Fracture, Fatigue and Failure of Materials
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Lecture 52
Failure Analysis (Contd.)

Hi there. So, we are at the 52nd lecture of this course fracture fatigue and failure of materials. And we are in the third module, which deals with the failure of materials and we will be discussing some more about failure analysis.

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So, the typical concepts that will be covered in this lecture are the following, we will be talking some more about the factor of safety, which has been already introduced in the last lecture. And then we will move on to the Fail-Safe design. So, far we have seen safe life design and now, we will move on to the Fail-Safe design and we will also try to figure out or find out the common causes that can lead to failure and based on that we can identify the importance of failure analysis.

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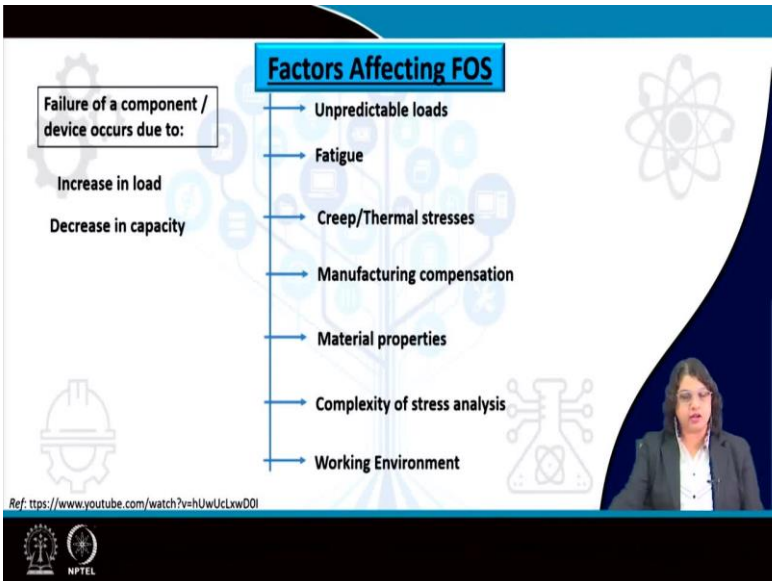

So, factor of safety basically ensures that a component or a device will not fail during the service lifetime that has been already determined. So, however, failure of a component may still occur and that may occur based on the 2 principle reasons first of all, there could be an increase in the load, then the specified value or the limit that is required for that particular service condition or there could be a decrease in the capacity and considering this load and the capacity and the uncertainties in this factors, factor of safety are determined.

However, when we try to find out the factor of safety even for a critical application or for some regular devices, which are used for daily basis for some applications, we need to understand the importance of the following factors for example, the unpredictable loads. In the last lecture, we have seen that how the presence of unpredictable loads in case of a car leads to much higher factor of safety than that for an aircraft which we know that will always runs with some specified number of persons or luggage or the predicted loads or meeting.

There are other factors such as fatigue is a very important factor there also, we have seen an example of an elevator or lift that we typically use which runs with the cables and then there are the fatigue of the individual component of the entire device that we should consider. Creep or thermal stresses becomes very challenging in case we are talking about and high temperature applications such as a furnace or in fact the engines of an aircraft for high temperatures along with the load levels are there and we have to consider that for predicting or for finalizing the factor of safety in such occasions.

Then there could be some manufacturing compensation means that sometimes even if we design accurately during the manufacturing process itself, there could be some loss or there could be some regional stress concentration there could be some manufacturing defects that we have seen such as the machining marks or shrinkage cracks the porosities etc. which can lead to even earlier failure which can trigger the fracture or fatigue failure to occur.

Materials properties are of course, always of concern we need to use particular material for certain applications based on its strength or other properties not only mechanical properties sometimes material is chosen for its being lightweight. For example, for the aircraft application, we along with the mechanical properties, we also have to see about the density or the specific properties like the specific strength and all to see the way that those are capable or whether those are suitable for certain applications.

Complexity of stress analysis so, during the designing process itself we try to figure out the exact values of the stress and based on that the factor of safety are determined but often based on the complexities in the design or based on the variation in the load levels during service it is not always possible to predict the exact load or stress level. So, there is some complexities of the stress analysis and we often approximate things that may or also account for while determining the factor of safety.

And then the working environment is also of concern if we are talking about using a material or component or a device in a marine atmosphere versus an ambient condition of course, there will be some influence of the marine environment and we should always consider that. So, that will also dictate what kind of material we will use, what kind of designing that should be preferred etc. and considering all those factors actually we can determine the efficient factor of safety.

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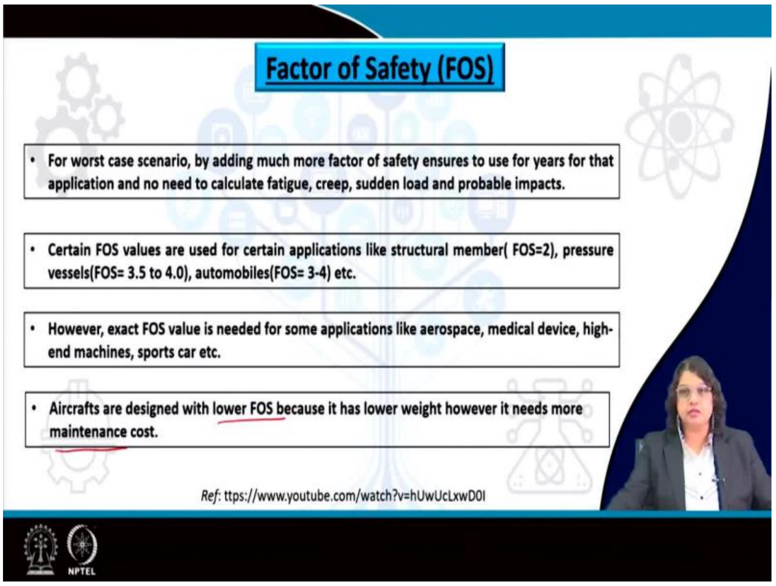

Now, for the worst-case scenario by adding much more factor of safety we can ensure the usage for years or for a certain period of time with knowing that that component or device is not going to fail even if there are worst case scenario that are applicable. So, for that case, we actually do not need to calculate the fatigue or creep or sudden load for individual factors because we anyway are keeping the factor of safety very, very high.

Certain factor values are used for certain applications such as the structural member we use the FOS value of 2, for pressure vessels we use of highest FOS values of 3.5 to 4, for automobiles we have seen that the fracture FOS values are quite high of around 3 to 5 or 4 sometimes.

Now, all these values some particular numbers are as the FOS are determined based on considering all those factors the behavior of creep, the failure conditions under fatigue loading or different kinds of loads etc. All these are being taken care of and finally, some approximation is being done to figure out a number a specific number it is not possible to check each and every bicycle frame or car or aircraft.

Just for the test and then we can use a FOS rather it is being done of course, and we use as typical condition as possible close to the service conditions and then based on that, we kind of consider all the factors and come to a particular number that if FOS is 2 for example, we know that the actual stress that will be implemented during service is 100 MPa, we consider the design stress to be 200 MPa in case the FOS is 2 and based on that we determine all the other factors or all the other design criteria and we design a component based on that.

However, exact FOS value is needed for some applications for example, aerospace application, medical device, high end machine sports car etc. in which we cannot just simply rely on a specified number rather we need the exact value of the FOS. For example, for the case of aerospace, we have already seen that if we cannot keep the FOS to a very high value, there is a tie between the factor of safety and the actual service conditions or the service stress that are required based on which actually the fuel efficiency the overall price everything are being determined.

So, based on those factors also, we need sometimes very specific values of FOS for subtle critical applications. Typically, as I mentioned that aircrafts are designed with lower FOS, because it has lower weight that needs to be maintained, however, it needs more maintenance costs. So, this is another point of concern that we should care for which is that the if the FOS is lower for example, for the case of aircraft, we have seen the FOS is only 1.5 or something like that, but if we keep the FOS, so low, we have to continuously inspect it.

So, it should go under regular inspection, so that there is no scope for any kind of defects to generate and that may lead to the catastrophic failure. At any cost for the safe life design, we do not want the component to fail. So, for that, whatever is needed, we should do and for that the prime importance one is more or less is the factor of safety more is the maintenance that needs to be maintained and for that even higher costs will be also necessary.

So once again, there is a tie that how much cost saving can be done by using a lower FOS and how much costs will be required for the maintenance and based on that we can determine.

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Now, overall, this is what is safe life design that we were discussing so far that products will be safe to use for certain time period and once that time period is over products are often removed from service at a specific design life. So, sometimes it even happens that we could not detect any crack or defect or anything like that, but since the time period is already over, we have to retire that item from usage. So, that is called retirement of course, and often those are completely healthy or it appears like healthy and we still have and we cannot use it.

The reason is that, that there could be some defects that might have generated at some internal part of the structure which could not be detected and we cannot take chances particularly for critical applications. If we are flying in an aircraft we under no circumstances are like it to break. So, we cannot take chances and if the time period is over, we simply have to retired it from the service.

So, safe life design technique is employed particularly in critical systems like which are very difficult to repair or whose failure may cause severe damage to property. Some examples are for the case of pumps or valves or filters; in case of aircraft, the landing gears, air conditioning, etc. those are the components for which the safe life design are typically used.

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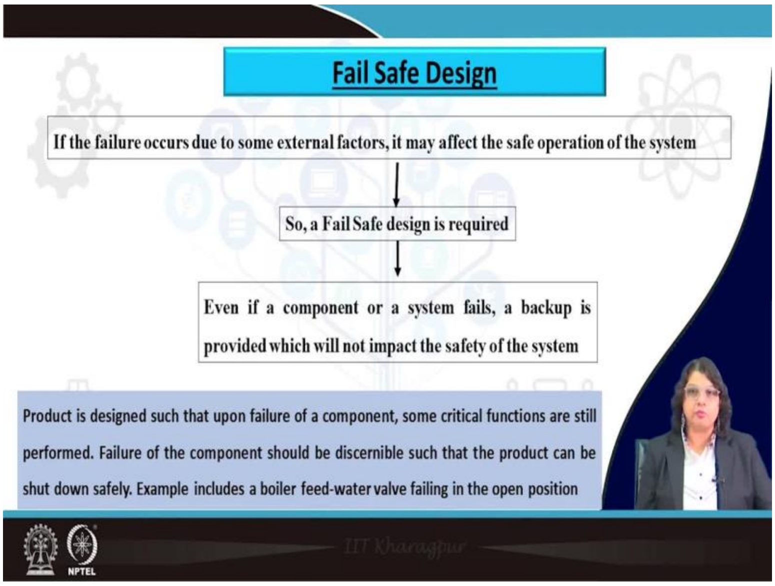

Now, if the Safe Life design is not appropriate, we have to go for the Fail Safe design. So, let us see what is that? Now, if the failure occurs due to some external factors, it may affect the safe operation of any of the component in this case, we are talking about an aircraft, but this is true, this is valid for any of the component and for that, we need a Fail Safe design.

So, even if a component or a system fails, there should be a backup which will not impact the safety of the aircraft or for that matter any component. So, this is what is meant for the Fail Safe design which says that there should not be any failure of the overall component or device should not fail even if one part of the component or one component in general has a failure.

So, a product is designed such that upon failure of a component some critical functions are still performed. Now failure of the component should be discernible such that the product can be shut down safely. So, we get an intimation that some of the competent might have failed, but that may not lead to a catastrophic failure.

So, examples include a boiler feed water valve falling in an open position, more common example would be failure of a bridge for example, if we are talking about the bridge structure, where there is a load sharing mechanism such as the Golden Gate Bridge in California or for that matter, the Vidyasagar Setu in Kolkata, India, you can see that there are the bridges are made in such a way that even if there are failure in some part, there will be load sharing by the other component and that will not affect the overall safety of the bridge such that there will not be any catastrophic failure. One of the component fails the other components will come forward and share the load.

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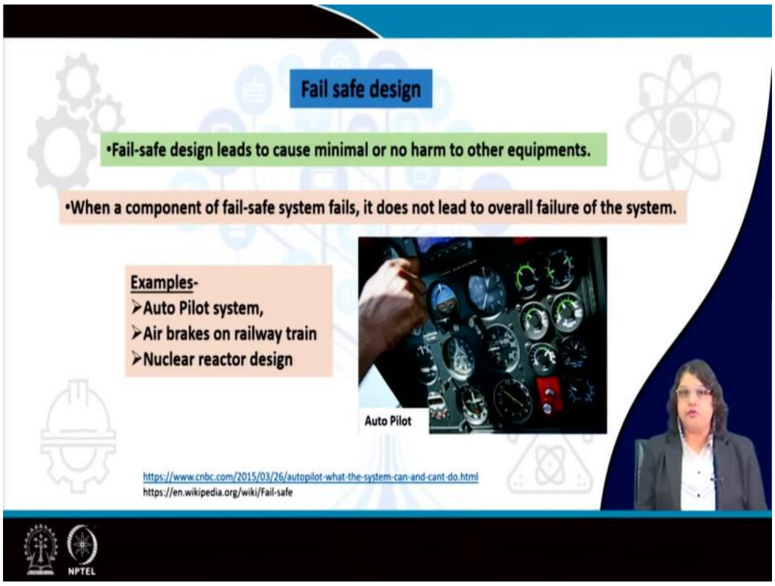

So, Fail Safe design leads to cause minimal or low harm to other equipments and when a component of a Fail Safe system fails, it does not lead to overall failure of the system. Examples are autopilot system or air brakes on railway train. So, in case of critical applications, as we mentioned that for the case of aircraft or for the case of train, even if there are one of the engines fails, there should be some supporting engines which should take forward, same goes for the air brakes.

And for nuclear reactor also we have to maintain the Fail Safe design so, that the entire structure should not fail catastrophically.

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Now, based on this the safe design principle apart from the Safe Life and Fail Safe design, there is a redundant design principle which says that additional product components or systems they take over the principal function of the failed component of a system. In some cases, like in the case of Fail Safe, they can partly take up the function of the failed component or in case of this redundant design, the supporting components can actually entirely take up the principal function of the failed component and the examples include multi engine airplanes.

So, as I mentioned that there are multiple engines and if one of the engines break down there should be others, which not only just share the load, but actually completely overlap it or completely take the action of the failed engine. Standby electric generators are also considered as redundant design and dual inline oil filters, emergency brakes, these are something which actually can completely take over the charges whenever required. So, that the entire device or structure or component should not fail catastrophically.

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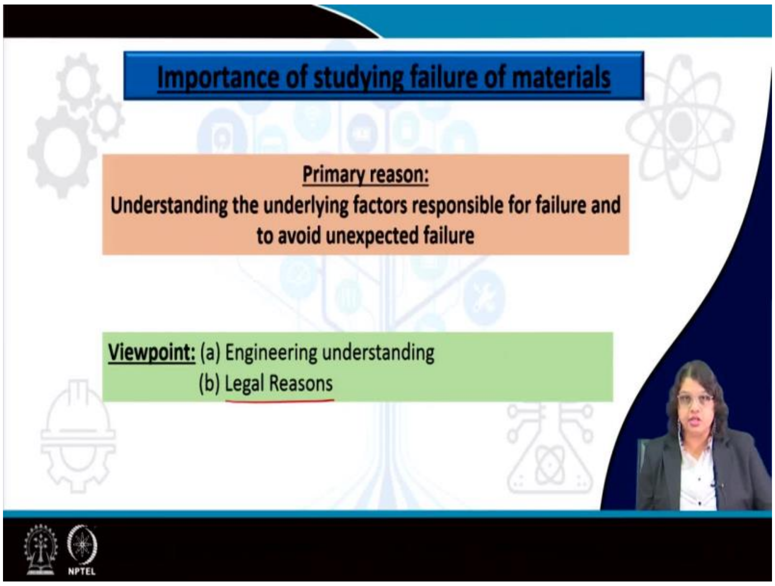

Now, there comes that why should we study failure of materials. So, failure comes with a negative tone and we are having this course itself with all the factors related to failure. So, if something has failed, why should we study that why should we spend so, much of time and resources just to study whatever has already failed in service? Of course, the reason is to understand the underlying factors which are responsible for failure and to avoid unexpected failure.

So, this has been clarified in the very beginning itself that those are the primary reasons but so, far we being having this engineering background, we always think of the reasons for failure as the engineer for the engineering purposes to make the component or make the device better, so, that it may have an improved life or improved performance it should not fail.

But there is another viewpoint also which is very very important for the legal purposes. So, that also makes studying the failure analysis of any device or component very, very important for legal reasons. So, let us see what do we mean by each of these reasons such as engineering or legal.

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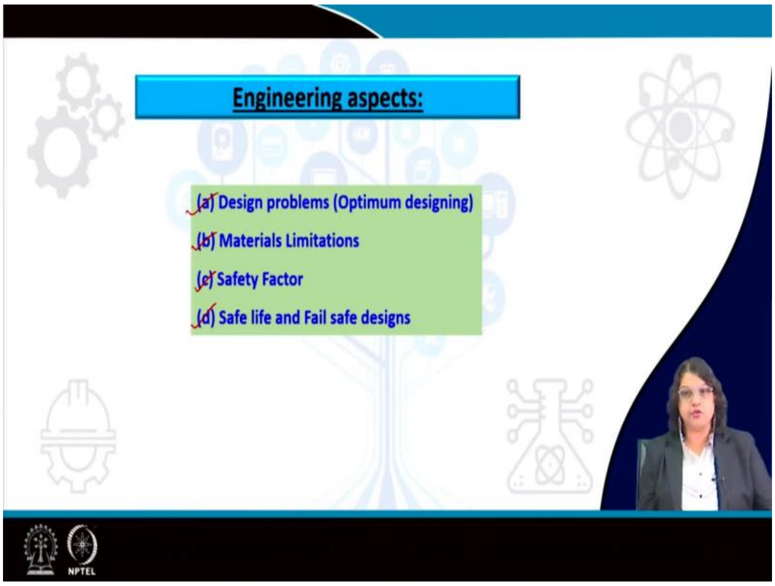

So, the engineering aspects include that what are the problems with the designing and how can we make this how can we make this as the optimum designing, we have already seen that how over designing and under designing could lead to early onset of failure or increased price but optimum designing gives us the best combination of properties with reduced price.

Now, there are some materials limitations, if we are talking about using a material or device in a marine atmosphere, we have to use some specific materials which are corrosive or corrosion resistant. Safety factor is another thing which we have seen how important this is to ensure no failure up to certain period of time and based on that a Safe Life design can be determined or applied in actual practice or there could be Fail Safe design in which even if one of the component fails, other components can share the load or can take up completely to serve the purpose so, that there should not be any catastrophic failure.

So, we are already familiar with all those factors and we are interested to look forward to achieve better and improved performances. So, that is the engineering aspect we are trained to think in that way.

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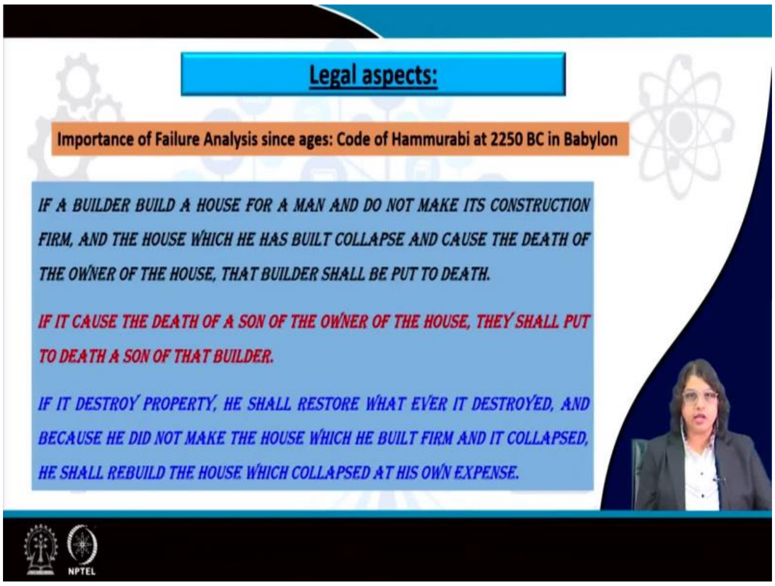

But what all of course is very very important is the legal aspect and not recently this legal aspect has been very, very important since ages. So, let me tell you give you an example of the Code of Hammurabi, the king so, this was in 2250 BC. So, almost 4500 years back in Babylon such kind of written code was found. So, what it says? Very straightforward. So, it says that if a builder build a house for a man and do not make its construction firm enough, and the house which he has built collapse, and cause death of the owner of the house, that builder should be put to death. End of story.

The man died in the house a builder is responsible for making a faulty design or not making the construction appropriate. So, the builder should be put to death. If it cause the death of a son of the owner of the house, they shall put to death a son of that builder. Now, this was very straightforward 4500 years back. So, if the son dies, then the son of the builder should have to die, things are not so straightforward these days, but the third point is very interesting.

So, it says that, if it destroys property, he shall restore. So, he means the builder shall restore whatever it destroyed and because he did not make the house which he built firm and it collapsed, he shall rebuild the house which collapsed at his own expense. So, the builder is being responsible, because he has not made the house up to the mark up to the expectation and he should take up the charges make up for the cost, do it once again and do it properly this time.

So, this is what is often been followed these days also, when we are talking about guarantee or warranty, we often it comes with any product or anything it is not necessarily with the house building but anything that is under those guarantee or warranty period means that if it is malfunctioning, the entire product has to be returned and a fresh one has to be given free of cost.

So, you can see that very structured codes were there even such a long time back and there has a lot of changes on them, but we still follow some specific ways by which we can ensure the life of a component. So, that makes studying fracture fatigue failure analysis very, very important. And often material scientist, materials engineers or failure analysis engineers are being preferred to call for any kind of lawsuits that has happened in case of any failure.

For example, the regular events that occurs is the failure of a car due to a car accident or due to any other reason, and you will often see that there will be a legal advisory like whose fault is that and then often it is necessary to prove that it might be the manufacturers' fault or it might be the drivers fault or some other reason, this is also very, very important if we are talking about the failure of aircraft.

So, there has been a lot of incidents which says that even if the aircraft has failed, there are the insurance companies who are supposed to pay for the failure even and they will like to do all kinds of investigation to show or to identify the actual reason for failure. So, whether it is the failure from the manufacturer side or whether there has been some environmental condition that led to the failure or there has been some faulty parts that are not working or the pilot has made some mistakes or all detailed kinds of analysis are being done to find out the actual reason for failure.

And in case it is being found that this is based on the defect that are already existing, then the manufacturer has to pay for that or has to take up some action to overcome such kind of problem for future. So, that makes studying failure analysis having a very good job profile also particularly for the people who are associated or who are familiar with the materials engineering or the relation between the properties of materials and failure of events, etc.

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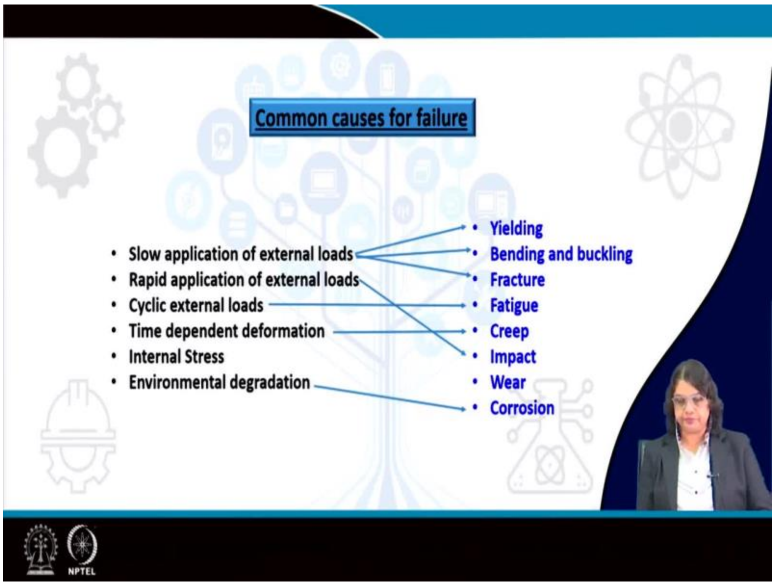

So, let us see what are the common causes for failure? So, typically, whenever there are failures, it has something to do with the mechanical loads, and we are talking about the engineering structures. So, loads are something stress or strain or load or displacement, these are some of the factors which can lead to most of the failures. So, this load can be applied either in a slow manner or in rapid or fast way or there could be cyclic load or time dependent deformation or high temperature deformation, internal stresses could also be present there could be some environmental changes like corrosive atmosphere or high temperature etc., which can lead to failure of structure.

And the properties which are associated with such factors are the following. For example, the slow application loads lead to the yielding or bending or buckling or in the worst case, it may fracture also depending on the kind of material, the kind of stress situation etc. And if there is a rapid application of load, then the impact properties are something which are relevant.

In case there are cyclic external load then the fatigue properties is of concern and we should determine the characteristics depending on the actual application of load we can determine whether it is under high cycle mode or low cycle mode or whether the crack initiation or fatigue crack propagation are of interest and we can understand the actual reasons for failure.

If it comes to time dependent deformation and creep properties of a material is something of importance and environmental degradation of course, comes with corrosion and wear and that is how we can understand that which of the material properties could be relevant for certain applications and based on that we can determine even the worst case condition the FOS etc.

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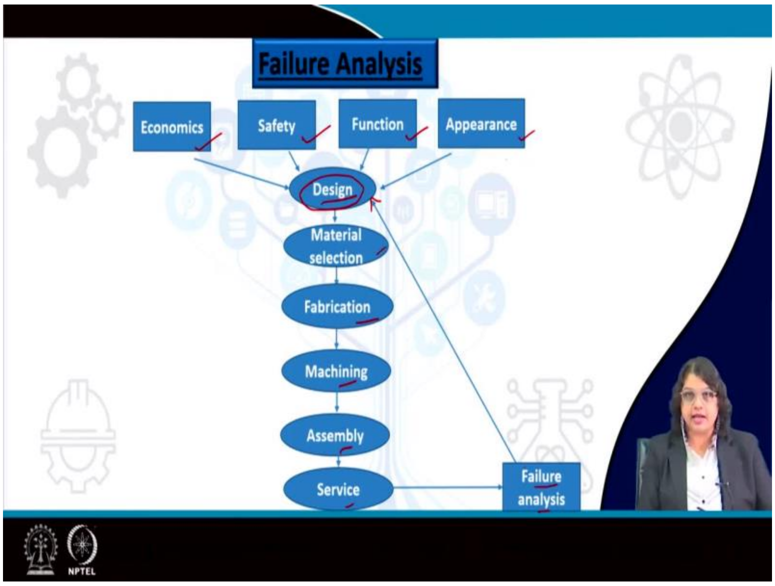

So, actually if we want to go for failure analysis, it actually influences several other factors for example, we already have talked about the importance of designing right we need to have an optimum designing for any component. Now, this optimum designing actually depends on several other factors for example, the economics of course, we cannot make it very, very expensive, at the same time, we cannot also compensate on any other important properties like the safety.

So, economics to make it cost effective safety is of concern of course, for almost all kinds of component and if you are talking about critical components like the biomedical devices or aerospace, it is the safety which is of more importance than even the economics.

But, function of course, it has to serve its purpose whatever it is meant for whatever load level stress level or whatever other kinds of properties that are expected the performances that are expected that should be made. Appearance also has a big role to play actually, whenever we design a component even if you go for buying a simple mobile phone for example, it is the appearance that is also very, very important apart from the functions and all other behavior are the properties we also should care for the appearance.

So, based on that design is determined and we try to fabricate that. Now, when we finalize the design the next question that comes is what materials should we use, if we are talking about an aircraft, we can think of several metallic systems such as the aluminium based alloys or titanium based allies or nickel based super alloys etc. depending on the application areas and where exactly we are applying these materials. Also, there are multi material systems which are used for such kind of structures.

If we are talking about let us say a chair, so, whether we can make this wooden chair or we can make it a metal frame. So, this depends on several other factors including all those 4. Now, once we finalize the material, the next part is fabrication, what kind of procedures should be used for fabrication, the machining, assembly and finally to service and all the steps in between can lead to or can generate some kind of defects at some point and that may lead to the overall failure.

So, once the failure occurs for whatever reason, it could be the environmental reason or it could be any of the defects already present there or it could be because the safe limit has been exceeded whatever is the reason, we need to do a proper failure analysis and then again, we need to start from this designing part once again and go through all the factors.

So, that whatever understanding that we developed from this failure analysis can lead to an overall improvement in the performance, the next time we are designing a component.

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So, it should successful failure analysis should have improvement in the design and that is also in relation to the material selection, manufacturing inspection procedure etcetera every and all these factors should be properly taken care of.

So, here are some examples. So, there are houses in the typhoon prone region of Japan. So, actually these are in Kobe you can see that this is very near to the sea and these are very much prone to have typhoons and as a result, all the structures like the buildings, those are where they are the buildings of the residents are made very strong and robust to overcome or to deal with the typhoon conditions.

Now, what happens is that now this being very near to the sea and Japan being an island country, it is also very much prone to earthquake. So, once there was an earthquake and almost all the structures which were made very robust just to encounter the typhoon, now for the earthquake, those kinds of robust structures are not favorable.

For earthquake prone regions actually structures buildings need to be made from woods or some lightweight materials such that it should not lead to a collapse or should not damage much. Now, since those regions are those cities where having all those robust building the earthquake actually lead to a very catastrophic damage all over the city and that is something very important.

So, failure analysis of course, has been done on the basis of typhoons, but they have not taken care of the fact that there could be an earthquake also. Partly because this is not an earthquake prone zone, but it happened once and that leads to catastrophic failure. So, we cannot ignore any of the factors. And that makes the proper failure analysis and time to time reputation of those very much important. Failure analysis should also implement some evolution in the design principle.

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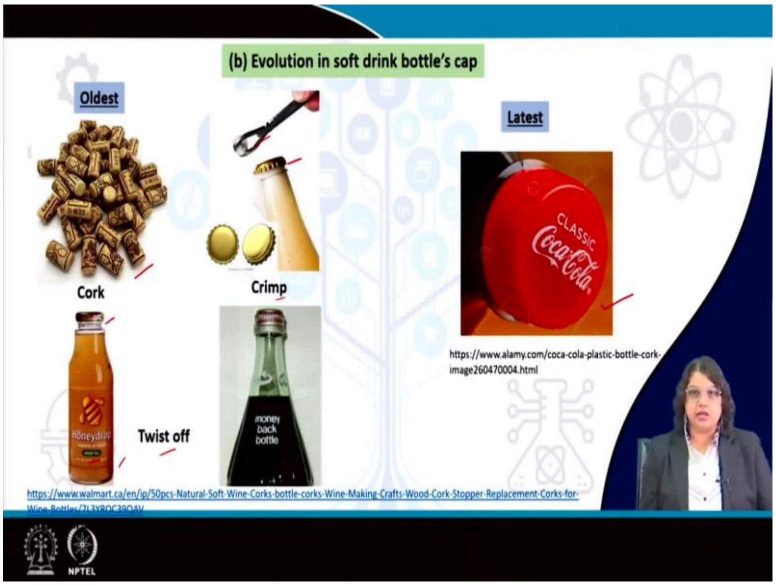

The second example shows the cap of a soda bottle or aerated carbonated water bottle a soft drink bottle. So, initially, there has been corks to make this leak proof, because there is some pressurized liquid there. So, it is typically sealed with cork. The cork as you can understand that it is difficult to open and then there could be a burst sometimes. And then later on, it has been evolved to this kind of metallic caps having the crimps which needs to be open through an opener.

Now, again this become problematic sometimes we do not have the opener, we always have to carry the opener to remove that. So, next it was used or a twist of kind of cap as you can see here, which we often use these days also in case of the jam bottles and all we can simply it is sealed and we can simply twist it and open it, now this is fine.

But for holding jam or in this case, I think this is a green tea that is the bottle here, but if you are talking about this carbonated water or liquid for that matter, then this kind of twist off caps are not so essential not so effective, why because there has been many incidents where they just have some leakage somewhere or there is some defects or some non-uniformity in the cap metal sheet and that led to a catastrophic failure.

So, all at once broke down it because the liquid inside is under pressure. So, that leads to failure of any of the pores or any of the defects on the cap surface can lead to a sudden failure of the entire structure. So, later on, there were some perforated caps which were used and finally, we have moved on to the plastic caps as you can see, which are very convenient to open which are very convenient to restore it or use it for any other purpose.

So, this is how the evolution of the design has happened based on the failure analysis for each of these incidents. So, failure does not necessarily have to be always catastrophic, but based on the convenience of our usage, we can also use the concepts to make things better and make lives easier.

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And based on the different kinds of failure analysis actually, if we are talking about on bottle caps or anything, but a serious or for the engineering components, we actually use the failure analysis to determine or define some codes and specifications and standards. So that we can set a particular system of failure analysis method or particular system of testing, which can be used in worldwide and we have the same kind of results.

So, one of these which are very frequently used, at least for the purpose of materials testing is the ASTM it stands for American Society for Testing and Materials. And most of the tests that we do for example, the tensile compression test, fracture toughness test fatigue test, all those lab scale tests are being done as per the ASTM standards.

So, all the specimen geometries the machine capacity is the load levels. Everything are as per this ASTM standard that need to be maintained for the case of manufacturing also, there are some standards and as you have seen in the flowchart previously, that there are the design the materials, the different manufacturing processes, all these are related and all of these factors could lead to failure.

So, there are actually standards for each of these for the case of manufacturing there is the Occupational Safety and Health Administration or OSHA that is typically being used for the case of design, there is this American Society of Mechanical Engineers that is one of the standards which are again followed worldwide, then there are federal aviation administration standards or codes particularly for the aircraft structures and all.

So, there are several others standards which are there and there are handbooks for that also and these are a few of them, which I mentioned here.

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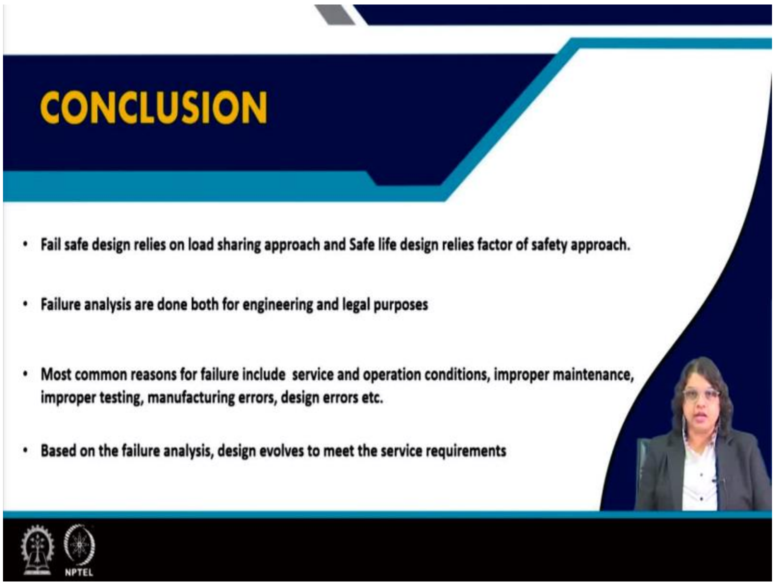

So, let us conclude this lecture with the following points here that Fail Safe design particularly relies on load sharing approach and on the other hand Safe Life design as we have seen relies on the factor of safety and that ensures that no failure within a certain time period. Failure analysis are done both for engineering purpose as well as for legal purpose and we have seen that how legal purpose could actually lead to a very important factor for pursuing the failure analysis.

Most common reasons for failure could be the service or the operation conditions, improper maintenance and improper testing or manufacturing errors or there could be design errors all as well. And based on the failure analysis, there can be evolution in the design to meet the service requirement.

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