Basics of Mechanical Engineering-1

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Week 04

Lecture13

Static and Fatigue Loading, Critical Loads (Part 1 of 2)

Welcome to the next lecture in this course on Introduction to Mechanical Engineering. This lecture is more focused towards Static Load and Fatigue Load. Static load means you try to develop a system, a part. Let us take an example of a bridge. So, the bridge is laid.

It has its own weight without any vehicle movement is called as Static load. Student standing on the chair without any movement is called as Static load. A heavy block kept on top of a table without moving is called as static load. Fatigue load means when a student jumps on top of a bridge, if car keeps coming and going at high speeds. If there is a road which is laid where in which you have a road roller going,

And then you have a truck which is speeding at 100 kilometers, a bike speeding at 100 kilometers, a cycle speeding at 10 kilometers, all of them trying to cross the bridge. It is a Fatigue load. It can be uniform load or it can be non-uniform load, but crossing the bridge. So, this tries to create a fatigue to the bridge. So, when you try to develop bridges, dams, buildings, you are supposed to think in mind to construct for next 100 years.

So much of efforts will be made to understand what is the fatigue load and how much material should I add to the existing structure such that it can withstand the service conditions.

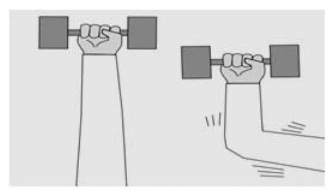
Contents

In this lecture, we will try to see what is Static load. What is Fatigue load? Mechanism of Fatigue Failure. Factors Affecting Fatigue Life.

Critical load, Buckling load, Ultimate load, a bridge case study. Then one or two numerical problems. Finally, we will try to recap what we covered in this lecture.

Static Loading

- Static loading refers to forces or loads that are applied gradually and remain constant or change very slowly over time.
- These loads do not cause significant motion within the structure and are typically used in scenarios where the force is steady and predictable.
- Understanding static loading is crucial in structural analysis and design, as it ensures that structures can withstand constant forces without undergoing significant deformation or failure.
- Accurate assessments of static load is essential for ensuring the safety & longevity of Engg Projects



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Static load refers to forces or load that are applied gradually and remain constant or change very slowly over time. So, it is applied gradually, released gradually and remains constant.

The first time you try to keep a brick on top of a table, you apply it and then for a long time it is kept constant. These loads do not cause significant motion within the structure and are typically used in scenarios where the force is steady and predictable. For example, you try to construct a house very close to the seashore. So, the breeze, the sea breeze is never constant. Sometimes there is a surge of heavy wind or there is a mild breeze which goes.

So here it is not a static load. So, these loads, the static loads do not cause significant motion within the structure and are typically used in scenarios where the force is steady and predictable. A man trying to lift a dumbbell. Gradually he lifts and then gradually he pulls down and there is no moving part here. It is only a dumbbell weight which goes up and down.

Understanding static load is crucial in structural analysis and design as it ensures that the structures can withstand constant force without undergoing significant deformation or failure. For example, if you see large tanks, petroleum tanks, which are very close to the city and when you enter, for example, you enter Delhi or you enter Kanpur or you enter Kolkata, you see outskirts of the city, there used to be petroleum storage tanks. These storage tanks of its own has a heavy load. So, constructing them, it has to be constructing on top of a soil, it needs lot of static analysis. And when the petrol is filled into the tank, it becomes though a static, but an impact load keeps coming.

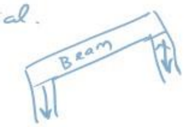
When it is drained out also, a sudden surge of load which gets exhausted. So, here the building of a storage tank is a static load. So, accurate assessment of static load is essential for ensuring the safety and longevity, that is the reliability, longevity of engineering projects. Bridge does not move; it is a static load.

Static Loading

- Evaluation of static loads involves analyzing material properties, load distribution, and the overall geometry of the structure.
- A structure's static, non-moving weight including its integral components is referred to as **"Dead Load"**. The walls, roof, columns, stairs etc. constitute a static load that normally doesn't change over the life of a building. The different component loads can be added together to determine the dead load for the entire structure.

Material	Unit Weight KN/m^3
Aluminum Alloy	27.0
Plain Concrete	23.5
Prestressed Concrete	24.5
Reinforced Concrete	24.0
Granular soil/Crushed stones	22.0
Steel	77.0
Hardwood	9.5
Softwood	6.0
Water	9.8

Dead load = Vol. of member × Unit weight of material.
Vol. of beam = 10 × 0.6 × 0.3 = 1.8 m^3
Unit wt of RCC beam = 24 kN/m^2
Dead load = 1.8 × 24 = 43.2 kN



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Evaluation of static load involves analyzing material properties, load distribution and overall geometry of the structure.

A structure's static, non-moving weight, including its integral component is referred as dead load. The wall, roof, column, stairs, etc., constitute a static load that normally does not change over the life of the building. The different components loads can be added together to determine the dead load of the entire structure. So here we have given unit weight. For example, aluminium alloy, it is kilo newton per meter cube.

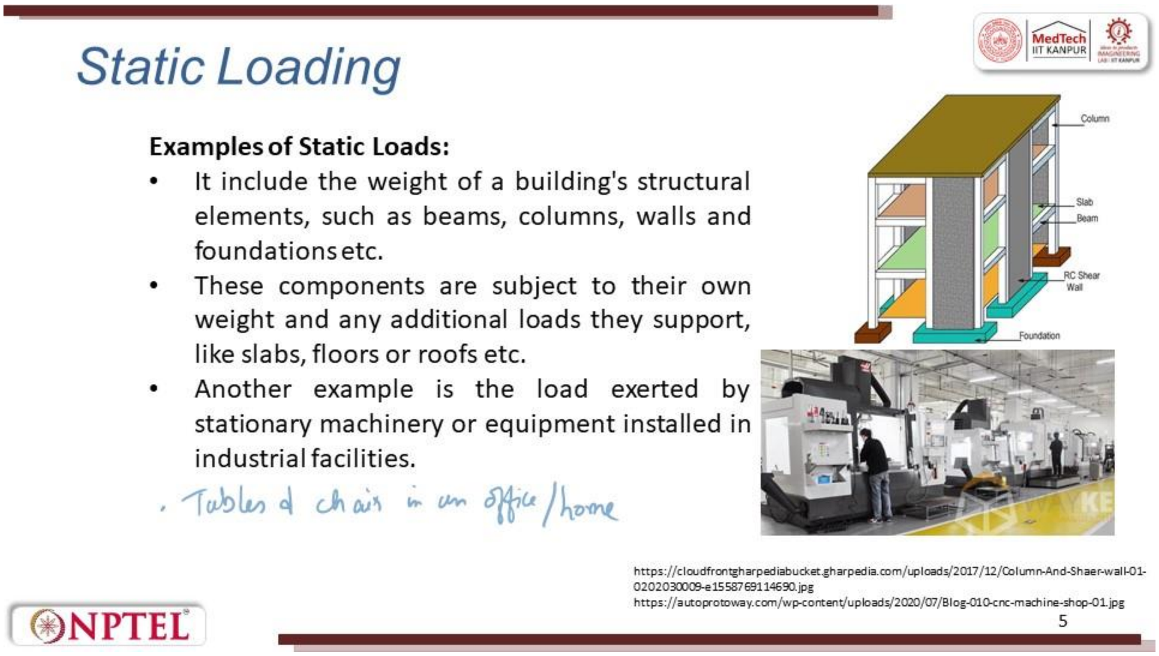
So, what they are trying to say is one meter cube of aluminium alloy, what will be its unit weight so that dead load how do we calculate dead load is going equal to volume of member multiplied by unit weight of material.

Example, $volume\ of\ a\ beam\ =\ 10\ \times 0.6\ \times 0.3 = 1.8\ m^3$

$$Unit\ weight\ of\ RCC\ beam = 24\ k\ N/m^2$$

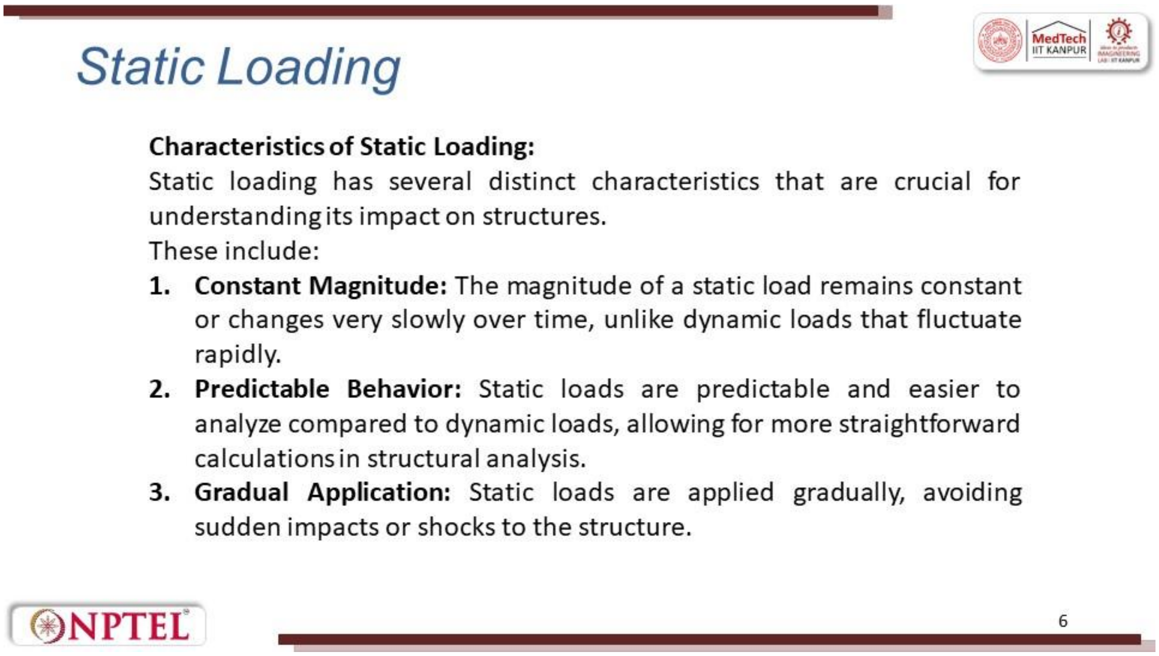
$$Dead\ load = 1.8\ \times\ 24\ = 43.2\ kN$$

This is how they try to calculate the dead weight. so, if you want to understand the problem, it is something like this. So, this is the beam which is resting on two pillars or the load falls down.



So you can have some more example of static load. It includes the weight of a building's structural element such as beam, column, wall and foundation.

These components are subjected to their own weight and any additional loads they support like slab, floor or roof. Another example is the load exerted by a machine or an equipment installed in an industrial environment. As I discussed with you, tables and chair in an office/home is also an example for static load.



What are the characteristics of a Static load? The static load have several distinct characters that are crucial for understanding its impact on the structure.

It includes constant magnitude. The magnitude of a static load remains constant or changes very slowly over time unlike dynamic loading that fluctuates rapidly. Predictable behavior: Static loads are predictable and easier to analyze as compared to that of dynamic loading. allowing for more straightforward calculation in static or structural analysis. Gradual application, static loads are applied gradually, avoiding sudden impact or shock to the structure.

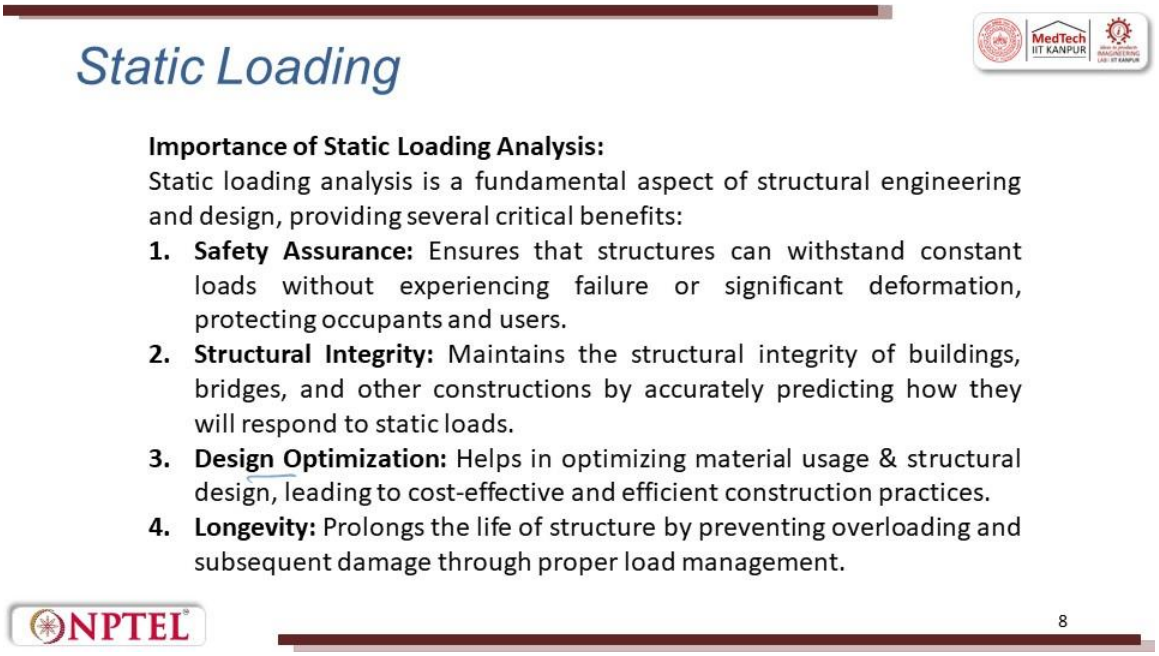
Static Loading

4. **Long Duration:** Static loads are typically applied for extended periods, requiring the structure to support the load over time without significant deformation.
5. **Uniform Distribution:** Often, static loads are uniformly distributed across the structure, leading to even stress distribution.
6. **Safety Factors:** Engineers incorporate safety factors to account for any unexpected increases in load or material imperfections.
7. **Material Dependence:** The ability of a structure to withstand static loads depends heavily on its material's properties e.g. strength and elasticity.
8. **Load Path:** Static loads follow a predictable load path through the structure, easing in design of supports and foundations accordingly.

Long duration, the static loads are typically applied for extended periods requiring the structure to support the load over time without significant deformation.

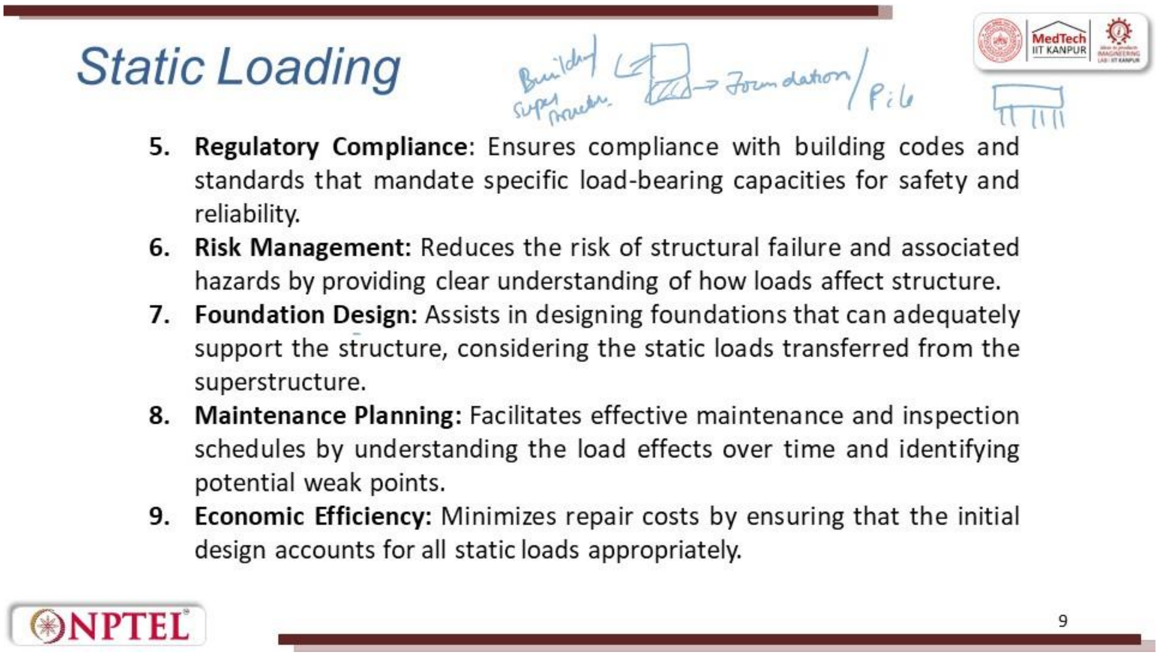
A building you construct goes for 50 years. Uniform distribution, often static loads are uniformly distributed across the structure leading to even stress distribution. Safety factor. Engineers incorporate safety factors to account for any unexpected increase in load or material imperfections. Material dependency. The ability of a structure to withstand static load depends heavily on its materials property such as strength and elasticity. Please make a note.

That's why we studied material property. Load path: Static loads follow a predictable load path through the structure from one. If you have a truss or if you have multiple components, the load will be distributed in them. So predictable load path through the structure easing in design of supports and foundation accordingly.



The Importance of Static Loading Analysis. Static loading analysis is a fundamental aspect of structural engineering and design, providing several critical benefits. Safety assurance ensures that the structure can withstand constant loads without experiencing failure or significant deformation, protecting occupants and users. The other important thing is structural integrity. Maintaining structural integrity of buildings, bridges and other constructions by accurately predicting how they will respond to static loads. Design optimization helps in optimizing material usage and structural design leading to cost effective and efficient construction.

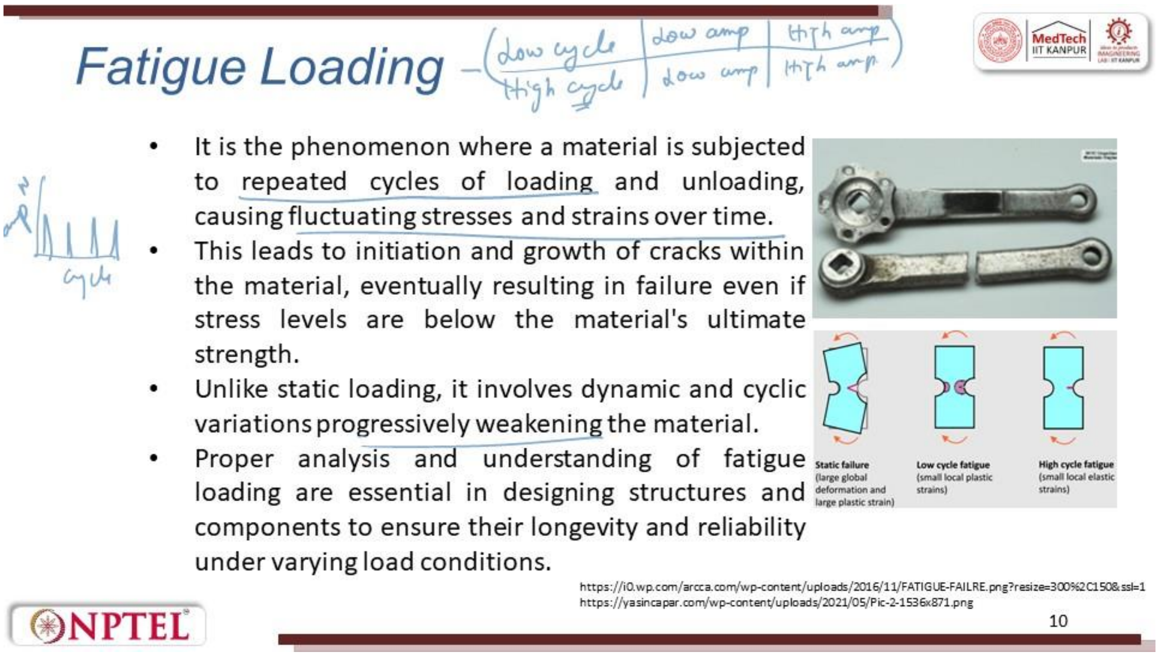
So, for design optimization it is used. Longevity is another importance of static load analysis.



The Regulatory Compliance ensures compliance with building codes and standards that mandate specific load bearing capacity for safety and reliability. Risk management reduces the risk of the structural failure and associated hazard by providing clear understanding on how loads affect structure. Foundation design. See, foundation is the base.

So, you have a building, you will have a foundation. This is called as foundation. Today, the foundation which was earlier made as area wise, now it is replaced by piles. So that means to say a building now will rest on piles. So now it reduces the volume of material usage and still tries to give a proper support to the building.

So, foundation design assist in designing foundation that can adequately support the structure considering the static loads transferred from the superstructure. The building is called as a superstructure. This is called as building or it is called as Superstructure. Maintenance planning facilitates effective maintenance and inspection of schedules by understanding the load effects over time and identifying potential weak points is also part of static analysis. Economic efficiency, minimizing repair cost by ensuring that the initial design cost for all static loads are appropriately done.



Next, let us move into the topic of Fatigue Loading. It is the phenomena when a material is subjected to a repeated cycle of loading and unloading, causing fluctuating stresses and strains over time. So that means to say, suppose you are walking on a staircase. So, it is loading, unloading from one floor to one stair to the other, one stair to the other, engine rotating at a high speed, connecting rod, crankshaft, and then a boy jumping. a trampoline jump. So, all these things are fluctuating load.

This leads to initiation and growth of cracks within the material. Eventually, resulting in a failure even if the stress levels are below the ultimate strength of the material. See, we understood that the ultimate tensile strength is going to be the highest point after which the material fails. This is for a static loading condition. In dynamic or in fatigue loading condition, because of the static load, the tensile stresses on the skin of the material comes into existence, tensile compression, and you keep doing it repetitively, it causes a failure even before it reaches the ultimate tensile strength.

A failure will happen early. So cyclic loading is a very important thing which you have to calculate and you have to make a note of it. Unlike static loading, it involves dynamic and cyclic variation progressively weakening the material. Suppose if there is a small crack and this crack while undergoing cyclic loading, this crack undergoes faster. So, I have compared three.

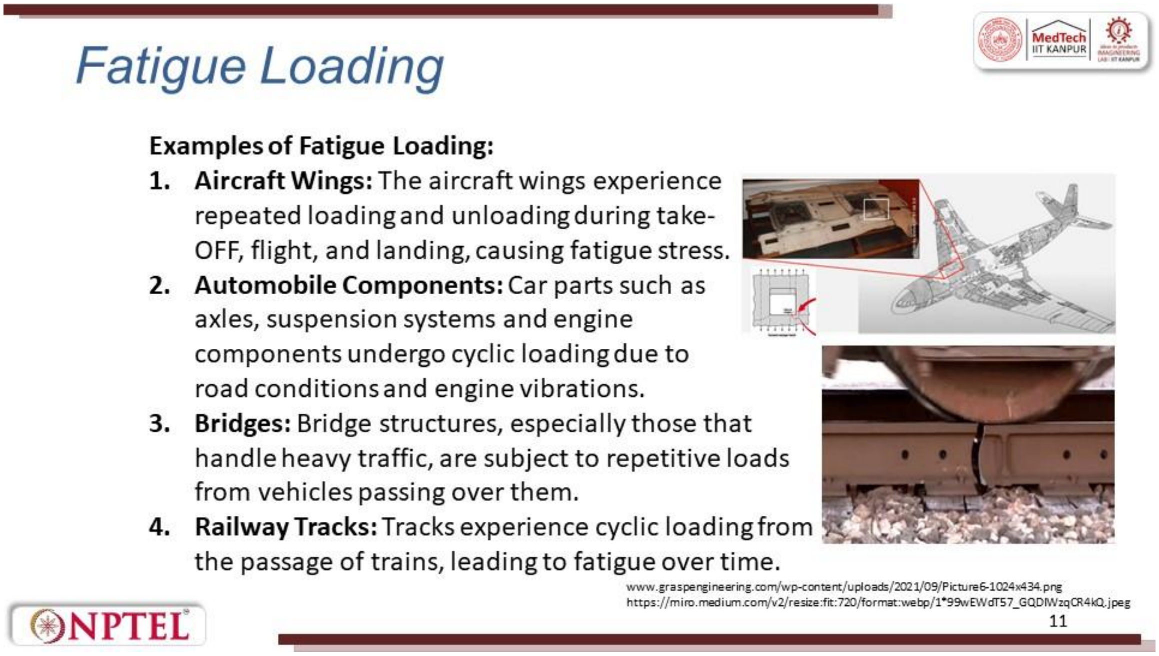
One is Static Failure. You can see large global deformation and large plastic strains come into existence. And I have put the sample like this. Generally, we discuss it like this, but I have put the sample like this. Then low cycle fatigue, small plastic strains come into existence.

Low cycle fatigue means the frequency in which you are bending is very low. So, there can be four conditions. One is low cycle; another one is high cycle. Then comes the low amplitude and high amplitude. Low amplitude and high amplitude.

Low cycle frequency is an activity which happens maybe twice a second, 5 times a second, 10 times a second. That is low cycle and the amplitude, the load. So, what we are trying to talk about amplitude with respect to cycle or something. So, amplitude is very low. It can be in Newton, kilonewton, whatever it is.

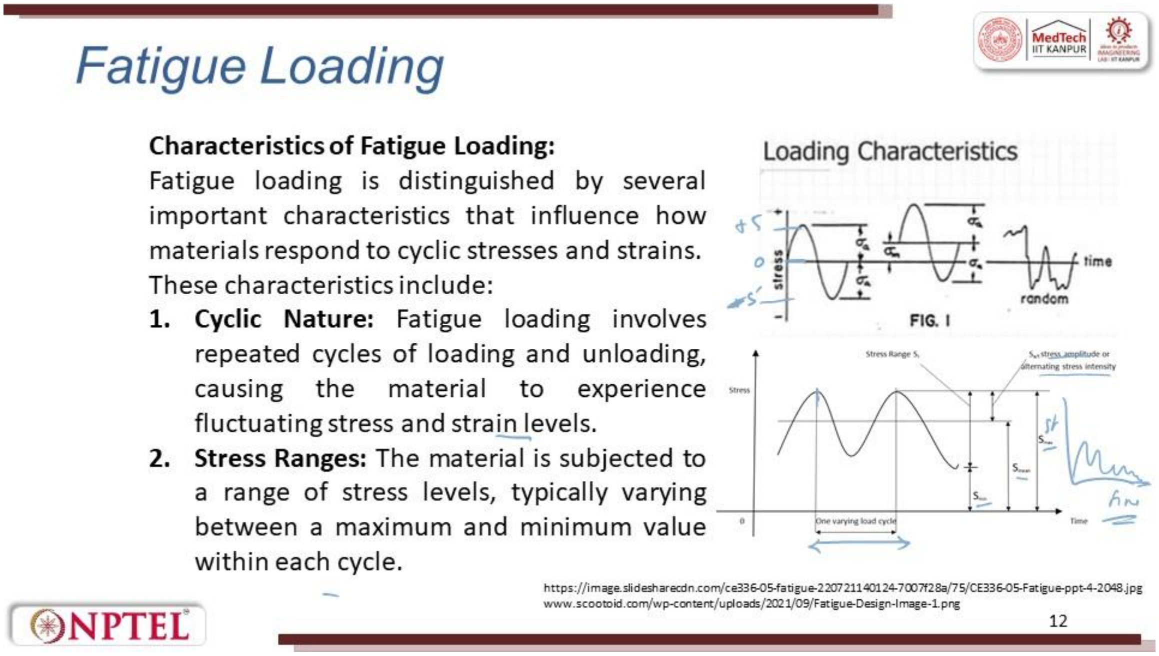
When we talk about high cycle, the frequency in which it happens goes higher than 50 Hz, 100 Hz, sometimes in kilohertz, megahertz. And here, when we talk about kilohertz and megahertz, the amplitude will be in 10 microns. Here, the amplitude, maybe the displacement or the loads, the amplitude can be in terms of 1 centimeter, 2-centimeter, 5 centimeters. High amplitude can be 1 inch, 2-inch, 3 inch something like that. So, if you talk in terms of displacement and if you talk in terms of weight, it can be 1, 10, 100 and when we are talking about high cycle and weight if you see, it will be grams less than grams and when you are going to high amplitude.

It will be less than that, depending upon your situation, by the way. So, these things you can have multiple combination, low cycle, low amplitude; low cycle, high amplitude; high cycle, low amplitude; high cycle, high amplitude. You can have combinations. When we look at the high cycle fatigue, small local elastic strains are seen here. Proper analysis and understanding of fatigue loading are essential in designing structures and components to ensure the longevity and reliability of varying loads.



Examples of fatigue loading are aircraft wings very high speed; it goes at a very high speed. There can be droplets of water cloud or something which comes and hits. So, fatigue loading can be Thermal Fatigue loading or it can be Mechanical Fatigue loading, the aircraft wing experiences repeated loading and unloading during takeoff and landing and it also causes lot of fatigue stress the landing year which is used in the plane when it is landing. So that is a Fatigue load. Automobile components, car parts such as axle, suspension systems, engine components undergo cyclic loading due to road conditions and even vibration.

Bridges, especially those having heavy traffic are subjected to repetitive loading. And railway tracks, on the track the wheel is rotating is again a cyclic loading.



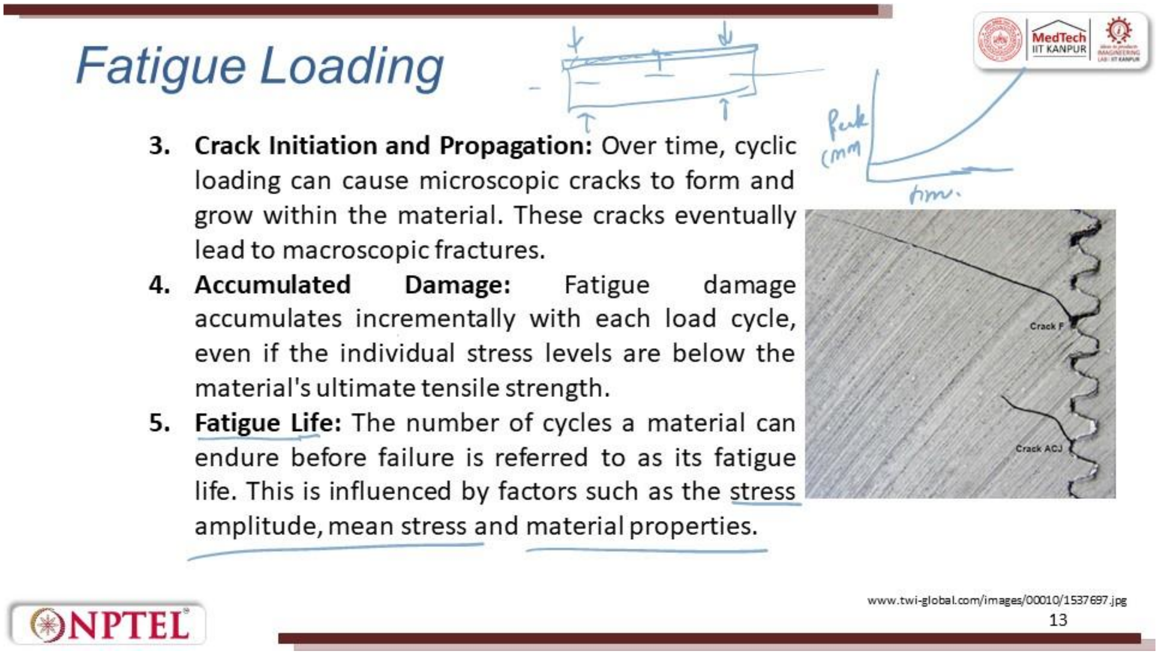
The characteristics of fatigue loading, this is a loading character. So, you can see stress with respect to time. So, it is cyclic with respect to an axis which is 0.

Here it is +5 megapascal or -5 megapascal, whatever it is. And then every time the swing happens with respect to 0 neutral point. Now there can be a possibility, the neutral point itself is shifted. So that is another Cyclic Loading condition. The third one is again a Cyclic Loading condition but completely random.

All these things are possible. The fatigue loading is distinguished by several important characteristics that influence how material respond to cyclic stress and strain. The cyclic nature and the stress range. Cyclic nature, the fatigue load involves repetitive cycles of loading and unloading causing the material to experience fluctuating stress and strain levels. Stress range, the material is subjected to a range of stress levels, typically varying between a max and a min value within each cycle.

So, if you see here, this is one cycle and here you see one overall load cycle is, it is almost the pitch cycle. And here if you see the stress amplitude or attenuating stress intensity, it can be stress amplitude or alternating stress intensity. So here is the S max, this is S mean and this is the S lower peak, right. Maximum, minimum, this is the average. The stress also can attenuate.

For example, it can attenuate like this and go. So, this is stress with respect to time. So here it is a cyclic load, but it gets attenuated because of its property.

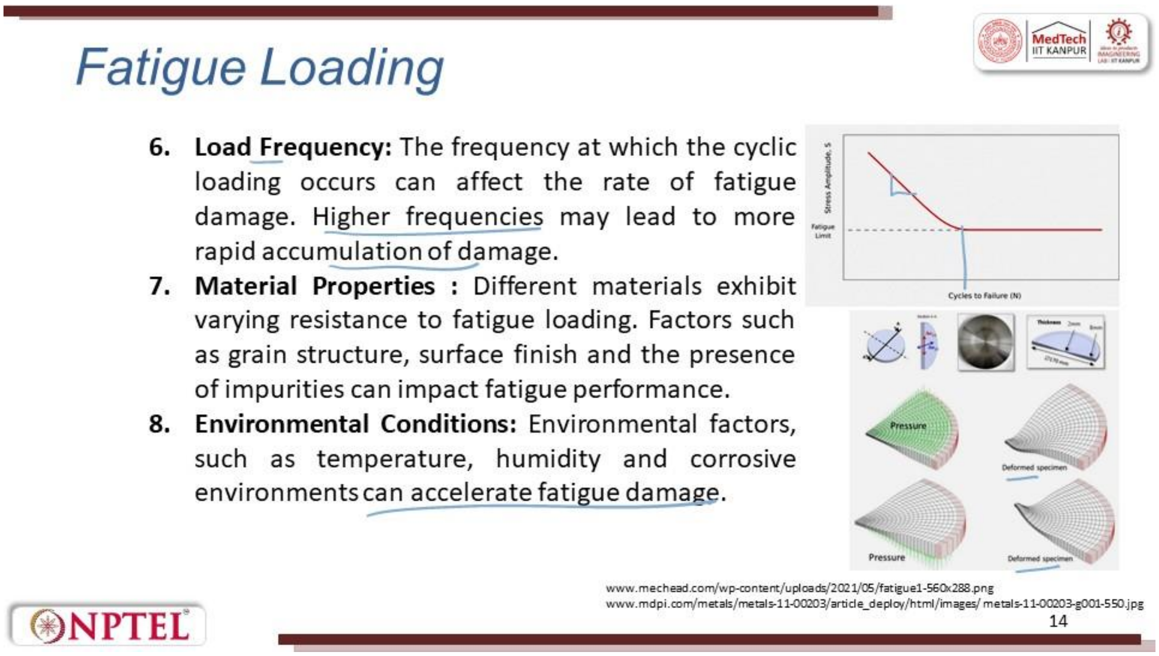


Crack initiation and Propagation is also a characteristic of fatigue loading. The crack whatever is there on the surface, it starts and if there is no crack, it starts initiating. Why?

Because the surface, if it is very hard, suppose you have a surface which is very hard and now you have cyclic loading which is coming, right. This hard surface now will try to initiate cracks. So, the crack initiation can happen. Moment a crack gets initiated, the cracks can also grow. The Crack Initiation and Propagation is also a characteristic feature of fatigue loading.

Over time, cyclic loading can cause microscopic cracks to form and grow within the material. These cracks eventually lead to macroscopic fracture. The accumulated damage, the fatigue damage accumulates incrementally with each cycle load. For example, if there is a crack, this crack grows with every cycle. For example, if we try to take the peak of crack growth in millimeter with respect to time, what will happen is it keeps on going like this exponentially.

Many at times it is exponentially growing. So first it grows slowly and then it goes very fast. So, the fatigue damage accumulates incrementally with each load cycle even if the individual stress levels are below the material's ultimate tensile strength. Fatigue life, the number of cycles a material can endure before failure is referred as fatigue life. This is influenced by factors such as Stress Amplitude, Mean Stress and Material Property. Fatigue life is very important.



As I have already told you about the Load Frequency. So, you can see the frequency at which the cycle loading occurs can affect the rate of fatigue damage. High frequency may lead to more rapid accumulation of damage. High frequency is very important.

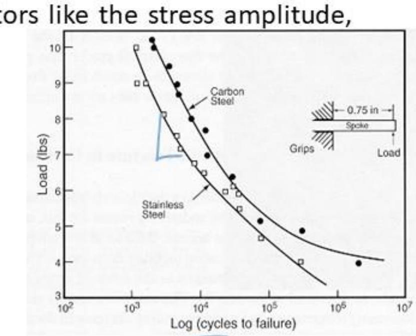
So, if you see the stress amplitude, this is the fatigue level. Stress amplitude with respect to cycle of failure, you can see it moves down. The slope is very rapid till a certain cycle and then it gets saturated. The different properties, different material exhibits varying resistance to fatigue loading. Factors such as grain structure, surface finish and the presence of impurities can impact fatigue performance.

The environmental conditions such as temperature, humidity, corrosion, etc. environment can accelerate fatigue damage. So, you can see here a pressure, a deformed specimen, a normal specimen and a deformed specimen. By applying pressure and releasing pressure, you see how does it change.

Fatigue Life and S-N Curves

Fatigue Life: It refers to the no of cycles a material can withstand before failure occurs due to fatigue loading (N_f)

- This life span is influenced by several factors like the stress amplitude, mean stress, material properties and environmental conditions etc.
- The fatigue life is crucial for predicting the durability and reliability of materials and structures that are subjected to cyclic loading over their operational lifetime.
- The **S-N curve** describes the relation between cyclic stress amplitude and the number of cycles to failure.



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Fatigue life and S-N curve. Fatigue life, it refers to the number of cycles a material can withstand before failure occurs due to fatigue loading.

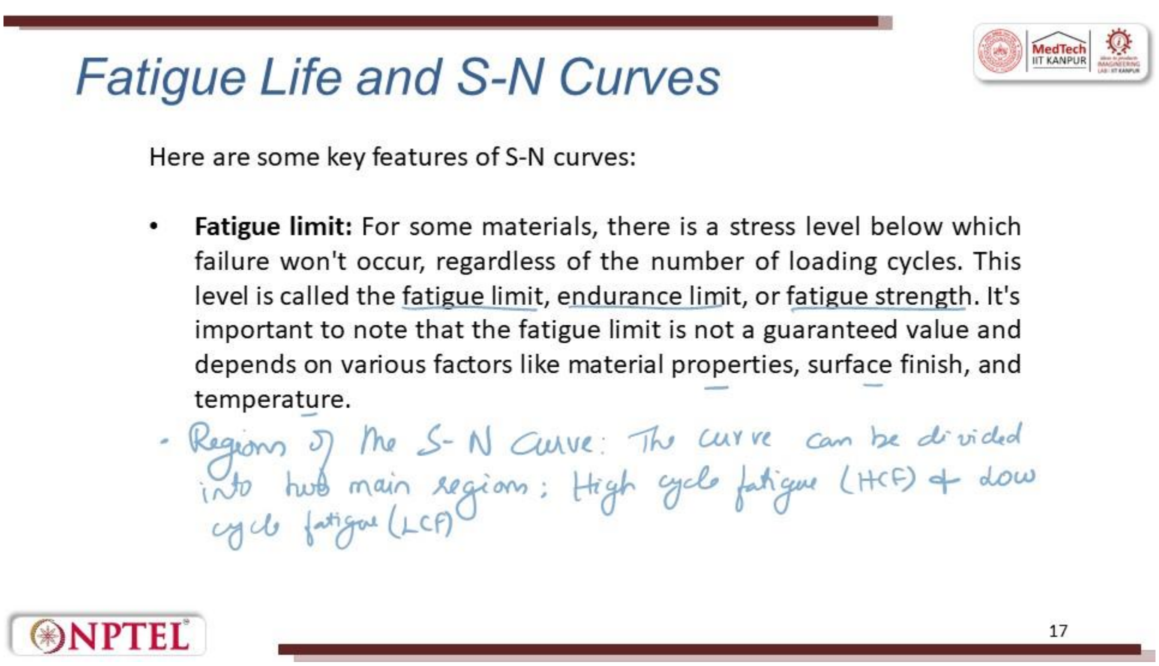
It can be represented like (N_f). So, you can see generally they do it on log-log graph because log-log graph means you can accommodate lot of data points. So, the load will be in linear scale, this will be in log scale. So, you can see here for two different materials, they are given stainless steel and then they are given for carbon steel. The interesting part is you can try to take a slope of it or try to take the response into a line equation and then try to take it to a structural analysis and incorporate. The lifespan is influenced by several factors like the stress amplitude, mean stress, material properties and environmental condition.

The fatigue life is crucial for predicting the durability and reliability of materials and structures that are subjected to cyclic loading over the operational lifetime. Cycle Bearing, shaft, landing gear axle, tyre, everything you can see here, fatigue life is crucial for predicting its durability and reliability. The fatigue life will be always described through a S-N curve. They will always ask; do you have a S-N curve for the given material? Many of the new materials which are coming, it is yet to be developed.

And some of them they try to run for certain number of cycles or what do they do is they try to do an accelerated test. For example, they try to double the load and see what is a failure and then they say double the load it has withstand so much. So, it is an accelerated lab test failure. So, we can try to predict that this is what is the response and some of the materials are run for years together to get the S-N curve response. The S-N curve describes the relationship between the cyclic stress amplitude and the number of cycles to failure.

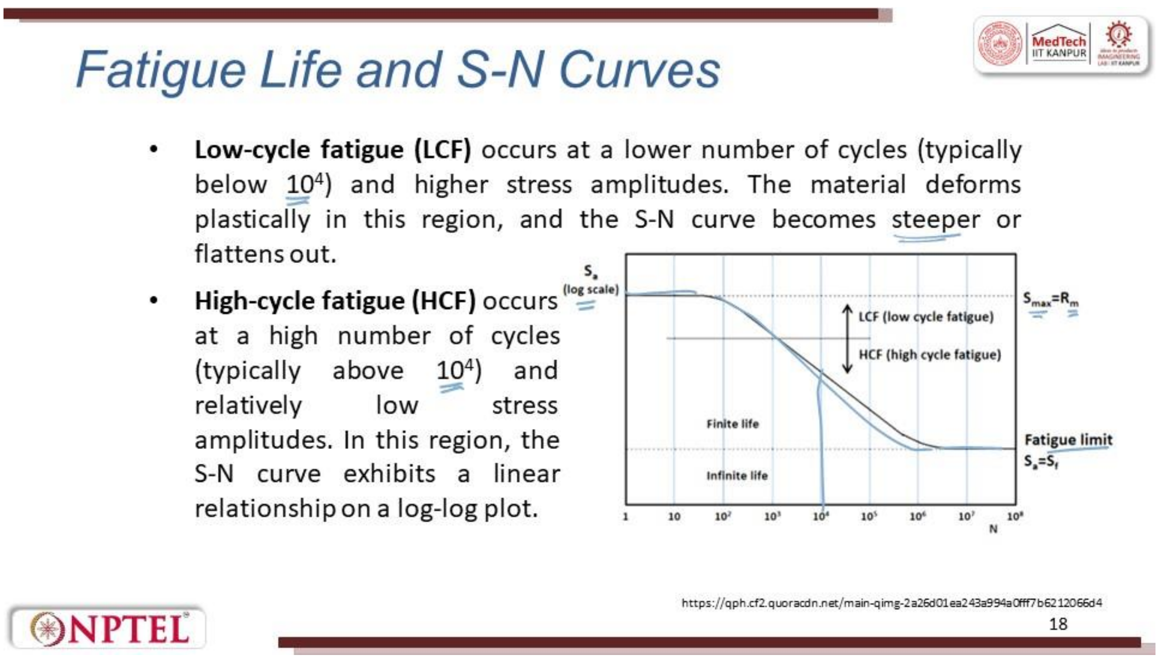
The SN curve, also called as Wöhler's curve, is a graphical representation of the relationship between stress amplitude and the number of failures for a particular material. So, you can see low cycle fatigue, high cycle fatigue limit, then this is the low cycle fatigue and this is for high cycle fatigue how is the response and in the x axis you see here stress taken in the log scale number of cycles to failure again taken in the log scale. So, you can have S f and S 1000. So, you can see here this is the fatigue life. So, it reduces drastically when it goes to 10 to the power 6.

S-N curve also called as Uhler's curve is a graphical representation of the relationship between stress amplitude and the number of cycles. So, stress amplitude becomes S and number of cycles becomes N. That is why it is called as S-N curve. These curves are generated through specialized fatigue tests where a specimen is subjected to repeated cyclic loading until its fracture. The data is plotted with stress amplitude on a vertical axis and number of cycles in the horizontal axis, both in the logarithmic scale. Here are some key features of S-N curve.



Fatigue limit: For some material, there is a stress level below which the failure would not occur, regardless of the number of loading cycles. This level is called as Fatigue limit or Endurance limit or Fatigue strength. This is very important. So, there is a stress level below which the failure would not occur. So, every part or every material you design, you manufacture, your build should make sure that this limit is known.

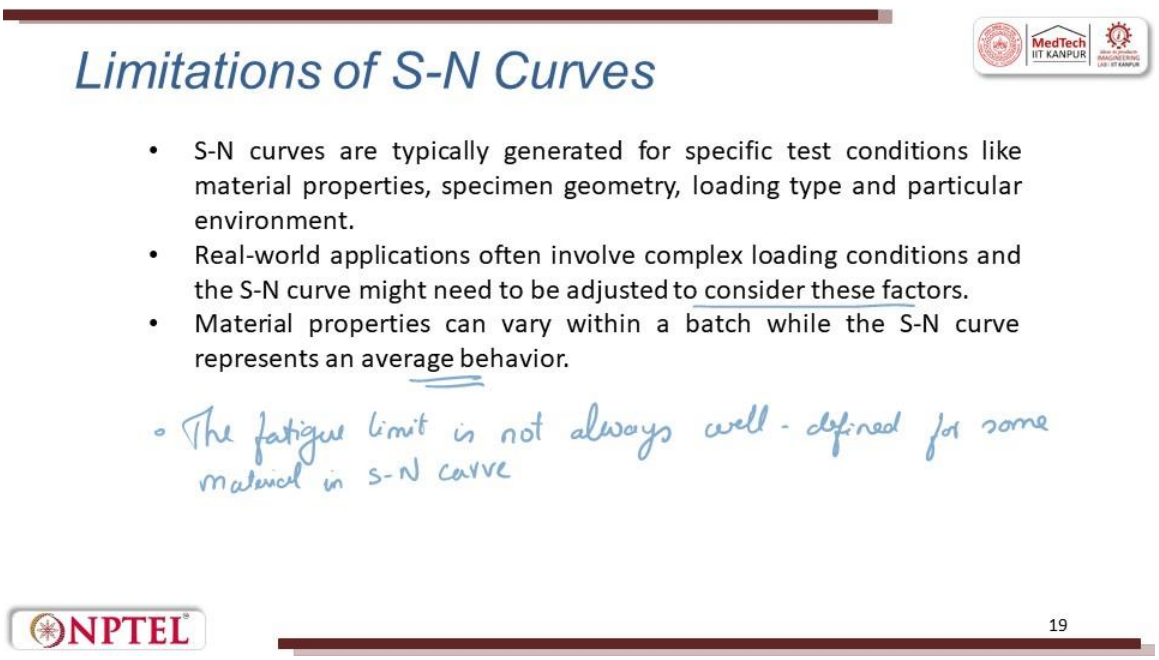
It is a stress level below which the failure would not occur regardless of the number of loading cycles. The level is called as fatigue limit, endurance limit or fatigue strength. It is important to note that the Fatigue limit is not defined a guaranteed value and depends on various factors like material property, surface finish and temperature. So, this also is for room temperature they would have done, for higher temperature they would have not done. If there is a rough surface there will be a crack growth happening and also the material properties.



So, the regions of the S-N curve. The curve can be divided into two main regions. One is called as High Cycle Fatigue (HCF) and Low Cycle Fatigue, which is LCF. The Low Cycle Fatigue (LCF) occurs at a lower number of cycles, typically below 10^4 and higher stress amplitude. The material deforms plastically in this region and the S-N curve becomes steeper or flattened out.

High Cycle Fatigue, the cycle occurs at a higher number of cycles, typically above 10^4. It can go up to 10^6 and relatively low stress amplitude. In this region, the S-N curve exhibits a linear relationship on a log-log plot. So, you can see here 10^4 is here. So, this is finite cycle, this is infinite cycle, this is the fatigue limit.

This is the fatigue limit here. You have low cycle fatigue and you have a high cycle fatigue log scale. You can see here stress maximum which is R_m. This is a curve. So, this is what is the flattening which we are talking about and this is what is a linear response we are talking about. The above one is called as Low Cycle Fatigue and the below one is called as High Cycle Fatigue.



The S-N curve are typically generated for specific test conditions like material properties, specimen geometry, loading type and particular environment. Generally, what we do is for bearings we do, for gears we do and then we do for shafts. These for mechanical engineering components, these things we do and nowadays what they do is they also try to construct scale down of a flat or a building and then they also try to do the for-disaster management, they try to do the S-N curve and see what is the response. So real world application often involves complex loading conditions and the S-N curve might need to be adjusted to consider these factors.

Typically, what do we do is we know the load, we go to the S-N curve and do the twice of the loading of whatever is the complex situation. So, we doubly make sure that the entire thing gets accommodated and then we do a test. Material properties can vary with a batch while the S-N curve represents an average behavior. Fatigue life, the fatigue limit is not always well defined for some materials. In S-N curve for example for composite materials it is not done for ceramic materials for certain type it is not done still it is a big scope of research. Thank you very much