Basic Construction Materials
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Lecture – 4
Materials Engineering Concepts – Part 1
(Characteristic Value and Stress-Strain Behaviour)

Hi, today we are going to cover characteristic value and stress-strain behavior of various materials. So there will be three lectures that I am planning in these materials engineering concepts. Today is the first lecture.

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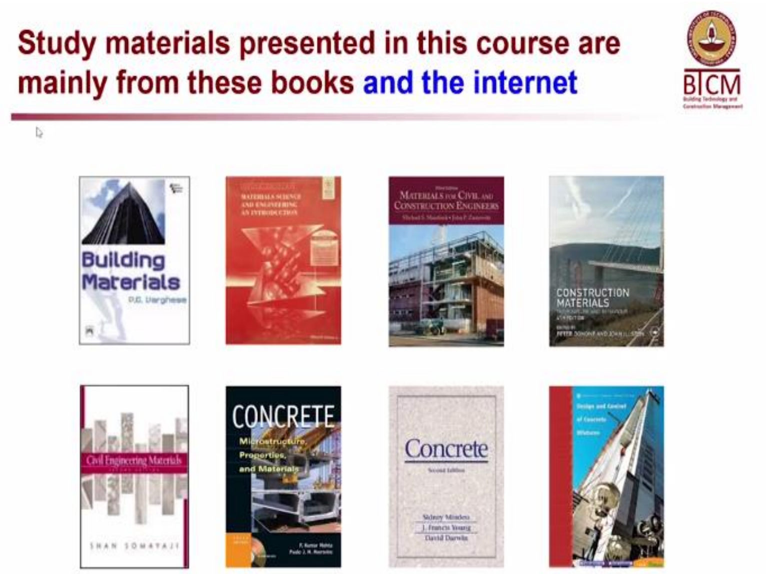

Furthermore, these are the reference books I use in this course module, and also we use a lot of information or photographs etc., from the internet.

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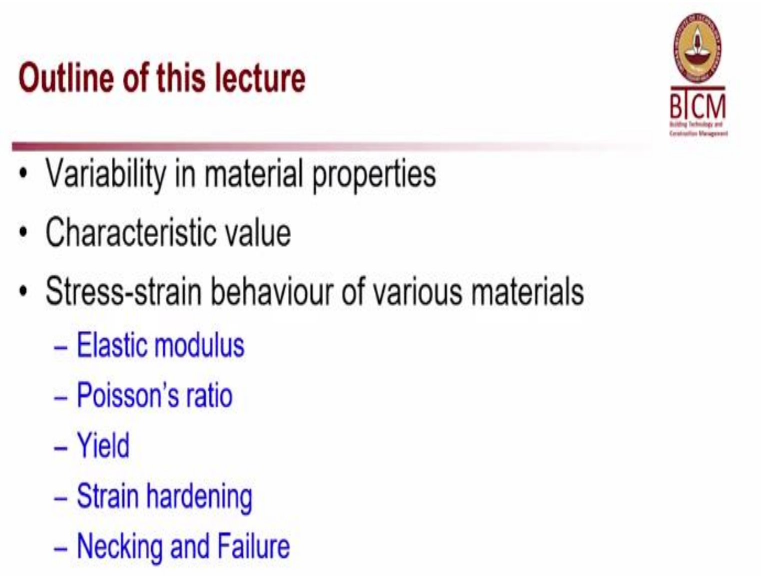

Now outline of this lecture. We will first cover variability in various material properties. It also addresses this variability in the properties in the design process that is where we use something called characteristic value. And then also we will discuss the stress-strain behavior of various materials. We will cover elastic modulus, Poisson's ratio, yield strength, strain hardening, necking, failure, etc.

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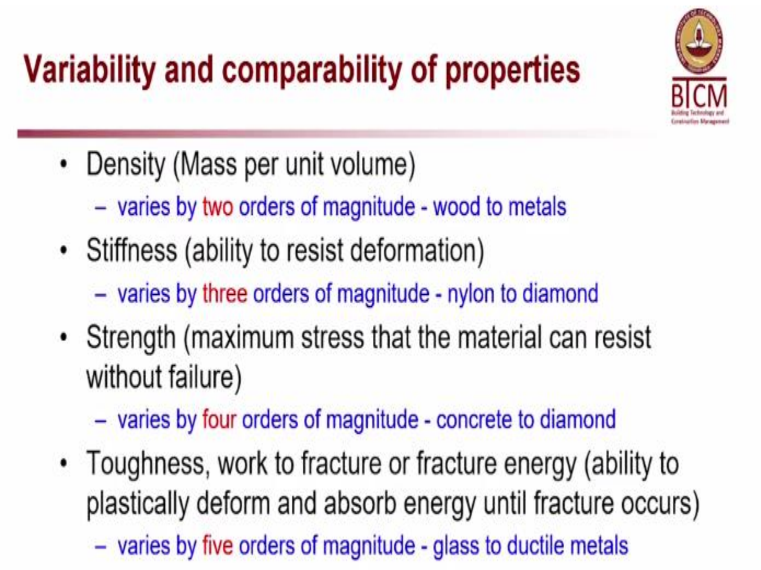

So variability and comparability of properties: So I will cover just two three material properties to tell you where we see the variability and what it is about. So first, let us say talk about density. What is density? It is the mass of a material per unit volume of the material, and it can vary significantly from material to material. From wood to metals, there could be an order of magnitude difference of about two if we look at it.

Another parameter is stiffness which is the ability of any material to resist deformation, and it can vary. If we talk about from nylon to diamond, it can vary in three orders of magnitude. Moreover, strength is another essential parameter which we look at while designing. Most of the time, we give much importance to the material's strength, and it is nothing but maximum stress that the material can resist without failure.

There could be a difference in the order of magnitude up to four times from concrete to diamond. Now toughness is another parameter known as work to fracture or fracture energy. What is it? It is the ability to deform and absorb energy plastically until a failure occurs. For example, if we look at the glass, the toughness is very low.

Whereas when we compare that to a very ductile material, the toughness can be very high. In other words, the ductile materials can absorb much energy before it actually fractures or fails.

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Material	Density (tonne/m³)	Stiffness(E) (GPa)	Strength or limiting stress (MPa)*	Work to fracture (toughness) (kJ/m²)	Relative cost per unit	
					mass	volume
Diamond	3-5	1000	50000	-	$2 * 10^6$	$8.9 * 10^5$
Common pure metals	5 -19	20 - 200	20 - 80	100 -1000	-	-
Structural steel	7.85	195 - 205	235 - 450	100- 130	1.0	1.0
High strength steel	7.85	205	260 - 1300	15 - 120	-	-
Cast iron	6.9 -7.8	170-190	220 - 1000	0.2 - 0.3	-	-
Silica glass	2.6	94	50 - 200	0.01	3.4	1.1
Titanium and alloys	4.5	80 - 130	180 - 1320	25- 115	27.5	1.6
Aluminum & alloys	2.7	69 - 79	40- 630	8 - 30	5.0	1.7
Timber	0.17 - 0.98 (dry)	0.6- 1.0 perp grain 9 - 16 par grain	90 - 200 tens 15 - 90(comp)**	8 -20 Crack perp grain 0.5 - 2 crack per grain	-	-
Spruce (Par to grain)	0.5	13	40 - 80	0.5 - 1	1.0	0.06
Concrete	1.8 - 2.5	20 - 45	4 - 10(tens)	0.03	0.7	0.12
Epoxy resin	1.1 - 1.4	2.6 - 3	30 - 100	0.1 - 0.3	3.8	0.53
Glass fibre component(grp)	1.4 - 2.2	35 - 45	100 - 300	10 - 100	-	-
Carbon fibre composit		180 - 200	600 - 700	5 - 30	-	-
Nylon	1.1 - 1.2	2 - 4	50 - 90	2 - 4	7.5	1.1
Rubber	0.95 - 1.15	2 - 10	15 - 30	-	-	-

par = parallel; perp = perpendicular; tens = tensile; comp = compressive; grp = glass-reinforced plastic

How do we use such properties in structural design?

Now, this is a table with these properties we just discussed. I do not want to go through the entire table which you can pause the video here and have a look at this table for a few minutes, and then you can understand the variability of these different parameters across different materials and also within the same material. For example, if we look at the concrete, we can see that the density can vary from 1.8 to 2.5, when we talk about the stiffness of concrete, it varies from 20 to 45 GPa. If we are talking about strength, I mean again, we keep on modifying concrete. So we see a lot of variability in the same type of materials by changing small things or the material design. So in industry or when we practice, we see a lot of such variations in the properties of materials. Now how do we use these properties in the structural design? We have to take care of the variability while designing, and at the same time, we need to be safe.

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Before we talk about safety, I would also tell you different materials used for similar purposes. For example, let us say we want to design a truss or a tension member in a truss. We can use steel, use timber there are many options available. For example, we can see steel in a truss member and wood both can take tensile loads.

We are essentially trying to tell that for the same application. We can use multiple materials. Now in such a case, how would we choose a material? For example, here also we have a brick column and a concrete column. So, both will have different strengths. Based on the material's availability, how costly each material is, and we look at something technically what is the material's weight.

What are the limiting dimensions and the minimum useful life or the durability part of it okay. So cost is a critical component, and then we have to look at the weight of the material and then limiting dimensions. For example, if we use a very low strength material for a column, we might have a massive column. Even in this picture, we can see that the brick column is enormous in diameter.

If we replace that brick column with a concrete column with a very high-quality concrete or high strength concrete, we can have a very slender concrete column that will also give us more floor space. So there are different aspects which we have to think about. If we are talking about a beam, we can get more floor height if we use a concrete beam and replace it with a wood beam.

I mean, the clear distance from the floor to the bottom of the beam could be different in both cases. So it depends on various limiting dimensions that architects are always concerned about, so we want to create more space inside our buildings. So these are different things which we have to consider. Aesthetics and personal preferences are also essential to consider.

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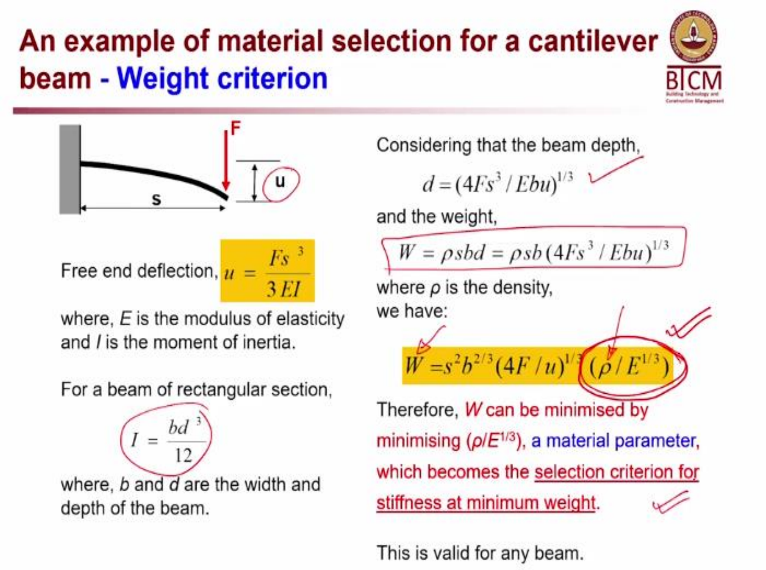

Now we talked about the weight criterion, right. So how do we choose a material based on its weight? So here I am going to show you an example, I am not going to go in detail about this slide that you can view later or pause and understand these equations, but the example here we are talking about is a cantilever beam where you apply a force F at the end of the beam or the free end of the cantilever.

$$u = \frac{FS^3}{3EI}$$

u is the deflection at the free end of the cantilever

F is the force at the free end of the cantilever

S is the length of the cantilever beam

E is the modulus of elasticity

I is the moment of inertia, by looking at the cross section we can calculate that.

For a rectangular section, the Moment of Inertia I is defined as

$$I = \frac{BD^3}{12}$$

Now we can plug this I into the first equation or the equation in the orange box. We get

$$d = \left(\frac{4FS^3}{Ebu}\right)^{1/3}$$

from this, we can get an expression for the weight (W) that is

$$W = \rho \mathrm{Sbd}$$

Where ρ is the density

$$W = \rho Sb\left(\frac{4FS^3}{Ebu}\right)^{1/3}$$

$$W = s^2 b^{2/3} (4F / u)^{1/3} (\rho / E^{1/3})$$

Now when we look at that expression and look at different variables in that, we know that this part

$$(\rho / E^{1/3})$$

is only dependent on the type of material which we use, the density, and the modulus of elasticity, both of them are material parameters. They do not change as the dimension of the beam is changing, but all other parameters can change. we can change the load(F), we can change the length of the beam(S), the width of the beam(b), etc., can be changed.

But if we want to design the beam based on the material parameter and reduce the weight, we can say that. If we are going to reduce the density, it can reduce the weight.

So we have to minimize the below-given parameter so that the weight can get reduced

$$(\rho / E^{1/3})$$

Which is a material parameter, and it becomes the selection criteria for stiffness at minimum weight.

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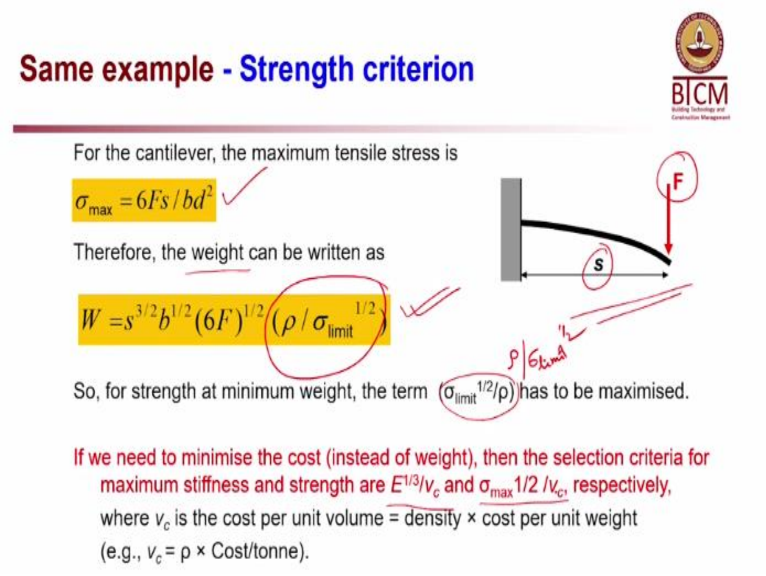

Now we also use strength as a criterion for designing material systems. For the same cantilever beam example, let me show you how that can be done. We can see the same diagram with the force F acting and the beam's length as ’s’. So, the maximum tensile strength can be expressed like this.

$$\sigma_{max} = \frac{6FS}{bd^2}$$

Where ‘b’ is the beam's width, and ‘d’ is the beam's depth.

Then we can express the weight as

$$w = s^{3/2} b^{1/2} (6F)^{1/2} \left(\rho \ / \ \sigma_{max}^{1/2}\right)$$

Now here we have to see that when we want to reduce the weight and also consider the strength as a criterion, so we have to maximize the below parameter

$$\left(\sigma_{max}^{1/2}/\rho\right)$$

If we need to minimize the cost instead of weight, that is the third criterion. The selection criteria for maximum stiffness and strength are based on the stiffness criteria and this sigma max criteria, respectively, where V_c is the cost. So we have to see whether we want to look at the weight or strength, or cost. What is our main criterion? Accordingly, we develop a formulation that will help us minimize or maximize a particular parameter, which is generally adopted in various applications.

And then because it is not only strength and weight that we have to consider, money is also significant, so we also talked about cost. So we have to think about various aspects and then see which is the most feasible solution for us to adopt.

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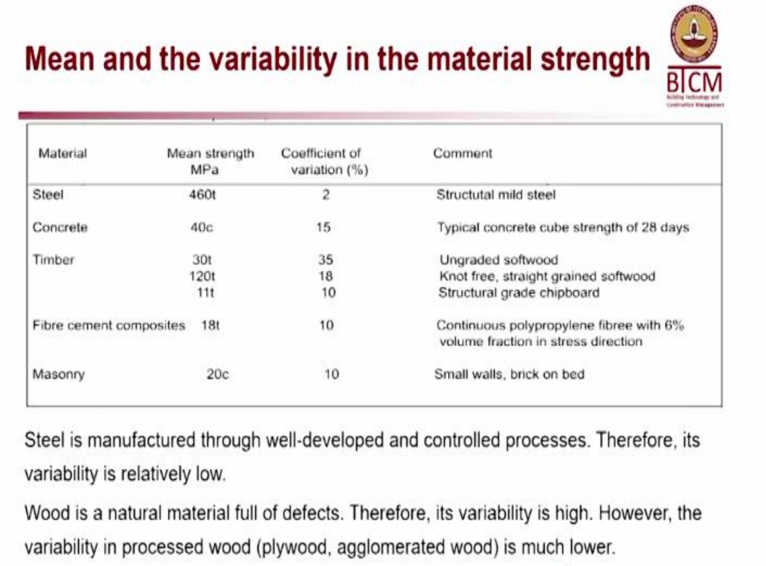

Mean and the variability in the material strength

Material	Mean strength MPa	Coefficient of variation (%)	Comment
Steel	460t	2	Structutal mild steel
Concrete	40c	15	Typical concrete cube strength of 28 days
Timber	30t 120t 11t	35 18 10	Ungraded softwood Knot free, straight grained softwood Structural grade chipboard
Fibre cement composites	18t	10	Continuous polypropylene fibree with 6% volume fraction in stress direction
Masonry	20c	10	Small walls, brick on bed

Steel is manufactured through well-developed and controlled processes. Therefore, its variability is relatively low.

Wood is a natural material full of defects. Therefore, its variability is high. However, the variability in processed wood (plywood, agglomerated wood) is much lower.

We can look at this table and see that we can choose different materials for the same application. However, the cost will be exorbitantly high in the case of a diamond, so we may not go for it. So but definitely, we sometimes compare if we want let us say for a building if you are talking about column beam sections, whether structural steel or concrete, which is a better option for us to go.

So there cost can play a role, for example, here cost in the case of steel if it is 1, in case of concrete, we can have that 0.8 that is the main reason why concrete is sometimes more popular than steel. So different options are available. We have to have tables of information like this before choosing what material to be used. So when the cost is neglected, sometimes diamonds can be used, titanium, aluminum, wood, epoxy are the best, but when the cost is neglected but that is not the case in most applications.

So when the cost has to be minimized, conventional materials such as wood, concrete, the steel might be more beneficial. And of course, we have to think that the time and location where we construct. For example, if we are talking about wood where much timber is available, it might be cheaper there but not in places where it is not easily or abundantly available. Furthermore, concrete, steel all depend on where the manufacturing plants are located, where the cement plants are located.

Various factors govern the cost of different materials. So we have to think about the cost also while selecting materials in addition to the technical features. So many important aspects are neglected. This table is straightforward. We also have to think about durability, toughness, construction time, transportation, etc., and many other parameters before choosing a particular construction material.

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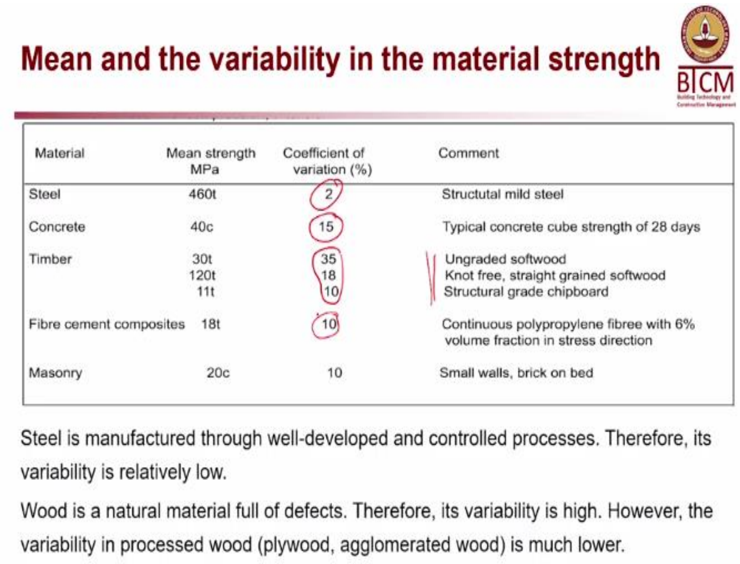

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Now there are mean and variability in the material strength. For example, when we look at steel here, there is a term ‘t’ here that is standing for tension, all these ‘t's in this are for tension, and then ‘c’ is for compression.

When we look at steel, let us say steel with the mean strength of 460 MPa, and you can expect that the coefficient of variation of steel is about 2%.

Variation of the tensile strength of steel is about 2% and whereas the similar variation coefficient of variation for compressive strength of concrete can be about 15%. Because steel is a more homogeneous material than concrete and steel is manufactured with much better quality manufacturing processes. In contrast, in concrete, we use natural materials like aggregate, even cement.

I mean, cement is processed, we can say. However, there are aggregates that have much variability in their properties. The interface between the cement and aggregate will also be different at different points within the concrete that also depends on how the concrete was placed and how it was compacted lot of factors play. Generally, we expect a wider variation in the properties of concrete compared to that of steel.

Now in the case of timber, we expect much more. You can see here 35, 18, 10. You can look at here also different types of timber we are talking. So if it is ungraded, that means more naturally available timber you can expect much more variation in the properties, so like in the fiber-based cement composite, you have less because it is more or less manufactured and also better controlled even if there are cracks, etc., the fibers tend to bridge those cracks and minimize the variation in the properties, Similarily masonry

We can see this variability across different materials which are used, and that has to be considered in the design process. We cannot always use the mean value for the design process. That means 50% if we are using the mean value for the design process, it means 50% of the values will be above the design value and 50% will be less. So that means there is a very high chance of failure of the structure. So what do we use?

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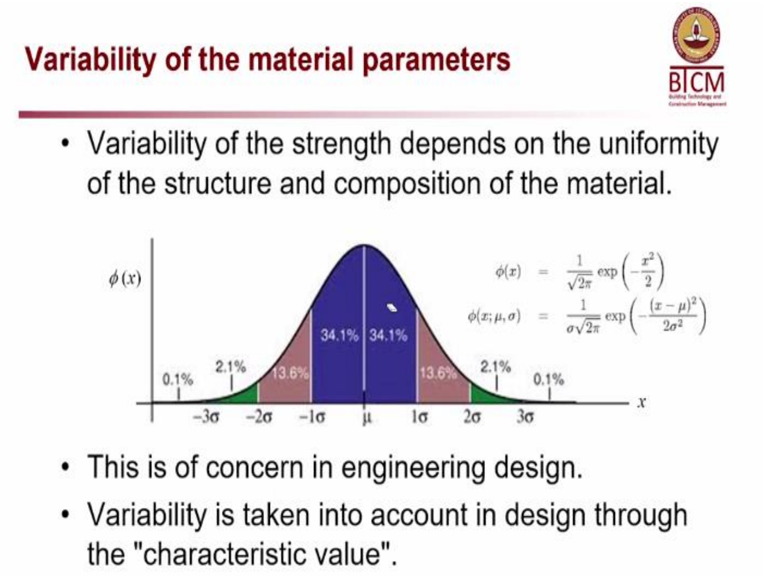

We use something called characteristic value. Now, what is this characteristic value? So it is a variability of the strength that depends on the uniformity of the structure and composition. So many variabilities are possible. Typically, we express this variability in terms of normal distribution in general, and then we use this word characteristic value.

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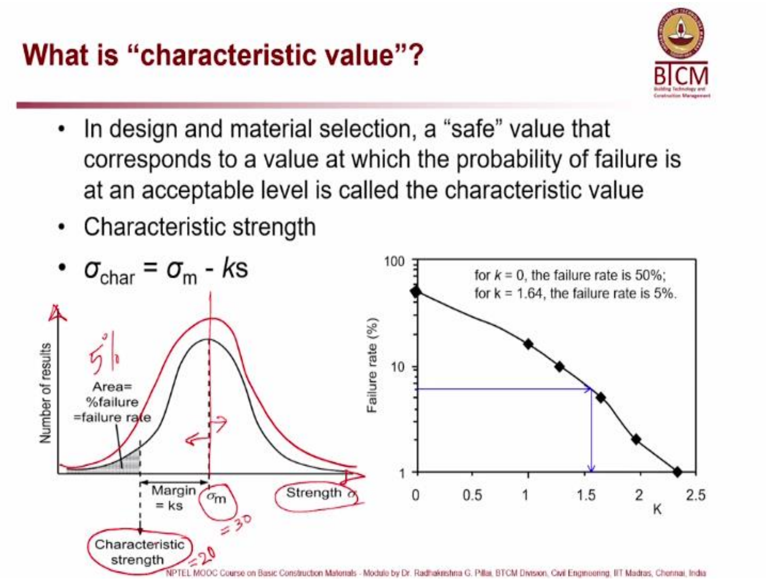

What is characteristic value? In the design and material selection, characteristic value is the value that we can consider as a safe value that corresponds to a value at which the probability of failure is acceptable. To understand, see the graph in the bottom left, so if we plot, let us say we do 100 tests on the concrete cube, let us say we take a concrete cube and perform the strength test on all those cubes. Then we plot these 100 values then we would get a bell-shaped curve distribution. This is what we call a normal distribution.

This is the strength of the cube. It is plotted like this, and then for each values, how many specimens actually have that particular strength? So, on the horizontal axis or abscissa, we have compressive strength and on the vertical axis, we have a number of specimens that give that particular strength okay.

Now what I am showing here is the average strength of all those 100 specimens might be σ_m, which means that on the left side of this vertical dash line, we have 50% of the specimen, on the right side, we have 50% of the specimen. So here we have 50%, here we have 50% that is the mean value.

Now, if we use that value for the design, what it means is that the probability of failure of that material is 50% because 50% of the material might have a higher strength than the mean value, and 50% of the material might have lower strength than the mean value. So this is not acceptable for design purposes. So we use something called characteristic strength or characteristic value, which is typically assumed to be around 5% okay.

So this region which is shaded, is typically taken as 5%. So that means if my average value σ_m let us say it is equal to 30 MPa, for the design purpose, I might consider the characteristic value, which might be let us say 20 or 25 or something like that, approximately 20 or 25, depends on the variability of the material okay. In the case of steel, this difference between σ_m and characteristic strength will be very less, in the case of concrete, it could be higher.

So we have to think about characteristic value, which is the value we use for design purposes and not the mean value, not the average strength. So it is very important to consider.

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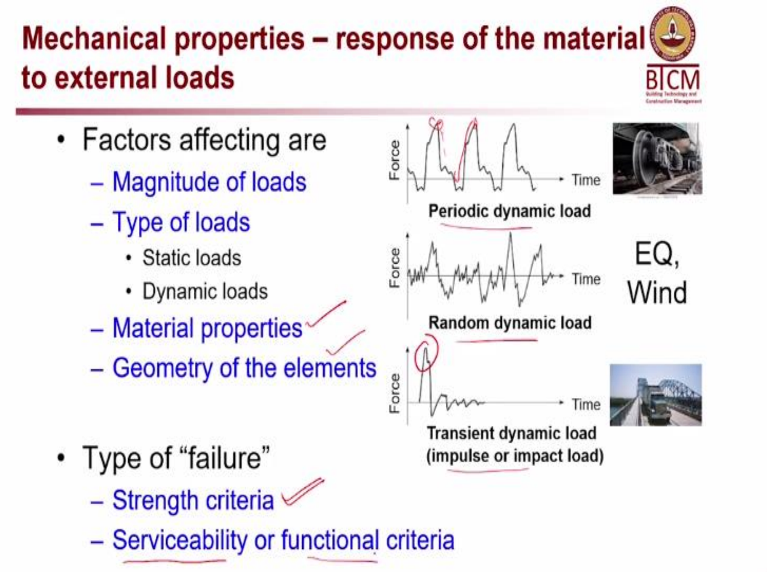

Now let us look at some mechanical properties of the materials and the material's response to external loads. So how these responses? They are dependent on the magnitude of the loads definitely and the type of load. For example, if we look at the type of load, I show three graphs

- periodic dynamic load
- random dynamic load
- transient dynamic load

Periodic dynamic load

Suppose a railway track. When a train goes through a particular point, we can say that every wheel will come in kind of a very uniform way. The loading will be kind of uniform but dynamic, not uniform periodic but dynamic in nature. Every wheel when it passes we will have let us say, the wheel passes here, and then the wheel moves away from that point. Then, so load comes down and again the next the following wheel comes and then it reaches something like that okay.

Random dynamic load

Earthquake and wind loads are examples of that and transient dynamic load impulse or impact load.

Transient dynamic load

Let us say we have a heavy vehicle passing through a bridge. So the moment the vehicle enters the bridge, that column might experience an impact load, just a fraction of a second. So we have that impact load here, and then it dies down as the vehicle moves away from that particular column.

Like these, different types of loads are there, and then definitely material properties influence the performance of the material or how the materials respond to the load and the geometry okay. These are material properties and the size and shape of the elements also matter a lot when we think about the material's response.

How can the typical systems fail? There are two types of failure

- **Strength failure**

  Strength criteria are typically when we talk about collapse or fails or breaks into two, etc. If we are talking about strength criteria for a column, I can say the applied load is more than the capacity of the concrete material's strength.

- **Serviceability or functionality failure**

  Something like a deflection, If we are talking about a bridge, I can say the deflection at midspan or the center of the bridge has to be within, let us say 1 centimetre or something like that, 1 centimetre or 2 something, some limit we will provide for the deflection. It is not that bridge will fall or break into two, but there will be some deflection. However, we want to limit that deflection so that it is comfortable to use that structure. So that is one example of serviceability criteria or functional criteria.