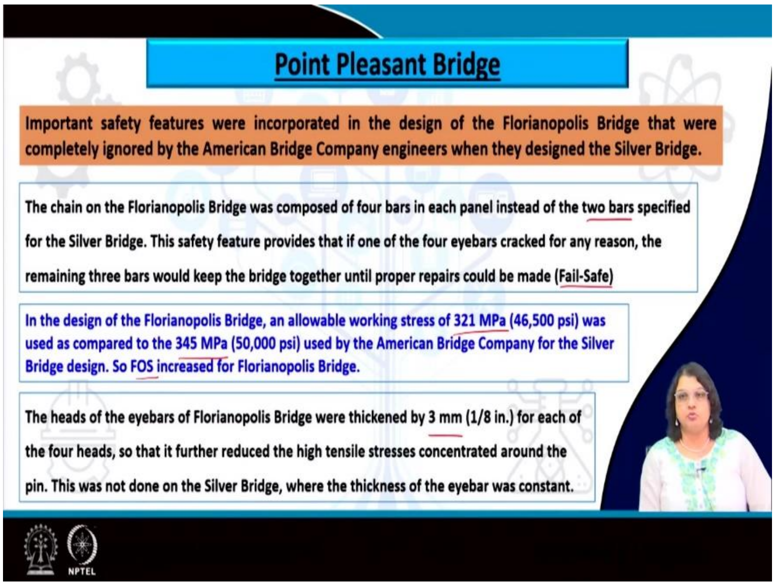

However, the important safety features were incorporated in the design of the Florianopolis Bridge, that means the Brazil Bridge, which, however, completely ignored by the American Bridge Company engineers when they designed the Silver Bridge, so let’s have a comparison of the Point Pleasant Bridge versus the Florianopolis Bridge in Brazil and see how exactly these two are similar or different. Of course, both of the bridges used eyebar configuration so that way both of them are similar construction wise, but still, there were some differences between the two.

The chain on the Florianopolis Bridge were composed of 4 bars in each panel, instead of 2 bars specified for the Silver Bridge. So, the Silver Bridge used lesser number of bars, only 2 bars. And in case the of the Florianopolis Bridge, they were double the numbers. And as a result, the safety feature provided that if one of the 4 eyebars cracked for any reason, the remaining 3 bars would keep the bridge together until proper repairs could be made. So that means that that design for the Florianopolis Bridge in Brazil was as per the fail-safe criteria.

So even if one of the parts deforms or breaks for whatever reason, the other parts, which in this case are the 3 bars they are supposed to get the load up to a certain extent so that they can avoid a catastrophic failure. Such kind of design however, were not available for the case of the Silver Bridge. And the design of the Florianopolis Bridge allowable working stress of 321 MPa was considered whereas for the case of the Point Pleasant Bridge or Silver Bridge, the working stress that could be allowed is much higher, 345 MPa.

So, it has a difference of only 24 MPa, which to you might be appearing as not a significant difference, but this is certainly a huge difference. If you are talking about the usage of bridges for decades, for several periods of time and several frequencies of different kinds of vehicles that are going to use this we in certain cases, we should not exceed whatever is the limit set for us. So, the Florianopolis Bridge has much lower working stress that are allowed compared to the Silver Bridge.

And certainly, if the allowable working stress is more that actually hampers the factor of safety, which means the factor of safety reduces. The factor of safety for the Florianopolis Bridge was much higher than that for the Silver Bridge. The heads of the eyebars of Florianopolis Bridge were thickened by 3 millimeters for each of the foreheads so that it further reduced the high tensile stresses concentrated around the pin. However, this was not done on the Silver Bridge, where the thickness of the eyebar was constant. So, that was another difference, which later on people realize that those are the differences, those are the safety precautions that should not have hampered under any circumstances.

So, based on the criticality of application, we often need to understand that which of the factor needs to be considered with more caution than the other. Now, why we are doing this comparative study between the 2 bridges is that the one in Florianopolis Bridge, which is in Brazil, which were made almost in the similar time period using similar kinds of design considerations did not fail it did not collapse rather the Point Pleasant Bridge having using even similar kinds of design criteria, but based on some minor differences, which appeared minor at that time led to the final collapse of the thing.

And we also realized that how fail-safe design could have would have been very, very important. Now, you might also think that why did the Americans thought of changing these factors which the Brazil bridge have not. The particular reason for this is to make the bridge lightweight. So, instead of 4 bars they used 2 bars or instead of thickening the bars by 3 millimeters, they have done it at a much lower value and maintain constant.

So, all those were meant to make the bridge lightweight and lightweight was supposed to be more efficient, but only up to certain extent. If there is some defect or if the fracture crack initiates at some point, then it would not have served the purpose which exactly is what has happened for the case of the failure of Point Pleasant Bridge. So, we will look into more details of this soon.

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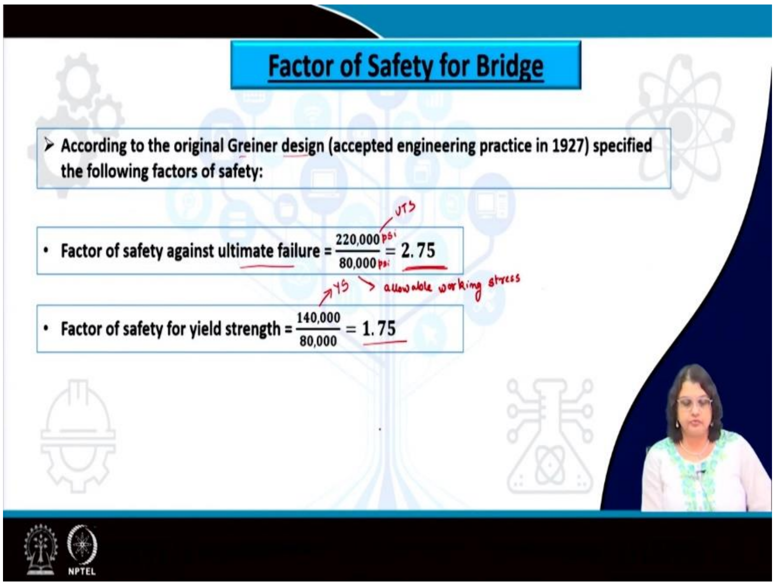

Let’s calculate the factor of safety for the bridge. Now, factor of safety for the case of the actual Greiner design is supposed to be 2.75 and this determination is being done based on the ultimate tensile strength. So, in this case, the ultimate tensile strength is to 220,000 psi and the allowable working stress. So, this is the allowable working stress for the case of bridges that should be maintained is 80,000 psi.

We have already discussed about the importance of factor of safety particularly for bridges and how a factor of safety can be determined. So, accordingly for the case of Greiner design, we can see that the factor of safety based on the ultimate tensile strength is expected to be around 2.75. On the other hand, factor of safety consideration based on the yield strength, so, this one here on the numerator is the yield strength of 140,000 psi and based on this we get a factor of safety value of 1.75.

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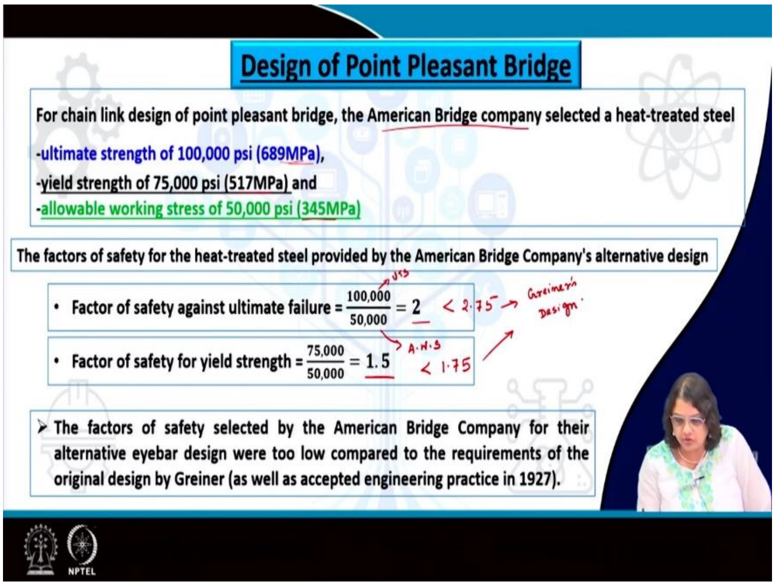

Now, let's see, what are this criteria for the case of Point Pleasant Bridge. Now, for the chain link design of the Point Pleasant Bridge, the American Bridge company, they set a value for the factor of safety as well. So, they use the heat-treated steel. Now, when we are finalizing the material, material has a particular property it has a particular ultimate tensile strength and yield strength. So, in this case, the ultimate tensile strength is 689 MPa or since we are talking about the psi unit, so, it is 100,000 psi and yield strength 75,000 psi.

So, considering this they have also reduced the working stress to 50,000 psi, 345 MPa, which means that this one, this particular steel is supposed to yield at a value of 517 MPa and ultimate tensile strength. So, that means, it will fracture at 689 MPa and much lower stress of 345 MPa has been maintained. But how much lower is that, that is related to the factor of safety. So, let's do the factor of safety calculation for based on the American Bridge company's design.

And in this case what we see is the factor of safety based on the ultimate tensile strength of 100,000 psi and this is once again the allowable working stress. So, this comes around 2 remember the last slide we have seen that as per the Greiner's design this is much lesser than 2.75. Based on the yield strength also we are getting the value of factor of safety as 1.5 which was once again lesser than the Greiner's design which is 1.75. Of course, if we are compensating on the factor of safety, so that may lead to some effect on the sudden or criticality of the failure event.

The factor of safety selected by the American bridge company for their alternative eyebar design. Alternative in terms of the previous design that we have seen for the case of Brazil bridge. So, this factor of safety values were too low compared to the requirements of the original design by Greiner so these are the numbers for the Greiner's design both of this.

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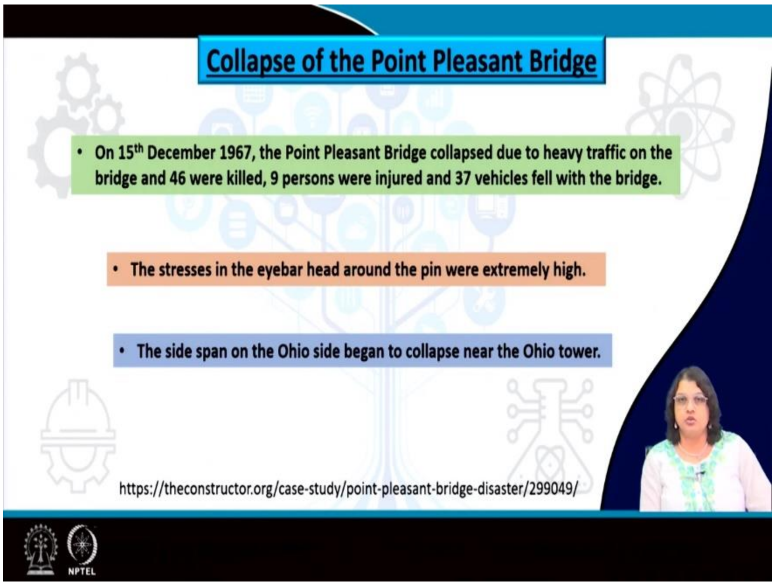

So, that anyway had led to the collapse or the Point Pleasant Bridge and let's see the sequence of the events that has happened. So, this happened on a chilly morning of 15 December 1967. When the Point Pleasant Bridge collapsed due to heavy traffic on the bridge, bridge was heavily used, this being the month of December, and people were busy with their Christmas shopping and all so bridge was quite populated. And then it was suddenly collapsed suddenly, so when even the cars were running, or using the bridge, they were the side foot walk has been used. And suddenly the bridge collapsed all of a sudden, and there were several vehicles or cars that fell into the chilly water of the Ohio River.

So, around 37 it is documented that 46 were killed, but there were other information which says that much more than that number of people were actually drowned which were recovered much later or has not been put into the statistics. There are several persons who have been injured also.

So, although you may still think that the number of person that has been killed or that has been a victim of this catastrophic incident were not that much compared to what has happened to the previous case histories that we have discussed like for the case of Titanic, where 1500 people were dead, for the case of the Alexander L'Kielland, there were 123 number of people were dead. In this case is numbers appeared to be quite less, but it is not about the number of people that makes a failure incident worthwhile.

More than that, it is actually of absolute shock, right, not everyone is using a ship for traveling like in the Titanic or for the oil rig but bridges are something which are very commonly used by most of the peoples around the world. So, if something happens like that, that is a shock. Of course, that does not mean that the other failure events are not important. Of course, they are, but the point is that this is directly affecting the local and the common peoples all across the globe so, this is something to worry about, of course.

And what has been realized later on is that the stress is in the eyebar head around the pin were extremely high. And the side span on the Ohio side began to collapse near the Ohio tower. So, these are what happened sequentially. This eyebar part, the stresses has rose to a very high value and then on one side of this particularly one which is near to the towards the Ohio tower that started to collapse.

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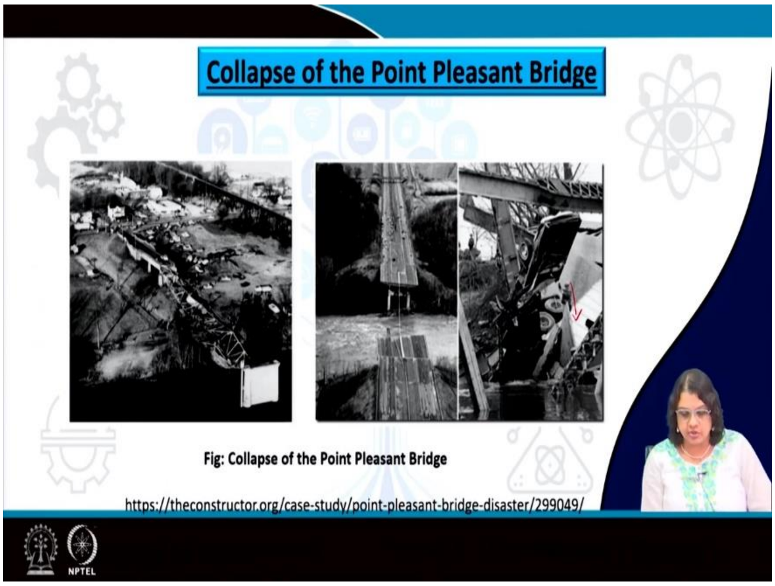

So, you can see the images here and how the cars have been pulled into the water or recovered later on after the incident. And these are the images that were taken by the journalist or the photographers at that time itself.

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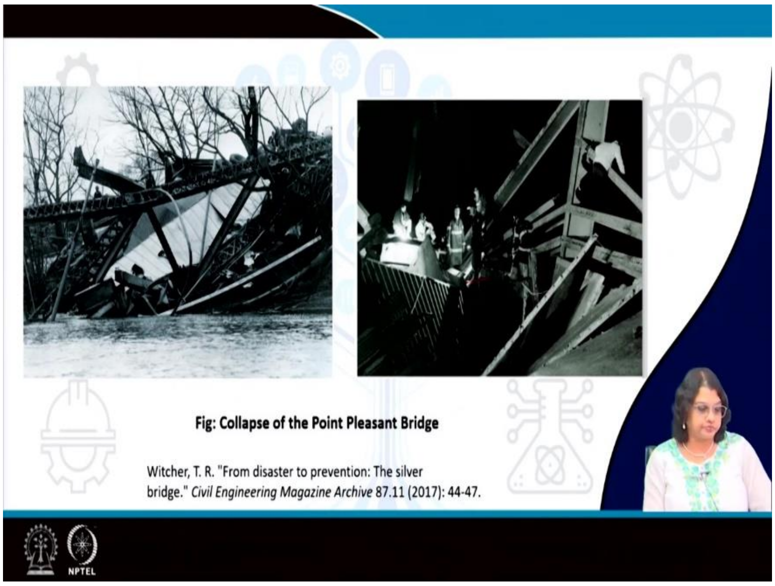

And then there were some rectification works also that went along some failure analysis also has been done and the pictures are taken during those periods. Just to show you that the kind of incident that has happened and in such a giant bridge. If that collapse, all of a sudden will be a really memorable incident. And there are once again if you go to the various websites that are available, you can understand how people have reacted to that there were many survivors of the incident who have seen others drowned and they could somehow recover from there. So, that was a really shocking incident for them.

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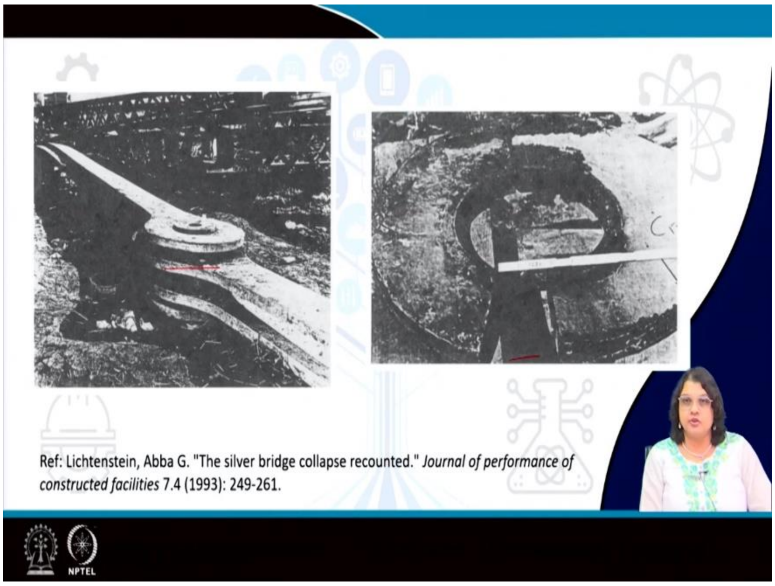

And once again that entire such a huge structure has been very thoroughly examined after the failure, after the collapse to find out what could be the reason and these were the eyebars that has been recovered. And then one particular eyebar been also pinpointed, which was expected to be the actual reason for the failure.

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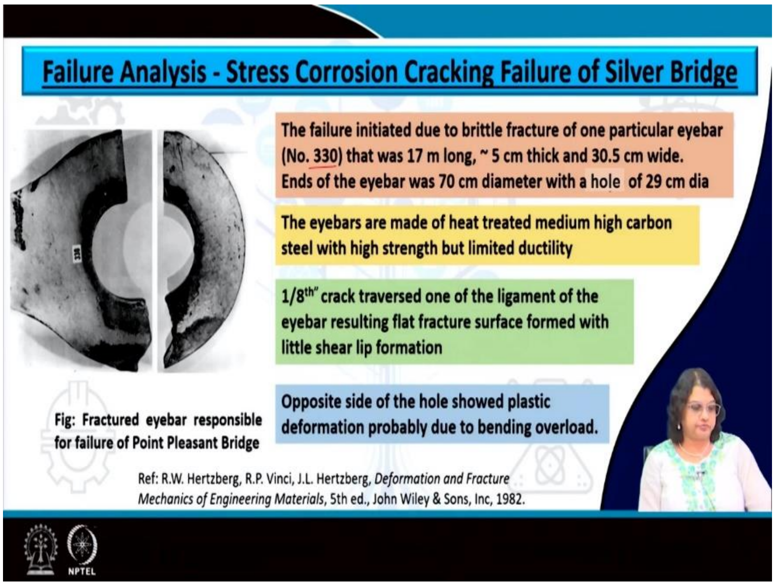

So, we will look into that in more detail. So, it has been figured out that the failure initiated due to the brittle fracture of one particular eyebar. So, this number was 330. So, that particular eyebar which was actually 17 meter long, 5 centimeters thick and 30 centimeters wide such a huge eyebar and the ends of the eyebar were 70 centimeter in diameter with a hole of 29 centimeters. So, you can see this broken eyebar that has been recovered and the brittle fracture is actually apparent from the very flat fracture surface.

Of course, we know by now that flat fracture surface signifies that edge is a brittle fracture. On the other hand, if had it been in ductile fracture there had been extensive shear lip kind of location.

Now, the eyebars are made of the heat treated medium high carbon steel, which has very high strength, so, the strength level was more or less maintained as per the required criteria, but this kind of material has very low ductility. We know that strength and ductility in most of the cases are inversely related so, that is the same thing here also. Heat treatment has been done to enhance the strength, but somehow ductility has to be compensated.

So, it was noted that a $1/_8$ th crack, $1/_8$ th inch of a crack traverse from one of the ligaments of the eyebar from one end of the eyebar and resulting to the fracture surface which is completely flat with little shear lip formation and opposite side of the hole showed plastic deformation probably to the bending overload. So, where from the crack has started the other side of the hole actually showed some evidence of plastic deformation to some extent.

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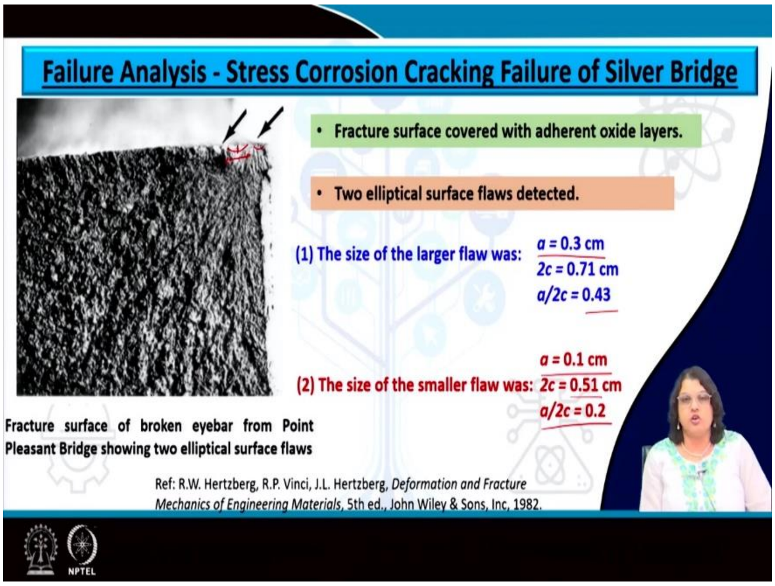

So, detailed fractographic analysis you can see that this is the fracture surface and then they have been pointed the location for 2 cracks here. The entire fracture surface has been noted to be covered with rust first of all and then the adherent oxide layers. And after removing those oxide layers and the rust it has been noted that there were 2 elliptical surface flaws as pointed here with the arrows.

Now, the size of the larger flaw is something like it has a depth of 0.3 centimeters. So, that means, this one here the half of the minor axis and 2c of 0.71 so like that. The overall major axis is 0.71 centimeter and a by 2c which this ratio is very very significant as we have seen earlier also that is around 0.4. The smaller crack on the other hand a value of 0.1 centimeter and 2c value of 0.5 and that makes us a by 2c ratio of 0.2. So, a detailed calculation has been done based on this different flaw sizes to see that what would have been the stress and whether that has exceeded the working stress or not.

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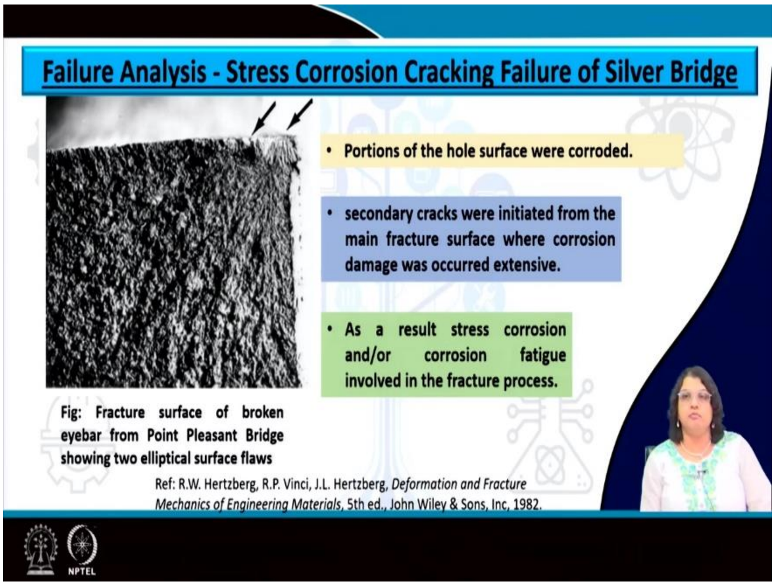

So, it was also realized that portion of the holes, you know the eyebar which is having the hole in it, that is seems to be corroded as well. So, secondary cracks were initiated from the main fracture surface where corrosion damage was occurred extensively. And as a result of this stress corrosion and corrosion fatigue gets involved and that might have led to the fracture surface. So, these are all the presumptions that has been taken at the point of the failure analysis.

So, the fracture surface first of all has been recovered from one particular eyebar, so, that eyebar has to be indicated and then detailed fractographic investigation has been done which showed the presence of elliptical cracks. And then based on that, the rust of the oxide composition or the presence of the branched crack all this had led to the final determination of the reason for the actual failure. So, we will look into more details of that.

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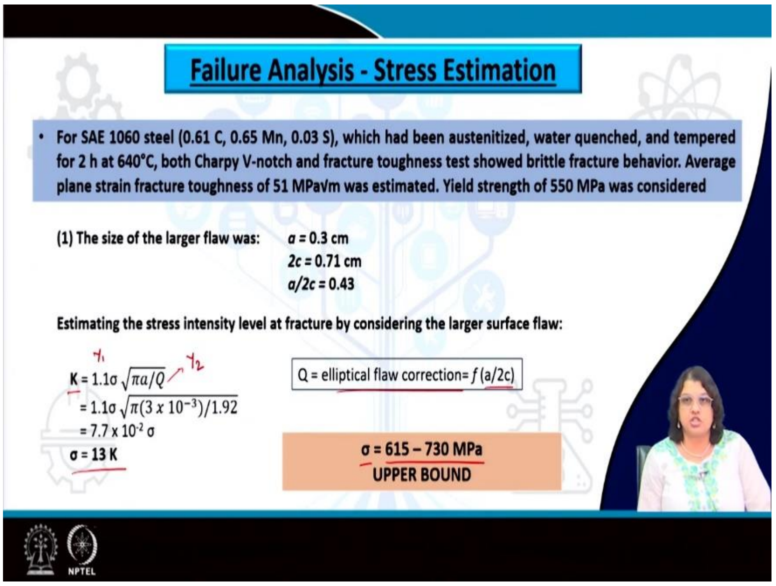

For that, first of all, the kind of steel that has been used as I mentioned that this is a 1060 category of steel which has been 0.6 percent of carbon, 0.65 of manganese and point 0.03 sulfur. So, this was austenitized, water quenched and then tempered for 2 hours at 640 degree centigrade. So, these are the standard procedures heat will procedures that are followed to achieve higher strength and toughness. So, the kind of toughness that is noted for this material is 51 MPa$\sqrt{m}$ that is the plane strain fracture toughness and we know that the plane strain fracture toughness is the lower bound value.

So, of course, they should have been exceeded the number in case there was a plane stress condition there. Yield strength of the material is around 550 MPa. Now, let us do some stress analysis based on the flaw size that we have already seen on the fracture surface. So, of course, the larger flaw will be the more dangerous one. So, we will do the calculation based on the larger flow and based on the K value that is related to the position of the crack the crack is present at the edges.

So, of course, we need to use the Y_1 value as 1.1 or 1.12 if you want to be more specific and then we have also used the parameter Q which is related to the function of a / 2c that is the elliptical flow correction parameter. We have also seen that and based on this sigma is noted to be 13 times K. So, for that we found that the value of sigma should be 615 to 730 MPa, some values like that, and that is obviously the upper bound value because we are considering the larger crack here. So, that is the highest limit for the sigma value that the material might have reached at the point of failure.

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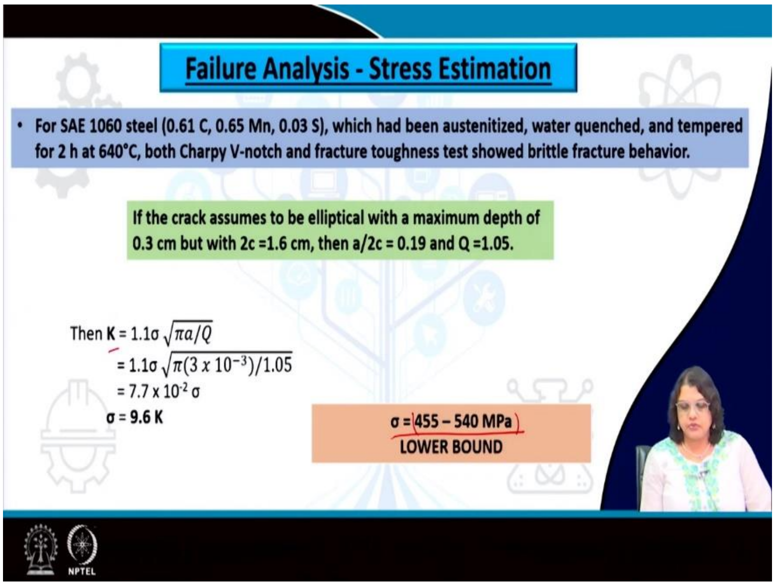

And once again, if we are considering the crack as the elliptical one with a maximum depth of 0.3 centimeter but with 2c being 1.6 centimeter, then, a / c value should be 0.19 or close to 2.2 and Q value should be 1.05. So, based on that, if we are figuring out the K value and considering the value of K to be not exactly as 51 MPa$\sqrt{m}$, but varying over 50 to 60 MPa$\sqrt{m}$. We get the value of sigma as 455 to 540 MPa. So, that is considered as the lower bound value. So, that means, that the stress at the point of fracture might have been within this range at the lower bound or the upper bound value.

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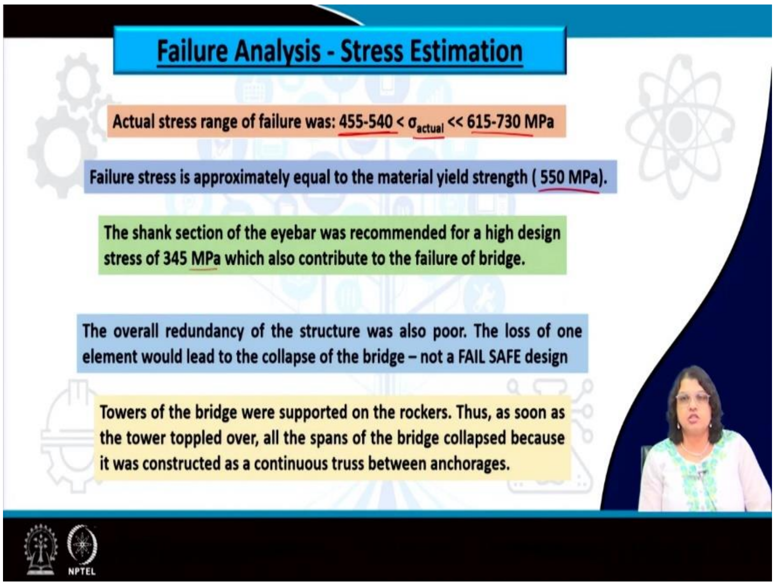

And this gives the actual stress range at the point of failure is lying between this 455 to 540 which is the lower bound and the upper limit is 615 to 730. It might have been within this 2 levels and failure stress is approximately equal to the material yield strength and in this case, because the material is very much brittle and the materials yield strength is around 550 MPa. The shank section of the eyebar, the central one was recommended for a high design stress of 345 MPa. We have already seen that how the allowable stress is very important now, the allowable stress is 345 MPa. However, we see that the actual stress, even if it uses the lower bound value that is exceeding the allowable working stress or 345 MPa.

So, certainly that will lead to some effect on the failure of the bridge. And most importantly, the overall redundancy of the structure like the failsafe condition was very poor. The loss of one element would lead to the collapse of the entire bridge. So, not a failsafe design that is one of the major drawbacks of this Point Pleasant Bridge. The towers of the bridge were supported on the rockers. Thus, as soon as the tower toppled over all, the spans of the bridge collapse one by one and so this happened almost like simultaneously and because it was constructed as a continuous truss between the anchorage that led to the failure of the road as well. So, everything just went down.

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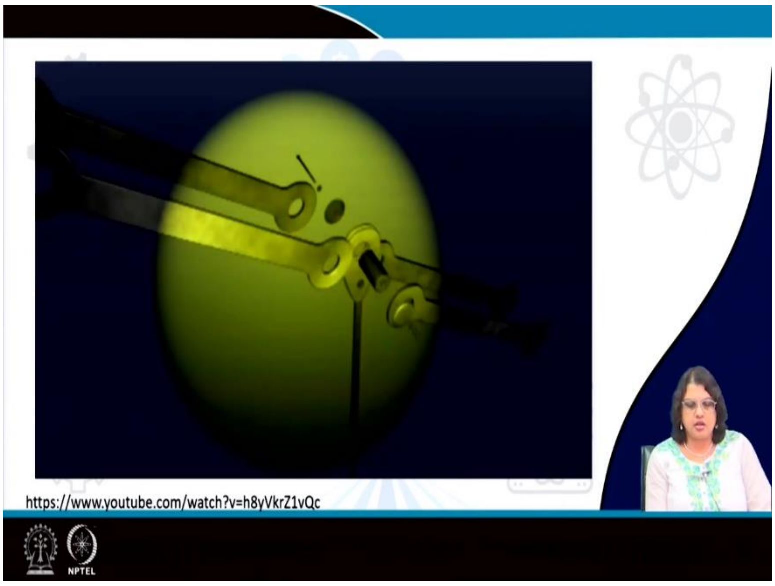

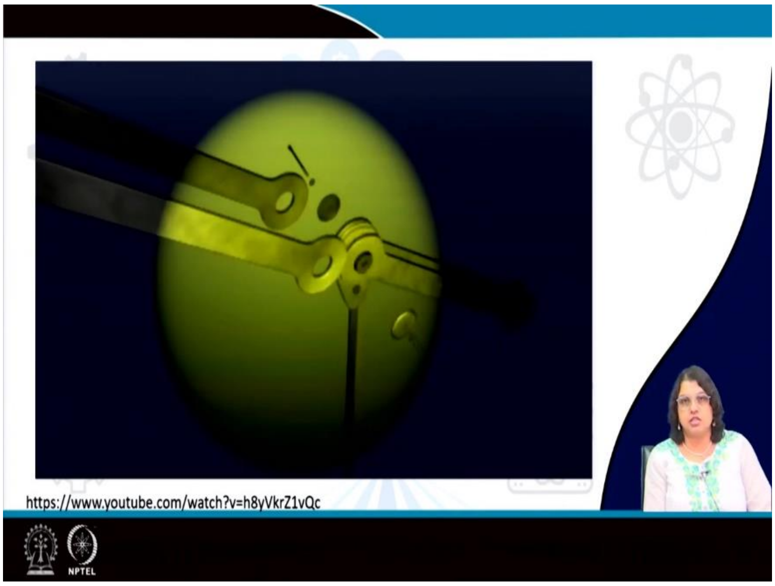
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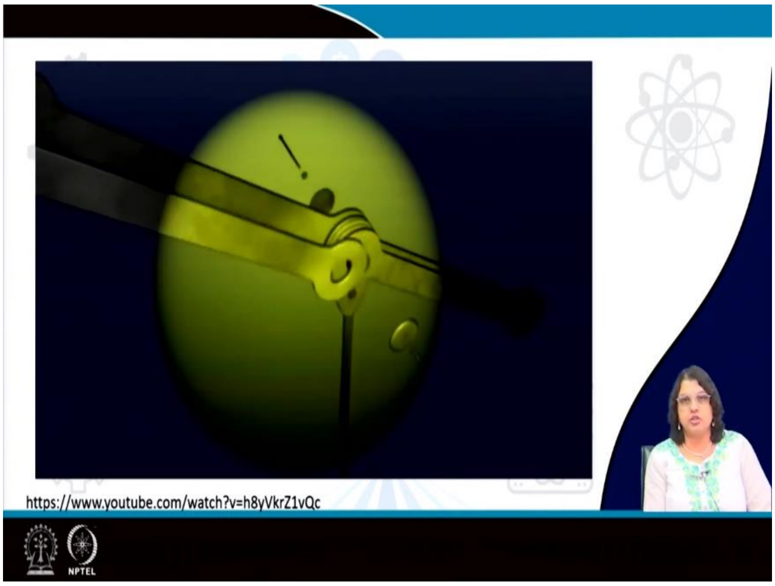
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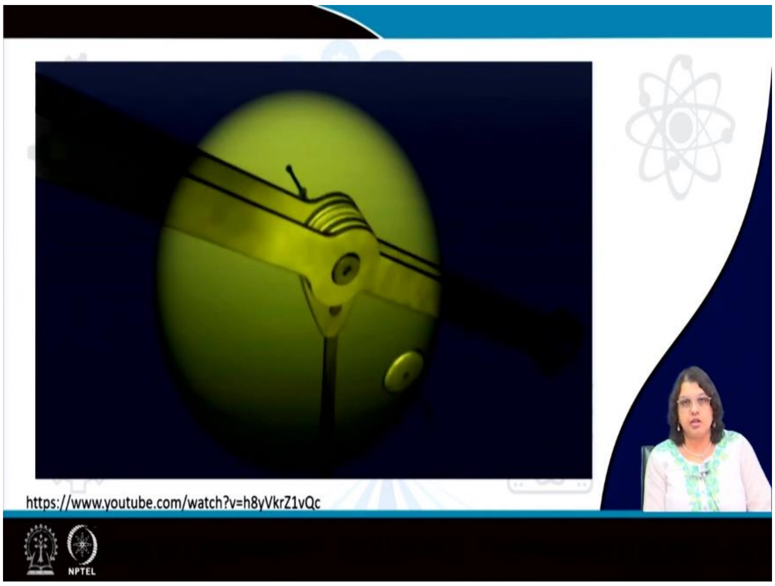
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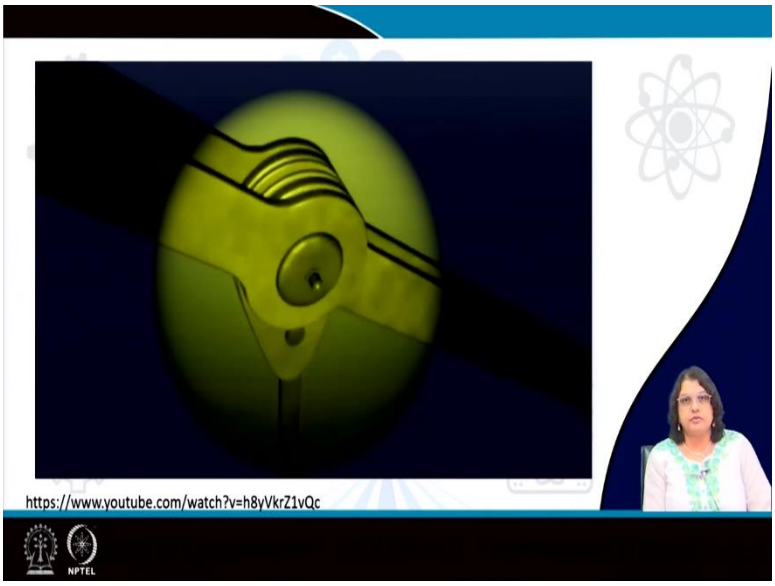
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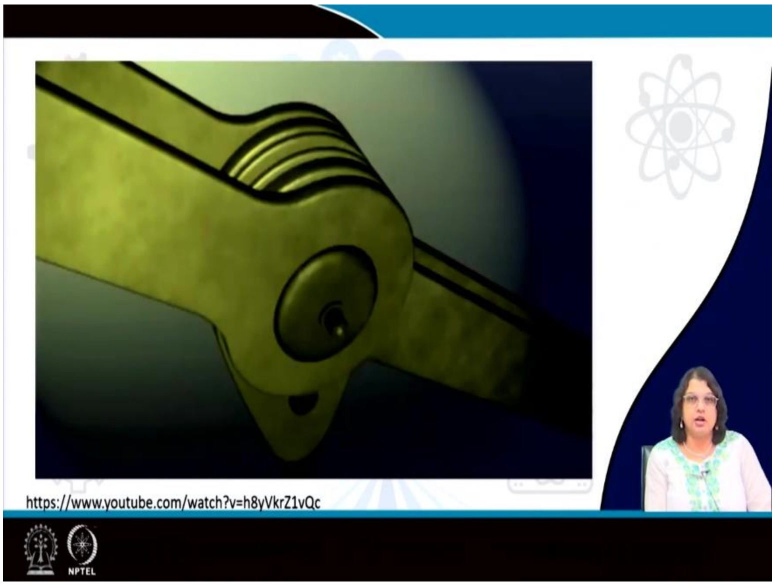
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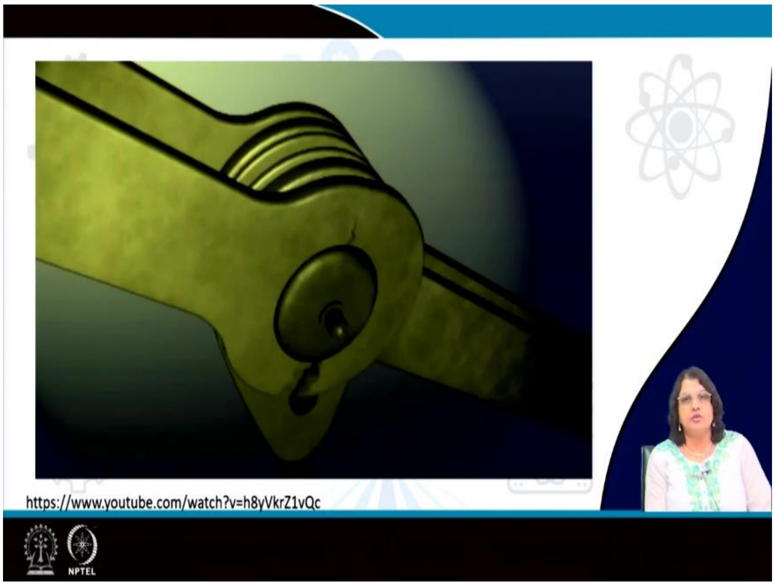
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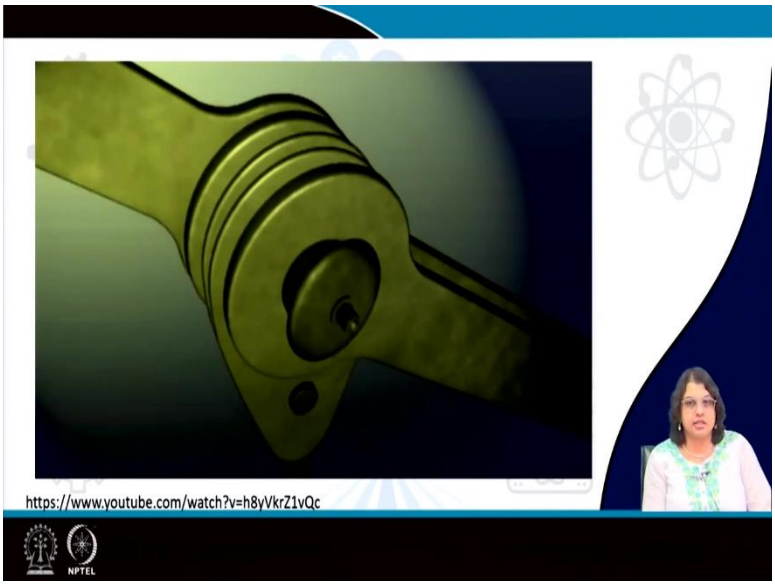
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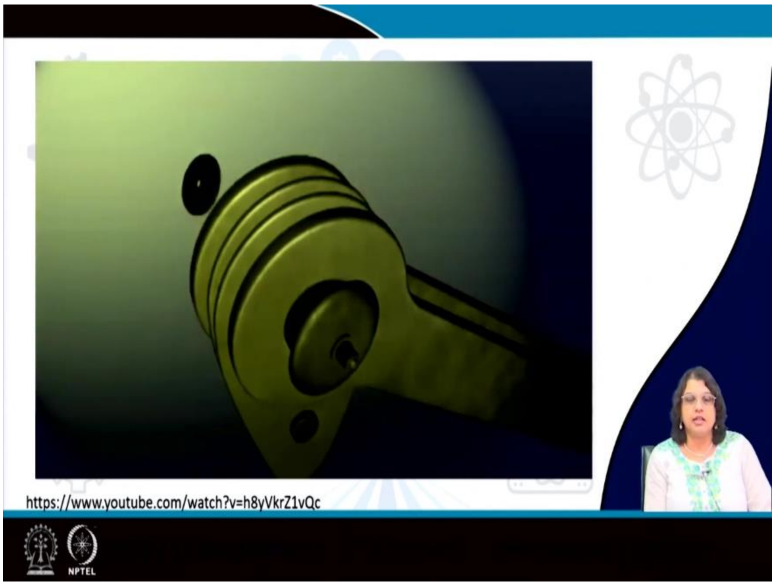
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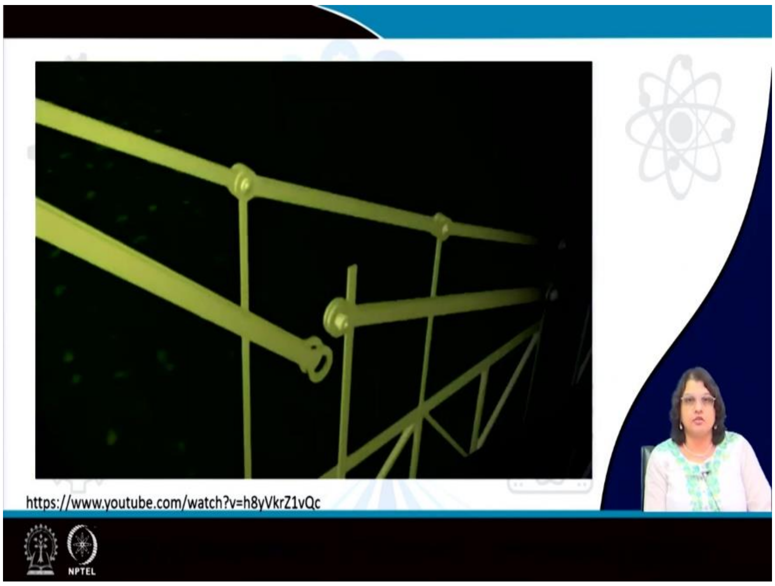
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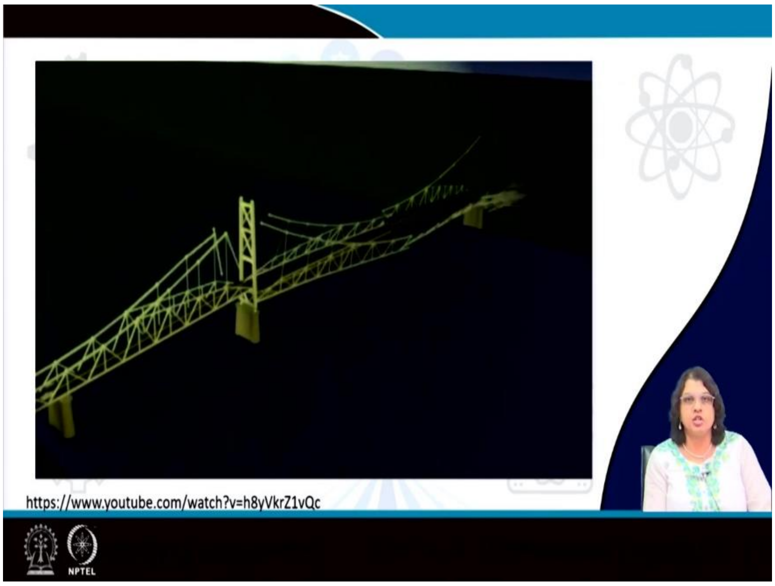
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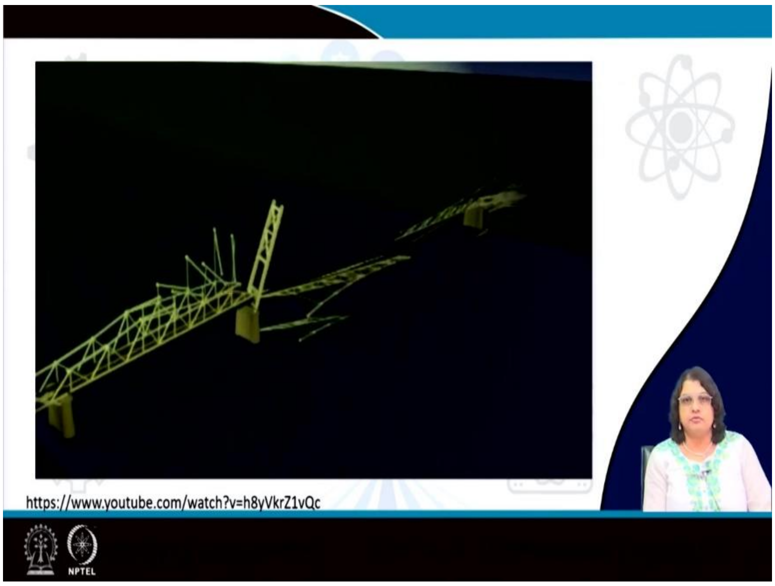
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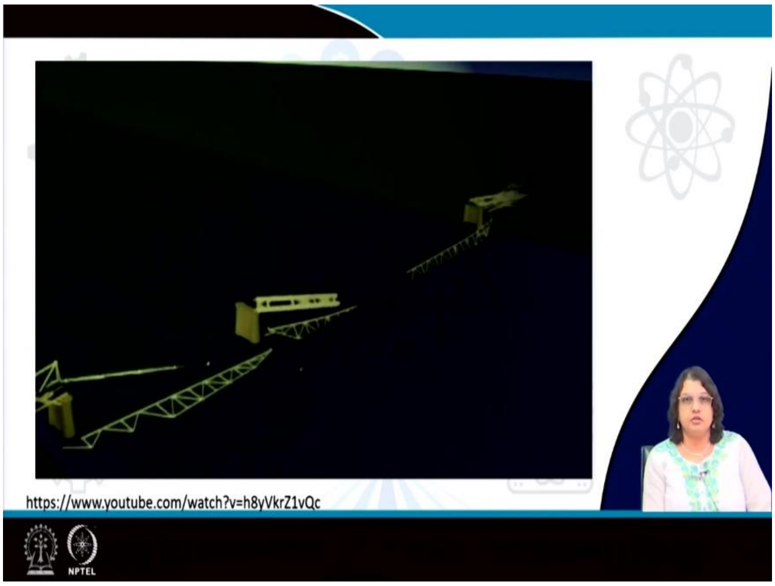

So, here is an example for that. And you can see that this has been already shown that how the eyebar are being fitted here. And now it is capable of moving to some extent, but whenever there is a crack, so, that initiated at one location and that led to the failure of that eyebar and as a result, what you can see is there will be some amount of deformation as well as there was exceedingly high stress. And then the other side of the eyebar also fails and once the one of the chain fails, that leads to the non-uniformity and the stress distribution to the other parts and you can see how the entire bridge just collapse all of a sudden.

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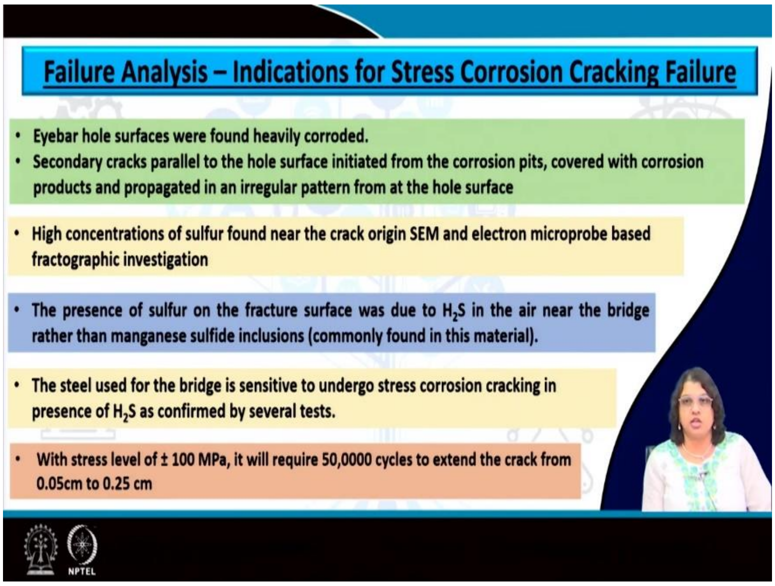

So, this kind of failure actually also indicated the importance of failsafe design at the very first place. So, when we started finding out their exact reason for the failure the crack has been located, but then the question should be that how the crack has been initiated at the very first place. So, at that point, it was noted that the eyebar hole surfaces were highly corroded even secondary cracks parallel to the whole surface were noted to initiate and those are particularly initiated from the corrosion pits covered with corrosion products and propagated in an irregular pattern from the whole surface.

So, this along with the high concentration of sulfur that are found near the crack origin, so, all different kinds of fractographic investigations have been done, including the compositional analysis which showed the presence of high amount of sulfur there and near to the crack origin. So, based on this it is realized that there could be some importance of sulfur in the failure.

Now, the presence of sulfur on the fracture surface is due to the presence of H_2S, hydrogen sulfide in the air near the bridge. So, there were some industries there near to the bridge locality that might have released the hydrogen sulfide and which could be one of the reasons for the hydrogen embrittlement there. And however, manganese sulfide inclusions are such kind of things were not seen on the fracture surface like we have seen already for the case of Titanic steel, how the presence of manganese sulfide was located near to the crack. So, that was one of the reasons for the brittle failure of the steel.

Apart from other results in this case for the case of the Point Pleasant Bridge, however, manganese sulfide was not found although presence of high amount of sulfur was located. So, it was later on investigated and understood that those has come from the H_2S from the surrounding air. The steel use for the bridge is very sensitive to undergoes stress corrosion cracking in presence of this hydrogen sulfide atmosphere as so this has been also confirmed by several tests.

So, with stress level of plus minus 100 MPa also, if we consider there was a detailed investigation of one of the results could have been fatigue. So, it has been realized since bridges are the structures where there are repeated loadings based on the kind of vehicles that are using fatigue is of concern, but it was realized that considering a stress level of 100 MPa plus minus which means a 200 MPa range that may lead to more than 5 lakhs of cycles to extend the crack from point 0.05 centimeter to 0.25 centimeter.

Now, that includes a very high number of cycles and that also kind of indicating that fatigue is not the main reason for the failure rather stress corrosion cracking is the one which actually led to the initiation of the crack and the final fracture because there was no proper load sharing mechanism that has been used.

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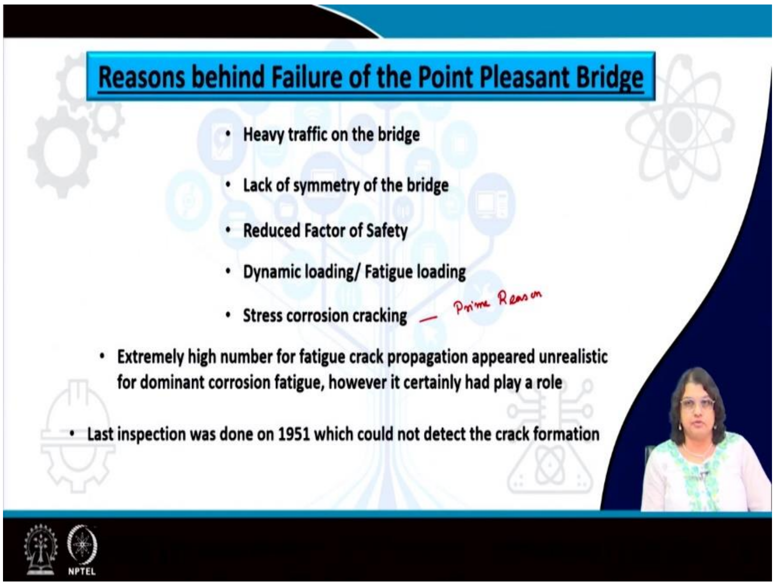

So, if we try to pinpoint the exact reasons behind the failure of the Point Pleasant Bridge, all these factors are important such as heavy traffic on the bridge, lack of symmetry in the bridge and reduced factor of safety as we have seen with respect to the Brazil bridge, dynamic loading or fatigue loading could be one of the reasons, and stress corrosion cracking is the prime reason that is what we have found. So, we can consider this as the prime or the most dominant reason, and the other factors of course, are the accessory, and the other factors are on the other hand, they are the secondary reasons for the failure.

Now, extremely high number of fatigue crack propagation appeared unrealistic for dominant corrosion fatigue that might have occurred. However, it certainly had played a role in the final fracture. Another important thing to notice here is that the last inspection was done on 1951. So, quite some years earlier with respect to the incident date, however, that inspection could not detect any crack formation. Partially because the method for inspection for bridges were not so streamline and systematic at that period which could not have the required facilities that are required for investigating a crack of such a small dimension.

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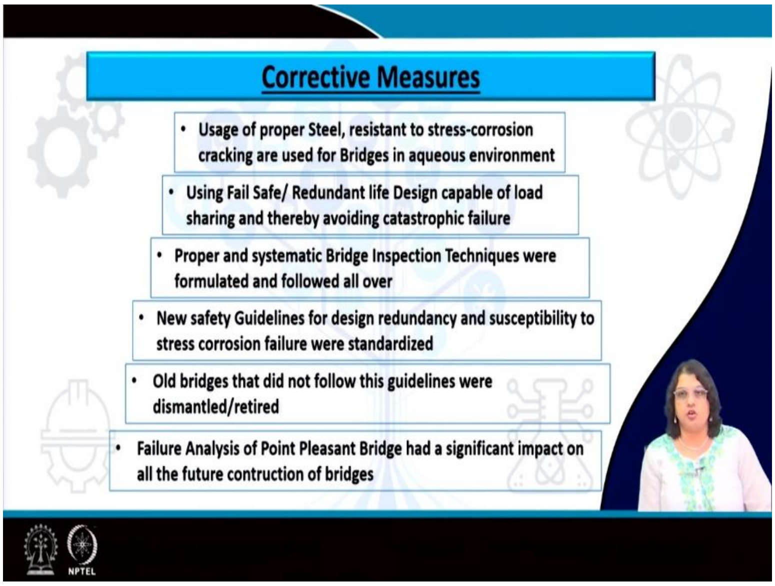

So, based on the failure of course, any kind of failure analysis should come with the corrective measures and what has been done here is the usage of proper steel which are resistant to stress corrosion cracking for the construction of bridges in aqueous environment. And using the failsafe or the redundant life design that is the most important one. So, such kind of design should be capable of load sharing and thereby should avoid catastrophic failure. And proper and systematic bridge inspection techniques were formulated after this incident has happened and such kind of systematic technique is being followed all over the world.

New safety guidelines for design redundancy and susceptibility to stress corrosion failure were also standardized and based on that all the old bridges that did not follow these guidelines were either dismantled or retired. So, failure analysis of Point Pleasant Bridge had a significant impact on the future construction of all the bridges worldwide. So, that made it a very important incident in history of failure analysis.

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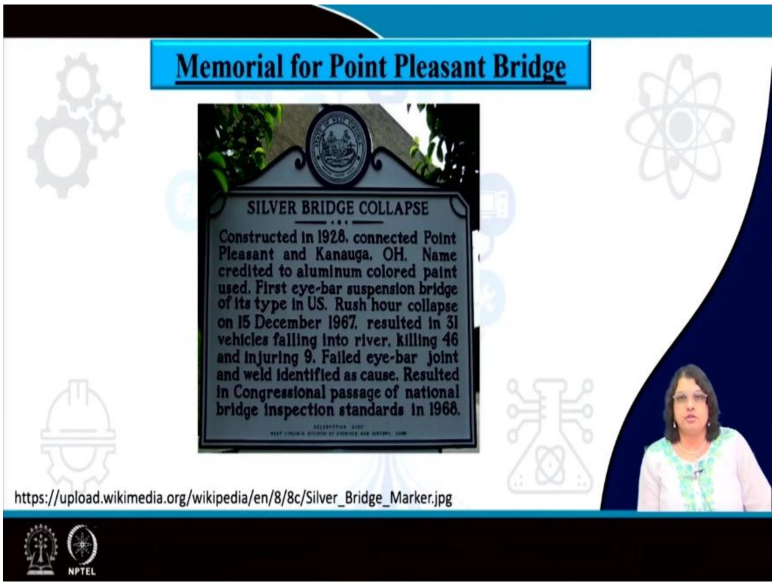

So, this is the memorial for Point Pleasant Bridge.

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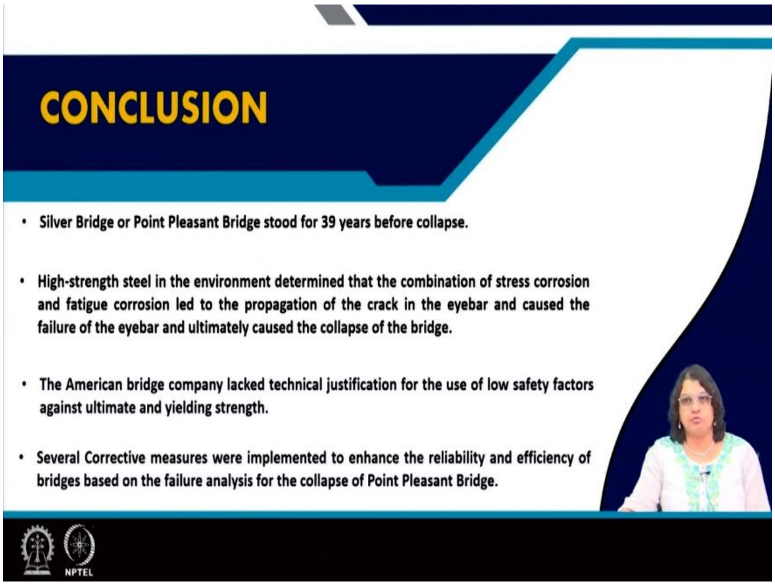

Let us conclude this lecture with the following points that Silver Bridge or Point Pleasant bridge stood for 39 years before collapse. So, it is not that within a year or so it failed it served its purpose for several decades and then suddenly it collapsed on one fine day. So, the high strength steel that has been used for the making of this eyebar that are used for the bridge in the environment determined that the combination of stress corrosion and fatigue corrosion are the primary reasons that led to the propagation of the crack in the eyebar and caused the failure of the eyebar and ultimately the entire bridge collapsed.

So, the American bridge company lacked technical justification for the use of low safety factors as we have seen, that the safety factors that has been maintained for the Point Prison Bridge is not up to the mark for the Greiner's design against ultimate and yield strength. And after this failure incident, however, several corrective measures were implemented to enhance the reliability and efficiency of bridges all across the globe. And all those corrective measures were actually determined based on the failure analysis of the collapse of the Point Pleasant Bridge. So, following other references that are used for this lecture. Thank you very much.