Engineering Fracture Mechanics

Prof. K. Ramesh
Department of Applied Mechanics
Indian Institute of Technology, Madras

Module No. # 01
Lecture No. # 02
Spectacular Failures

In the last class, we had seen what is the brief outline on the course on Engineering Fracture Mechanics. Then, the concepts from strength of materials were reviewed. The idea that was emphasized was, whatever the concept that you had learned, are very useful, but the knowledge you gained is limited. And, when you want to characterize the material, one of the simplest test that was done was, tension test.

The focus on the tension test was, you have an elastic region, followed by a large plastic zone, then only the material fails. But once people had moving parts in their design, like locomotive started failing, people felt a simple tension test is not sufficient to characterize the material completely. Something more needs to be done.

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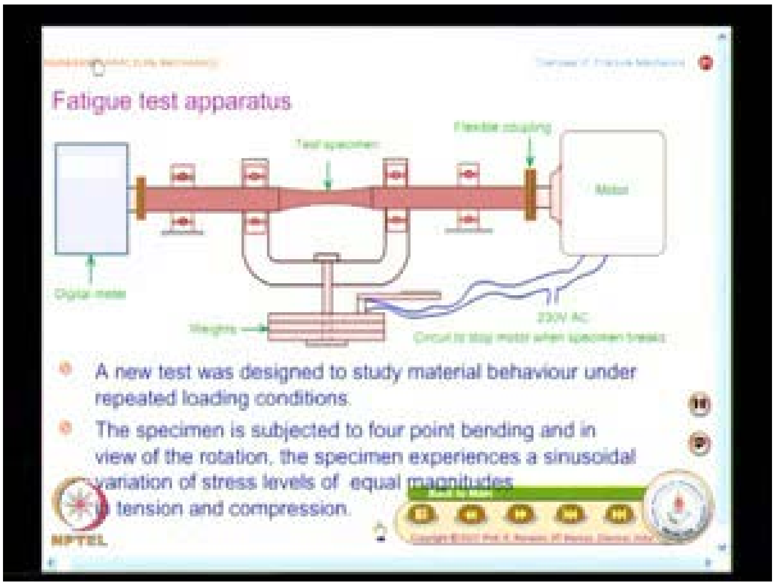

So, this prompted the use of designing a new test, what is known as a fatigue test. And we had also looked at, the focus was to find out, apply a repeated loading on the specimen and the test was confined to measuring only the number of cycles, when the test specimen fails eventually. So, you do not record any other information in between. So, it is an improvement from a simple tension test. In service condition, you have repeated loading. So, you have been able to simulate a repeated loading and also perform a test until the specimen breaks. So, you collect voluminous data and this data is presented, in a nice form, for you to process.

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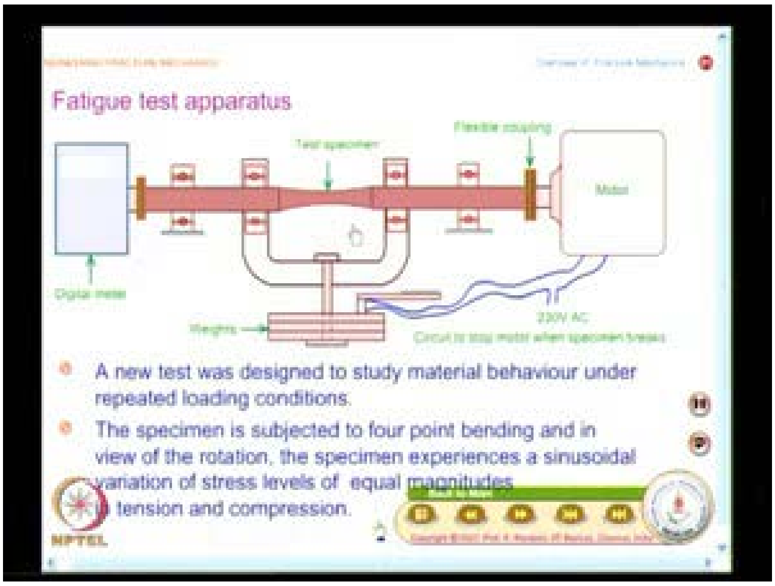

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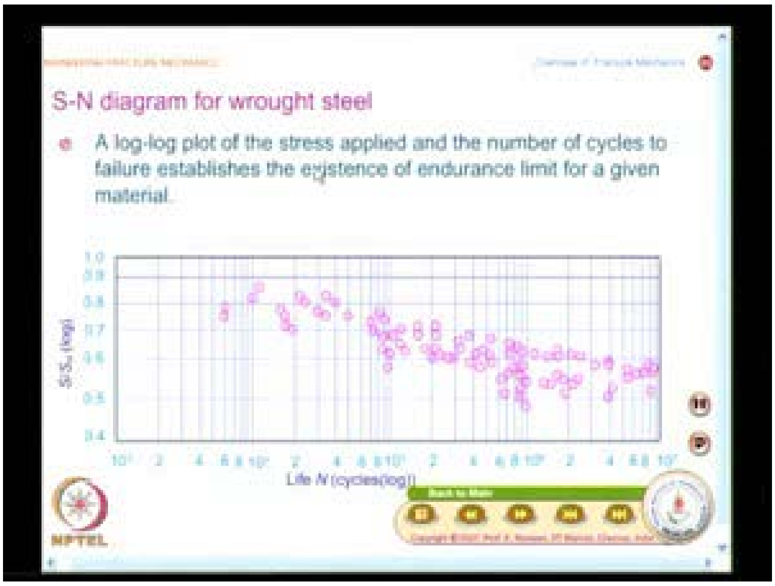

And, you have a log-log plot of the stress applied and the number of cycles to failure.

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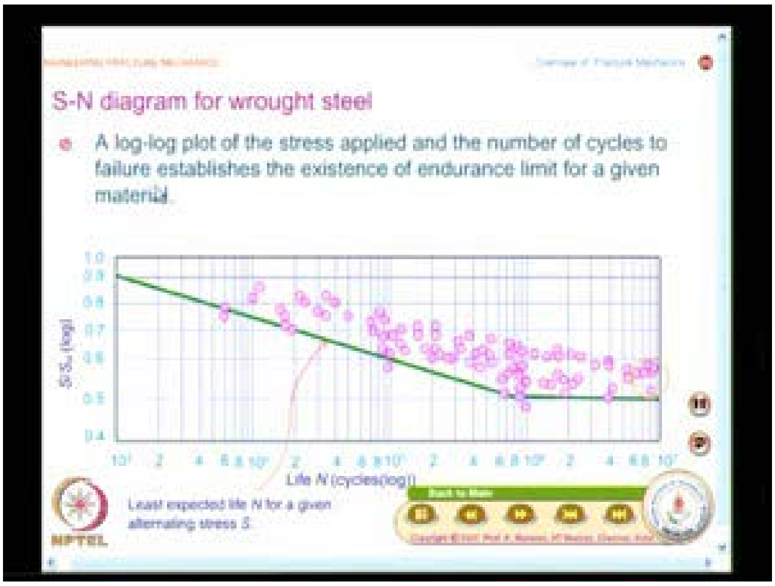

In fact, arriving at, what should be the way x axis to be plotted and y axis to be plotted is not simple and what you see here is, you have a scatter of data. This is an indication of an experiment well performed. So, in an experiment, normally, you will have scatter of data and you take your time to make a sketch of this graph. Whatever the data that you have got, you need to make some sense out of it. You know, if you look at the genesis of concept of stress as well as strain, it started from performing load elongation curves.

Then, instead of plotting as load elongation curve, if you plot it as stress versus strain, you will have just one graph for a given material. So, if you look at any development engineering, collecting data is one aspect of it; reporting data and trying to find out a meaning from the data, is equally challenging. So, in the case of a fatigue test, they decided to plot a log-log graph between the life, in number of cycles and you have the y axis is, whatever the amplitude of the alternating stress divided by the ultimate tensile strength.

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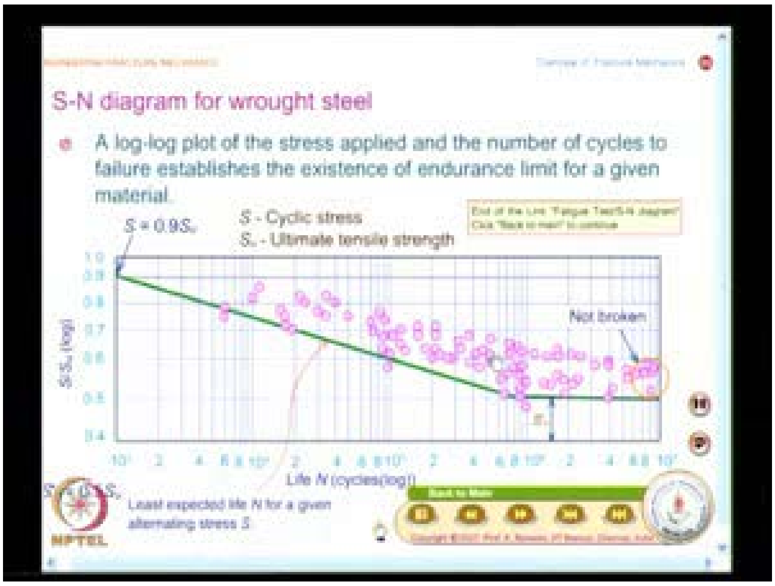

And what you find here is you are in a position to draw a line like this; that gives the least expected life N for a given alternating stress S. And, you also have from a design point of view, a convenient parameter call the endurance limit. So, what you find is, if you load the specimen, only to the endurance limit, it gives an impression that, you will have infinite life without any problem. It is very convenient parameter from design point of view. See, the modern research tells, there is nothing like endurance limit for any of the material. Every material fails after sufficient number of cycles.

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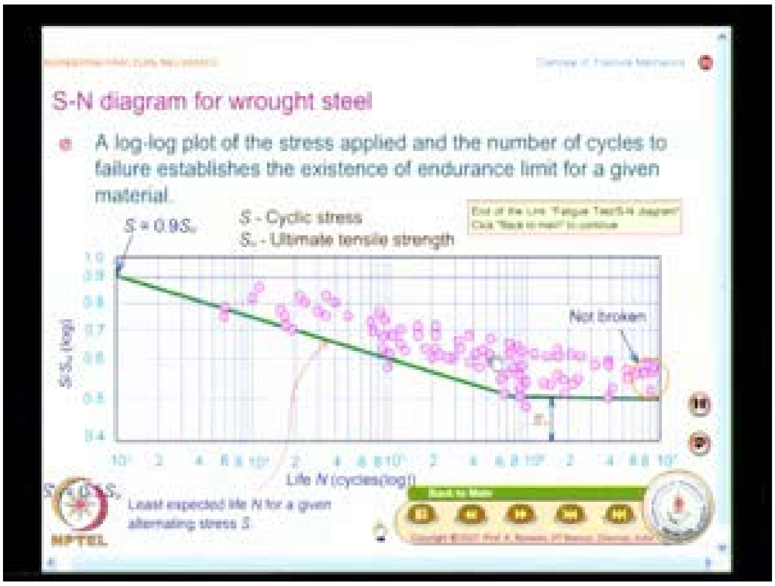

And you will also have to appreciate one more aspect, when you have got this endurance limit, for which you have to perform a fatigue test, there are also attempts to find out an empirical relation, involving the result of a tension test; and what you find here is, the endurance limit is given for this rod steel as 0.5 times the ultimate tensile strength.

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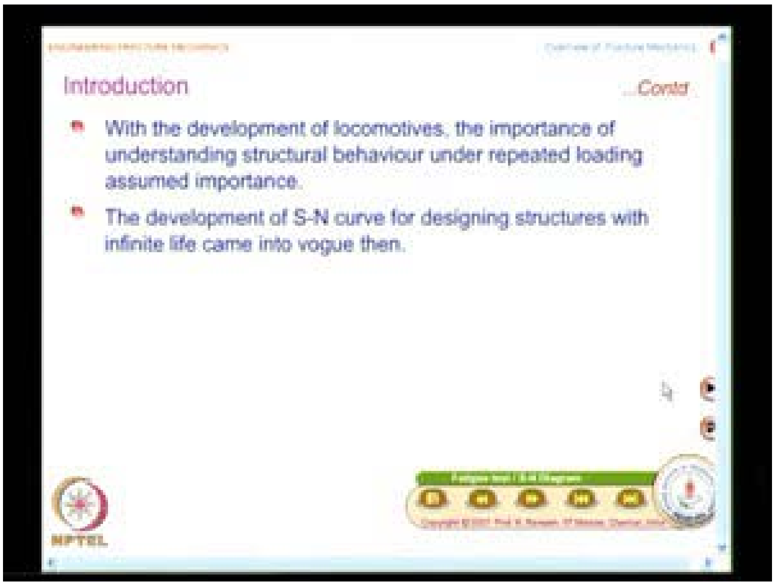

So, what you find here is the development of S-N curve for designing structures with infinite life came into vogue then. So, that is an improvement. From tension test, you have graduated to simulate what happens in actual service condition, if not completely, at least very close to simulating alternating loads on the structure, because when you do a fatigue test, you go for a sinusoidal loading.

If you really go to actual service condition, you will have variable amplitude loading, which could be using Fourier series; you will be able to convert at that, as a series of sinusoidal loading. And, there are ways, fatigue itself is a vast subject, there are ways how to count the number of cycles and what you have to go about, so on and so forth. But the important aspect here is you have been able to improve your design methodology, by bringing in the aspect of alternating load. Definitely this approach, to some extent, has recognized the failure due to crack growth.

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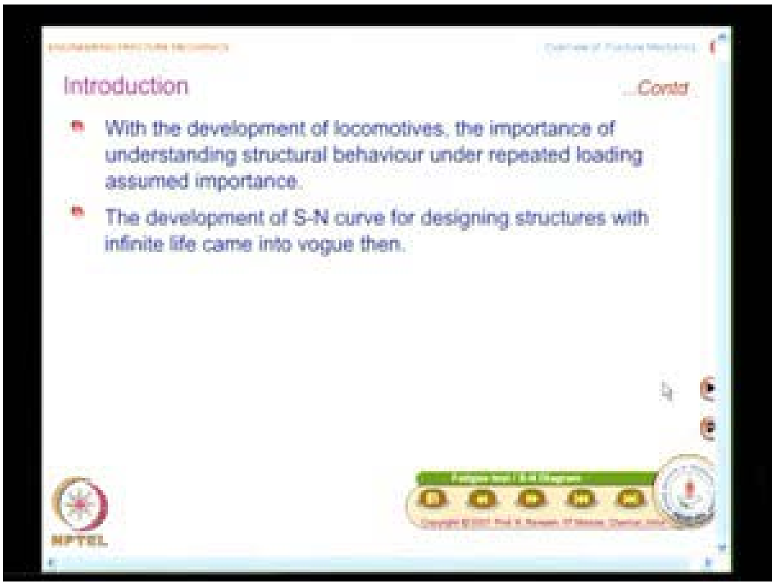

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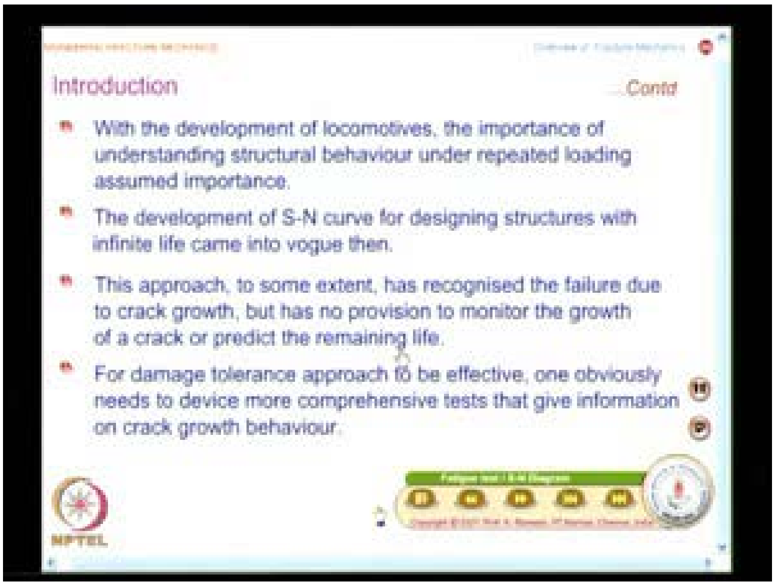

We have already seen how the test was performed. The test was performed only to record the number of cycles. So, there was no provision to monitor the growth of a crack or predict the remaining life. So, this we look at, from the point of view of fracture mechanics. Now, we know a crack is very important, it grows; its growth has to be understood properly. Then you say that, you will have to find out even the data pertaining to crack growth, but considering the tension test, definitely fatigue was an improvement.

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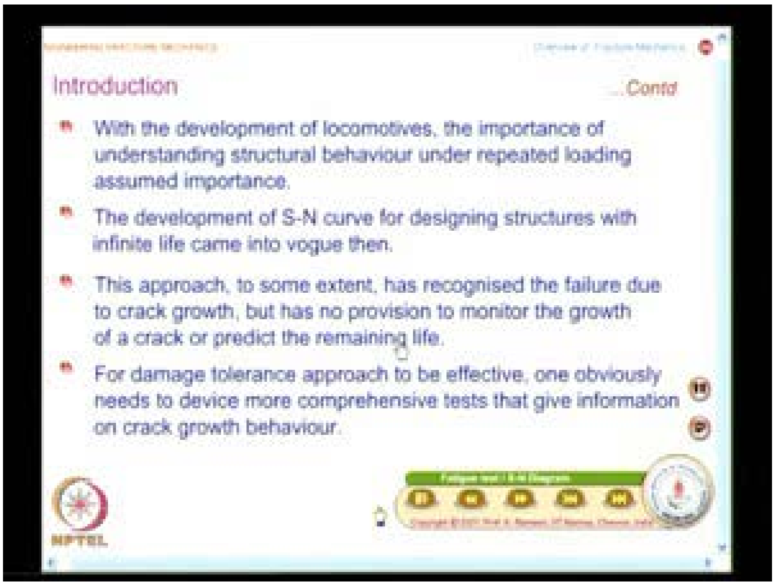

So, obviously, for damage tolerance approach to be effective, one needs to device more comprehensive test, that gives information on crack growth behavior. So, this is very important, without which you will not be able to do a damage tolerance approach. So, anticipate that, we will have to have a new test, if we have to practice fracture mechanics.

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And before we go into that, let us look at what we have in doing, in conventional design. The conventional design approaches are done with the premise that, the material is an elastic continuum, without any material defects or flaws. See, this is how you can proceed, because even if you read mechanics, you start from rigid body mechanics, then, you graduate to deformable solids. When you go to deformable solids, what do you do? You do not directly take up non-linear behavior, you idealize the deformation as small and it is also linear, it makes your life a lot more simple.

On the similar vein, when you have started modeling the material behavior, it was convenient, purely out of convenience, you consider that, it is an elastic continuum. And what are the design approaches you had? You have one approach, design based on strength. There is another approach, design based on stiffness.

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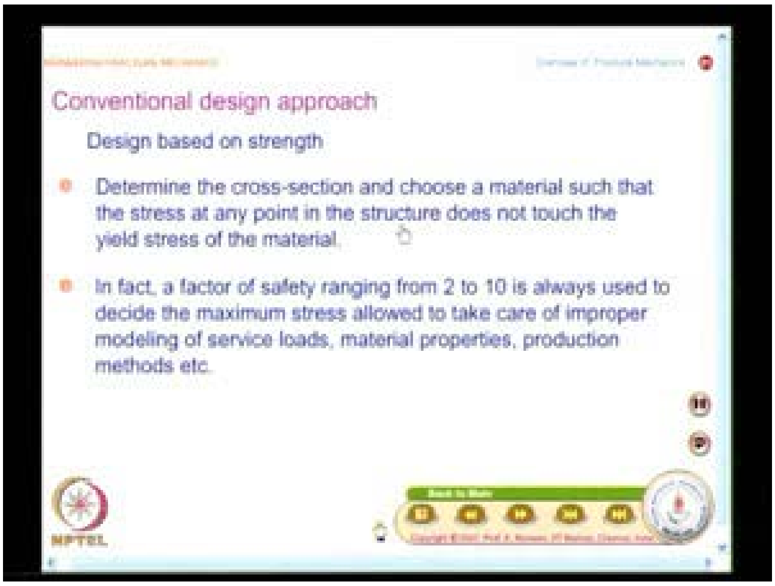

So, in design based on strength, what do you do? You would determine the cross-section and choose a material such that, the stress at any point in the structure does not touch the yield stress of the material. Because we have already seen, in the case of conventional design approach, yielding was considered as a failure. And I have also mentioned, most of the mechanical and aerospace components serve well below the elastic limit.

So, it is a good starting point. So, you limit your stresses, such that, they are well below the yield stress. And one of the other important aspects of conventional design approach is, you do not operate with the yield strength to start with. You bring in a factor called factor of safety, because there may be mistakes in calculating the service loads; there may be over loads; there may be material defects. So, to take care of all these aspects, you bring in a concept of factor of safety.

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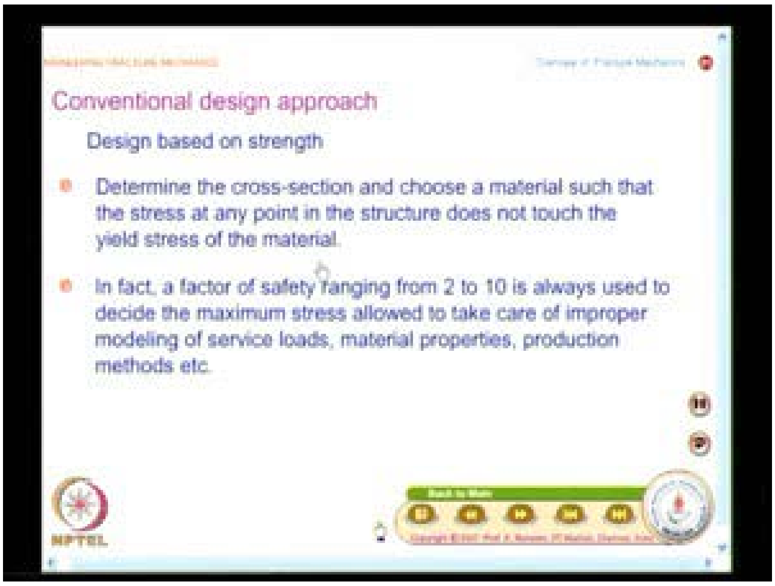

And you have seen in several designs, it ranges from 2 to 10. So, this is always used to decide the maximum stress allowed, to take care of improper modeling of service loads, material properties as well as production methods. And if you really look back, you know, if you have this cable ropeway cars, where you have a very difficult service condition and safety is very, very important and it is also exposed to the gusts of wind and you have factor of safety of the order of N. On the other hand, if you come to our Ambassador cars, this was operating with the factor of safety of 4. On the other hand if you look at Maruti, it is of very thin sheet metal work and there is also a demand on fuel consumption deduction. So, they want to bring down the dead weight. So, they bring down the factor of safety. When you bring down the factor of safety, your analysis has to be more and more precise.

So, you have to have a tradeoff between cost for analysis and the gain you get out of it; obviously, the aerospace structures, if you do the analysis the gain is more. For very conventional day to day activities, you want to have a foolproof design methodology, that would give a reasonable values on the final cross-section. So that, there is a tradeoff between detailed analysis and a simplified procedure. So, one of the designed approaches, is you do it design based on strength.

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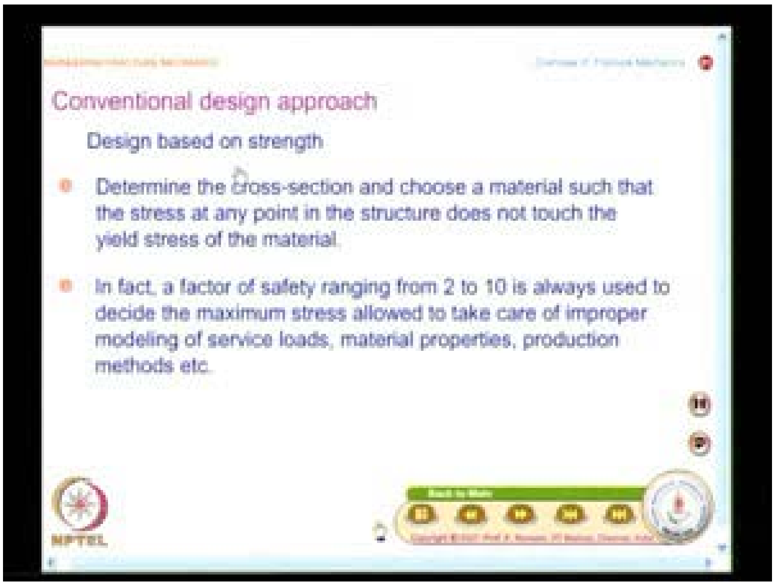

And you essentially determine the cross-section. If you find the cross-section, you cannot modify because of certain restriction. You can choose a better material to withstand higher stresses.

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The other design approach, what you have is, designs based on stiffness. You know, for many of this mechanical and aerospace components, the satisfactory performance of the component depends on deflection or deformation, whatever that comes across. So, you limit the values on the deflection, so that, you find out what is the geometry or what is the cross-section that you have to do, for a given design approach. And if you really look at, when you have a shaft design, people go for mild steel and there it is actually dictated by the deflection. If you go by the strength calculation, you will have a shaft which is of very small dimension, but from deflection point of view, it may experience the larger deflection.

So, the deflection limits the size of the cross-section. So, you will go for a larger size of cross-section. So, in a shaft design is really a dictated by the deflection. And also you find, you use the low strength material for shaft. On the other hand, you have springs. Springs are made of very high strength material. And if you really look at, you have a compression spring or a tension spring. In actual practice, it is really experiencing a torsional load. So, you design it for shear. So, you have to know, if you have a done a course in design, you use different materials for different applications. Shafts are made of only mild steel and when you have a spring, it is always made of high strength steel.

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So, the focus here is, when I have relative moving parts, the deflection or deformation plays a very important role. Because you have to maintain close tolerance levels and usually designed based on stiffness.

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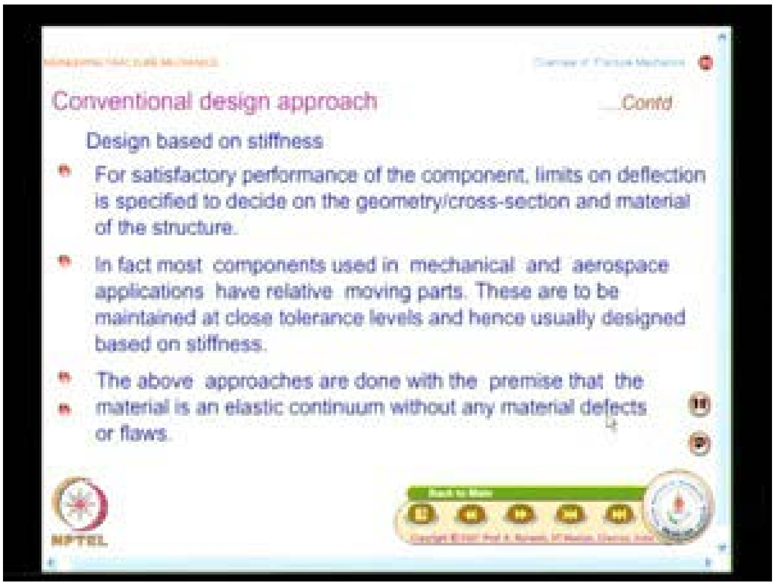

And again it is emphasized, all these approaches to the design are done with the premise that, the material is an elastic continuum without any material defects or flaws.

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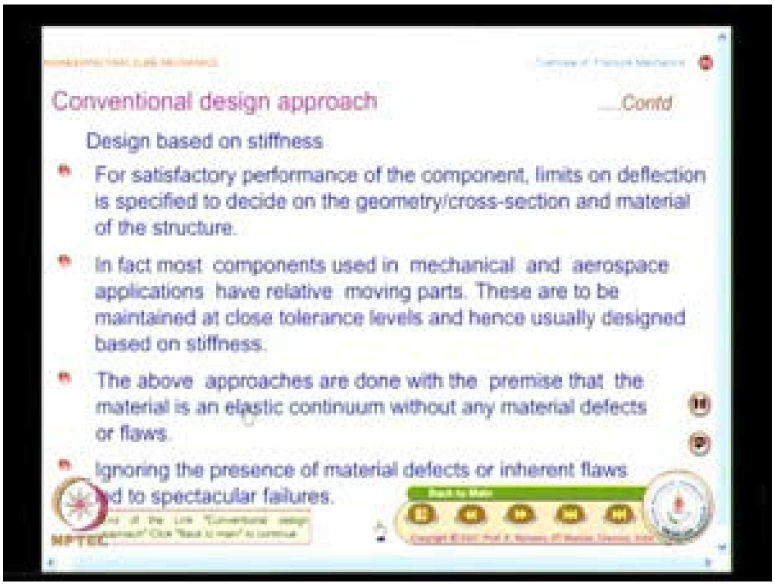

It is purely out of convenience. There is no other reason. If they had better mathematical model and simplified approaches, they would have also incorporated what happens when you have a flaw. Purely out of convenience, the initial design approaches were confined to considering the medium as elastic continuum. And it has worked well. You could do some kind of an engineering based on this, but what is the situation now?

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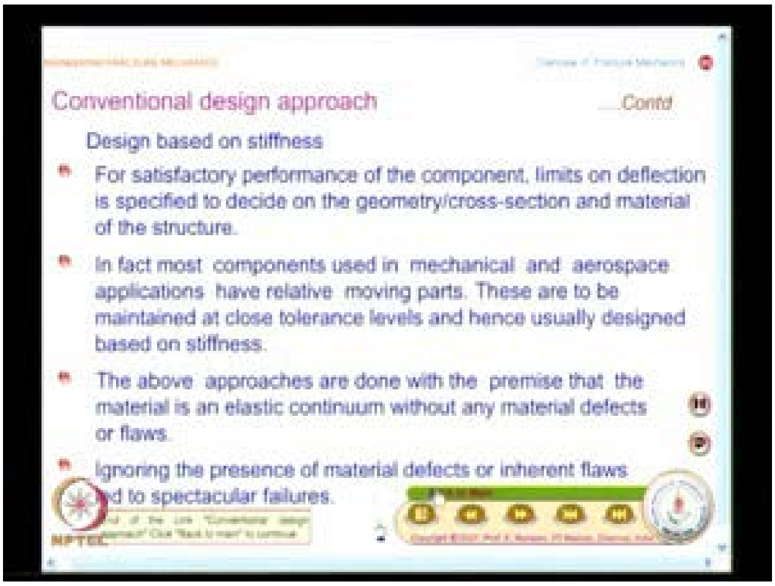

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See, you have to look at the modern structural environment is much more complex in terms of operating temperatures, aggressive environments and types of loading, etcetera. See, now you find people go to space and come back to earth. So, they have to pass through the barrier to earth and very high temperatures are developed. It is about order of 1600 degrees Centigrade. You never even dream of that kind of operating conditions earlier and you have cryogenic engines. So, you have demands, that are far different from what was initially thought of in conventional design approaches.

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And in addition what do you do? You also have requirement for optimization.

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And these optimization requirements have resulted in reduction in the weight of structures, which in turn leads to, enhanced operating stress levels. So, what we want to do is, we want to take out as much as possible from the material that I have put in for making a structure. So, you would not have a tradeoff. So, we want to have optimized structures. So, that means, I should do more analysis. When you do more analysis, I should also go closer to reality.

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And obviously, if you ignore the presence of material defects or inherent flaws, it will definitely lead to spectacular failures. In fact, that is what has happened.

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So, finally, if you want to have a successful design of engineering structures, for long term life, requires many things. It requires understanding of the different modes of failures and degradation mechanisms. See, this was never understood in conventional design. Only in modern design, you also look at, there are degradation mechanisms. So, this fundamentally, makes a difference in damage tolerant approach. So, you have to understand the degradation mechanisms and what are they?

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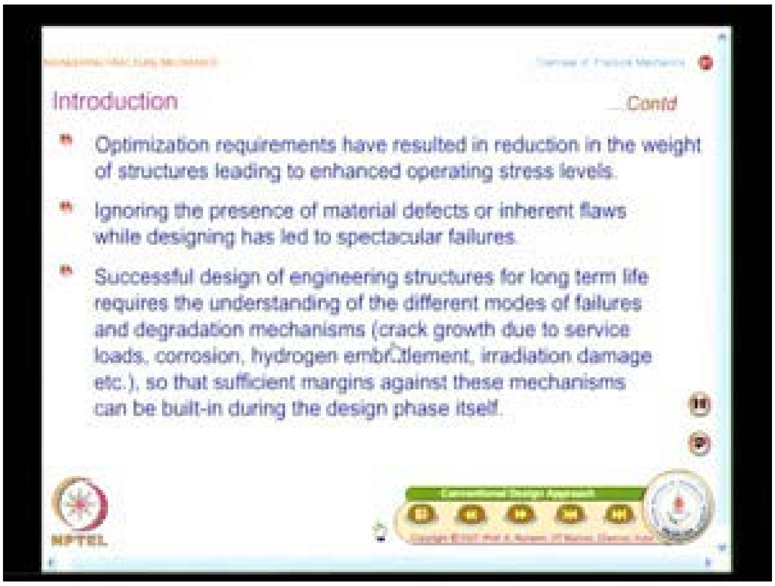

Crack growth due to service loads, problems due to corrosion and also special problem due to material becoming brittle. One of the important causes is hydrogen embrittlement.

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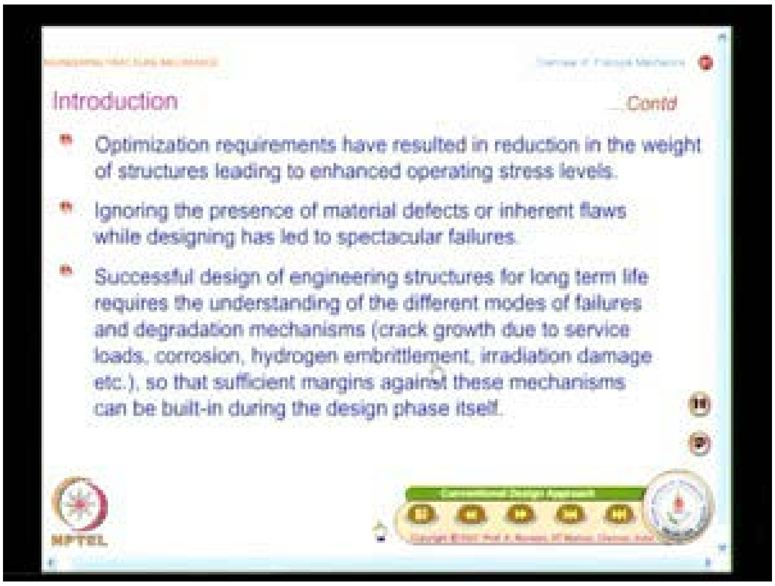

And you know, in fuel cells, one of the major drawback is the structure becomes brittle because of hydrogen entrapment and you have nuclear power for these days and the major problem there is, damage due to irradiation. So, these are all degradation mechanisms. Unless you understand the degradation mechanisms, you will not be able to provide sufficient margins against these mechanisms. So, if you know that, you could incorporate that in the design phase itself. So, the idea is, the modern design will have to address the issue of degradation mechanisms. Before we really take a fracture mechanics, let us look at the spectacular failures.

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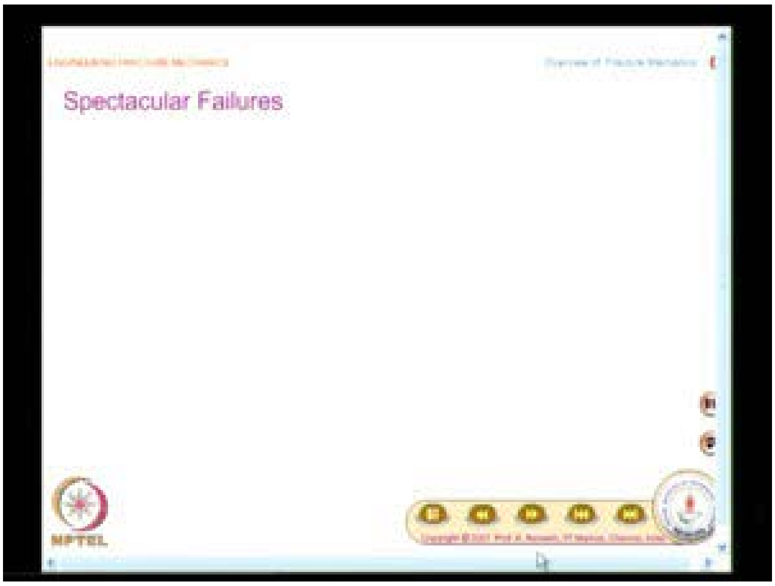

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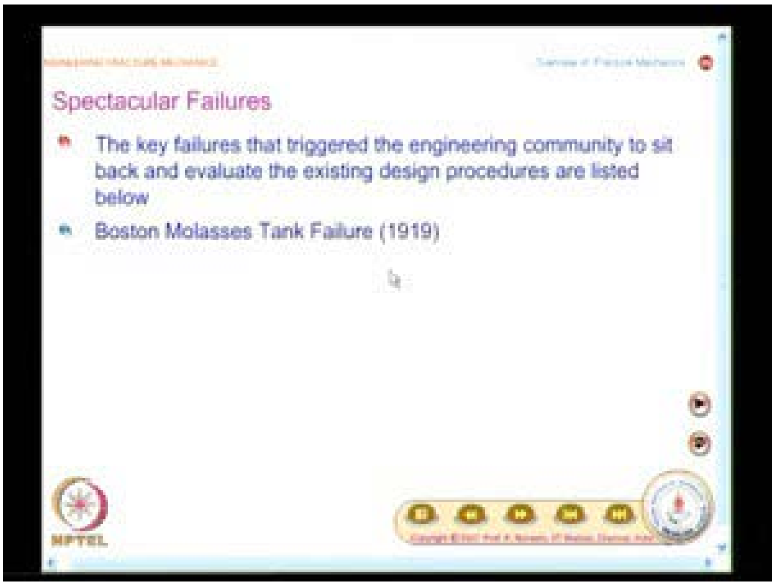

Why they are called spectacular failures? Now, we are going to look at the key failures that triggered the engineering community to sit back and evaluate the existing design procedures are listed. They were very, very important failures. So, one famous failure was Boston molasses tank failure. This happened in 1919. In fact, I am going to give you a list of 4 such failures, over a span of about 17 years.

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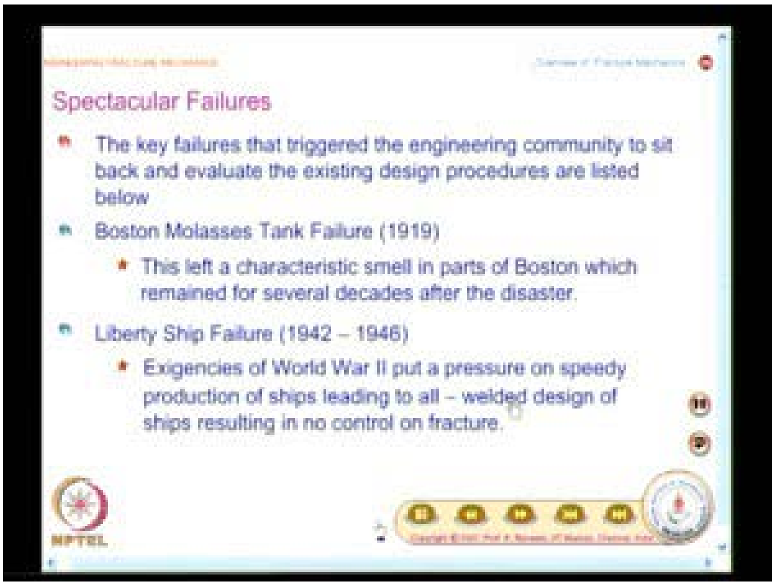

And, what was important in Boston molasses tank failure? And you all know, when you travel in a train, if you cross the sugar cane factory, you have the smell of molasses. It is not pleasant to smell and certain failures are spectacular because people remember for years, because of its notoriety.

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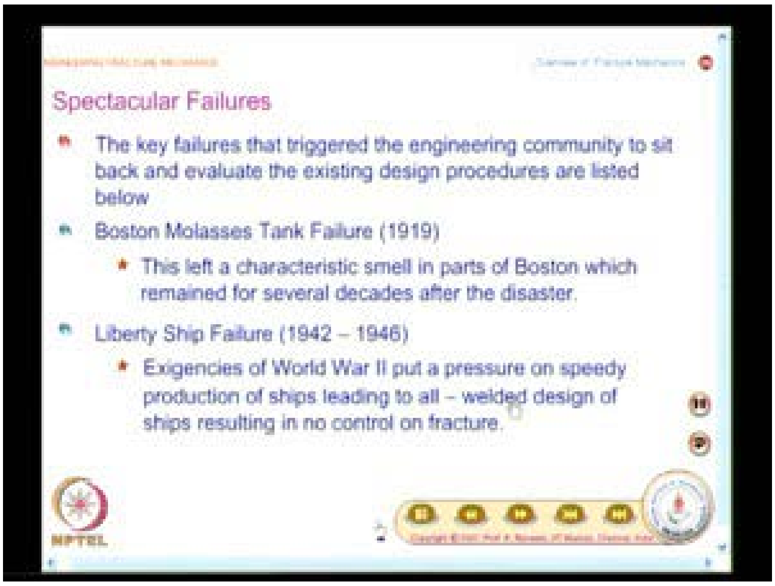

The problem with molasses tank failure was this left a characteristic smell in parts of Boston, which remained for several decades after the disaster. So, people cannot, even if they want to forget that such a thing happened, a smell will remind them. So, it becomes a very important and you have to go investigate, what happened, how this happened, why it happened. So, this is what made that engineering community to think and evolve new design approaches. Another famous failure was Liberty ship failure. This is between 1942 to 1946.

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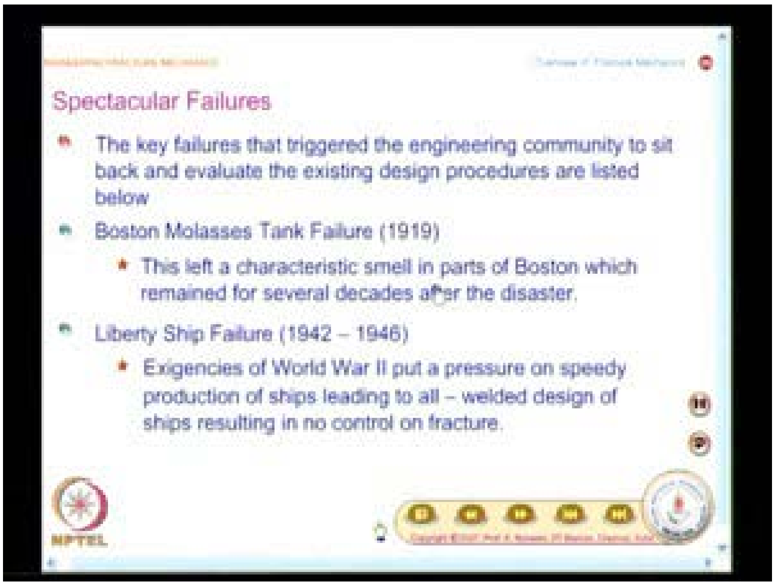

Exigencies of World War 2 put a pressure on speedy production of ships leading to all-welded design. Prior to that, people had ships made of riveted design and it takes quite a bit of time to fabricate a ship. When they switched over to welded design, they could quickly make the ships. They also paid a heavy price for it.

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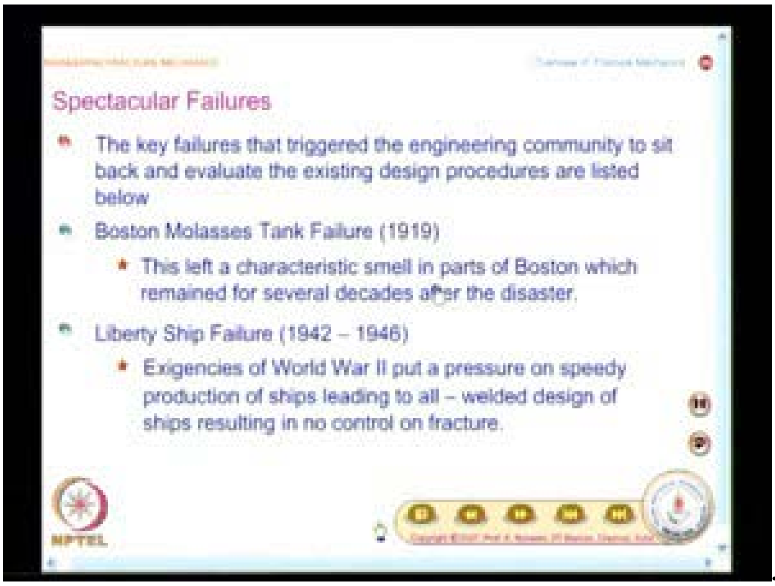

What happened was, the ships failed; there was absolutely no control on fracture. In fact, you would see each one of these disasters, one after another in elaboration.

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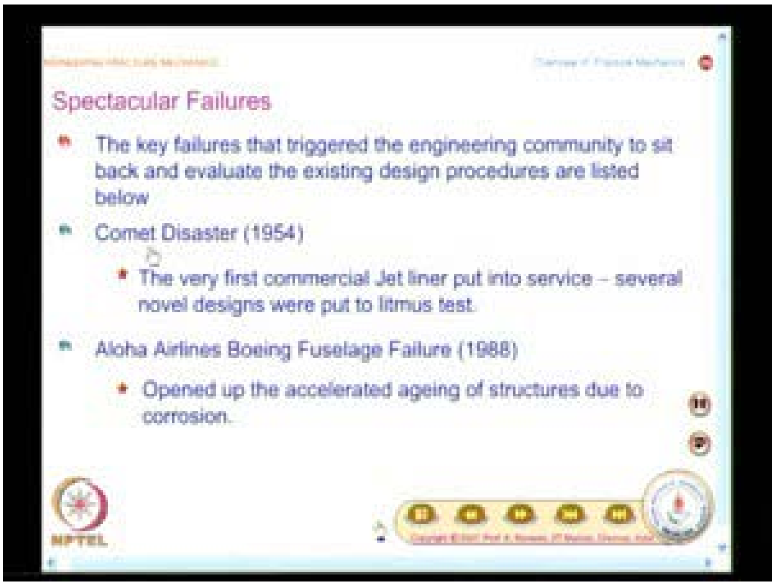

Right now, we only have a short summary. Later, we will have, also have a look at, in detail, some of these failures. The another disaster which we will look at is the comet disaster. This happened in 1954. The importance of comet is, this was the first commercial jet liner put into service. Until then, they were all only propeller planes. Because it is a jet liner, several novel designs were put to litmus test. And we will see, what was the problem and how this was diagnosed and solved. And very recently, in 1988, you had Aloha Airlines Boeing fuselage failure. It has really opened up the accelerated ageing of structures, due to corrosion. People ignore corrosion totally in their design. So, we will go one failure after the other. We will look at what happened in the Boston molasses failure.

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So, what happened was without warning. That is the key aspect. See, you had seen a tension test; you take a mild steel specimen or a ductile specimen and pull it, you have always noticed, you have a questioning; it goes through extensive plastic deformation before it fails. So, you naturally conclude, when we make a structure out of a ductile material, it would give you some kind of a warning before it fails. What happened in the case of molasses disaster? Without warning, in January 1919, molasses surged over Boston and a frightful flood devastated a vast area of the city.

You know, you can imagine, tsunami comes and you have sea water engulfs the country. Now, we hear such disasters. And, there have also been volcanoes, which totally submerge the cities. All those disasters are happened, where there are no one will remain to tell you what happened. But in Boston molasses failure, very unusual, you see a flood of molasses affecting the city. You had 2.3 million gallon Boston molasses tank, which was only 3 years old at the time of failure. See, this is the pity. Now, normally when you design a structure, you want it to come for 50 to 60 years. And, you do not expect a failure to happen in just 3 years. And, the tank was very huge. It was 50 feet tall and 90 feet in diameter.

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Just to give you a rough size and this also gives you, an idea of what is the kind of devastation that occurred and this figure, courtesy, is from Boston library.

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And really, look at how the failure happened. The tank came apart with a thunderous cracking and an estimated 14,000 tons of molasses caused havoc. And, the molasses travelled with a speed of 40 to 56 kilometers per hour. And, it was not easy to clean. It took six months to clean up the place. Not only this, after a cleaning, if there is no smell, people would have forgotten Boston molasses disaster.

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The pity was, the smell was coming for decades. In fact, the molasses actually continued to creep out of the ground and cracks in the sidewalks for 30 years. So, you, even if you want to forget, you cannot forget this. The smell remained for decades, a distinctive atmosphere of Boston. And, this shows another picture of how the devastation was and this is again, the courtesy goes to Boston public library.

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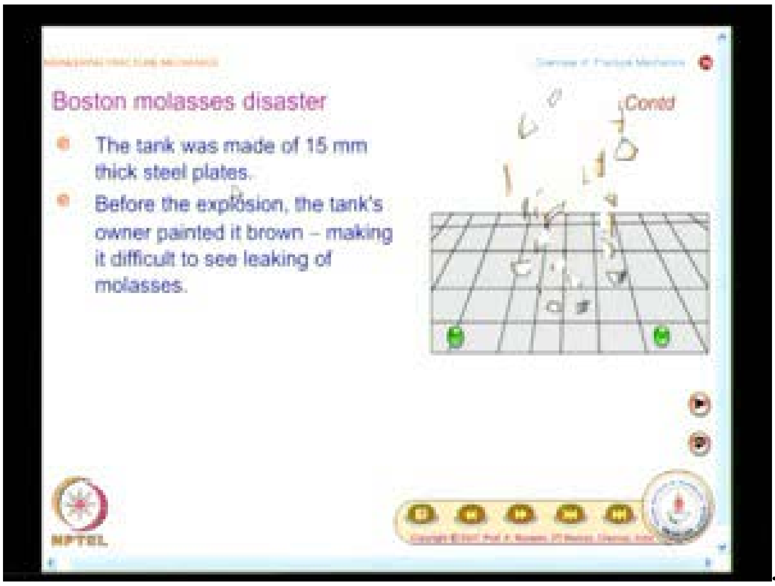

Let us look at what happened. First thing is, the tank was made of 15 millimeter thick steel plates. Very thick, you know. 15 millimeter thick is very very large. So, one should really realize, I have made out of very thick plate, why should I worry, and what happened?

Before the explosion, the tank's owner painted it brown. Even this is looked at. When you look at the failure analysis, people want to find out, what kind of mistakes could have happened. What is the color of molasses? Molasses is brown. Without knowing that, the owner of the tank painted it brown. The result is, even if there is a leak, it will be very difficult to spot, if there is a leak in the tank. And the tank is so huge. You cannot view it, unless you have a contrast in color. And, in fact, in modern design you have, what is known as leak before break. In all nuclear power installations, it is mandatory; the heat exchanger tubes have to go through L V B criteria. That is why, I want to emphasize, in the case of Boston molasses failure, there was no scope for having a look at whether the tank was leaking. That is one indication, that some reinforcement need to be done or removes molasses, so that, you bring down the pressure build up and so on and so forth.

And this is very, very important. See, if you look at your Indane cooking gas, it is actually odorless. People have added that smell, so that, if there is a leak, you would respond to it by smell and go on to take corrective measures. Either, you go and open the windows, do not switch on the light. Some corrective mechanism is possible, if you are alert. So, in all nuclear power installations, L V B criterion is very, very important. And, what happened? The failure investigators found out, that the possible cause was a sudden temperature change, as the temperature on the previous day was minus 17 degrees Centigrade and on the day of occurrence, it was 4.5 degree Centigrade. So, that is a thermal shock. So, thermal shock precipitated. And what they concluded? See, in conventional design, whatever they do not understand, they put it as a factor of safety.

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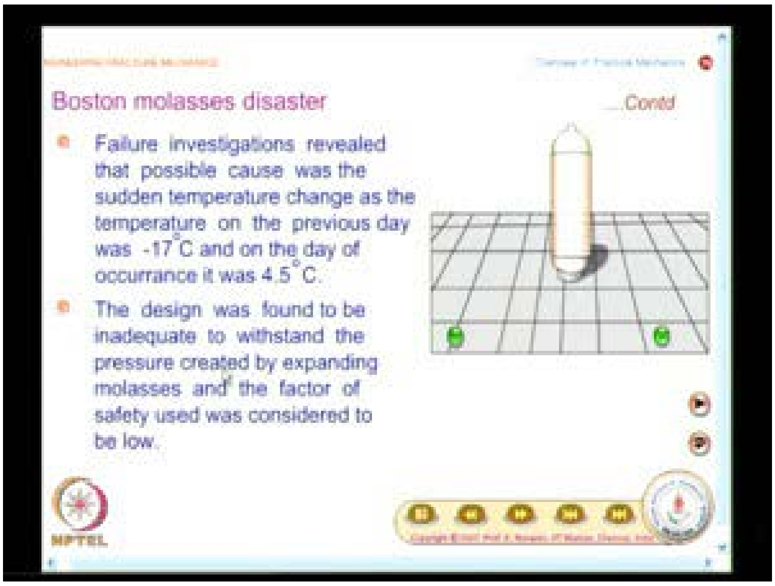

So, it happened in 1920. So, in those days, people concluded finally, the design was found to be inadequate to withstand the pressure created by expanding molasses and the factor of safety used was considered to be low. And this is too trivial conclusion, because they were used to bring in a factor of safety. So, they concluded, it failed. So, something has gone wrong. So, increase the factor of safety. So, this is not going to solve the problem, because you are not really looking at the root cause of the problem. It is only a cosmetic changes in your design approaches…

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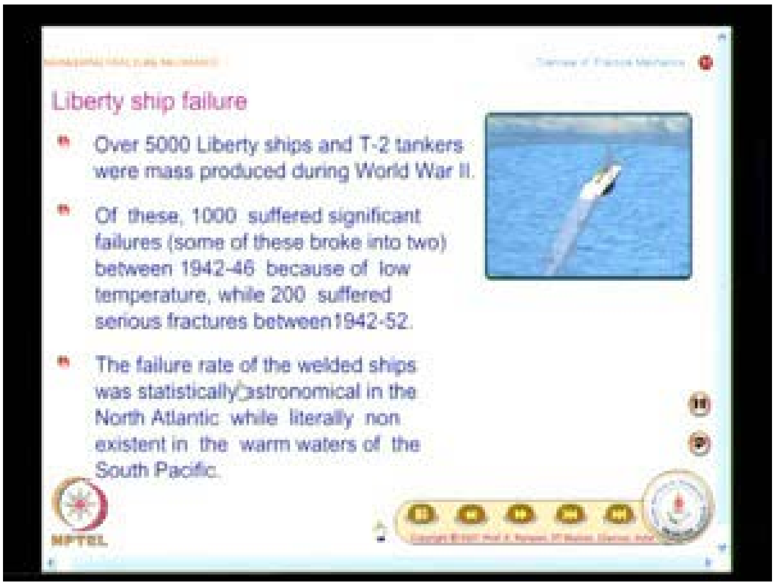

And people really burned their fingers in Liberty ships. And look at, over 5000 Liberty ships and T-2 tankers were mass produced during World War 2. See, this is very important. It appears in the history of ship building. Nowhere you find, a same design was used to produce such a large number of ships. If the ships were successful, no one would have worried. But you find, the failures where astronomical. You know, you have to be in shame, because you know, the whole scientific community was clueless, why such failures have happened. And you look at the failures. Of the 5000 ships, thousand suffered significant failures, and in fact, some of them broke into 2. Imagine a ship breaking into 2. It is made of ductile material and it broke into 2 all of a sudden. See, that is the most dangerous part of it.

So, between 1942 and 46, thousands suffered. And, because of low temperature, is what they were able to identify at that time. And, between 1942 to 52, they had also improved some of the methodologies and 200 suffered serious fractures in this time frame. So, definitely you will have to look at and find out what has happened. And observation was, the failure rate of the welded ships was statistically astronomical in the North Atlantic, while literally, nonexistent in the warm waters of the South Pacific.

So, they understood, yes, this is something to do with low temperature. Low temperature is one cause and you also have welded ships. Because previously ships were made of riveted joints and when they moved over from riveted joints to welding, first thing they observed was, there was weight reduction; very quick in fabricating the ship; I was told that, within a week they could fabricate one ship. This is how, they have achieved, because the war exigencies required more and more fleet to be generated at a short time.

But the result was, you find, there were many failures, that needs to be looked at and the cause needs to be ascertained.

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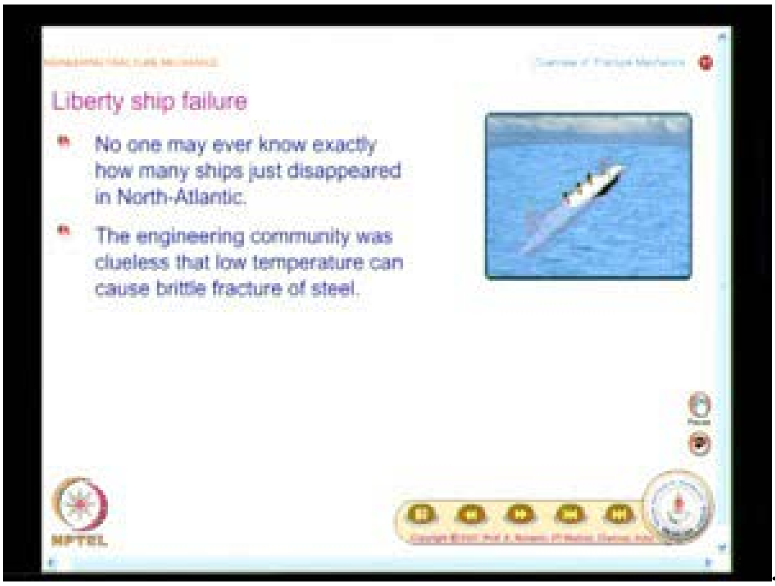

And it is also mentioned that, no one know exactly how many ships just disappeared in North Atlantic. The engineering community was clueless that low temperature can cause brittle fracture of steel. In fact, the navy formulated a committee, a board, to go into the details and find out what really caused such failures, and come out with recommendations. In fact, I have access to that report, thanks to the Project Liberty ship program and I would read the foreword, that would be more revealing. I would just read from that. See, the foreword starts like this, 'early in the war, welded merchant vessels experienced difficulties in the form of fractures, which could not be explained. The fractures, in many cases, manifested themselves with explosive suddenness and exhibited the quality of brittleness, which was not ordinarily associated with the behavior of a normally ductile material, such as ship steel'. So, they formulated a committee.

And, the committee was given a dictum, what they should do. And, that is also very important. You know, it is very nice to see, how people have looked at it. See, there are two ways when a failure happens, you just condemn the scientists are so useless; whatever the funding we give to them, goes down the drain and condemn them and go with your life; this is one approach, which we commonly if come across in India, because you know, when you have GLSV failure, people only first laugh, they do not look at, there are genuine problems, when you are dealing with modern technology.

So, people have to be sympathetic and provide proper way of analyzing data and come out of the problem. And imagine, out of the 5000 ships, 1000 ships break. They had serious fractures and some of them broke into 2. It is really a sort of a blot on the engineering community which designed it. But what you will have to appreciate is, the fractures were very systematically analyzed, you would also say some of that graphs, and useful data was collected. In fact, it is the naval research board, which funded fracture mechanic research initiate.

So, you find fracture mechanics grew from such a study. And, the board was given this kind of dictum, to investigate. That also I will read. The secretaries' directive to the board, read in part, as follows: make a complete investigation of the matter, here by submitted and upon the conclusion of its investigation, will report the fax, establish they are right. And I would say, it is really a scientific approach. When you face failures, investigate, find out what is the cause, so that, you do not repeat it again; rather than ridiculing failures. Because failure has always been a method for inventing new ideas. Without failures, nothing has happened. If you really look at the bridge design, people built a suspension bridge. After a few months of operation, it violently vibrated and the whole bridge collapsed. Then people realized resonance is very important.

So, the key is, when you face failures, analyze it systematically. And, this was done a very nice scientific analysis. And the dictum reads like this, 'if the fax establish the existence of defects, in their designs of or in the methods being followed in the construction of such merchant vessels, which in the opinion of the board adversely affect the sea worthiness there off; the board will also submit its recommendations, as to the measures which should be taken to correct such defects'. So, it is very clear. You know, people have realized, that design is one aspect, the construction is another aspect and how well the construction practices are enforced; because when you are doing welding, you know welding is a very tricky manufacturing process; and you are talking about way back; and in those days people have not fully understood the welded defects. So, the board was very scientific in its approach, open minded and carefully collected voluminous data and beautifully characterized it.

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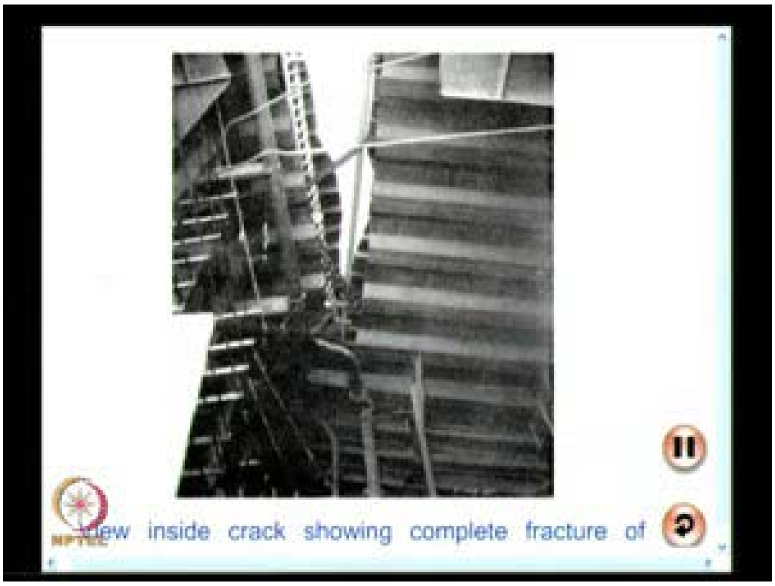

And if you really look at, the whole analysis started when you had this T-2 tanker Schenectady broke into two in the warm waters of, in the cold waters, you should not say warm waters, in the cold waters of Swan island and this is the tanker. This ship broke into two. You see the fracture here and this figure is from Project Liberty ship and what you had was, the water temperature was about 4.5 degree centigrade. Then the problem was taken up seriously. And, this shows the fracture through the deck. You can see how the entire deck has fractured. It is a very serious matter.

So, what you find is, these calamities focus attention on the fact that, normally ductile mild steel can become brittle under certain conditions. So, if you really go to metallurgies, you know, they have understood now, there are something called ductile to brittle transition. We will have a look at it. There is nothing like a material is always ductile. Above certain temperatures, it may behave in a ductile fashion; below some temperature it may become brittle; that kind of an understanding came about.

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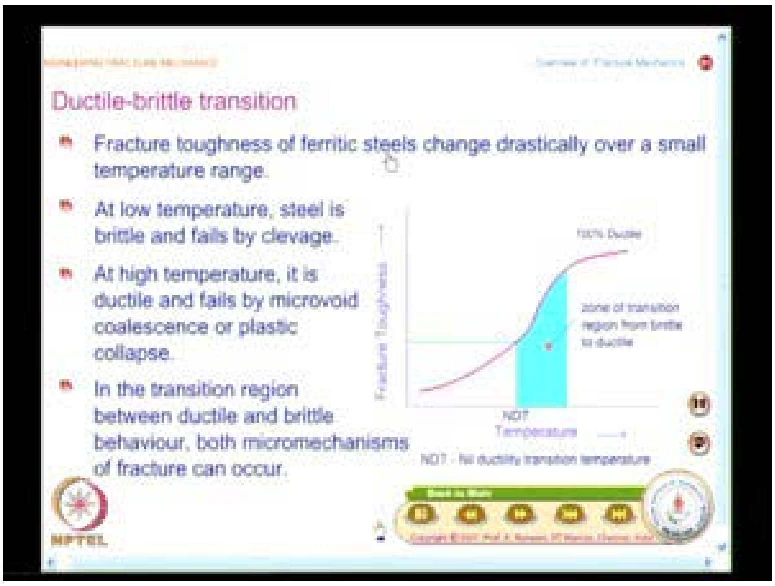

And this is what you see in a ductile to brittle transition. And it is reported that, fracture toughness, which you would learn in this course, this was found to vary for ferritic steels over a small temperature range. At low temperature, steel is brittle and fails by clevage. At high temperature it is ductile and fails by microvoid coalescence or plastic collapse. And, this is how you have, you can make a neat sketch of it. So, you plot temperatures versus fracture toughness and the graph is like this.

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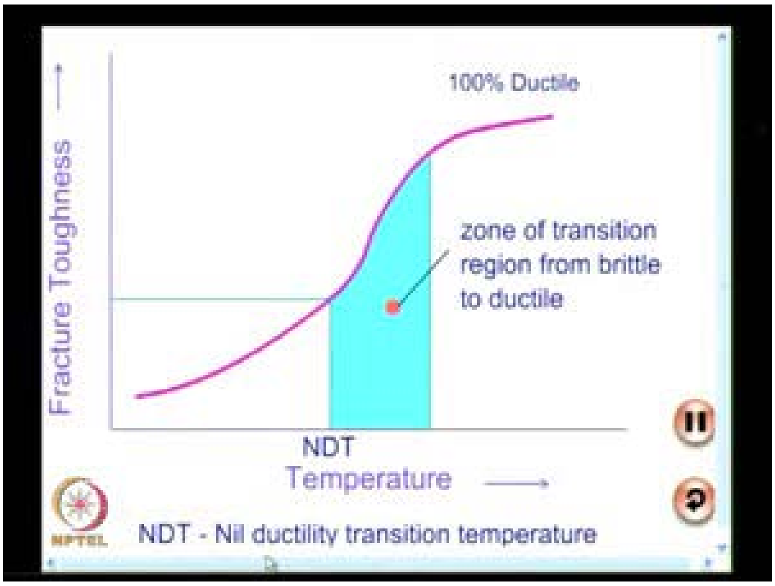

So, in this region, the material is 100 percent ductile; below this temperature, which is labeled as NDT, the expansion is nil ductility transition temperature. So, you find there is a transition zone, from ductile to brittle and what people have found is, I had already mentioned that, there are degradation mechanisms, particularly in nuclear power plants. People have to understand, how to safely guard the nuclear power plants; what they found was, when the structure is exposed to radiation, there is a drastic change happens on the nil ductility temperature. And people have understood and call it as a radiation shift.

So, what you find here is, the whole graph shits to the right. So, this is called radiation shift and you find the nil ductility transition temperature has increased. So, that means, over a period of time, the nuclear power installation degrades because of exposure to radiation. This aspect needs to be taken into account at that design phase itself; that is what is important.

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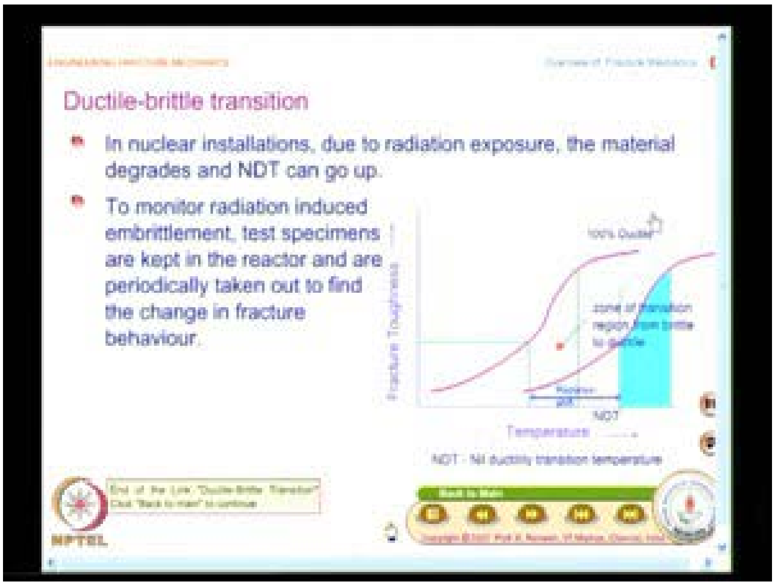

So, the Liberty ship failure has shown you very important things; that there is a concept of changing from ductile to brittle; there is a temperature, transition temperature and a related concept is radiation introduces a sort of embrittlement. So, what they do is, they keep test specimens in the reactor and take out periodically and tests it is ductility. It is done. That is why you have robots are used and you have, because it is all nuclear, you have exposure to radiation. In fact, robotic technology got developed, purely when they have to handle things related to nuclear installation, to start with.

So, they have to take out the material periodically, test specimens are kept inside the reactor, take out periodically and conduct the complete test, without any human intervention. It has to be done by robotic arms and tools and so on and so forth. And this is how you have to monitor any of those installations. So, what you find from a Liberty ship failure is, a ductile material can become brittle. So, that is the important learning that you gained from that. And it all started from the failure of this ship, and this was docked in the yard. You know this is what is important; it is not that this failure has happened in heavy sea.

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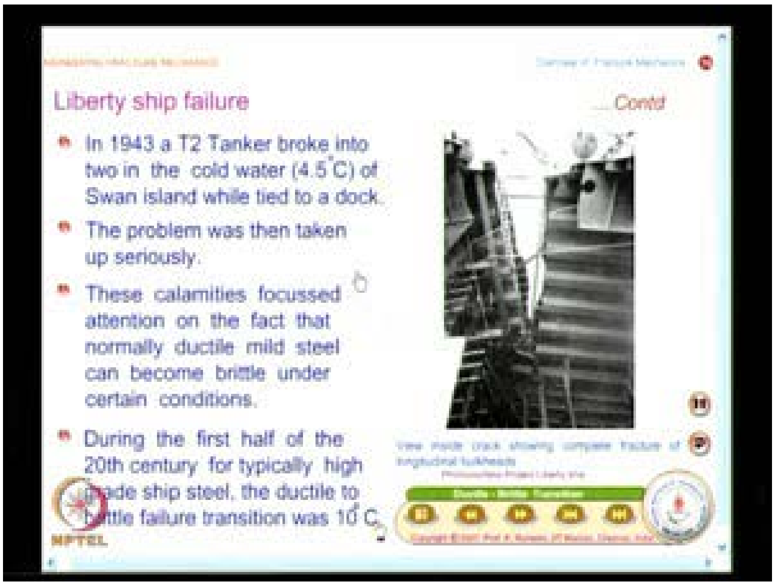

Heavy sea, people would have ascribed this to very heavy loads, that is coming up because of high waves, and or some bomb has been dropped on to the ship; some such explanation you can give, but you do not expect a ship kept in the yard to break. So, that alerted, it is something to do with the structural design and the environment. And if you really look at, during the first half of the 20th century for typically high grade ship steel, the ductile to brittle failure transition was only 10 degree centigrade. That is too high. Because the operating temperature is far below this. You know, you never had this kind of an exposure earlier.

If they had stuck only with riveted ships, cracks would have formed, but they would have got stopped in another rivet hole. In a welded ship, what happened was, there was nothing to arrest. So, the crack has gone through the full shape and fracture occurred. They would not have got alerted, transition in temperature is a major cause. And there is also data associated with these failures.

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And as I have mentioned it earlier, below the NDT, you find the ship broke like glass; that means, without warning, suddenly the ship breaks into two. It is very dangerous; there is not even time for you to escape out. And, in fact, such failures have happened and it has been recorded and analyzed; what you will have to look at is, people have analyzed all those failures.

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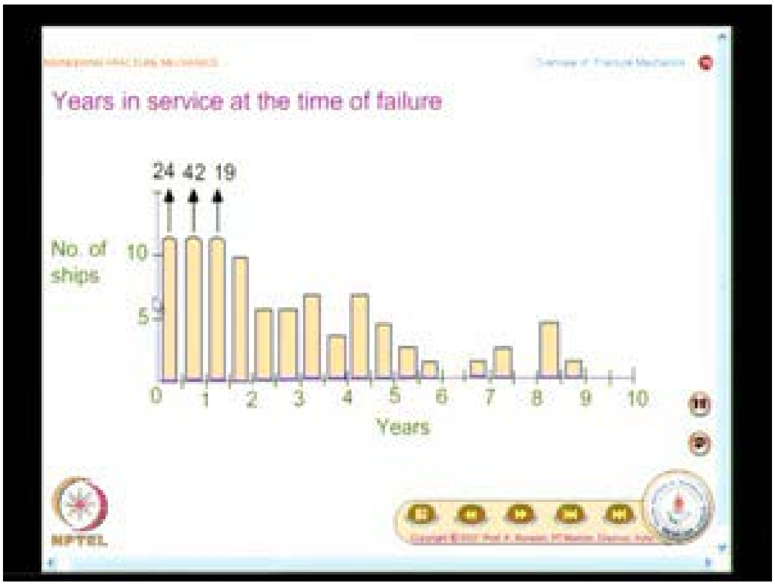

And several such graphs are available and what you find is, the ship is designed; within the first few years, you had so many failures. This is something unhealthy and this gives for a period from 42 to 52 and you also have another set of graphs, which shows the condition at sea.

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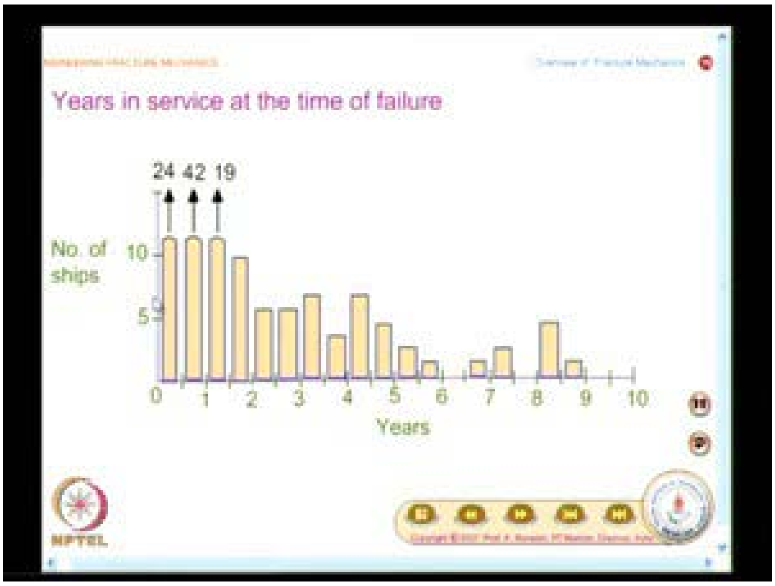

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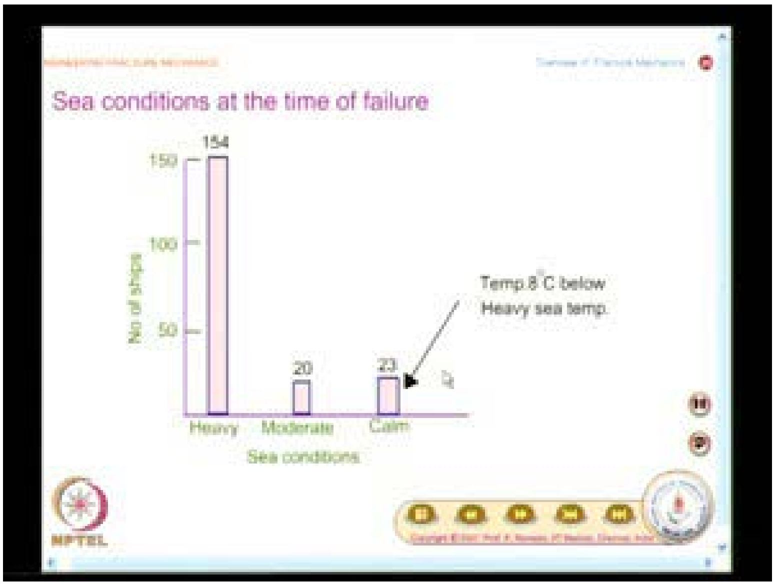

I think you need to make a copy of this. Because the focus here is, there were failures in heavy seas about 154, in moderate sea condition it is about 20, when the sea is calm, it is about 23. That is what alerted the scientists, to look at critically, what has caused the failure and if you find this, in this kind of situation, the temperature is 8 degree centigrade below the heavy sea temperature. So, this all came about by looking at critically, what has caused the failure. So, from that data, you are able to segregate and find out, even under calm sea conditions, failure could happen and it has happened.

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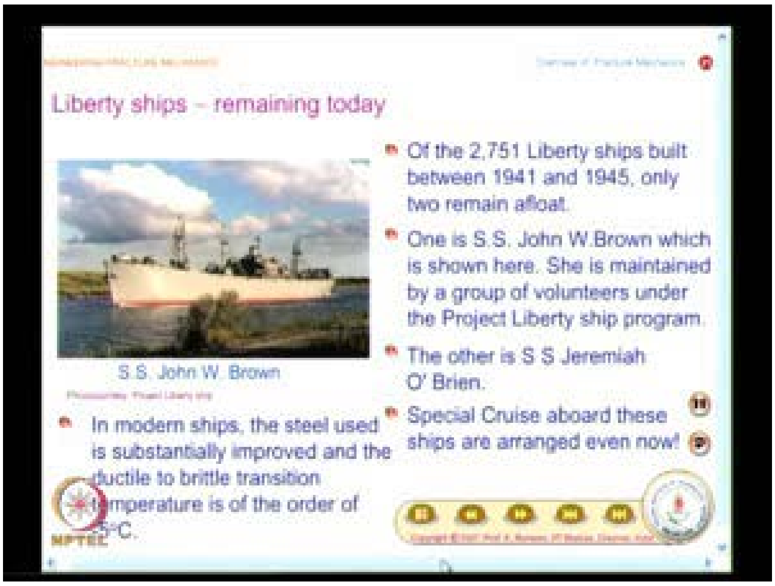

And finally, you know, you do not have to feel that the design was very bad. You still have a nice Liberty ship available. Out of the many ships fabricated, two still remain and it appears, now, you can go for a jolly ride in this. They remember this, nostalgic memories and what is recorded is, out of the 2751 ships built between 1941 and 45, only two remain afloat. And it is all named on the soldiers who fought in this war, S S John W Brown and another one is Jeremiah and right now, you have special cruise aboard these ships are arranged, even now. And if you really look at the modern development, you had seen the ship steels in the middle of 20th century and the NDT as something like 10 degree centigrade. Now, it has been brought down to something like minus 4.5 degree centigrade; this is one aspect of it; that means, when there is a failure, improve the material.

So, people have studied the material and they have been able to bring down this nil ductility transition temperature. So, the new steels are like that. Another improvement is you bring in in-built crack arresters as part of a design. And what do these crack arresters do? They prevent easy crack propagation. So, that is the way, you have to handle fracture. You have to find out some way to improve your design and also salvage. When there is a crack, you do not allow it to propagate easily.

So, in this class what we have looked at was, we started looking at the fatigue test and the focus was, you only find out the number of cycles for the specimen to fail; you do not take any note of how the crack propagates while you perform the test. Then, we looked at, what are all spectacular failures. Of the four, we have been able to see two of them; one is the Boston molasses failure; another is a liberty ship failure. And what I pointed out was, people were not detracted by the failures. They took this as a challenge and the failures were systematically analyzed to cull out relevant data to improve future design. Thank you.