Fracture, Fatigue and Failure of Materials
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Lecture 51
Failure Analysis

Hello everyone, we are at the 51st lecture of this course Fracture Fatigue and Failure of Materials. And today we are starting the third module which is failure. And we will be discussing on some topics related to failure analysis.

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So, let us see what we have in store for this lecture. First of all, we will get you introduced to the concepts of failure analysis. And then I will talk about the optimum design, particularly the safe life design, which is often used to prevent failure or get improved life of the component. And I will also discuss about the factor of safety.

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So, let us see, what do we actually mean by failure analysis. So, basically, whatever insights that we have developed so far on the fracture mechanics, as well as the fatigue characteristics of materials, and along with that time to time, we have also discussed the influence of micro structures on the mechanical behavior such as the strength toughness, fatigue behavior, etc. just to improve or control the various mechanical characteristics of materials as per the required service conditions. So, now, we are going to use up all those insights or concepts that we have developed to analyze the real service failure.

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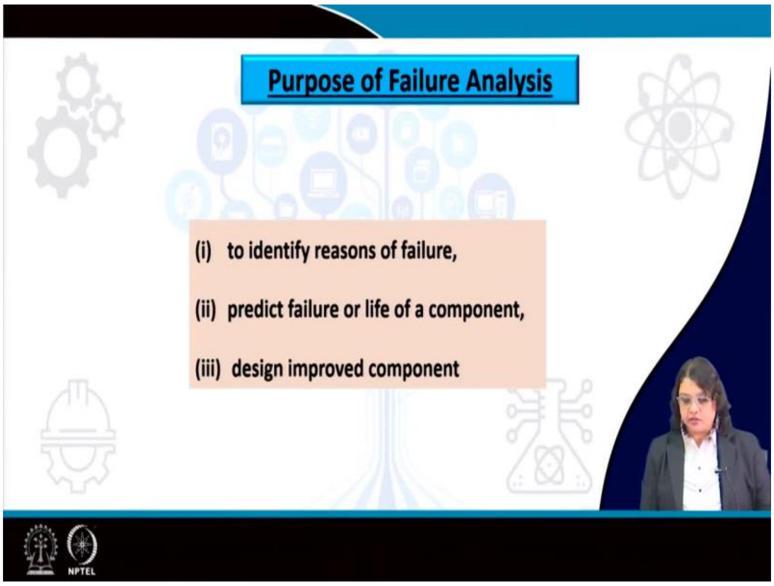

And the purpose actually of failure analysis in general is first of all to identify the actual reasons for failure, why the failure has happened. Again, the main purpose is to predict failure or life of a component, so, that we can in advance be prepared about what is the estimated lifetime and that along with the failure analysis, we can design improved component with improved performances or improved life based on the proper failure analysis.

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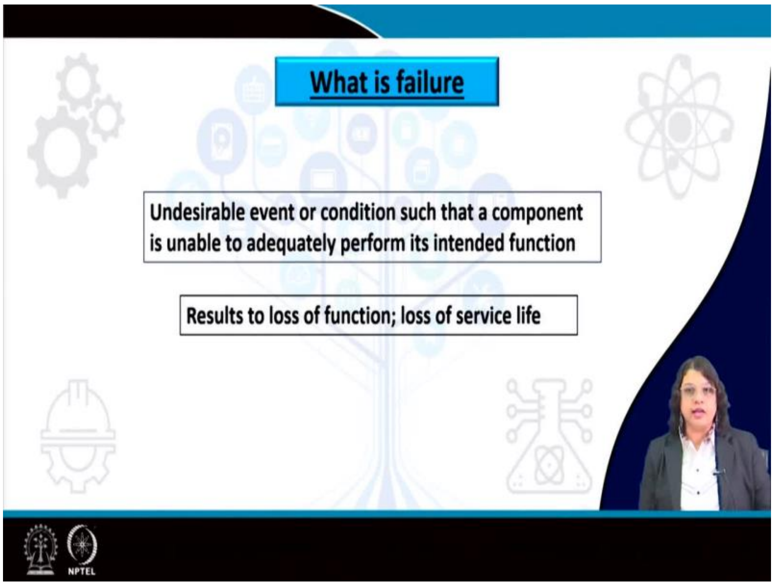

So, for that, first of all, we need to understand what is failure? Now, failure does not always necessarily means fracture or fatigue, rather failure means that whenever there is an undesirable event or condition such that a component is unable to adequately perform its intended function. So, what it was meant to be and it is not capable of performing up to that limit is what is termed as failure.

So, that failure may results to loss of function at the very first place and in some cases that are loss of service life and on the occasion of catastrophic failure there are even loss of lives as well.

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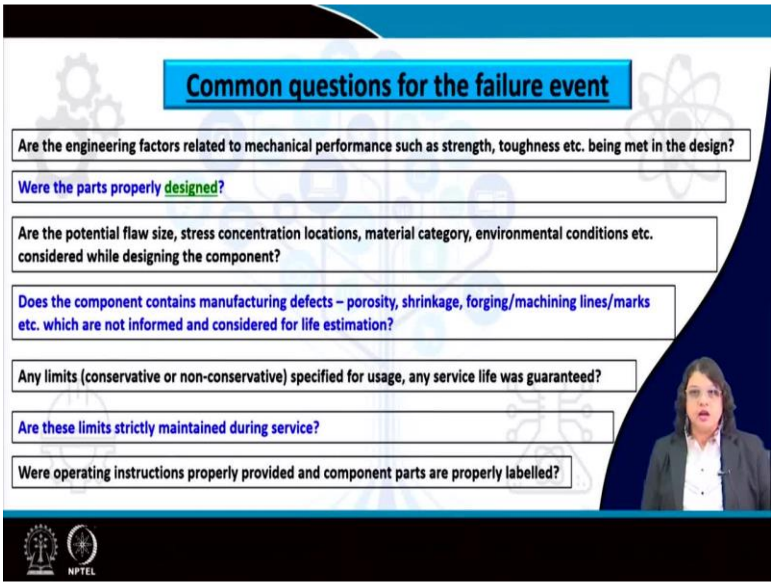

So, whenever a failure occurs the first question or a series of questions that we commonly asked are the following. Are these engineering factors related to the mechanical performance such as the strength toughness etc for the component are being made properly in the design or not? Were the parts properly designed? and when we say properly design, what we actually mean is are the potential flaw size, stress concentration locations, material, different kinds of materials we can use for certain applications, the environmental conditions for service etc all these factors have been considered for designing the component or not?

Does the component contains manufacturing defects such as the porosity, shrinkage, forging or machining marks etc. and which are not informed and considered for the life estimation? So, whenever we purchase anything you can think of anything for even our regular use, we understand that, that kind of component that device that equipment must have some kind of life estimation, we understand that this will survive for a year or 2 years or 10 years or something like that.

And if something is failing even before that, that is a matter of concern and then we have to understand that whether all the design or all other considerations has been properly taken care of or not. So, the next question would be any limits has been set particularly for the usage or any service life that was guaranteed? We often purchase things which has some kind of guarantee or warranty.

So, that means that that component or device is supposed to run for that number of years or whatever timeframe that has been provided to us and are these limits strictly maintained during service?

So, there are often some limits, we cannot use it for higher stresses or for strains or any other kinds of such restrictions, whether those restrictions has been properly maintained or not, for example, if we buy any household equipment, it comes with a warranty period of course, but then at the same time, if we are damaging it by any means, due to our own negligence, such as it is falling down, then those kind of damages will not be incurred by the warranty period.

So, that is what we need to ensure that whether whatever limits has been specified, whether those has been properly maintained or not during the service conditions. And of course, this is also very important that all the operating instructions should be properly provided and the components should be properly labeled. So, that later on we cannot claim that something has not been informed properly and based on that, some failure might have happened also.

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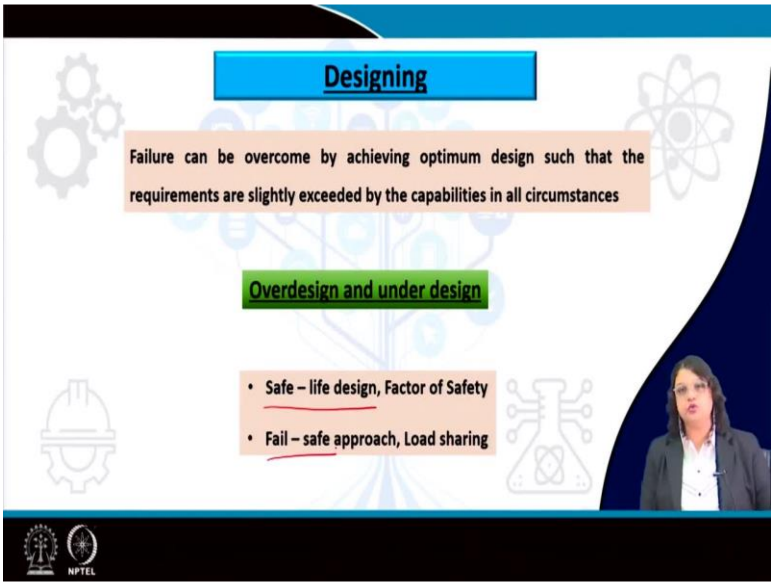

So, this also leads us to the very important factor which is designing, we need to properly design any component or device or instrument equipment, whatever you can think of. So, failure actually can be overcome by achieving the optimum design such that now, what is optimum design? Design means that, the requirements whatever the service requirements are, this could be based on in terms of stress or strain or some other kinds of performances and those requirements should be slightly exceeded by the capabilities and that should be done in all circumstances.

So, there are ways by which we can either over design it or under design it. Over designing means when the requirements are highly exceeded by the capabilities means that we need a certain equipment for a certain performance and it is actually capable of performing to a much higher level than that. So, that means that obviously, it will not fail in the service condition at any cost. So, that is known as the over designing.

And under designing means that when the requirements are not being met by the capabilities of the components, so, that is under designing, but what we actually need is an optimum design. Along with that, there are 2 other kinds of ways by which we typically design any kind of engineering components which are known as the safe life design and the fail-safe design.

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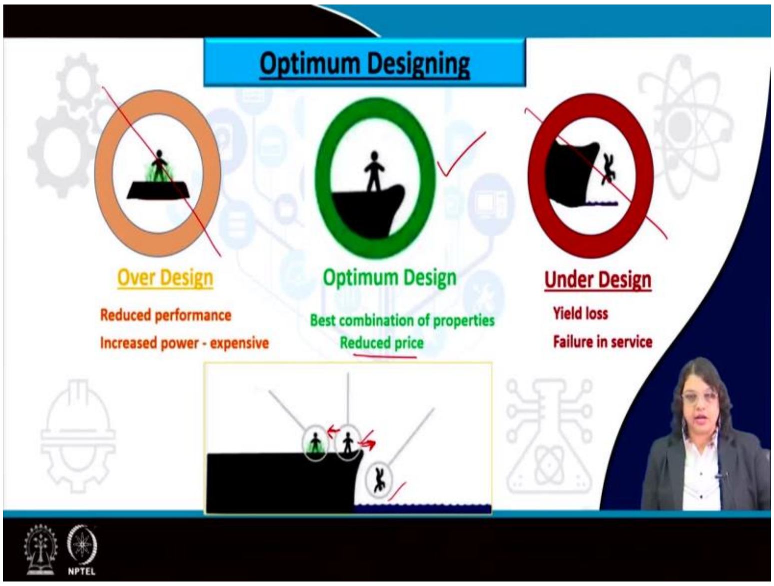

So, we will go through each of this, but first of all, let us see, what do we mean by the optimum designing? So, as I mentioned over designing means that when the requirements are highly exceeded by the capabilities. In that case, of course, we do ensure that there will not be any failure in the service condition, but that will however, it may reduce the performance to some extent, it may make the device slow.

For example, for the case of aircrafts, if we try to make it over designed, it will be so heavy that it will not be able to fly at all. So, that in that sense, it is not performing its optimum or whatever purpose it is meant for. And of course, over designing always comes with an additional costs. So, it makes the product expensive and we often need to when we are thinking of the engineering applications or structural applications, cost is another factor which is a very important factor that we should also keep in mind while designing. So over designing in that way can be ruled out.

On the other hand under designing means that it is maybe just up to the limit in for which the requirement and the capabilities are the same or maybe the capabilities are little less than the requirement. So in that case, there will be definitely failure during the service and this is not an intended situation. So this is obviously again ruled out.

So what we are left with then is the optimum design in which we obtain the best combination of properties. As you have already seen in the different events. For example, when we are talking about strength and toughness we know that we strength and toughness usually are inversely related. So, if we are enhancing the strength we have to cut off all the toughness.

So, depending on the performance we have to come to an optimum level so that the strength is not too high or the toughness is not too low. So, that best combination of properties can only be obtained through optimal design and of course, the optimum design since it is not as much overly done as over design. So, the price is also comes down to quite a bit.

So, this is just an example of how the over and under designing are? And how that will lead to total failure and whereas, the optimum design is just enough so, we cannot move in this way not necessarily need to move in this way or we should not never move in that way. So, we have to be at the optimum designing level always to get the best performance at the most convenient price.

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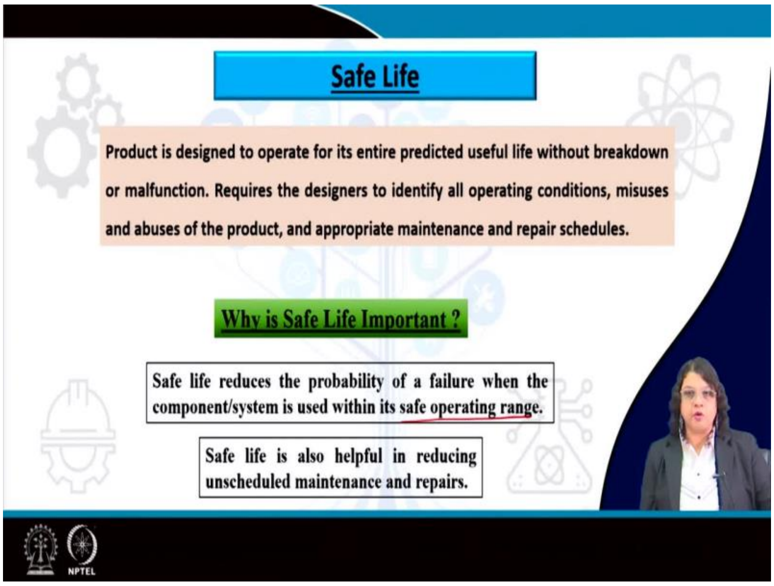

Now, let us see, what safe life is? Typically, in case of a safe life, the product is designed to operate for its entire predicted useful life without breakdown or without any kind of malfunction. So, this requires the designers to identify all the operating conditions, whatever the stress level will be, or whatever if there are any environmental conditions, everything should be taken care of while designing.

Even the misuses and abuses of the product will also be considered and appropriate maintenance and repair schedule also need to be done. So, when we are talking about a component which is designed under the safe life criteria, we should know that it will not fail under any circumstances even if we are misusing this or over applying the stress it will not fail under any condition up to the limit.

Now, we cannot make such things for infinite lifetime, we have to predict some timeframe also. So, let us say we are purchasing a component or an equipment which will survive for one year guaranteed without any failures after one year, we have to do some maintenance or some repair so that it can survive for even longer. So, that is what is safe life and why is it important? Because it reduces the probability of failure when the component or system is used within its safe operating range. So, we kind a guarantee that it will not fail within that timeframe.

Safe life is also helpful in reducing unscheduled maintenance or repair. So, we have to have a timeframe over which the maintenance has to be done. For example, if we are talking about let us say an aircraft, we cannot do a daily basis maintenance or checking of whether there has been any defect formation or not or for the example of a bridge, but you can also see that bridges or flyovers or such kind of structure super structures are often being repeatedly undergo maintenance schedule or they have been investigated for the development of any kind of cracks or defects or any such things which can lead to failure.

So, we predict some timeframe after which it will run smoothly. And after that we need to determine whether there has been any defect or not if there has been then we have to do the required procedure to overcome this defect or maybe even stop it from service and if not, then we can again keep on continuing using that based on the modified timeframe now.

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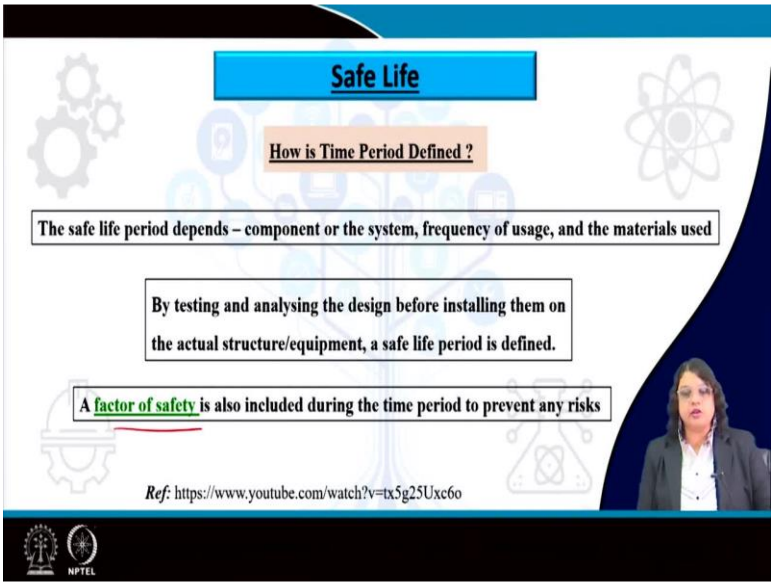

So, that means that this timeframe is very, very important for safe life. Safe life cannot be for infinite life we have to define a time period over which it will behave in a safe life form. So, how is this time period defined? Basically, the safe life period depends on the components or the system the frequency of usage and materials used. If you are talking about flyover let us say then what kind of vehicles are using that what is the frequency of usage what are the materials that are used for this flyover?

So, based on that we can estimate a time period. We have already seen in the case of fatigue behavior that how we can determine the lifetime of a bridge or a flyover and there are some other complexities also that we need to consider while we are designing it for the real situation.

And of course, we need to pursue detailed testing and analyzing the design before installing them on the actual structure or equipment and a safe life is defined based on that. So, of course, there are a series of investigations that are done on the lab scale and not only that, even the entire structure sometimes are tested for example, aircrafts are tested, the entire structure of the aircrafts are tested even the various parts are being tested for different frequencies or different loading conditions, not only aircraft even the commonly used bicycles that we regularly use on a daily basis.

Even for such kind of items also all the parts are being tested the entire bicycle are being fatigue tested to find out the performance of that and then only we can define a safe life period, and the most important thing for safe life is that we consider a factor of safety during the time period to prevent any risks.

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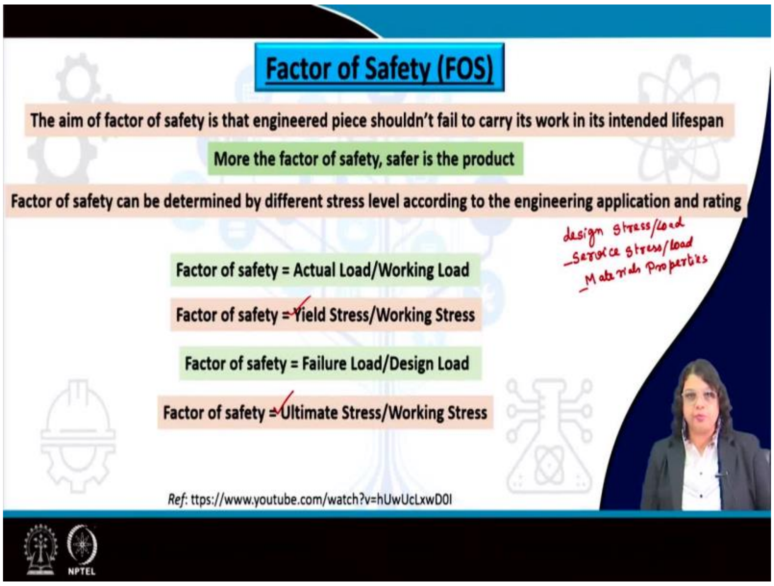

So, this factor of safety basically means that we apply some constant or we whatever is the service requirement in terms of let us say stress, we actually consider the factor of safety such that we the design stress could be even higher. The aim of this factor of safety is that the engineering engineered piece should not fail to carry its work in the intended lifespan. So, we design it for which is capable of having higher stress limit and then we use it we know that in service it will be used at a much lower load and we know that there is a factor of safety, which will never be exceeded during service and that is how we ensure that the safe life will be obtained.

So, you can understand that this is a kind of over design, but how much over design can we still considered as optimum that depends on what kind of services what kind of applications we are talking about. So, of course, more the factor of safety, safer will be the product and factor of safety can be determined by the different stress level according to the engineering application and rating. So, we need to understand how this factor of safety can be determined.

So, basically, when we are talking about factor of safety, there are different parameters that are in our mind for example, there is something known as the design stress, stress or load or strain whatever is required and there is something which is the service condition. So, the service stress or load and also there are the materials properties. So, this design stress actually considers the materials properties and the factor of safety so, that it exceeds the service condition.

So, let us see how the factor of safety is determined? So, factor of safety can be determined based on the actual load. So, what is used in service condition divided by the working load. Of course, often this working load and actual load may or may not be the same working load could be whatever is applied to the entire component whereas, actual load could be different at the different parts of the component. So, we have to take care of that.

Factor of safety can also be defined as the ratio of the yield stress to the working stress. So, yield stress considers the materials property and working stresses the actual service condition that we need to consider for service. Factor of safety is also defined as a failure load to the design load, design load is based on which we know that this is capable of performing a certain service, but failure load is the critical value of the load which when it exceeds will fail or will fracture. So, that ratio is also very, very important to determine the factor of safety.

Sometimes factor of safety is also determined as the ratio of the ultimate stress to the working stress. Now, whether to consider the yield stress or whether to consider the ultimate stress as the materials property of importance that depends on the actual service condition, actual component that we are talking about.

So, different usage of materials or for different components actually accounts for the different methods by which a factor of safety can be determined. So, it is not a fixed one that we define and that will serve the purpose for all different kinds of components. We need to consider what particular application we are talking about and then we can determine the appropriate factor of safety.

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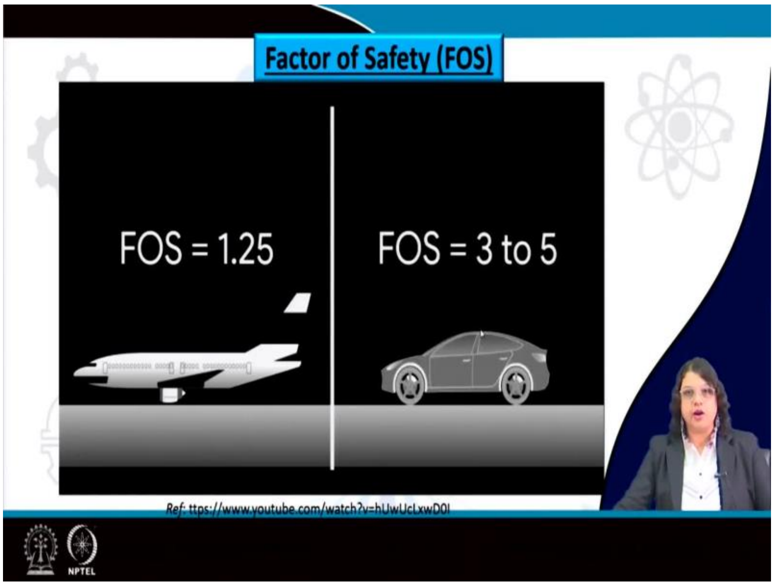

So, here is an example, which will highlight the importance of factor of safety. So, this is an aircraft for which the factor of safety is 1.25 and for the case of a car factor of safety is 3 to 5.

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So, does that mean that aircrafts are less safer than car because the factor of safety for the aircraft is lesser than that of the car? Of course not. We travel the aircraft with an idea that it is not going to fail soon. So, why is this differences in the factor of safety for a critical application like an aircraft versus a car which we commonly and regularly use.

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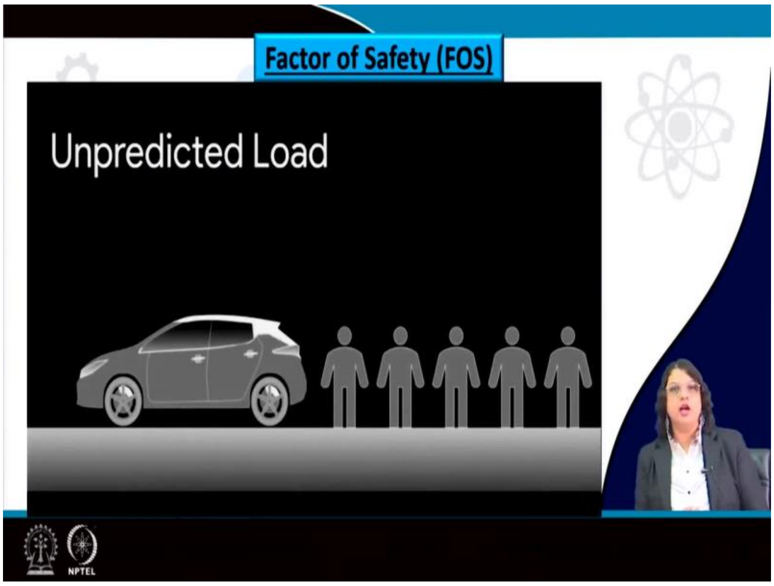

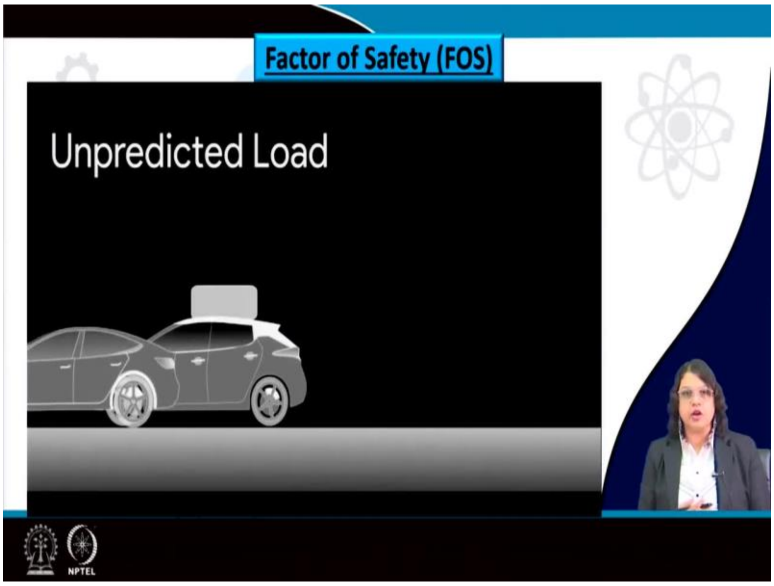

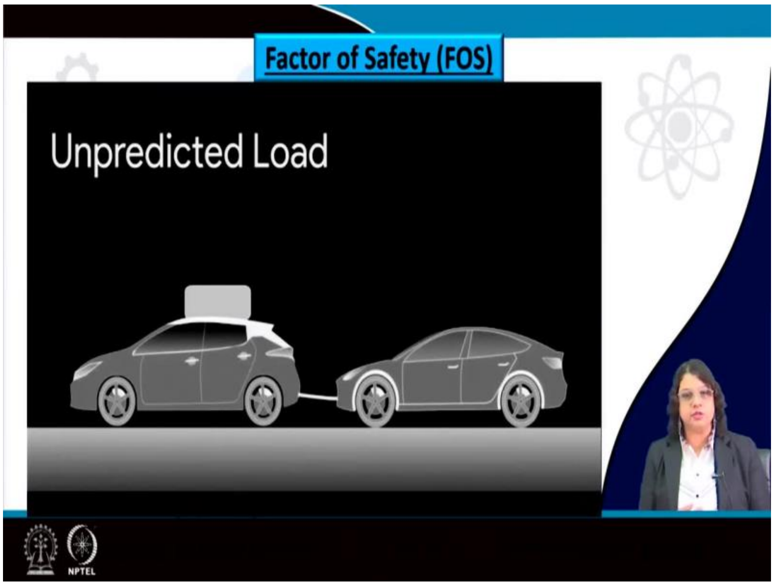

So, let us see the importance of unpredicted load. Actually, when we try to determine the factor of safety for the car, we know that this is a 5 seater car. So, there are 5 persons who are supposed to travel and then there will be some luggage if you are going for some places we may have some extra luggage sometimes it may need to carry more than another car for toing purpose or something sometimes we even have more than 5 number of people.

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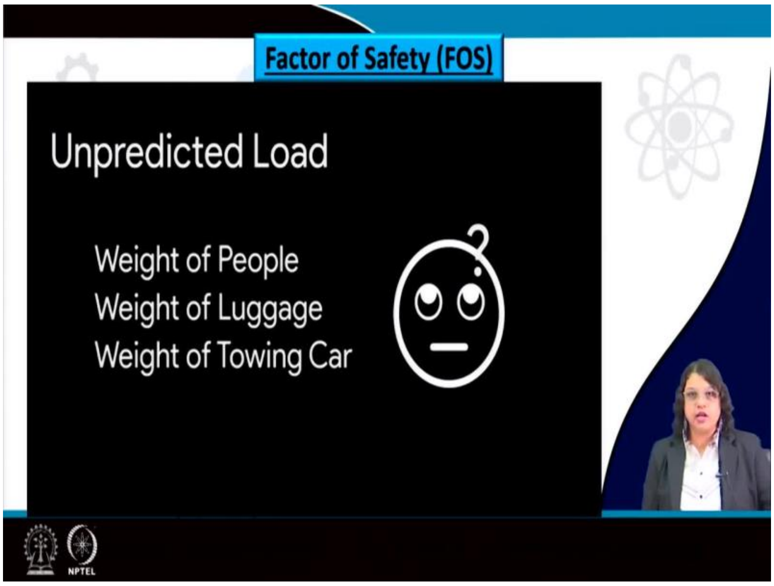

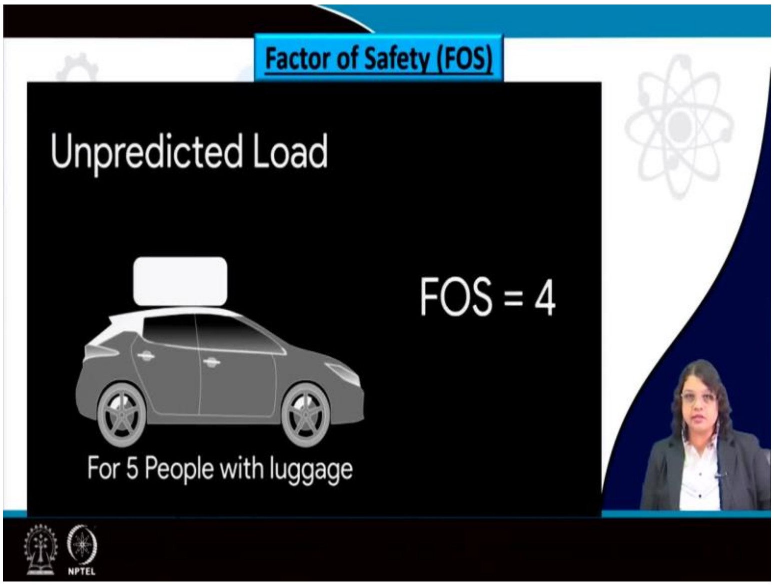

Often we squeeze things squeeze persons in a car to get use of it and we cannot expect that a car will break down in any condition. So, if we are squeezing more people, the car will break down this should not happen. So, that is the reason that we keep the factor of safety to a very high value considering this unpredicted load.

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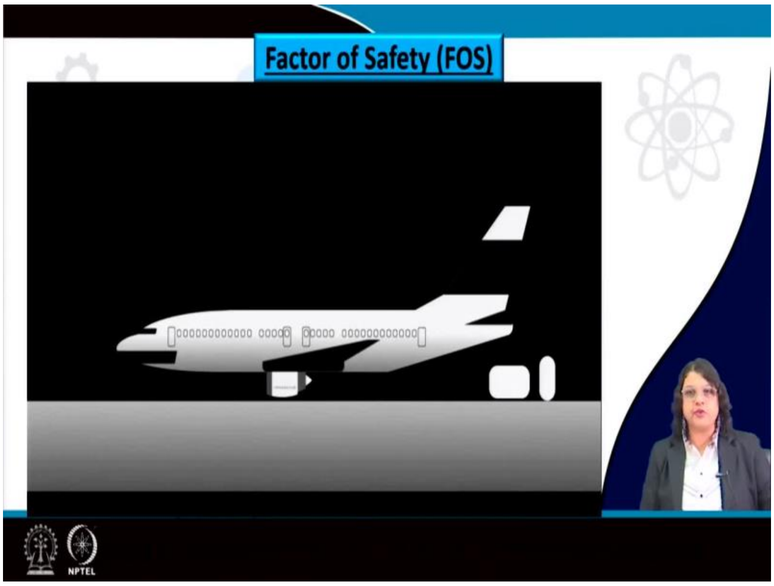

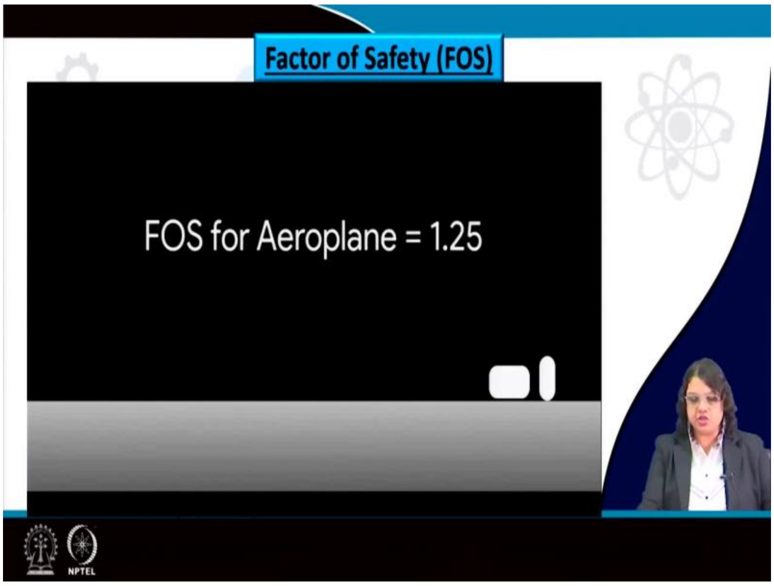

Aircraft on the other hand has a very specific number of persons that can fly and the total amount of luggage we have often seen that if we have extra luggage that will be just leftover. And since the considerations are so specific, and we know that an aircraft will never even allow even one extra person right unlike the car.

So, the factor of safety for the aircraft is maintained to a very low value and this actually helps in first of all, reducing the price and reducing the weight more is the factor of safety more materials will be consumed and that will make the aircraft have higher weight and higher rate means lesser fuel efficiency, less fuel efficiency means higher cost. So, that is why factor of safety is kept quite low for an aircraft in comparison to that for a car where the prediction of load is not so specific for the case of a car. So, that is the importance of factor of safety.

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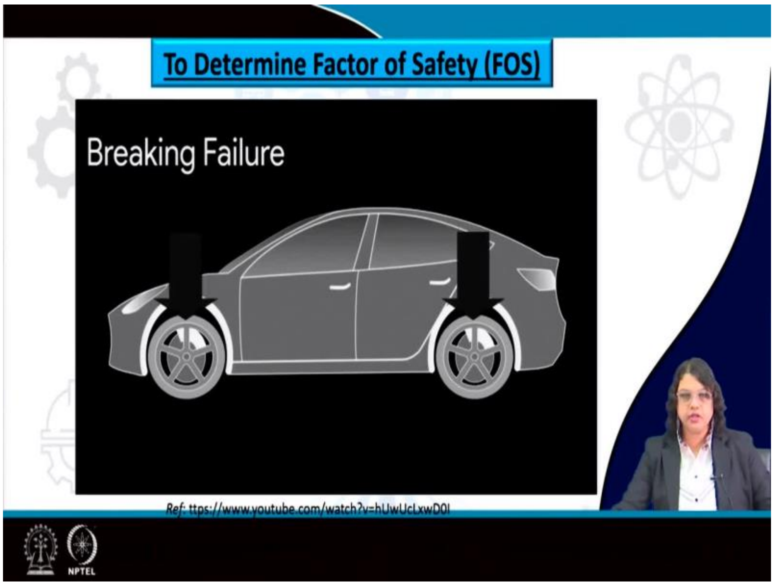

Now, when we are talking about factor of safety, we also have to consider that what is important here what is actually failure. So, for the case of a car, what happens is let us say now, there are different parts of the car and then different parts may undergo different kinds of damage. There could be different components may fail at different stress levels and the factor of safety for each of these component could be different and we finally have to consider an overall factor of safety for the entire device or component or equipment that we are talking about.

So, let us once again look into the example of a car and let us see what the failure is. So, for this purpose, we are considering the wheels for example, so, wheels we know are the circular things which rotates and give the motion to the car.

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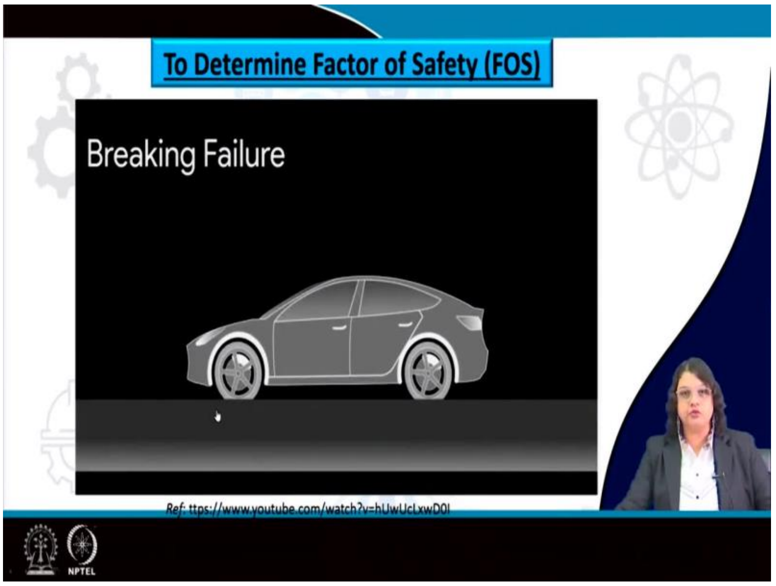

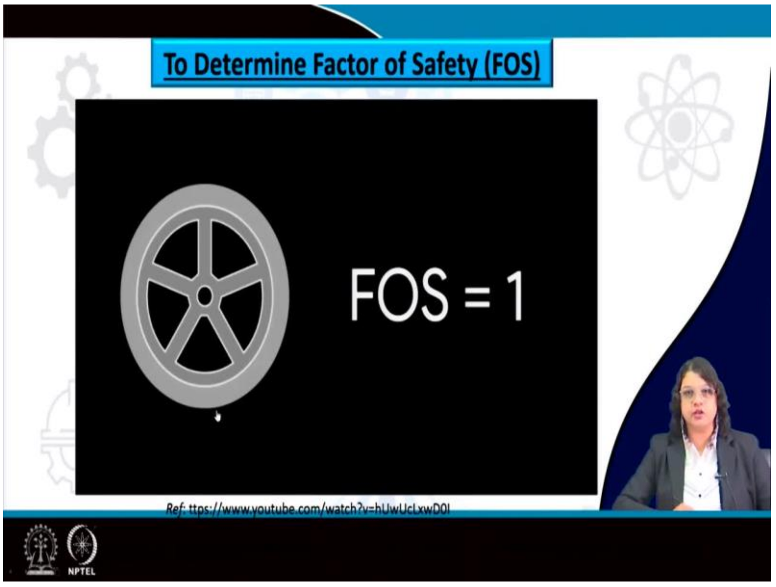

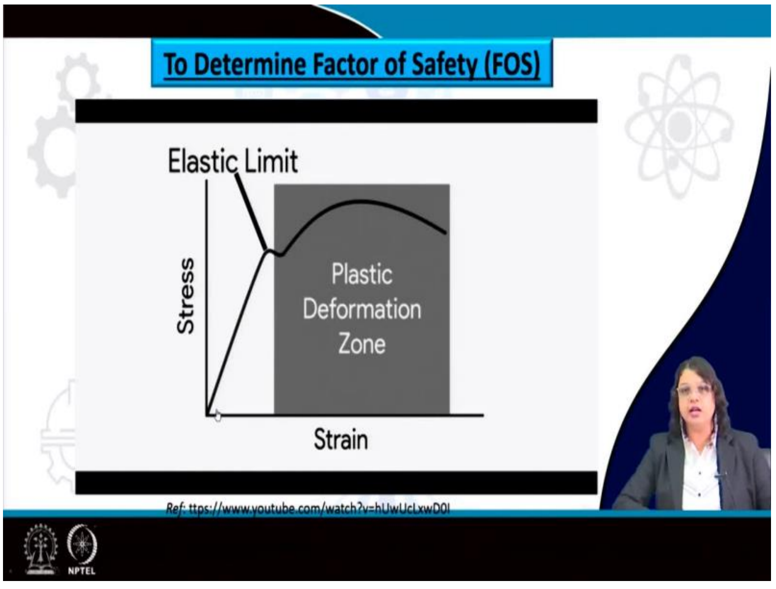

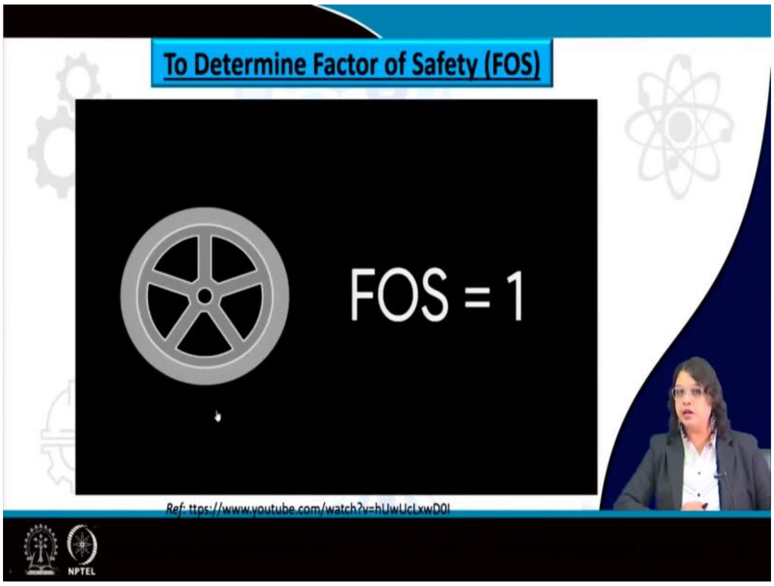

Now, under any circumstances if there is some permanent or plastic deformation on the wheels, the wheel will not be circular anymore and you can see the wheels are getting elongated and that may lead to a toppling of the car. Now, if we are considering the stress strain curve, it is up to the elastic point that is important will the material that is used for will should not exceed the yield point, so that it turns into an elliptical one and that may lead to the failure.

So, failure in that case is relevant just to maintain its circular shape that means that it should not exceed the yield point and the factor of safety for that purpose is kept just 1 we cannot exceed the yield point at any cost.

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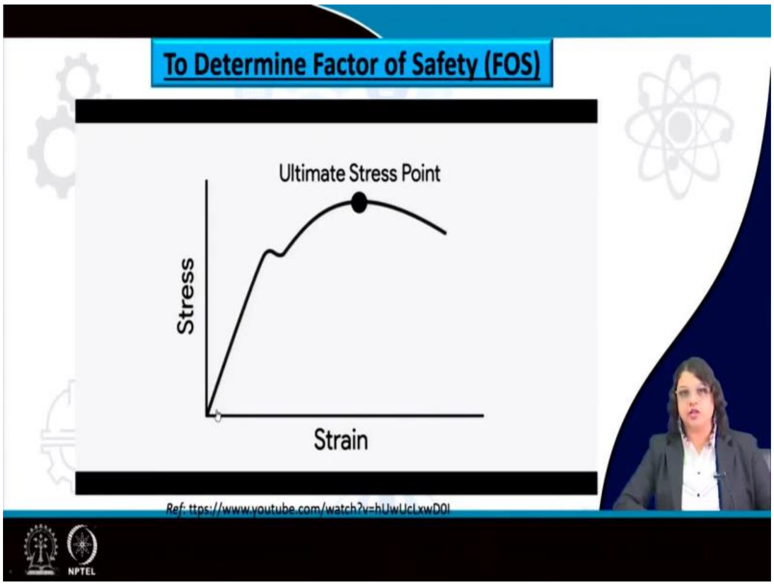

On the other hand, at some cases it is the breaking the complete failure which is relevant for the ultimate tensile stress of the material.

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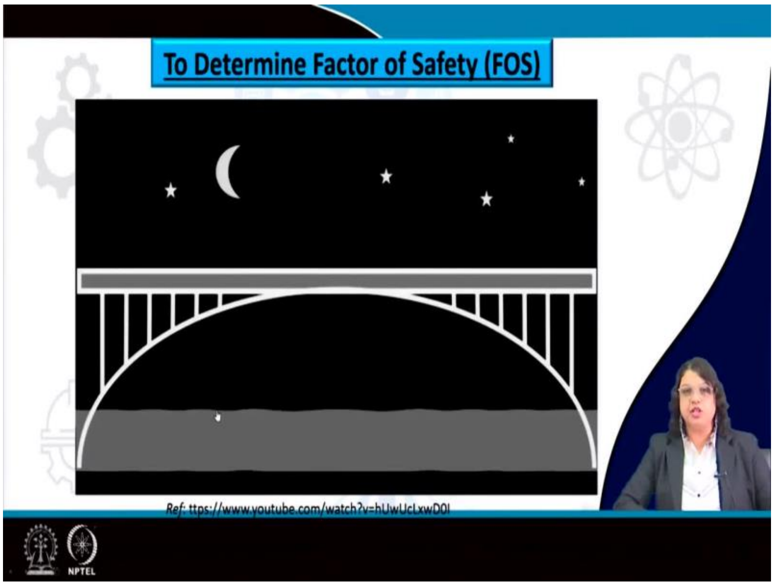

For example, the bridge if we are talking about if there is a certain amount of plastic deformation that may not be catastrophic, but if it fails, if it like breaks from somewhere, then that will be a catastrophic failure and at that point, the stress of concern or the material property of concern is the ultimate tensile strength of the materials and that is why you have seen previously how the factor of safety are determined.

Sometimes considering the yield stress and sometimes considering the ultimate tensile stress and sometimes even considering the design of the actual loads.

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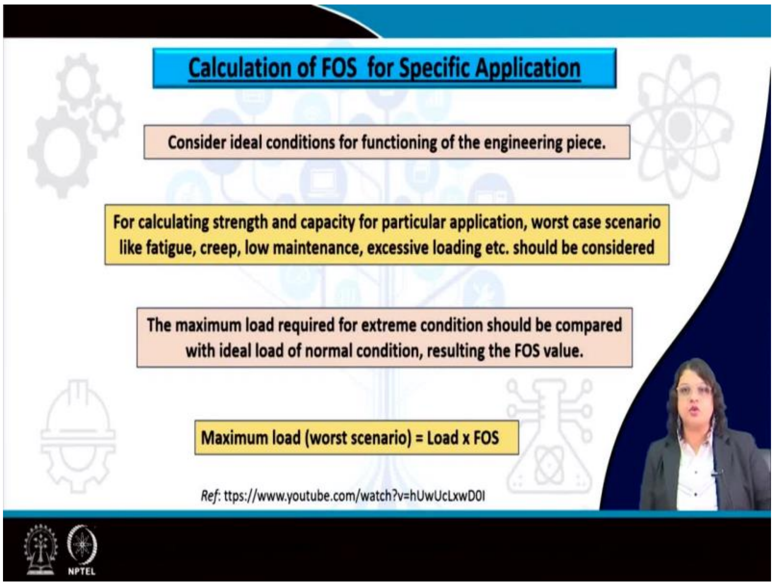

Now, for specific applications, if we are talking about a very specific applications or critical applications, then we often need to calculate the factor of safety considering the ideal conditions or functioning of the engineering piece as I mentioned that the entire aircraft or the entire bicycle frame are being tested to find out the factor of safety.

Now, for calculating strength and capacity for particular application, often we use the worst case scenario like fatigue creep, low maintenance, excessive loading, etc. as you have seen for the case of the cars, we often use more number of persons, we pack the luggage to the maximum extent, we often do not go for the regular service period that are being already prescribed.

So, we have to consider all this into account to find out the worst case scenario and even under that worst case scenario, for example, servicing of the car was due a few months back and we somehow forgot or did not get time or whatever happened, we could not do that, but that does not mean that if I am using this a few months after and the car will just break down in the middle of the road that should not happen.

So, all these are being considered as the worst case scenario and all these are being considered while calculating the factor of safety. The maximum load required for extreme condition should be compared with the ideal load of normal condition and that will result to the factor of safety usually, the maximum load for the worst case scenario is the load that is typically being used into the factor of safety that is how we determine the safe usage of that component or device.

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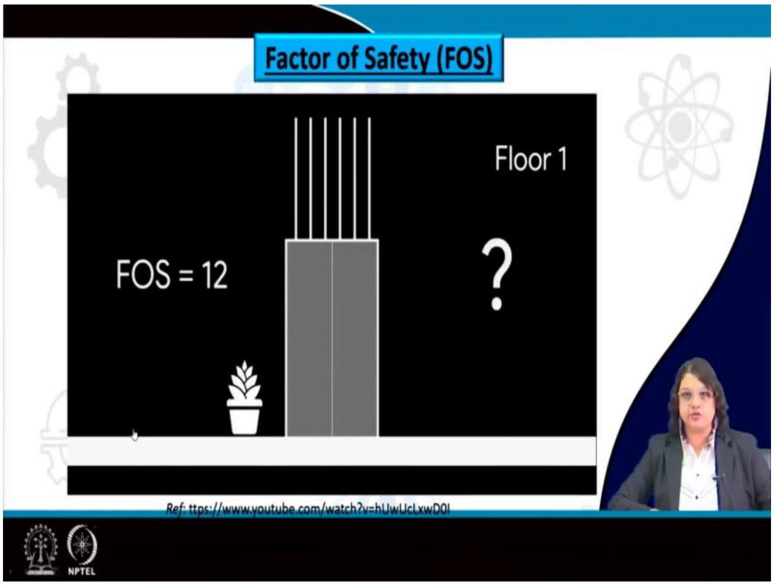

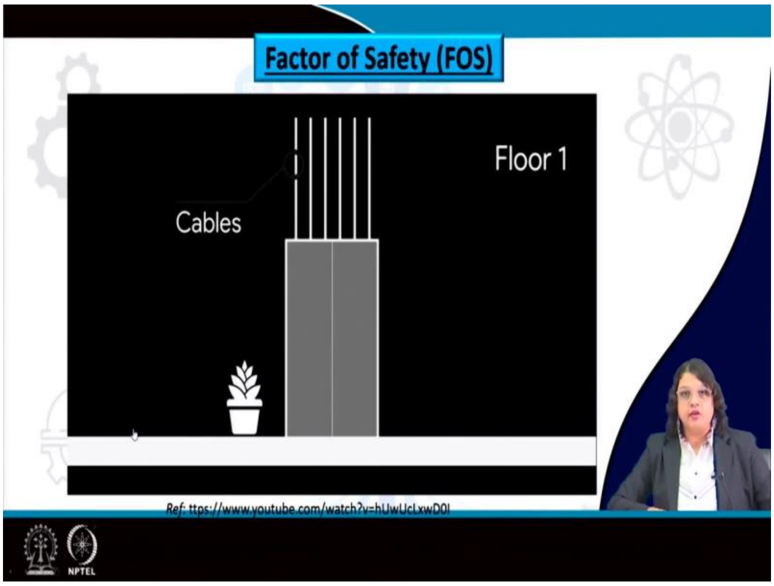

So, often there are fatigue failure, which is also very important factor for considering the factor of safety. So, this is an example of a lift, an elevator, which travels for million number of times and we use a very high factor of safety of 12. Now, why is that? Even higher than a car.

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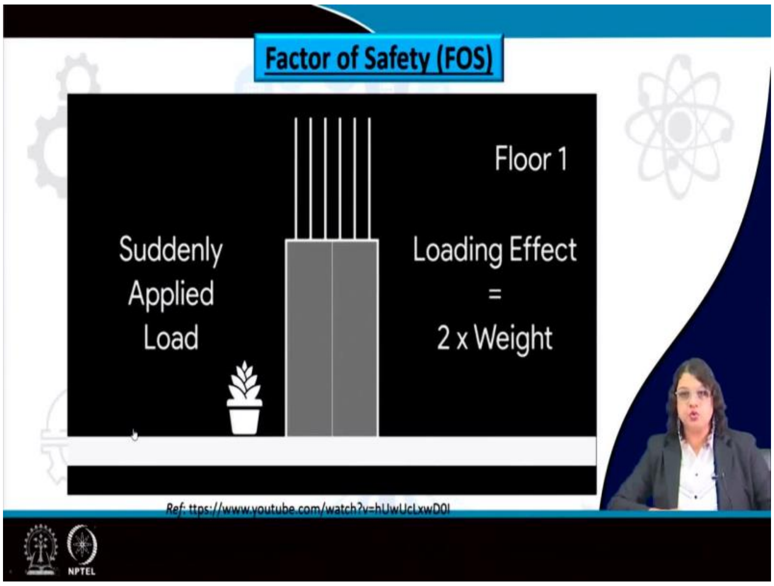

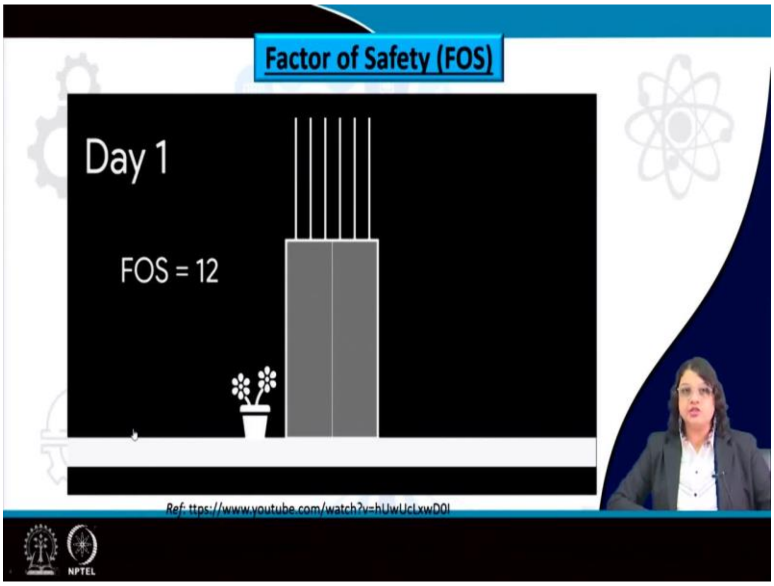

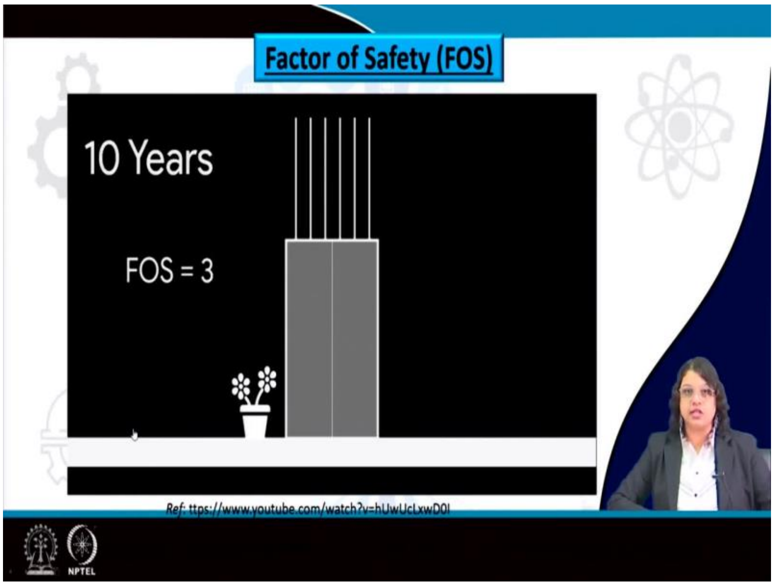

Now elevators are actually linked with the cables. Now cables are made of different material than the elevator. And every time we are using the elevator, you must have noticed that there is a jerk every time we start it or whether or whenever it stops with each of these jerk actually we are applying more and more load. So it is almost 2 times the weight that is being applied with this sudden condition.

And we have seen that how overloading can influence the fatigue behavior also. And when we say fatigue actually an elevator if it runs for let us say 10 years, it runs for million number of times different people are using sometimes even more number of persons are accessing the elevator than the record number and we do not want it to fail at any cost and it will just drop down it should not happen never.

So, we keep the factor of safety very very high, but that does not mean that it will be constant. So on day one factor of safety is 12 but after using it for 10 years factor of safety is still high much higher, but 3 only so much less than that of 12 but at any cost it should not fail.

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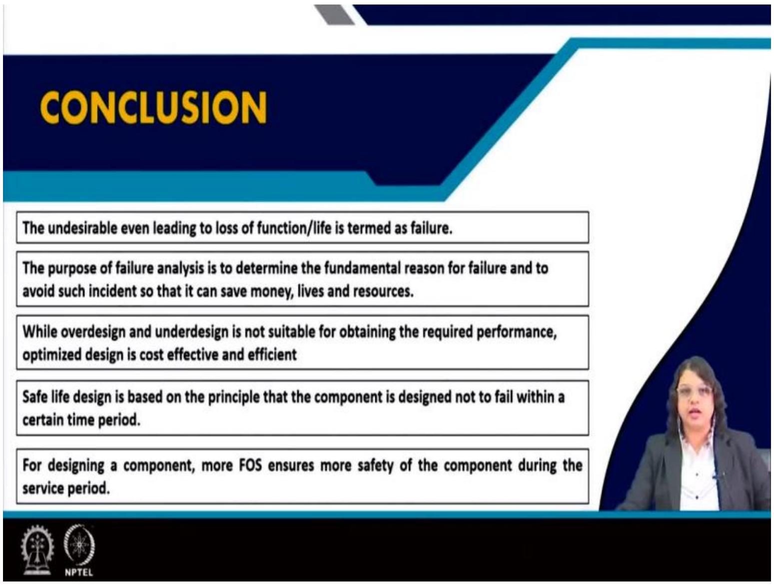

So, with that, let us conclude this lecture that the undesirable event leading to loss of function or life is termed as failure that is what we have seen failure does not necessarily mean that it has to undergo catastrophic fracture, but whatever service or the performance that it is meant for if it is incapable of doing that, then that is termed as failure.

The purpose of failure analysis is of course, to determine the fundamental reasons for failure and to avoid any such incident so, that it can save money lives and resources. While over designing and under designing both are not suitable well over designing could ensure a safe life but it at the same time it may reduce the performance or it may enhance the cost of the product.

On the other hand under design will of course fail in service and that should never be recommended. Optimized design on the other hand is the cost effective one as well as it is very much efficient to get the best of all the properties that are required. Safe life design is actually based on the principle that the component is not supposed to fail within a certain time period and we have seen that how this time period are being determined based on the different applications and based on the criticality of the service conditions.

And we have also seen that how a factor of safety is typically used that ensures more safety of the component during the service period and that ensures that there will not be any failure within the required or within the time frame that has been provided.

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So following other references that has been used for this lectures. Thank you very much.