Fracture, Fatigue and Failure of Materials
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Lecture 54
Failure Analysis-case Study-Titanic

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Hello everyone, we are at the 54th lecture of the course fracture fatigue and failure of materials. And in this lecture, we will be talking about failure as module 3, but most interestingly we will be talking about a case study. And this case study is related to the sinking of Titanic. So, let us see what are the lecture contents?

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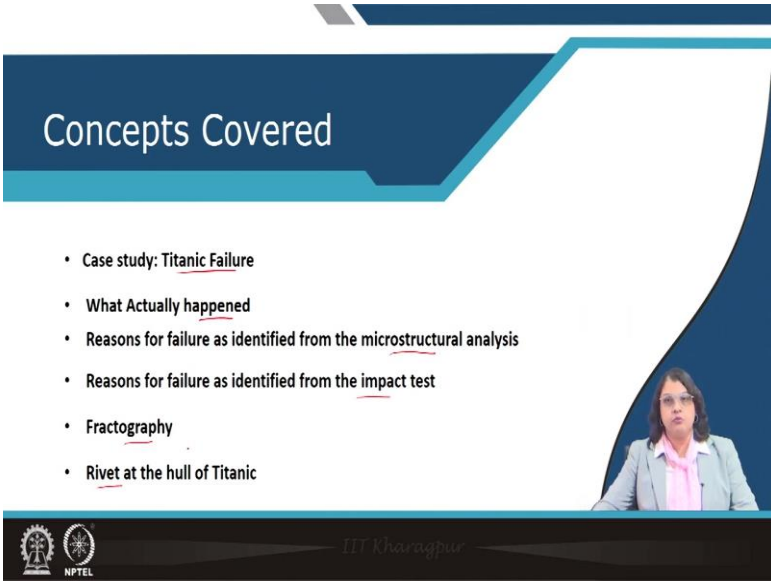

What we have is detailed analysis of Titanic failure or sinking of Titanic, I am sure that most of you are very much aware of the incident the sinking of Titanic, or you might have also seen the movie on Titanic. And in this lecture, we will see that what actually has happened and particularly we will be looking from the perspective of metallurgical engineering and I will try to figure out the reasons for the sinking of Titanic as identified from the microstructural analysis or the impact test or from the fractography or from the rivets that are being used in the shape.

So, all those will be discussed in detail to find out the reason and the lessons that we have learned and how we can use this for better structures these days. So, we are talking about an incident which has happened more than a century back.

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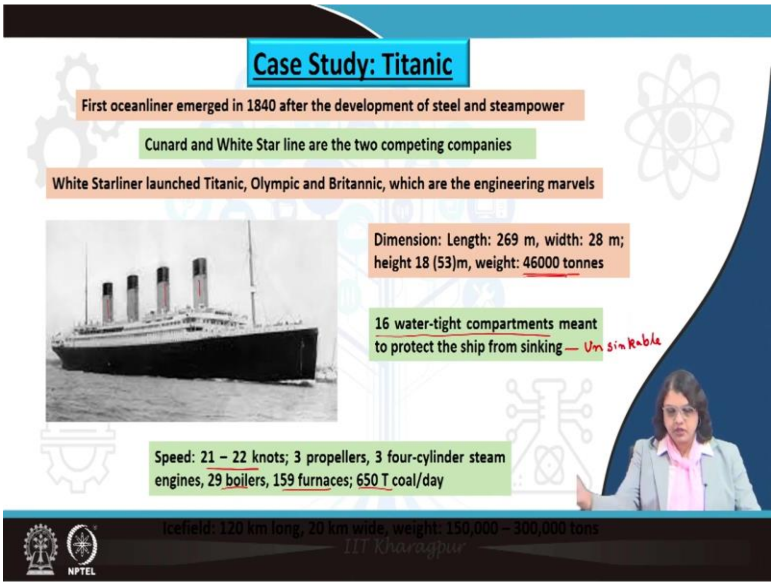

So, the sinking of Titanic has actually happened on the year 1912. In fact, all this ship business came into the picture almost 150 years back it all started at around 1840. When steel and steam powers are already been discovered and are in use then only the first ocean liner emerged. And they were the 2 companies who are competitive to each other, they are the Cunard and the White Star Line. Now, this White Star Line actually launched 3 ships altogether at the same period Titanic, Olympic and Britannic. And these are like the engineering marvels they are capable of sailing at a very high speed and for a long distance.

So, this was really came as a surprise to the entire community that how ships can be used for not only for carrying the cargoes or mails, but this will be also can be used as a passenger ships as well. So, you can see the image of Titanic and it is a huge one the superstructure having a length of around 270 meter and width of around 28 meters. Most importantly, it is really heavy structure with the weight of something like close to 50,000 tonnes. And the engineering marvel when I said the design is actually it consists of 16 watertight compartments at the base, which is meant to protect the ship from sinking. So, Titanic was actually named as unsinkable. It was considered as an unsinkable vessel, that is not going to sink and it is the irony of nature that it actually sank in its maiden voyage itself.

So, we will look into the event what actually has happened before that, let me also give you some more statistics, which says that the speed of the ship is very, very high which is around more than 20 knots around 21 to 22 knots which are quite high, if we are talking about in that respect particularly on those days. It has 3 of the propellers which are working so, we can see here the 4 pillars out of that 3 are working and one for the show just to maintain the design. And these are run by 3 four-cylinder steam engines. There are 29 boilers for this and 159 furnaces, so, these are just a number and you can imagine how big the structure is.

It uses around 650 tons of coal per day. So, when we are talking about the weight, it also means that the amount of coal that it is using and the reserve cool that needs to carry just for them for running the ship itself apart from any other rated.

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So, Titanic was actually empowered with speed and luxury of course, it is known for its speed and that it being unsinkable and all but you can get whatever luxurious life you can imagine off on Titanic. So, it has featured several items such as a swimming pool, the gymnasium, electric horse and camel for the gymnasium, squash court etc. Along with an extraordinary decor you can see the decorations here and superb cuisine as well. Of course, these are meant for the mostly the wealthy passengers.

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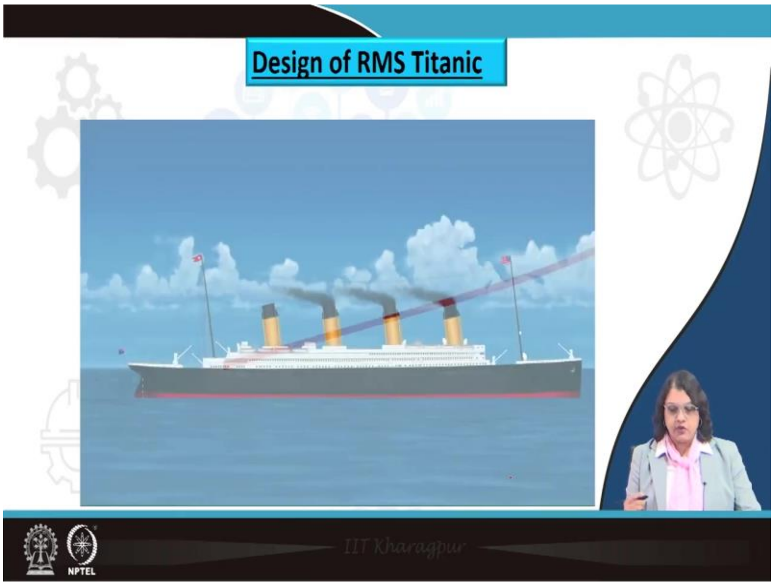
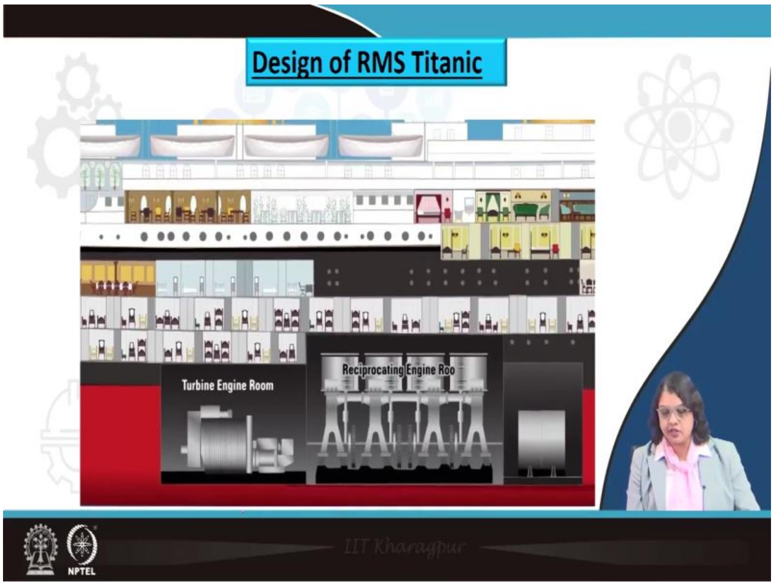
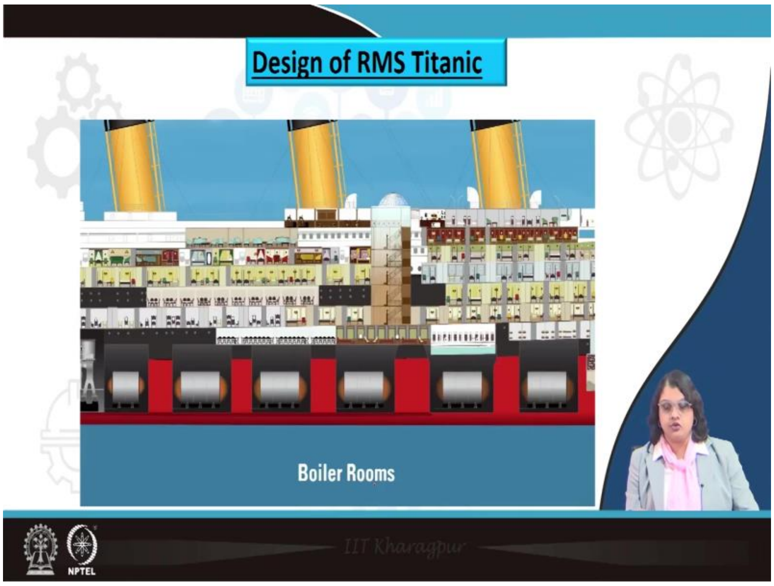
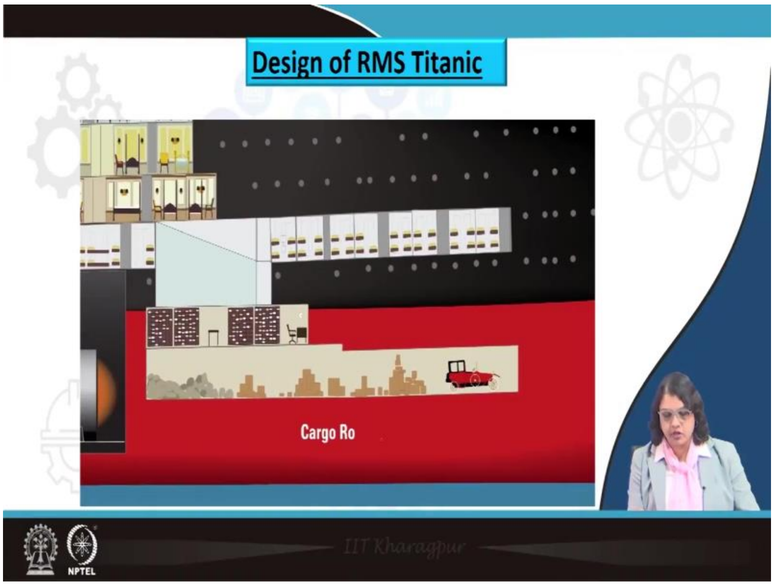





Design of RMS Titanic
Boiler Rooms
NPTEL
IIT Kharagpur


Design of RMS Titanic
Cargo Ro
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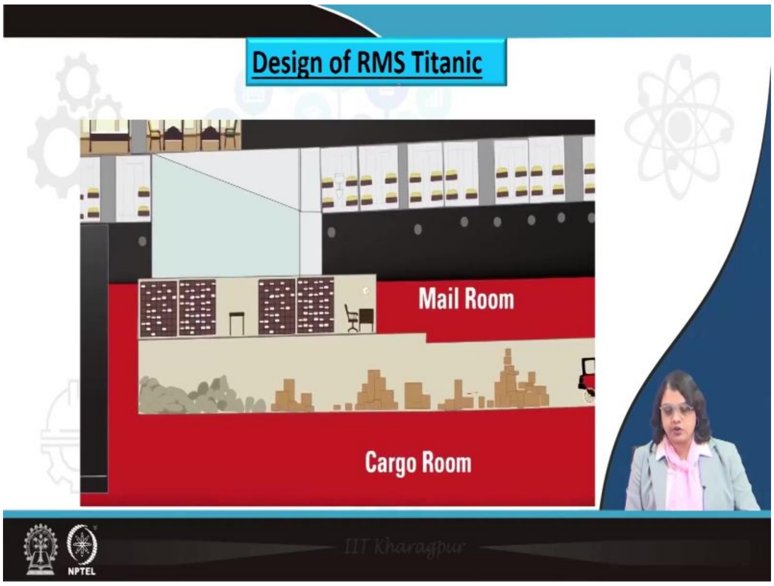
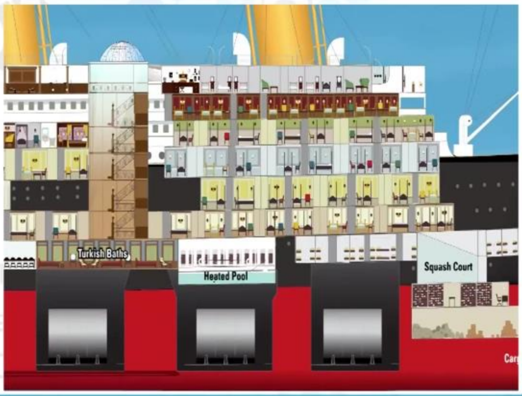
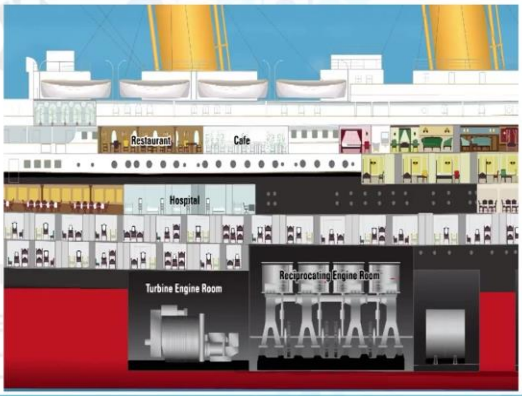
IIT Kharagpur


Design of RMS Titanic
Mail Room
Cargo Room
NPTEL
IIT Kharagpur

Design of RMS Titanic



Design of RMS Titanic



Design of RMS Titanic

Design of RMS Titanic

Design of RMS Titanic

Design of RMS Titanic

And we will look on to the ship structure in this video here. As you can see, there are 3 other running propellers here and this is the turbine engine is for the main propeller and the reciprocating engine is for the side propellers. So, this is the boiler room where all the boilers are being kept and then this has to be fed with the coals to generate the energy to run the ship. Let us look into the other features that are present in the ship. Such as this is also meant for carrying the cargo so, there is a cargo room and you can see that even the automobiles have been transferred in the cargo room. And then there are the mail room Titanic is actually known as the Royal Mail ship. So, it one of the purposes is to carry the mails and it carries more than seven million of individual mails along with the packs of mail as well.

And if you are looking on the other amenities, you can see the squash court that are there they are the heated pools, and Turkish baths which were very famous and luxurious at that time. In fact, there was a hospital which was even more advanced than the hospitals those are there in the land. Then there are restaurants and cafe to get whatever the passengers need. Third class rooms are of course, near to the bottom line. And then there are second class rooms and the first classrooms and particularly the Parlour Suites, which are very, very well decorated as per the Jacobean style.

And you can see some of the furniture and most importantly, the staircase of Titanic is very well known for its art. So, all those where when lavishly made to entertain the passengers.

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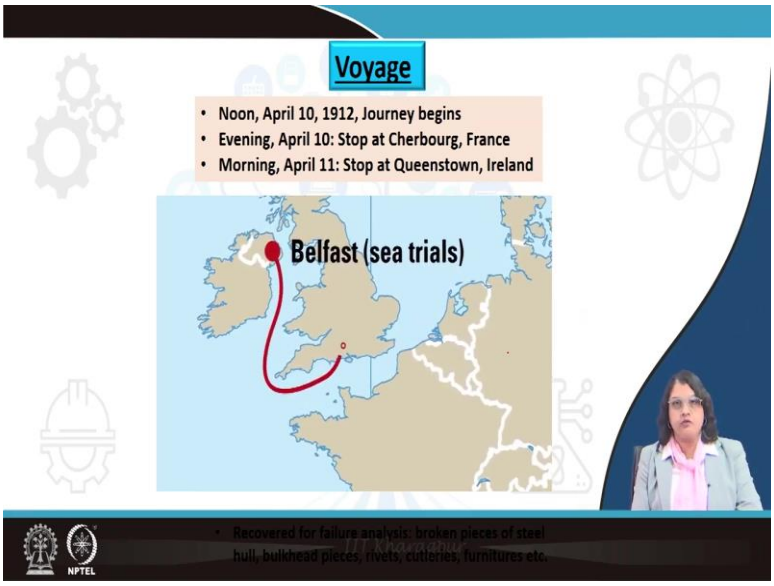
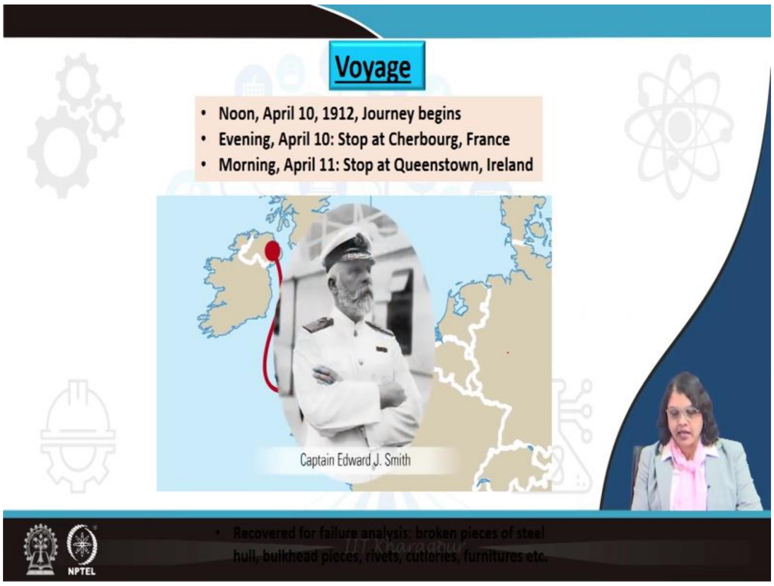
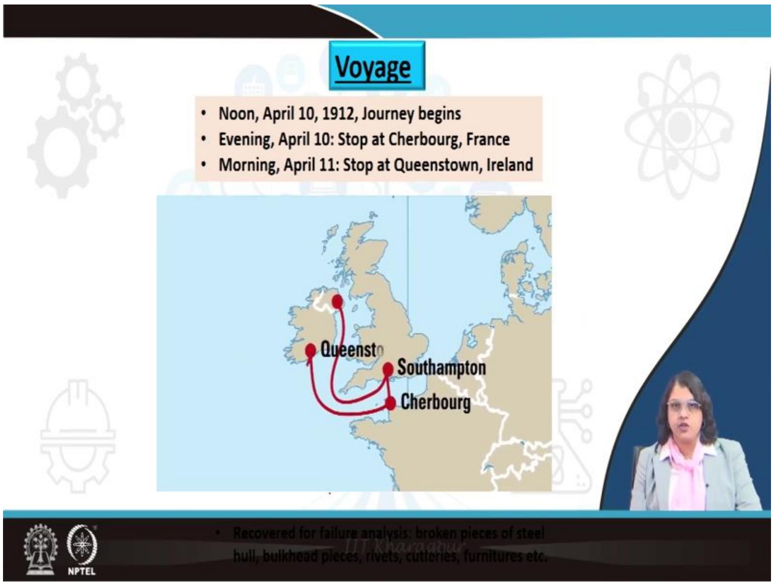
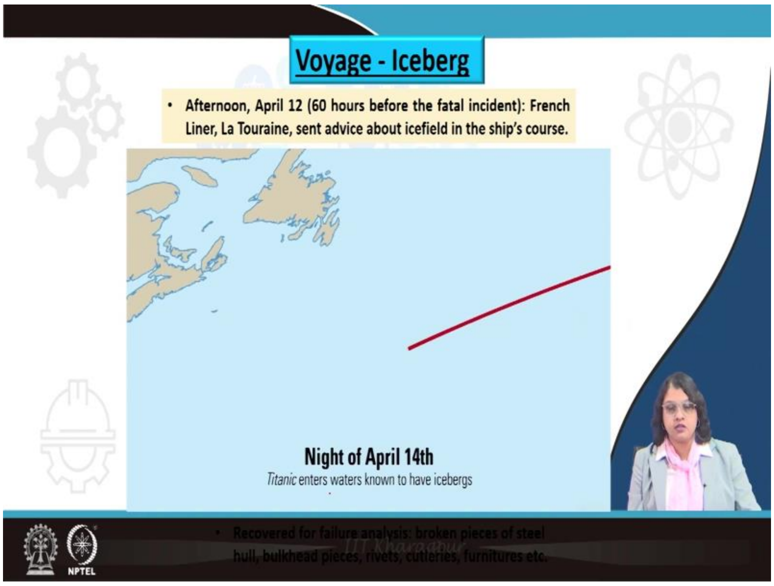
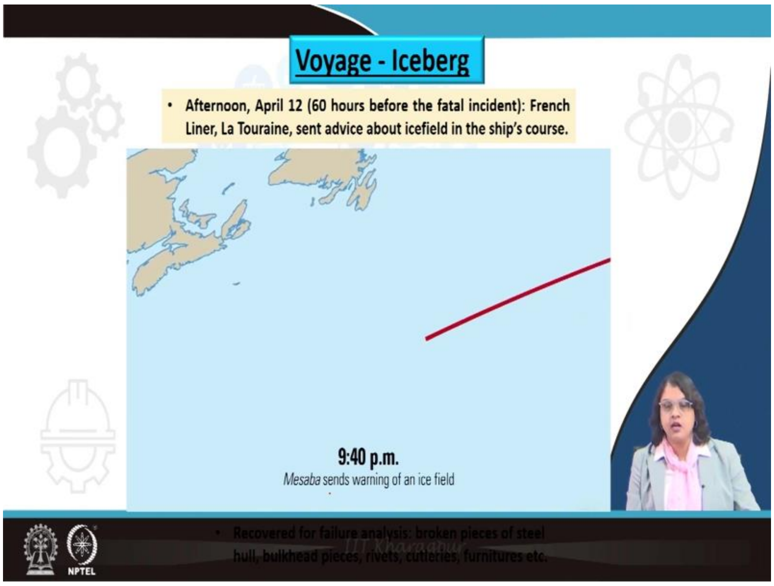
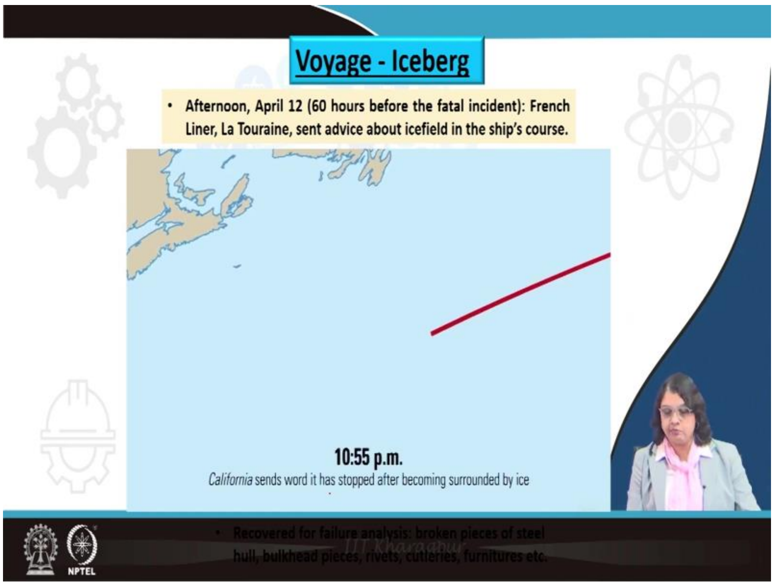


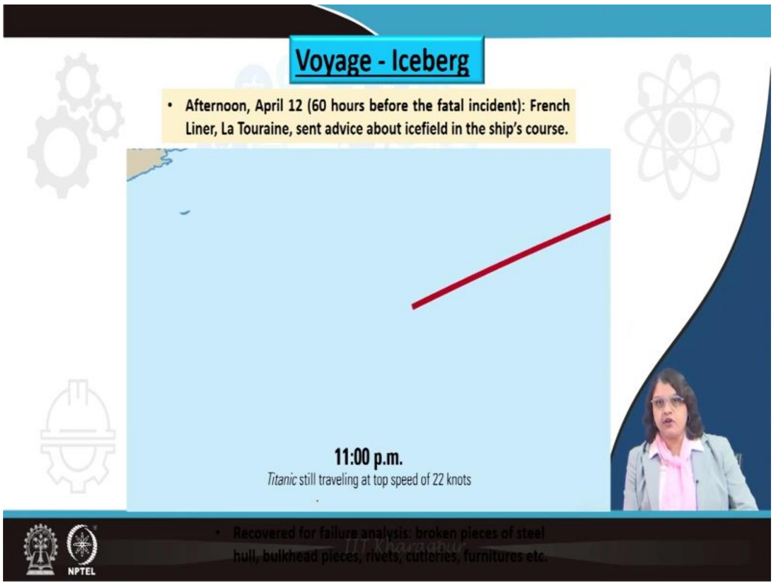


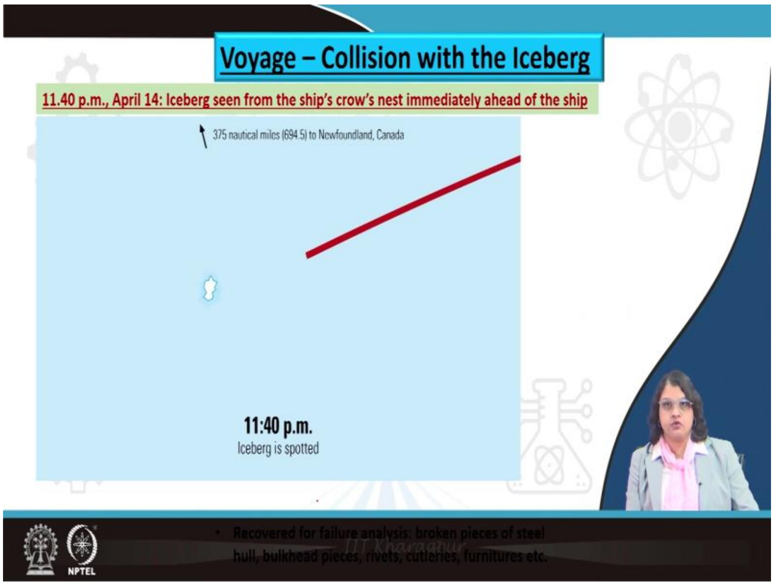


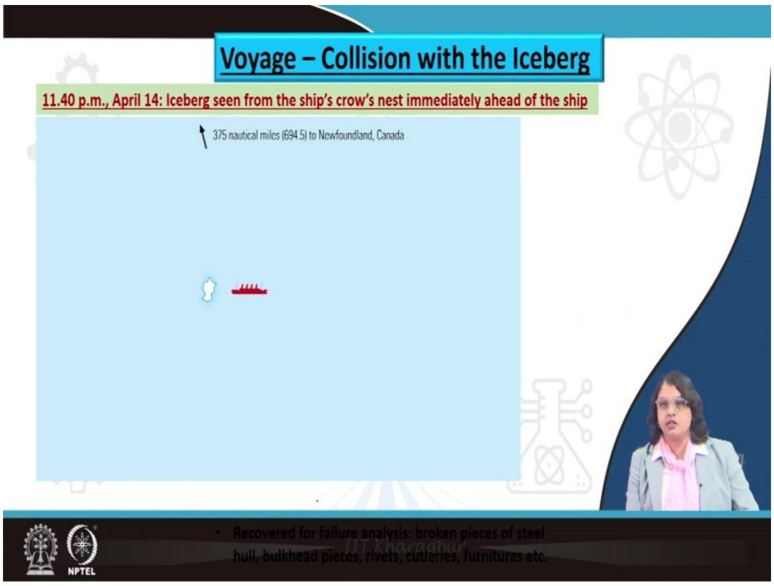

Voyage - Iceberg
• Afternoon, April 12 (60 hours before the fatal incident): French Liner, La Touraine, sent advice about icefield in the ship's course.
Night of April 14th
Titanic enters waters known to have icebergs
• Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL

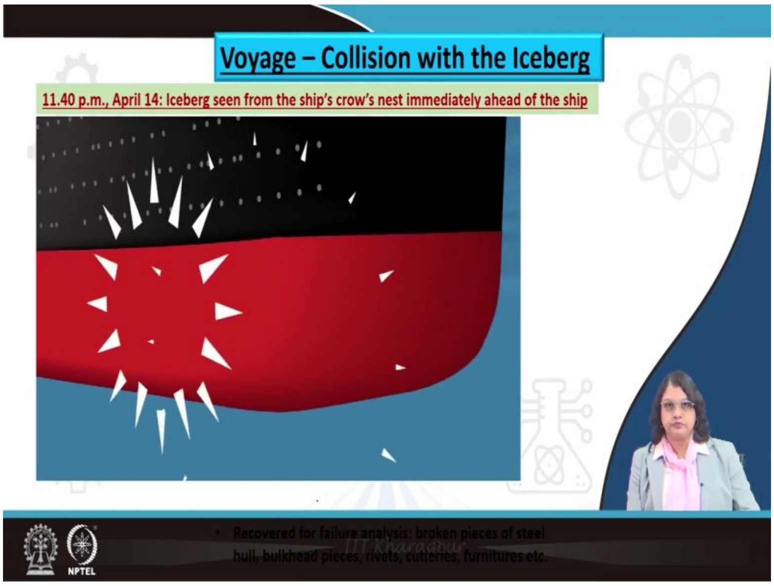

Voyage - Iceberg
• Afternoon, April 12 (60 hours before the fatal incident): French Liner, La Touraine, sent advice about icefield in the ship's course.
9:40 p.m.
Mesaba sends warning of an ice field
• Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage - Iceberg
• Afternoon, April 12 (60 hours before the fatal incident): French Liner, La Touraine, sent advice about icefield in the ship's course.
10:55 p.m.
California sends word it has stopped after becoming surrounded by ice
• Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage - Iceberg
• Afternoon, April 12 (60 hours before the fatal incident): French Liner, La Touraine, sent advice about icefield in the ship's course.
11:00 p.m.
Titanic still traveling at top speed of 22 knots
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage – Collision with the Iceberg
11.40 p.m., April 14: Iceberg seen from the ship's crow's nest immediately ahead of the ship
375 nautical miles (694.5) to Newfoundland, Canada
11:40 p.m.
Iceberg is spotted
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage – Collision with the Iceberg
11.40 p.m., April 14: Iceberg seen from the ship's crow's nest immediately ahead of the ship
375 nautical miles (694.5) to Newfoundland, Canada
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage – Collision with the Iceberg
11.40 p.m., April 14: Iceberg seen from the ship's crow's nest immediately ahead of the ship
NPTEL
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
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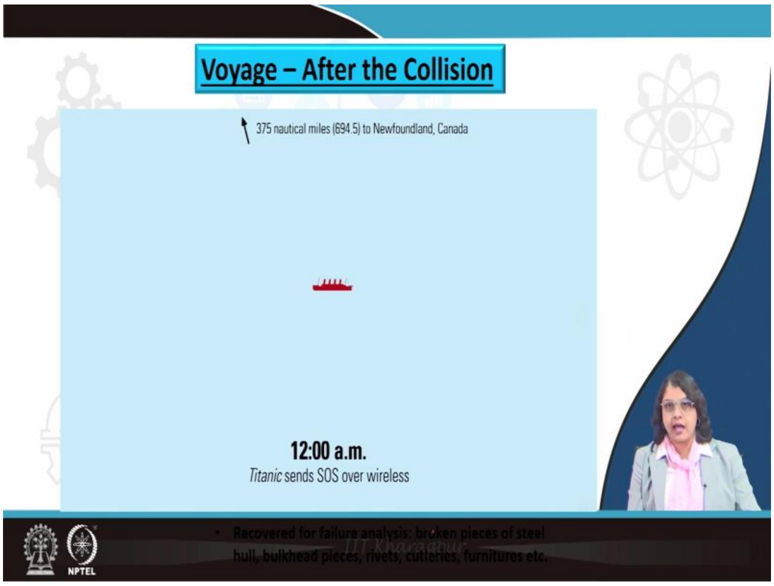
Voyage – After the Collision
375 nautical miles (694.5) to Newfoundland, Canada
12:00 a.m.
Titanic sends SOS over wireless
NPTEL
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
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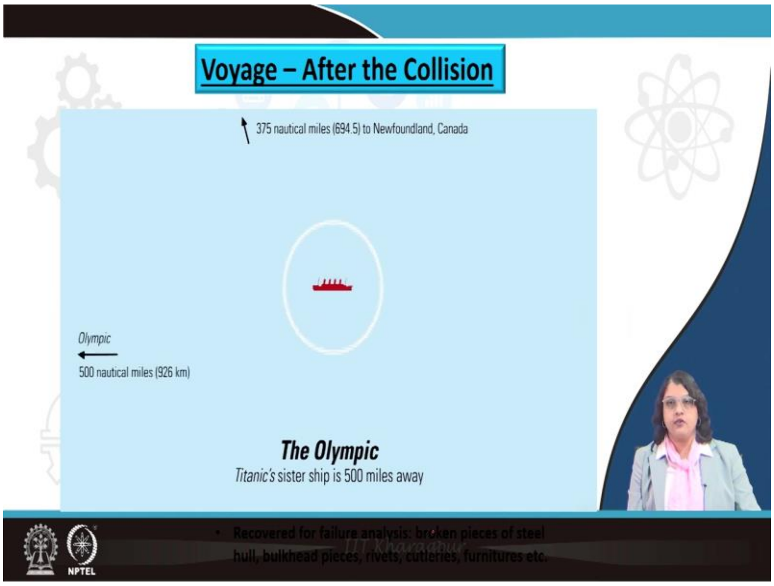
Voyage – After the Collision
375 nautical miles (694.5) to Newfoundland, Canada
Olympic
500 nautical miles (926 km)
The Olympic
Titanic's sister ship is 500 miles away
NPTEL
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
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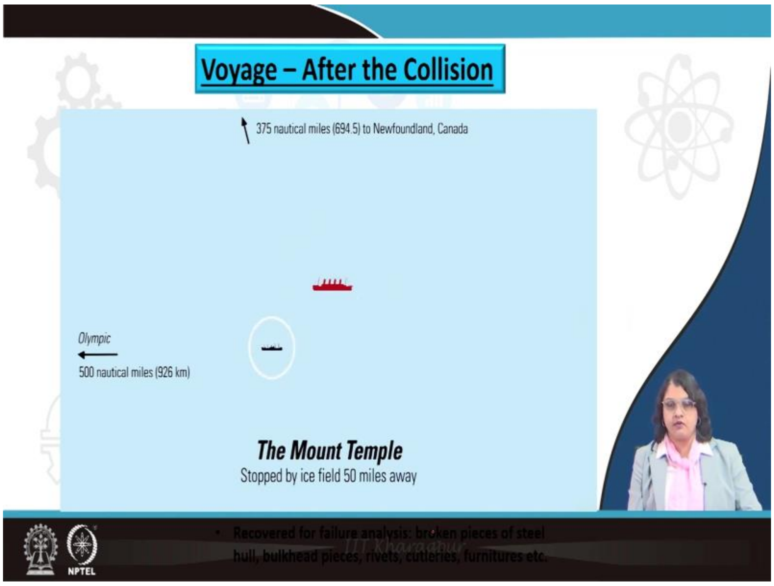
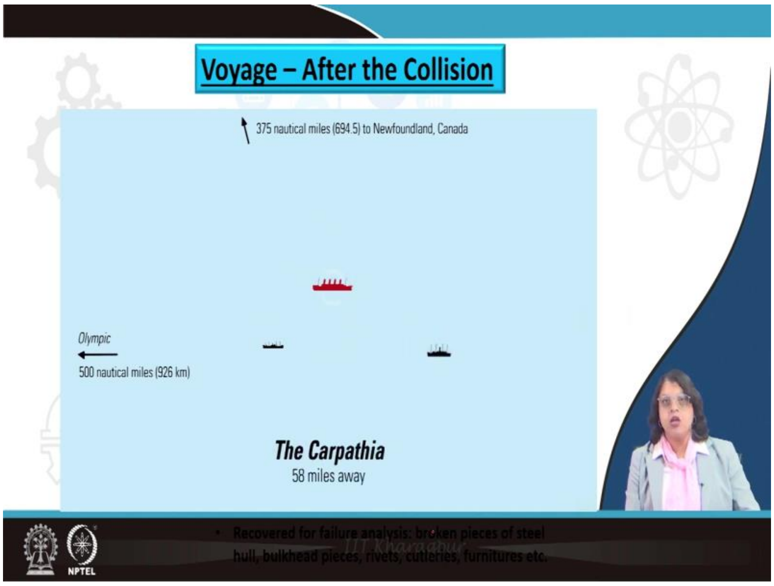
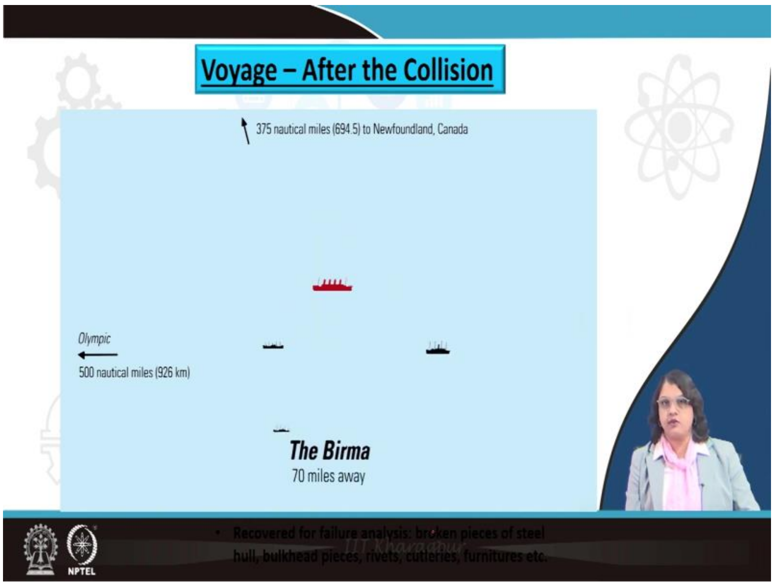
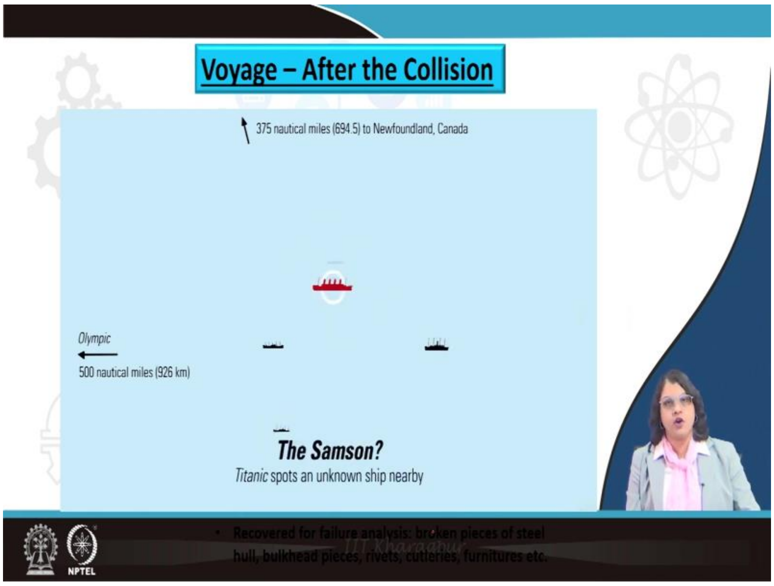
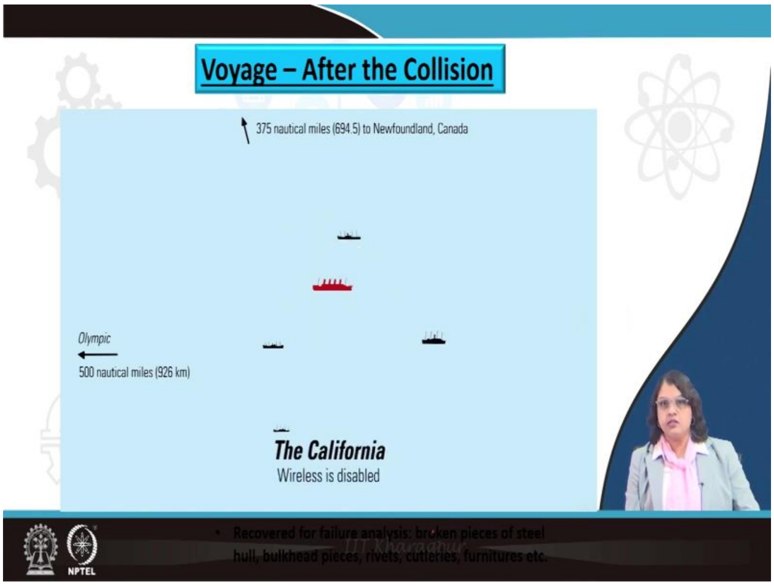
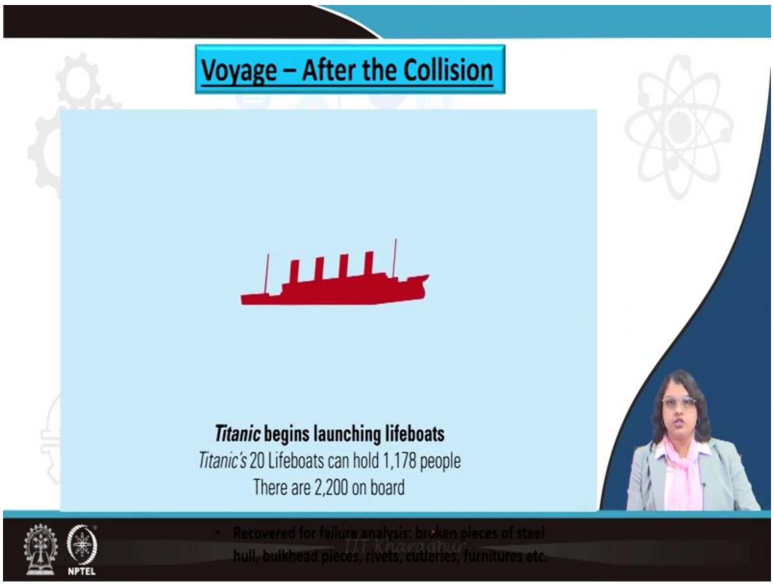

Voyage – After the Collision
375 nautical miles (694.5) to Newfoundland, Canada
Olympic
500 nautical miles (926 km)
The Mount Temple
Stopped by ice field 50 miles away
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL

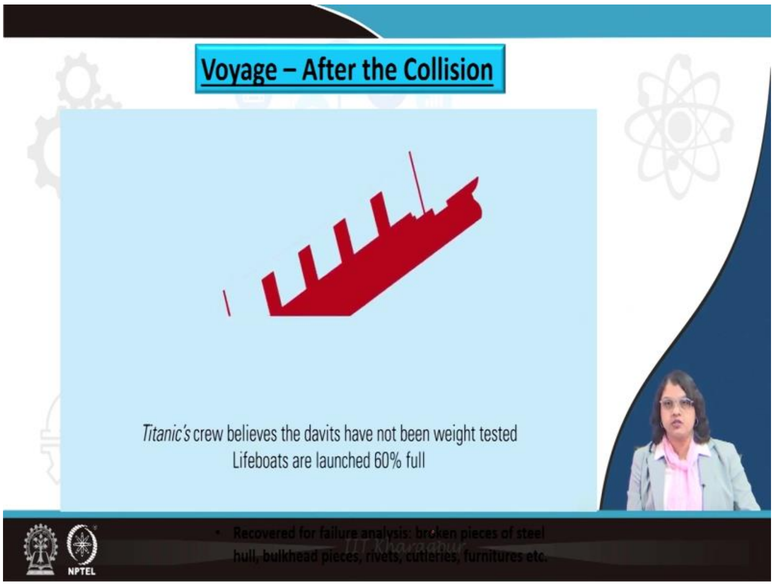

Voyage – After the Collision
375 nautical miles (694.5) to Newfoundland, Canada
Olympic
500 nautical miles (926 km)
The Carpathia
58 miles away
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL

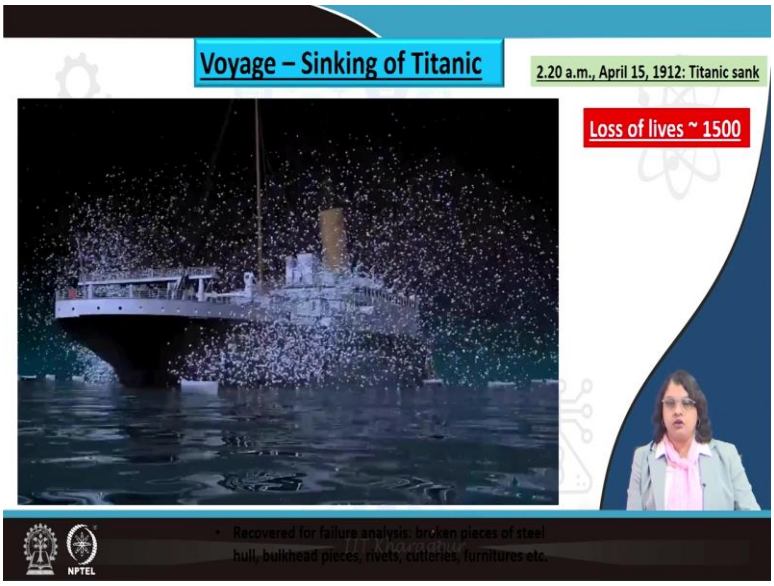

Voyage – After the Collision
375 nautical miles (694.5) to Newfoundland, Canada
Olympic
500 nautical miles (926 km)
The Birma
70 miles away
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage – After the Collision
375 nautical miles (694.5) to Newfoundland, Canada
Olympic
500 nautical miles (926 km)
The Samson?
Titanic spots an unknown ship nearby
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage – After the Collision
375 nautical miles (694.5) to Newfoundland, Canada
Olympic
500 nautical miles (926 km)
The California
Wireless is disabled
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL


Voyage – After the Collision
Titanic begins launching lifeboats
Titanic's 20 Lifeboats can hold 1,178 people
There are 2,200 on board
Recovered for failure analysis: broken pieces of steel hull, bulkhead pieces, rivets, cutleries, furnitures etc.
NPTEL





So, initially there was a trial almost a year back before the maiden voyage has started from Belfast, and then the actual voyage has started on April 10, 1912, under the captain ship of Edward J. Smith, who was known as a million years Captain. Because he was very famous amongst the millionaire passengers started from Southampton and had a stop at Cherbourg, France. And finally, another stop it leveled at Queenstown, Ireland, from which it set the final sail. Now on the afternoon of April 12. So, the day after which started from Ireland, that is almost 60 hours before the fatal incident that happened. Titanic was first intimated by the French liner about the presence of ice filled in the ship's core.

So, whatever part it was assigned to there were some icebergs that has been already informed to Titanic, which however, has been overlooked. And on the night of April 14, itself, April 14 is the one when the incident happened. So, Titanic entered into the water full of iceberg and there are several ships which are nearby send the message to Titanic about the presence of iceberg which are quite big and cannot be avoided. For example, California sent a message even at close to 11 o'clock in the night.

And the captain however, did not pay attention to all those messages and the traveling at a very high speed at the maximum speed of 22 knots, then only at around 11:40pm. On the night of April 14, iceberg was first noted by Titanic scrolling itself. So, ship has a Cronus to look for the any such things beforehand and once they have noted the iceberg, they tried to stop the ship immediately and that actually has reduced the speed but could not avoid the collision. And it has collided as you can see how the collision has happened. And within 40 seconds actually, after finding the iceberg at around 11:40 this collision happens.

And this actually struck the ship near the hull 4 meter above the keel, those are the points of contact that has happened. And in next 10 seconds just within 10 seconds of the collision. 100 meter of hull plates got damaged and rivets are popping out which led the first five of the 16 watertight compartments got opened up. So, you remember when I said that there were 16 watertight compartments that were meant to make the Titanic unsinkable. However, out of that five got damaged and the rivets pop out and the hull plates got open, which means the water can right away gush in and that is what has happened.

So, around 12am. So, this all happened at around 11:40. Or close to that, and then around 12am, when they realize that this is in danger, initially, it was thought that maybe the impact was not that much. But when they realized that this is in danger, they start sending messages. So, it is and there were several ships which were nearby received the SOS and they were trying to help but most of the cases they were either too far away or they are itself surrounded by the iceberg so that they cannot reach only there was one ship which did not respond to it.

And that was very near to Titanic, which could have saved but this was possibly an illegal Norwegian ship for seal hunting. So, they did not respond. And once the SOS was not working and the wireless got disabled because the water already started in on the ship itself. Then they started using the flares to attract other ship to let them know that the ship is in danger. After that, when they realize that no other one is coming for help, or it was not possible not enough time water is already getting into the ship. There were lifeboats that are being launched, but there were only 20 lifeboats, there has to be more than those 20 lifeboats were enough for around 1100 people.

Although within the ship, including the passengers and crew members, there were almost 2200 people. So, lifeboats were sufficient only for up to 50 percent of the people on the ship. But however, the initially launched, lifeboats were only 60 percent full so they have not even launched the lifeboats with the full capacity. And there are several reasons for that, which are being discussed or which have been shown in the movie also, and nothing to do with the metallurgical factors as such. But what we can see here is that how the ship has actually broken apart into 2 pieces, as if this is just like a toy. And it sank finally at around 2:20am on April 15th. And we know that there was around loss of lives of 1500 people, which could not survive.

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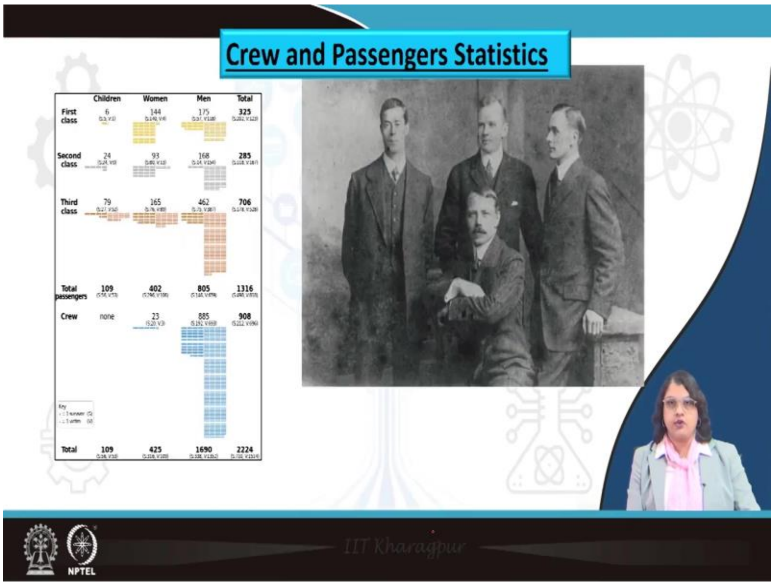

So, this is total statistics. If you look on, there were around 2224 total passengers plus crew members and out of that 1514 lost their lives and survivor is only 700 people.

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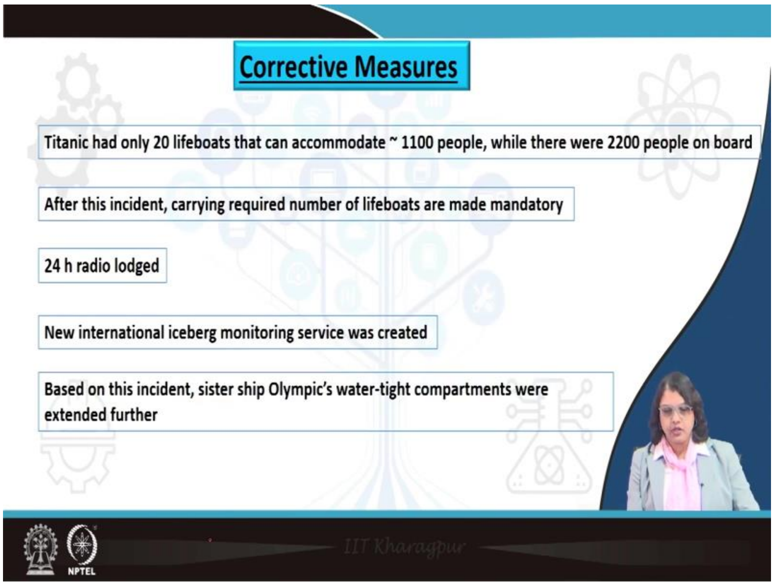

So, of course after the incident, it almost shook the entire world. People were in shock because Titanic as I mentioned, this was like an engineering marvel and was not supposed to sink considered as unsinkable, but still it sank. And not only that, in its maiden voyage itself, it could not even complete its first journey, it sank. So, of course, there were some corrective measures that has been taken, realizing that what actually might have went wrong, so that it should not happen in future. But those kinds of corrective measures are done based on the overall reasons such as Titanic, carrying less number of lifeboats, particularly, not to endanger the beauty of the ship. So, not enough number of lifeboats were kept on the deck so, that the view from the deck to the surroundings will not should not be obstructed by the lifeboats.

So, after this incident, it has been made a mandate that enough number of lifeboats need to be there needs to be stationed on any ship. There was some 24-hour radio that was launched and new international iceberg Monitoring Service was created such that all the ships traveling through such paths can get informed about iceberg. Based on this incident actually, Titanic's sister ship, as I mentioned that Titanic has 2 other sister ships, Olympic and Britany. So, in case of the Olympic, the watertight compartments were extended farther to avoid such failure. Anyway so, after at around 1935 finally, White Star Line has been taken over by its longtime competitive owner of Cunard.

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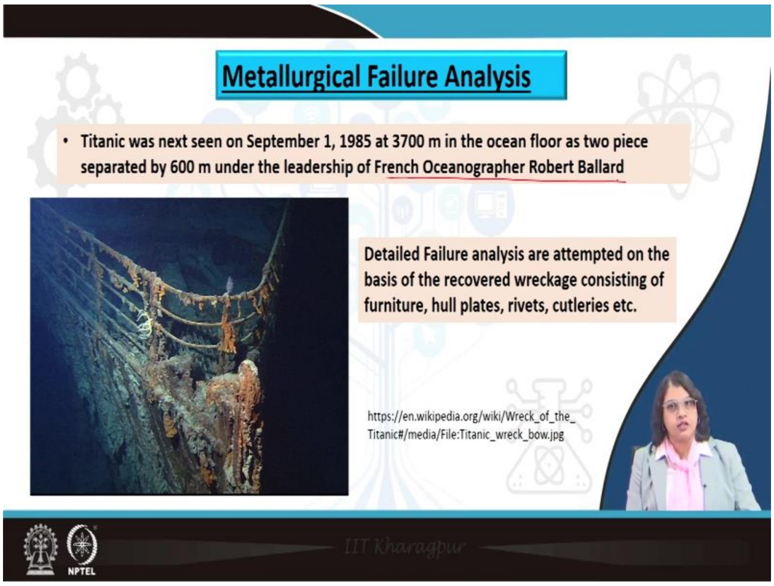

So, let us look into our part here. So, far all those corrective measures were taken based on the general understanding about what may have went wrong? But the actual reason for the failure can be well understood from the metallurgical failure analysis if we can do that. So, Titanic was next seen the incident happened in 1912. And it was next recovered on 1985 in September 1 of 1985 at around 4 kilometers beneath the sea level, and 2 pieces were separated by 600 meters. And this entire wreckage recovery has been done under the leadership of French oceanographer Robert Ballard. You can see the image here how the entire thing is covered with rusticles.

And there has been a lot of damage that has already happened, but still, some pieces were recovered from the wreckage such as the furniture, the hull plates, rivets, cutleries, etc and detailed failure analysis has been done based on that

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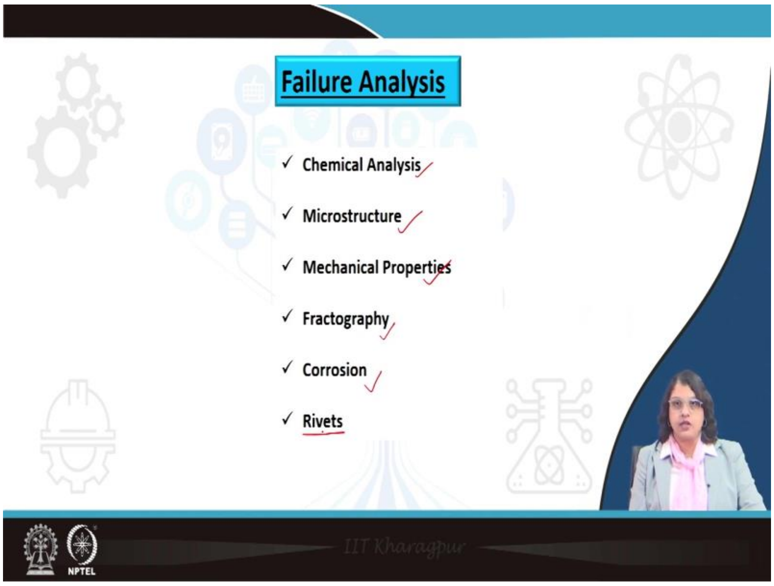

And when I mentioned the failure analysis, of course, there is a series of investigation that has been done as we have seen just in the last lecture that what kind of testing needs to be done if we want to pursue a detailed failure analysis. So, this is a perfect example to see how failure analysis has been done and what we can learn from them. So, initially, some chemical analysis has been done followed by the microstructure investigation both at the macro and the micro level. And then mechanical properties are being determined fractography has been very carefully examined to understand the reason for failure, if there are any further effects of corrosion as well.

And there is one important thing which are the rivets that has been very carefully analyzed. We will go through that in details soon.

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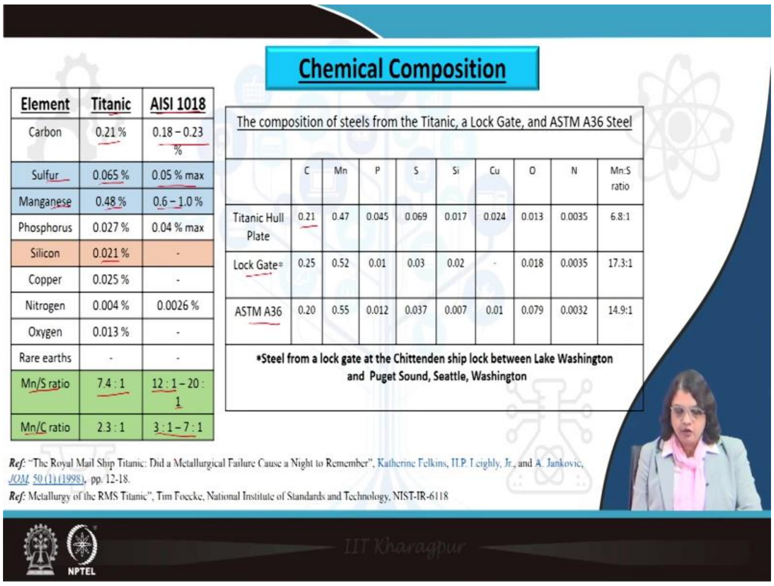

So, let us see the chemical composition. So, whenever such kind of thing happens like a failure happened for the case of Titanic, the first thought that might have come to you are the steel might not be suitable for the sheet making. And when we talk about the steel, the first element that comes to our mind is carbon, maybe the carbon content of the steel is too high. That may have made it a brittle one. But if we look into the details of the chemical composition of Titanic, and in comparison, to that, the chemical composition of the modern-day shipbuilding steel, for example, AISI 1018 or in another separate study, it has been compared with the lock gate steel or the ASTM A 36 steel which are used in these days.

And we can see that more or less the carbon content is actually within the limit that is well within the limit. So, there is no issue with the carbon content to be higher or lower. Rather what happens is that the sulfur content is pretty high, then even the maximum limit of 0.05. And now, we have 0.065 percent of sulfur. Same goes for the manganese, but on the other side, for example, manganese needs to be within a limit of 0.6 at least and what they have is even less than 0.5 percent. Now, this may appear very small changes in the composition, but this may lead to serious changes in the properties or the behavior of mechanical behavior of the material.

There was some amount of silicone also as a slag and most importantly, what we can see is the manganese is to sulfur ratio has not been maintained, it has to be within 12 is to 1 to 20 is to 1 and it is far below than that. Manganese is to carbon ratio has also not been maintained. And if you just go back to the previous lectures, you will see the importance of manganese particularly for the case of ductile to brittle transition, we know that manganese is the one element which is having a positive effect on the ductile to brittle transition behavior. Which means that the manganese is to carbon ratio has to be maintained above 3 is to 1 which was not at all maintained here.

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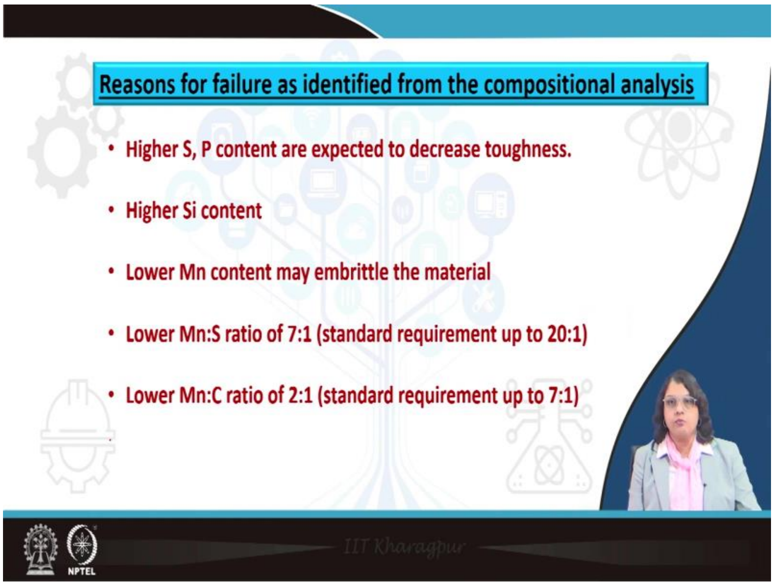

So, if we can understand the failure analysis on the basis of the composition, we can say that the higher sulfur and phosphorus content actually lead to reduction in the toughness. High silicon content is also one of the reasons and lower manganese is expected to embrittle the material, lower manganese is to sulfur ratio, lower manganese is to carbon ratio are the culprits which actually reduced the toughness had enough manganese sulphide inclusions which might have also led to fracture. So, far this is what we understand from the compositional analysis.

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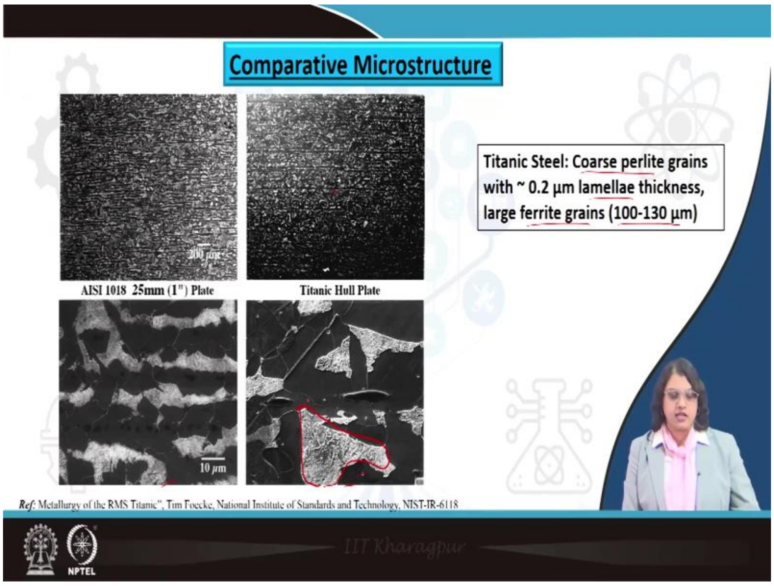

So, let us now look into the microstructure as the microstructure is very important, particularly if we are talking about the mechanical properties and its correlation with microstructure, we know that we can increase the mechanical performance of a material if we modify the microstructure. And if we say the mechanical performance again, there are 3 very vital factors first of all the strength, ductility and toughness, there are other parameters also other properties which are very, very important. But let us talk about these 3 important parameters at the very first hand and how microstructures are controlling these parameters.

Now, when we are talking about strength or even ductility or toughness, we know that there is one way by which we can achieve combined increased strength, ductility and toughness and that is through microstructure refinement. So, smaller grain size or microstructural size is very, very important for that. What we see for Titanic steel is it has coarse pearlite grains which you can see here, which has very high lamellae thickness and large ferrite grains, more than 100 micrometers, which is quite coarse. You can compare the Titanic microstructure particularly at higher magnification with the AISA 1018. The model shipbuilding steel and we can see that there are much coarser structures, which are present here for the case of Titanic which actually must have affected the overall mechanical performance of the material.

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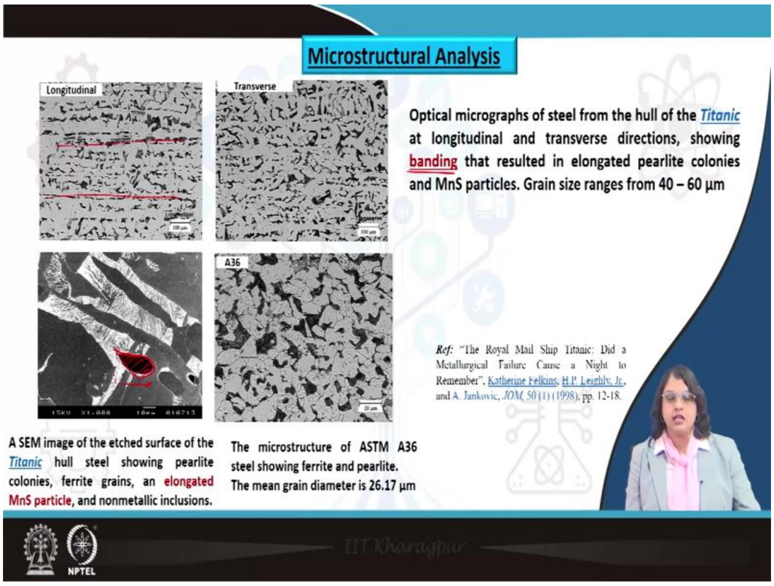

Not only that, we can also look into some banding structures, if we look into this carefully, there are some bandings that we can see in both the longitudinal and transverse directions, which means that there should be some non-uniformity and properties as well. And non-uniformity in properties is not something that we want to have in any structures, because that may lead to early failure even without expectation not only that, what else we can see here are the presence of this manganese sulfide inclusions.

So, if the manganese content is low and then because of the higher sulfur content major part will be used up in making manganese sulphide inclusions which are quite big, we can see that this is almost like 50 to 100 micrometer, big manganese sulphide inclusions which are formed and such big inclusions are of course, very much prone to initiate crack and lead to fracture. Not only that, all the manganese are being used up in making this manganese sulfide inclusions which means that it will affect the ductile to brittle transition temperature as well.

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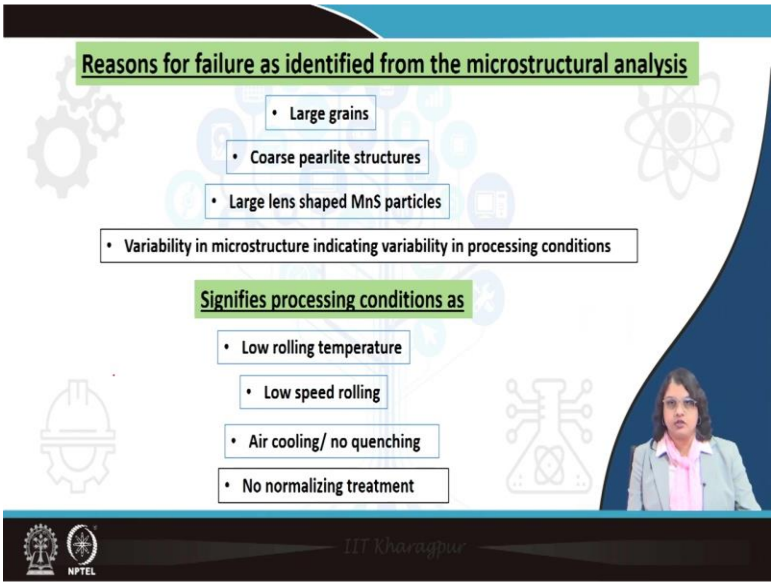

So, if we are analyzing the reasons for failure from the microstructure itself, we can see that there are large grains with the coarse pearlite structures as well as large lens shaped manganese sulfate particles all this can lead to failure particularly the banding also suggested that there could be variability in the microstructure and that may also indicate about the variability in the processing conditions. So, processing conditions at those time like in the beginning of 1900, they were not very much knowledgeable about using higher rolling temperature and also this also is one of the reasons that the microstructure has not been formed as per the required criteria as per the present model is shipbuilding steel.

So, lower rolling temperature has been used with low-speed rolling and there was no point quenching that has been used, which means that lead to the coarsening of the microstructure, no normalizing treatment has also been used to refine the grain structure further.

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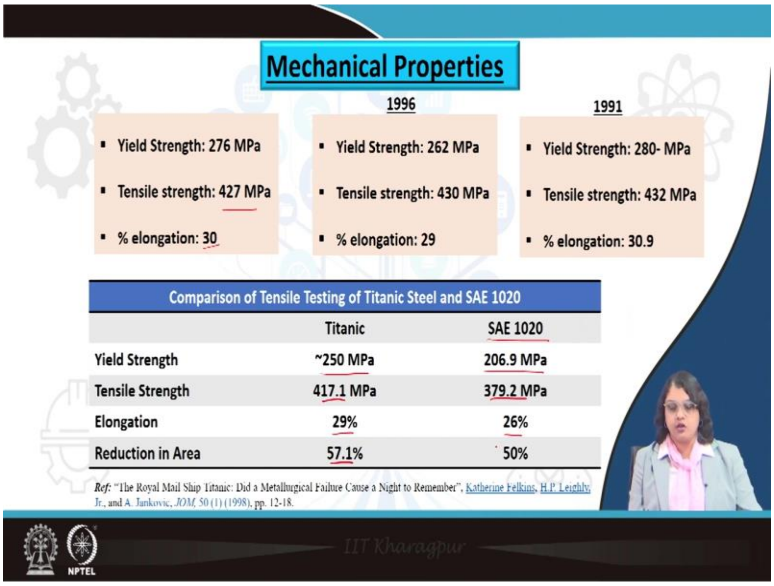

So, next coming as I said the microstructure is very closely related to the mechanical properties of the material and these are the investigations on the Titanic steel that has been recovered particularly from the hull plate. And you can see that investigations has been done in several places. So, volatile times and what has been found overall is that it has a strength of something like 260 to 280 MPa and tensile strength of 400 or more than 400 MPa. And percentage elongation, which is signature for ductility is around 30 percent. So, when we have this number, what we next want to do is to compare it again with the modern-day shipbuilding steel, and this has been done thoroughly.

And what we can see is that it has a yield strength of around 250 MPa, which is actually higher than this SAE 1020 steel that is used in these days. So, several kinds of shipbuilding seats are used for the comparison purpose just to check that whether the properties of this titanic steel is up to the level. And what we can see is that both the yield and ultimate tensile strength are actually exceeding the present-day steel and not only that, the reduction in area which again signifies ductility is also quite comparable, same goes for the elongation signifying the strain or the ductility.

So, that means that the strength and ductility wise it is as comparable to modern day shipbuilding steel, which means, they have used the best possible quality of steel that are available that time which would have been sufficient for utilizing it for shipbuilding and that could have survived longer. So, what went wrong?

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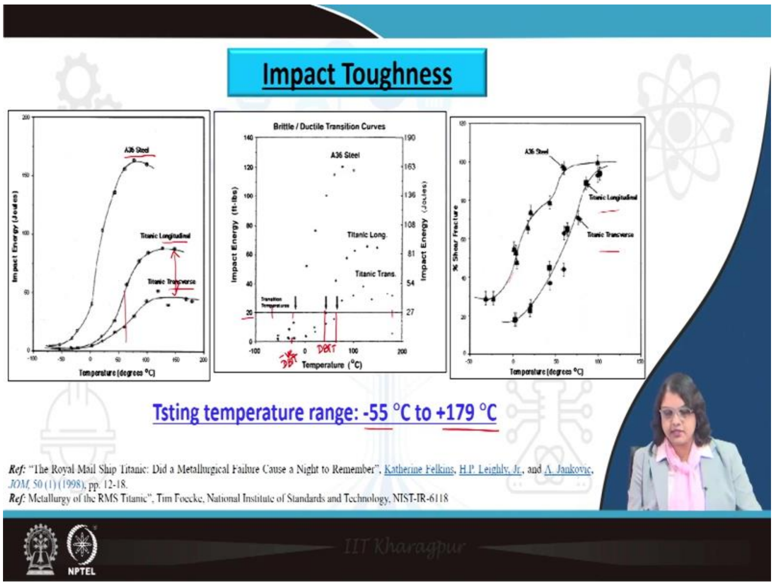

So, the next thing in the mechanical properties apart from strength, toughness and ductility is the impact toughness that is of interest, particularly if we are talking about using it in ship which is running at a very, very low temperature and stuck with an iceberg. So, the impact testing has been done and what we can see here is this is for the modern steel and this is for Titanic, you can see the these are the investigation showing the same kind of results for the 2 separate investigations for your reference. And what we can see here, are the 2 observations is that first of all the longitudinal and transverse specimens which are made from the longitudinal and transverse hull plate are actually showing differences in the properties quite some differences in the properties.

And this is not at all unwanted situation as I mentioned that anisotropy in the properties are never good news, which means that it will serve only as the worst possible case we do not know at the point of service that which way the loading will come. So, we want to have quite uniform properties all throughout otherwise, only the worse properties will take the lead and that may lead to fracture early fracture. This is the shear fracture percentage and here also we can see the longitudinal and transverse has quite some different values. And not only that, the second observation that we can see from the impact toughness testing is that they are ductile to brittle transition temperature and whichever way we want to measure that.

There are different ways for measuring the DBTT as we have discussed in the lecture, and what we can see here that if even if we are talking about 50 % strain or some particular value of 20 Joule impact energy. We can see that this titanic one is having quite some high value of DBTT. So, quite some positive value and in comparison, the modern-day steel has a negative

DBTT negative means below the 0 °C. So, sub 0 temperatures so, obviously, we have also discussed this in the previous lectures that lower DBTT is always preferred such that in service condition, it should not transform into a brittle one and fail.

So, testing temperature range was minus 55 to 180 almost 180 °C to check for the transition from ductile to brittle, but we can see.

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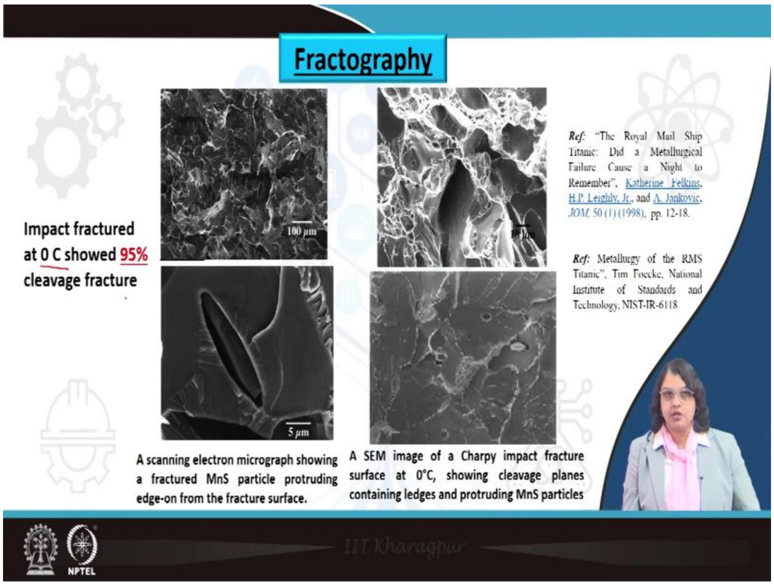

But in any case, we have seen for the Titanic that DBTT is quite low, when we have looked into the fractography in details, the impact tested carried out at 0 °C showed 95 % cleavage fracture. Once again signature for brittle failure and that means that it has already undergone to brittle nature at that temperature of 0 °C itself.

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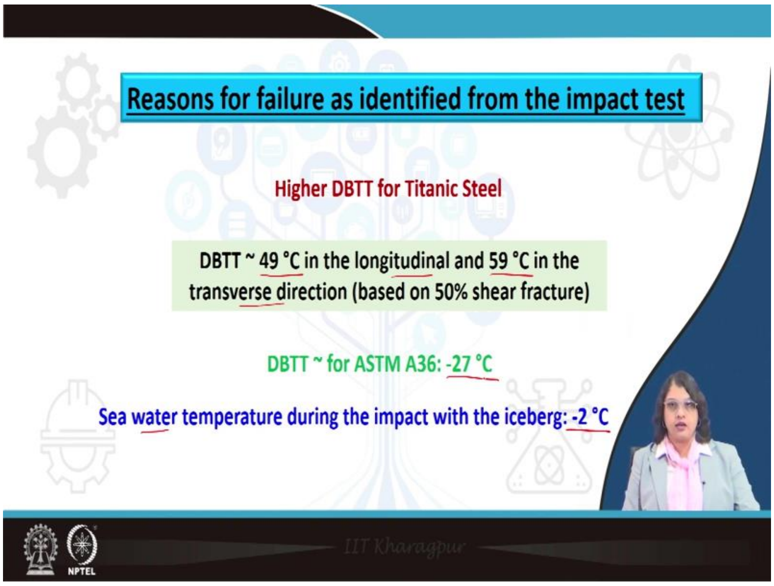

It should be mentioned and you should be aware of the fact that the seawater at the point of the coalition was around minus 2 °C. So, that means it is sub 0 and what we have seen from the lab scale testing from the recovered piece is that the DBTT is actually above 0 °C much above 0 °C. And on the detail investigation in the impact test, what we can figure out is the higher DBTT for Titanic still as high as almost like 50 °C under longitudinal and close to 60 °C in the transverse direction. While for the case of the modern shipbuilding steel, it is around minus 27 °C.

So, you can understand that this is one very major reason for the failure of Titanic that it has failed in a brittle manner. Otherwise, it would not have failed possibly, it might have some change in the shape, but it might not have cracked. And that could be one of the reason. Now, it was not very well known the concepts of DBTT and impact was not very well known at that time and that is one of the reason that they did not pay attention they have used a steel which has good strength and ductility and toughness in general. But they have not paid attention to the impact of misbehavior, how the material behavior will change completely at low temperature that was not taken care of without anyone’s fault.

But, at the same time, it should be also noted that that had there been no impact it would not have failed.

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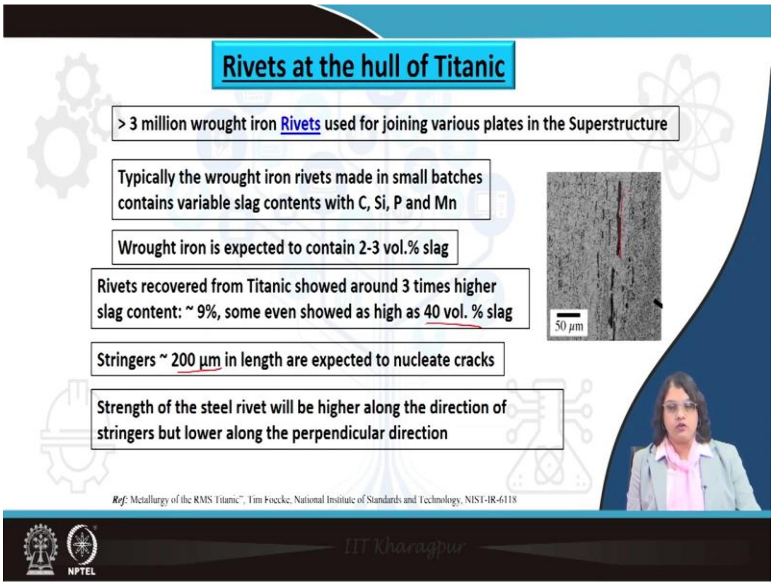

So, the other very, very important factor that played on the sinking of Titanic are the presence of rivets. Now, the superstructure use more than 3 million rivets and this rivets at that time was made from the wrought iron they were produced in small batches. And that once again led to differences in the composition and contents from batch to batch. Typically, the wrought iron rivets are may consist of slag also and the slags are mostly consist of carbon, silicon, phosphorus, manganese et cetera. And wrought iron is expected to have slag quantity of around 2 to 3 volume percent. But in reality, whatever rivets has been recovered from the wreckage, it has shown that it contains more than 9 percent of slag.

Even some of the rivets actually showed slag content as high as 40 %. So, 40 % slag, slag is nothing but impurity slag means there these stringers which can lead to crack initiation very easily and stringers of size of around 200 micrometers, almost like 0.2 millimeter, these are quite big and quite prone to initiate cracks. So, those were present on the rivets. Now, you may think that rivets are really, really small compared to the giant superstructure of Titanic of the ship. So, how could rivets can actually lead to failure of the entire ship.

So, we will look into that, but, let us have a look on the stringers that we are talking about. So, these are such big inclusions were present on the slag itself. And not only that, they are having non uniformity in the properties also, the strength of the steel rivet is higher along the direction of stringers. But if the stringers are located perpendicularly to the loading direction that may lead to a lower value of strength.

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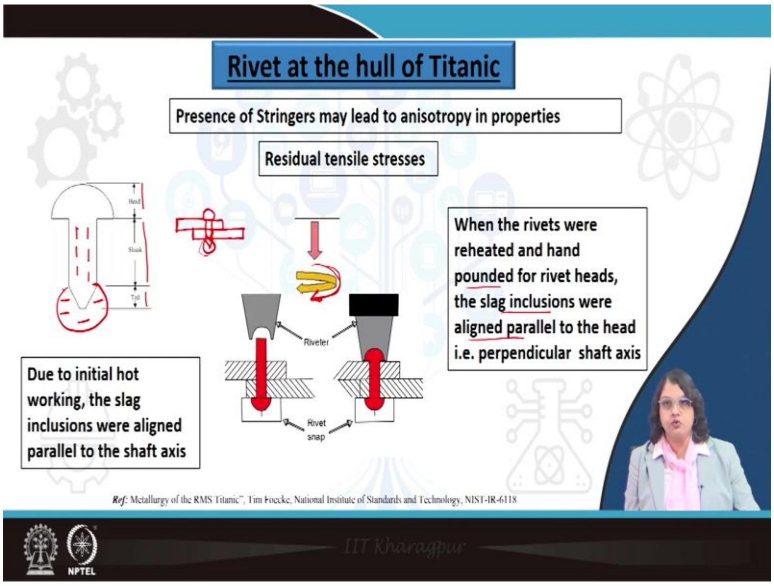

So, we will look into that that how the stringers or the presence of that can actually lead to the overall failure. As I mentioned that these stringers lead to the anisotropy in the properties and anisotropy is something that is not very well come off in the actual component not only that, it has residual tensile stresses also. We have seen previously that how the residual stresses in the compression mode is beneficial, but not in the tensile mode. So, residual tensile stress is one second bad news, but more than that, what is very, very interesting here is the structure of the rivet and the alignment of the stringers on the rivets itself.

So, let us see what it is? Rivet typically consists of structure like this it has a shank and a head and a tail. So, the tail part and part of the shank actually moves to a plate if we have 2 plates which needs to be connected, so this is one plate and this is another plate and we need to join it with the rivet. So, we basically put the rivets like this, and then, something like this and then on the steel part we add the other head. And let us see what happens now, initially when we are making distributes when the rivets are being made in the wrought process itself, due to the initial hot working the slag inclusions were aligned parallel to the shaft axis.

So, whatever inclusions the stringers that we have seen just in the last slide, this were aligned in a direction like this, because we they have applied some high temperature for the working and it always aligns along the working direction, we have also seen that. Now, the next step is when we put the other head on the tampered and this is also being done at some high temperature and we apply a torque to this. And we will be doing this at high temperature and hand pounded, what happens apply the torque to this what happens is that the slag inclusions were aligned parallel to the head.

So, now it is being aligned on this other side itself, these inclusions are being aligned like this, which is parallel to the head based on this torque direction and these are perpendicular to the shaft axis. So, we have the inclusions aligned in different ways along the shaft and along the head. So, so far is fine, it will not have caused a problem in case there was no load applied to this.

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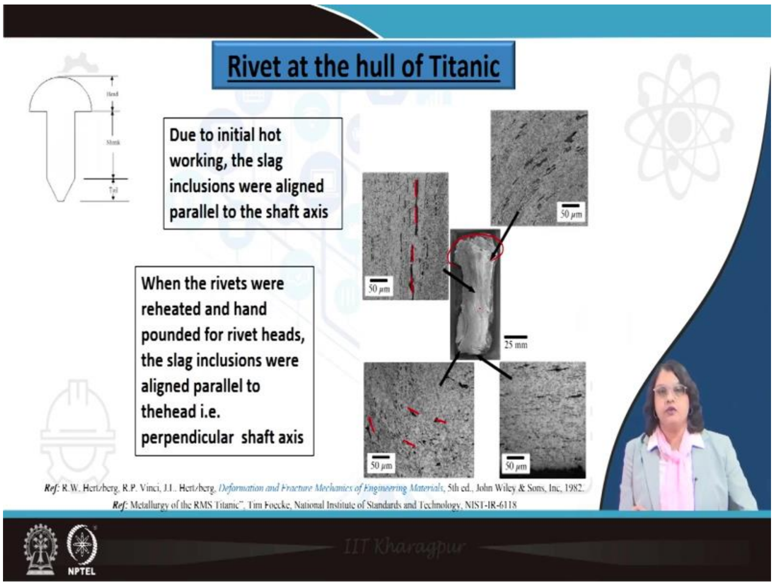

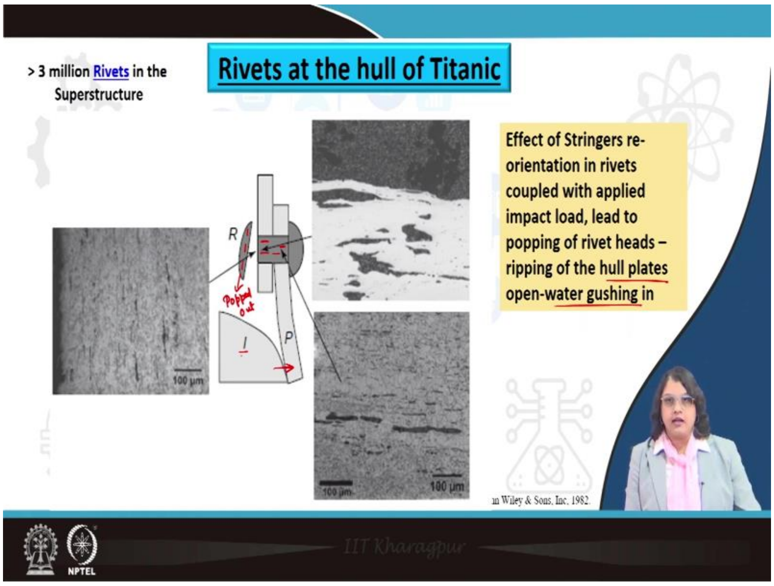

Now, what happens is when it hits the iceberg. So, this is the example how the inclusions are aligned along the shaft axis perpendicular to the head and along the head however, these are aligned perpendicular to the shaft axis. So, this is what we can understand from here. Now, this would not have been a problem this difference in the alignment of the stringers on the shaft or on the head would not have been a problem. In case there was no load applied, but, when the iceberg hit the ship, there has been a different kind of scenario completely different. And let us look into that in more detail.

So, this is the iceberg here, and when it hits the ship hull plates and it applies the tensile stress along this direction. Now, we will see the stringers which are located parallel to the shaft axis is fine, we know that the stringers which are oriented parallel to the loading direction is fine. The problem is the one which is oriented perpendicular to the loading direction this was the head that we are that they have mounted and that lead to the stringers oriented parallel to the head, but perpendicular to the shaft axis which means perpendicular to the loading direction.

And as a result, cracks is easily generated on those and that leads to popping out of the rivet heads. So, that actually led to the opening of the hull plates and that leads to the gushing in of the water. And once, it started all the kinds of events happened in all the 5 compartments, which the iceberg has hit and as a result, water started entering into that and that led to the sinking of the entire ship.

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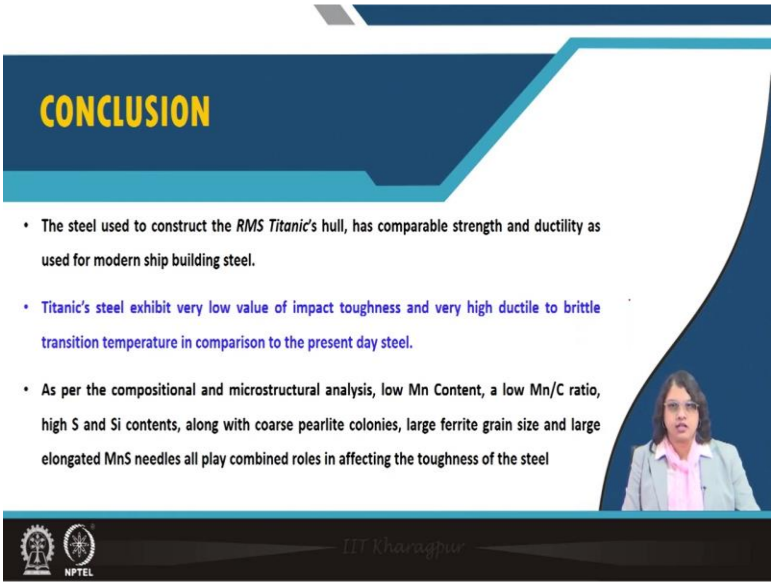

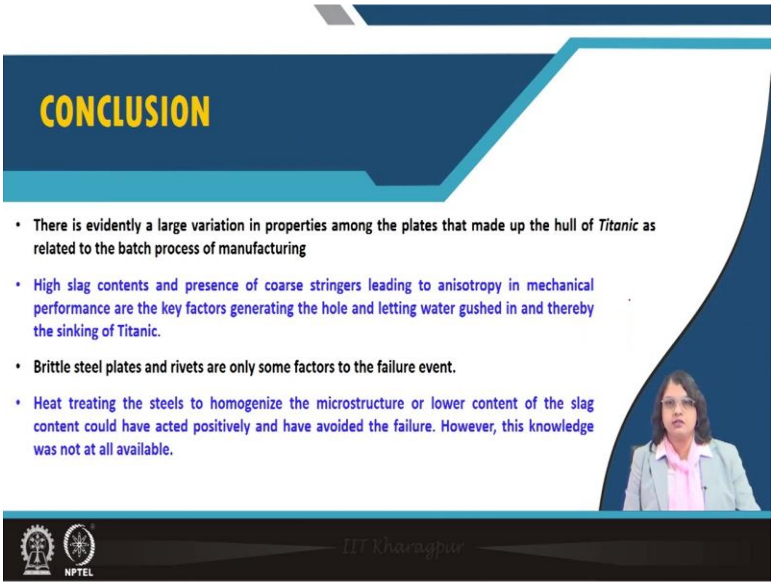

So, let us conclude this event that the steel used to construct the royal man ship Titanic hull has comparable strength and ductility as used for the modern shipbuilding steel. So, there was no issue with the quality of the steel as far as we are talking only about the mechanical properties based on the strength and ductility. Titanic steel exhibit very low value of impact toughness and very high ductile to brittle transition temperature as high as 50 to 60 °C, whereas, the one that is used for the present-day steel is around minus 27 °C. The iceberg water was around a minus 2 °C, which made it fail in a brutal fashion quite easily.

As for the compositional microstructure analysis, we have seen that low manganese content, low manganese is to carbon ratio, high sulfur and silicon contents, along with the coarse pearlite colonies, large ferrite grain size and large elongated manganese sulfide needles all play a combined roles in affecting the toughness of the steel. So, this is there is not one factor that we can pinpoint all those acted simultaneously and led to the catastrophic event to occur. So, there is evidently a large variation in properties among the plates that has been well studied for the failure analysis and that means that the ones that has been used for the actual making of the Titanic must have a significant scattered significant variability in the properties.

And that are all related to the batch process of manufacturing. High slag contains and presence of coarse stringers leading to anisotropy in mechanical performance are the key factors, generating the hole and letting water gushed in and thereby, the sinking of Titanic. And brittle steel plates and rivets are some factors for the failure even in fact, the heat treating the Steel’s to homogenize the microstructure, that kind of concept was not available at that point. But if that has been done or the lower content of the slag, could have acted positively and have avoided the failure however, this knowledge as I mentioned was not available at that time.

And later on, it will realize that what the shipbuilding still needs to have the properties the important properties and this has been maintained so far. So, following are the references that are used for this lecture. Thank you very much.