Basics of Mechanical Engineering-1

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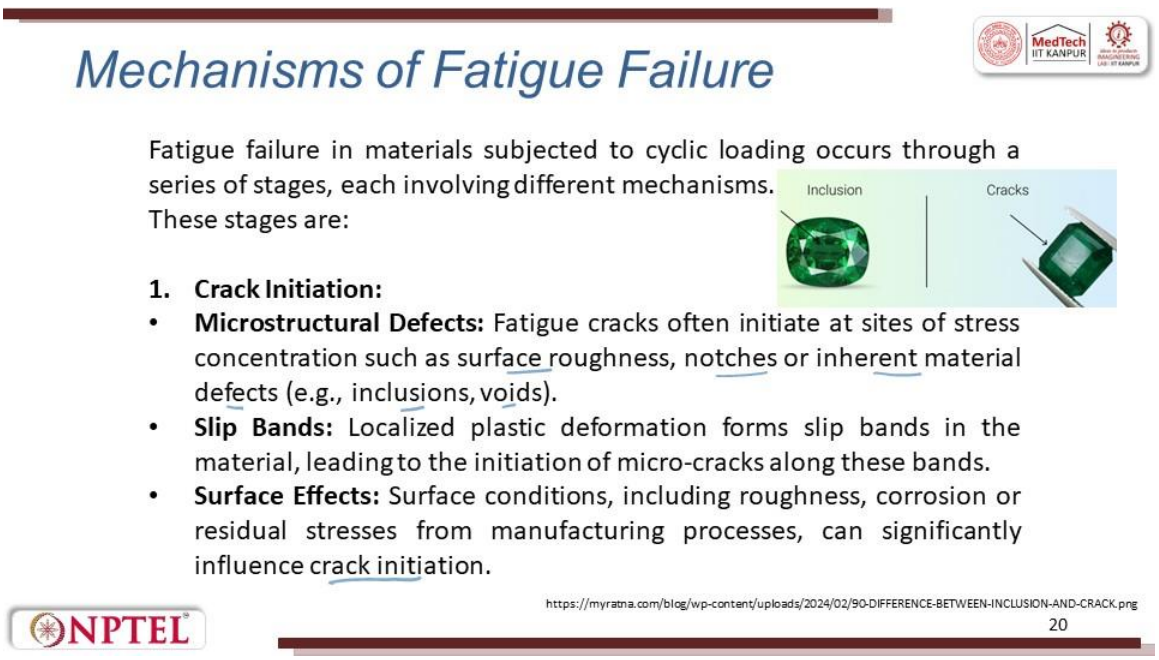
Week 04

Lecture14

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

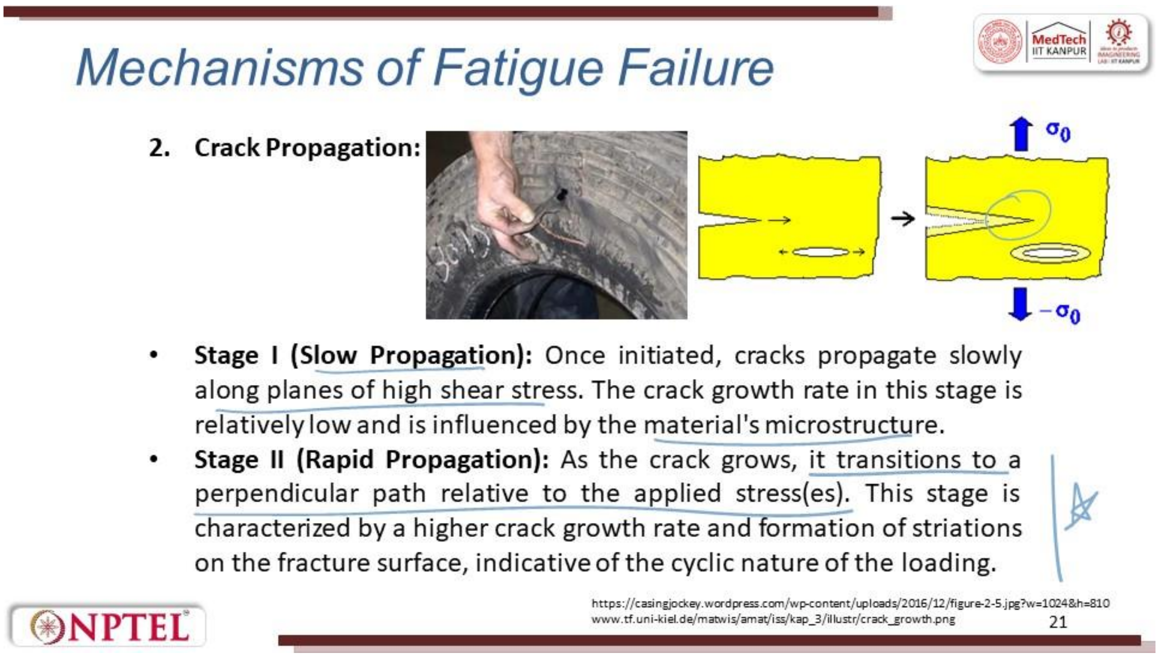
Welcome to the next lecture in this course on Introduction to Mechanical Engineering. This lecture is more focused towards Static Load and Fatigue Load.



What are the Mechanisms for Fatigue Failure? The fatigue failure in materials subjected to cyclic loading occurs through a series of stages. Each involving different mechanisms.

Take a diamond. So this is inclusion and this is where is the crack and you can see the crack grows to break it open. The Crack Initiation, it can be a Microstructural Defect. Fatigue cracks often initiates at sites of stresses, stress concentration such as surface roughness, notches or inherent material defects like inclusion and voids. If there is a void, from this void by cyclic load the crack initiates.

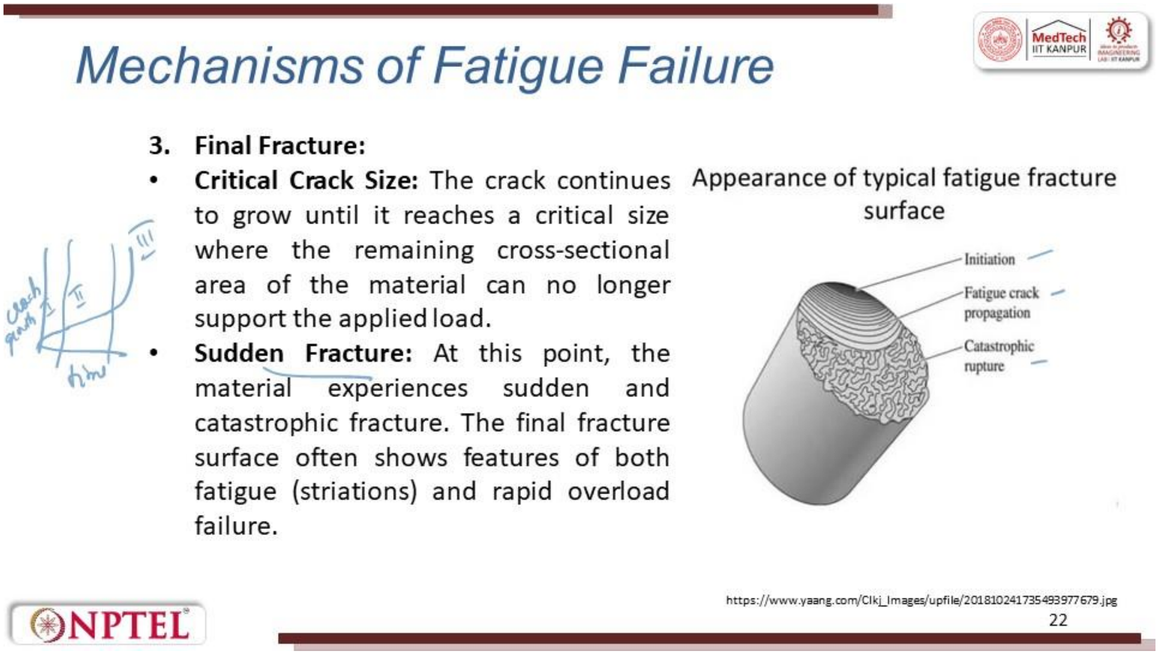
Slip band: Localized plastic deformation forms slip band in materials leading to the initiation of micro cracks along these bands. Surface Effects: surface conditions including roughness, corrosion, residual stresses from manufacturing processes can significantly influence the crack initiation. So these are all crack initiation possibility. Microstructural crack can happen, Slip Bands can happen, Surface Effects can happen. So this is Crack Initiation. How does a crack start in a fatigue load?



The next is Crack Propagation. How does the crack propagate? So it has two stages, stage 1 and stage 2. Stage 1 is called as Slow Progression.

Once initiated, the crack propagates slowly along planes of high shear stress. The crack growth in this stage is relatively low and is influenced by material microstructure progression along a plane of high shear stress. Next, take the stage 2, Rapid Propagation. As the crack grows, it transitions to a perpendicular path relative to the applied stress. This stage is characterized by higher crack growth rate and formation of striations on the fractured surface, indicative of cyclic nature of the loads.

This is very important. Please make a note. Stage 2, Rapid Propagation. As the crack grows, it crosses the initial and then goes into the rapid growth. It transitioned to a perpendicular path relative to the stress. So look at this, relative to the applied stresses. This stage is characterized by higher growth rate and formation of striations on the fractured surface.



The last one is the Final Fracture. So first it initiates, then it propagates, then it fails. So if you see the speed with respect to crack growth, it will be first stage initiation, it will be slow. It will be almost slow.

Then the propagation also, it will be very slow. Then it relatively goes. So this will be stage 1, this will be stage 2. And this is stage 3. Stage 3 is Final Fracture.

So critical crack size, the crack continues to grow until it reaches a critical size. You can see initiation, fatigue, crack, propagation, catastrophic failure. You see that this is a catastrophic failure. You can also see if you try to break a stick, you see a catastrophic failure. You can see also the initiation, propagation, everything.

The crack continues to grow until it reaches a critical size where the remaining cross section area of the material can no longer support the apply load. Sudden fracture. This is more common. Dominant in brittle materials, at this stage the material experiences sudden and a catastrophic failure. Sudden breaking of axle. Two years back when I was trying to ride my bicycle, all of a sudden the axle, pedal axle gave off and I slipped, fell down.

It is because of sudden fracture. And how do you know it? It is the crack is there. We always assume that when we do regular over oiling of that, these cracks are taken care.

Mechanisms of Fatigue Failure

4. **Influencing Factors:**
- **Stress Ranges:** Higher stress ranges accelerate crack initiation and growth.
- **Load Frequency:** Higher frequencies can lead to faster fatigue failure due to increased cyclic loading.
- **Environmental Conditions:** Corrosive environments can exacerbate fatigue by causing corrosion fatigue, where the combined effects of cyclic loading and corrosion accelerate crack growth.
- **Material Properties:** The intrinsic properties of the material, such as toughness, hardness and microstructure play significant roles in its resistance to fatigue failure.

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What are the Influencing Factors? The influencing factors for the mechanism of fatigue failure is the stress range. Higher stress range accelerates crack initiation and growth. Load frequency, higher frequency can lead to faster fatigue failure due to increase in cyclic load. Environmental conditions, corrosion environment can exacerbate fatigue by causing corrosion failure where the combined effect of cyclic loading and corrosion accelerates the crack growth. The intrinsic property of the material such as toughness, hardness and microstructure plays significant role in its resistance to fatigue failure.

Factors affecting Fatigue Life

Fatigue life is influenced by a variety of factors, which can significantly impact the durability and performance of materials subjected to cyclic loading.

Its key factors include:

1. **Stress Amplitude:** Higher stress amplitudes generally decrease fatigue life. The relationship between stress amplitude and fatigue life is often described by the S-N curve, where lower stress amplitudes result in longer fatigue lives.
2. **Mean Stress:** The mean stress (average stress in a loading cycle) can affect fatigue life. Tensile mean stresses typically reduce fatigue life, while compressive mean stresses can enhance it.

The Factors affecting Fatigue Life. The fatigue life is influenced by variety of factors which can significantly impact its durability and performance subjected to cyclic loading. One can be Stress Amplitude. The second one can be Mean Stress. The stress amplitude means higher stress amplitudes generally decreases fatigue life.

The relationship between the stress amplitude and the fatigue life is often described by a S-N curve. Where lower stress amplitude results in a longer fatigue life. Keep this in mind. Lower fatigue cycle leads to a longer fatigue life. Mean stress: Mean stress is otherwise called as Average stress in loading cycle can affect the fatigue life. Tensile means stress typically reduces the fatigue life while compressor means stress tries to enhance the life.

Factors affecting Fatigue Life

3. **Stress Concentrations:** Features such as notches, holes, and sharp corners create stress concentrations, leading to higher localized stresses that can significantly reduce fatigue life.
4. **Surface Finish:** Rough or poorly finished surfaces have higher stress concentrations, promoting crack initiation and reducing fatigue life. Smooth and polished surfaces can improve fatigue performance.
5. **Material Properties:** Intrinsic properties of the material such as strength, hardness, ductility and toughness play a crucial role in fatigue life. Materials with higher strength and toughness generally exhibit better fatigue resistance.

Stress Concentration is another factor which affects fatigue life. Stress concentration means a feature like a notch, hole, sharp corner creates a stress concentration leading to higher localized stresses that can significantly reduce the fatigue life. That is why a hole is always made circular and not square. So all these edges will be stress concentrated points when you put this into fatigue loading.

Surface finish: rough or poorly finished surface have higher stress concentrations promoting crack initiation and reducing fatigue life. Smooth and polished surface can improve fatigue performance. Material properties, intrinsic properties of the material such as strength, hardness, ductility, toughness play a crucial role in fatigue life. Material with higher strength and toughness generally exhibit a fatigue resistance. So toughness, the area under the curve, you remember the stress-strain graph.

Factors affecting Fatigue Life

6. **Residual Stresses:** Compressive residual stresses, often introduced by processes like shot peening or surface rolling, can improve fatigue life by hindering crack initiation and growth. Tensile residual stresses have the opposite effect.
7. **Environmental Conditions:** Corrosive environments can accelerate fatigue crack growth through mechanisms like corrosion fatigue. High temperatures can also affect material properties and fatigue behavior.
8. **Load Frequency:** Higher frequencies of cyclic loading can increase the rate of fatigue damage accumulation, potentially reducing fatigue life.
9. **Load Ratio:** The load ratio (ratio of minimum to maximum load in a cycle) influences fatigue life. Different load ratios affect the mean stress and stress amplitude experienced by the material.

The Residual Stresses which we have discussed in the previous lectures, compressive residual stresses often introduced by process like shot peening or surface rolling can improve fatigue life by hindering crack initiation and growth. Environmental conditions like corrosion, see if you have a crack and then what happens, the water can go and sit inside or an acid can go sit inside, the crack is very small. So once this liquid or something goes inside, so now this fellow accelerates the growth, can accelerate fatigue crack growth through mechanisms like corrosion fatigue. Higher temperatures can also affect the material property and the fatigue behavior. Load frequency is higher frequencies of cyclic loading can increase the rate of fatigue damage accumulation and potentially reducing the fatigue life.

Load ratio: the ratio of load minimum to maximum load in a cycle influences the fatigue life. Different load ratios affect mean stress and stress amplitude experienced by the material.

Factors affecting Fatigue Life

10. **Grain Size and Microstructure:** Finer grain sizes generally enhance fatigue resistance due to improved crack initiation resistance. The material's microstructure, including phases and inclusions also affects fatigue life.
11. **Thickness and Size Effects:** Thicker and larger components tend to have shorter fatigue lives due to the increased probability of flaws and stress concentrations.
12. **Service Conditions:** Real-world service conditions, such as varying load amplitudes, complex stress states and multi-axial loading can significantly impact fatigue life.

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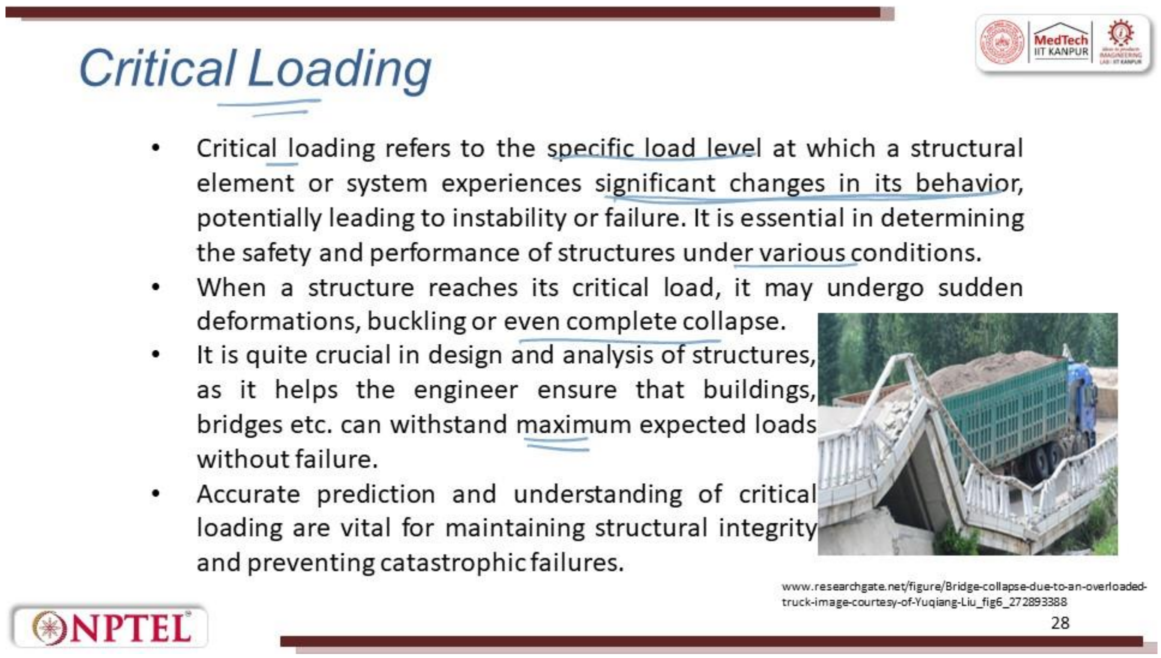
The Grain Size and the Microstructure. Fine grain size generally enhances the fatigue resistance due to improved crack initiation resistance. So that is why we always try to quench the sample and other things.

Grain size refinement. The Thickness or the Size Effect. Thicker and larger components tend to have shorter fatigue life due to the increased probability of flaw and stress concentrations. The Service Conditions also play an important role in the fatigue life. The real-world service conditions such as varying load amplitude, complex stress states and multiple axial loading can significantly affect the fatigue life.



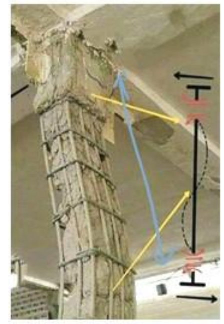
Critical Loads. Critical Loading refers to a specific load level at which a structural element or a system experiences significant change in its behavior, potentially leading to instability or failure. It is essential in determining the safety and the performance of structure under various conditions. When the structure reaches its critical load, it may undergo a sudden deformation, buckling or even complete collapse. Critical load is very important. It is crucial in design and analysis of structures as it helps the engineer to ensure the building, bridge etc. to withstand maximum expected load without failure.

So critical load is important. Accurate prediction and understanding of critical load are vital to eliminate catastrophic failure.

Buckling Load

It is the specific load level at which a slender structural member experiences sudden deflection or bending, leading to instability.

- Unlike other types of structural failure, buckling occurs without significant prior deformation and happens even when the material stress is well below ultimate strength.
- This phenomenon is critical in the design of columns, beams and other slender structures to represent the point at which they will no longer support additional load and collapse.
- The buckling load depends on various factors including the member's length, cross-sectional shape, boundary conditions and material properties.



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What is Buckling Load? It is a specific load level at which a slender structural member experiences sudden deflection or bending leading to instability. This is a column.

So this column suddenly tries to deflect. So this is called as Buckling Load. So there the critical load is after which there is a ketoscopic failure. But buckling is if the specific load level at which the slender structural member experiences a sudden deflection or bending leading to instability. Unlike other types of structural failure, buckling occurs without significant prior deformation and happens even when the material stress is well below the ultimate strength.

So you keep it in mind, critical loading and buckling loading. This phenomena is critical in designing columns. Beams and other slender elements to represent the point at which no longer support additional load and the point at which they will no longer support additional load and collapse. So, it is buckling. It is the initial stage towards failure.

The Buckling Load depends on various factors including member's length, cross-section, shape boundary conditions and material properties.

Ultimate Load

It refers to the maximum load a structural element or system can withstand before experiencing complete failure.

- It represents the upper limit of a structure's capacity to bear external forces, beyond which it irreversibly deforms, fractures or collapses down.
- It is a critical parameter in structural engineering, as it defines the point at which the material or structure fails catastrophically.
- Determining the ultimate load involves considering factors such as material properties, geometry, load application methods and environmental conditions.
- Ensuring that structures are designed to be within safe limits below ultimate load is vital to prevent failures and ensure safety and longevity of bridges, buildings and other infrastructure.

www.reddit.com/r/CatastrophicFailure/comments/bhkbrb/house_collapses_after_the_removal_of_a_load/?rdt=53804

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What is Ultimate Load? It refers to the maximum load a structural element or a system can withstand before experiencing complete failure. There is a difference between Critical Load and Ultimate Load. Critical load refers to a specific load level at which a structural element or system experiences significant change in the behavior.

Significant change in the behavior. Here experiences complete failure. It represents the upper limit of the structural capacity to bear external forces beyond which it irreversibly deforms, fracture or collapses down. It is a critical parameter in structural engineering. Determining the ultimate load involves considering factors such as material property, geometry, load application method and environmental conditions.

Ensures the structure are designed to be within the safe limit before ultimate load is vital to prevent failure and ensure safety and longevity of bridges.

Critical Loading

Importance of Understanding Critical Loads:

1. **Enhancing Structural Safety:** Knowledge of critical loads ensures that structures are designed to withstand maximum expected forces, preventing catastrophic failures and ensuring the safety of occupants.
2. **Preventing Catastrophic Failures:** Understanding critical loads helps in identifying thresholds at which structural elements may fail, allowing for design modifications to prevent sudden and severe failures.
3. **Optimizing Material Usage:** Accurate determination of critical loads helps avoid overdesigning, leading to efficient use of materials and cost savings in construction.
4. **Ensuring Long-term Reliability:** Designing structures with consideration of critical loads ensures their durability and performance throughout their service life, reducing the need for frequent repairs.

Importance of Critical Load. Understanding of critical load is important. Because it will try to help us in Enhancing Structural Safety. It helps in Preventing Catastrophic Failure.

It helps in Optimizing Material Usage, Ensuring Long-term Reliability. The Critical load, right. So in old buildings, if there is a small deflection or something, they try to give supports. So understanding the critical load helps them to understand, there is a need for the support and then they start giving. Same with respect to buckling load, okay. So critical load also plays an important role.

Critical Loading

Importance of Understanding Critical Loads:

5. **Facilitating Maintenance and Inspection:** Knowledge of critical loads aids in the maintenance and inspection processes by identifying critical areas that may require reinforcement or repair.
6. **Cost Efficiency:** By preventing overdesign and ensuring efficient use of materials, understanding critical loads contributes to overall cost efficiency in construction projects.
7. **Compliance with Standards:** Ensuring that structures are designed to withstand critical loads helps in meeting building codes and standards, which are essential for regulatory approval and public safety.
8. **Informed Decision-Making:** Engineers can make informed decisions regarding design, materials, and construction techniques based on the understanding of critical loads, leading to better-engineered structures.

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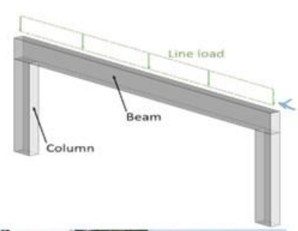
So, Facilitating Maintenance and Inspection, Cost Efficiency, Compliance with Standards and Informed Decision Making all are very important that you should know the critical load.

Case Study: Bridge Design

Design Considerations

1. **Material Selection:**
   - **Static Loads:** Steel for strength and ductility, reinforced concrete for durability.
   - **Fatigue Loads:** High-strength low-alloy (HSLA) steel with surface treatments.
2. **Safety Factors:**
   - **Static Loads:** Safety factors of 1.5 to 2.0 for steel and concrete.
   - **Fatigue Loads:** Safety factors of 1.3 to 1.5 for components under cyclic loading.



https://assignmentpoint.com/materials-structures-functions-utility-etc-and-types-of-bridges-based-on-span/
www.structuralbasics.com/wp-content/uploads/2022/10/Dead-line-load-applied-on-beam-supported-by-columns.jpg

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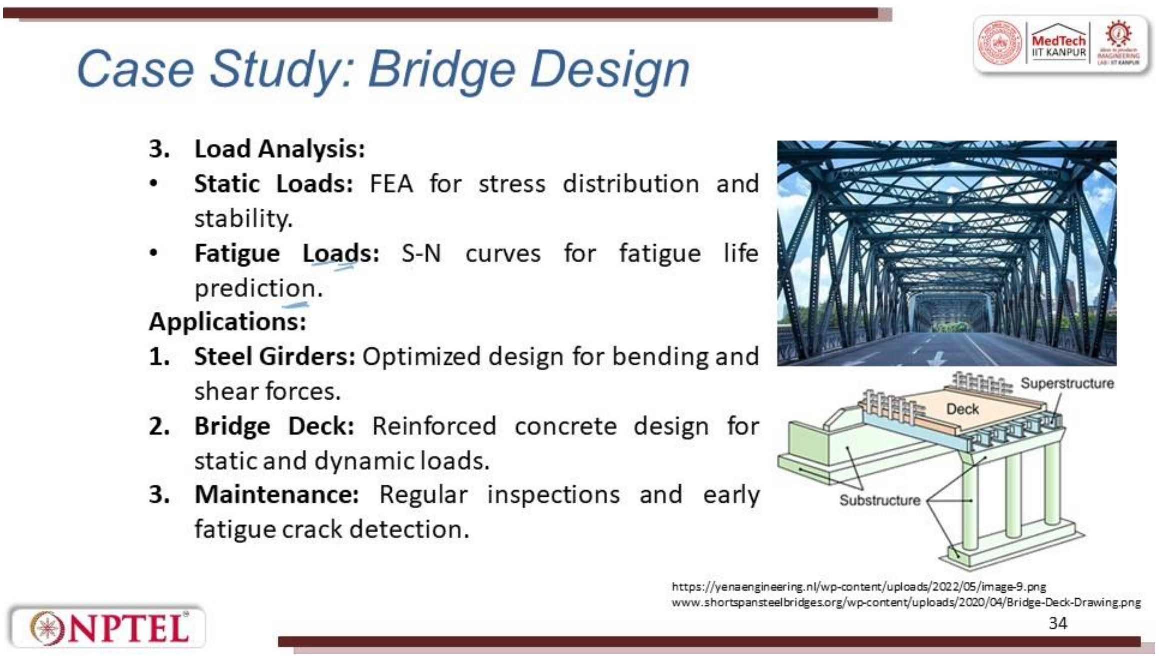
Let us try to take a case study and discuss. Take a case study of a Bridge. So, in a bridge, we try to make a bridge wherein which the car keeps going in one direction.

So here this is the beam, this is the column. The column supports or the column is in the vertical direction, beam is in the horizontal direction and on top of it is the line load. So the design consideration when we are trying to do a bridge is static load. Steel for strength and ductility, reinforcement concrete for durability. Fatigue loads, high strength low alloy steels with surface treatment is always considered for fatigue loads.

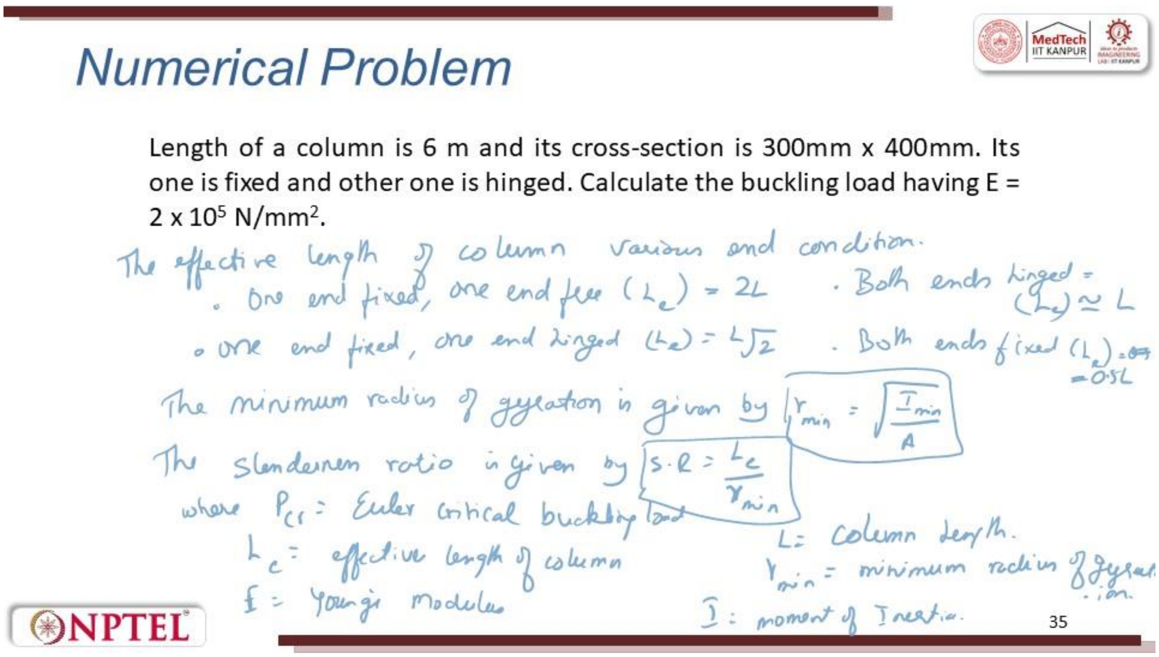
Then safety factors, the safety factor of 1.5 to 2 for steel and concrete is considered. Fatigue life, the safety factor of 1.3 to 1.5 for components under cyclic loading are considered.



The load analysis, static load, FEA for stress distribution and stability is done for a static load. Fatigue load, S-N curve for fatigue life is predicted. These are the considerations for bridge.

And applications, whatever we have considered, it can be used in making steel girders. Here the optimized design for bending and shear force it tries to take. Bridge deck design. Bridge deck is reinforced concrete design for static and dynamic load is done.

Maintenance, regular inspection and early fatigue crack detection is also considered in the bridge design.



So, let us try to solve a numerical problem. So, a length of a column is 6 meters and its cross section is given. Its one end is fixed and the other one is hinged. Calculate the buckling load having E equal to 2×10^5 N/mm^2.

So, the effective length of column for various end consideration or end conditions.

First is one end fixed, one end free (L_e) = 2L.

If both ends are hinged, then it is going to be (L_e) ≈ L.

If one end fixed and one end hinged, (L_e) = $\sqrt[L]{2}$

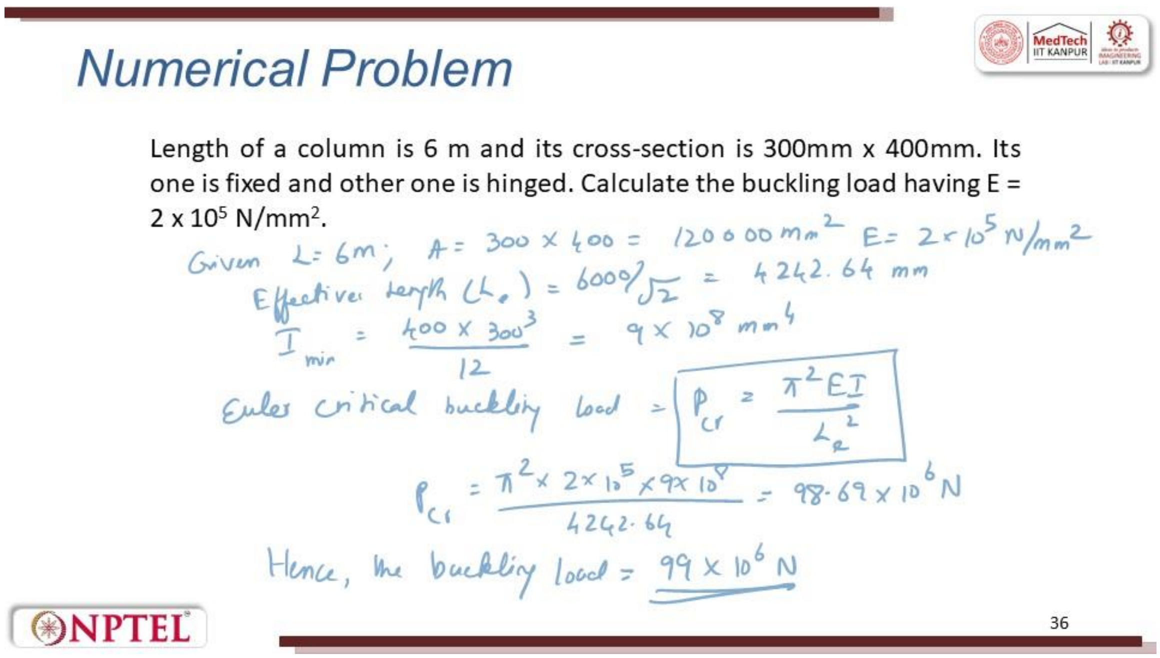
If both ends are fixed, the (L_e) = 0.5L

The minimum radius of gyration is given by $r_{min} = \sqrt{\frac{I_{min}}{A}}$

The slenderness ratio is given by $S.R = \frac{L_e}{r_{min}}$

So, where P_{CR} is nothing, but is Euler critical buckling load. L_e is the effective length of column.

And E is the Young's modulus. Okay. L is the column length. R_{min} is the minimum radius of gyration and I is the moment of inertia.



So, now given L = 6 meters, A = 300 × 400 = 120000 mm^2, E = 2 × 10^5 N/mm^2.

So, the effective length is (L_e) = $^{6000}\sqrt{2} = 4242.64\ mm$

Now, I_{min} = $\frac{400\times300}{12} = 9 \times 10^8\ mm^4$

I is the moment of inertia.

The Euler critical buckling load = $P_{CR} = \frac{\pi^2 EI}{L_e^2}$

$$P_{CR} = \frac{\pi^2 \times 2 \times 10^5 \times 9 \times 10^8}{4242,64} = 98.69 \times 10^6$$

Hence, the buckling load is 99 × 10^6 N. I am just rounding it off.

To Recapitulate

- What is static loading and why is it important in engineering?
- How does fatigue loading differ from static loading?
- What are critical loads and why do engineers need to consider them?
- Explain the concept of S-N curves and their significance in fatigue analysis.
- What are the characteristics of fatigue loading and how does it affect structural integrity?
- Differentiate between buckling load and ultimate load. Provide examples.

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To recap what we have seen in the lecture, we saw what is static loading and why is it important in engineering. How does fatigue loading differ from static loading? What are the critical loads and why do engineers need to consider them? Analyzing the concept of S-N curve, what are the characteristics of fatigue loading and how does it affect the structural integrity, the difference between critical loading, buckling loading and ultimate loading was covered.

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These are the references which we have used in preparing this lecture. Thank you very much.