Fracture, Fatigue and Failures of Materials
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Lecture 58
Failure Analysis – Case Study – Comet

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Hello everyone. We are at the 58th lecture of the course Fracture, Fatigue and Failure of Materials. As we have come towards the end of this course, let us discuss one more on a case study which is the air crash of Comet aircraft.

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So, the following topics will be covered in this. First of all, I would like to highlight what is the significance of Haviland De Comet in Aviation industry. Actually, this particular aircraft company played a lead role in modifying the aviation industries in the way that we are seeing it today. So, please fasten your seat belt and let us have an exciting lecture on this particular case study.

So, we will talk initially about the early years and how this comet aircrafts are different from the others and then we will slowly move on to the air crash incidence that has happened and of course the failure analysis which is the main purpose of this course and this particular lecture and from there we will also see that what are the new insights that are developed from this case study.

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So, let us talk about the comet aircraft which as you can see here this is the newest fastest airliner in the world that was at the time of launching it in 1950s early 1950s. So, basically the design work of this comet aircraft started on the late 1940s and it actually marks the beginning of Jet era and stunned the world with its design intricacies.

In fact, the design of comet aircrafts was very similar to the modern aircrafts that we use on these days. You can see this is of course a simulated image of the comet aircraft and you can see that how sleek the design is in comparison to the propeller driven aircraft which were very common at those days in 1950s.

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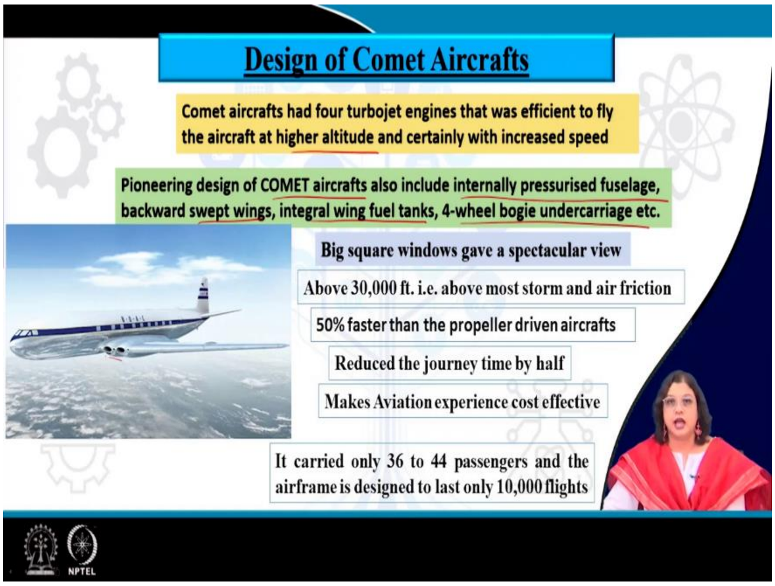

So, comet aircraft had four turbojet engines that was efficient to fly the aircraft at higher altitude and certainly with increased speed. So, that was the main key point for the comet aircraft that this one is the first one to use the turbojet engines that we use these days. So, you can see the engines here two on this side and two on the other side of the wing where there are the four turbo jet engines are located.

So, the pioneering design of comet aircrafts also include internally pressurized fuselage. Now this aircraft based on this turbo jet engine application it is capable of flying at much higher altitude as mentioned here and obviously flying at higher altitude at one point will give more speed because the friction from the air or the storms are much lesser and at the same time this will also have some issues with the pressurization of the cabin, so that the passengers who are using that should be in comfort.

So, for that the design of comet was also pioneer in including the internally pressurized fuselage which was not very common for the propeller driven aircraft at those days. It also had backward swept wings, integral wing fuel tanks and four-wheel bogie undercarriage etcetera. So, in all sense this comet aircraft design was marvellous and at that point it was not appearing that this is having any error in the design that may lead to fracture.

It has big square windows also that give a spectacular view to the passengers while they are on travel and it can fly at a much higher altitude of around 30,000 feet which is above the storm and air friction. It also is capable of flying at a 50 percent higher rate than the propeller driven aircrafts and that of course has reduced the journey time by half and if that is so then that makes aviation experience also very much cost effective.

So, basically what it does is as it is flying at a much higher altitude at a much higher speed, it has a much better fuel efficiency and these are all reflected in reducing the cost for the tickets and so journey or this aviation was actually get very much common to the common people. So, this comet aircrafts initially were meant to carry around 36 to 44 passengers and the airframe is designed to last for about 10,000 flights.

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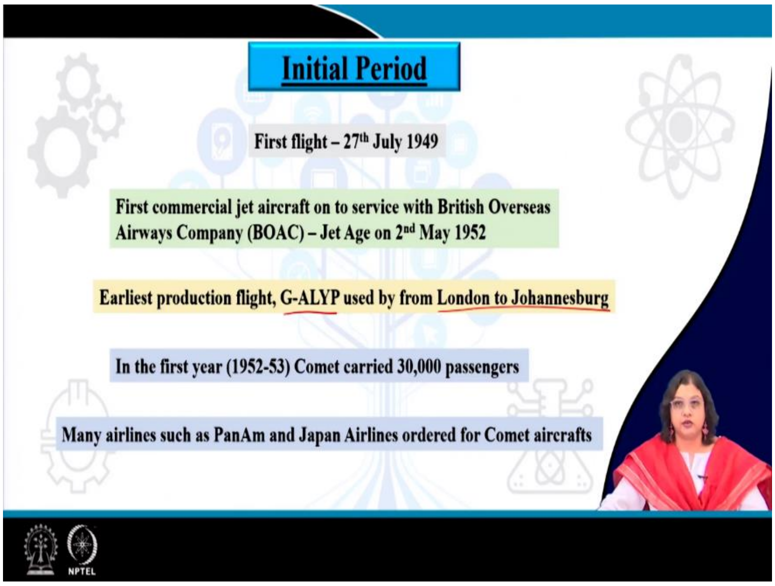

So, during the initial period, first flight which was an experimental trip was started on 27th July 1949 but actually it has been used as a first commercial jet aircraft on the service with British Overseas Airways Company or BOAC as it is popularly known as and the beginning of the jet age has started on 2nd of May 1952.

So, the earliest production flight which is named as, so this is the nomenclature that they used G-ALYP that is used by the BOAC for the travel from London to Johannesburg. So, such a huge distance has been covered by this aircraft and in the first year so within this span of 1952-

53 comet aircrafts carried around 30,000 passengers worldwide and many airlines such as the PanAm, Japan Airlines amongst others ordered for several of the comet aircrafts.

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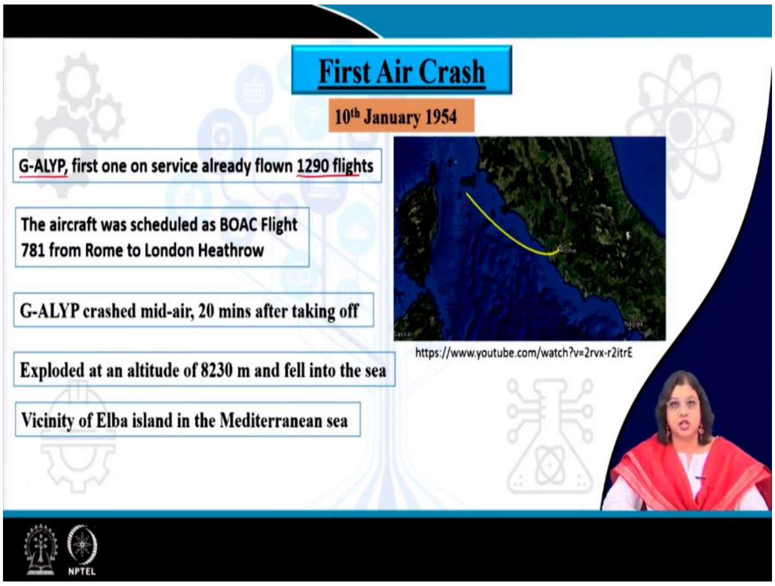

Now, the first air crash that has happened is not very late that is just in 1954, 10th of January. So, that means almost like two and a half years in service and then suddenly there was the first air crash that was noted.

So, initially of course it was thought that there was nothing wrong in the design for the first 2.5 years there was no complaint and it served really well as you can see that many of the companies, airline companies were actually very much interested to buy more aircraft to recruit in their crew but suddenly everything has come to a standstill when the first incident happened on 10th of January, 1954.

So, again the first aircraft that was used that one only failed or had an air crash after 1290 flights. So, that means that this was the 1291st flight for this particular aircraft when the crash happened. The aircraft was scheduled as BOAC flight 781 from Rome to Heathrow and it crashed mid-air 20 minutes after taking off. Actually, it exploded at an altitude of 8000 meter and fell into the sea in the vicinity of Elba island in the Mediterranean Sea.

So, you can see the position where it has actually crashed and it landed on the water actually, there were no evidence that what has happened only there were some fishermen who saw that something has crashed and fell into the water.

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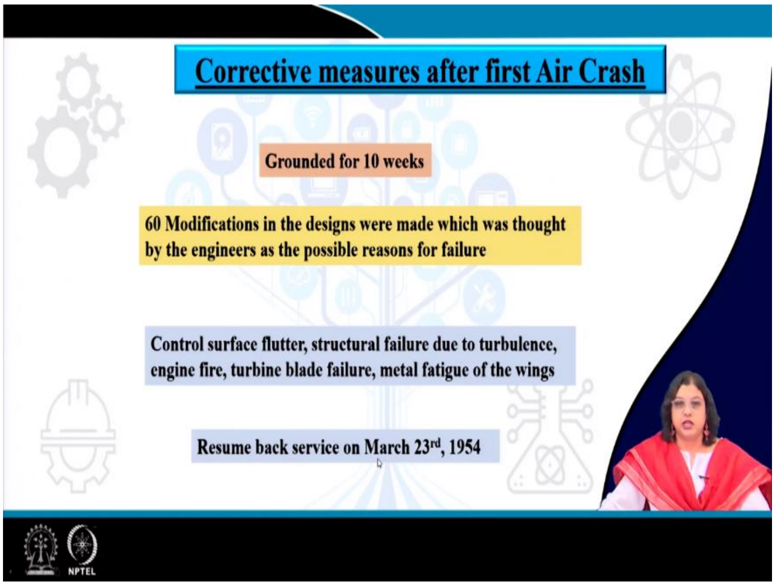

So, following that some corrective measures were taken. So, the aircraft companies were grounded for 10 weeks to do some detailed survey about what went wrong and they really did a detailed survey based on what could have been the possible reasons for the failure and they could come up with around 60 modifications in the designs which were implemented in the next level and then it has been used again.

So, the following modifications are some of the examples such as the control surface flutter or structural fatigue due to turbulence, engine fire, turbine blade failure or metal fatigue of the wings all those has been considered and checked and after that it resumed back a service on March 23, 1954.

So, so far everything seemed fine they have performed a detailed analysis and as much as the knowledge that was available at that time and based on very limited information about the crash because there were no evidence, it just went inside the sea so it was very difficult to get the wreckage also and within 10 weeks they have done the best possible thing and it has resumed packet service on March 23, 1954.

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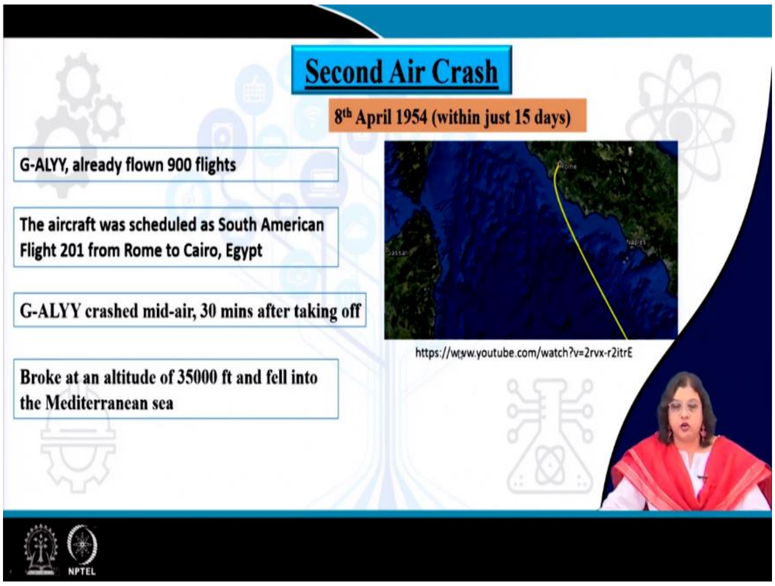

And then the second air crash happened very unfortunately within just 15 days of after it is resuming its service back. So, it happened on 8th of April 1954. There was another aircraft this time its nomenclature was G-ALYY which has already flown 900 flights, this was scheduled as a South American flight 201 from Rome to Cairo, Egypt and on the way after just 30 minutes of taking off it just crashed mid-air once again broke at an altitude of 35,000 feet and failed again on the Mediterranean Sea. As you can see here the position where it crashed and once again it everything has went inside and all the passengers and the crew members were all dead.

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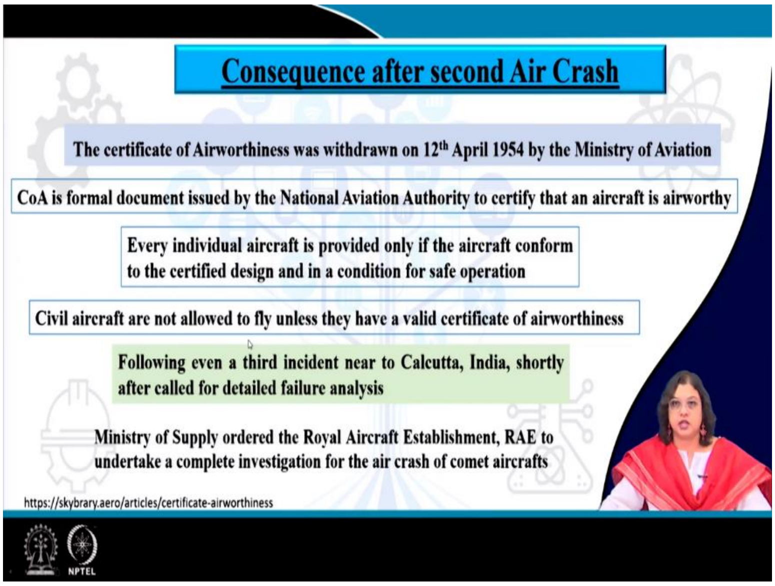

So, these two air crashes has actually shook the nation once again because this is not something that we will look forward to. There should be always an improvement in the design to make things more and more user friendly but at the same time there should not be any compromise on the safety.

So, after the second air crash the certificate of Airworthiness was withdrawn from them by the ministry of aviation and if you are wondering what is the certificate of airworthiness, here it is the certificate of Airworthiness is basically a formal document which is issued by the National Aviation Authority to certify that an aircraft is airworthy.

Now what is airworthy? Basically, every individual aircraft has to get those kind of certificates and that is issued based on the design and the condition for safe operation, so that kind of guarantees that this particular aircraft is suitable for using as an for the aviation. So, civil aircraft are not allowed to fly unless they have a valid certificate of airworthiness.

Of course, after this there were comment, organization was very very careful and at the same time very much concerned about the incident and even at that time there was a third incident that happened over Calcutta, India and shortly after this second incident and that called for a detailed failure analysis.

The ministry of supply ordered the Royal Aircraft Establishment commonly known as RAE to undertake a complete investigation for the air crash of comet aircrafts and a series of investigations has been performed.

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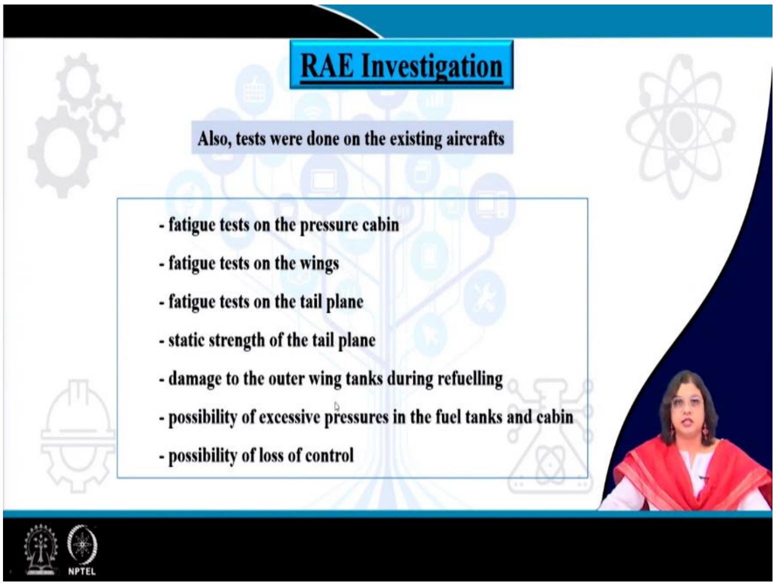

So, let us see what has been done. So, tests were done on the existing aircrafts one which are already there and which has not undergone any crash and for those fatigue tests were done on the pressure cabin, on the wings and as well as on the tail plane, static strength of the tail plane was also determined damage to the outer wing tanks during refilling has been considered, possibility for excessive pressures in the fuel tanks and cable has been also considered and tasted and possibilities for loss of control has also been tested.

So, actually blindly many of the investigations has been done since not much information was available at that moment considering the fact that most of the wreckage could not be recovered but they have a constant effort also to recover the wreckage and initially some experiments and testings were done on the existing aircraft and this were also accompanied by the investigation on the wreckage which were discovered later.

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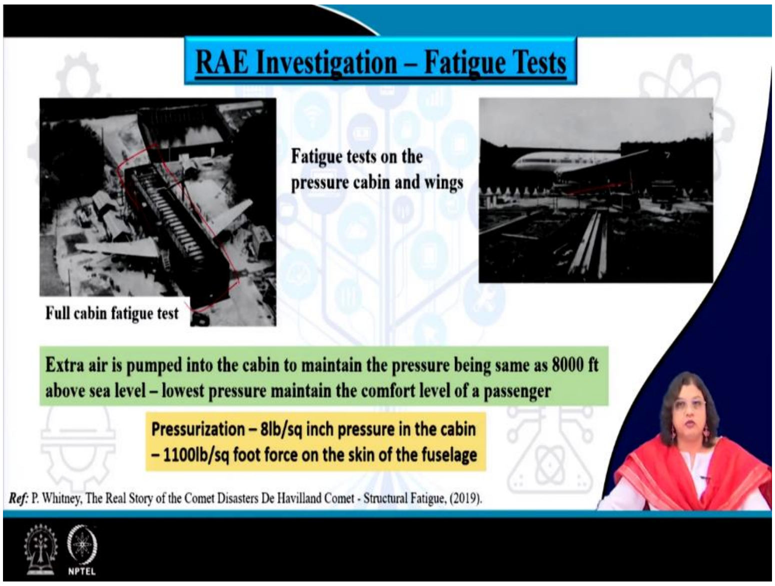

So, fatigue test on the pressure came in and wings were initially done at the very first place. So, you can see that this is an entire aircraft which is under testing for the wing so in this picture you can see that the wings are under testing and this one is for the full cabin fatigue test. So, the entire cabin has been enclosed in some structure to perform the fatigue test of this.

So, I will elaborate on how this test has been done. So, typically extra air is pumped into the cabin to maintain the pressure which is almost like 8,000 feet above the sea level whatever the pressure would be similar kind of pressure has been maintained.

So, this is actually the lowest pressure that is maintained based on the comfort level of a passenger and this kind of pressurization actually leads to around 8 pound per square inch of pressure in the cabin which is equivalent to 1100 pound per square foot on the skin of the fuselage.

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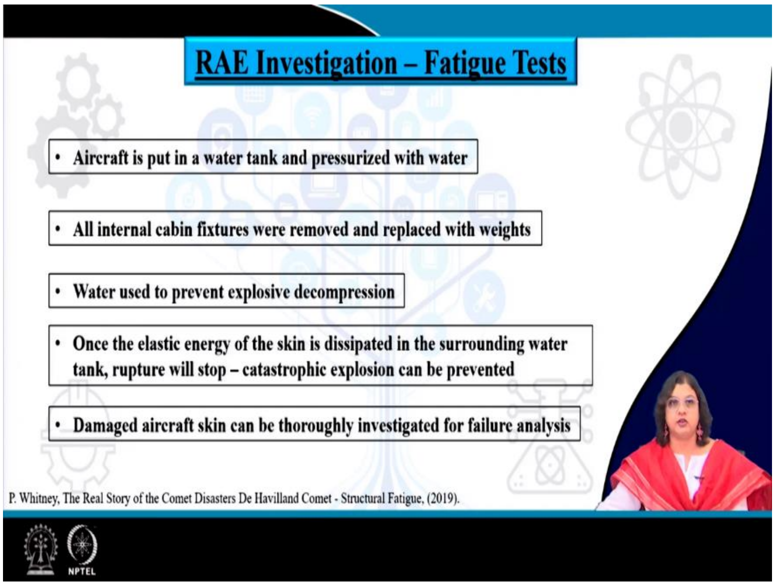

And the aircraft is also put in a water tank and pressurized with water, so another effort, this is the way by which the aircraft is put in a water tank and pressurized with water all the internal cabin fixtures were removed and replaced with weights and water is used to prevent the explosive decompression.

So, what happens is that repeated pressurization and depressurizations are being done and in case there is any crack or defect or weak locations arise once the elastic energy of that particular defect is getting released in the surrounding water, rupture will not occur because water basically can be compressed to the maximum level. There is no change and as a result the catastrophic explosion can be prevented.

Now you may worry that why the catastrophic explosion needs to be prevented? First of all for the safety of the entire locality and not only that it will actually have help to keep the fuselage intact and that will help us or help them to investigate further about what actually is the location of defect, the initiation of crack or defect that led to the final fracture. So, damaged aircraft skin can be thoroughly investigated for failure analysis which has been of course done.

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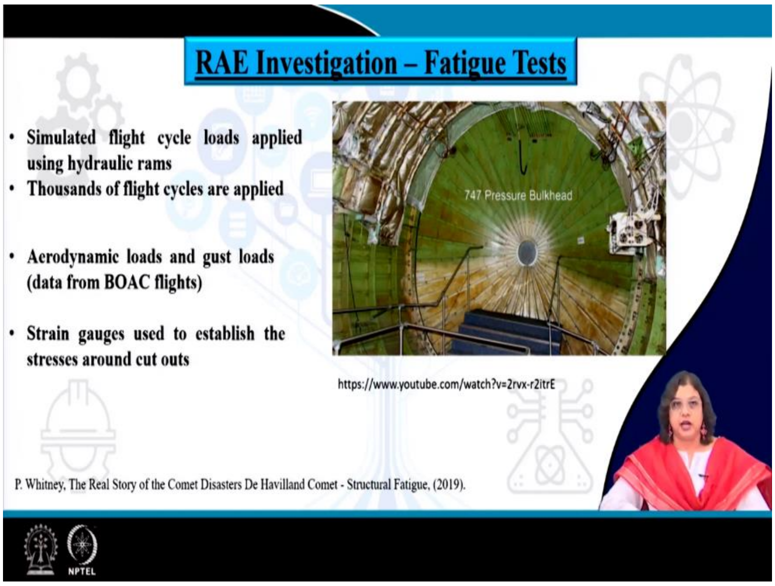

And there were some simulations also which were done. So, the flight cycle loads were applied using hydraulic rams and similar kind of loads were used as which were used for the service. Thousands of light cycles are actually applied and the aerodynamic loads and gust loads are obtained from the data of the BOAC flights and the same kind of stress levels are being applied and there are strain gauges which is used to determine the stresses and the strains around the cut outs or around different locations.

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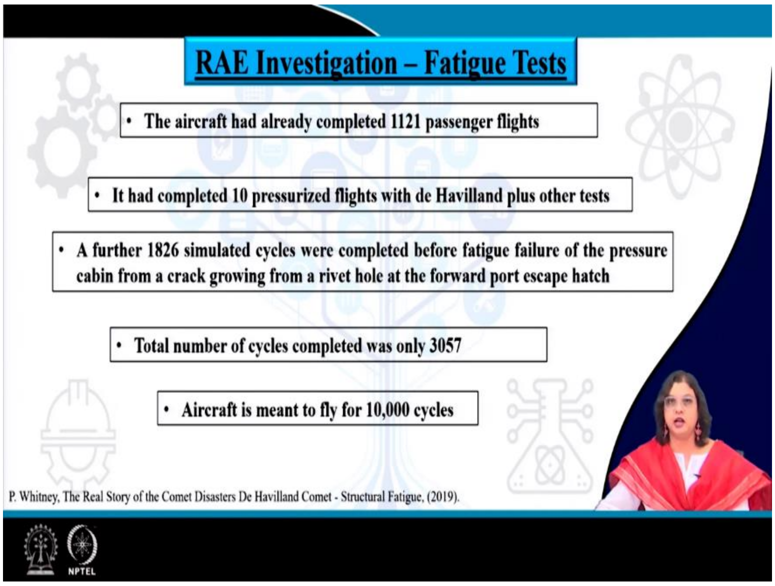

Now what they found is that, the initial known fact was that the aircraft had already completed 1121 passenger flights, the one which has been tested. It has also completed 10 pressurized flights with de Haviland plus other kind of tests initially. And during this kind of simulation based test it has survived for 1826 number of cycles, so as a result as a whole you can see that the total number of cycles, so cycles means number of flights. So, it can survive for only up to 3057 number of flights or number of cycles.

Now all the comet aircrafts as per the design criteria they are capable of flying up to 10,000 cycles which of course have not had met by this particular one which has been tested, it has failed only up after 3000 cycles.

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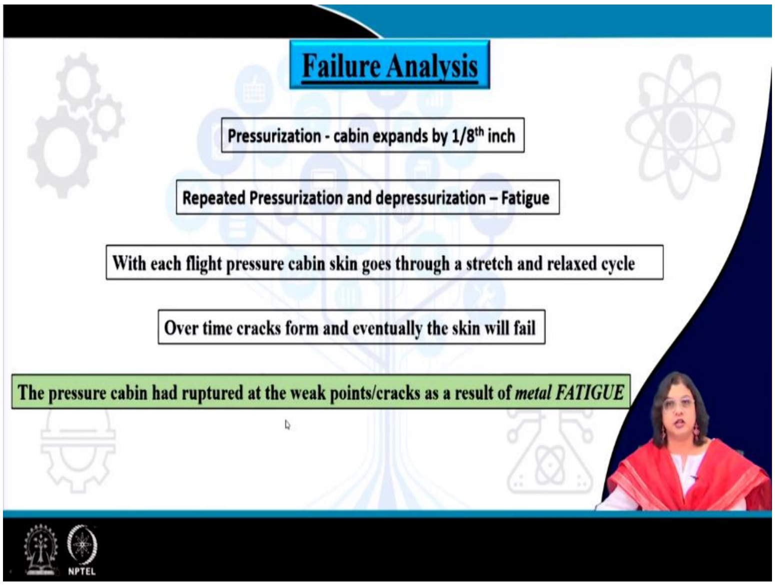

Now what could be the possible reason? Actually during the pressurization the cabin expands like a balloon of course it is a metal one so it will not expand like the rubber balloon but it still expands by about one eighth of an inch and of course during the depressurization so when the pressure is being removed, let us say during the landing or when it is at the lower amplitude, at that point it is this kind of expansion is coming back to the 0 level.

So, repeated pressurization and depressurization calls for a fatigue and with each flight pressure cabin skin goes through a stretch and relaxed cycle. Of course, this is not a very good situation because anything that undergoes such kind of repeated stress or strain hysteresis will lead to early initiation of fatigue crack, as we have seen particularly for the low cycle fatigue case which is under strain control thing so this one is also there is a variation in the total volume and then again it is coming back to the relaxation cycle and keep on continuing there.

So, over time cracks are bound to form and that will eventually let the skin fail and if the skin of the aircraft fails of course that will lead to a catastrophic failure. The pressure cabin had ruptured at the weak points or cracks as a result of metal fatigue. So, this is what has been determined from this thorough investigation.

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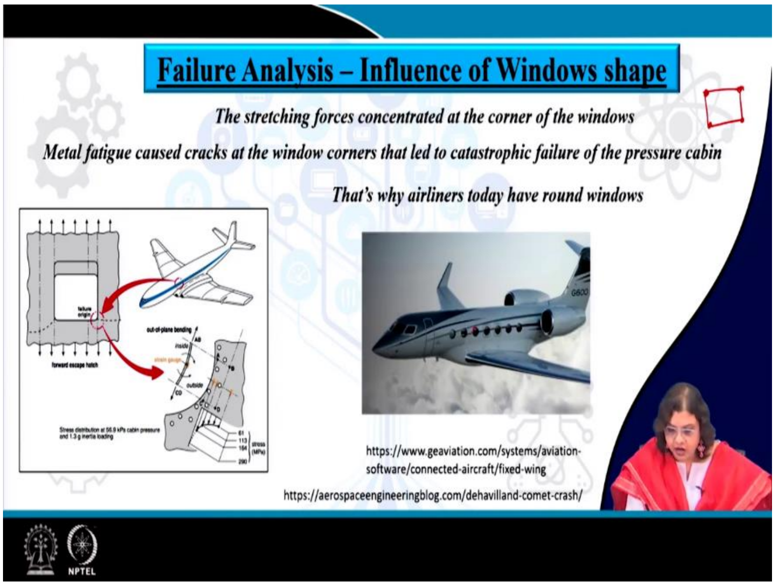

Now they have also realized that when such kind of experiments has been performed, the cracks has to initiate from some location and in most of the cases they have seen that the stretching forces concentrated at the corner of the windows.

Now please note the windows that are being used in such planes, as mentioned earlier are square windows the like the typical shape of the doors and windows that we use for any place. So, similar kind of square windows were used there also and due to the repeated pressurization and depressurization such corner of the windows which are the source for stress concentration. So, if we have a square structure of course these are the locations which are having higher stress concentration and that may lead to early initiation of crack.

So, that is exactly what has happened and they have done a detailed analysis of the stress distribution at the different parts and have come to the conclusion that the window corners are the one that has initiated the cracks and that is one of the very good reason that why the airliners today have round windows. As you can see here the windows are either round or oval but not square anymore. So, they have learned it through a very hard lesson that the square window should not be used.

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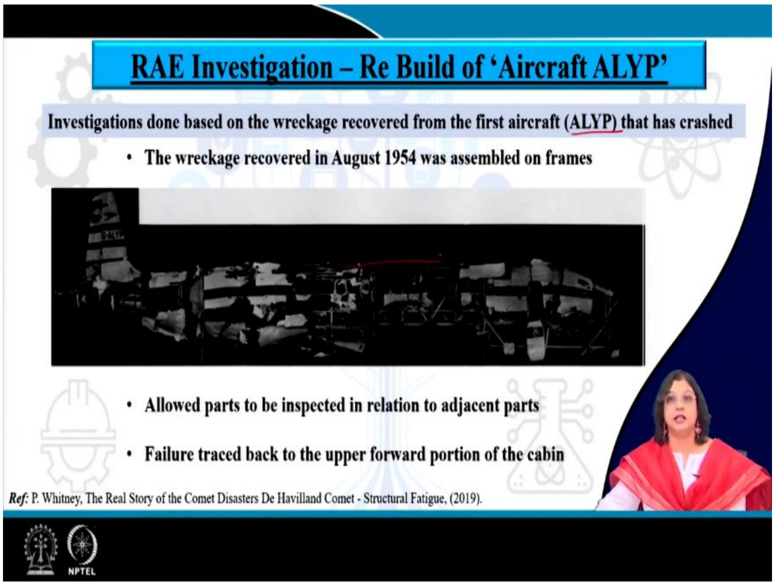

Now that was the investigation that was done based on the available aircraft through the lab scale experiments. On the other hand, investigations were also done based on the wreckage recovered from the first aircraft that has crashed. Now out of all the crashes this one for this particular one which was actually the first aircraft A-LYP for that major part of the wreckage could be recovered and that is the reason that they have performed a detailed analysis of what went wrong.

The wreckage was recovered in August 1954, so a few months after the actual incident and they were assembled on frames. You can see how the entire the aircraft structure has been tried to be filled up with the wreckage that have been obtained. Of course, many of the parts could not be filled up because those were not obtained from the sea.

So, this actually led to have a very good way of investigating that not only what went wrong but also which part actually is the one which led to certain kind of failure. So, all the parts has been very carefully analysed and based on the fracture surface or any other kind of investigation they can understand that which part of the aircraft does it belonged to and what would have been the stress level at that particular location.

So, failure traced back to the upper forward portion of the cabin that is when where it might have started in the actual incident.

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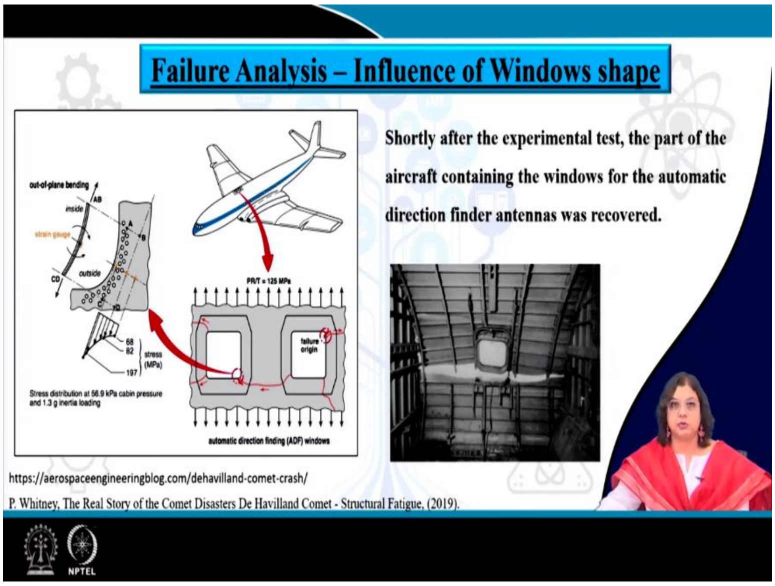

Now shortly after the experimental test, the part of the aircraft containing the windows for the automatic direction finder antennas was recovered and they have again found this from the wreckage and they have realized again did all the calculations to understand that how the failure has initiated from the corner. You can see the failure origins has been marked here, so this is directly from the wreckage and that kind of matches with what they have obtained from the investigation based on the experiments.

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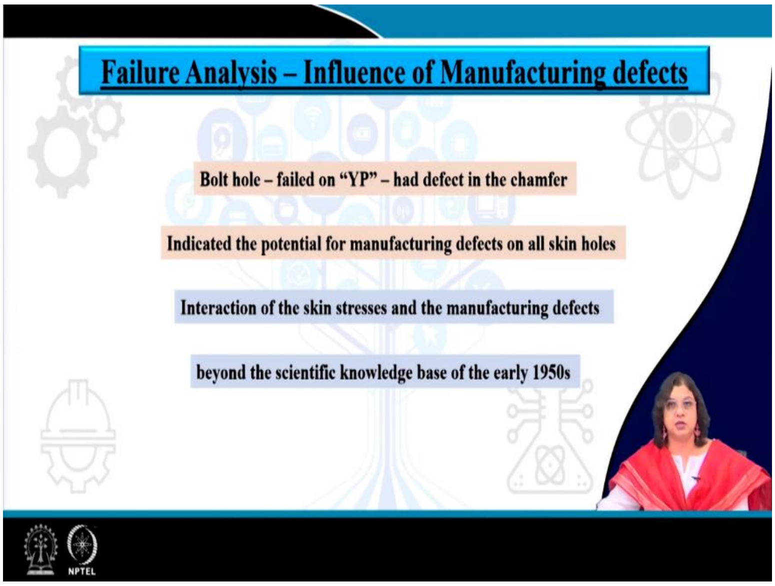

Apart from that there is something else also that were had made a significant impact on the failure analysis. What they found is that the bolt hole failed on this aircraft and that had a defect in the chamfer. So, this indicated the potential for manufacturing defects on all the skin holes.

So, wherever they have holes those are mostly from the rivets that are used for joining plates, so they have actually used both kind of joining the welding and the rivets but it is the rivet holes or the cracks that has been generated while punching the rivets that could be actually a possible reason that is what was thought at the time of the investigation from the wreckage.

So, interaction of the skin stresses and the manufacturing defects for what has been concerned and that however was beyond the scientific knowledge based on the early 1950s.

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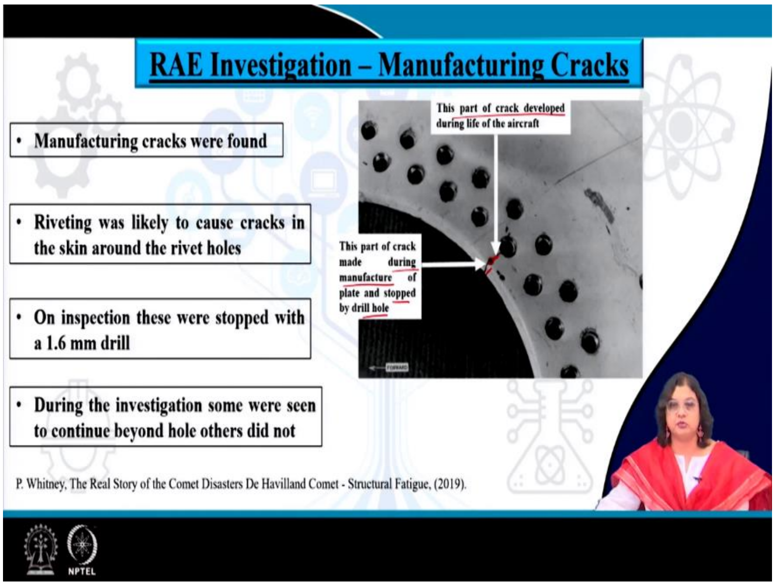

And what they could understood from the detailed study is that, so some part of the hole that has been punched that lead to formation of a crack during the manufacturing process itself and that could have been stopped by drilling a hole. However, you can see that this part of the crack developed during the life of the aircraft.

So, if there is any kind of manufacturing defect already existing and then with the repeated pressurization and depressurization that kind of crack is bound to expand or increase in length as per the fatigue and that may lead to the failure of the entire aircraft. So, this manufacturing defects were located and noted and riveting was likely to cause cracks in the skin around the rivet holes that were found and an inspection this was topped with a 1.6 millimetre drill as you can see here.

However, during the investigation some were seen to continue beyond the hole while some others, do not. So, we never know that how these defects will actually behave in presence of repeated pressurization and depressurization but certainly such defects are the source from which the crack might have initiated and led to the catastrophic failure.

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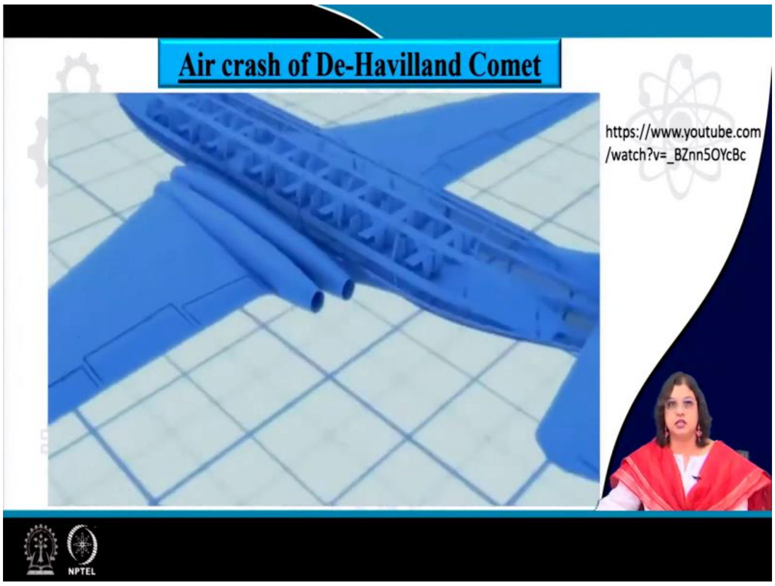

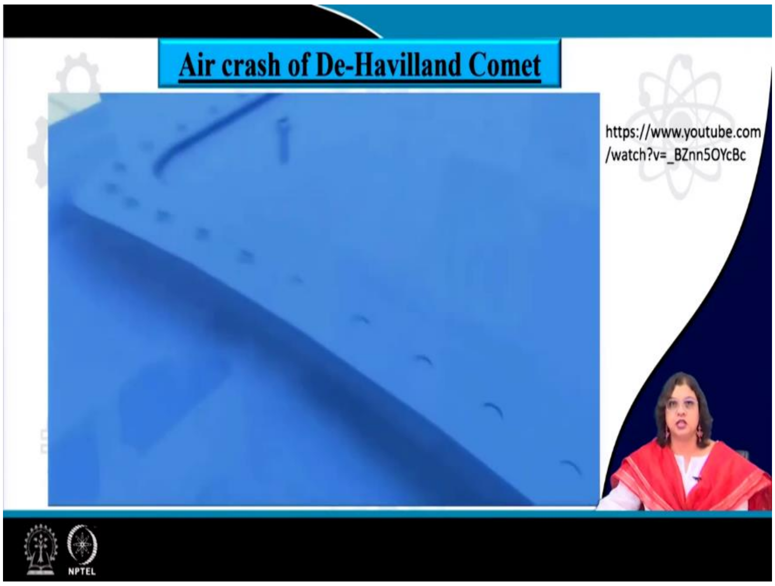


Air crash of De-Havilland Comet
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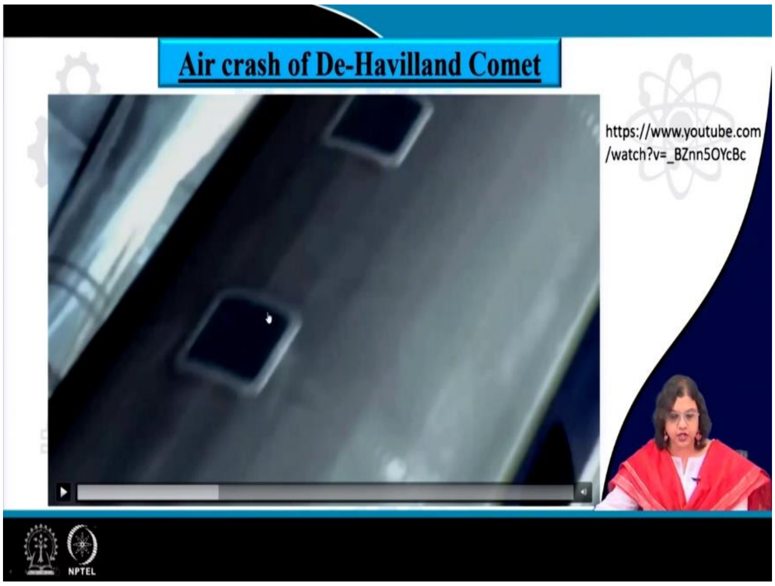
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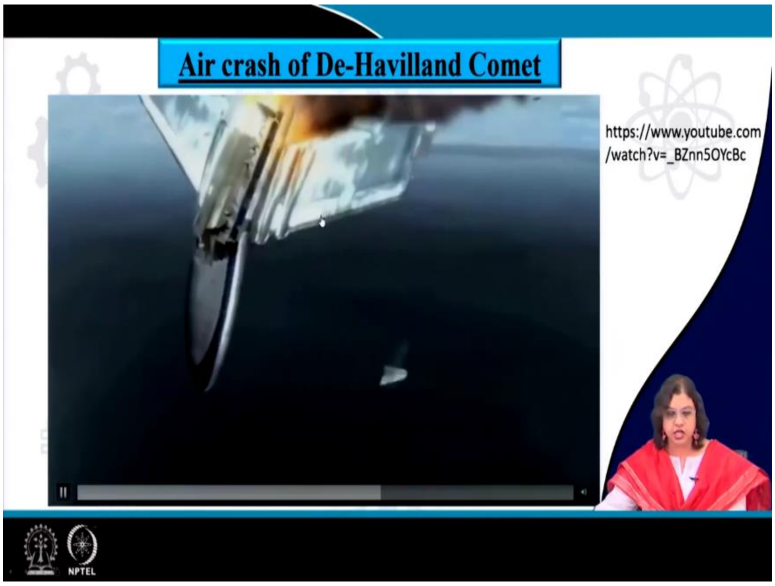
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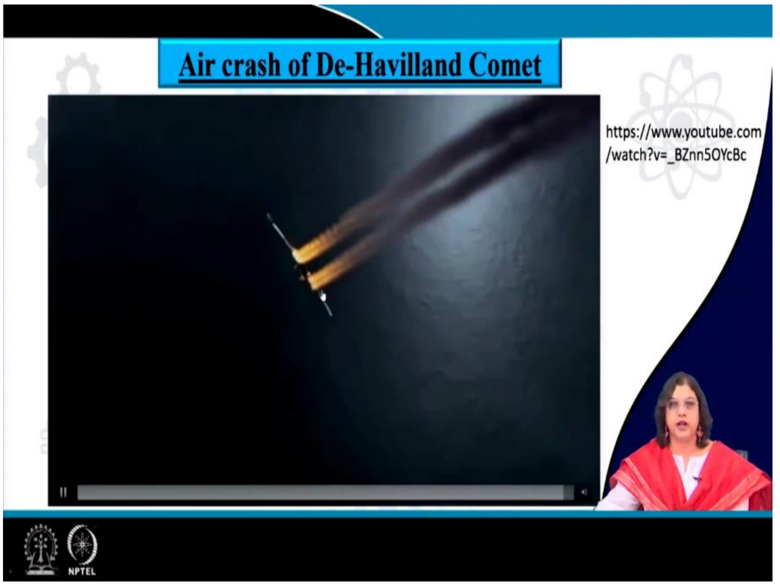

So, this can be well understood from these videos, you can see that these are again the simulated videos and the thin aluminium skin which is really really very thin just to have pressure saving and you can see that the rivet while punching may form some defects there.

Now there are repeated pressurization and depressurization as we have discussed and with this the cracks are bound to get extended and it has been again simulated that how the failure has happened and of course the defects if propagated may lead to fractures.

So, if we look into this structure you have to carefully note about these windows and you will see that how the fracture has actually happened or started from this part. We have also seen this from the wreckage that they have recovered these windows are the one that has been recovered and all the stress analysis has been done on these corners.

So, let us look into this the crack has been expanded and you can see the mid portion is the one that has been initially flown off and then the tail one and finally the entire aircraft has already crashed and fell down into the sea.

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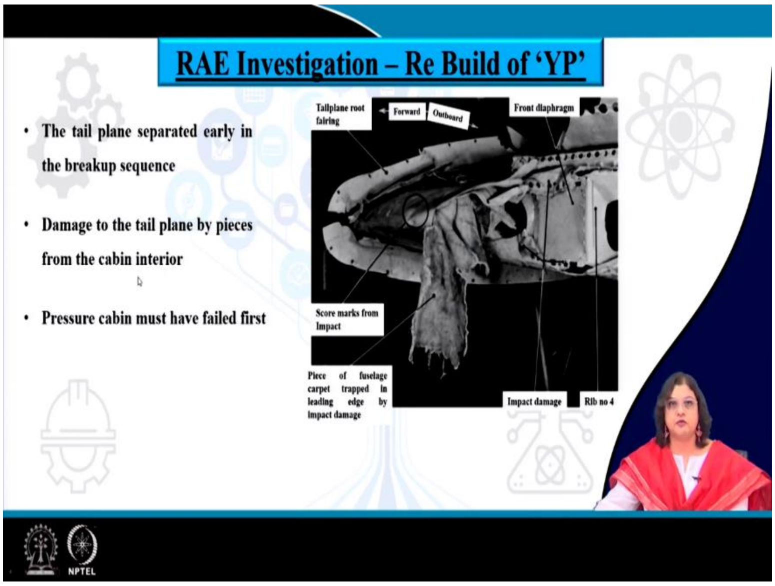

So, all the structures, all the parts as recovered from the wreckage you can see that they have been arranged and the tail plane were separated early in the breakup sequence and this damage on the tail plane is by the pieces form and the cabin interior you can see the carpets also hanging here got stuck actually and the pressure cabin must have been failed first which is what we have noted from the video also.

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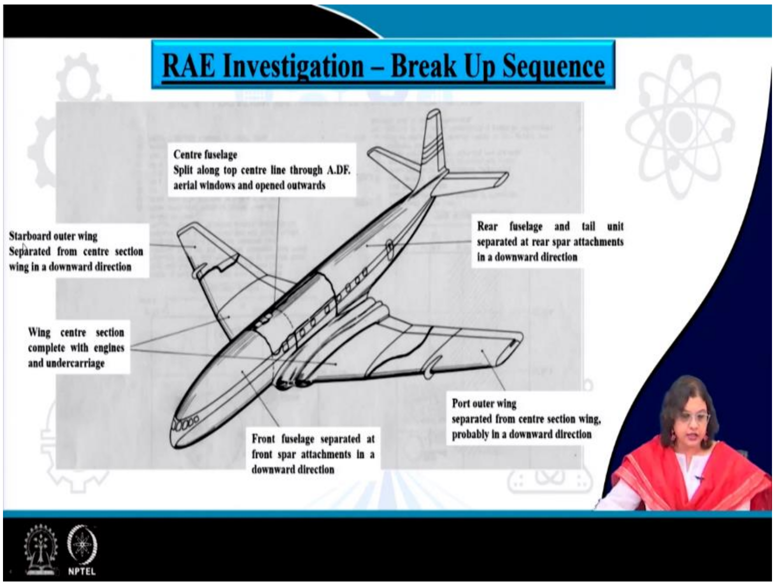

So, this is the sequence of the failure that has happened the centre fuselage. So, this part here with the top windows that split along the top centre line and the aerial windows had open outwards and then the starboard outer wing separated from the centre section wing in the downward direction and wing centre section complete with engines and undercarriage and the front fuselage separated at front spar attachment in a downward direction and all the other part also has failed in a similar fashion and that led to the catastrophic failure.

So, it is just the matter of one small crack that can extend at one particular cycle of light that may lead to the entire catastrophic fracture. So, that means that any such kind of cracks that might have generated during the operation needs to be very carefully and closely monitored.

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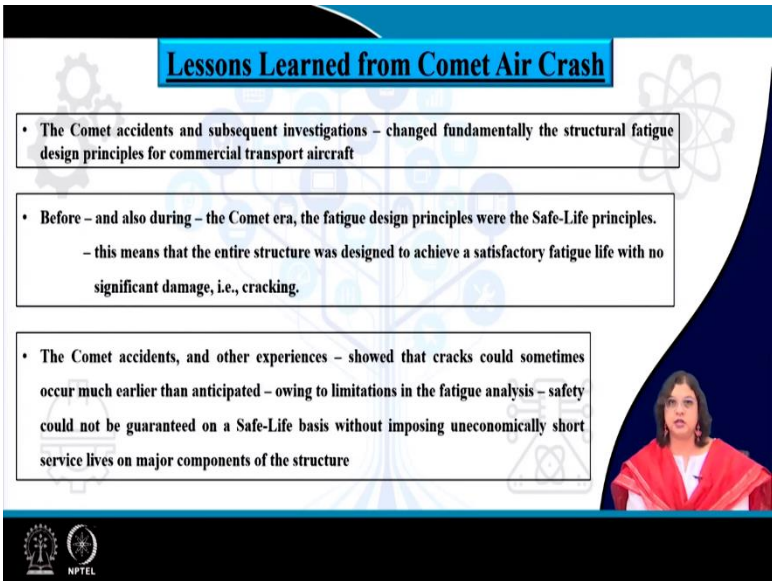

So, whatever lessons that has been learned from the comet air crash are the following, the comet accidents and subsequent investigations they have actually changed the fundamentally understanding of the structural fatigue design principles which are should be used for commercial transport aircraft.

So, before the incident and also during the comet era the fatigue design principles were considered based on the safe life principles. We have seen that for the case of safe life, the entire structure was designed to achieve a satisfactory fatigue life with no significant damage and we apply certain factor of safety and we assume that the component of the structure is not going to fail within this time period.

The comet incidents and other experience however showed that cracks could sometimes occur much earlier than anticipated and those cracks going to limitations in the fatigue analysis often went unnoticed.

So, safety could not be guaranteed on a safe life basis without imposing the uneconomically short service lives on major component of the structure. So, if we consider the safe life approach then we really have to consider a very short time period through which we can guarantee that there will be no failure.

Now when it comes to aircraft safety is a prime concern and we cannot take any chances as you have seen that the cracks might have initiated from one small rivet hole and that lead to the fracture of the entire component.

Now at that period or at that time there was no proper ways to investigate on the formation of the crack through the repeated inspection and often such kind of small cracks are within the rivet head itself. So, it is very difficult to monitor them also, so if we are considering based on the safe life approach, the overall time period has to be maintained very very short so that even if there are cracks that may not lead to fracture at all. Of course, then it will not be economic anymore and that is not a feasible design.

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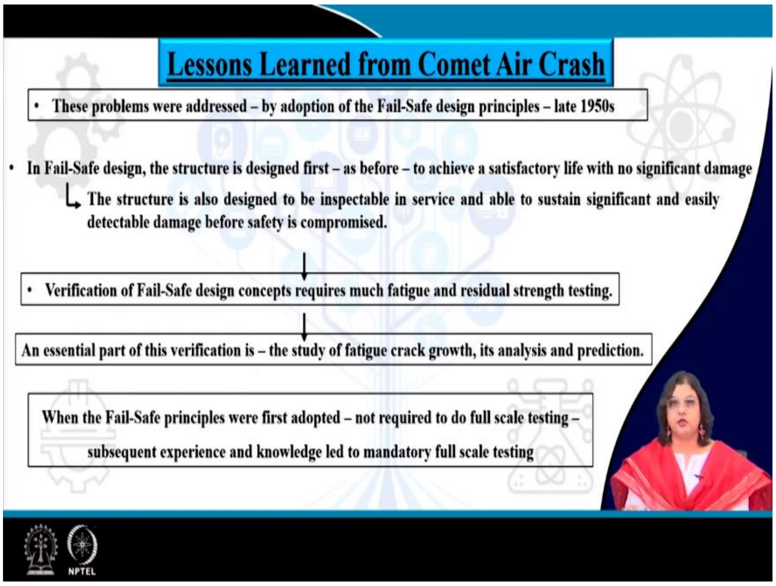

So, these problems were addressed by the adoption of Fail-Safe design in the late 1950s, in Fail-Safe design the structure is designed first as the previous one and to achieve a satisfactory life with no significant damage.

So, safe life is also maintained and then the structure is also designed to be inspectable in service and able to sustain significant and easily detectable damage before safety is compromised. So, often it is very important to detect the damage and the regular ways of inspection is not sufficient to inspect or to find out a very minor cracks of a millimetre or sub-millimetre range.

So, for that if there is any way that that kind of defect formation can be indicated that may be helpful. So, that is what is used in the modern technology. Now verification of Fail-Safe design concepts required much fatigue and residual strength testing. An essential part of this verification is to study the fatigue crack growth, its analysis and prediction.

So, even if we know that a crack has been initiated, we cannot discard the entire aircraft. We cannot retire it from service because that will be too much expensive. So, what is necessary for then is to understand that how far the crack can be grown without any catastrophic failure.

So, we can determine the life period based on the crack growth rate as we have seen how we can use the da/dN versus delta K curve, the Paris regime to understand how much cycle the crack will require to grow from a certain length to another one. And based on that we can still predict the life cycle of an aircraft for certain applications.

So, when the Fail-Safe principles were first adopted it was not required to do full scale testing. So, not the entire aircraft were being tested but subsequent experience and knowledge made it mandatory to perform a full-scale testing.

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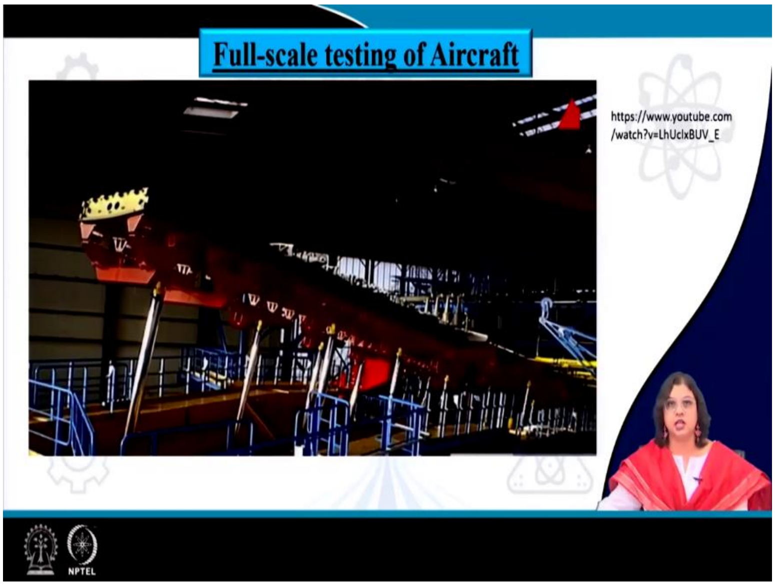

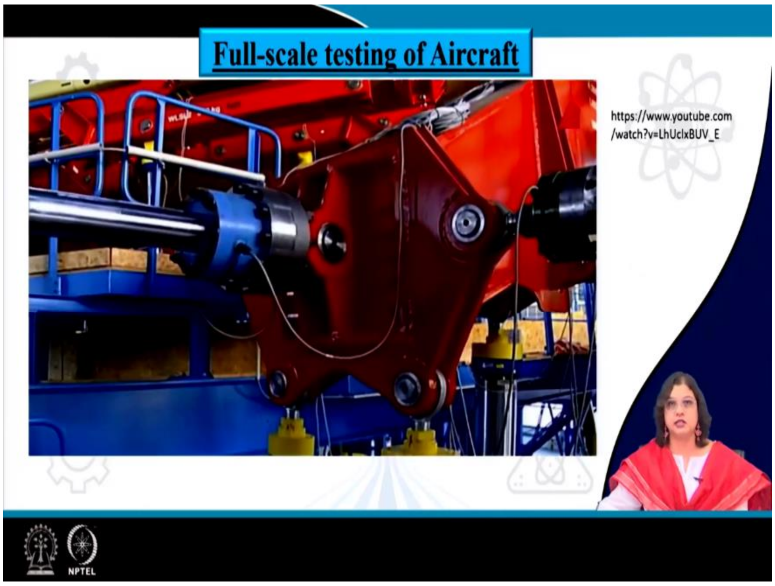

So, let us see here what I mean, you can see here that a full aircraft a total aircraft one is being tested for fatigue and all the parts, the wings and the fuselage and the engine parts and all the different parts are being tested in the service condition to understand whether it is capable of performing at those particular conditions and if it is so then for how long, for how many cycles or how many flights can be covered by this kind of aircraft.

So, this kind of robust testing techniques are being used these days so that we can have the aircraft completely safe and the next time you are boarding on an aircraft you should not worry at all.

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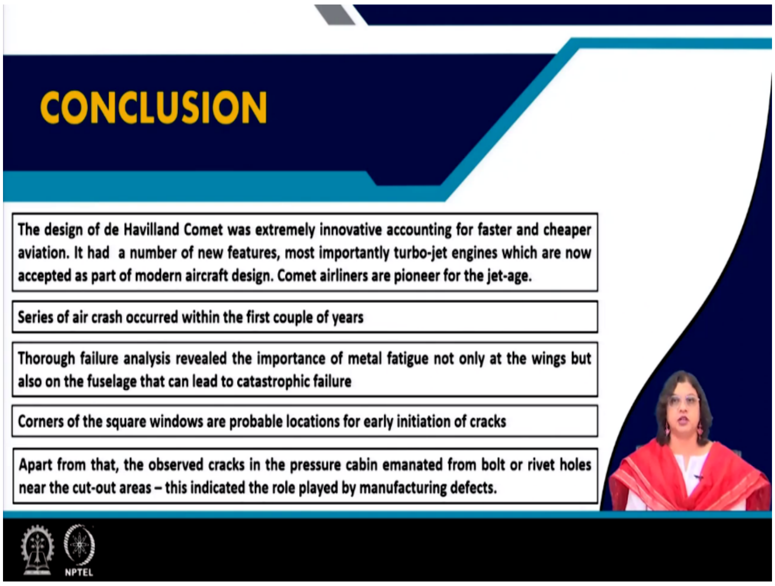

So, the conclusion of this lecture as follows, the design of de Haviland Comet was extremely innovative that accounted for faster and cheaper aviation. It had a number of new features, most importantly the turbo-jet engines which are now accepted as part of modern aircraft design.

So, comet aircraft was really pioneered in this and a series of air crash however happened within the first couple of years and thorough failure analysis has been performed based on that in those incidents and that revealed the importance of metal fatigue which can occur not only at the wings but also on the fuselage that can lead to catastrophic failure.

It has been found that corners of the square windows are the probable locations for early initiation of cracks and this has also made that for the present aircraft we use the circular or the oval windows. Apart from that it is also observed that cracks in the pressure cabin could actually generate or could start from the bolt or the rivet holes near the cut-out areas and this indicated the role played by the manufacturing defect so that also is very very important.

So, whenever we are using riveting as we have seen for the case of Titanic also, the rivets were actually there was a different problem in the case of Titanic where the heat treatment or the orientation of the inclusions was of question but in this case for the comet aircraft, we see that the defects minor cracks that has developed from the rivet holes that due to repeated pressurization and depressurization can undergo fatigue loading and that can lead to crack extension and catastrophic failure.

So, every minor thing that we are using for any structure or component has to be very very carefully designed and implemented to avoid such failure.

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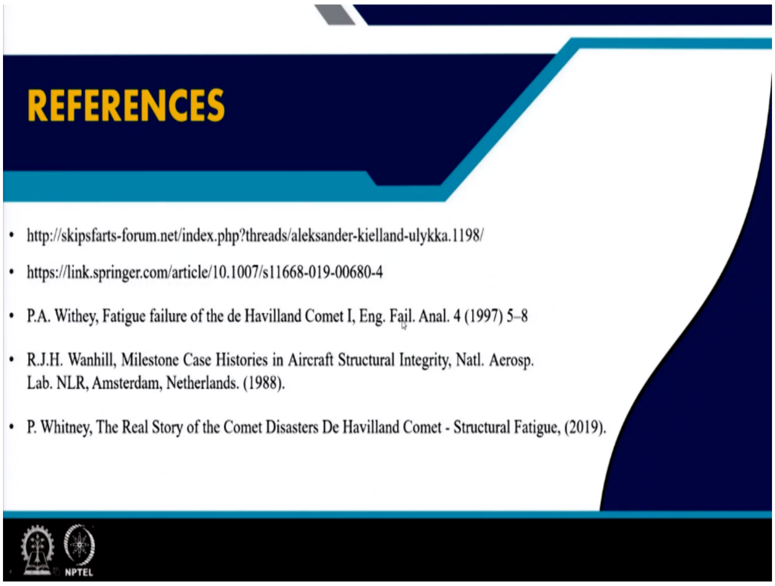

So, following are the references that has been used for this lecture. Thank you very much.