Fracture, Fatigue and Failure of Materials
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Lecture 53
Failure Analysis (Contd.)

Hi there, welcome back and we are at the 53rd lecture of this course. Fracture, Fatigue and Failure of Materials. And in this lecture also, we will be continuing on the third module, which is on failure, and we will look up on some more reasons and processes of failure analysis.

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So, let us see what we have in store for this lecture. First of all, we would like to find out the reasons for which we pursue the failure analysis and what are the methods, what how exactly we do the failure analysis. And there are actually different methods the most important one is the root cause analysis as well as the failure mode and effect analysis based on which we perform the failure analysis systematically.

And we will also look into the sequence of events that need to be followed to pursue failure analysis in a professional way.

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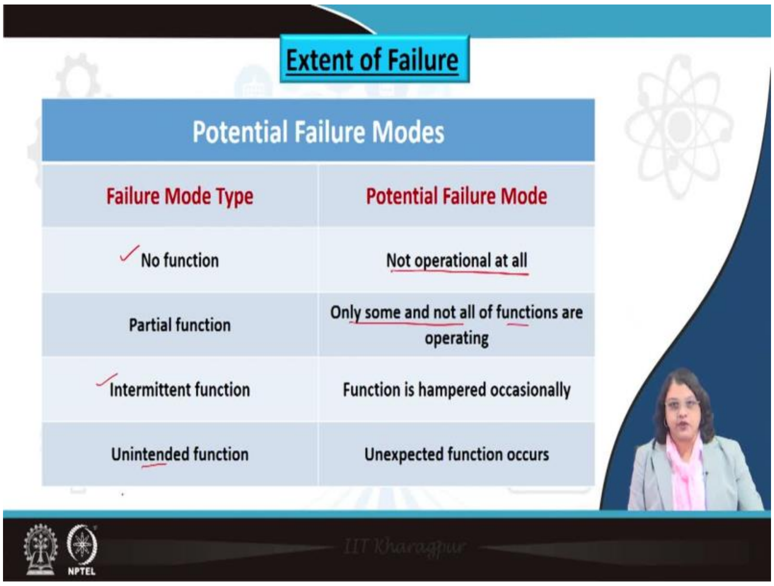

So, we have seen in the last lectures that what exactly is failure? Failure means when something is not able to perform its intended function, it may not always have to break down completely or lead to a catastrophic event, but anything which is not capable of performing its intended function can be termed as failure.

So, there could be different modes of failure, there could be complete disability, which is known as no function, which means that the system or the component is not at all operational also, there could be partial function. So partial function means partial failure as well. So that means that some of the functions are operating, but not all of them. So, only partly it has been failed or there could be intermittent function. And intermittent function means that the function is hampered occasionally we often see that something is not working, and then after a while, it started working again, which does not guarantee however, that it will keep on working properly.

So, there could be some events or failure suddenly and we need to then figure out that what is the actual reason for that and how we can solve that. Or there could be also unintended function, which means that it is still performing but not as per the expectation. So, there could be some unexpected function that occurs. So, these are the different ways by which failures can be categorized.

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And whatever is the case, whether it is a full failure or partial failure, we need to understand that why failures typically happen and then several reasons for failure to happen. The most common are these. Such as there are some service or operation condition changes, which could be due to not proper using that are due to the misusing of the service or the operating conditions or this could be also because of the improper maintenance.

Sometimes something some of the equipment even for our daily usage are supposed to be serviced within some specified time as we have discussed in the last lectures very extensively on the field safe design as well as the safe life design. So, the basis of the safe life design is that it is meant to be useful for certain period of time and within that or even beyond that, we need to do the maintenance properly for the proper usage of this.

Sometimes we do not do that for several reasons and if we are not doing that maintenance properly, then of course, there can be failure of that component or that system as a whole. Sometimes, there are maintenance being done, but there are improper testing or inspection which means that let us say we are talking about a flyover.

So, there has to be repeated inspection to understand whether any crack has generated which can lead to failure. Now, if that kind of testing or inspection has not been done properly, so, we could miss any such formation of defects and that means that we have no idea that when that defect can go grow to a crack and lead to the final failure.

So, if the inspection has not been done properly, certainly there could be even some failure which again will be considered as unexpected. Now there could be errors while assembly system with the multi component system if there is a problem with the assembly itself that of course means that it may not function in a proper way in the expected way and that can lead to failure.

Fabrication or manufacturing errors or other factors which can lead to failure if something is not been fabricated properly or lead to the generation of defects during the process of fabrication itself, that can certainly lead to failure.

So, these test, you might have heard about the additive manufacturing concepts, which means that 3-dimensional object can be built layer by layer like a printing it is also known as 3D-printing, but when we are talking about the metal additive manufactured components, that are often possibilities that that can generate some defects which if we overlook, and we do not analyze the importance or the effect of such kind of defect formation on the overall function, we may lose the proper functionality and that may lead to failure.

So, this was just an example for you to understand the importance of the fabrication or manufacturing errors that can lead to the total failure. Then there could be design errors also now, these are very vital and in certain cases this definitely happened and lead to the catastrophe events.

For example, if the stresses for example, if we are talking about a flyover once again, if the stress that will be implemented on the flyover has not been calculated or estimated properly. So, then of course, whatever design we are making that is not sufficient for the proper functioning of the flyover and that may lead to the failure.

Once again failure does not necessarily mean the whole catastrophic event, but any one component if that is not working, that means that it has failed to perform. Material selection also is very very important and while we are selecting the material, we actually have to consider the material properties also.

For example, if we are talking about an aircraft structure, we know that we have to choose a material which has to be lightweight and at the same time it should have certain strength and elastic modulus and toughness and fatigue resistance, creep resistance etc. all together.

Now, depending on which part of the aircraft we are going to use it whether it will be used in the fuselage or whether it will be used on the wings or at the engines, we can choose different materials. For some cases it is the high temperature as well as the fatigue properties that is of importance, or some cases may be that may not lead to such high temperatures such as the fuselage with respect to, or in comparison to the engine parts.

The engine parts will require higher temperature. The fuselage will not attain such a high temperature so, we can use different materials, but for that at the very first time, we need to understand the properties of the materials which we are going to use, so that we can choose the actual material the proper material for a certain application, if not, then that can lead to some design errors and that may lead to the overall failure afterwards.

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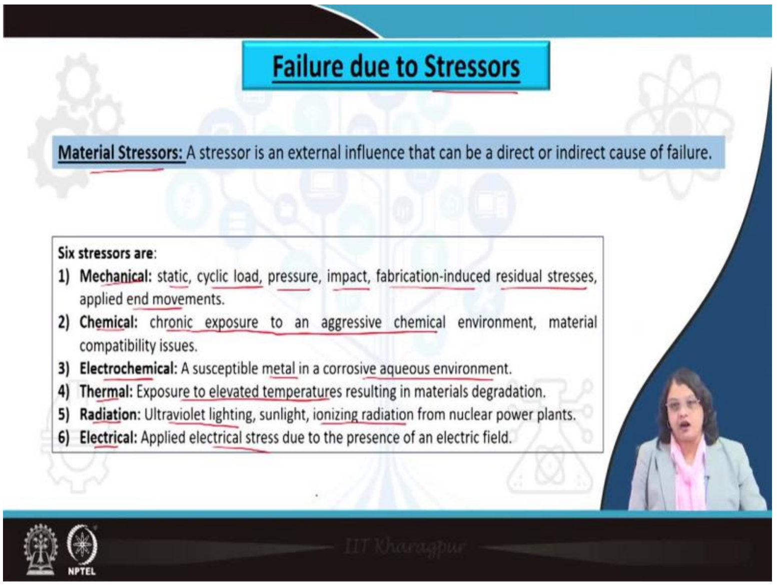

Now, failures often happen due to the stressors now, what is the stressor? This material stressor are actually the external influence that can be direct or indirect cause for the failure. Now, there are six different kinds of stressors that are typically present and that may have an influence on the failure. There could be mechanical stresses, and this mechanical stresses include static or the cyclic load like whether it is a monotonic condition or fatigue condition that is being applied.

Pressure of course, and impact whether the stress is being applied at a higher strain rate or not, whether there are some residual stresses that are generated during the process of fabrication itself or during the end usage. So, this all can act as a mechanical stressor which means that this can lead to a sudden change in the stress values that it is meant to be used for. And as a result that can lead to the defect generation or that can lead to any failure.

There could be chemical stressors as well. And this means that if you are using some component or system within the chronic exposure to an aggressive chemical environment or there could be not an aggressive environment, but there could be two material which are not compatible with each other and there could be some chemical reaction.

So, we have seen the influence of environment assisted cracking in presence of the corrosive or aggressive atmosphere as well as. For example, liquid metal embrittlement we have seen that even two metals which are not compatible with each other can lead to further corrosion or such kind of reactions, that can lead to the overall failure for the functionality of the component or the system as a whole.

Now, similarly, there are electrochemical stressors also, which means that a metal in a corrosive aqueous environment often undergoes this corrosive reaction leads to generation of corrosion product we have seen this along with the presence of stresses can actually deteriorate the condition even further and can lead to early onset of failure.

There could be thermal stressors also particularly relevant when we are using a material or using a component or system at a higher temperature, then this exposure to this elevated temperature results in materials degradation and we know that, how creep properties are very much important for such kind of applications, which are meant to be used at a higher temperature and we should consider all those factors while choosing a certain material or choosing the other parameters at the point of designing itself.

Now, there could be radiation stressors as well particularly these are used for the nuclear reactors or if you are talking of such kind of applications, there could be ultraviolet lighting. Even sunlight is also not favorable for certain materials or certain applications, ionizing radiation, particularly from the nuclear power plants are very much detrimental and we have to take care of this or consider this while the proper usage of the component.

There could be electrical stressors as well, such as the Applied Electrical stress due to the presence of an electric field. So, that can also act as a stress concentration and lead to the generation of defect or crack and lead to the final failure. So, we have to consider all these factors all the stressors while designing at the very first instance.

So, now that we know that there are failure events which are inevitable and there are several reasons for those failures, what we actually need to do after the failure is to do the failure analysis.

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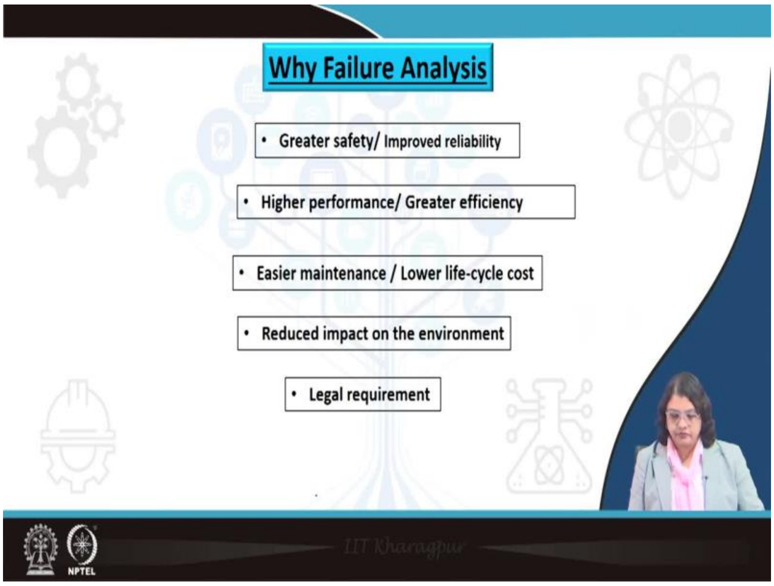

So, this is a kind of post-mortem study in most of the cases and the failure has already happened and we are trying to figure out why exactly has failure happened. So, that other we need to figure it out or find out the reasons for failure, but my question is, why should we do failure analysis? what are the reasons for doing failure analysis as a whole?

So, of course, if we are doing failure analysis, and then if we are implementing the insights that we have developed from the failure analysis, we actually can achieve greater safety or and that means improved reliability for the component the next time it is being used, we know that the possibilities of failure will be reduced to a great extent and that will certainly help in increasing the reliability of the usage.

So, there has been events of failure on several structures. For example, if you are talking about an aircraft, there has been events when we have seen that the aircraft structure has failed completely, an air crash has happened. And if we do not do proper failure analysis, we will not be able to make it better so that we can use the whatever component or whatever system you are talking about, let us say aircraft in this case, we will not be able to use it properly if we are not doing the failure analysis and if we are not learning from where it went wrong, and how what could we do to improve the properties further. So, that also works with improving our reliability as well.

Of course, if we are using that concepts, we will be able to achieve higher performance. And that means we will be able to achieve greater efficiency as well. And that will mean that there will be easier maintenance as well as lower lifecycle costs. So, as we have discussed about the safe life concept, if we are able to determine the life of certain component or system as a whole, then of course, we do not need to do the maintenance at every occasions, but rather we can determine a time period after which the maintenance need to be done.

So if we are reducing the number of times a maintenance need to be done, we are actually reducing the lifecycle cost and if we are reducing the lifecycle cost, we actually are reducing the prices for the overall market usage. Again, let us take the example of an aircraft structure if we know that certain component for example, the wings of the aircraft, that needs to be undergoing maintenance or inspection after a certain period of time and not before that, we can safely use that up to that limit and which means that the lifecycle costs will reduce and if the lifecycle costs will reduce actually that in some way or the other will affect the overall cost of an aircraft or an airplane tickets as such.

So, that means that we will be directly benefited by such kind of events. One of the another reason for failure analysis is to have reduced impact on the environment, there are often attempts to make the components or the systems more and more environment friendly to save our ecosystem. And if something is not working, if we can understand the reasons for the failure, we can actually make them in a better shape, which we can make them much more environment friendly, that should be our target.

Then of course, there is a legal requirement that is very, very important. And again, in the last lectures, we have discussed that how legal requirement could actually be the reason for performing failure analysis and this is valid for almost everything that fails, we perform the failure analysis often based on this legal requirement as well.

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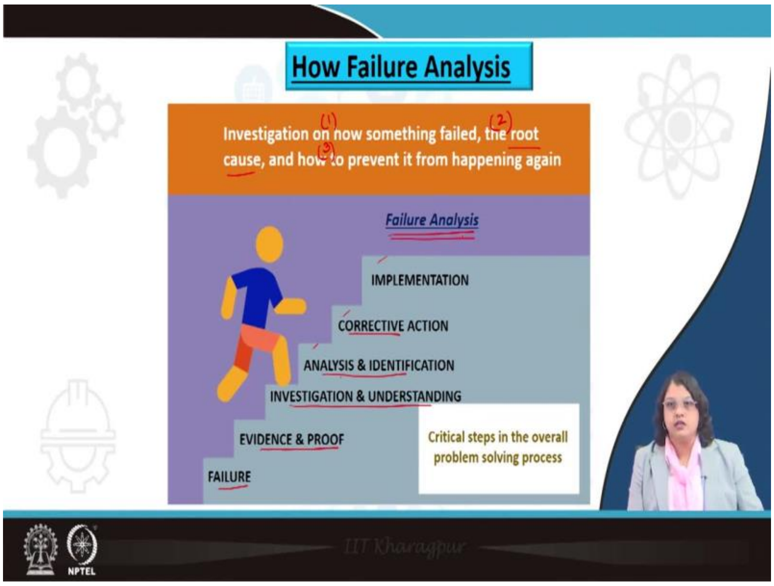

So, how do we do the failure analysis? Actually, there are series of steps, that we need to overcome to do the failure analysis in a proper way. So, investigation should be performed on how something anything which is a component or a system has failed, the actual root cause for the failure and how to prevent it from happening again. So, these are the three steps that need to be followed at the very first hand or actually, these are the basic steps for any kind of failure analysis method. That how this happened? What are the root cause? And how we can use this understanding that we are developing from the failure analysis to prevent future failure events.

As you can see that this is actually like a staircase that we need to climb up to get the failure analysis. So, initially, whenever a failure happened, we need to have the evidence and the proof of failure what actually has failed, and what are the evidence for that? So, it is like a detective job when we do the failure analysis being a detective and to find out what actually has happened.

So, as I mentioned that, this is in most of the cases, this is a post-mortem event, which means that failure has already happened. And we being the materials engineers or material scientists, we look into that from an engineering perspective and see that try to find out that what are the actual reasons that led to the failure? So, based on this evidence, and proof we actually do a detailed investigation to find out the reasons for failure.

So, we need to analyze and identify the root causes. And once we understand that, what are the reasons for failure the next step would be to determine some corrective action which means that if we are implementing this corrective action, then the failure will not happen based on this reasons. There could be other reasons that may lead to the failure, but if you are talking about one particular failure, and we are able to find out the exact reason for the failure, we should try to plan for some corrective actions such that failure should not happen on that component based on this particular reason, that we have found out.

And once we determine these corrective actions, of course, we need to implement that. In the next patch, we should implement the corrective actions that we have determined such that we can get rid of the failure based on that particular reason that we have understood from the failure analysis. So, these are the steps one needs to follow to do the final failure analysis of a broken or a failed system or component.

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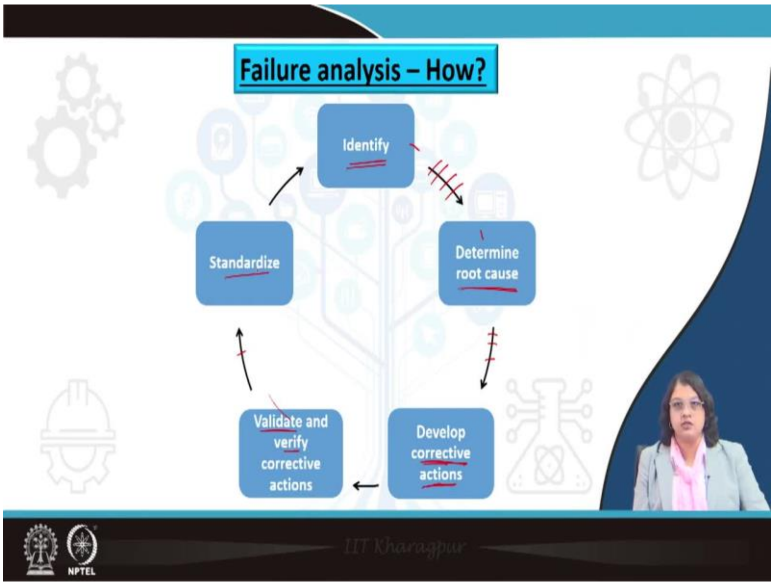

So, how exactly we do that, what are the steps once again, we need to identify initially, what has failed, it is not so easy. If you are thinking that it is very easy, something has failed, and we can just look and understand that this has failed. What is the big deal here? But this is not so simple. If something has failed, we have to understand that where the failure was started from, where exactly has it failed? So that location we need to pinpoint.

So, that is part as the identification and then we need to find out the root cause for the failure. We again need to pursue different kinds of steps from going from this step to this step here itself, there are several other steps that we need to follow to determine the root cause.

And as I mentioned that once we found out the reason, we actually should develop the corrective action again, there are several steps that needs to be followed to come to this step for the corrective actions and once we implement the corrective actions there, we also need to validate this and verify this which means that we have to run and rerun the set of experiments again and again to validate that no failure is happening, if we are implementing this corrective actions.

So, we have to confirm that whatever ways we are suggesting as a corrective action, they should be validated properly. And once it is done, once we are confirmed and totally sure that, if we are using such kind of corrective actions, then failure will not happen at all for this particular reasons, then we need to standardize that, so that others do not need to repeat all the steps again and they can just use a standardized way of generating or fabricating any component and they will not face such kind of failure in practice.

So, as we have already seen that failure analysis leads to a generation of several standards, for example, one is the ASTM standard that we use for testing of materials. So, often these are the results of a series of investigations that have already been performed and we do not need now to repeat those kind of experiments and if we want to test a material, we simply need to get a get hold of an handbook in which all the ways of testing a material has been documented and we can use a standardized procedure.

And if we just simply mentioned that we have used an ASTM standard of something, some number then everyone else in the world whoever is reading our document will understand that this has been performed in a well standardized method and there should be nothing wrong in the testing procedure itself. So, this is just an example of testing method, but there are standards for several other things, which came up from the failure analysis itself.

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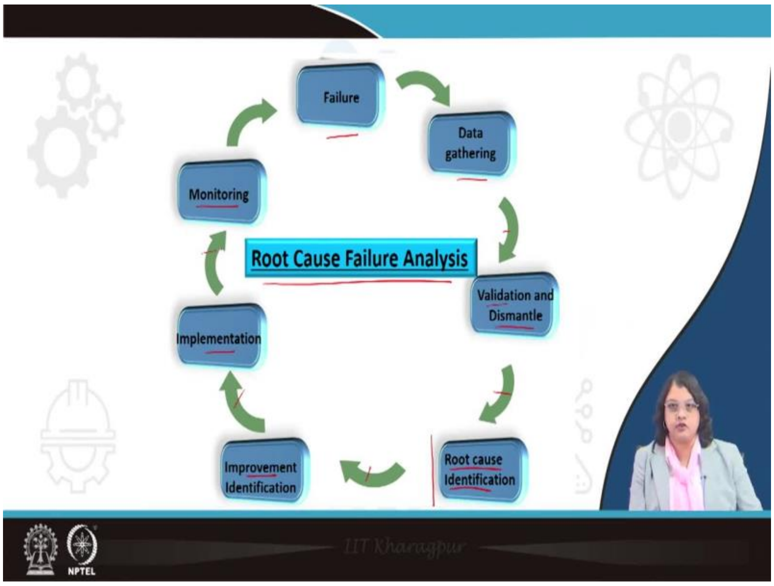

So, basically this root cause failure analysis as I mentioned that this is one of the important method by which failure analysis are being done this also are related to such kind of steps for example, once the failure has happened, we need to gather all the data, which means, when the failure has happened? What was the service condition at the point of failure? How exactly does the fracture surface looks like? Or we can trace back to the actual locations whatever it is, we will discuss in more details later on, but we need to gather all the data that is available there.

And based on that, we actually we often need to validate and dismantle. So, sometimes it is often necessary to dismantle the entire system to figure out or find out where exactly the failure has started. And based on again this kind of investigation, we should be able to find out the root cause, once again, if we are able to find out the root cause, then the next step and this is the most important step if we are stopping till here that we understand the reason for failure then our job is half done, we have understood the reason for failure.

So, what next, we want to improve it better not this time, fine the next time at least it should not fail. So, that means that it needs the improvement, we have to understand that how the improvement can be done and we have to figure out the steps for that and this needs to be implemented. Once it is implemented, we also need to validate that by constant monitoring.

So, these are basically the same kind of steps or general steps that I mentioned. And much more detail analysis should be done at every point at every step to get rid of the failure even for the future events.

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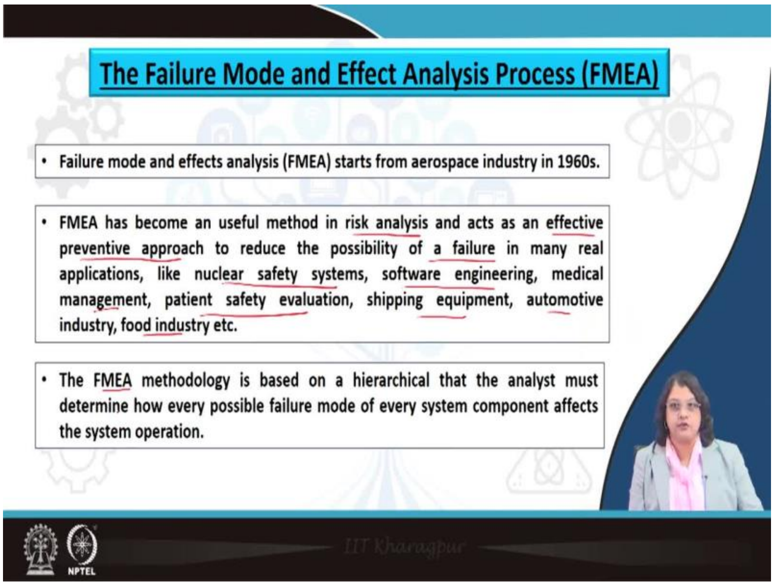

Then there is another method by which failure analysis are being done, which is the Failure Mode and Effect Analysis process, often known as FMEA. So, what it does is, it also are being used for pursuing the systematic failure analysis again a standardized procedure, but it was first used particularly for the aerospace industries in 1960s. And then all it is being used for several other industries as well for particularly for risk analysis and also acts as an effective preventive approach.

So, that we can prevent the failure if we do such kind of analysis beforehand. So, overall the possibilities of failure are being reduced and this kind of method is particularly suitable for nuclear safety system, software engineering, medical management often which are very very critical applications we need to do this FMEA procedure beforehand to understand that failure will not happen, patient safety valuation, shipping equipment, automotive industries food industries etc. such kind of analysis method are often used.

Basically, this FMEA methodology is based on a hierarchy that the analyst must determine the person who is doing the failure analysis must determine how every possible failure mode of every system component affects the system operation. So, if there is most of the cases we use multicomponent system right a system is made up of several components.

Now, each of these components are meant to perform different, different functions. And as a result the overall function of the system is achieved. Now, how the failure of each of this component can affect the overall performance of the system that is of importance and that needs to be done sequentially to understand the reasons for failure and how we can prevent that.

So, root cause analysis, where mostly dealing with the post mortem analysis when the failure has already happened and we try to figure out the actual reason for that and then we try to improve condition such that failure will not happen. FMEA methodology on the other hand, it is mode of an analysis method which is related to the failure of each individual component to figure out the ways by which the overall system failure can be affected.

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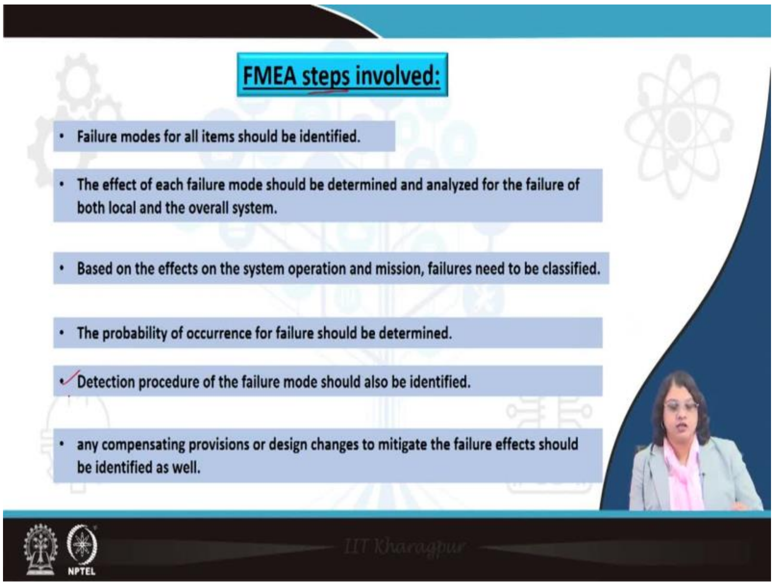

So, if we are talking about the steps here for FMEA we know that for this to be used, actually failure modes of all items should be identified at the very first place. So, how the each of these components are being failed, that needs to be understood and the effect of each failure mode should be determined and analyze for the failure of both the local performance as well as the overall system.

And based on the effects on the system operation admission failure needs to be classified as well. The overall performance of the system or the failure of each of the component leads to some local failure. So, all this needs to be well understood documented and classified. The probability of occurrence or failure should be determined as well.

And the detection procedure or failure modes should be identified. Now, this is also very, very important step, we have to understand that when we are saying that we need to do periodic inspection, what do we mean by inspection? What are the exact locations on which we need to do the inspection?

For example, if you are talking about an aircraft structure or a bridge of flyovers, and those are huge structures. So, when we are doing inspection, we cannot do this on every inch or every millimeter scale, but at the same time, we need to do the inspection in the micro level to figure out if there has been any millimeter level or sub millimeter level crack that has initiated.

So, what are the exact locations that we should look for maybe there could be some corner some stress concentration region some join some welding, which are the more prone to initiate cracks or defects and we should look for that. So, this detection procedure and how we can do that, what are the typical characterization methods that should be used for an inspection, we cannot do a TEM study for example in our inspection.

We cannot actually dismantle in some cases, all the components sometimes we have to do this as a whole structure and we then have to identify that how the inspection can be done so, that we can look for individual components even in a multi component system. So, all this needs to be very well understood. Any compensating provisions or design changes to mitigate the failure efforts should be identified as well as per the FMEA steps.

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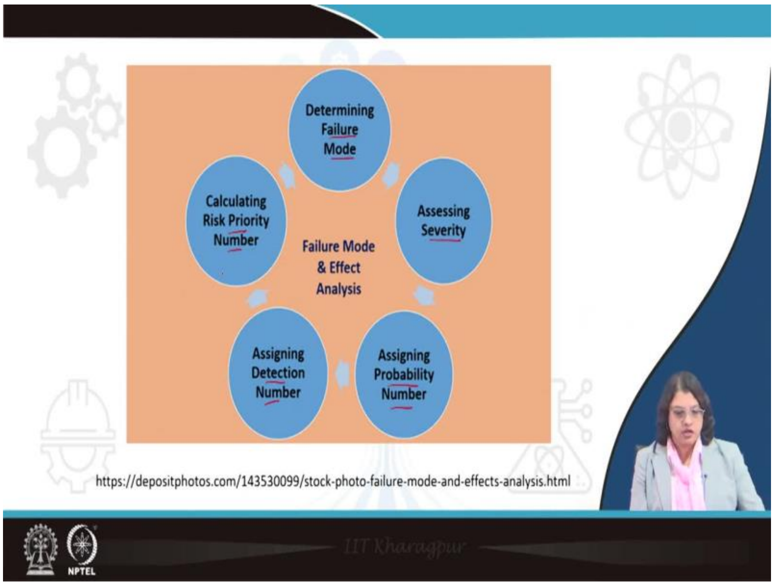

So again when we are looking for the different steps in a flowchart, we see that we initially need to understand the failure mode. And based on the severity of the failure mode for each of the component, we assign a probability number so that we can understand that, this has a possibilities of failure may be a higher possibilities of failure or lower possibilities of failure etc. And based on that we need to also assign a detection number and circulate the risk priority number.

So, by this way, we can understand that if you are using such component or such system, it has a certain probability of failure and we have to always use it for with this knowledge beforehand.

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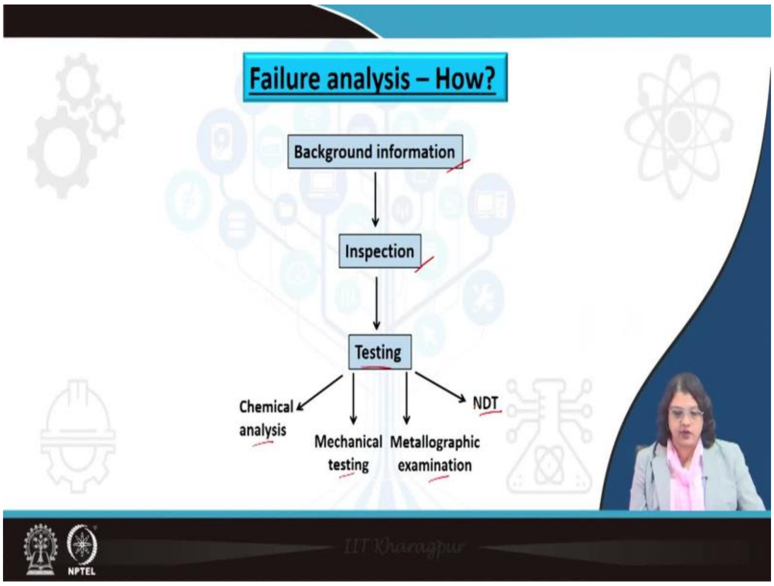

So, let us see how actually in practice, we are doing the failure analysis by whichever mode we are talking about whether this is a root cause analysis or FMEA we need to follow some steps, as we have understood. So, far all this has been told in a virtual way in a qualitative way, where we have explained the steps.

Now, let us see how we actually do it in practice particularly if we are talking about the metallurgical or materials engineers coming into the practice of failure analysis. So, as I mentioned, that initially we need to have all the background information like a true and honest detective, we have to gather all the information, which could be relevant at some point for the failure analysis.

And following that, we need to do the proper inspection of the failed component or system or failure surface and we have to use different kinds of testing procedures and this may include some chemical analysis, mechanical testing metallographic examination, sometimes a nondestructive testing also in in some cases, we cannot destroy the component or the broken piece also. So, we need to do the nondestructive testing as well.

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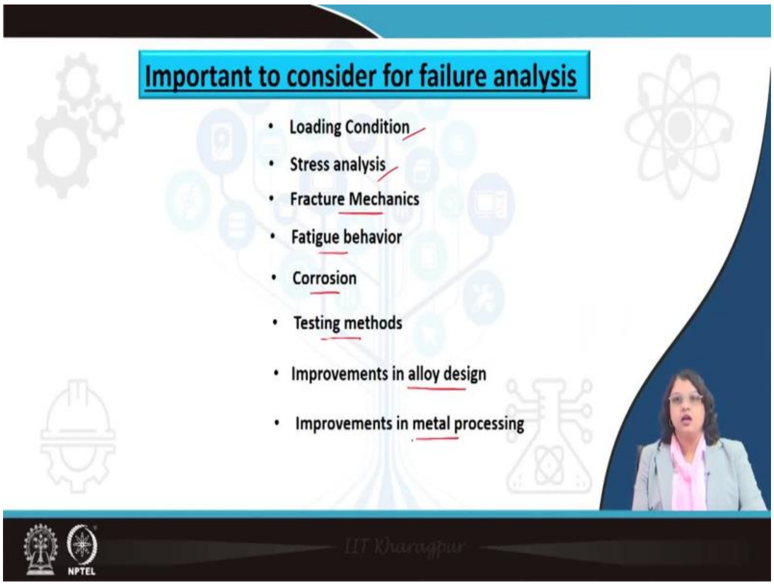

But before we do the failure analysis, we also need to understand that what we are looking for we have to have an idea, we do not know the exact reason for failure yet, because the analysis has not been completed, but still we have to understand that what are the probable reasons for failure and what are the exact factors that we are looking at. We cannot do things blindly.

So, typically, the reasons for failure of engineering structures happen because of the following relevant conditions such as the loading condition, or the stress analysis, at the different sections, then there could be reasons like fracture mechanics as a whole whether the mode of failure what kind of mode of failure has happened, fatigue behavior, of course, whether the component or system has undergone cyclic loading or not, whether there has been some influence of environment on the failure different kinds of testing methods that we are going to use, we have to have knowledge about such kind of testing methods as well, we cannot simply pursue a testing a characterization if we do not understand about the process of testing as well as what kind of results it may generate .

And the alloy designing as well as metal processing, those are also some of the factors that we need to have some knowledge on.

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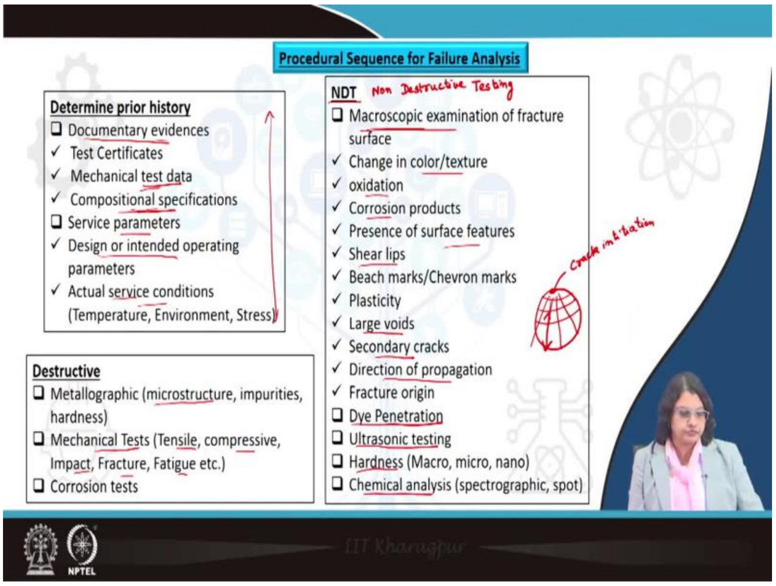

So, let us see the procedural sequence that are used for the failure analysis. So, first of all, we need to find out the prior history and for the prior history, we typically have to rely on that documentary evidences. So, there are the test certificate, some mechanical test data the compositional specifications that has been already provided by the supplier or vendor or the manufacturer.

When we are purchasing let us say we are purchasing a block of steel. Then if we are purchasing that for any uses that we are talking about whoever is supplying that should give us this documentary evidences like what is the composition of the steel what are the typical mechanical properties whether it has a high strength low strength part of the quantified values of the strength the ductility toughness etc.

So, all those details have to be provided based on this only be can know that whether this block of steel is suitable for certain application or not. And the service parameters are often being mentioned also in those documents like whether we can use this in the moist condition in the for the marine structures or not, whether there are some design or intended operating parameters that need to be maintained the actual service condition whether we can use this at high temperature or not all those need to be mentioned.

So, if you are talking about an aircraft structure something that we are going to use for the wings of the aircraft, let us say we have to use a material and if we are buying titanium or an aluminium alloys for such application, we need to have the information about the exact composition, the mechanical properties of those materials, the actual service conditions for which it should be suitable, and then we have to use this for the service.

But still failure may happen. So, these are the information that we can gather after the failure about the material, but still failure has happened and now, our job is to find out the reason why? So, of course, we need to do the testing to understand whether all these conditions has been met or not.

Initially, we will go with the non-destructive testing. So, let me just write the full form here. So, NDT are often used at the very first hand so, that we do not destroy the broken piece and we can still gather some information and reasons for the failure. So, first of all, we will do a macroscopic examination of the fracture surface if there is any change in color or texture, which may indicate some oxidation or corrosion that might have happened presence of surface features if there are any different kinds of features for example, we have already seen that how the ductile fracture and the brittle fracture, how different they will look like, if there are any signatures for fatigue failure that has happened, whether we can see the beach marks, so, all those things can be understood from the macroscopic examination as well.

So, the shear lips indicates the fracture as in the ductile mode again on the width of the shear lip we can determine whether it is very much ductile or moderately ductile etcetera, we can also actually understand whether it has undergone plane strain or plane stress condition just by looking on the fracture stress on the fracture surface itself.

Whether we can see some large void on the practice surface which indicate the possible sites for the crack initiation at the very first place, whether we can see some secondary cracks, if we see some secondary cracks, we can understand about the stress levels there also whether this is at the initial value of ΔK or higher values of ΔK.

In case of fatigue fracture we have seen how the cracks will look different in case we are at the different regimes of fracture. Direction of propagation can also be understood from the fracture surface itself. If for example, in case of fatigue failure, we know that the fracture mostly initiates from the surface. So, this is the crack initiation site and how do we figure this initiation site because from the initiation itself we can see some patterns which will indicate that the crack has actually started from here and it follows or it moves forward along this direction of the final fracture. So, we can trace back the direction and lead to the crack initiation site.

We can do some dye penetration tests or ultrasonic testing also to find out if there is any change in the modulus or where the crack is initiated from, we can do some hardness testing like the indentation method, which is not totally non-destructive, but also we are not doing any major cutting of the samples or specimen so, that can be still considered as a non-destructive mode itself.

And of course, we should do the chemical analysis to figure out if there is any composition or change or if the composition has been as per the prescribed values, etcetera. And once we are done with the non-destructive testing, often we need to do the destructive testing as well, for which we need to have a detailed understanding about the microstructure.

So, now, the just the fracture surface at the macroscopic level might not be sufficient and we need to go for microscopic or sometimes even in the sub-micron level to understand the different features or if there are presence of inclusions, if they presence of striations which signify once again the fatigue loading based on the width of the striation itself, we can figure out the loading conditions. So, all those needs to be determined.

And then of course, in most of the cases we need to do the mechanical testing, such as tension test, compression tests, sometimes bending tests, impact fracture, fatigue all those kinds of tests needs to be done. First of all to see whether the values that has been quoted in the certificates whether they are matching with that or even there could be some changes in the local values based on the composition of changes or based on some particular environmental condition. So, we can figure out the actual reason for failure based on all those detailed kinds of testing.

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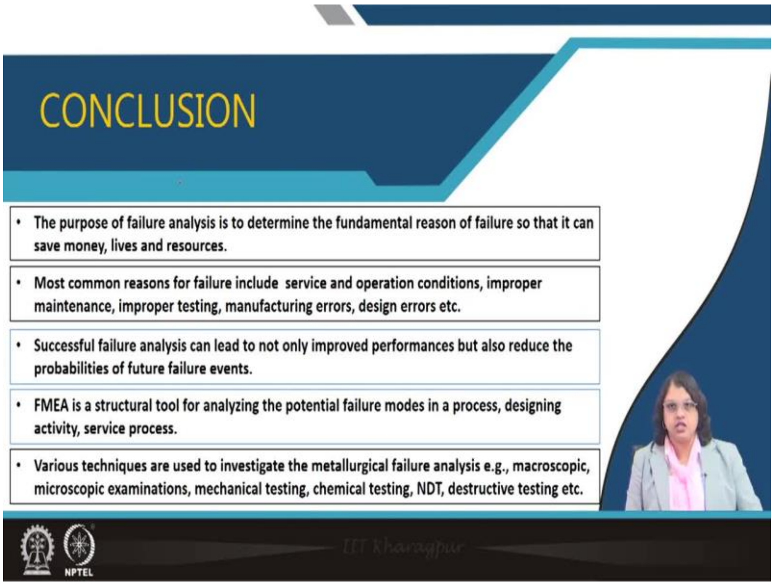

So, those are the ways by which failure analysis needs to be done in a systematic manner and let us conclude this lecture with the following points, that the purpose of failure analysis is to determine the fundamental reason of failure so, that it can save money, lives and resources. Most common reasons for failure include service and operation conditions improper maintenance, improper testing also sometimes can lead to failure and errors in manufacturing or even calculating the design conditions etc.

Successful failure analysis if we do that can lead to not only improved performances, but also reduces the probabilities of future failure events. And we have seen that how we can use the FMEA method for analyzing the potential failure modes in a process, designing activity and service conditions.

So, various techniques are used to investigate the metallurgical failure analysis. Typically, we do the macroscopic investigation followed by the microscopic examinations mechanical testing, chemical testing and of course, non-destructive testing at the initial phase and then the some destructive testing as well.

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